Study on Floor Response Spectra by Parameter Uncertainty for Base Isolated Nuclear Power Plant Structures

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For a seismic design of the equipment and components mounted on nuclear power plant (NPP) structures, floor design response spectra (FDRS) are used. A generation method of FDRS is suggested in the USNRC Regulatory Guide 1.122. FDRS is generated by peak-broadening and smoothening of FRS to account for uncertainties not included in FRS. As base-isolated structures have additional uncertainties in the property of the isolation device, it should be reconsidered when generating FDRS. This is not considered in the current guide which is based on fixed-based structures. In this study, uncertainties in the base isolated structures that affect FRS are explained and important parameters are selected. A simple structural model and an NPP structural model are used for the analysis. The structural models are seismically isolated using linear isolation bearings. Computed FRS with parameter variations are investigated if the current FDRS generation guide is suitable for a base isolated structure. It has been shown that a variation in isolators has a more significant role in the variation of FRS than changes in the superstructure property. The Regulatory Guide 1.122 is shown to be applicable to linearly base isolated NPPs, but amplification of peak is needed if the isolator has a large damping ratio.

I. INTRODUCTION

NPP structures should be designed to meet the seismic demands to ensure the safety of the entire system. The whole system includes the NPP structure itself plus equipment and components mounted on the structure. For the seismic design, a dynamic analysis is conducted on the NPP structure and the analysis is often conducted using the mathematical model of the structure. However, a detailed representation of the real structure including all systems mounted on the structure is complex and difficult owing to the multiplicity of the systems. To handle this problem, the floor response spectrum (FRS) methodology is used on various floors where important systems and components are mounted. FRS is obtained by a spectral analysis or time history analysis on the structure. For the design of the components, the computed FRS are revised as FDRS to account for uncertainties based on USNRC Regulatory Guide 1.122, which provides the FDRS generation method. The guide is basically based on fixed-based structures and considers various factors of uncertainties to construct an FDRS.

Meanwhile, as the means of reducing the seismic demand, the base-isolation of the structures has been under study until now. The base isolation, also known as a seismic base isolation, is one of the ways to protect structures against earthquake forces.[1] It decouples a superstructure from the ground motion, which makes both a superstructure and components remain safe under excitation. However, looking at the base-isolation from the view of generating FDRS, it adds additional uncertainties in the property of isolation bearings. The conventional guide, based on fixed-based structures, might not be the one for base-isolated structures. The FDRS generation guide on base-isolated structures has yet to be established. Thus, it should be reexamined whether the conventional guide is also appropriate for the base isolated structure. In this study, two base-isolated structures with different types of bearings are analyzed to examine the conventional guide.

II. FLOOR RESPONSE SPECTRUM AND FLOOR DESIGN RESPONSE SPECTRUM

To ensure the safety of equipment and components mounted on their floors against seismic motion, a dynamic analysis of them should be conducted. However, a coupled analysis of a structure and its components is complex and time consuming.

Thus, equipment is separately analyzed using the floor response spectra. The generation process of FRS using the time history method is represented in Fig. 1. Ground-response-spectrum-compatible time histories are used as input ground motion to the structural model. The response at the floor of interest is then used as the input motion of a single-degree-of-freedom oscillator. The maximum response of each oscillator with a different frequency is used to compose FRS. FRS calculated from this process does not account for uncertainties. Uncertainties coming from various factors should be considered when generating FDRS. An approximation of a real structure using a numerical model, input values of the structural properties, analysis methods, material properties, and modelling techniques of soil and other factors contribute to the uncertainties. Generally, the soil parameter has the most substantial effect on FRS. USNRC Regulatory Guide 1.122 states that calculated FRS should be peak-broadened and smoothed to account for the uncertainties.[3] Fig. 2 shows a representation of the FDRS generation. At the peaks of the FRS at frequency f_j, the peak widths are broadened by $\pm\Delta f_j$, which is calculated using a procedure that considers the variation in the frequency owing to variations in the significant parameters. If such a procedure is not applied, 15% of peak broadening ratio is commonly used and recommended.

