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SEISMIC RESPONSE OF THE ACR™ REACTOR BUILDING

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ABSTRACT

The Advanced CANDU Reactor or the ACR™ is developed by Atomic Energy of Canada Limited (AECL) to be the next step in the evolution of the CANDU product line. It is based on the proven CANDU technology and incorporates advanced design technologies. Two standard designs of the ACR are developed: ACR-1000 and ACR-700. The ACR is designed to incorporate the latest advances in design and construction techniques and to be cost competitive while achieving higher safety and performance standards.

This paper describes the methodology of the seismic qualification of the ACR reactor buildings. The ACR standard plant is conservatively qualified for a design basis earthquake with peak horizontal ground acceleration of 0.3g and for a wide range of soil/rock foundation conditions. The input design ground response spectra address current technical issues such as earthquake input motions with high frequency content and near field effects.

The structural behavior of the ACR-700 reactor building under the design earthquake is determined using two dynamic models. The dynamic characterizes of the reactor building are established using a stick model and a three-dimensional finite element model. In developing the dynamic models, considerations are given to the details of both the containment and internal structures, and to location and weight of major equipment and systems. The soil-structure-interaction effects are considered in the seismic analysis. The structural responses of the reactor building due to the design basis earthquake are determined and are used for the assessment of the reactor building stability. The seismic responses of the reactor building include displacement and acceleration responses and base shear and overturning moments.

Keywords: seismic, earthquake, finite element, dynamic stability, and soil-structure-interaction

1. INTRODUCTION

The ACR-700 reactor building consists of the containment structure and the internal structure. The containment structure and the internal structure are supported on a common base slab, Figure 1. The containment structure is made of prestressed concrete and the internal structure is made of reinforced concrete and structural steel. The containment structure is part of the containment system and provides the outer boundary of the reactor building.

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The internal structure consists of reinforced concrete shear walls and floor slabs, which support the equipments and systems of the nuclear power plant. Both the containment structure and the internal structure are structurally independent above the common base slab.

The parameters of the design basis earthquake for the ACR plant are given in Table 1. The peak vertical ground motion parameters are taken as 2/3 of the horizontal motion parameters. The seismic design approach is based on principle on CSA/CSA-N289 series of standards, Reference 1 to 5, and in general satisfies the international and IAEA standards. The Ground Response Spectra (GRS), Figure 2, are developed for soil and rock sites according to methods described in CSA/CSA-N289, Reference 3. These spectra are based on amplification factors associated with the 90th percentile versus the normally used 84th percentile in other standards.

For rock sites and for near-field earthquake sources, the frequency content of the ground response spectra as defined in N289.3 and in other similar standards may not be sufficient. To cater for these conditions, the control frequencies for the rock sites GRS are changed to 14 Hz and 40 Hz from 8 Hz and 33 Hz usually used for soil sites. This change would enrich the frequency content of the spectrum in this frequency range to address the current state of knowledge for the nature of the Central and Eastern North American earthquakes.

Two sets of three statistically independent design acceleration time histories are generated to be compatible with the rock and soil design ground response spectra. The generated time histories have to satisfy the requirements given in N289.3, Reference 3. The requirements are to envelope the design ground response spectra and to adequately match the target compatible power spectral density function.

In order to design a standard plant that can be located at many sites without major changes, the potential sites for the ACR plant are evaluated and classified. Foundation conditions are found to range from rock sites to shallow and deep soil sites. Nine generic soil profiles were developed and are used in the seismic design of the ACR plant. Along with the fixed-base case, the nine design soil profiles provide a wide envelope of the range of potential ACR sites.

For each soil profile, the total depth to bedrock and the variation of dynamic soil properties are established to provide reasonably conservative results. This results in an overall plant design that has a significant design margin when qualified for any single specific site condition, Reference 6. The variations of maximum shear wave velocities with depth assigned for each of the soil profiles are presented in Figure 3 and Table 2.

2. REACTOR BUILDING MODELS

Two models of the ACR-700 reactor building are used to investigate its seismic structural behaviour due to the design earthquakes: a stick model and a three-dimensional finite element model. The dynamic characteristics obtained from one model are validated by the characteristics obtained by the other model. In developing the seismic analysis models, considerations for the details of both the containment and internal structures, in addition to location and weight of major equipment and systems, are made. The material damping ratios, specified in N289.3, Reference 3, are used in accounting for the damping characteristics in both models.

