Effect of Nonlinearity of Building and Components on Response Correlation of Nuclear Power Plants

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Abstract: The severe accident at the Fukushima Daiichi Nuclear Power Plant has emphasized the need for improving the safety as an urgent issue. Probabilistic risk assessment (PRA) plays a crucial role in ensuring safety. Considering seismic correlation is of particular importance in the evaluation of seismic risk, as common cause failures can occur due to earthquakes. We have examined the effect of building nonlinearity on the response correlation between rigid components. This paper focuses on the nonlinear effects of building and components on response correlation. The effects of vibration characteristics were also investigated. The analysis model uses the PCCV of a reactor facility, considering shear and bending nonlinearities, and the response of each component was obtained through time history response analysis. Comparing the response correlations between nonlinear and linear buildings, the correlation coefficients in the nonlinear building are smaller than those in the linear building. In addition, the influence of component nonlinearity on the correlation was also evaluated. The results of the comparison indicate that the correlation between components with linear properties was greater than that between components with nonlinear properties.

Keywords: Seismic Correlation, Seismic PRA, Common Cause Failure, Nonlinearities

1. INTRODUCTION

The 2011 severe accident at the Fukushima Daiichi Nuclear Power Plant highlighted the urgent need to enhance the safety measures against various external hazards. Probabilistic risk assessment (PRA) plays a crucial role in ensuring safety of nuclear power plants. In earthquake-prone countries such as Japan, the common cause failure (CCF) induced by earthquakes poses a critical threat. Seismic PRA is essential for identifying weak points in structures, systems, and components (SSCs) within nuclear power plants. However, seismic correlations can distort PRA results, thereby necessitating the investigation of the factors influencing these correlations and their effects on the results. Seismic correlation refers to the statistical relationship between component failures, which includes both their responses and capacities.

Research on seismic correlation has advanced through the Seismic Safety Margins Research Program (SSMRP), which evaluated the occurrence probabilities of accident sequences and core damage frequency (CDF) while considering correlation effects. Additionally, the Direct Quantification of Fault Tree using Monte Carlo Simulation (DQFM) method was developed to incorporate these correlations. Despite these advancements, a standardized method for setting correlation coefficients remains undeveloped.

The Atomic Energy Society of Japan's (AESJ) standards recommend that seismic correlations between components be realistically considered. Given the difficulty in quantifying these correlations, evaluations often assume complete dependence (correlation coefficient: 1.0) or complete independence (correlation coefficient: 0) to gauge their impact on PRA results. NUREG-1150 established empirical correlation rules for the Surrey and Peach Bottom power plants, but these rules lack generality. Further studies, such as those by Ebisawa et al. (2015) and Komine et al. (2023), have investigated correlation coefficients in both linear and nonlinear regions.

This study focuses on components with varying vibration characteristics, with natural periods ranging from 0.05s to 1.0s. Initially, it examines the effect of building nonlinearity on response correlations between components with different vibration characteristics by scaling seismic motion. Subsequently, it investigates the combined effects of building and component nonlinearity on response correlation, considering component nonlinearity through yield displacement calculations. The simple model used in this study does not take into account the interaction between the components and the building. Therefore, this study attempts to trend how nonlinearities in the building and components affect the damage correlations.

2. Calculation of correlation coefficients

2.1. Analysis Model

The analysis model is a nine-degree-of-freedom model targeting the reactor containment vessel made of reinforced concrete (PCCV) of a nuclear reactor facility. Nonlinearity in shear and bending is considered. The restoring force characteristics in the shear direction use a tri-linear model with peak-oriented behavior, while the restoring force characteristics in bending use a degrading tri-linear model. This model was created by the Nuclear Safety Analysis Office of the Japan Nuclear Energy Safety Organization as part of the development of probabilistic safety assessment methods related to earthquakes (Part 3) [8]. Komine (2023) [7] also used the same model. This model was used for time history response analysis. The parameters of the model are listed in Table 1. Install components with various natural periods at each node. This allows for various condition settings based on the location of the equipment and the natural period. The model is designed to input seismic data in the horizontal direction. Therefore, this study deals only with input seismic motion in the east-west direction. The response spectra of the input earthquake motion are shown later, all of which are in the horizontal direction.

