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DEVELOPMENT OF EVALUATION METHOD FOR SEISMIC ISOLATION SYSTEMS OF NUCLEAR POWER FACILITIES - SEISMIC FRAGILITY EVALUATION OF EQUIPMENT-

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ABSTRACT

This paper provides a part of series of “Development of Evaluation Method For Seismic Isolation Systems of Nuclear Power Facilities”. This part describes the seismic fragility evaluation for equipment of the seismic isolated plants.

In order to respond the regulatory requirement of residual risk evaluation, a research on residual risk evaluation of the seismic isolated plants is proceeding as a part of the Japan national project of seismic isolation. As efforts for this research, realistic capacities of seismic isolators are studied by braking tests of full-scale seismic isolation systems and of crossover piping are studied by shaking tests of scaled model and static tests by simultaneous loads of in-plane and out-of-plane. Fragilities of the seismic isolators and crossover piping are evaluated based on the results of these studies.

Seismic response characteristics of the seismic isolated buildings show strong non-linearity and large displacement because of the vibration characteristic of the seismic isolation system. Therefore, response characteristics specific to the seismic isolated buildings such as non-linear response and relative displacement between isolated building and non-isolated building shall be considered in the fragility evaluation methodology for equipment of the seismic isolated plants.

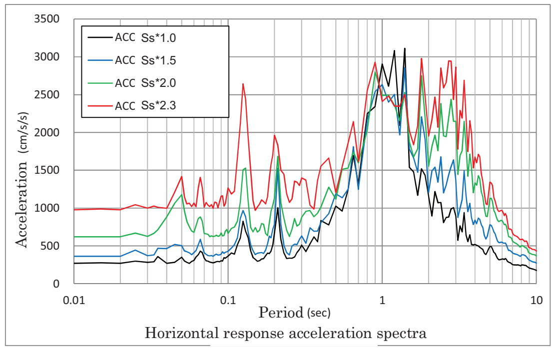
This paper focuses on the seismic fragility evaluation of equipment of the seismic isolated plants considering the relative displacement and non-linear response of the buildings. Representative equipment of isolated plants are selected and fragility evaluations of the equipment are performed based on the results of the response analysis of buildings and crossover piping.

Result of seismic PRA using fragility values obtained in this study is reported in other part of this series of papers.

METHODOLOGY OF FRAGILITY EVALUATION

Fragility evaluation methodology which assumes a linear relation between seismic input and response of SSCs, such as Zion method, cannot be applied to SSCs with seismic isolation because of their

nonlinearity of response. Figure 1 shows an example of floor response spectra of a seismic isolated building with gradually increased seismic input.
In order to cope with this nonlinear characteristic of the seismic isolation, a methodology to obtain a fragility curve of a SSC by using the least square approximation from plots of failure probabilities at some input seismic acceleration level is considered.



Ss: Basic input earthquake for this series of study.

Figure 1. Example of floor response of the isolated building

Failure probability $F(A)$ for an input seismic motion A is calculated by formula (1) as a conditional failure probability of the realistic response $f_R(A, x)$ exceeding the realistic capacity $f_S(x)$.

$$F(A) = \int_0^{\infty} f_R(A, x_R)\left(\int_0^{x_R} f_S(x)dx\right)dx_R \qquad (1)$$

The realistic response $f_R(A, x)$ is represented as a log normal distribution with median $R_m(A)$ and logarithmic standard deviation $\beta_R(A)$, as the following formula.

$$f_R(A,x) = \frac{1}{\sqrt{2\pi}\beta_R(A)\cdot x}\exp\left\{-\frac{1}{2}\left(\frac{\ln\left(\frac{x}{R_m(A)}\right)}{\beta_R(A)}\right)^2\right\} \qquad (2)$$

The realistic capacity $f_S(x)$ is represented as a log normal distribution with median S_m and logarithmic standard deviation β_S, as the following formula.

$$f_S(x) = \frac{1}{\sqrt{2\pi}\beta_S \cdot x}\exp\left\{-\frac{1}{2}\left(\frac{\ln\left(\frac{x}{S_m}\right)}{\beta_S}\right)^2\right\} \qquad (3)$$

In the case of evaluations for components, median and logarithmic standard deviation of their realistic capacity and realistic response can be determined based on their material properties, various test results, parameter study of structure response analysis, etc. However, in the case of crossover piping between buildings, fatigue failure will be critical for failure of the piping, not primary stress as in other components. Therefore, unlike the conventional method, the realistic capacity needs to be evaluated based on the fatigue curve of piping. To evaluate the realistic capacity distribution of the crossover piping, a methodology whereby the realistic capacity distribution is obtained by assuming that the best estimate fatigue curve and design fatigue curve are correspond to median and lower limit respectively is constructed, as shown in Figure 2.