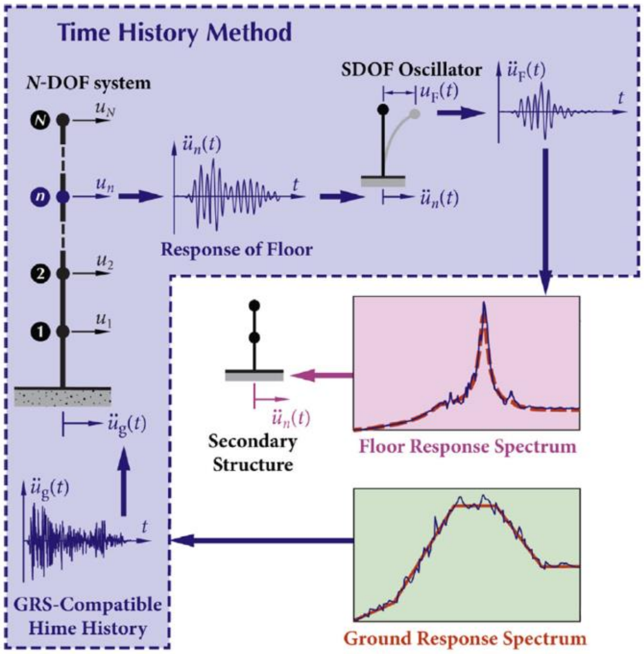


Fig. 1. Generation of floor response spectra using time history method[2].

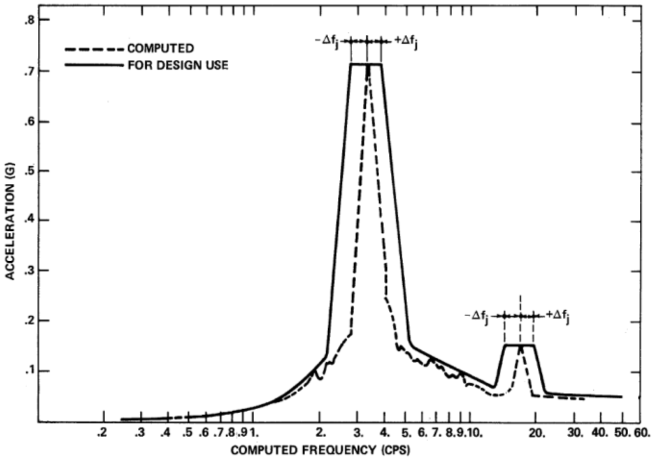


Fig. 2. Peak broadening and smoothing of FRS (USNRC Regulatory Guide 1.122).

III. NUMERICAL ANALYSIS

III.A. Structural models

III.A.1. 3-storied building

A three-storied building is represented by a lumped-mass stick model and is depicted in Fig. 3. The mass of each floor including the mass of the slabs, walls, and any heavy components is 250000 kg each. The stiffness of the beam representing each wall, k, is 431MN/m. A fixed-based model and a base-isolated model are shown on the left side and right side in each figure. The isolated model has one isolator whose isolation periods are 1.0, 1.5, 2.0, and 2.5 s. A different isolation period was adopted to investigate its effect on the variation of FRS. The isolation bearing is a linear rubber bearing. Natural rubber bearing with 2% damping and high damping rubber (HDR) bearing with 15% damping are used for the analysis.

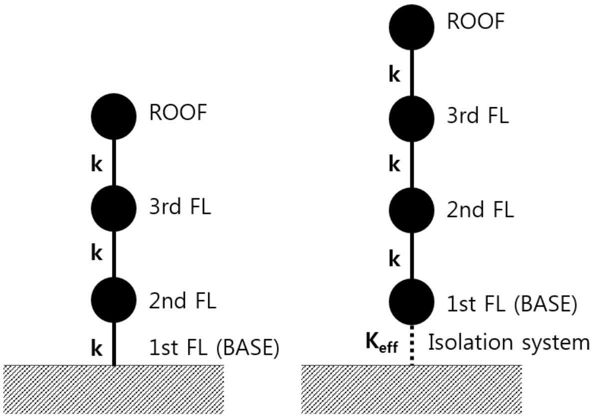


Fig. 3. Structural models of three-storied building – fixed-based and base-isolated.

