Seismic Design Bases of the US-APWR Standard Plant

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Abstract

The purpose of this technical report is to present the seismic design bases of the US-APWR standard plant.

This report describes:

- Establishment of Input Ground Motion Acceleration Time Histories
- Development of Generic Layered Soil Profiles
- Enhancement and Validation of the SASSI Model of PS/B
- Development of SASSI Model of R/B Complex
- Consideration of Concrete Cracking in Dynamic Modeling

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List of Acronyms

The following list defines the acronyms used in this document.

3-D	**three dimensional**
ARS	**acceleration response spectra**
CENA	**central and eastern North America**
CIS	**containment internal structure**
CM	**center of mass**
CSDRS	**certified seismic design response spectra**
DCD	**design control document**
EW	**east-west**
FE	**finite element**
FH/A	**fuel handling area**
GMPE	**ground motion prediction equation**
ISRS	**in-structure response spectra**
MCP	**main coolant piping**
MHI	**Mitsubishi Heavy Industries**
NRC	**Nuclear Regulatory Commission**
NS	**north-south**
PCCV	**prestressed concrete containment vessel**
PS/B	**power source building**
RAI	**request for additional information**
R/B	**reactor building**
RCL	**reactor coolant loop**
RCP	**reactor coolant pump**
RG	**Regulatory Guide**
RV	**reactor vessel**
SC	**steel-concrete**
SG	**steam generator**
SDOF	**single degree of freedom**
SRP	**Standard Review Plan**
SSI	**soil-structure interaction**

TF	**transfer functions**
TR	**technical report**
US	**United States**
V	**vertical**
WNA	**western North America**

1.0 INTRODUCTION

The design of US-APWR standard plant structures is based on the analyses of the seismic responses of dynamic models, considering the effects of soil-structure interaction (SSI). Consistent with the US-APWR design control document (DCD), the seismic response analyses incorporates each of the following issues:

- development of adequate acceleration time histories compatible to the US-APWR certified seismic design response spectra (CSDRS) used as input design ground motion in the analyses;

- consideration of generic soil profiles that can provide an adequate representation of conditions at candidate sites within the continental United States (US);

- adequate consideration of the frequency dependence of the SSI;

- ability of the models to adequately represent the dynamic properties of the structures, and to address the effects of concrete cracking on the seismic response.

This report documents the development of time histories of the three ground motion components compatible to US-APWR CSDRS. The time histories are synthesized using seed ground motion recordings that are in full compliance with the criteria of Standard Review Plan (SRP) 3.7.1 (Reference 1), Subsection 3.7.1.II.1B. In addition, the seismic design is to be based on a set of SSI analyses performed using the computer program ACS SASSI (Reference 2) that captures the frequency dependence of the SSI system and addresses the effect of the soil layering and elevation of the ground water table. These SSI analyses consider generic profiles representing layered subgrade properties. The development of the generic layered site profiles consistent with the CSDRS are documented in this technical report.

A finite element (FE) structural model for SSI analyses of the bounding power source building (PS/B) configuration is developed and converted into ACS SASSI format. This report presents the PS/B FE structural model and the results of the validation analyses performed to demonstrate its ability to accurately represent the dynamic properties of the PS/B at all important modes of vibration.

The standard design of the reactor building (R/B) complex is based on seismic response analyses of lumped mass stick models representing the dynamic properties of the prestressed concrete containment vessel (PCCV), containment internal structures (CIS), and the R/B resting on a common basemat foundation. To account for the effects of dynamic coupling of the CIS with the equipment and the piping, the analysis of the R/B complex is also enhanced by including lumped mass stick models representing the stiffness and mass inertia properties of the major equipment and piping, as described in Technical Report MUAP-08005 (Reference 3). The coupled model of the R/B complex is enhanced to incorporate single degree of freedom (SDOF) models representing the out-of-plane response of flexible slabs and walls. This report presents the methodology used for development of the SDOF and describes the enhanced lumped mass stick model for SASSI analyses of the R/B complex.

The methodology and structural modeling approach used in the SSI analyses of R/B complex and the PS/B will address the effects of concrete cracking on the seismic response of the buildings by adjusting the stiffness properties of the structural members affected by the concrete cracking. This report describes how the effects of the concrete cracking are addressed in the dynamic modeling of R/B complex and PS/B.

The CSDRS compatible ground motion time histories, the generic layered profiles and the structural dynamic models described in this report define the input for the SSI analyses of the US-APWR standard plant seismic Category I structures. A subsequent report will be issued in April, 2010, to document the methodology and the results of these SSI analyses. Sections 4.3.4 and 5.3.3 of this report present the methodology and the results of the validation analyses of the PCCV lumped mass stick model. The validation of the lumped mass stick models of the CIS and R/B will be performed following the methodology used for validation of the PCCV model. The results of these validation analyses will be presented in a subsequent report to be issued in April, 2010.

2.0 PURPOSE

The purpose of this technical report is to outline the technical approach related to the seismic design bases, and the dynamic modeling and methodology used for seismic response analyses of the US-APWR R/B complex and PS/Bs. This report outlines the general methodology used for the SSI analyses of the R/B complex and PS/Bs.

A detailed discussion regarding the following input parameters and modeling issues is also provided to resolve request for additional information (RAI) questions and comments by the NRC, as summarized in Table 2.0-1:

1. Establishment of CSDRS compatible acceleration time histories
2. Development of generic layered soil profiles and strain compatible properties
3. Development of the SASSI lumped mass stick model of R/B complex
4. Development and validation of the SASSI FE Model of PS/B
5. Consideration of Concrete Cracking

Table 2.0-1 Resolution Methodology for RAI Questions on Seismic Design Basis (Sheet 1 of 3)

RAI #	Question #	Issue	Resolution Methodology
Generic Subgrade Profiles for SSI Analyses and Development of Spring Stiffnesses for Foundation Analyses			
496	**3.8.5-23**	Shape of basemat, mass center of structure	The methods used for dynamic modeling of the re-configured R/B complex is a more uniform rectangular shape over its depth. The dynamic analysis results for the R/B and reactor coolant loop (RCL) will be presented separately in Revision 1 of MUAP-08005, “Dynamic Analysis of the Coupled RCL-R/B-PCCV-CIS Lumped Mass Stick Model”.
496	**3.8.5-24**	Uncertainties in soil properties in each subgrade type	Changes are incorporated in the standard plant seismic analysis with respect to consideration of layering effects in the subgrade, through the use of generic layered soil profiles and the consideration of frequency-dependence of the subgrade.
Cracking Effects in Dynamic Analysis and in Development of ISRS			
212	**3.7.2-8**	ISRS considering local vibration modes	The R/B dynamic stick model analysis uses “lollipops” at key locations where slab and wall flexibility are important to account for in the dynamic analyses. The development of the PS/B finite element dynamic model captures slab and wall flexibility effects directly in the dynamic modeling.
212	**3.7.2-15**	Effects of potential concrete cracking	The effects of potential concrete cracking on structural stiffnesses are considered in the development of local vibration modes for the ISRS. Updated ISRS, derived with consideration given to potential concrete cracking, will be presented in updated seismic analysis reports MUAP-08005 and MUAP-08002 for the R/B and PS/Bs, respectively.
497	**3.8.4-33**	Effects of concrete cracking on lateral displacement	Cracking effects (in-plane and out-of-plane) for reinforced concrete shear walls are accounted for as described in this report. Concrete cracking affects the magnitude of the calculated lateral displacements of the R/B complex. Lateral displacement calculations will also include effects due to differential settlement on the overall computed displacements. The current DCD limits for acceptable settlement are given in Chapter 2 Table 2.0-1.

Table 2.0-1 Resolution Methodology for RAI Questions on Seismic Design Basis (Sheet 2 of 3)

RAI #	Question #	Issue	Resolution Methodology
497	**3.8.4-38**	Effects of concrete cracking on seismic analyses	The effects of concrete cracking on the seismic analysis results are discussed in detail, including the discussion of how these effects are incorporated into the seismic analyses.
Validation of the dynamic models (including sufficient ability to capture high-frequency content of the input motion)			
211	**3.7.1-6**	Ensuring adequate DOFs in the dynamic models to capture seismic response in high frequency range	Enhancements made to the dynamic models as described in this report ensure that the criteria of SRP 3.7.2 II A (iv) are met.
212	**3.7.2-3**	Validation of R/B lumped mass stick models	Additional information with respect to validation of the US-APWR lumped mass stick models is provided.
212	**3.7.2-17**	Description of how lumped mass and distributed mass models meet SRP 3.7.2.II.3C	Additional information is included on the validation comparison between the dynamic responses of the lumped mass stick models and the FE distributed mass models, including description of the frequency domain time history analysis of the fixed base detailed FE model.
212	**3.7.2-18**	Modeling methods and validation of dynamic model for PS/Bs	The seismic design of the PS/B is based on time history analysis of the PS/B FE model, which meets the dynamic analysis criteria of SRP 3.7.2, Section II.1.A.