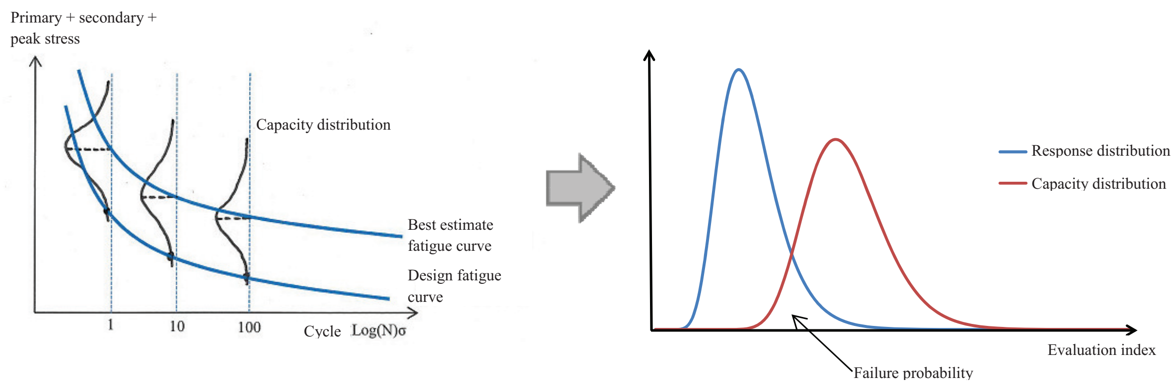


Figure 2. Piping fragility considering fatigue failure

The methodology to create a fragility curve for failure probabilities which are discretely obtained by the process shown above is shown as follows.
The mean fragility curve is represented by the following formula.

$$P_f = \Phi\left[\frac{\ln\left(\dfrac{a}{Am}\right)}{\beta_c}\right] \qquad (4)$$

Where,

- Pf: Failure probability
- Φ: Standardized cumulative normal distribution function
- a: Input acceleration
- Am: Median capacity
- β_c: Combined logarithmic standard deviation $\left(\beta_c = \sqrt{\beta_R^{\ 2} + \beta_U^{\ 2}}\right)$
- β_R: Logarithmic standard deviation for randomness
- β_U: Logarithmic standard deviation for uncertainty

The inverse function of formula (4) is shown as follows.

$$\Phi^{-1}(P_f) = \left(\frac{1}{\beta_c}\right)\cdot\ln(a) - \left(\frac{1}{\beta_c}\right)\cdot\ln(Am) \qquad (5)$$

This formula represents a straight line with the inclination of $1/\beta_c$ and the intercept of $-(1/\beta_c)\ln(Am)$. Therefore, the inclination of $1/\beta_c$ and the intercept of $-(1/\beta_c)\ln(Am)$ can be obtained from an straight line created by the least square approximation of plots of $\Phi^{-1}(P_f)$ and $\ln(a)$ which are calculated from failure probability (P_f) at input acceleration a. Consequently, β_c and Am are calculated from $1/\beta_c$ and $-(1/\beta_c)\ln(Am)$.

CROSSOVER PIPING

Fragilities of crossover piping between an isolated building and a non-isolated building are evaluated using realistic response distributions which are obtained as the results of parameter study of structure analysis considering variation of factors which are sensitive to the structure response and some cases of input seismic motion.

