한국전산구조공학회
1992년도 가을학술발표회 논문집

원자력발전소 보호시스템 캐비넷의 내진검증

Seismic Qualification of Plant Protection System Cabinet for Nuclear Power Plant

정 명 조* 박 근 배** 황 원 걸***
Myung-Jo Jhung, Keun-Bae Park, Won-Gul Hwang

ABSTRACT

A method to verify seismic qualification of the plant protection system cabinet for a nuclear power plant is presented. A finite element model of the cabinet is developed and correlated to the dynamic properties observed during in-situ vibration test of the actual structure. The results of the modal analysis provide insight into the fundamental dynamic properties of the structure. Techniques for verifying structural integrity and operability are exemplified by summarizing response spectrum and time history analyses of the structure.

1. INTRODUCTION

The IEEE Std. 344-1987 (Ref.1) establishes the procedures to verify that Class 1E equipment meets its performance requirements during and following one safe shutdown earthquake (SSE) preceded by five operating basis earthquakes (OBE). Reflecting the need for seismic qualification, the plant protection system (PPS) cabinet is designated seismic category I per USNRC Regulatory Guide 1.29 (Ref.2).

This paper presents the method for assessment of PPS cabinet seismic qualification. To assure functionality, the structural integrity of the cabinet must be assessed and the equipment must be qualified for the effects of the seismic excitation. The seismic qualification is addressed by structural analyses using the finite element models developed from structural drawings. The results of in-situ structural tests are used to verify the analytical model by comparison of analytical and test frequencies. The results of modal and transient analyses show the effect of design modifications upon fundamental dynamic properties and seismic environments. The structural loads are obtained using the response spectrum analysis. The seismic environments are obtained by transient dynamic analysis and supplied in the form of

* 한국원자력연구소 원자로기계설계실 선임연구원
** 한국원자력연구소 원자로기계설계실 책임연구원
*** 전남대학교 공과대학 기계설계학과 교수

in-equipment response spectra (IERS). Method to verify the operability is presented using these IERS and capability spectra obtained from test data. The criteria for the cabinet structural integrity is based on American Institute of Steel Construction specifications (Ref.3) and the ASME code (Ref.4). The criteria for equipment operability is obtained from qualification test data.

2. REFERENCE DESIGN

The PPS cabinet is 150" long x 54" deep x 90" high and weighs approximately 12400 lbs. The external cabinet structure is constructed from A36 steel welded steel angle, square and rectangular tubing frames encased in 7-gage sheet metal plates (Fig.1). This structure is divided into four subsections with Marinite insulating material sandwiched between 10-gage sheet metal forming barrier walls. Exterior sheet metal panels are welded to the frame structure. At each barrier wall only one of the two sheet metal panels are welded to the frame structure. The other barrier sheet metal panel is bolted, through the Marinite, to the welded sheet metal panel. The internal equipment is mounted from the front frame, the front frame and interior supports, or the inner rear door. Interior supports are generally mounted from uni-struts bolted to the barrier walls.

The finite element model of the reference design is developed to evaluate natural frequencies and its response to the seismic excitation. The model consists of 445 nodes, 254 three dimensional beam elements, 372 plate (shell) elements and 150 mass points. The model is shown in Fig.1. The model describes the frame structure, interior and exterior panels, base and top members, and the mass distribution of the structural members and the mounted equipment contained within the cabinet (Fig.2). Boundary conditions representing the bolted connections to the control room floor are applied to the model.

An eigenvalue analysis of the cabinet is performed to get the natural frequencies using the reduced Householder procedure of the ANSYS code (Ref.5). The analysis results are compared with test data verifying the adequacy of the structural model to accurately represent the fundamental dynamic properties of the cabinet. Table 1 shows the fundamental natural frequencies in the side-to-side and front-to-back directions. Typical mode shapes from the analytical model associated with Table 1 are shown in Fig.3.

The seismic excitation used in the seismic qualification is represented by an acceleration time history at the base of the structure. The floor response spectra (FRS) generated from the time history motions are used directly in a response spectrum analysis for the structural load evaluations. To obtain IERS, time history analysis is performed. Three mutually orthogonal accelerations are simultaneously applied to a structural model. Fig.4 shows the excitations and its corresponding spectra. The time history excitation consists of a 24 second duration transient. The three accelerations are shown to meet the appropriate requirements for statistical independence.