III.A.2. Base isolated NPP

A base-isolated NPP structural model is depicted in Fig. 4. The superstructure consists of lumped-mass and beams, and the nuclear island and base mat are modelled using solid elements. The isolation period of the model in the horizontal direction is 2.09 s. The base isolation layer of the structure consists of 454 bearings. As a three-story building, the NPP model adopted both natural rubber bearings and HDR bearings.

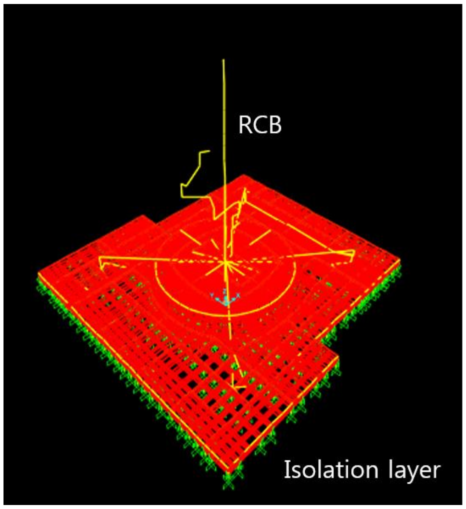


Fig. 4. Structural model of base-isolated NPP.

III.B. Uncertainties in the structural model

III.B.1. Factors affecting FRS

Uncertainties in developing FRS come from various factors: the approximation of a real structure in the structure modelling process, errors in the input values of the structural properties, an analysis method, and other factors result in different results. The modelling of soil and the soil material properties also have an effect on the FRS. Generally soil properties largely accounts for the uncertainty in the FRS, but the variation in the soil-related parameters are ruled out in this study because most NPPs are built on a hard-rock foundation.

For base-isolated structures, additional uncertainties are added owing to the variation in isolation devices. The properties of the isolators come to have different values from the expected values because of the manufacturing process, temperature changes, aging effects, and others. However, the property variation in the isolators is restricted when it is applied to an NPP. ASCE provisions state that the mechanical properties of the isolators shall not vary over the lifespan by more than 20% from the values from the analysis and design, with 95% probability[4].

III.B.2. Parameter variation for the study

For the study, the important parameters related to the generation of the FRS were selected. Structural stiffness and isolation stiffness were selected as the key parameter of the superstructure and isolation layer, respectively. Variations in other factors were assumed to be negligible when calculating the FRS.

First, to figure out how much the conventional peak-broadening ratio 15% can envelop the variability of structural stiffness of the fixed-based structure, it was changed by -50% to +50%. The maximum variability of the structural stiffness, found from the analysis of a fixed-based structure, were used for an analysis of the base-isolated structure with a variation of superstructure stiffness to the same extent.

The isolation stiffness was changed by 10% and 20% for the analysis, as the values are limited to change by 20% with 95% probability. Meanwhile, aging of the isolators has a considerable portion of the variation limit of 20%, and the initial variation of the isolators owing to the manufacturing process is guessed to be around 10 % (Ref. 5). As uncertainties due to aging cannot be reduced, and the initial uncertainties can be decreased by the quality control during the manufacturing process, it has been assumed that variations of rubber bearings at the time of the design would be 10% for analyzing results.

III.C. Input earthquakes

For each variation model, time history analyses with 30 ground motions were conducted. A large number of earthquake time histories are required to obtain a reliable FRS; for example, two spectrum-compatible time histories may give a significantly different FRS[2]. The input earthquakes were matched to the Regulatory Guide 1.60 spectrum[6] scaled to 0.5 g. As depicted in Fig. 5, a red bold line represents the design spectra, and other lines are the spectrum of the generated time histories. The generated time histories generally match the design spectrum, but spectral acceleration values are higher at high frequencies. However, this is negligible because higher spectral values at high frequency have little effect on the base-isolated structures as they have a very low fundamental frequency compared to the high frequency domain.