2.1 Stick Model

The stick model is a lumped-mass model with degrees of freedom defined at each node. The dynamic model consists of two sticks, one stick represents the containment structure and the other stick represents the internal structural as shown in Figure 4.

The mass of the containment structure and that of the internal structure are lumped at 29 nodes. The mass and mass moment of inertia at each node of the structure are determined by lumping the mass of the walls, the concrete floors, steel platforms, major equipment, and equivalent masses for superimposed dead load and live loads. The mass nodes are connected by 3D beam elements that represent the stiffness characteristics of the structure. For the internal structure, the center of mass at each floor is not coincident with the center of the stiffness. Rigid elements are defined at each floor to connect the center of mass with the center of the stiffness to represent the floor eccentricity.

The mass of the base slab and the mass contributions from the containment structure, the internal structure, and the equipment supported on base slab are lumped together at one node. Rigid links are defined between the base slab and the stick models of the containment structure and the internal structure to represent the thickness of the base slab.

Equivalent soil springs are introduced at the bottom of the reactor building to consider the interaction between the reactor building and the foundation medium in the seismic analysis, Reference 7. Six springs are defined to represent the stiffness properties of the foundation medium in three translation and three rotational degrees of freedom. Each spring is connected to the base slab at one end and is fixed at the other end. The spring stiffness properties are provided in Figure 5 for nine cases of the foundation medium. Equivalent damping ratios are used to model the damping characteristics of the foundation medium including radiation damping.

The modal characteristics of the ACR-700 stick model including the modes of vibration and their associated mode shapes are obtained using the computer program STARDYNE.

2.2 3D Model Finite Element Model

The 3D-finite element model of the ACR-700 reactor building is developed using the computer program ANSYS, Figure 6. The model includes the internal and the containment structures along with the base slab, Figure 7. The foundation medium is represented by a super-element with the appropriate boundary conditions.

The containment structure is modelled using shell elements. The containment buttresses and airlock openings are included in the containment structure model. The mass of the containment steel liner is accounted for in the dynamic analysis by scaling up the mass density of the containment shell. The finite elements defined for both wall and dome are parallel to the prestressing tendons (hoop and vertical) and to the steel reinforcement.

The internal structure walls and floors are modelled using shell elements. The shell elements for the concrete internal structure are assigned the applicable thickness. Major openings in the shear walls and floor slabs of the concrete internal structure are considered in the model. The mass of the internal structure is based on the masses of concrete structures, structural steel, steel platforms, major equipments, and equivalent masses for superimposed dead load and live loads.

The base slab is modeled using solid elements. The base slab nodes and elements are defined such that the connectivity with the containment structure, the internal structure and the foundation medium is properly modeled. Constraint equations are introduced at the nodes connecting the containment and the internal structures to the base slab. The constraint equations are defined to establish a moment transfer connections between the containment structure, the internal structure and the base slab.

The foundation medium is presented in the 3D model by a cylindrical island. Only the stiffness characteristics of the foundation medium are considered in the analysis. Solid elements are used for the foundation medium; however since the sub-structuring technique is used in the seismic analysis, the foundation medium is further defined by a super-element. The foundation medium nodes and elements are defined such that connectivity with the base slab is properly achieved. The different layers for the design soil profiles are considered in the foundation medium model.

The boundary conditions of the reactor building 3D Model are applied to the foundation medium super-element. All nodes at the bottom surface of the soil medium are restrained in all degrees of freedom (translations in three directions). Symmetrical restraints are defined on all nodes on the curved surface of the foundation medium island.

The modal characteristics of the ACR-700 3D finite element model including the modes of vibration and their associated mode shapes are obtained using the computer program ANSYS.

3. SEISMIC RESPONSE OF THE REACTOR BUILDING

Figure 8 shows the fundamental frequencies of the lateral modes of vibration for the reactor building supported on the ten cases of foundation medium obtained by the two analysis models. A very close agreement between the two sets of reactor building modal characteristics can be observed. The fundamental lateral frequency for the combined system of the reactor building and its supporting foundation medium ranges between 4.20 Hz and 1.16 Hz based on the supporting foundation medium.