Table 2.0-1 Resolution Methodology for RAI Questions on Seismic Design Basis (Sheet 3 of 3)

Establishment of Input Ground Motion Acceleration Time Histories			
211	**3.7.1-1**	Nonexceedances of the ground motion time histories	This report presents three time histories which are generated, using ground motion recordings of earthquakes as the seeds. The systemization and the characteristics of these time histories are in full compliance with the requirements of SRP Subsection 3.7.1.II.1B, and therefore represent an appropriate time history representation of the modified Regulatory Guide 1.60 response spectrum.
211	**3.7.1-2**	Enveloping the target response spectra.	See resolution methodology for Question 3.7.1-1.
211	**3.7.1-3**	Generation of time histories based on seed recordings of earthquake motion.	See resolution methodology for Question 3.7.1-1.

3.0 OBJECTIVES

3.1 CSDRS Compatible Ground Motion Time Histories

In full compliance with the requirements of SRP 3.7.1 (Reference 1), Subsection 3.7.1.II.1B, Option 1 Approach 2, the objective is to synthesize a set of three time histories, by using ground motion recordings of earthquakes as the seeds, a set of three statistically independent time histories that are compatible with the two horizontal directions and the vertical direction of the US-APWR CSDRS. These new acceleration time histories will be used as input ground motion for the set of SSI analyses described within this technical report. Development of the new time histories also addresses RAI 211-1946, Questions 3.7.1-1, 3.7.1-2, and 3.7.1-3, regarding the content of the acceleration time histories used in previous revisions of the DCD.

3.2 Generic Layered Soil Profiles and Strain Compatible Properties

The objective is to provide a set of input subgrade properties for the SSI analyses that are compatible with the US-APWR CSDRS and the strains generated by the input ground motion. A set of generic layered soil profiles are developed to be used as input for the set of SSI analyses described within this technical report. These subgrade properties envelope the effects of geological, geotechnical, and hydrological site parameters for representative nuclear power plant sites within the continental US. The generic layered profiles, for which strain-compatible properties, shear- and compressional-wave velocities and corresponding hysteretic damping values are developed, provide a wide variation of properties that addresses soil properties uncertainties for typical sites across central and eastern North America (CENA). The use of generic layered profiles addresses the subject of soil properties in RAI 496-3735, Questions 3.8.5-24 and 3.8.5-25. The SSI analyses of the set of generic layered soil profiles also consider the effects of the frequency dependence of the SSI, the layering of the subgrade, and the elevation of water table. This technical report also addresses issues regarding seismic analyses requirements discussed during a conference call between the Nuclear Regulatory Commission (NRC) and Mitsubishi Heavy Industries (MHI) on September 28, 2009.

3.3 Enhanced ACS SASSI Lumped-Mass-Stick Model of R/B Complex

The objective of the ACS SASSI model is to provide an adequate representation of the dynamic properties of the building, and to be able to capture SSI effects related to the flexibility of the basemat foundation. The model will be used for the SASSI analyses of the R/B complex and will be able the incorporation of effects on the seismic response of the building due to frequency dependence of the SSI impedance, layering of the subgrade, elevation of the water table, and scattering of input ground motion.

An ACS SASSI lumped mass stick model of the R/B complex is developed for the set of SSI analyses. The coupled lumped mass stick model of the R/B complex is enhanced by adding SDOF models to capture the out-of-plane response of flexible slabs and walls and to address modeling concerns raised in RAI 212-1950, Question 3.7.2-8. The stiffness properties of the model are also adjusted to address concerns raised in RAI 497-3734, Questions 3.8.4-33 and 3.8.4-38, regarding the effects of concrete cracking on the seismic response of the building. The enhanced lumped mass stick model is then translated into ACS SASSI to represent the stiffness and mass inertia properties of the structures above the ground elevation, and integrated with a three dimensional (3-D) FE model of the R/B complex basement. The SASSI models incorporate the latest configuration of the R/B basement, which eliminates the previous “dent” in the foundation underneath the PCCV area and also “boxes out” the region underneath the R/B fuel handling area. These configuration and modeling enhancements minimize irregularities in the R/B basement as noted in RAI 496-3735, Question 3.8.5-23. RAI 211-1946, Question 3.7.1-6, raised concerns about the adequacy of the R/B complex model. The enhanced R/B lumped mass stick model, combined in ACS SASSI with the FE model of the basement, provides adequate degrees of freedom to ensure that the modeling requirements of SRP 3.7.2 (Reference 4), Section II A (iv) are met, and that the seismic response in the high frequency range is captured.

A set of validation analyses will be performed to demonstrate the ability of the R/B stick model to adequately represent the dynamic properties of the structure. The results of the validation analyses, which are also in response to RAI 212-1950, Question 3.7.2-3, will be presented in a subsequent technical report.

A set of SSI analyses will be performed on the ACS SASSI lumped mass stick model of the R/B complex resting on the surface of the set of generic layered subgrade profiles. The set of acceleration time histories presented in this report will be used as input ground motion at the bottom of the basemat foundation. The SASSI analyses will provide results for 0.5%, 3%, 4%, 5%, 7%, and 10% damping acceleration response spectra (ARS) at lumped mass locations and member forces of the stick elements representing the shear walls at each major floor elevation. The results obtained from the different sets of SASSI analyses will be enveloped and then compared with the results obtained from the direct integration time history analyses for benchmarking. The envelope of the ARS results will be used to develop in-structure response spectra (ISRS) that will be broadened in a manner that will ensure applicability of the standard design for a wide variety of candidate sites. The resulting ISRS will therefore capture the effects of potential concrete cracking on structural stiffness and local vibration modes, as noted in RAI 212-1950 Question 3.7.2-15. The results of these SSI analyses will be presented in a subsequent technical report. The subsequent technical report will include both the broadened ISRS used for design as well as the unbroadened spectra extracted directly from the analyses results. The updated ISRS will also address the development of ISRS noted in RAI 498-3782, Questions 3.9.2-61 and 3.9.2-62.

3.4 ACS SASSI FE Model of the PS/Bs

The objective of the ACS SASSI FE model of the PS/B is to adequately represent the dynamic properties of the building in all important modes of vibration, and to be able to capture SSI effects related to the flexibility of the basemat foundation. The objective of the SASSI analyses of the PS/B FE model, to be documented in a subsequent technical report, is to provide input design parameters that will appropriately address the effects of the frequency dependence of the SSI impedance, layering of the subgrade, elevation of the water table and scattering of input ground motion.

A 3-D FE model is developed to analyze the seismic response of the PS/Bs considering SSI. A set of fixed-base static and modal analyses are performed on the detailed FE model of the PS/B buildings, before being translated into ACS SASSI. The results of the two models are compared to verify the accuracy and the refinement of the PS/B dynamic model. A set of ACS SASSI analyses are then performed on the dynamic FE model of the PS/B resting on the surface of a uniform half-space with very high stiffness to simulate fixed base conditions. The acceleration response spectra results, at selected locations obtained from the SASSI analyses, are then compared with the corresponding results obtained from the fixed base modal-superposition time history analyses of the detailed FE model.

The development of the ACS SASSI FE Model, and its validation described above, address the subject of RAI 212-1950, Question 3.7.2-18, and the lumped mass stick model method previously used for the PS/B.

A set of SSI analyses will be performed on the ACS SASSI FE model of the PS/B using the set of generic layered subgrade profiles and acceleration time histories presented in this report as input. The SASSI analyses will provide results for 0.5%, 3%, 4%, 5%, 7%, and 10% damping ARS at selected locations within the building. The envelope of the ARS results at selected locations obtained for the different SASSI analyses will be used to develop ISRS that will be broadened in a manner that will ensure applicability of the standard design for a wide variety of candidate sites. The resulting ISRS will therefore capture the effects of potential concrete cracking on structural stiffness and local vibration modes, which was noted in RAI 212-1950, Question 3.7.2-15. The ISRS will serve as input for seismic design of Category I equipment and components. The SASSI analyses will also provide maximum acceleration results at all nodal points that will be enveloped and used to develop SSE loads for the design of the PS/B structure. The objective of SASSI analyses of the PS/B FE model, to be documented in a subsequent technical report, is to provide input design parameters that will appropriately address the effects of the frequency dependence of the SSI impedance, layering of the subgrade, elevation of the water table and scattering of input ground motion. The updated ISRS presented in a subsequent technical report will include both the broadened ISRS used for design, as well as the unbroadened spectra extracted directly from the enhanced seismic modeling and analyses results. The updated ISRS addresses the development of ISRS as noted by RAI 498-3782, Questions 3.9.2-61 and 3.9.2-62.