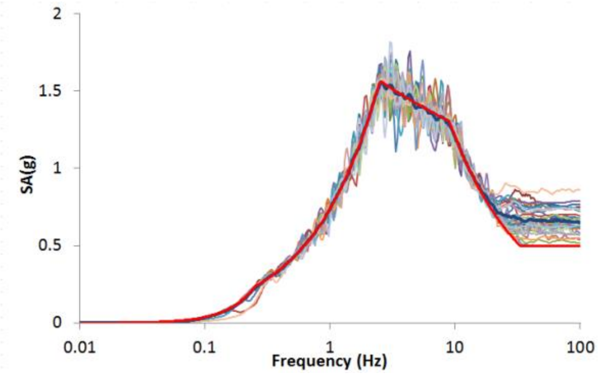


Fig. 5. Regulatory Guide 1.60 spectrum and spectrum of 30 earthquake motions.

IV. RESULTS AND DISCUSSION

IV.A. FRS variation of fixed-based structure model

For each analysis, FRS with 5% damping ratio was computed at the top of the structure where the largest response occurs. The calculated spectrum from 30 ground motions were averaged and depicted in Fig. 6. The grey bold dotted-and-dashed line represents a 15%-broadened spectrum. The broadened spectra roughly envelopes the FRS calculated from models with 30% structural stiffness variation. That is, the allowable stiffness variation range is about 30% under a conventional FDRS generation guide when there are no other factors influencing the FRS.

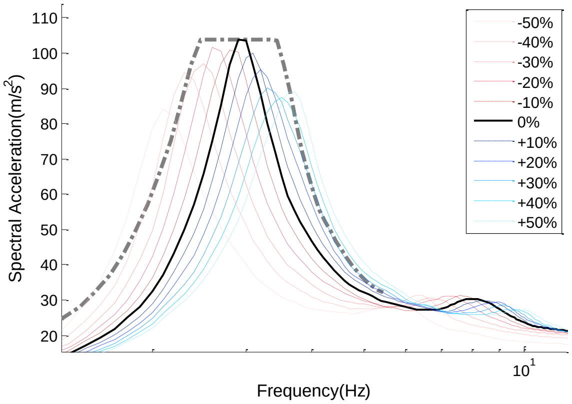


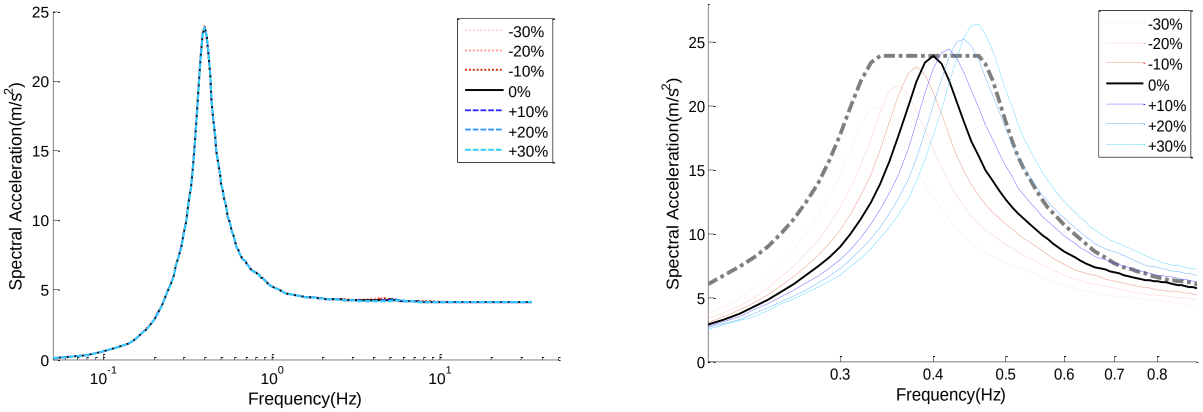
Fig. 6. FRS variation of fixed-based structure as stiffness value changes.