A seismic analysis of the reference design is completed by applying the seismic response time histories. The amplitudes of the seismic time histories are increased by 10 % to account for unforeseen regulatory and design changes. The time history analysis produced response time histories at locations throughout the cabinet. From the response time histories the response spectra at locations throughout the cabinet were developed and compared to the capability spectra obtained from tests. The applied excitation had peaks at 8 Hz which corresponded to the fundamental natural frequencies of the reference design. A comparison of the peak response and the input peak in Fig.5 indicates that the response magnification is 3.5. A typical comparison is shown in Fig.6. This resulted in responses exceeding the capability spectra as expected. Therefore, modifications to the reference design were required to produce response spectra enveloped by capability spectra.

3. DESIGN MODIFICATION

The reference design is modified to increase its stiffness. Modifications include additional vertical members on the outer side walls, horizontal members in the top of the cabinet running in both the front-to-back and side-to-side directions, and gusset plates located in the upper corners of each bay on the rear face. In addition, the cabinet is welded along the perimeter frame members to the control room floor rather than bolted.

The design modifications were incorporated into the finite element model. The model consists of 450 nodes, 312 three dimensional beam elements, 380 plate (shell) elements and 150 mass points.

The natural frequencies were evaluated for the modified design. Table 1 shows that all cabinet frequencies are greater than the frequency peaks of the seismic response spectra. The modified cabinet's side-to-side frequency increased from 8.0 Hz to 13.8 Hz and front-to-back frequency increased from 7.8 Hz to 85.8 Hz as compared to the reference cabinet's. The mode shapes associated with the first two side-to-side modes are shown in Fig.3. Comparing the mode shapes of two designs demonstrates that base flexibility is dominant in the front-to-back mode of the reference design. Since the modified design is base welded, base flexibility is eliminated, resulting in a large increase in the front-to-back frequency of the modified design.

The time history analyses for modified PPS cabinet model were completed for SSE and OBE. The three excitation directions, east-west, north-south, and vertical, were applied simultaneously since the excitations are statistically independent for each direction. Based on the transmissibility data, an 8 % structural damping value was used in the time history analyses.

4. EVALUATIONS

STRUCTURAL INTEGRITY

The response spectra analyses of the PPS cabinet model are completed to evaluate stresses in the cabinet structure for the SSE and OBE. The responses spectra analyses combined modes according to the 10% method for each excitation direction and combined the stress results from the three excitation directions by the square root sum-of-the-squares method. The input response spectra is based on the peak broadened spectra and amplified by 10%.

A criteria for acceptance of structural stresses is that given in the AISC code (Ref.2). For example, the maximum stress ratio was calculated for all beam members in the model using the following equation if $f_a / F_a \leq 0.15$:

$$\text{Stress ratio} = \frac{f_a}{F_a} + \frac{f_{by}}{F_{by}} + \frac{f_{bz}}{F_{bz}}$$

where f_a = calculated axial stress

f_{by} = y-axis bending axial stress

f_{bz} = z-axis bending axial stress

F = allowable stress in given direction.

The maximum stress ratio for plate members was obtained by dividing the maximum stress intensity for any plate by one-half the material yield stress. If the stress ratio is less than 1.0, the members are acceptable.

An OBE evaluation addresses the structural fatigue occurring from the postulation of recurring OBE events. The peak OBE structural loads can be obtained from a response spectrum analysis using the OBE FRS as input excitation. For fatigue evaluations, the maximum stress intensity is converted to alternating stress intensity to determine the allowable number of cycles using the design basis fatigue curves. The benefits of modified design lead to a lower stress condition and increase the cabinet's overall structural frequencies to values exceeding the peak of the FRS, thereby reducing the amplification (1.2) of the seismic excitation as shown in Fig.5.

OPERABILITY

The time history analysis produced time histories through the PPS cabinet. From these time history responses, response spectra were generated. The analytically derived response spectra were compared to capability spectra at cabinet and equipment mounting locations. The capability spectra are measured values for tests.

By comparison the IERS before and after design variation, a reduction in seismic environment is observed for the effect of the modification. Side-to-side and vertical IERS at the status panel assembly for the reference and modified designs are presented in Fig.6. The side-to-side peak IERS level for reference design is approximately 13 g's ; or an amplification of the peak of the FRS by a factor greater than 3.5. With the effect of design variations, the structure is more stiffer than reference design. Therefore the peak IERS level is approximately 5g's ; or an amplification of the peak of the FRS by a factor greater than 1.2. The comparisons between these two sets of IERS demonstrate the variations in amplification of IERS which can occur due to the relationship between the structural frequencies and dominant frequency range of the FRS.