3.5 Consideration of Concrete Cracking in Dynamic Analyses

The objective of the concrete cracking evaluation is to appropriately address the effects of concrete cracking in the dynamic structural models used for SSI analyses of the R/B Complex and PS/B.

Provisions of the current NRC and industry standards are reviewed for consideration of the effects of concrete cracking when modeling the effective stiffness of reinforced concrete members for dynamic analyses. The stresses in the reinforced concrete members under the most critical seismic load combination are evaluated and used to assess the potential for concrete cracking. The stiffness of the reinforced concrete members that crack under the most critical load combination are adjusted based on the provisions and recommendations of the standards.

4.0 APPROACH

4.1 CSDRS Compatible Ground Motion Time Histories

One set of three-component statistically independent time histories of seismic motion is developed for use as the input motion in the earthquake response analysis of the US-APWR standard plant. The three individual directional time histories were developed to represent the ground motion for the three orthogonal earthquake components. Following the requirements of SRP 3.7.1 (Reference 1), Subsection 3.7.1.II.1B, Option 1 Approach 2, two compatible to the horizontal ("H1" in the east-west [EW] direction, and "H2" in the north-south [NS] direction) and one compatible to the vertical ("V") are developed.

The three orthogonal directions may be alternately referred to within this technical report using the following different designations:

H1 = Direction 1 = Northridge BAL 90 = NS = Plant north-south = Global X-axis

H2 = Direction 2 = Northridge BAL 180 EW = Plant east-west = Global Y-axis

V = Direction 3 = Northridge Vertical = Vertical = UD = Up-Down = Global Z-axis

Approach 2 is utilized with the objective of generating artificial acceleration time histories whose response spectra achieve approximately mean based fits to the target CSDRS presented in Figures 3.7.1-1 and 3.7.1-2 of the DCD. The average ratio of the ARS calculated from the artificial time histories to the corresponding target CSDRS is kept only slightly greater than one. The spectral acceleration ratio is calculated frequency by frequency.

The BAL (Mt Baldy) recording of the January 14, 1994, Northridge earthquake (magnitude M6.7), is used as the seed ground motion for generating the time histories. The Northridge BAL recording was selected because it has the required duration and correlation (statistical independence among the three components comprising the time history).

The recorded time histories were spectrally matched to the target response spectrum at the damping values of 0.5%, 2%, 5%, 7% and 10%, using the RSPMatch code of "Non-Stationary Spectral Matching" (Reference 5). This code is based on a low frequency modification of the procedure described in "Generation of Synthetic Time Histories Compatible with Multi-Damping Design Response Spectra" (Reference 6). This method is designed to retain non-stationary features of the input ground motion in the course of spectrally matching it to the target spectrum.

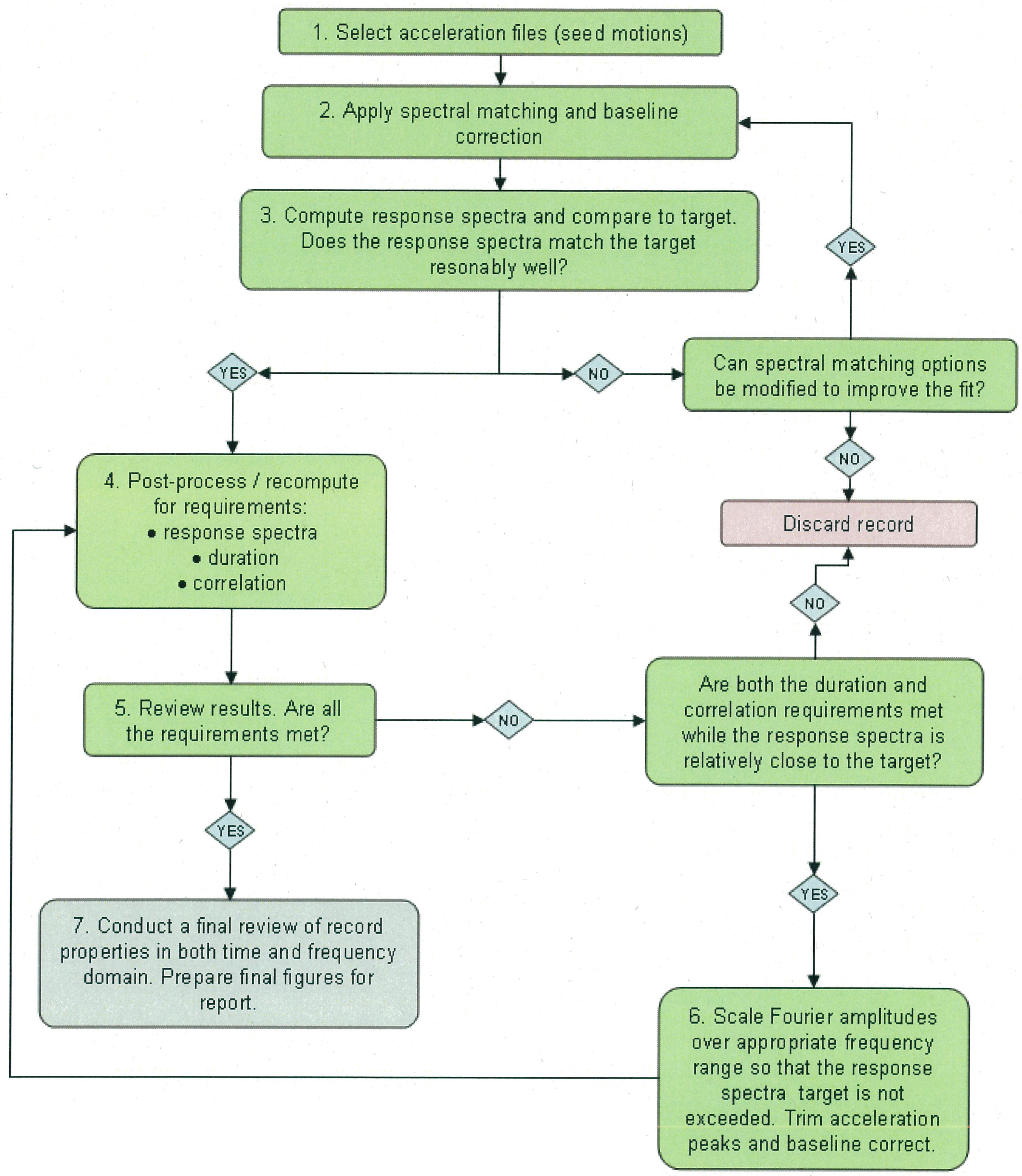


Figure 4.1-1 Computation and Post-Processing Flow Chart

The computation and post-processing scheme is summarized in Figure 4.1-1 and detailed below.

1. Select seed ground motion time series. A segment of the record time series was selected to optimize the duration of the record, measured by the method described below. This was done by visual inspection of the time series and truncation of the record. This is referred to as the original seed record.

2. Run the RSPMatch code. Complete a large number of runs to find the optimal combination of settings to use in RSPMatch. Retain copies of these iterative results along with their documentation. The optimal procedure was found to be as follows:

   a. Run RSPMatch to simultaneously match the target for the five damping ratios defined in the target and multiple iterations.

   b. Apply baseline correction to the matched time history.

   c. Rerun RSPMatch to match only the 5% damped spectral target, only with a single iteration.

   d. Apply baseline correction to that time history.

3. Repeat these steps as needed to find the optimal spectral match of the time series to the target. Transmit the resulting acceleration time series for post-processing.

4. Run the MatLab post-processors:

   a. Combine the data files after spectral matching and baseline correction using a MatLab script. There is one file for each record component.

      This software reads the files and combines the data for a given station into a single matrix/table in a standardized fashion: Columns are as follow:

      1. Time vector
      2. First horizontal component (smaller azimuth angle, as saved in file extension)
      3. Second horizontal component (larger azimuth angle, as saved in file extension)
      4. Vertical component

   b. Post-process the data using a MatLab script. This script reads the files generated above and performs the following tasks. Each task is an option in the script that can be enabled/disabled.

      1. Plot time series (recorded and modified motions)
      2. Compute and plot response spectra (modified motions only)
      3. Compute the Arias intensity and duration (recorded and modified motions)
      4. Compute components correlation (recorded and modified motions)
      5. Compute and plot spectrograms (frequency content with time)

5. Review record properties from post-processing. If the record matched all the criteria, it was considered to be final. If the record did not match one of the criteria, it was discarded. Exception: In cases where the duration and correlation criteria were

matched but the 5% damped S_a was slightly below the target at isolated periods, proceed to step 6.

6. [Optional] For the exception case defined in Step 5, the post-processors from Step 2 of 4b was run. An iterative process for scaling the Fourier amplitudes over appropriate frequency bands was used until the response spectrum met the target.