Piping

(1) Piping fatigue evaluation
In general, piping elbow is considered to be most critical part for the fatigue failure of the crossover piping. Therefore, in this section, evaluation for the piping elbow is focused on.
Evaluation for Main Steam (MS) crossover piping between isolated reactor building and non-isolated turbine building of PWR is shown here as a representative of the crossover piping. Analysis model schematic of the MS crossover piping is shown in Figure 3. Eight basic cases are specified considering combination of variation of three sensitive factors of the building isolator, i.e. horizontal rigidity of laminated rubber, initial rigidity of lead plug and yield shearing strength of lead plug. Response analysis for these eight basic cases are conducted at input seismic motions of Ss (basic input earthquake for this series of study) multiplied by factor α_h (α_h = 1~2.3).
Fatigue evaluation of parts of the MS crossover piping is conducted by multiple input analyses with input of time history waves whose parameters are varied as mentioned above. Analysis region of the MS crossover piping is between anchor points which are respectively placed on the isolated building and non-isolated building. Applied analysis code is ABAQUS.
Results of the fatigue analysis are shown in Figure 4. Blue line and red line in Figure 4 show, respectively, ASME design fatigue curve and NUPEC prediction fatigue curve based on the test of ultimate piping strength.

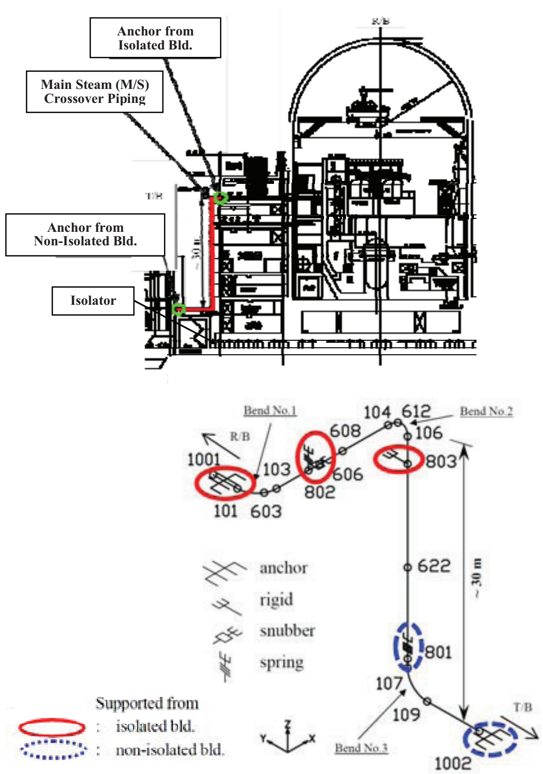


Figure 3. Analysis model of MS crossover piping

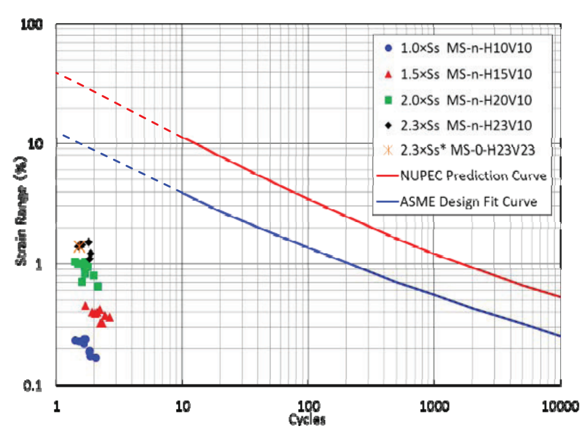


Figure 4. Results of fatigue analyses of MS crossover piping

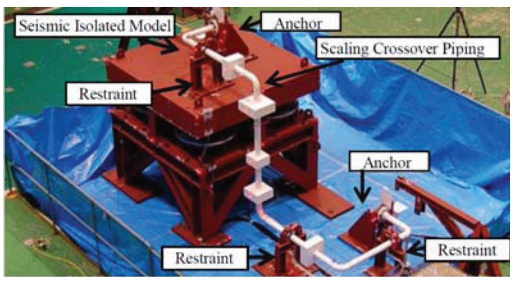
(2) Fragility evaluation

Realistic response distributions of the MS crossover piping at the input acceleration levels are created from the results of the response analysis mentioned in the previous section. Realistic capacity distribution of the MS crossover piping is created by assuming that the design fatigue curve and NUPEC prediction (best estimate) fatigue curve are 3σ and median respectively. NUPEC prediction (best estimate) fatigue curve has been found to correspond to median capacity in shaking tests and fatigue tests, as shown in Figure 5.

