원자력발전소 보호시스템 캐비넷의 내진검증

Seismic Qualification of Plant Protection System Cabinet for Nuclear Power Plant

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요 약

원자력발전소중 안전과 관련된 구조물은 지진의 가능성에 대비하여 그의 구조적 안전성과 가용성이 검증되어야 한다. 본 논문은 원자력발전소 보호시스템 캐비넷을 예를 들어 그에 대한 내진검증 방법을 보였다. 캐비넷의 유한요소모델을 작성하여 동특성을 구하였고 그 모우드값을 입력지진스펙트럼과 비교한 결과 구조물의 1차모우드가 입력스펙트럼의 peak와 일치함으로써 설계변경의 필요성이 대두되었다. 이 peak 값을 피하기 위하여 캐비넷의 구조를 변경하였고 변경된 구조물에 대하여 응답스텍트럼해석과 시간이력해석을 수행하여 구조적 건전성과 가용성을 보임으로써 설계변경된 캐비넷의 내진검증을 확인하였다.

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 the dynamic characteristics are obtained. The results of the modal analysis provide insight into the fundamental dynamic properties of the structure, which correspond to the frequency of the peak values of the input seismic spectrum. It necessitates the design modification of the reference cabinet. 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) as endorsed by USNRC Regulatory Guide 1.100 (Ref.2) establishes the procedures to verify that safety-related electric (Class 1E) equipment meets its performance requirements during and following one safe shutdown earthquake (SSE) preceded by a number of 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.3).

The method to assess PPS cabinet seismic qualification is exemplified by application to a

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이 논문에 대한 토론을 1993년 12월 30일까지 본학회에 보내주시면 1994년 6월호에 그 결과를 게재하겠습니다.

typical design in the control room of the nuclear power plant. 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 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.4) and the ASME code(Ref.5). The criteria for equipment operability is obtained from qualification test data.

2. REFERENCE DESIGN

The PPS cabinet is 150′ long×54′ deep×90′ q미 high and weighs approximately 12400 1bs. The external cabinet structure is constructed from A36 welded steel angle, square and rectangular tubing frames encased in 7-gage sheet metal plates as depicted in 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 is 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 unistruts bolted to the barrier walls.

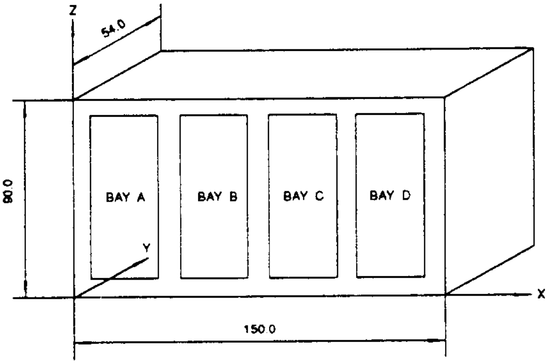

Fig.1 PPS Cabinet Layout

The finite element model, as shown in Fig. 2, 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,

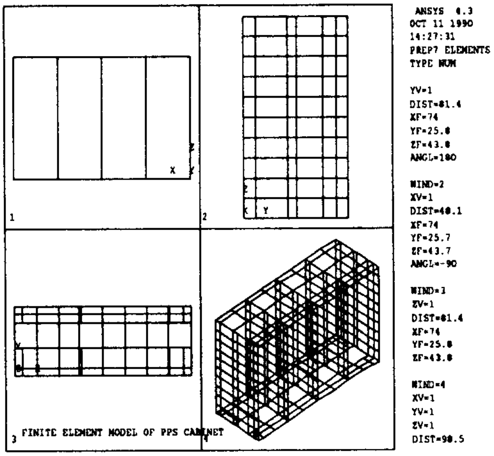

Fig.2 Finite Element Model

372 plate (shell) elements and 150 mass points. 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. Boundary conditions representing the bolted connections to the control room floor are applied to the model. Concentrated masses representing the PPS cabinet equipment are distributed through the finite element model based on the center of gravity location of the equipment and the location of its supports using the ANSYS mass element STIF 21 (Ref.6).

An eigenvalue analysis of the cabinet is performed to get the natural frequencies using the reduced Householder procedure of the ANSYS code. 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. Summary of Frequencies

Direction		Reference	Test	Modified
Side-to-side (X)	1st	8.0	7.0	13.8
	2nd	–	–	19.4
Front-to-back (Y)	1st	7.8	8.0	85.8
Vertical (Z)	1st	>33	>33	>33