The seismic analysis of the ACR-700 reactor building is based on the modal characteristics obtained for both dynamic model and the 3D finite element model described above. All modes below 33 Hz are considered in the modal combination process. The CQC method is used for modal combination and the SRSS method is used to combine the three seismic responses to the three-directional seismic input. Each of the two seismic analyses produces a set of structural responses.

The seismic responses of the reactor building stick model include the floor displacements and accelerations in addition to the inter-story shear forces and bending moments. The variation of the seismic responses along the height is determined for the containment structure and the internal structure using the stick model. Figures 9 and 10 present the displacement and acceleration responses of the containment structure due to a horizontal component of the GRS for the ten cases of foundation medium. The inter-story shear forces and bending moments for the containment structure are provided in Figures 11 and 12.

The seismic responses of the reactor building 3D finite element model include contours of the nodal displacements and nodal accelerations. In addition, contours depicting the directional stresses in the shell and solid elements are obtained. A seismic component, of the three components of the GRS, is applied one at time to the 3D finite element model. The analysis is carried out for the ten cases of the foundation medium. Figures 13 and 14 present the contours of the containment structure displacement and acceleration responses due to a horizontal component of the GRS for the case of A-1 soil profile. Similar contours for the internal structure displacement and acceleration responses are provided in Figures 15 and 16. Figures 17 and 18 present the von Mises stress contours for the elements of the containment and internal structures due to a horizontal component of the GRS for the case of A-1 soil profile.

Transient dynamic analyses are carried out using the stick model subjected to the design acceleration time history. The analyses resulted in acceleration response histories at nodes (floors) at which major equipment are attached. Using the acceleration response histories, the response spectra at each of the floors are calculated for each soil condition. The floor response spectra are enveloped and broadened to produce the design floor response spectra in the horizontal and vertical directions.

4. SEISMIC DESIGN OF THE REACTOR BUILDING

The output of the seismic analyses carried out for the ACR-700 reactor building is used in its general structural design in the preliminary and detailed phases of engineering.

The seismic responses obtained from the analysis of the stick model are used in the preliminary design of the reactor building. Both inter-storey shears and bending moments are employed in confirming the adequacy of the wall thickness for the containment and internal structures. Checking the seismic stability of the reactor building against sliding, floatation and overturning is based on the nodal acceleration responses. Uplift studies of the reactor building are carried out using the nodal acceleration responses as well. The reactor building has safety factors against sliding; floatation and overturning that exceed the levels specified in seismic design codes, Reference 3. The reactor building uplift studies indicate that maximum reached uplift would still be less than 30% of the base slab total area which is considered acceptable.

The seismic responses obtained from the 3D finite element model are used in the structural design and detailing of concrete walls and floors of the containment and internal structures. Acceleration and displacement responses confirm the nodal responses of the stick model.

The design floor response spectra are used in the seismic qualification of equipment anchored to and supported on the containment and internal structures. The detailed design of steel structures supported to the concrete internal structure uses the design floor response spectra as well. The floor response spectra at the top of the concrete internal structure and at the top of containment structure are shown in Figures 19 and 20.

5. SUMMARY AND CONCLUSIONS

The ACR nuclear power plant seismic design is based on sound principles and practices that are consistent with international codes and standards. The application of the Canadian seismic approaches including the state-of-the-art tools and techniques has ensured a robust design of ACR nuclear power plant which is conservatively qualified for a peak horizontal ground acceleration of 0.3g and for sites with a wide range of soil/rock properties.

A review of the seismic analysis and design of the ACR-700 reactor building is presented. The seismic analysis is the basis of the seismic design approach for meeting the safety design requirements. The analysis is carried out using a stick model that captures both mass and stiffness characteristics of the reactor building. A detailed 3D finite element model that captures areas of irregularities and stress concentration is used in the analysis as well. Examples of the seismic structural responses are presented along with the main dynamic characteristics of the reactor building taking into accounts the soil-structure-interaction.