   The records were re-processed for baseline correction before the final post-processing. This involved the trimming of peaks exceeding the PGA target and baseline correction of the acceleration time series

7. Final post-processing was done to verify that the time histories matched all the criteria. The baseline-corrected records are post-processed following the detailed procedure from Step 4. A final review of the data and plots generated by the post-processors was performed.

4.2 Development of Soil Profiles and Strain Compatible Properties

In place of the generic subgrade properties for a uniform half-space that served as the basis for seismic analysis in the DCD, a complete suite of profiles and depths to basement material was developed. The profiles were initially developed to cover the entire range of generic site conditions from deep soft soil to firm rock that may exist across CENA. The initial profile development recognizes that for the softer conditions, the shallow materials would be either removed or improved for appropriate foundation conditions. From the exhaustive suite of candidate sites, a subset of profiles and depths to basement material is selected. Strain compatible properties, shear- and compressional-wave velocities and corresponding hysteretic damping values, are developed for the subset of profiles and basement depths that are consistent with the CSDRS. The suite of profiles is based on averaging measured profiles with similar velocities at sites located in western North America (WNA), and CENA, coupled with judgment. Because measurements typically do not extend to the same depths for all profiles averaged within groups of similar surficial geology or velocities, as the number of available profiles generally decreases rapidly with depth as noted in "Surface Geology Based Strong Motion Amplification Factors for the San Francisco Bay and Los Angeles Areas" (Reference 7). Therefore, judgment was used to extend the generic profiles at the deeper depths.

To make the suite of profiles regionally appropriate for CENA sites, the basement conditions are set to that of hard rock, about 9,300 ft/sec (2.83 km/sec, EPRI Technical Report [TR] TR-102293 [Reference 8]). This value is consistent with the hard rock site conditions defined in EPRI TR-1009684 (Reference 9) ground motion prediction equations (GMPEs) that are currently used to characterize the hard rock hazard in CENA. The generic profiles are classified using $\overline{V_S}$ (30m), the average shear-wave velocity over the top 30 meters. This classification is consistent with current practice for building codes and is a convenient metric with which to distinguish the initial profiles, prior to soil removal or improvement. The initial suite of eight candidate profiles is illustrated in Figure 4.2-1 to depths of 500 feet and ranges in $\overline{V_S}$ (30m) from soft soil at 180 m/sec to firm rock at 2,032 m/sec. Also shown is the consensus basement shear-wave velocity for CENA at 2.83 km/sec, as referenced by EPRI documents TR-102293 (Reference 8) and TR-1009684 (Reference 9). To accommodate the possible range in profiles for CENA, a suite of profile depths to hard rock conditions is developed ranging from 25 feet to 2,000 feet. The suite of seven profile depth bins is listed on Table 4.2-1 along with the $\overline{V_S}$ (30m) values for each category. Also listed on Table 4.2-1 for reference is the hard rock crustal model, the top layer of which defines the CENA basement rock conditions (EPRI TR-102293 [Reference 8] and TR-1009684 [Reference 9]).

4.2.1 Selection of Profiles

The profiles adopted for the development of CSDRS consistent strain compatible properties include 270 m/sec, 560 m/sec, 900 m/sec, and 2,032 m/sec. The development of strain compatible profiles considers additional soil removal if necessary to maintain a minimum (-1σ) strain compatible shear-wave velocity of at least 800 ft/sec. Four depths of soil/rock profiles above the hard rock foundations are considered: 100 ft, 200 ft, and 500 ft. Due to the stiffness of the 2,032 m/sec firm rock profile, only a 100 ft deep profile reflects realistic site conditions and represents a residual soil (saprolite) over weathered rock and underlain by hard rock. The profile is intended to reflect hard rock foundation depths after removal of the soft surficial residual soils.

For compressional-waves, a water table depth at the surface (foundation level) of each profile was assumed. The US-APWR DCD specifies a water table depth of 1 foot below the foundation which, for the development of vertical motions, is equivalent to the surface. Due to the absence of fluids over the top 1 foot, the lower compressional-wave velocity has a very minor impact on vertical motions for the softer profiles.

4.2.2 Development of US-APWR CSDRS Strain Compatible Properties

To characterize the range in strain compatible properties for each profile and depth to basement conditions in a fully probabilistic manner, each base-case profile is randomized in velocity as well as nonlinear dynamic material properties. Thirty realizations were generated for each profile category and depth to basement. Equivalent-linear site response analyses was then performed (refer to EPRI TR-102293 [Reference 8] and NUREG/CR-6728 [Reference 10]) on each random profile for horizontal motions while linear analyses were used for vertical motions (refer to EPRI TR-102293 [Reference 8] and NCEER 97-0010 [Reference 11]). For the horizontal component site response analyses, modulus reduction and hysteretic damping curves from EPRI TR-102293 (Reference 8) are used. The curves are appropriate for generic soils comprised of gravels, sands, and low PI clays (refer to Reference 8). Control motions reflect a representative magnitude of M7.5 for CENA hazard and are consistent with the spectral shape of the CSDRS. A point-source model is used to develop control motions (refer to References 8 and 10). Source distances (loading levels) are adjusted such that the median 5% damped response spectrum developed for each profile and depth to basement approaches, but does not exceed, the CSDRS. The resulting strain compatible properties are developed as median and ±1σ estimates from the analyses of the random profile realizations.

Table 4.2-1 Initial Profile Categories

Categories $\overline{V_S}$ (30m)
180
270
400
560
740
900
1,364
2,032
Depth to Hard Rock (ft) for each Category
25 ± 10
50 ± 20
100 ± 40
200 ± 80
500 ± 200
1,000 ± 400
2,000 ± 800

Hard rock crustal model (References 8 and 9)

th (km)	Vs (km/sec)	Vp (km/sec)	P (cgs)
1	2.83	4.90	2.52
11	3.52	6.10	2.71
28	3.75	6.50	2.78
	4.62	8.00	3.35