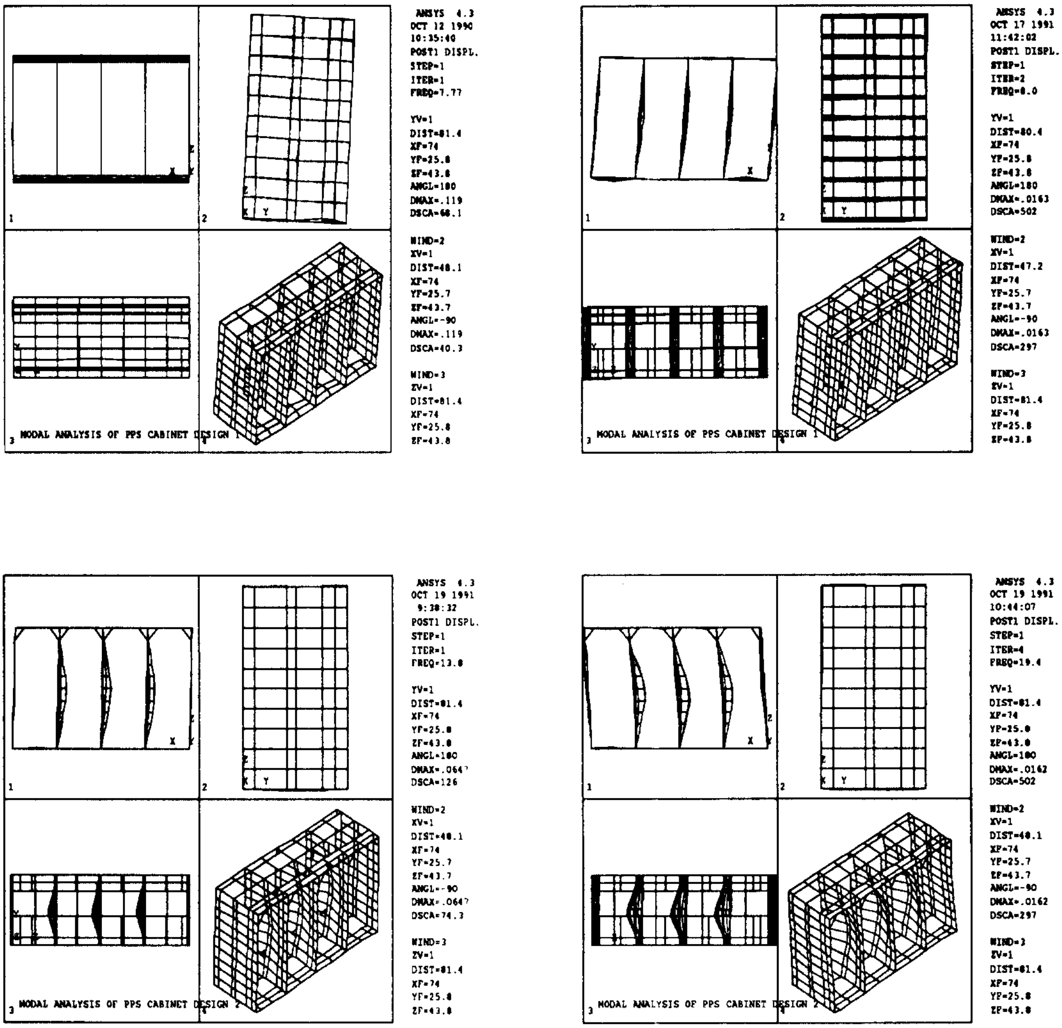

Fig.3 Mode Shapes of PPS Cabinet for Reference (Upper) and Modified (Lower) Designs