6. REFERENCES

1 CSA/CAN3–N289.1, “General Requirements for Seismic Qualification of CANDU Nuclear Power Plants.”

2 CSA/CAN3–N289.2, “Ground Motion Determination for Seismic Qualification of CANDU Nuclear Power Plants.”

3 CSA/CAN3–N289.3, “Design Procedures for Seismic Qualification of CANDU Nuclear Power Plants.”

4 CSA/CAN3-N289.4, “Testing Procedures for Seismic Qualification of CANDU Nuclear Power Plants.”

5 CAN/CSA–N289.5, “ Seismic Instrumentation Requirements for CANDU Nuclear Power Plants.”

6 M. Elgohary, A. Saudy, and T. Aziz, “Seismic Design Features of the ACR Nuclear Power Plant,” Paper #K01-4, Transactions of the 17th International Conference on Structural Mechanics in Reactor Technology (SMiRT 17) Prague, Czech Republic, August 17 - 22, 2003.

7 ASCE 4-98, “Seismic Analysis of Safety-Related Nuclear Structures”.

Appendix of Tables

Table 1: Design Basis Seismic Ground Motion Parameters

Parameter	Soil Site	Rock Site
Peak Horizontal Acceleration (g)	0.30	0.30
Peak Horizontal Velocity (mm/s)	365.8	213.3
Peak Horizontal Displacement (mm)	274.3	93.2

Table 2: Shear Wave Velocities for Different Soil/Rock Profiles

Category	D		C			B			A
X - Depth to Bedrock (m)	90.0		60.0			30.0			9.0
Soil Profile	D-1	C-3	C-2	C-1	B-3	B-2	B-1	A-2	A-1
Layer (I) = 9.0 m	160	160	330	570	340	500	590	340	590
Layer (II) = 21.0 m	190	190	380	670	430	650	760	----	----
Layer (III) = 30.0 m	230	800	460	800	----	----	----	----	----
Layer (IV) = 30.0 m	260	----	----	----	----	----	----	----	----

