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Improvement of the component fragility evaluation method considering dynamic nonlinear characteristics of the building on seismic PRA of nuclear power plant

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Abstract

The objective of this study was to improve the component fragility evaluation method on the Seismic Probabilistic Risk Assessment, which contributes in establishing a more realistic component fragility evaluation in terms of building response that takes into consideration dynamic nonlinear characteristics regarding nuclear power plant (NPP). In the 2011 off the Pacific coast of Tohoku Earthquake, several NPPs observed nonlinear response of buildings due to the large earthquake. In order to improve component fragility evaluation, enhancement based on the lessons learned from recent knowledge and technique is required. Currently in Japan, seismic response analysis regarding buildings has been conducted by using a nonlinear lumped mass model. The building response analysis result provides a probability density function of the seismic floor response in the installation position of the component based on the time history seismic response analysis for each seismic level evaluated. In this study, a novel fragility method was developed. The lognormal distribution curve of seismic response of the component provides a combination of the floor response spectra in the component natural period and component response factor which includes logarithmic standard deviations. The presented method can be expected to provide a realistic and reasonable solution to obtain the fragility curve of components in NPPs.

Keywords: Seismic PRA, Component fragility evaluation, Dynamic nonlinear building response

1. Introduction

As a result of the Fukushima Dai-ichi Nuclear Accident caused by the earthquake and tsunami, the necessity to enhance nuclear safety improvement was shared by the nuclear community in Japan. Therefore, industry-based initiatives in voluntary efforts toward safety enhancement based on the Probabilistic Risk Assessment (PRA) have been conducted in response to the recommendations of the advisory committee of the Japanese government. The Nuclear Risk Research Center (NRRC) of the Central Research Institute of Electric Power Industry was established in October 2014 to organize and develop modern methods of PRA involving nuclear operators and nuclear industry to continually improve the safety of nuclear facilities.

In the 2011 off the Pacific coast of Tohoku Earthquake, several NPPs observed nonlinear response of buildings due to the large earthquake. When a building observes nonlinear seismic response, the frequency of the motion shifts downward and the high frequency spectral response either increases or decreases. Depending on the relative relationship between the fundamental frequency of the item of component and building frequencies the input to the component may either increase or decrease as building goes nonlinear. These consequences haves resulted in increased attention to seismic risks for nuclear power plants. In seismically active countries like Japan, seismic issues continue to periodically arise in operating nuclear power plants. Risk-informed decision making is a combination of deterministic approach as well as probabilistic approach. One sophisticated approach of Seismic PRA (SPRA) is the introduction of latest technology regarding a deterministic design basis methodology, analysis model, database, etc.

In the current situation of Japan, seismic response analysis regarding buildings has been conducted by using nonlinear lumped mass analysis model. A Separation of Variables Method [1] was used for practical seismic PRA on a global basis regarding conventional evaluation of nuclear power plant. However, the Separation of Variables Method does not handle the dynamic nonlinear response property of the building in an appropriate manner, this method is treated by single probability density function (PDF). On the other hand, Seismic Safety Margin Research Program (SSMRP) Method [1] has an availability of handle the dynamic nonlinear response property of the building. In reality, the above-mentioned procedure would involve so many calculations that it is not considered practical.

The purpose of this study is to develop a realistic and reasonable solution to obtain the fragility curve of component in consideration of dynamic nonlinear characteristics of the building on SPRA of nuclear power plants. The point requiring enhancement is to incorporate the dynamic nonlinear characteristics of the building in a reasonable manner based on the basic principle of the conventional method of component fragility evaluation.

2. Conventional Method of Component Fragility Evaluation

Seismic PRA studies have been conducted in many nuclear power plants for over 30 years. The United States Nuclear Regulatory Commission (USNRC) published the “Reactor Safety Study” (NUREG-73/041, WASH 1400), a landmark study on safety of commercial nuclear power plants that used PRA methods to assess accident risks [2]. The first complete SPRA of a commercial nuclear power plant was during 1981 at the Zion Nuclear Power Plant [3]. The seismic capacities of the components are usually estimated using information on the plant design basis and component responses calculated at the design analysis stage. At any acceleration value, the component fragility representing the conditional probability of failure varies from 0 to 1. Development of the family of fragility curves using different failure models and parameters for a large number of components in the SPRA is impractical. Therefore, a simple model for the fragility was proposed and mainly used [1, 3, 5].