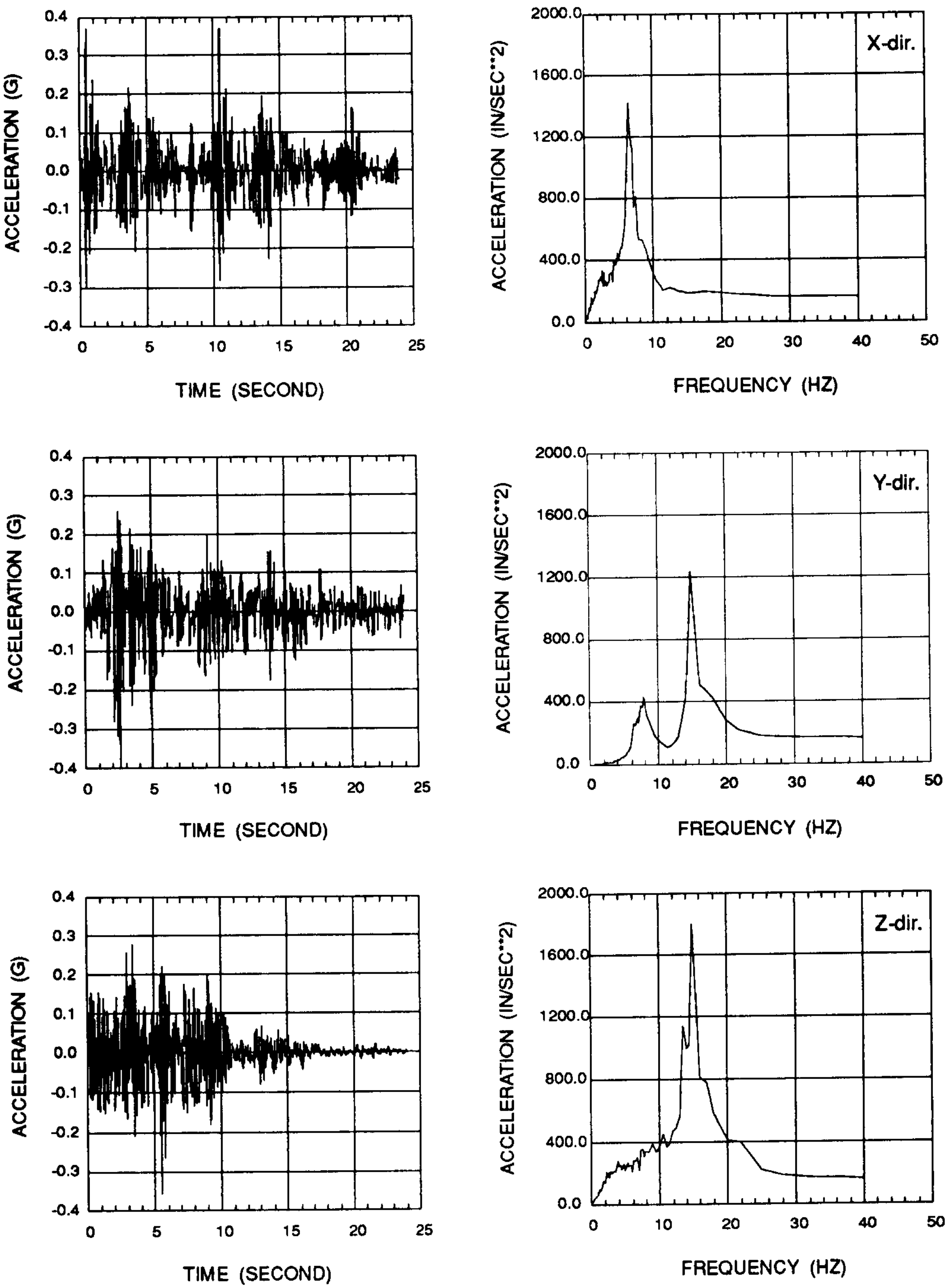

Fig.4 OBE Acceleration Time Histories and its Corresponding Spectra of Auxiliary Building Control Room Floor

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 the structural model. Fig.4 shows the excitations of 24 second duration and its corresponding spectra. Since the ANSYS code requires the displacement time histories, the acceleration time histories were integrated twice to produce displacement time histories (Fig.5).

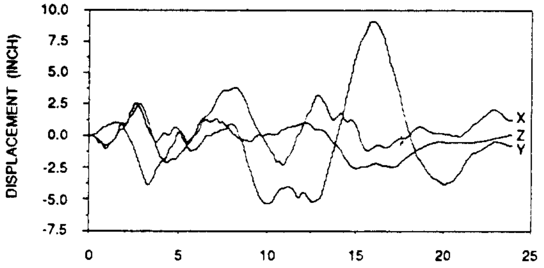

Fig.5 OBE Displacement Time Histories of Auxiliary Building Control Room Floor

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 around 8 Hz which corresponded to the fundamental natural frequencies in the reference design. Fig.6 shows a comparison of the peak response and the input peak, where node 351 with coordinate (0,0,0) indicates the point the excitations are applied and node 386 with coordinate (150, 54, 87.5) is the location the associated fuse box is installed. A typical comparison is shown in Fig.7, which 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.

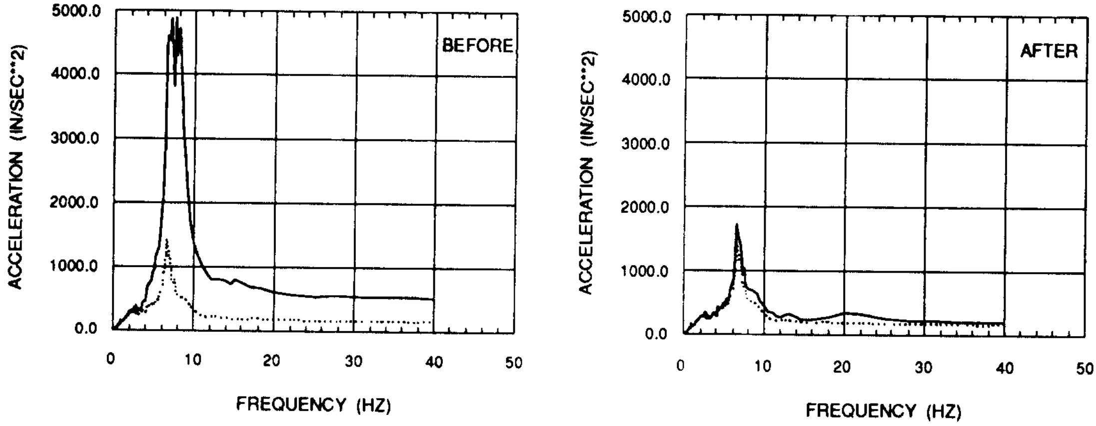

Fig.6 Response Spectra of Nodal Points 351 (solid line) and 386 (dotted line) for before-and after-Design Modification