Appendix of Figures

Figure 1: ACR-700 Reactor Building

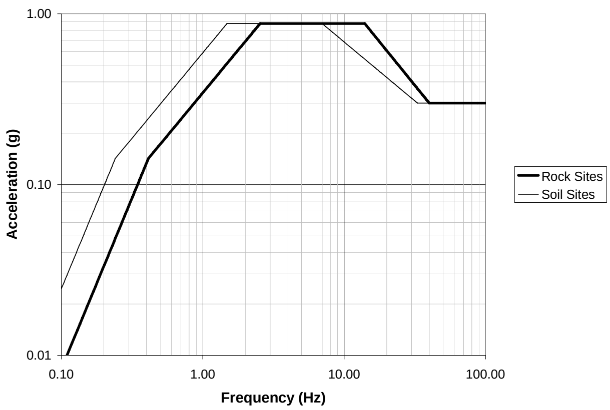

Figure 2: Design Ground Response Spectra

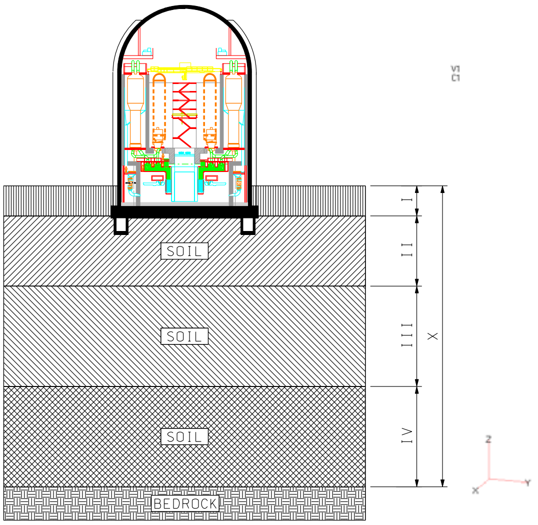

Figure 3: Design Soil/Rock Profiles

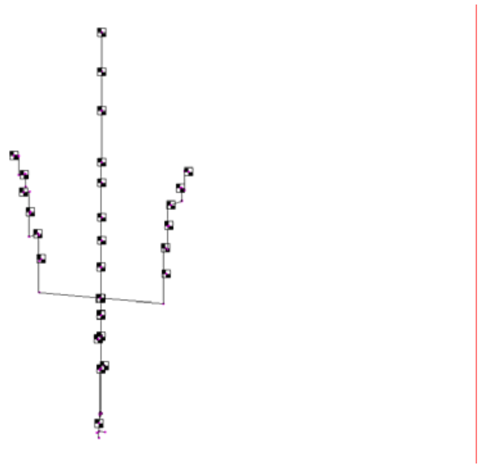

Figure 4: Stick Model of Reactor Building

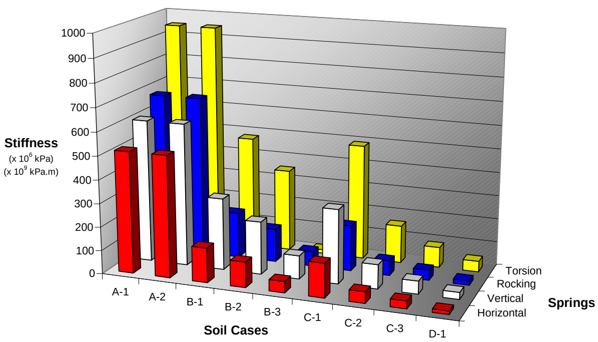

Figure 5:Stiffness of Equivalent Soil Springs

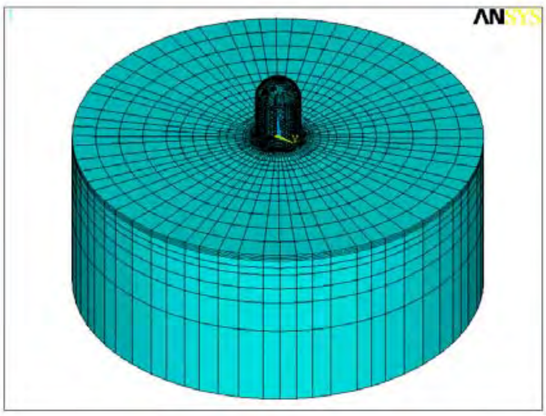

Figure 6:Model of Reactor Building and Soil

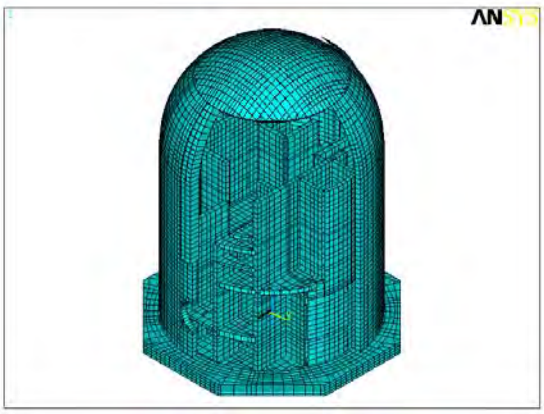

Figure 7: Reactor Building 3D FE Model