IV.B. FRS variation of three-story building

IV.B.1. Model with natural rubber bearing

To figure out the effect of superstructure stiffness variation on the FRS of base-isolated structures, a maximum of 30% variation were applied to the base-isolated model. The resulting FRS is shown in Fig. 7 (a). This is the result of 2.5s-isolation-period model at the top of the structure, and results of other models will be not depicted here because they have a very similar tendency with that of the 2.5s model. The results show that the variation in the superstructure stiffness has little effect on FRS, and thus studies will be focused on the variation of the bearings.

Fig. 7 (b) shows the FRS of different isolator stiffness, and the grey bold line is the 15%-broadened spectra. As the isolator stiffness changes, the peak of the FRS is shifted and the zero-period spectral acceleration changes. The model with less isolator stiffness has a lower peak at a lower peak frequency. The bold dotted line is 15%-broadened spectra and the broadening ratio covers the variation of isolator stiffness between +20% and +30%.



(a) Superstructure stiffness variation (b) isolator stiffness variation

Fig. 7. FRS variation of base-isolated three-story building (isolation period = 2.5 s).

The required broadening ratios for the model were calculated and are depicted in Fig. 8. The raw spectra should be broadened with the required broadening ratio from the peak to envelop the changed spectrum with variations in parameters. For all isolation periods, the required broadening ratio is under 15% when the isolator stiffness increases by 20% except for the 1.5 s model, which requires a ratio of slightly larger than 17%.

With the restricted variability of the isolator from the ASCE provision, the variability of the isolator at the time of the design has to be around 10%. In addition, note that the change in isolator stiffness value in this study is actually that of the "isolation layer stiffness." The variation of a single isolator is independent of that of the neighboring isolators, and the random arrangement of isolators leads to a smaller variation of the isolation layer stiffness. That is, a 10% broadening ratio is guessed to be sufficient for a structure with linear rubber bearing.

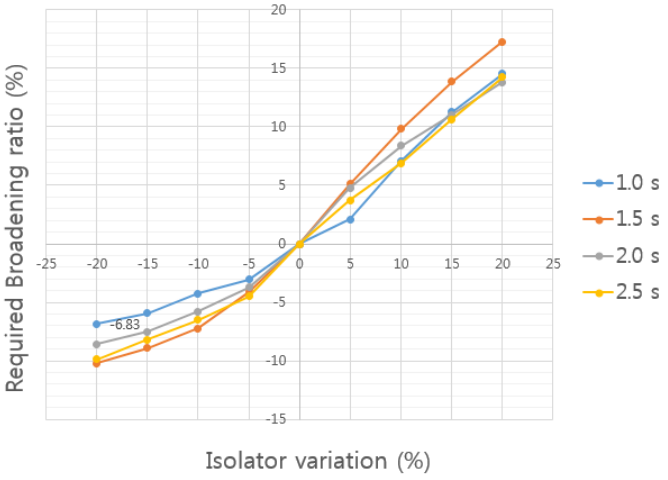
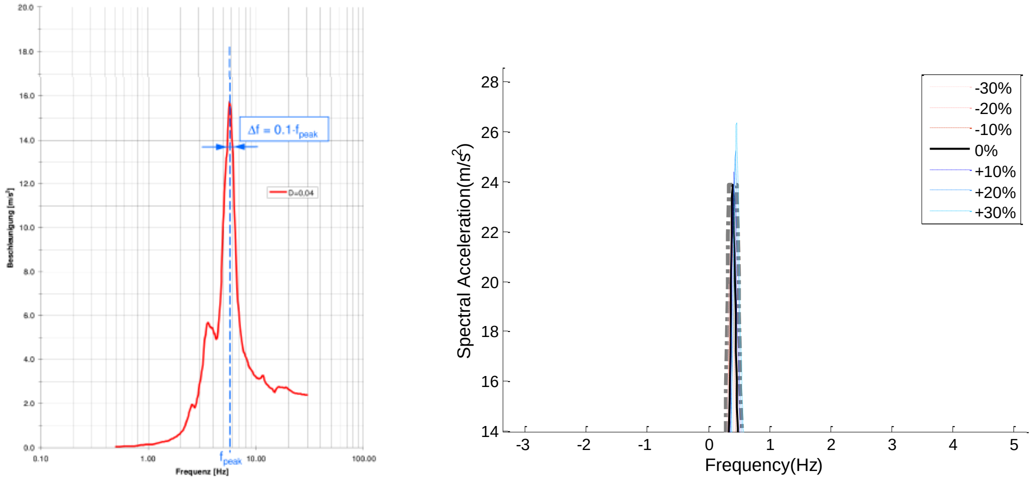


Fig. 8. Required broadening ratio of the base-isolated three-story model.