The lognormal distribution has been observed as a suitable representation of numerous random variables in the real world. Examples include the distribution of fatigue failure of materials, small-particle sizes, etc. Of course, in neither of these examples should the semi-infinite tails of the lognormal distributions be considered accurate. For seismic fragilities, a number of analytical assumptions indicate the acceleration level that would typically lead to failure of a nuclear component. It would be greater or less than some best-estimate prediction due to inherent randomness and uncertainty in knowledge of the earthquakes and the impacts on the plant component. It is well known that the mean of the sum of two or more random variables that follow any PDF, not even necessarily the same PDF, is equal to the sum of the means of the constituent variables. If the random variables are also uncorrelated (that is, they are independent), the mean of the product of these same random variables is also the product of the means of the two random variables. What is unique about random variables that follow the normal PDF is that any variable defined by the sum of these variables is also normally distributed. Similarly, the product of any random variables that are lognormally distributed is also lognormally distributed. This is not true of most PDF types and suggests one benefit of using normal or lognormal variables in the choice of the seismic fragility model; that is, that the sum or product of the variables associated with each assumption would have the same distribution type, although with different mean and variance.

One advantage of assuming that the uncertainties in these individual impacts are lognormally distributed is that no matter how large the uncertainty in each assumption’s impact, the predicted acceleration at which component failure would occur due to ground motion would never be negative, that is, it might be negative with some probability for normally distributed impacts. Therefore, based on physical grounds and convenience, the lognormal distribution was selected to describe the uncertainty in the impact of each assumption on the true failure acceleration. The central limit theorem of probability states that the sum of statistically independent random variables has an approximately normal distribution if it is the sum of a fairly large number of relatively small, independent errors. Because of the relationship between lognormal distributions, the central limit theorem also suggests that the product of a fairly large number of such random variables is approximately lognormal [6].

The above mentioned probability model is compatible with the scheme of SPRA to determine the core damage frequency of nuclear reactor. The equation for fragility given by the assumption of a lognormal distribution allows easy development of the family of fragility curves that appropriately represent uncertainty in fragility curves. For the quantification of fault trees in the plant system and accident sequence analyses, the uncertainty in fragility must be expressed in a range of conditional failure probabilities for a given ground acceleration.

2.1 Basic equation of failure probability

Fragility $F(\alpha)$ is evaluated as conditional probability that the PDF of realistic response $f_R(\alpha, x)$ exceeds the PDF of realistic capacity $f_S(x)$ are assumed to following logarithmic standard distribution which consists of median and logarithmic standard deviation. Where α is seismic level such as peak ground acceleration, x is response of component such as stress, displacement, etc. Fragility $F(\alpha)$ evaluates each seismic level of α as shown in Eq. (1).

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

PDF of the realistic response $f_R(\alpha, x)$ is represented by the following equation as a lognormal distribution, consisting of median $R_m(\alpha)$ and logarithmic standard deviation $\beta_R(\alpha)$.

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

Meanwhile, PDF of the realistic capacity $f_S(x)$ is represented by the following equation as a lognormal distribution, consisting of median S_m and logarithmic standard deviation β_S.

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

2.2 Conventional simple method

In the Separation of Variables Method, where a single PDF model is applied in modeling capacity as a random variable representing lognormal distribution with median and logarithmic standard deviation. The fragility curve represents the probability of failure of component for a given peak ground seismic motion level (left side of Fig.1).

In estimating fragility parameters, it is convenient to work in terms of an intermediate random variable called the “factor of safety”. The factor of safety, F, on ground acceleration capacity above the Safe Shutdown Earthquake (SSE) level specified for design, A_{SSE}, is defined as follows, where A is the actual ground motion acceleration capacity.

$$A = F\cdot A_{SSE} \tag{4}$$

$$F = \frac{Actual\ seismic\ capacity\ of\ element}{Actual\ response\ due\ to\ SSE} \tag{5}$$

This relationship is typically expanded to identify the conservatism or factor of safety in both the strength and the response.

$$F = \frac{Actual\ capacity}{Design\ response\ due\ to\ SSE}\times\frac{Design\ response\ due\ to\ SSE}{Actual\ response\ due\ to\ SSE} \tag{6}$$

$$F = F_C\cdot F_\mu\cdot F_{RS} \tag{7}$$

Where F_C is the capacity factor, F_{RS} is the structural response factor, and F_μ is the inelastic energy absorption factor (ductility factor). Nonlinear response of F_μ accounts for the fact that an earthquake represents a limited energy source, and many structures or equipment items are capable of absorbing substantial amounts of energy beyond yield without loss of function. In other words, it is modeled to increase the apparent capacity in the Separation of Variables Method.