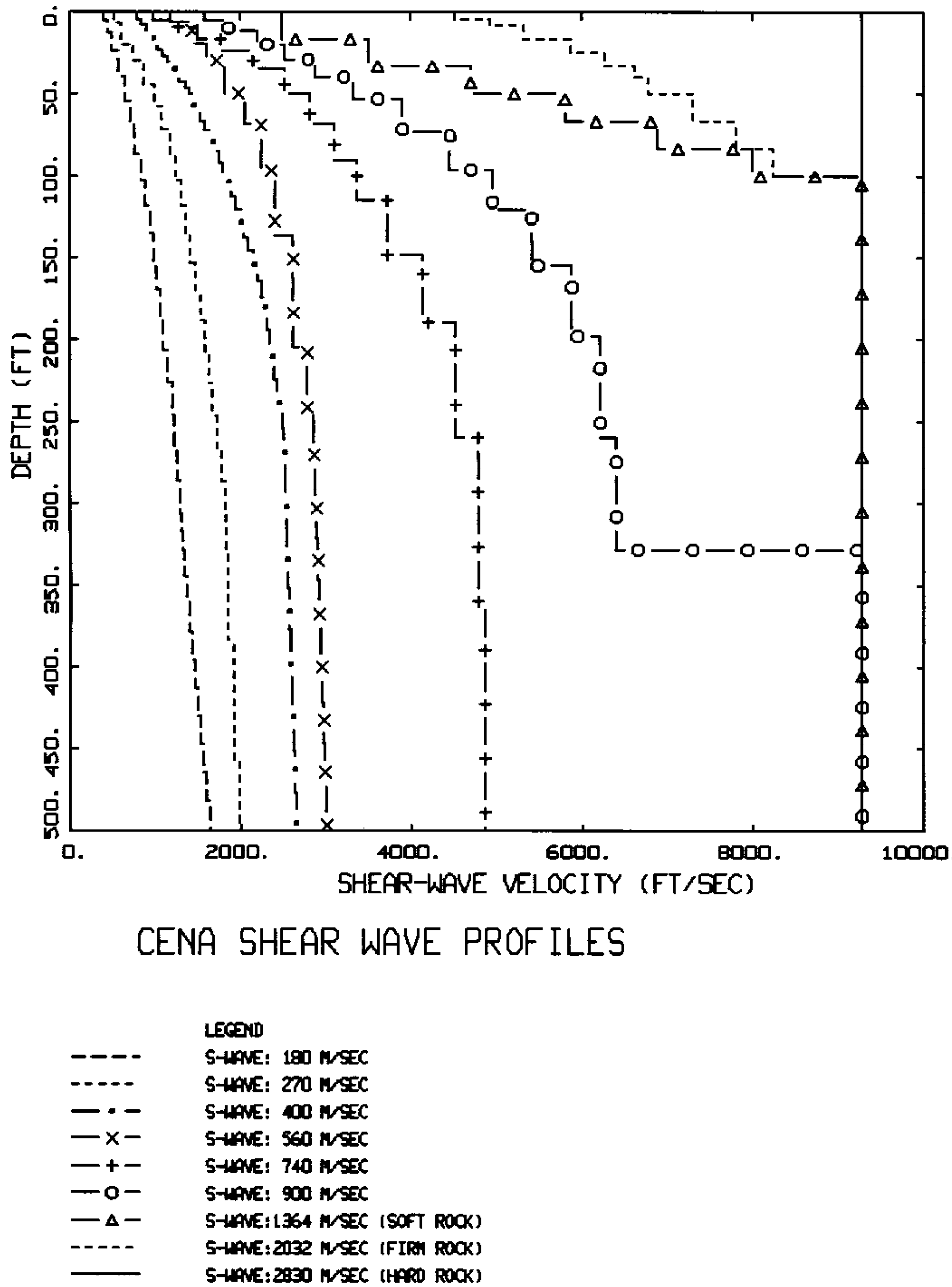


Figure 4.2-1 Top 500 ft of the Candidate Shear-Wave Velocity Profiles

4.3 Enhanced ACS SASSI Lumped-Mass-Stick Model of R/B Complex

4.3.1 Structural Modeling Approach

Three lumped mass stick models of PCCV, CIS and R/B used to represent the stiffness and mass inertia properties of the building structures above the ground elevation. As described in US-APWR Technical Report MUAP-08005, “Dynamic Analysis of the Coupled RCL-R/B-PCCV-CIS Lumped Mass Stick Model” (Reference 3), the lumped mass stick model of the CIS is coupled with a lumped mass stick models representing the stiffness and mass inertia properties of the major piping and equipment, such as the reactor vessel (RV), steam generators (SGs), and main coolant piping (MCP).

ACS SASSI 3-D beam and spring elements represent the stiffness of the reinforced concrete shear walls, PCCV, and the steel-concrete (SC) modules of the CIS. The cross sectional properties of the beam elements and the stiffness properties of the spring elements are developed following the methodology described in Subsection 3.7.2 of the DCD. Based on the analyses of the concrete cracking presented in Section 5.5 of this technical report, the cross sectional properties of the stick elements modeling the stiffness of the part of the fuel handling area (FH/A) providing enclosure to the crane are reduced to account for the in-plane concrete cracking of the NS exterior walls.

SASSI 3-D beam elements with high stiffness properties are used to rigidly connect different nodal points at the same floor elevation. The mass inertia properties of the structure, the equipment, the water in the pools and 25% of the live loads are lumped at major floor elevations by assuming the floor slabs are rigid in the in-plane direction. As a result, SDOF models are developed following the methodology described in Section 4.3.2 to capture the out-of-plane response of flexible slabs and walls.

A 3-D FE model is developed as described in Section 4.3.3 to represents the stiffness of the basemat, the walls and the floor slabs of the building basement, and the floor slabs at ground elevation. At ground elevation, the PCCV and the coupled CIS lumped mass stick model are rigidly connected to the thick central portion of the building basemat. Rigid beams connect the basement shear walls with the lumped mass stick model representing the above ground portion of the R/B and FH/A structure. The integrated model of the R/B complex is developed using the ANSYS computer program (Reference 12) and translated into the format of the computer program ACS SASSI (Reference 2) by using the built-in converter in ACS SASSI. Prior to the translation, the numbering of the SASSI model nodes is adjusted in order to minimize the bandwidth of the dynamic system matrices.

SSE material damping values are assigned to the SASSI structural model using material damping values given in Table 3.7.3-1(a) of the DCD. The SSI analyses will consider soil material damping values based on those associated with the generic soil profiles discussed in Section 5.2 of this report, and do not exceed 15%, as stipulated in SRP 3.7.1 (Reference 1).

4.3.2 Enhancement of the Lumped-Mass-Stick Models

The existing coupled lumped mass stick model of the R/B complex is enhanced by adding SDOF models to capture the out-of-plane response of flexible slabs and wall. SDOF oscillators are also used to capture the out-of-plane horizontal response of flexible walls. The vibrations of the masses, either slabs or walls, in the higher modes are assumed to be of secondary importance when the mass participation of these higher modes is much smaller then the primary mode. Therefore, they are included in the rigid mode response of the lumped floor mass.

The first step in constructing a SDOF stick model is investigating the responses of the slabs on each of the major elevations of the reactor building. Each elevation (including the section of the interior/exterior walls from the elevations above and below) is isolated from the remainder of the structure while vertical restraints are placed along the edges of the slabs adjacent to the walls. Figure 4.3.2-1 shows a FE model of the R/B floor slabs that is extracted from the detailed FE model of the R/B complex used for static analyses of the building. The section of the selected shear wall elements are set as massless to preclude any lateral excitation and then laterally restrained along the top and bottom. The sketch in Figure 4.3.2-2 shows the boundary conditions for the model.