5. SUMMARY

Presented in this paper are the evaluation methods to access the structural integrity and to verify operability for the typical PPS cabinet. Response spectrum analyses are employed for structural integrity evaluation and transient dynamic analyses are used to generate in-equipment seismic environments. Modal analyses reveal that the excitation peak corresponds to the fundamental natural frequencies of the reference design, thereby reinforcing the necessity of the design modification. The modified design which is more stiffer than the reference one is seismically qualified for SSE and OBE by analysis and comparison with test data for both structural integrity and operability.

REFERENCES

1. IEEE Std. 344-1987, "IEEE Recommended Practices for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations," The Institute of Electrical and Electronics Engineers, 1987
2. Reg. Guide 1.29, "Seismic Design Classification," Revision 3, US Nuclear Regulatory Commission, September 1978
3. AISC, "Manual of Steel Construction," 8th ed., American Institute of Steel Construction, Inc., 1988
4. ASME Boiler and Pressure Vessel Code, Sec.III, Rules for Construction of Nuclear Power Plant Components, 1989
5. G. J. DeSalvo and R. W. Gorman, ANSYS USER's Manual, Swanson Analysis Systems, Inc., June 1, 1987

Table 1. Summary of Frequencies

Direction		Reference	Test	Modified
Side-to-side	1st	8.0	7.0	13.8
	2nd	-	-	19.4
Front-to-back	1st	7.8	8.0	85.8
Vertical	1st	> 33	>33	>33