Table1. Model Parameters

Node	Height [m]	Mass [ton]
9	65.1	320.0
8	63.6	1390.0
7	57.6	3020.0
6	48.5	3380.0
5	40.5	5930.0
4	26.7	4780.0
3	19.9	3920.0
2	9.8	3230.0
1	6.0	2280.0

2.2. Analysis Procedure

STEP 1: Calculation of Yield Displacement

The yield displacement was calculated using 1.25 times the maximum response displacement of each component. This conservative value was chosen to be larger than the maximum response value. The response of the components was obtained through time history response analysis using the general-purpose 3D dynamic analysis program TDAP III. Given the nine-degree-of-freedom model, responses for components with natural periods ranging from 0.05 to 1.0 seconds installed at nodes 1 through 9 were obtained. From these responses, the yield displacement for each component was calculated. The input seismic motion used was BCJ-L2, a simulated wave published by the Building Center of Japan (BCJ) [9]. Since the simulated wave does not have a specific seismic base, it allows for a general value of yield displacement.

STEP 2: Calculation of Response

Next, the time history response analysis was repeated with different input seismic motions to obtain response waveforms for evaluating component responses. The input seismic motions were 94 waves selected from strong motion observation data published on the website of Japan Meteorological Agency (JMA) [10]. For each earthquake, waveform data was selected from the observation points with the highest "composite maximum acceleration of the three components (north-south, east-west, vertical)." Additionally, waveform data from the observation point farthest from the epicenter for that earthquake was selected. Following these criteria, a total of 94 waves were selected from all earthquakes published until 2021. This study compares the linear and nonlinear responses of the building. Three types of input data were used: 500 gal before building plasticization, and 1500 gal and 2500 gal after plasticization. Each of these was input into the time history response analysis. The natural periods and damping constants of the components were specified, with natural periods ranging from 0.05 to 1.0 seconds and a damping constant of 0.01.

STEP 3: Calculation of Component Responses
The response waveforms obtained from the time history response analysis in STEP 2 were used as input to calculate the component responses. The Newmark-β method was used to calculate the responses in the nonlinear analysis of the components. This method is suitable for numerically analyzing the dynamic response of structures and was chosen for its ability to handle yield displacement calculations. A parameter β of 1/4 was used.

STEP 4: Calculation of Correlation Coefficients
The correlation coefficients were calculated from the component response accelerations obtained in STEP 3. The formula for calculating the correlation coefficient is shown in Equation (1). Where, r represents the correlation coefficient, S_{xy} is the covariance of layers x and y, S_x is the standard deviation of layer x, S_y is the standard deviation of layer y, n is the total number of input seismic motions for the two-variable data layers (x, y), x_i and y_i are the individual accelerations, and $\overline{x}$ and $\overline{y}$ are the average accelerations. Since n represents the total number of input seismic motions, it is 94 in this case.

$$r = \frac{S_{xy}}{S_x S_y} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})^2}\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i-\bar{y})^2}} \quad (1)$$