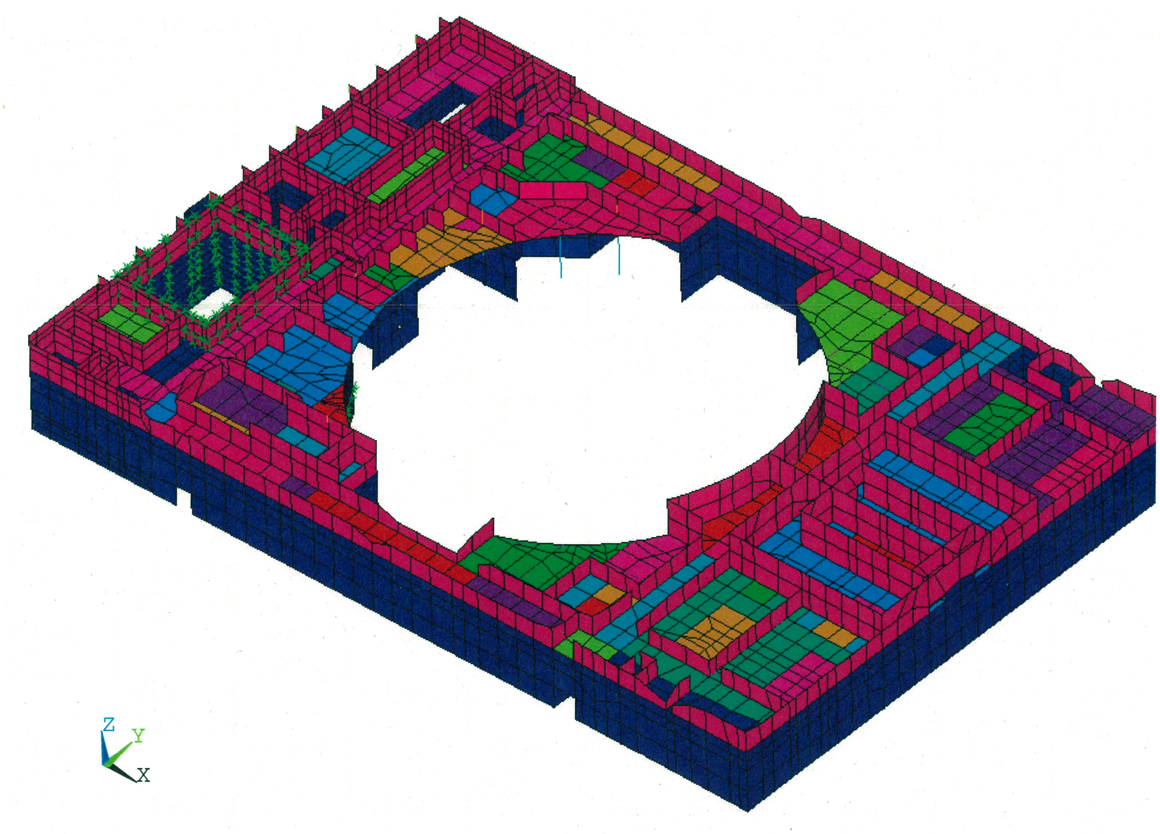


Figure 4.3.2-1 FE Model of Floor Slabs

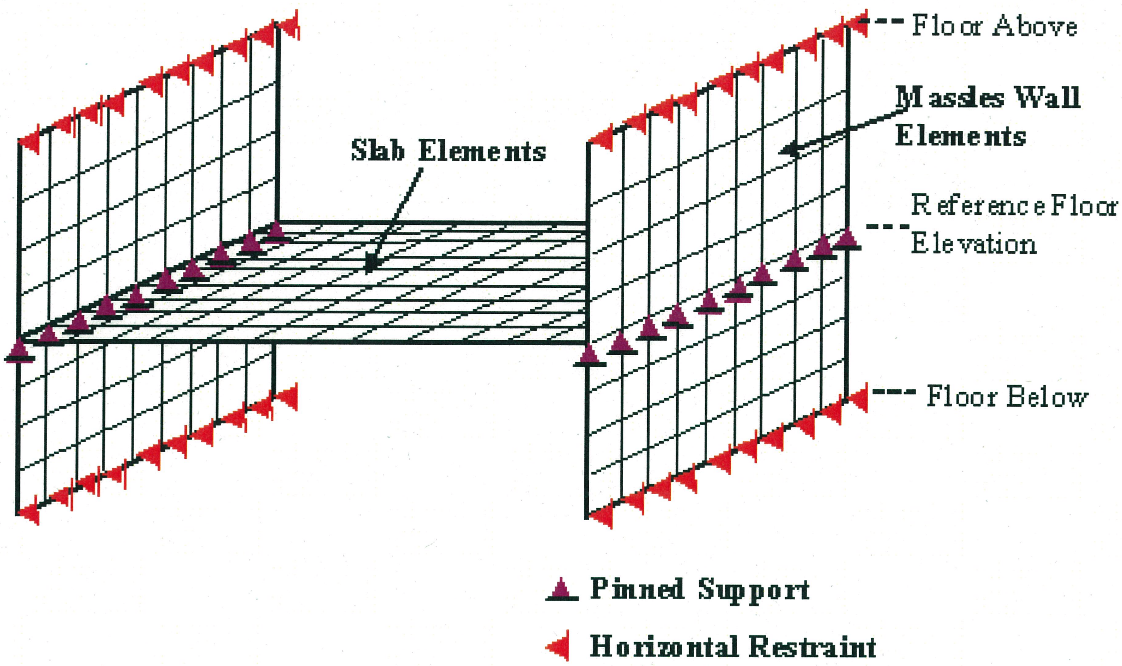


Figure 4.3.2-2 Floor Slab Model Boundary Conditions

The cracking analyses results presented in Section 5.5 indicate that under the most critical load condition the slabs of the R/B will crack, thus the moduli of elasticity of the selected slabs are reduced by 50% to simulate a cracked condition. Once the slices of each elevation are set, a modal analysis is performed to determine the vertical modes of the slabs which contain a high mass participation. The corresponding mass participation, frequency, and slab location of each mode are then extracted. The mass and frequency are used to determine an equivalent stiffness to use in the model through the following equation:

$$k = m_1 \cdot (2\pi \cdot f_1)^2$$

where m_1 is the mass participation and f_1 is the slab's resonant frequency.

The same slicing procedure is used to investigate the predominant modes of the exterior walls of the reactor building. Note that in the exterior wall modal analysis, the walls maintain their mass while the slabs are set as massless to prevent any vertical modes. Lateral restraints are also placed at the slab nodal points which are adjacent to the exterior walls.

In order to capture the effects of floor rocking through the out-of-plane response of the slab, the SDOF systems are attached to the stick models at the locations corresponding to the center of the actual floor slabs. This is performed by massless rigid beams connected to the center of rigidity of the floor, as shown in the Figure 4.3.2-3 below. SDOF oscillators are only included in the lumped mass stick model for the slabs and walls which contain out-of-plane frequencies of vibrations below the cut-off frequency of analysis of 40 Hz (a significant amount of mass must also be excited to be included). The component is considered rigid above this value.

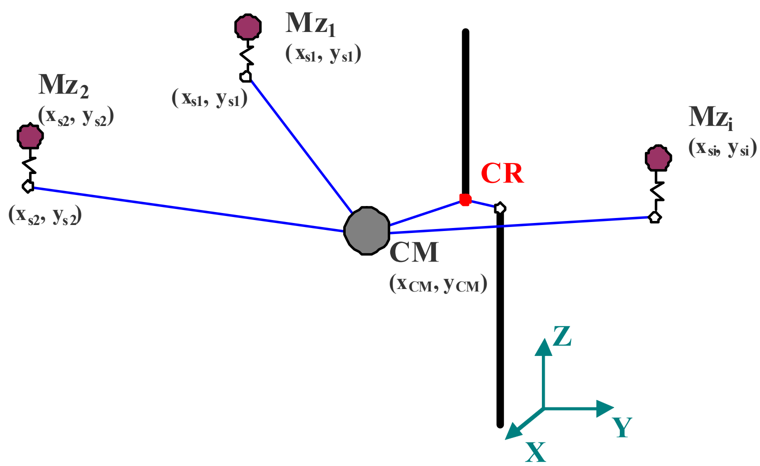


Figure 4.3.2-3 SDOF Elements Connections

In order to maintain the same overall mass inertia properties of the lumped mass stick model, at each floor elevation where flexible slabs or walls are present, the values of the lumped floor mass inertia parameters (Mz, Imx, Imy and Imz) that are assigned to the center of mass (CM) node have to be adjusted to account for the vertical slab masses. The following equations can be used to calculate the adjusted values of the vertical mass Mz_{CM} and mass moment inertia Imx_{CM}, Imy_{CM}, and Imz_{CM} lumped at the CM node:

$$Mz_{CM} = Mz - \sum_i Mz_{S1}$$

$$Im\,x_{CM} = Im\,x - \sum_i Mz_{S1} \cdot (y_i - y_{CM})^2$$

$$Im\,y_{CM} = Im\,y - \sum_i Mz_{S1} \cdot (x_i - x_{CM})^2$$

The FH/A walls were analyzed for a cracked concrete condition (the shear areas were reduced by 50%). This analysis modification was updated and incorporated into the FH/A properties of the stick model.

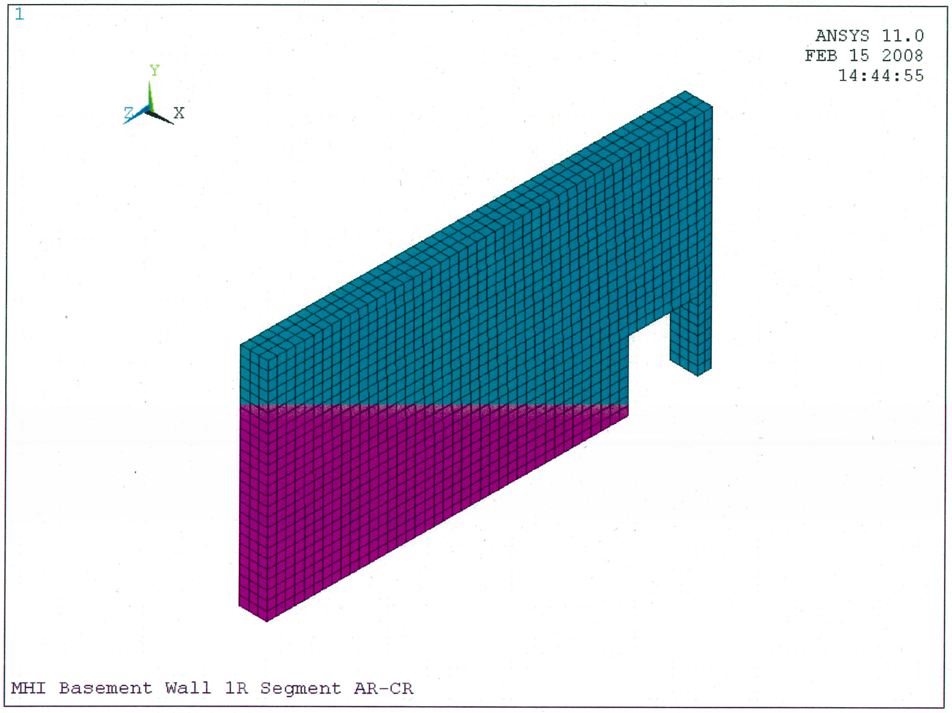
4.3.3 Development of SASSI FE Model of R/B Basement

A 3-D ACS SASSI FE model is developed for the R/B complex basement to capture the effects of the basement on the seismic response of the building. The development of the FE model ensures that an accurate representation of the overall stiffness of the basement structure including its mass inertia properties is provided. The ANSYS (Reference 12) preprocessor is used to generate the model geometry and FE mesh in a manner that allows simple modification to the model mesh size. SASSI 3-D shell elements are used to model the basement shear walls and the R/B slabs at the ground floor elevation. 3-D beam elements are used to connect the shell elements at the top of the shear walls of the 3-D SASSI FE model of the R/B basement to the lumped mass stick model representing the above ground portion of the R/B and FH/A.