The median factor of safety, F_m, can be directly related to the median ground acceleration capacity, Am, as follows.

$$Fm = \frac{Am}{A_{SSE}} \tag{8}$$

The logarithmic standard deviations of *F*, representing inherent randomness and uncertainty, are then identical to those for the ground acceleration capacity, *A*.

The Atomic Energy Society of Japan presented an additional simple method, which is called the JAERI method [7] (right side of Fig.1). This method assumes a linear response when calculating the actual response. Actual response is obtained by correction for the design response using the response factor. Failure probability is obtained by the conditional probability of failure, which is the obtained PDF of the realistic response exceeding the PDF of realistic capacity in correspondence to the ground motion level. The nonlinear factor based on the nonlinear response is treated by F_μ similar to the Separation of Variables Method. Nonlinear effects are taken into account as part of the response factor by dividing the realistic response in F_μ. PDF of the realistic response $f_R(\alpha, x)$ is represented by the following equation.

$$f_R(\alpha, x) = \frac{1}{\sqrt{2\pi}\beta_R x} \exp\left[-\frac{1}{2}\left\{\frac{\ln\left(x/(\frac{q^D}{F_{Rm}} \cdot \frac{\alpha}{\alpha^D} \cdot \frac{1}{F_\mu})\right)}{\beta_R}\right\}^2\right] \tag{9}$$

Where α_D is the design seismic ground motion at the bedrock and q^D is the design response corresponding to α_D, It is assumed that F_R follows a median of lognormal distribution F_{Rm} and logarithmic standard deviation β_R.

Meanwhile, PDF of the realistic capacity is derived as described in the aforementioned equation (3).

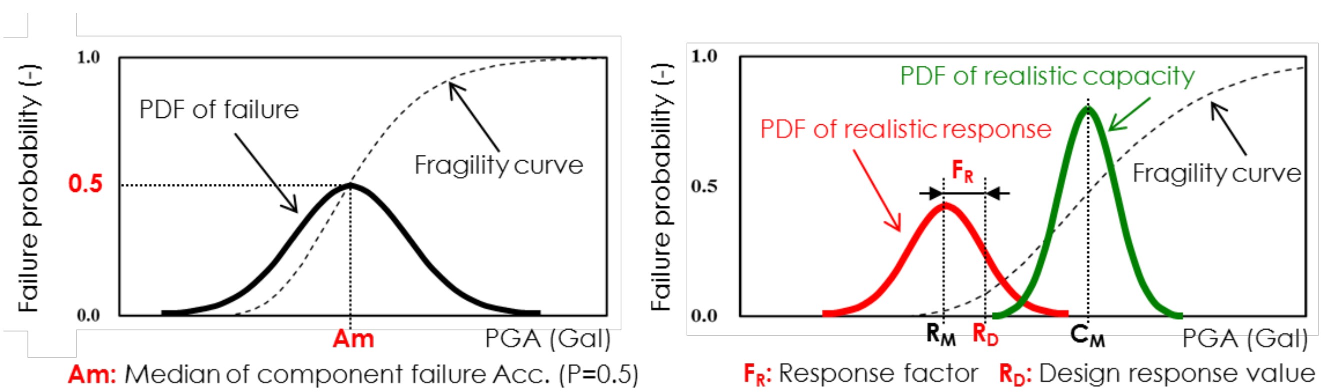

Fig. 1 – PDF of conventional simple method

(Left side: Separation of Variables Method, right side JAERI Method)

3. Component fragility evaluation considering dynamic nonlinear building response

3.1 Characteristics of the dynamic nonlinear building floor response

Seismic dynamic response analysis is carried out in consideration of dynamic seismic force based on the seismic design classification of Structures, Systems and Components (SSCs) in the nuclear power plant. The response of SSC due to seismic ground motion is calculated by the time history waveform of input. The structure can be assumed as almost elastic in the small deformation range. However, when the deformation increases, it is considered to be caused by a phenomenon such as a crack, yield, and slip. Therefore, the relationship of the restoring force and deformation is represented by the shape to draw the hysteresis loop. In other words, the nonlinear characteristics are exposed. Computer technology has rapidly developed after the earliest days of the SPRA, and study on the elastic-plastic seismic response analysis has improved.

In the 2007 Niigataken Chuetsu-oki Earthquake as well as the 2011 off the Pacific coast of Tohoku Earthquake that affected several nuclear power plants. Nuclear power plant buildings observed nonlinear response due to beyond design earthquake levels. With such a background, a seismic safety evaluation of the building in terms of the nuclear power plants in Japan has been conducted using dynamic nonlinear seismic response analysis. Methods of nonlinear dynamic seismic response analysis are lumped mass model and FEM model.