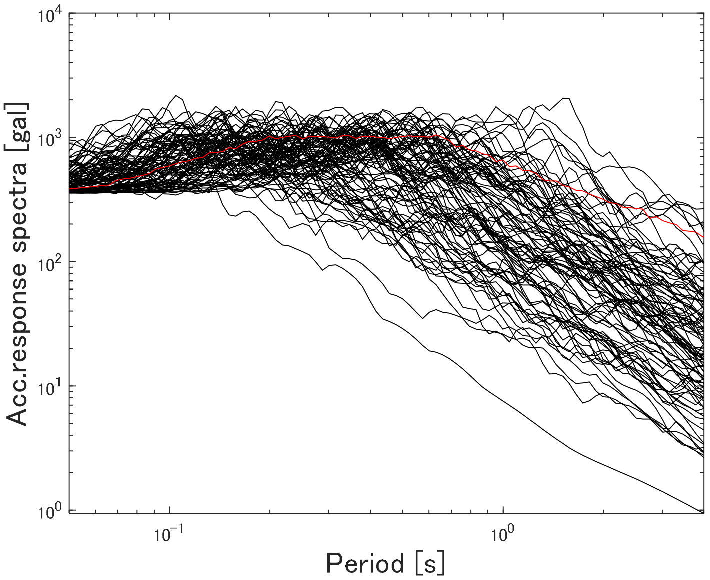

Figure1. Response spectra

Figure 1 shows the response spectra of the input earthquake motion. The black lines in the figure are for earthquake motion obtained from the Japan Meteorological Agency. The red line is the simulated wave of BCJ. The response spectrum was normalized to the maximum acceleration of the BCJ (355.66 m/s^2). Figure 1 shows that seismic motions with various spectra were used.

3. Analysis Results and discussion

In this study, a “reference component” was established and the correlation coefficients with that component were calculated. The reference device is determined by the installation location and natural period.

Figure 2 shows a comparison of the correlation coefficients at nodes 1, 5, and 9 for input accelerations of 500 gal (linear building) and 1500 gal (nonlinear building). The reference component is the one with a natural period of 0.05 seconds installed at node 1. The solid line represents the linear building, while the dashed line represents the nonlinear building. The natural periods plotted range logarithmically from 0.05 to 1.0 seconds, divided into 20 equal intervals. This approach reduces plotting bias when using a semi-log graph. Since Figure 2 examines the effect of building nonlinearity on correlation, both components remain in a linear state.
In the case of the linear building, a negative correlation is observed for natural periods greater than 0.2 seconds, whereas, in the nonlinear building, the correlation coefficient increases from around 0.3 seconds, indicating an

overall tendency for lower correlation coefficients in the nonlinear building. The reduction in correlation coefficients in the nonlinear building is attributed to the structure becoming nonlinear due to seismic motion, causing the response spectrum to be more significantly influenced by the input spectrum. The reason for the negative correlation is that the use of various types of earthquake ground motions can lead to negative correlations due to the large variation in shaking characteristics, such as short-period earthquakes with small spectra and long-period earthquakes with large spectra. Using many seismic motions results in lower correlations for each response spectrum, leading to overall lower correlation coefficients. The reason for the relatively large value of the NUREG-1150 rule may also be due to the number of seismic motions. Comparing the correlation coefficients for each node, there is minimal variation, indicating that the installation location has small effect on the correlation coefficients. This was confirmed for both the linear and nonlinear building cases. However, in the linear building, only at node 5 was a decrease in the correlation coefficient observed around a natural period of 0.06 seconds. This is likely due to the presence of a node of the second mode of vibration near node 5, causing its response to differ from that of the other nodes.