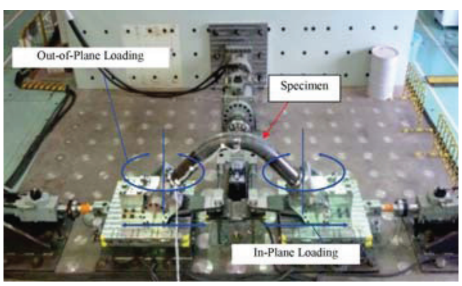
As mentioned in the previous chapter, failure probabilities at the input acceleration levels are calculated from these response and capacity distributions. And a fragility curve is created by the least square approximation of plots of the failure probabilities. Figure 6 shows the created fragility curve and its fragility value as a result is as follows.

- MS crossover piping: Am=5.26G, β_c=0.134

This result shows that the seismic failure probability of the crossover piping elbow is sufficiently small.



・Shaking test



・Fatigue test

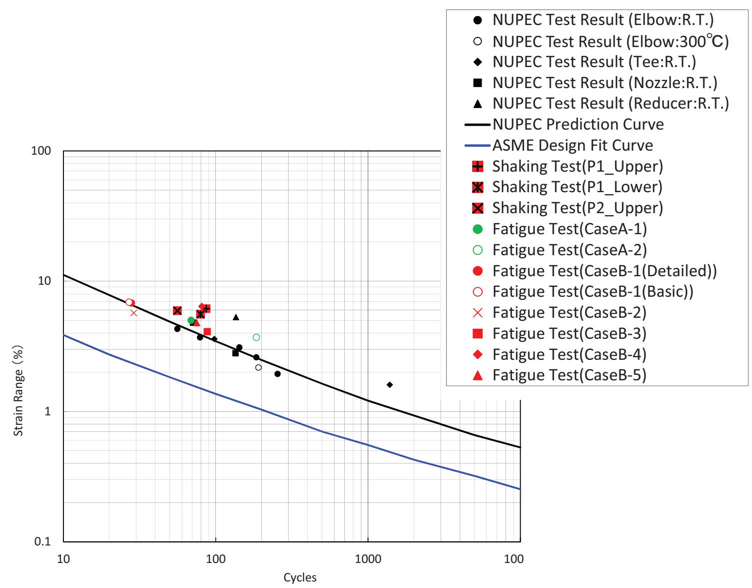


Figure 5. Results of tests for crossover piping

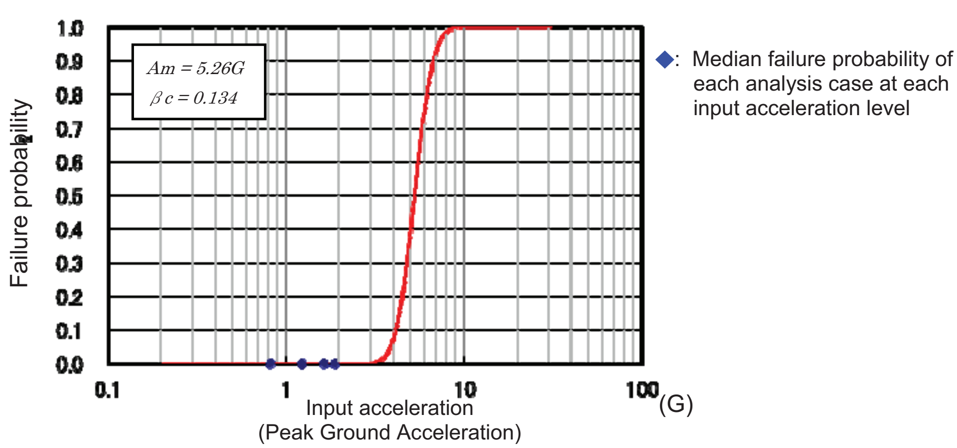


Figure 6. Fragility curve of MS crossover piping (piping elbow)

Bellows

(1)Bellows fatigue evaluation

Reactor Component Cooling Water (RCCW) system crossover piping of BWR is designed to absorb relative displacement between isolated reactor building and non-isolated turbine building by installing bellows. Evaluation for this RCCW crossover piping is shown here as a representative of bellows. Analysis model schematic of the RCCW crossover piping with bellows is shown in Figure 7. Analysis cases are specified in the same way as the piping elbow, as mentioned in the previous section. Response analysis for the basic cases are conducted at input seismic motions of Ss (basic input earthquake for this series of study) multiplied by factor α_h (α_h = 1~2.5). Analysis region, methodology and code are also same as the analysis for piping elbow mentioned in the previous section. Results of the fatigue analysis are shown in Figure 8.