There remains an issue in which the peak-broadening of FRS cannot envelop the amplified peak. In the calculation process of the FRS, there occasionally occurs a very narrow peak having little energy at the tip. This has been called a "needle peak" and suggests the clipping of spectral peaks where the width of their base is not greater than 10% of their center frequency, as shown in Fig. 9 (a)[7]. Looking at the FRS peak in Fig. 7 with a linear scale of frequency, needle peaks are observed in Fig. 9 (b). The width of the FRS was found to be less than 10%, and thus the amplification of the peak is neglibible in the generation of the design spectrum for the model.



(a) Reduction of the "needle peaks"[7] (b) unrealistic needle peaks in FRS

Fig. 9. Dealing with the needle peaks.

IV.B.2. Model with HDR bearing

The FRS of the base isolated model with an HDR bearing has lower spectral values, but with a broader peak, as depicted in Fig. 10. With a broader peak, the FRS with a parameter variation needs a larger broadening ratio to be enveloped. Fig. 11 shows an FRS with an isolation period of 2.5 s with an HDR bearing variation, and the grey bold line in (a) and (b) are 15%-broadened spectra and 10%-broadened spectra, respectively. The 15%-broadened spectra covers a HDR bearing variation value of between +10% and +20%, and the 10%-broadened one envelops the FRS with a +10% change in HDR bearing stiffness. It can be concluded that a larger broadening ratio is needed when the damping ratio of the isolation bearing is higher. In addition, peak amplification should be considered because the width of the FRS at the base is larger than 10% of center frequency.

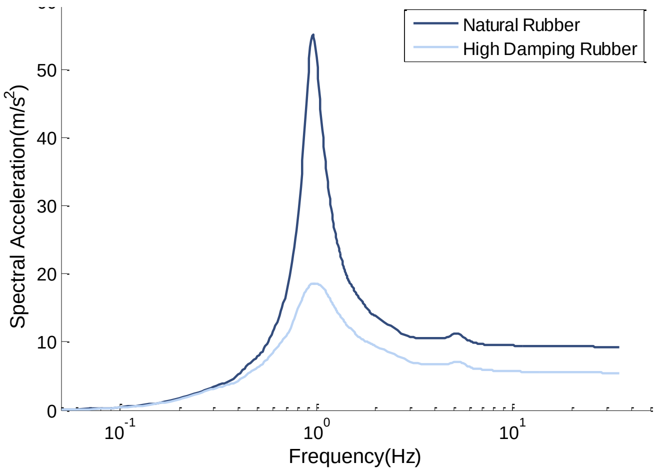
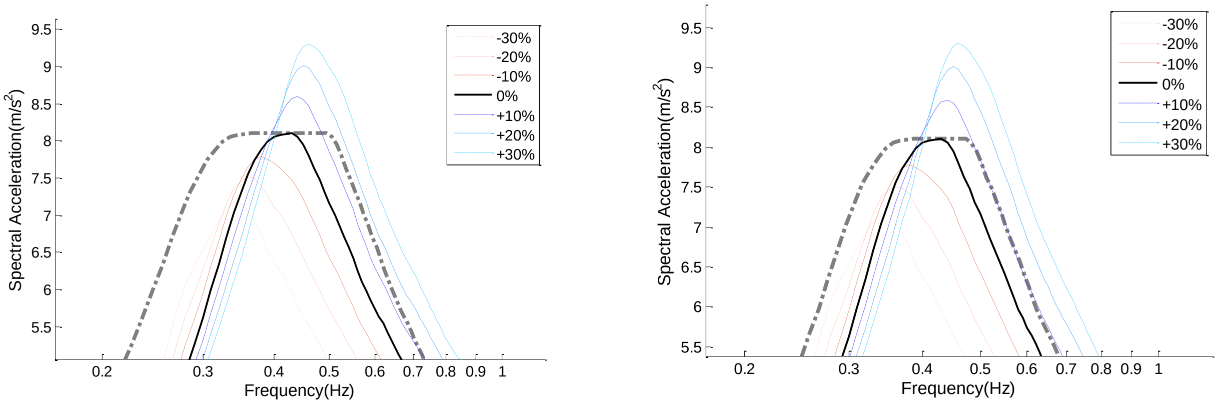