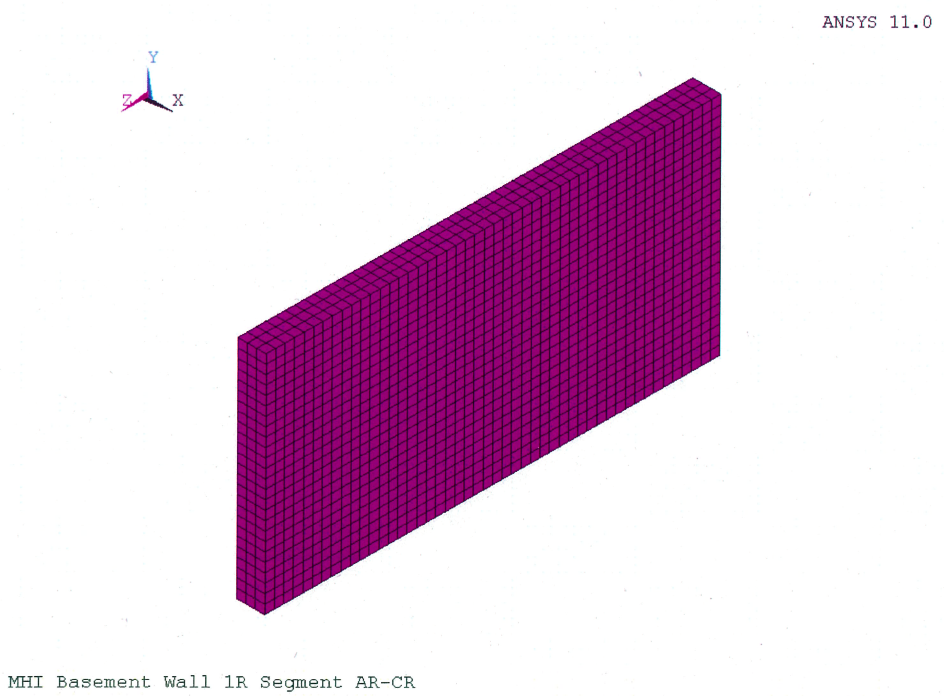
SASSI solid FE elements are used to model the stiffness and mass inertia properties of the basemat. The modeling of the thick central part of the basemat supporting the PCCV and CIS is simplified to minimize the size of the SASSI model. 3-D shell elements are added at the top of the basemat solid elements to accurately model the bending stiffness of the central part of the mat. Rigid shell elements are used to connect the thick portion of the basemat with the floor slabs at the ground elevation. Rigid 3-D beam elements connect the PCCV and CIS lumped mass stick models to the rigid shell elements.

The coarse FE mesh of the basement model does not always permit an accurate modeling of the openings of the walls. The elastic modulus material property assigned to the shell elements of the shear walls is adjusted to accurately model the wall’s shear stiffness, and account for the reduction of wall stiffness at the openings. A set of FE analyses is performed using ANSYS to obtain the stiffness reduction factors needed to adjust the material properties to account for the reduced stiffness of the shear walls with openings. The correction factors are obtained by comparing the results from the static analyses of two detailed solid FE models shown in Figure 4.3.2-4. Model A represents the actual geometry of the wall with openings, and Model B represents the wall without openings. Unit displacements are applied at the top of each model in both the in-plane and the out-of-plane directions, to calculate corresponding reactions that indicate the in-plane and out-of-plane wall stiffness. The ratio between the reaction obtained from Model A and Model B is used to determine stiffness reduction factors to adjust the elastic modulus of the wall material.

Unit mass weight is assigned only to the 3-D shell elements modeling the exterior shear walls of the basement and the portion of the basemat represented by 3-D brick elements. The remaining weight of the thick basement is lumped at a single node that is connected to the central portion of the foundation by rigid beams. The additional lumped mass and its location are calculated such that when combined with the mass assigned to the FE model of the basement it equals the overall lumped mass inertia properties of the basement (represented by lumped mass node BS01 in the DCD lumped-mass-stick model).



Model A of Actual Wall



Model B of Wall in SASSI Model

Figure 4.3.2-4 FE Models to Calculate Wall Stiffness Reduction Factors

4.3.4 PCCV Verification Methodology

To validate the PCCV stick model, various static and dynamic structural analyses with a "fixed base condition," are performed on both the stick model and a 3-D FE model of the PCCV and the results compared. Fixed end condition means applying full constraints on translation and rotation at the bottom of the PCCV structure. The dynamic model development and validation are performed as follows:

- The PCCV structure is then isolated from the detailed FE model of the R/B complex and the mass inertia properties of the FE are adjusted to include a 4.73 x 10^6 lbf accounting for the additional weight of snow, liner and polar crane on the structure. This model becomes the 3-D FE model of the PCCV. A fixed base condition is then applied on the 3-D FE model and the following three analyses are performed:

  Analysis 1: A 1g static analysis in all three directions.

  Analysis 2: A modal analysis. This is performed to obtain dynamic properties of the PCCV under the fixed base condition, such as natural frequencies and mass participation factors for the dominate modes.

  Analysis 3: A dynamic time-history analysis by modal superposition. A dynamic time history response analysis is performed using ANSYS and ARS are generated at representative locations.

  The results obtained from these analyses are utilized as the validation basis for the development of the structural dynamic lumped-mass stick model for the PCCV.

- A dynamic lumped mass stick model of the PCCV is developed using ANSYS (Reference 12). Loading and element attributes along the height of the PCCV structure are assigned as lumped masses supported by stick elements with zero densities, but with a stiffness representing that of the actual PCCV structure. As in the case of the 3-D FE model, the three types of analysis described above are also performed on this model. The results are then compared to that of the 3-D FE model to demonstrate the ability of the model to adequately represent the dynamic properties of the PCCV structure.

The methodology outlined above will be also used for verification of the R/B lumped mass stick model. The results of the validation will be provided in later technical report.

4.4 ACS SASSI FE Model of PS/B

The ACS SASSI FE model is modeled after the West PS/B of the US-APWR standard plant, since the East and West PS/Bs are nearly identical structurally. This model is used to represent both structures. The structural walls and slabs, including the floor slabs and roof slabs are modeled using shell elements, beams and columns are modeled as beam elements and the basemat is modeled using solid elements. At the connections between the basemat and the walls, the shell elements are extended into the basemat between the solid elements to transmit nodal rotations to the solid elements. The extended elements share nodes with the corresponding face of the solid elements but have no mass.

A dynamic structural model for the west PS/B is developed using ANSYS (Reference 12) and translated into the format of ACS SASSI (Reference 2) by using the built-in converter in ACS SASSI. The model is then validated by performing various static and dynamic structural analyses with a "fixed base condition," i.e. full constraints on translation and rotation at the bottom of the basemat. An SSI analysis can then be performed on the validated dynamic structural model with SASSI using the proper soil profiles. Dynamic model development and validation are performed in three steps as follows:

- Analyses are performed on a detailed static model to obtain the validation basis. The detailed static model is in an ANSYS format was translated from a NASTRAN format model that was used for basic structural design of the PS/B. The mesh sizes of the model are generally 3' to 4' and structural details such as openings in the walls and slabs are simulated in the model. The analyses include a 1g Static analysis, modal analysis and mode-superposition transient dynamic analysis using the corresponding ANSYS Solver.
- A dynamic ANSYS Model is developed using the ANSYS preprocessor and ANSYS Program Design Language. Loading and element attributes are assigned before meshing the geometry model so that it can be easily modified for various mesh sizes. To reduce the size of the model and permit coarser mesh, some minor structural details and wall/slab openings are not modeled in the ANSYS model. A 1g static analysis and a modal analysis, under fixed base conditions, are performed to obtain static load/deformation distributions and dynamic properties. The results are compared to the ones obtained from the analysis on the detailed static model to demonstrate the ability of the model to adequately represent the dynamic properties of the PS/B structure.
- The ANSYS Model is translated into a SASSI model using the built-in converter in ACS SASSI. Validation SSI analyses are performed with the PS/B dynamic model resting on the surface of a half-space with hard-rock properties to simulate the response of the structure under a fixed base condition. Transfer functions (TFs) and ARS are obtained from the SASSI validation analyses at selected nodes and are then compared to the results obtained from the analyses on the detailed static model.

To develop the ANSYS model, element sizes are selected such that the structural response will not be significantly affected by further refinement of the element sizes. The meshing of the structures also ensures that the discretized structure is able to capture the local responses and the responses of the significant modes of vibration which frequency is equal or below the highest frequency of interest, 50 Hz. Therefore, the dynamic modal analyses for various models with different element sizes under a fixed base condition are performed to compare both the dominant modal frequencies and accumulative mass fractions, i.e. accumulative mass over total effective (mobilized) mass. The adequacy of the mesh size is then investigated and a model is determined for further analysis.

Linear elastic dynamic and or static analyses are performed in this calculation. The PS/B's are reinforced concrete structures. Elastic properties of the structural concrete are used directly in the model and or served as basis to develop equivalent linear elastic properties for the cracked concrete. Element/member stiffness are adjusted for cracked concrete section properties based on the stress level (refer to Section 4.5 of this technical report). Element stiffness of shear walls and slabs are adjusted for the openings that are ignored geometrically in the model as well. The adjusting factor or stiffness reduction factor for openings is obtained from results of static FE analyses performed on two models: one with openings representing actual structure and one without openings representing slab/wall simulated in the ANSYS Model.