In the practice of the SPRA, it is important to heed the following two points. The first is to build the established model that takes into account the uncertainty based on the evaluated information from the deterministic seismic design analysis in an intelligent way. Secondly, it is important not to use a complicated building nonlinear analysis model that considers the interface between component fragility analysis and building fragility analysis as well as repetitive parameter studies such as iterative evaluation in the SPRA. In order to consider the interface to the component seismic input, it is reasonable to evaluate the building seismic response by using the matured technologies such as lumped mass dynamic nonlinear analysis model.

The example of the floor response spectrum considering dynamic nonlinear characteristics of the building is shown in Figure 2. The predominant period corresponding to the increase in the ground seismic motion level has shifted to the long period side. In general, the natural period of the building can be assumed to be longer than 0.1 sec. In addition, the natural period of the component can be assumed to be shorter than 0.1 sec.

In order to implement a more realistic component fragility evaluation of SPRA in the nuclear power plant, an improvement of the component fragility evaluation method considering dynamic nonlinear characteristics of the building is required.

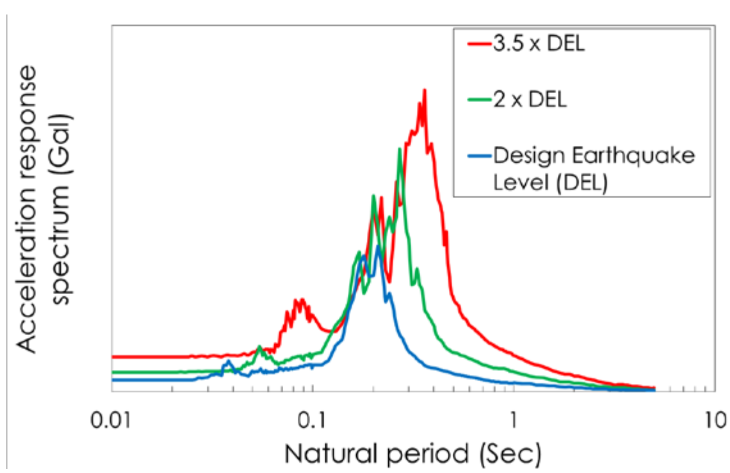

Fig. 2 – Example of the floor response spectrum considering dynamic nonlinear characteristics of building

3.2 Approach of the proposed method considering dynamic nonlinear characteristics of the building

The buildings and structures that should be considered when conducting SPRA of a nuclear power plant are reactor building, auxiliary building, and outdoor structures. On the other hand, the number of evaluated components through the SPRA consists from 200 to 400 in the nuclear power plant. The procedure of SSMRP method would involve so many calculations regarding component fragility evaluation. It is totally impractical from the perspective of the practical application of SPRA. The conventional simple method (Separation of Variables Method and JAERI method) evaluates conservativeness and uncertainty of response through the response factor. The response factor consists of four sub factors of F1 (Seismic response), F2 (Soil response), F3 (Building response) and F4 (Component response) as shown in Fig. 3.

In this study, the median of building floor response is evaluated by dynamic nonlinear analysis based on the seismic time history data on the engineering bedrock. Sub response factor (F1) is evaluated as conservativeness and uncertainty of the input time history waveform data which is considered to future eventuality seismic motion at the nuclear site corresponding to each evaluated peak acceleration level. Sub response factor (F4) is determined by the same means of Separation of Variables Method and JAERI Method.