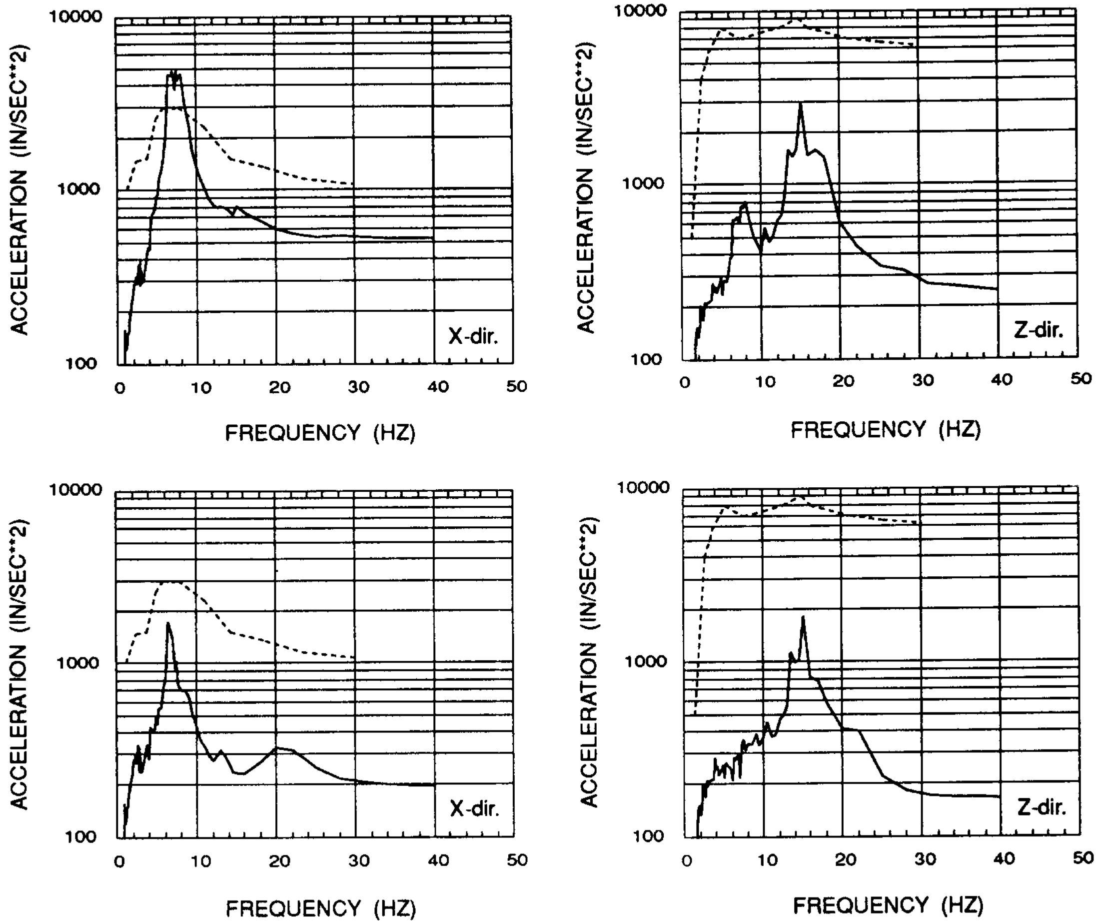

Fig.7 Comparisons between Generated Spectra and Capability Spectra for Reference (Upper) and Modified

3. DESIGN MODIFICATION

The reference design is modified to increase its stiffness. Modifications include additional vertical members on the outer side walls, horizontal members on 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 frquency 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 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

4.1 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 of 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.4). 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. Assuming 200 peak stress cycles, the maximum stress intensity due to OBE loading is obtained and the allowable number of cycles from Fig. I-9.1 of Ref.5 is calculated. Usage factor less than 1.0 is acceptable.

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 of the seismic excitation as shown in Fig.6.

4.2 OPERABILITY

The time history analysis produced response time histories through the PPS cabinet. From these time history responses, response spectra were generated. The analytically drived 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.7. 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 5 g'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. CONCLUSIONS

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.

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