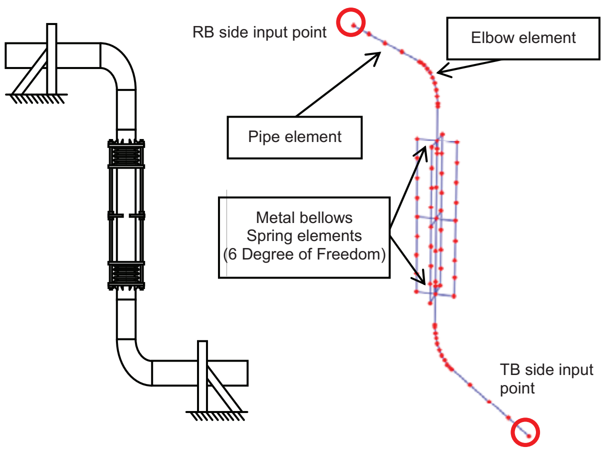


Figure 7. Analysis model of RCCW crossover piping

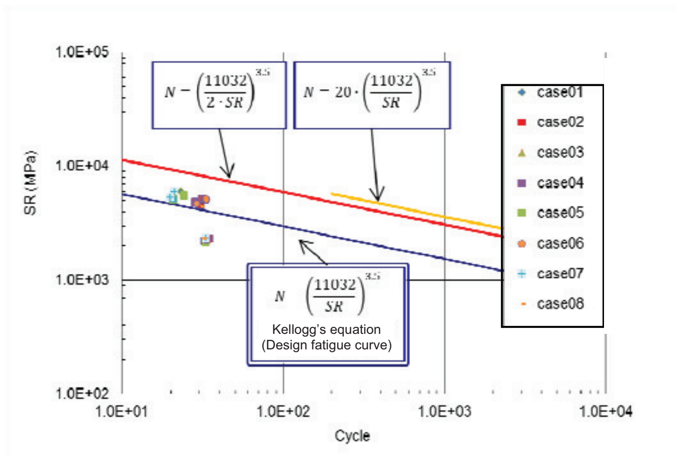


Figure 8. Results of fatigue analyses of RCCW crossover piping

(2) Fragility evaluation

Realistic response distributions of the RCCW crossover piping at the input acceleration levels are created from the results of the response analysis mentioned in the previous section. Realistic capacity distribution of the RCCW crossover piping is created by assuming that the design fatigue curve and the best estimate fatigue curve are 3σ and median respectively. The design fatigue curve of the metal bellows of crossover piping is obtained by Kellog's equation. And, because there is no available information about the best estimate fatigue curve of bellows, the best estimate fatigue curve is assumed to be twice stress and 20 times cycle of the design fatigue curve.

As mentioned in the previous chapter, failure probabilities at the input acceleration levels are calculated from these response and capacity distributions. And a fragility curve is created by the least square approximation of plots of the failure probabilities. Figure 9 shows the created fragility curve and its fragility value as a result is as follows.

- RCCW crossover piping bellows: Am=4.44G, β_c=0.3903

This result shows that the seismic failure probability of the crossover piping bellows is sufficiently small.