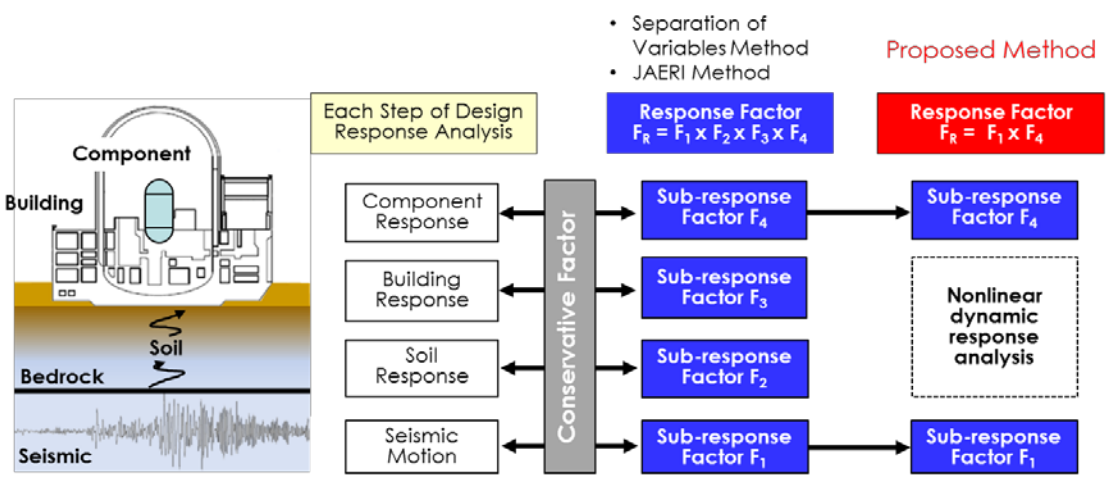

Fig. 3 – Conservative factors related to design response analysis with conventional and proposed method

Evaluation flow of the component fragility evaluation method considering dynamic nonlinear characteristics of the building are shown in Fig.4. The result of the design component response analysis is fundamental to the evaluation of the proposed component fragility evaluation method. Each input regarding evaluation of design response of component are provided from floor acceleration response spectrum corresponding to the installation position, natural period and damping of evaluated component based on the dynamic nonlinear seismic response analysis in the design seismic waveform input at the engineering bedrock. Design response of component is evaluated by the floor seismic input. The PDF of realistic component response at each fragility evaluated peak ground acceleration level is obtained by the median from design response assuming that linear response and conservative factor of F1 and F4, as well as logarithmic standard deviation of F1, F4 and uncertainty of the dynamic nonlinear seismic response analysis. Failure probability obtained as a conditional probability of failure, which is computed as the PDF of realistic response, exceeds the PDF of realistic capacity at each fragility evaluated peak ground acceleration level. Moreover, failure probability curve is determined by interpolation and extrapolation of these values in the acceleration range to evaluate the CDF. In this study, an analysis code was developed that embodies proposed fragility method. The equation for computation is described in the following section.