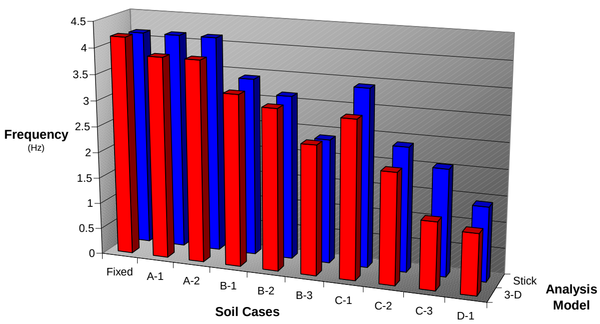

Figure 8: RB Fundamental Lateral Frequency

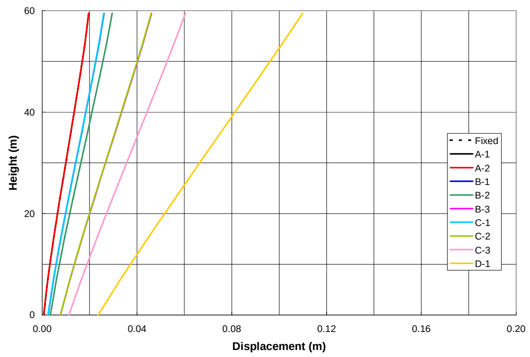

Figure 9: C/S Hori. Displacement Response

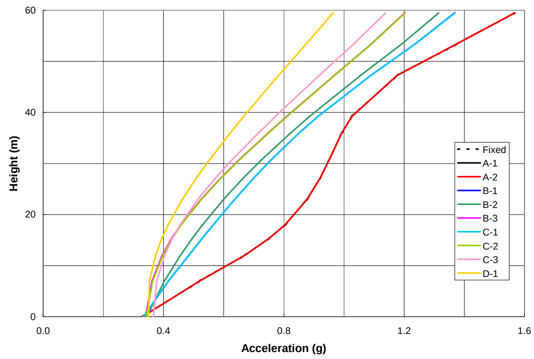

Figure 10: C/S Hori. Acceleration Response

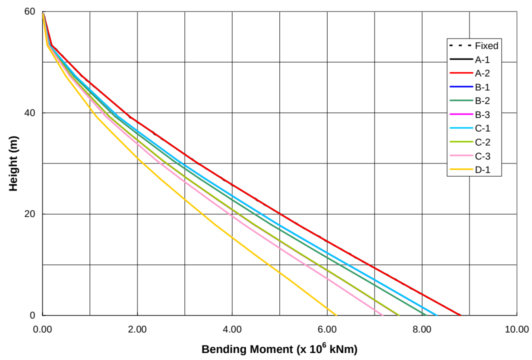

Figure 11: C/S Hori. Bending Moment Response

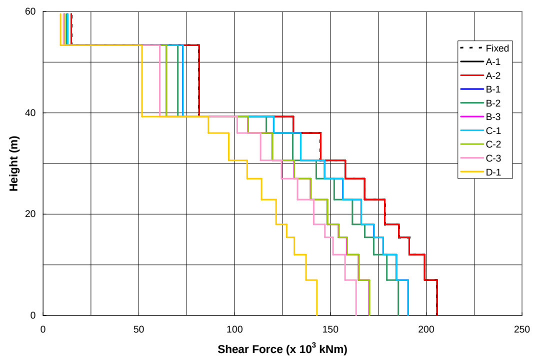

Figure 12: C/S Hori. Shear Force Response

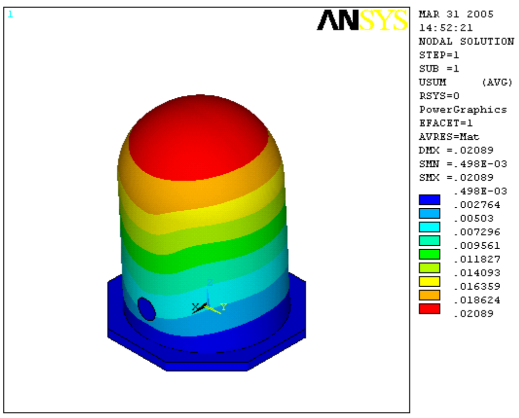

Figure 13: C/S Hori. Displacement Response

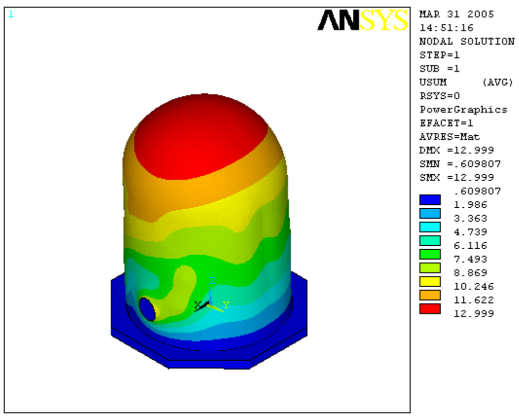