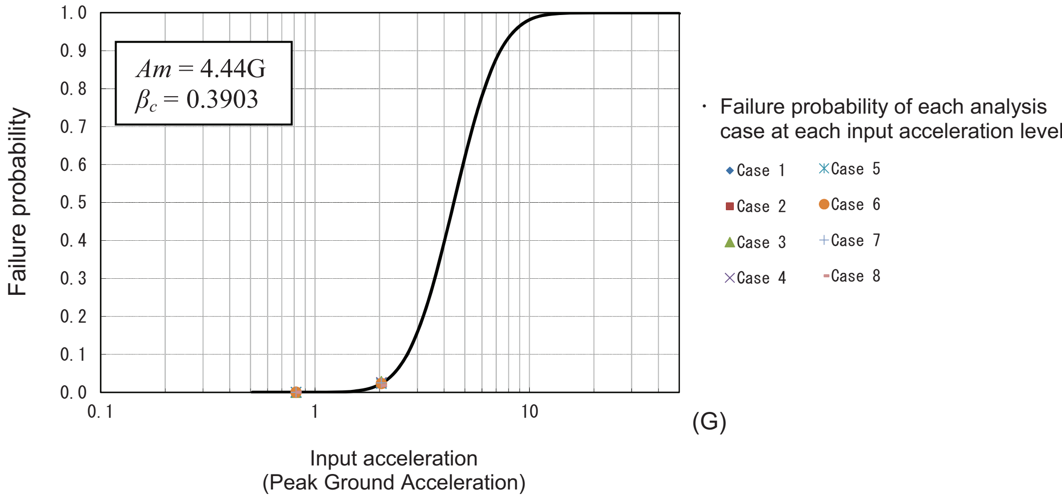


Figure 9. Fragility curve of RCCW crossover piping (bellows)

COMPONENTS IN THE ISOLATED BUILDING

Fragilities of components except for crossover piping (i.e. primary components, heat exchangers, electrical boards, etc.) which are placed inside the isolated buildings as shown in Figure 10 are evaluated based on the methodology mentioned in the first chapter.

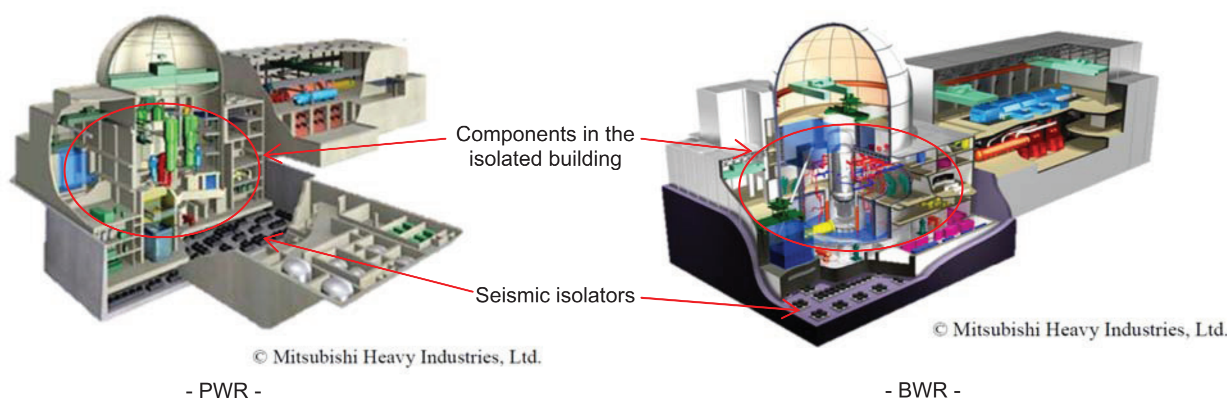


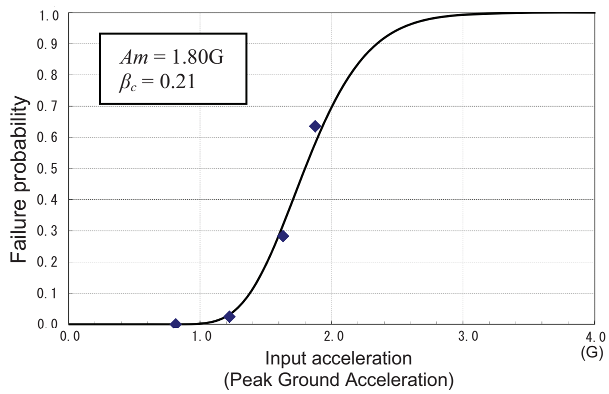
Figure 10. An example of plant arrangement with the seismic isolation systems