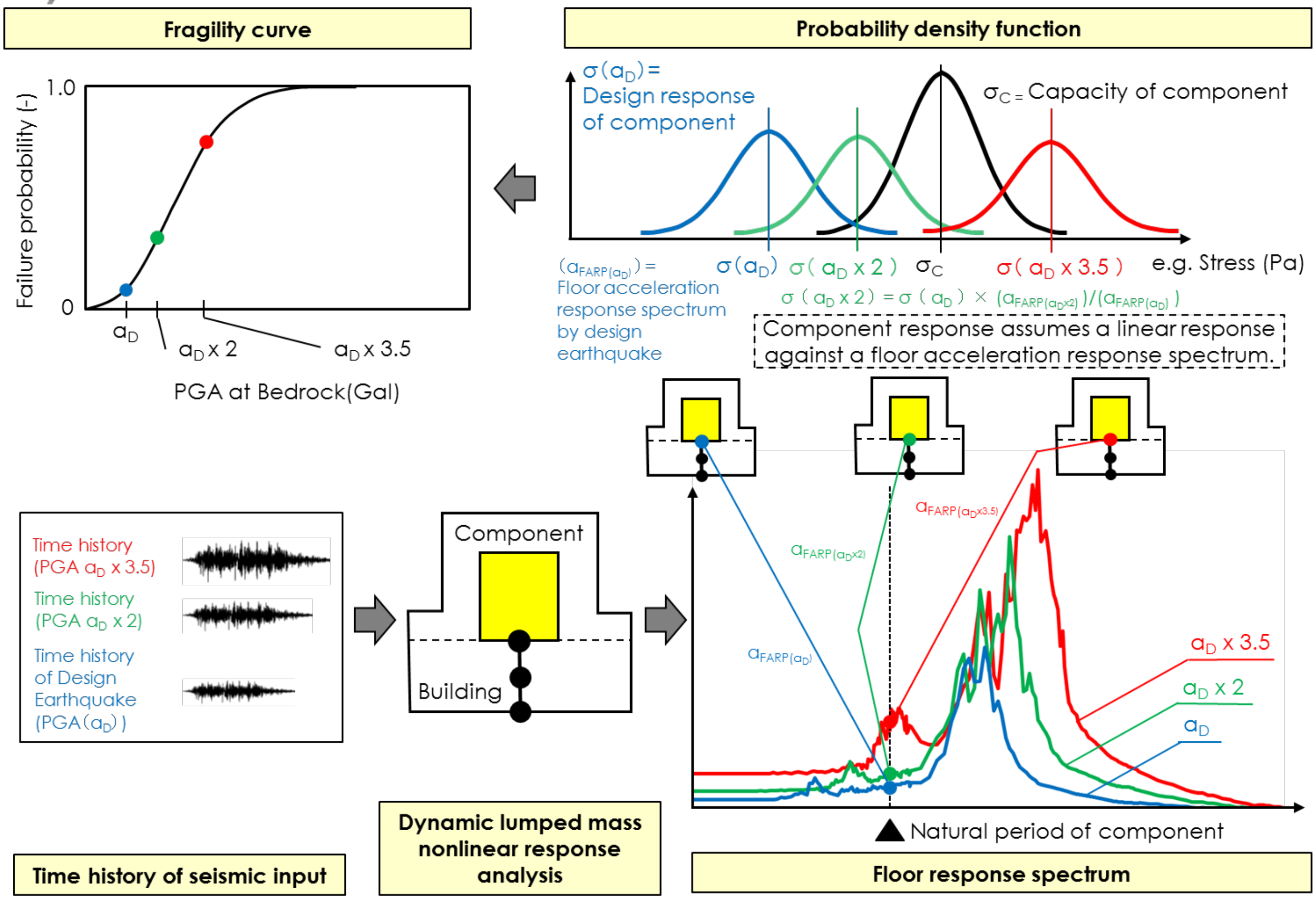

Fig. 4 – Concept of component fragility evaluation considering dynamic nonlinear building response

3.3 Evaluation equation for computation of component fragility by the proposed method

The lognormal distribution curves of seismic response of component are provided from floor response spectra (peak acceleration of floor) in the component natural period, which are the included median of a realistic response (exclude a conservative factor) and uncertainty, and response factor F1 and F4. The lognormal distribution curve of realistic capacity of component provides component capacity value based on the shaking table test, material structural strength data, etc., that include median of realistic capacity and uncertainty.

Fragility of component considering dynamic nonlinear building response $F_C(\alpha)$ is evaluated as conditional probability that the PDF of realistic component response $f_{CR}(\alpha, x_R)$ exceeds the PDF of realistic component capacity. $f_{CR}(\alpha, x_R)$, and $f_{CS}(x)$ are assumed to following logarithmic standard distribution which consists of median and logarithmic standard deviation. Where α is peak ground acceleration, x is response of component based on the floor seismic response on the installation position of the intended component. Fragility $F_C(\alpha)$ evaluated each peak ground acceleration level of α, as shown in Eq.(10).

$$F_C(\alpha) = \int_0^{x} f_{CR}(\alpha, x_R) \left\{ \int_0^{x_R} f_{CS}(x)\,dx \right\} dx_R \tag{10}$$

It assumes that the realistic component response $f_{CR}(\alpha, x)$ follows a logarithmic standard distribution of median and logarithmic standard deviation. The general expression is represented in the following equation.

$$f_{CR}(\alpha, x) = \frac{1}{\sqrt{2\pi}\beta_R x}\exp\left[-\frac{1}{2}\left\{\frac{\ln(x/Q_m(\alpha))}{\beta_R}\right\}^2\right] \tag{11}$$

Where, α is the seismic level of maximum peak acceleration at bedrock, x is index of failure evaluation, $Q_m(\alpha)$ is the median of building floor response corresponding to the seismic level α at the component installation position, and $\beta_R(\alpha)$ is uncertainty of component response corresponding to the seismic level α.

Moreover, the ratio between building floor response and component response is as follows.

$$\zeta = \frac{Q_{CR}(\alpha_{DSL})}{Q_{FR}(\alpha_{DSL})} \tag{12}$$

Where, $Q_{CR}(\alpha_{DSL})$ is the component response at design seismic level, and $Q_{FR}(\alpha_{DSL})$ is the building floor response (maximum acceleration) at design seismic level.

Component response is treated by linear response. Therefore, the realistic component response is represented by a substitute Eq. (13), response factor F_1 as well as F_4 into Eq. (11) leads to the following.

$$f_{CR}(\alpha, x) = \frac{1}{\sqrt{2\pi}\beta_R(\alpha)\cdot x}\exp\left[-\frac{1}{2}\left\{\frac{\ln\left(x/\frac{\zeta\cdot Q_m(\alpha)}{F_1\cdot F_4}\right)}{\beta_R(\alpha)}\right\}^2\right] \tag{13}$$

The uncertainty of component response $\beta_R(\alpha)$ is represented as follows.

$$\beta_R(\alpha) = \sqrt{\beta_{R_{FR}}(\alpha)^2 + \beta_{R(F_1)}(\alpha)^2 + \beta_{R(F_4)}{}^2} \tag{14}$$

Where, $\beta_{R_{FR}}(\alpha)$ is the uncertainty of building floor response corresponding to the seismic level α, and $\beta_{R(F_1)}(\alpha)$ is the uncertainty of the F_1 corresponding to the seismic level α.