Figure 3 shows a comparison between linear and nonlinear components. The reference component, as before, is the one with a natural period of 0.05 seconds installed at node 1. In the figure, the black line represents linear components (1500 gal), the blue line represents nonlinear components (1500 gal), and the red line represents nonlinear components (2500 gal). To consider building nonlinearity simultaneously, input data of 1500 gal or higher was used. The comparison focuses on the plastic state of the components at 1500 gal. For linear components, the correlation coefficient is approximately -0.2 around a natural period of 0.2 seconds, whereas for nonlinear components, the correlation coefficient is 0.2, both having the same absolute value. Even beyond a natural period of 0.4 seconds, similar values are observed, but overall, the correlation coefficients for linear components are smaller. This could be due to increased damping from hysteresis damping in nonlinear components, which increases the correlation coefficients. This analysis also considers building nonlinearity simultaneously. Hence, hysteresis damping from building nonlinearity is also present. However, in the case of nonlinear buildings with linear components, no significant increase in correlation coefficients was observed, suggesting that hysteresis damping in the components has a more significant effect on correlation. Next, the correlation coefficients for nonlinear components at 1500 gal and 2500 gal are compared. A trend of increasing correlation coefficients with larger input seismic motions was observed. This result further supports the idea that hysteresis damping affects correlation coefficients. Even in nonlinear components, the differences in correlation coefficients between nodes were minimal. This suggests that the effect of the installation location on correlation coefficients is small even for nonlinear components. In particular, there was no phenomenon of a decrease in the correlation coefficient due to the nodes of the quadratic mode, which was observed in the building linear. In the building and component nonlinearities, it was found that the mode nodes did not affect the response correlations. Figure 1 shows the standardized spectrum, but the period of the reference point is around 0.15s. Perhaps due to this effect, the correlation coefficient decreases toward the natural period of 0.15s. Beyond the reference point, the spectrum is scattered. In addition, the response in the nonlinear is greatly affected by the input spectrum. Therefore, the correlation coefficient tends to decrease rapidly toward the period of the reference point.

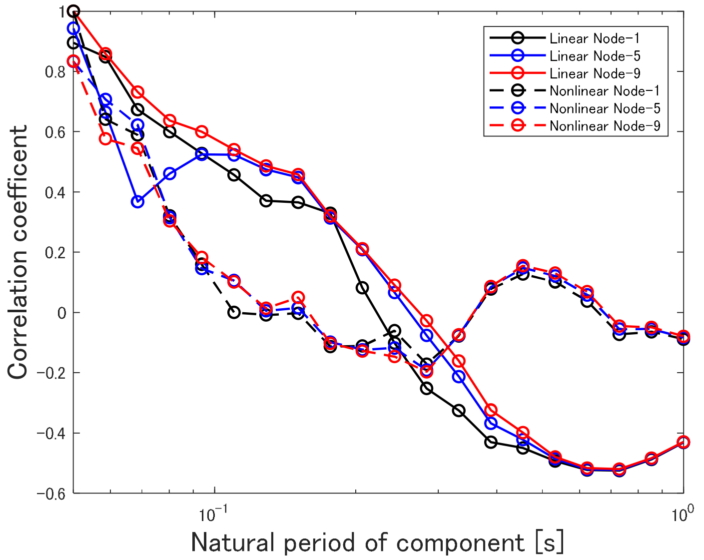

Figure 2. Comparison of correlation coefficients at 500 gal and 1500 gal

Figure 3 shows the correlation coefficients calculated with a damping constant of 0.01. The hypothesis suggested that hysteretic damping increases the correlation, so the correlation coefficients were recalculated with higher damping constants. The input seismic motion was 1500 gal, with the same reference component conditions. Increasing the damping constant from 0.01 to 0.05 in increments of 0.01, the correlation coefficients were calculated accordingly. Figure 4 shows the results. The correlation coefficients between the reference component and the components with a natural period of 0.2 seconds installed at each node were calculated. The results confirmed that the correlation coefficients increased with the increase in damping. With a damping constant of 0.01, the correlation coefficients were around 0.3 at all nodes. When the damping constant increased to 0.05, the correlation coefficients more than doubled. This trend was particularly strong for components installed at higher nodes, with node 9 showing an increase of approximately 2.7 times.