Response and capacity of components

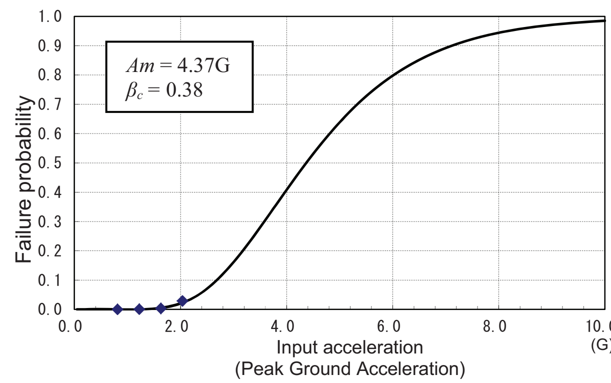
To evaluate the response of the components in the isolated buildings, design improvements to cope with response amplification in the vertical direction, which is the characteristic of the building isolation, are taken into consideration. Structure response analyses for multiple input acceleration levels are conducted to develop floor response spectra for each input acceleration level. Using the obtained floor response spectra, response of the components are evaluated and realistic response distributions are created considering uncertainty and randomness of the evaluation conditions.
Realistic capacity distributions are created by assuming median, uncertainty and randomness based on material properties of parts of the components, results of shaking test, etc.

Fragility evaluations

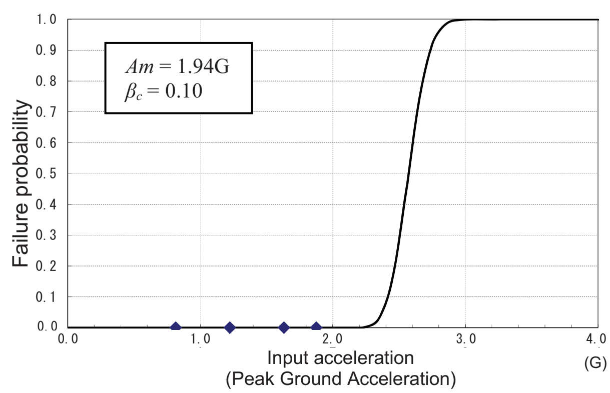
As mentioned in the first chapter, failure probabilities at the input acceleration levels are calculated from these response and capacity distributions. And fragility curves are created by the least square approximation of plots of the failure probabilities. Figure 11 shows the samples of created fragility curves of the components. And their fragility values as results are also shown in Figure 11.
From the results of fragility evaluations of components in the isolated buildings, it can be concluded that the building isolation is effective to lessen the fragilities of components and, as a result, to lessen Core Damage Frequency (CDF) of the plant.



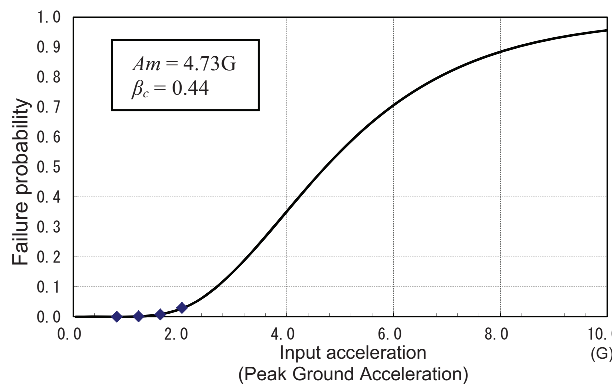
a) Primary component



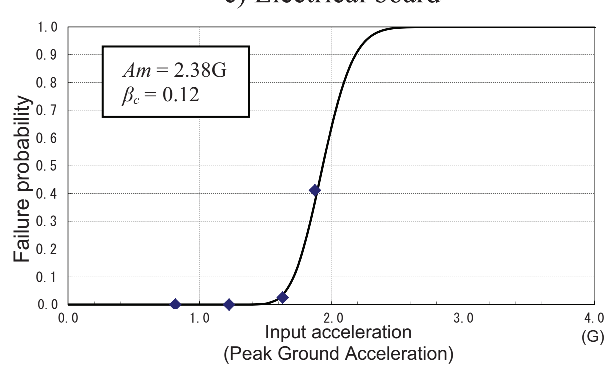
b) Piping



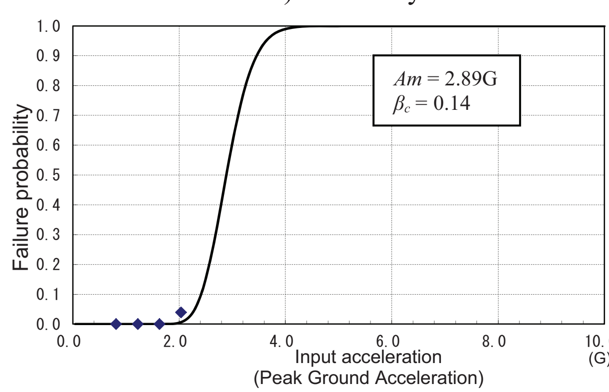
c) Electrical board



d) Cable tray



e) Heat exchanger



f) HVAC fan

Figure 11. Fragility curves of components (examples of results)

CONCLUSION

Contents and results of this study are summarized as follows.