Based on the criteria specified in SRP 3.7.2 (Reference 4), Section II.3.B, since the heaviest equipment weight (mass) is less that 1% of the total building weight (mass), the dynamic model does not simulate structure of the equipment. However, equipment weight (mass) is included in the model by adjusting floor slab density. The mass of equipment is distributed over a representative floor area or equipment support footprint area. Based on the criteria given in SRP 3.7.2 (Reference 4) Section II.3.D, in addition to the structural mass and permanent equipment weights (mass), mass equivalent to a floor load of 20 to 60 psf, depending on floor level and location, is included to represent dead weight of piping. Also, mass equivalent to 25% of design live load and 75% of design roof snow load are included. The floor/wall concrete density is adjusted to include those equivalent dynamic masses as mentioned above.

4.5 Consideration of Concrete Cracking in Dynamic Analyses

4.5.1 Evaluation of Reinforced Concrete Members Cracking

Traditional reinforced concrete members and elements are modeled as either cracked or uncracked sections, depending on their stress level due to the most critical load combinations in accordance with ASCE 4-98 (Reference 13), Section 3.1.2, and ASCE/SEI 43-05 (Reference 14), Section 3.1.2. For the uncracked sections/elements, the stiffness is directly obtained from the concrete linear elastic properties and the section or element geometric dimensions. For the cracked concrete, a reduction to the uncracked concrete stiffness is taken into account. The reduction factors shown in Table 3-1 of ASCE/SEI 43-05 are used in linear elastic analysis to address the effects of concrete cracking on the seismic response of the US-APWR seismic Category I structures. These reduction factors have been validated by the following methodology.

A first hand estimate of member stress levels under the service load state is made. To estimate the stress level of the reinforced concrete members, such as shear walls, beam/columns, and slabs, a few typical elements of each member are selected and member forces are obtained from the results tables presented in Appendix 3H of the US-APWR and detailed structural design reports.

The provisions of ACI 349-01 (Reference 15), Subsections 9.5.2.3 and 9.5.2.4, are used to calculate the effective out-of-plane cracked moment of inertia of flexural and flexure dominated members (slabs or girders). The calculations provide the reduction factor for out-of-plane bending by accounting for the stress levels in these structural members in the service state.

The relevant provisions of ACI 349-01 are used to evaluate the cracking of the shear walls due to out-of-plane bending. If the bending stress level in the shear wall is higher than the concrete cracking stress, the reduction factor for flexural rigidity in Table 3-1 of ASCE 43-05 (Reference 14) is used after being validated as described in Step 2.

For shear walls with in-plane shear stress levels higher than the nominal concrete shear capacity, the stiffness reduction factor in Table 3-1 of ASCE 43-05 is used to calculate the cracked in-plane stiffness properties.

For shear walls with in-plane shear stress levels lower than the nominal concrete shear capacity, the uncracked in-plane stiffness properties are considered in the dynamic analysis.

The first hand estimate of the level of in-plane shear stresses in the building shear walls is calculated using the results of lumped mass stick models for the member forces shown in US-APWR DCD Appendix 3H. Average shear stresses on the effective shear area of the shear wall at each major floor elevation are calculated and compared to the nominal shear capacity. The nominal shear capacity of the concrete wall is evaluated based in the provisions of ACI 349-01 as follows:

$$V_c = 2 \cdot (f'_c)^{0.5}$$ ACI 349-01, Equation 11-3

For 4,000 psi strength concrete:

$$V_c = 2 \cdot (4000\ psi)^{0.5} = 126\ psi$$

If the shear stress demand is greater than 126 psi, a detailed calculation of the shear strength that considers the effect of the ratio of wall height over length is performed based on ASCE 43-05 (Reference 14) Section 4.2.3.

Section 4.2.3 of ASCE 43-05 specifies that the in-plane shear capacity of low-rise concrete shear walls (i.e. walls where the ratio of height to length are less than 2.0) can be calculated as follows (refer to ASCE 43-05 for notation):

$$V_u = \phi \left[8.3 \cdot (f'_c)^{0.5} - 3.4 \cdot (f'_c)^{0.5} \cdot \left(\frac{h_w}{l_w} - 0.5 \right) + \frac{N_A}{4 \cdot l_w \cdot t_n} + \rho_{se} \cdot f_y \right]$$

The shear walls are also load bearing walls. The axial load 'NA' on the wall is usually a compressive load. Ignoring the compression force 'NA,' the above equation implies that the concrete nominal shear strength for a shear wall with a height of h_w and length L_w will be:

$$V_c = 8.3 \cdot (f'_c)^{0.5} - 3.4 \cdot (f'_c)^{0.5} \cdot \left(\frac{h_w}{l_w} - 0.5 \right)$$

The following calculation provides an example of evaluation shear capacity of a typical shear wall. Consider a typical ratio of 1.42 for wall height to length (35.92'/25.33' = 1.42) for a shear wall in the PS/B, with a concrete compressive strength of 4,000 psi, the nominal shear capacity is:

$$V_c = 8.3 \cdot (4000)^{0.5} - 3.4 \cdot (4000)^{0.5} \cdot (1.42 - 0.5) = 328\ psi$$

Note that, to calculate the total shear capacity, ASCE 43-05 (Reference 14) specifies the effective depth of the shear wall as:

$$d = 0.6 \cdot l_w$$ ASCE 43-05, Equation 4-5

Whereas, ASCE 349-01 (Reference 15), Section 11.10.4, specifies $d = 0.8 \cdot l_w$ as the effective depth. Therefore, the average shear capacity for a wall with height to length ratio of 1.42 over an effective depth of $0.8 \cdot l_w$ will be:

$$Vc = \frac{0.6}{0.8} \cdot 328 = 246\ psi$$

The corresponding shear stress demand is calculated by dividing the total shear force on the wall by an area of $0.8 \cdot l_w \cdot t_n = 0.8A_g$.

4.5.2 Adjusting Element Stiffness in FE Dynamic Models

Generally, shell and beam elements are used to simulate wall/slab, beam/column, respectively. The material (elastic modulus) and geometric (thickness) properties of the slabs are changed to reflect the dynamic mass and cracked concrete properties, with unchanged shear and axial stiffness, as discussed in Section 4.5.1. The modification of flexural properties to account for flexural cracking is as follows:

$$t_{cracked} = \sqrt{C_F} \cdot t$$

$$W_{cracked} = \frac{1}{\sqrt{C_F}} \cdot W_{concrete}$$

$$E_{cracked} = C_F \cdot E_{concrete} \cdot \left(\frac{t}{t_{cracked}} \right)^3 = \frac{1}{\sqrt{C_F}} \cdot E_{concrete}$$

where:

C_F = factor for the reduction of flexural stiffness (1/2).

$t_{cracked}$ = effective slab thickness to account for cracking.

t = gross section thickness.

$W_{cracked}$ = effective unit weight to offset the reduced stiffness and provide the same total mass.

$E_{cracked}$ = effective modulus to account for the reduction in thickness that keeps the same axial stiffness while reducing the flexural stiffness by C_F.

Those shear wall segments with out-of-plane stress levels being higher than the concrete cracking stress are modeled in the same way as floor slabs.

The material (elastic modulus) and geometric (area) properties of the beams and columns are changed to model the cracked concrete properties, with unchanged shear and axial stiffness and unchanged mass. The cracked concrete properties are modeled for one-half of the flexural stiffness. The modification of flexural properties and geometric (area) properties to account for flexural cracking is as follows:

$$A_{cracked} = \frac{A}{C_F}$$

$$W_{cracked} = C_F \cdot W_{concrete}$$

$$E_{cracked} = C_F \cdot E_{concrete}$$

where:

C_F = factor for the reduction of flexural stiffness (1/2).

$A_{cracked}$ = effective beam/column area to offset the reduced flexural stiffness and provide unchanged shear and axial stiffness.

A = gross section area of the concrete beam/column.

$W_{cracked}$ = effective unit weight to offset the reduced stiffness and provide the same total mass.

$E_{cracked}$ = effective modulus to account for the reduction in thickness that keeps the same axial stiffness while reducing the flexural stiffness by CF.

4.5.3 Evaluation of Concrete Cracking in Dynamic Analyses of SC Modules

A subsequent technical report will address potential effects due to cracking of the SC modules including stiffness reduction effects, effects on the seismic response, and consideration of cracking in conjunction with seismic and thermal loading. The discussion will address issues raised in RAI 497-3734, Question 3.8.4-42, and RAI 491-3733, Questions 3.8.3-16 and 3.8.3-25.