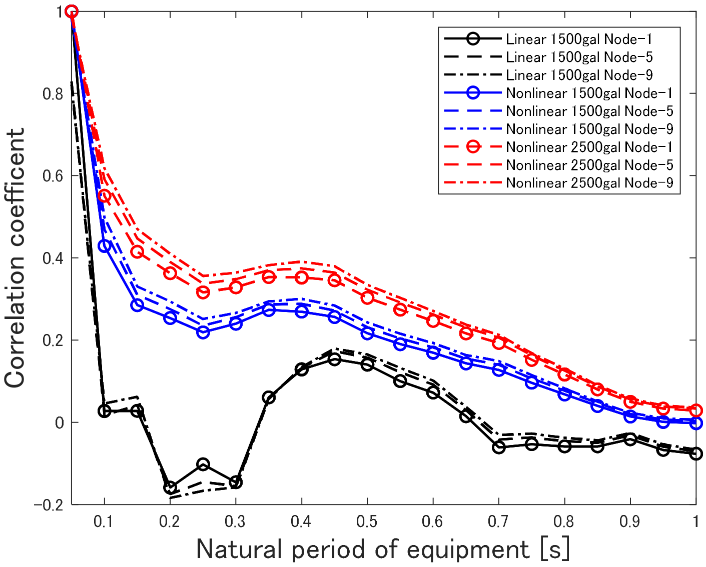

Figure 3. Comparison of component nonlinearity and component linearity

In this paper, all reference devices are assumed to be under the same conditions. It was considered that the values of the correlation coefficients could be changed by changing the installation location or natural period of the reference equipment. Since the results of this study did not show much effect of the installation location, the change of the natural period was considered to change the correlation coefficient more. Damping effects were also observed. Calculating correlation coefficients under various conditions is useful when considering seismic diversity.

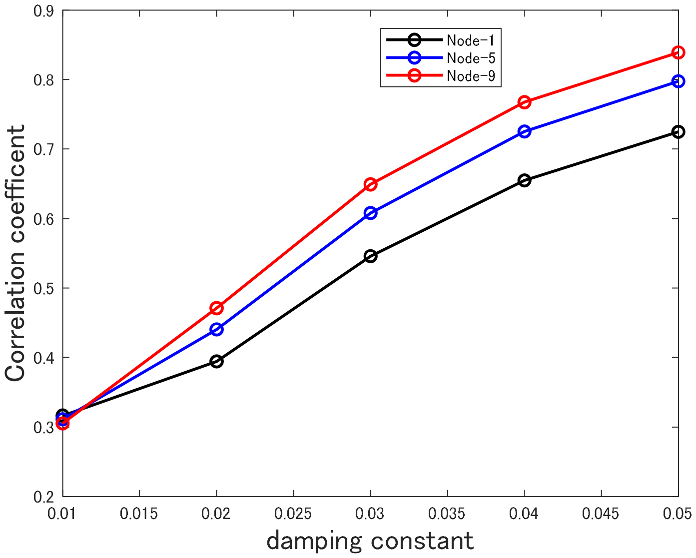

Figure 4. Comparison by Damping Constants

4. CONCLUSION

In this study, the effect of nonlinear responses of buildings and components to various seismic ground motions on the correlation coefficients of components with different vibration characteristics was evaluated. Nonlinear time history response analysis using TDAP III was conducted to calculate the responses at nodes in the specified model, and the responses of components with various natural periods installed at these nodes were evaluated to calculate the correlation coefficients. The nonlinearity of the components was considered by calculating the yield displacement from the maximum response displacement against a design ground motion generated by the building center of Japan (BCJ). The following are some of the findings of this paper.

(1) Comparing the linear and nonlinear building cases, smaller correlation coefficients appeared in the nonlinear building.
(2) The correlation coefficients showed minimal variation across different installation locations, indicating that the installation location has small effect. Both linear and nonlinear building cases exhibited this consistency.
(3) Comparing linear and nonlinear components, the nonlinear components showed larger correlation coefficients. The increase may be attributed to increased equivalent damping due to nonlinear hysteresis. Although the effect of hysteretic damping in the nonlinear building was not large, we should pay attention to the effect of nonlinearity on response correlation.

While the response spectrum in the nonlinear building is greatly influenced by the input spectrum, the same applies to nonlinear components. However, whether this also holds true for components installed in a nonlinear building remains unresolved and requires future investigation. In addition, since this time we are only looking at trends, detailed rule making is also an issue for the future. Also, since we are only looking at trends at this time, we plan to make detailed rules and examine how history affects component nonlinearities.

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