- Fragility evaluation methodology to cope with non-linearity of building response and fatigue failure resulting from building isolation is considered and demonstrated.
- Fatigue analyses for the elbow and the bellows of the crossover piping between the isolated building and the non-isolated building are performed. And their fragilities are evaluated based on above mentioned methodology and the results of the fatigue analyses. As the results, the seismic failure probability of the crossover piping is found to be sufficiently small.
- For the components placed in the isolated building, responses and fragilities are evaluated based on above mentioned methodology.
- From the results of the fragility evaluations, the building isolation is concluded to be effective to lessen the CDF of the plant.

Fragility evaluation methodology considered in this study is to be reflected to the seismic PRA standard of Japan in the future revision.

In many cases, fragility curves of components in a conventional (non-isolated) building show that the components have some failure probabilities in the region of design basic earthquakes. However, results of fragility evaluations in this study show that fragility curves of components in isolated building rise from the region of large input acceleration and their failure probabilities in the region of design basic earthquakes are significantly small. Figure 12 shows the comparison of fragility curves of a component in conventional building and isolated building.
Additionally, when a fail-safe mechanism is installed to the building isolation system, failure probability in the region of large input acceleration is expected to be reduced. And as a result, the fragility of the component will be improved further. Figure 12 also shows the expected fragility curve of a component in the isolated building with the fail-safe mechanism.

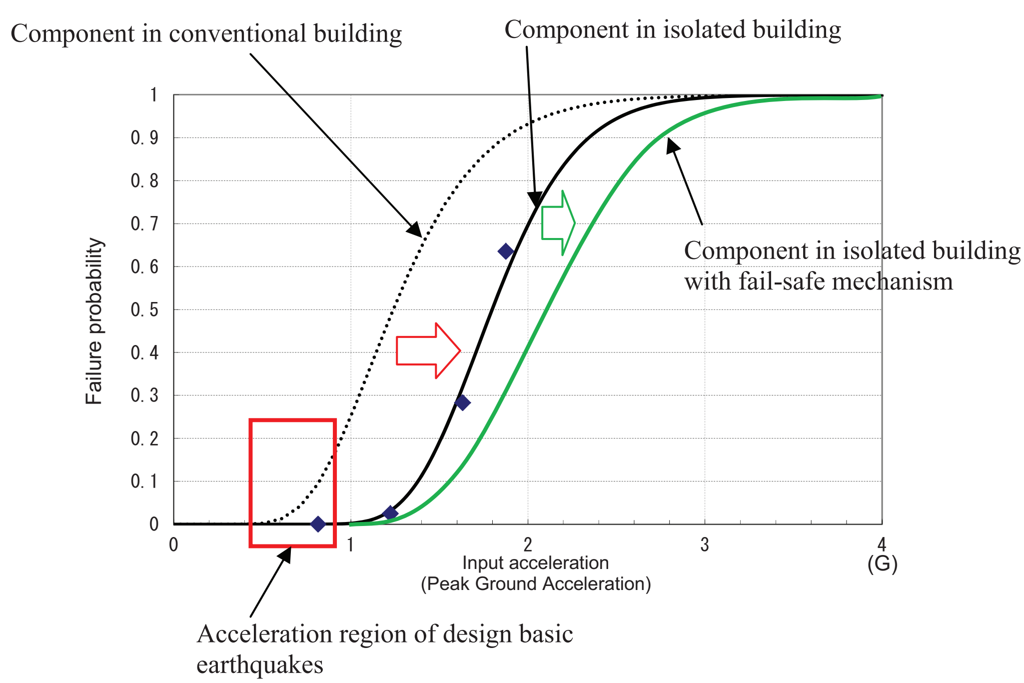


Figure 12 Comparison of fragility curves

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