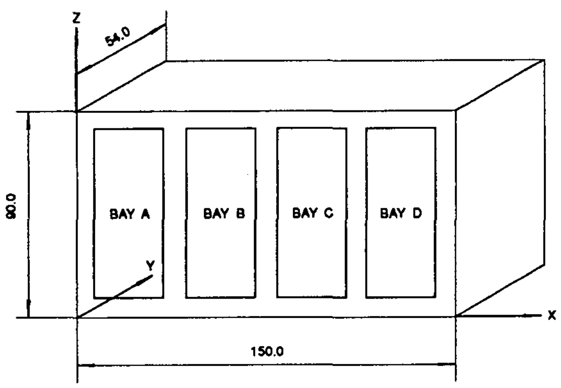

Fig.1 PPS Cabinet Layout

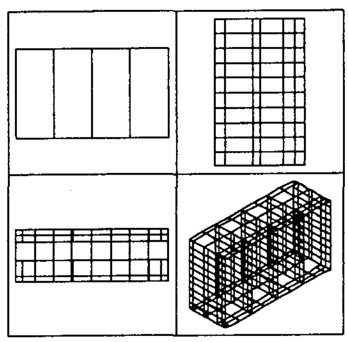

Fig.2 Finite Element Model

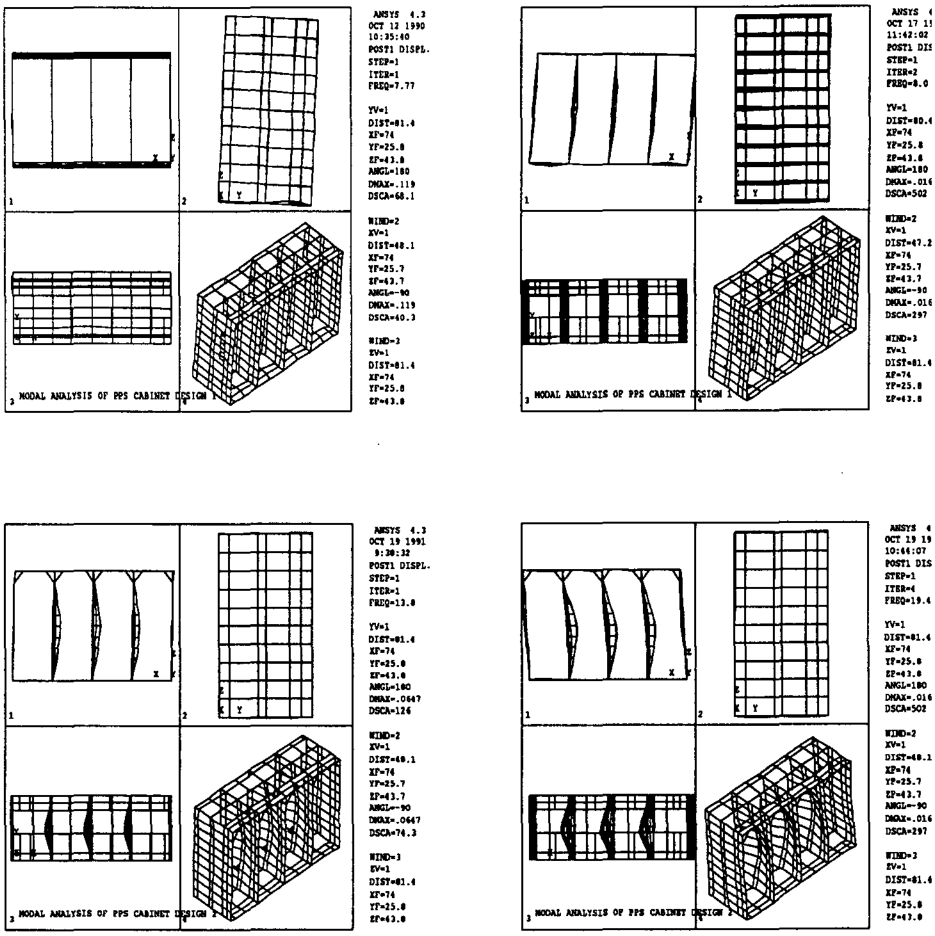

Fig.3 Mode Shapes of PPS Cabinet for Reference (Upper) and Modified (Lower) Designs

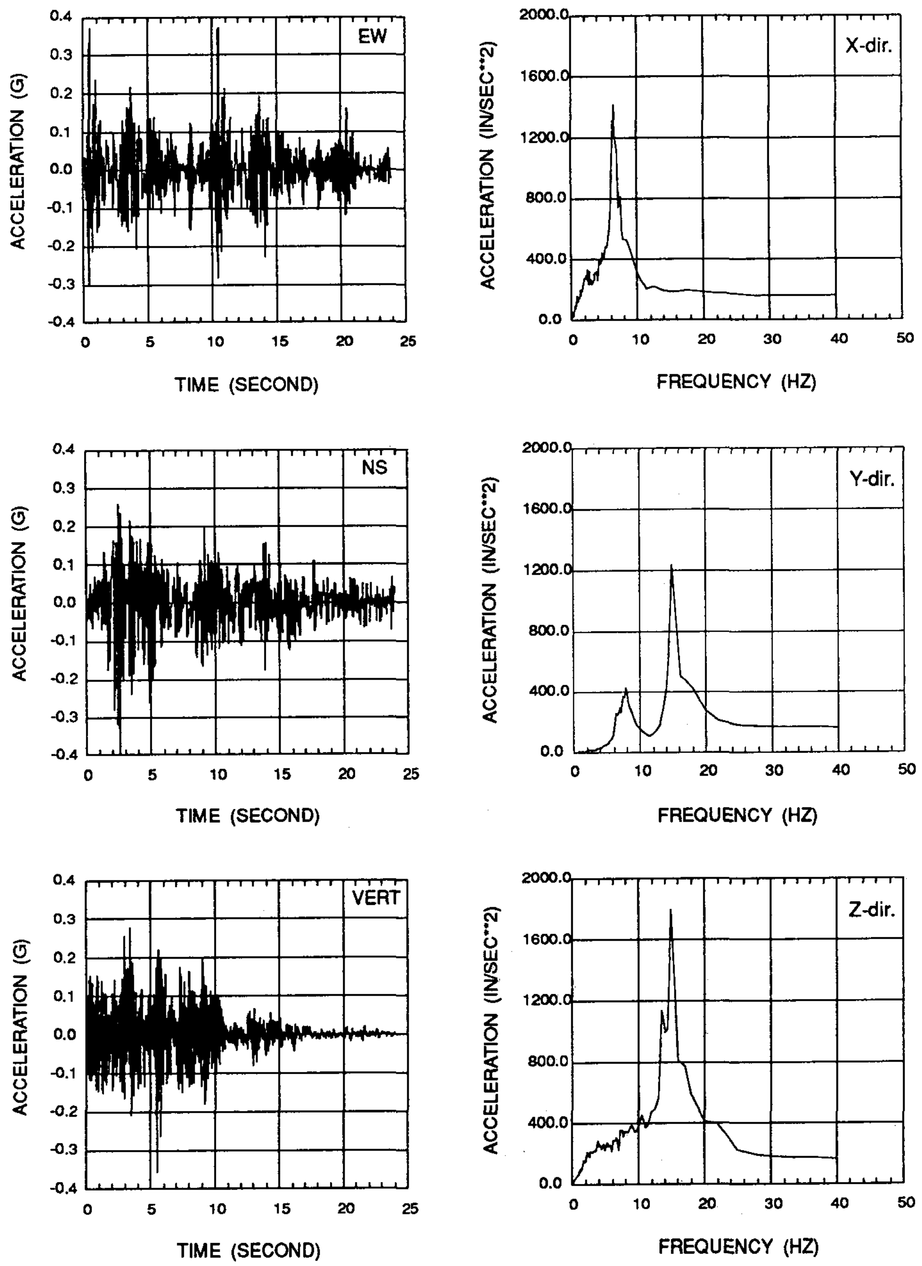

Fig.4 OBE Acceleration Time Histories and its Corresponding Spectra of Auxiliary Building Control Room Floor