Meanwhile, the realistic component capacity $f_{CS}(x)$ is represented by the following equation as a PDF consisting of median S_m, logarithmic standard deviation β_S.

$$f_{CS}(x) = \frac{1}{\sqrt{2\pi}\beta_S x}\exp\left[-\frac{1}{2}\left\{\frac{\ln(x/S_m)}{\beta_S}\right\}^2\right] \tag{15}$$

In addition, uncertainty β consists of aleatory uncertainty β^r, and epistemic uncertainty β^u which is represented as follows.

$$\beta = \sqrt{\beta^{r^2} + \beta^{u^2}} \tag{16}$$

The composite fragility curve $P_C(\alpha)$ is given by the following.

$$P_C(\alpha) = \Phi\left(\frac{\ln\left(\frac{\zeta\cdot Q_m(\alpha)}{S_m\cdot F_1\cdot F_4}\right)}{\sqrt{\beta_R(\alpha)^2 + \beta_S{}^2}}\right) \tag{17}$$

The fragility in reliability γ % is given by the following.

$$P_{C(\gamma\%)} = \Phi\left(\frac{\ln\left(\dfrac{\zeta \cdot Q_m(\alpha)}{S_m \cdot F_1 \cdot F_4}\right) + \sqrt{\beta_R^u(\alpha)^2 + \beta_S^{u2}} \cdot \Phi^{-1}\left(\dfrac{\gamma}{100}\right)}{\sqrt{\beta_R^r(\alpha)^2 + \beta_S^{r2}}} \right) \tag{18}$$

3.4 Entire Evaluation flow of proposed component fragility method

The input processing flow of component fragility evaluation considering dynamic nonlinear building response is shown in Fig.5. This method aims to develop a time history waveform database corresponding to the location where the component is installed in the building and evaluation points of the lumped mass analysis model in each fragility evaluation ground acceleration level. Therefore, development of a database of acceleration response spectrum by using the response spectrum analysis code is required. In this process, to get the peak floor response acceleration value from the database of acceleration response spectrum based on the information such as location, natural period, and damping in relevant to the object component.

The process above can be conducted automatically by software tool. For this reason, it is assumed that the man-hour of fragility evaluator will not largely increase. The preparation of other fragility input data such as realistic capacity, design response, component response factor and seismic response factors are conducted during usual man-hour.

As described above, the presented method is considered to be a reasonable approach from the view point of practical application.