Figure 14: C/S Hori. Acceleration Response

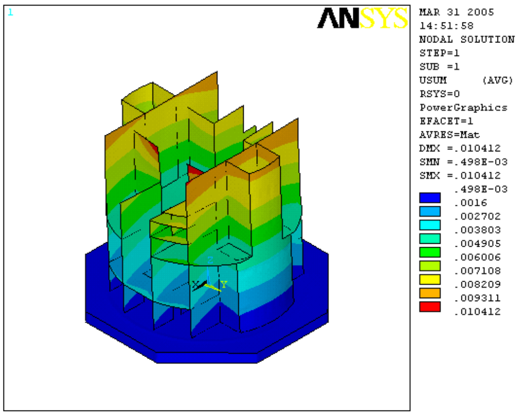

Figure 15: I/S Hori. Displacement Response

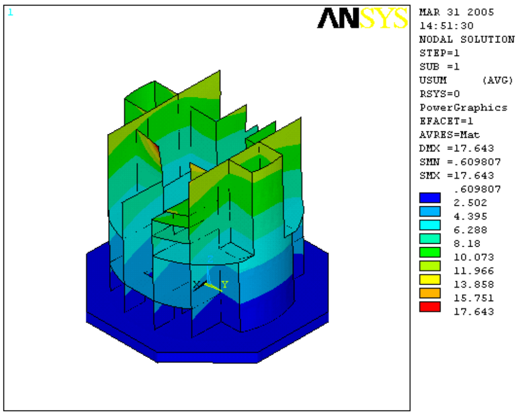

Figure 16: I/S Hori. Acceleration Response

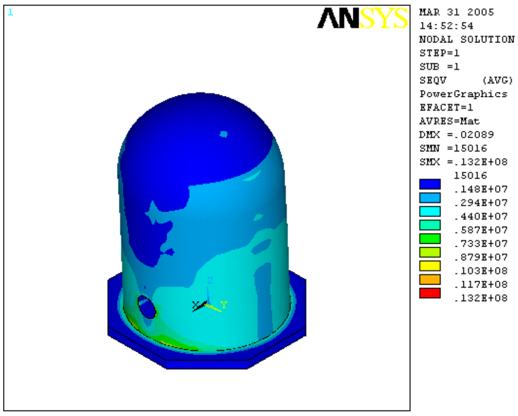

Figure 17: C/S von Mises Stresses

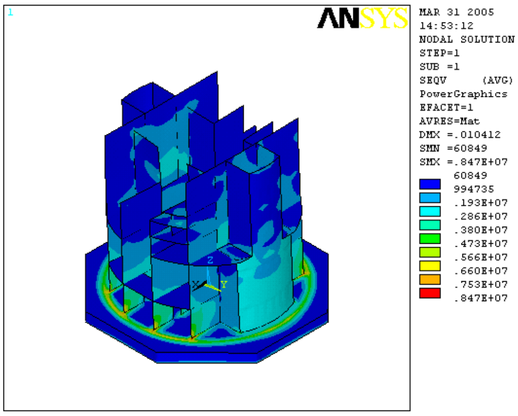

Figure 18: I/S von Mises Stresses

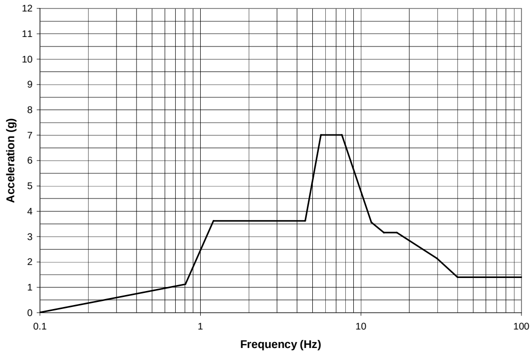

Figure 19: Horizontal FRS at Top of I/S

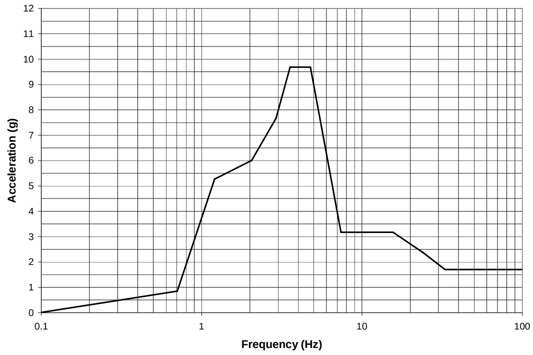

Figure 20:Horizontal FRS at Top of C/S