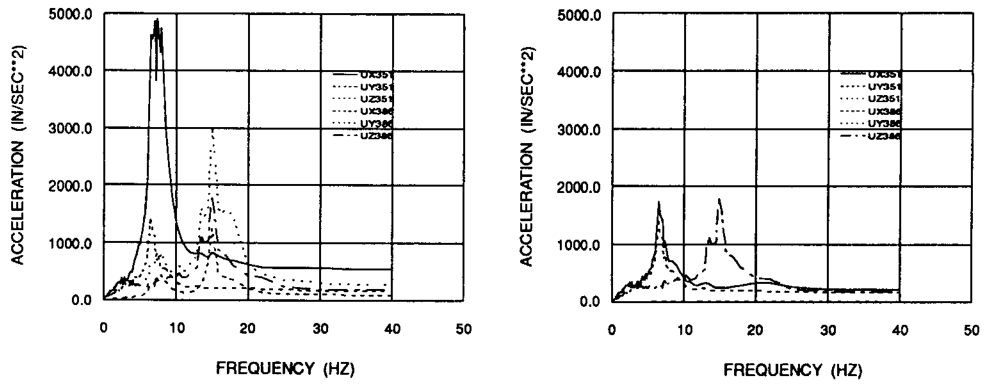

Fig.5 Response Spectra of Nodal Points 351 and 386 for Reference (Left) and Modified (Right) Designs

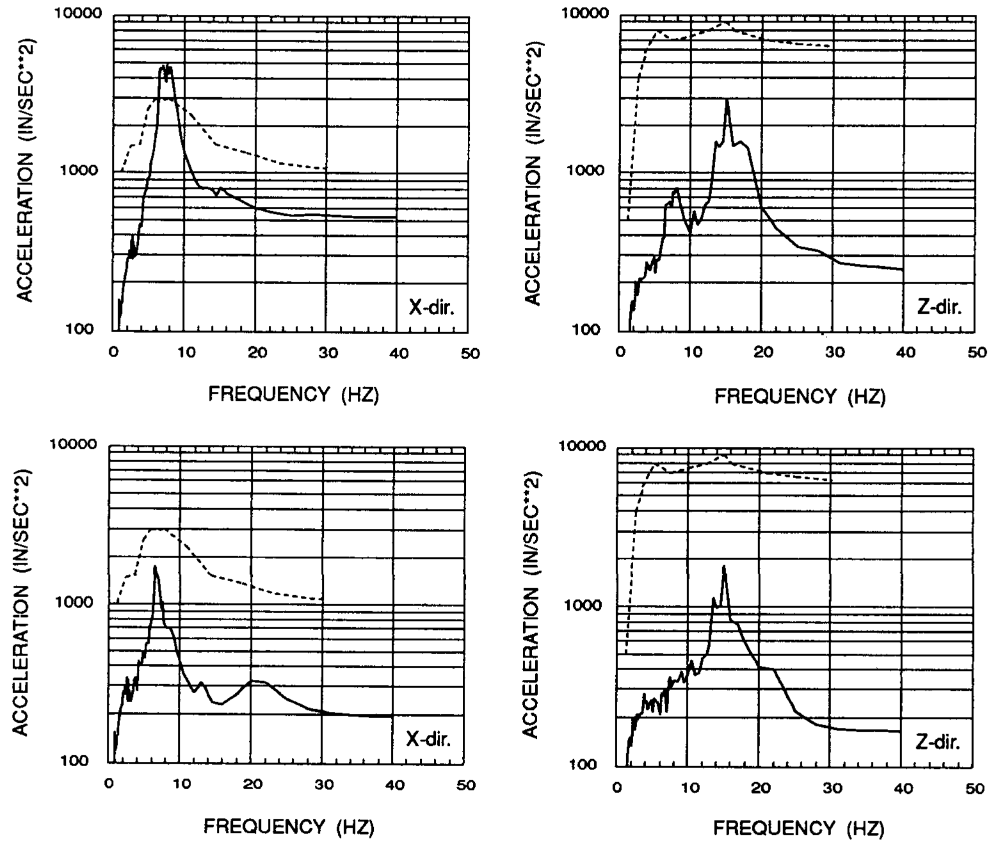

Fig.6 Comparisons between Generated Spectra and Capability Spectra for Reference (Upper) and Modified (Lower) Designs - Solid : Generated, Dotted : Capability