Fig. 10. FRS of base-isolated models with natural rubber bearing and HDR bearing (isolation period = 1.0 s).

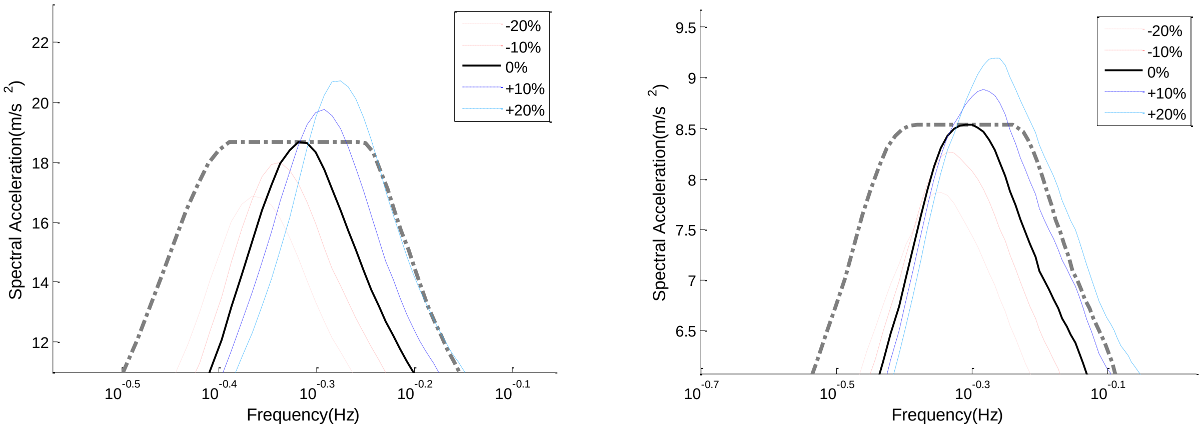


(a) 15%-broadened spectra (b) 10%-broadened spectra

Fig. 11. FRS variation of 3-storied structural model with high damping rubber bearing variation.

IV.C. FRS variation of NPP structural model

The FRS variations of NPP structural models on the change of natural rubber bearings and the bearing stiffness is plotted on Fig. 12 (a) and (b), respectively. The bold line in the figure is the 15%-broadened spectrum. Natural rubber bearing stiffness can be changed by a maximum of around +20%, to be enveloped within the broadened spectrum. The allowed variability is a bit lower than that of three-story building model. In the case of HDR bearings, the maximum variability of stiffness is between +10% and +20% within the broadened spectra, which is similar to the result of the three-story structural model. Overall, the variability of the isolation bearing in the NPP model has a similar effect as in the three-story building model.



(a) Natural rubber bearing model (b) HDR bearing model

Fig. 12. FRS variation of base isolated NPP with high damping rubber bearing variation.

V. CONCLUSIONS

A natural rubber bearing and HDR bearing were applied to two base-isolated models. A simple three-story building model and an NPP structural model showed similar results. When the stiffness of a natural rubber bearing is changed with a maximum variability range of 20%, the FDRS is generated by following the conventional guide enveloping the change in the FRS. At the time of the design, variability of the bearing is guessed to be around 10%, and thus the broadening ratio can be reduced compared with currently required ratio of 15%. For an HDR bearing with a high damping value, 15% of the broadening ratio may not be sufficient for the 20% variability of the isolator stiffness, but may be okay for the variation at the time of the design. In addition, the peak amplification is needed because the spectrum is broader for the HDR bearings.

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