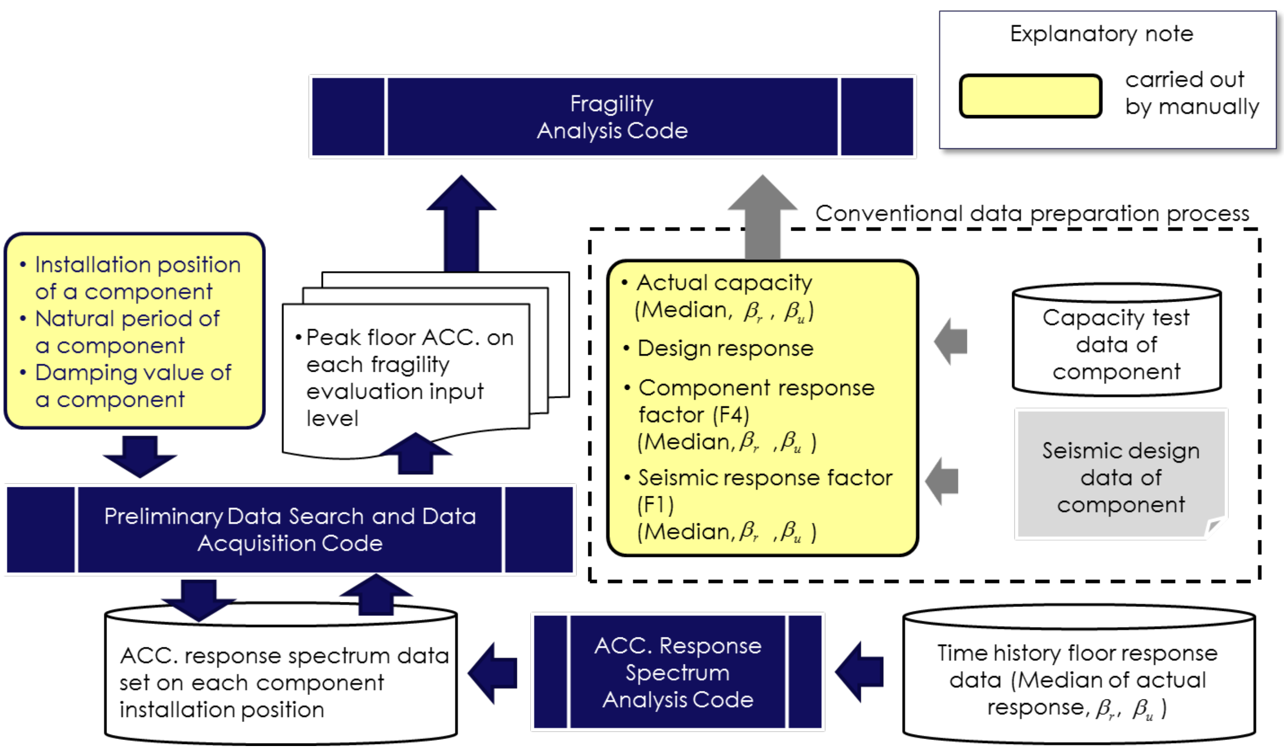

Fig.5 – Entire evaluation flow of proposed component fragility evaluation

3.5 Evaluation example

Relationship of peak acceleration of floor response based on the acceleration response spectrum and the peak ground acceleration at the engineering bedrock is shown in Fig.6. Conventional linear evaluation result of the relationship between the peak ground acceleration at the engineering bedrock and peak acceleration of floor response is represented by the straight line. In the case of consideration in terms of nonlinear characteristics of the building, peak acceleration of floor response based on the acceleration response spectrum are represented by the polygonal line according to the reduction rate in the figure.

The evaluation example results of the composite fragility curve in the case of *Am* determined 1500 Gal based on Fig.6 in consideration of the nonlinear characteristics of the building are shown in Fig.7. If the nonlinear floor response in 1500 Gal, evaluation PGA level decrease 85% is compared to the linear response, the failure probability of component decreases 54% in these evaluated PGA level. In these three cases, each β has the same value as a precondition to evaluate the composite fragility curve.

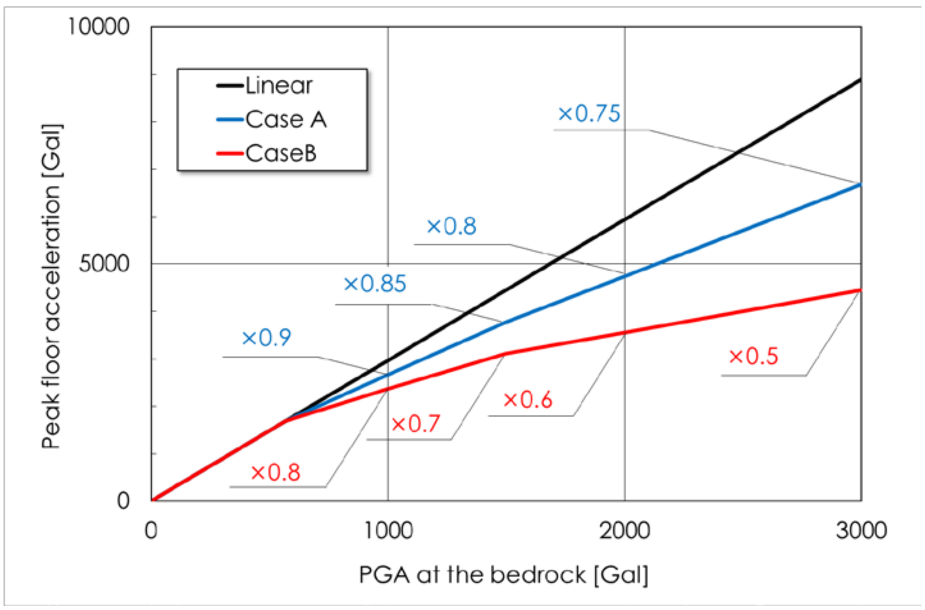

Fig. 6 – Relationship of peak acceleration between floor response and PGA at the bedrock in the example case

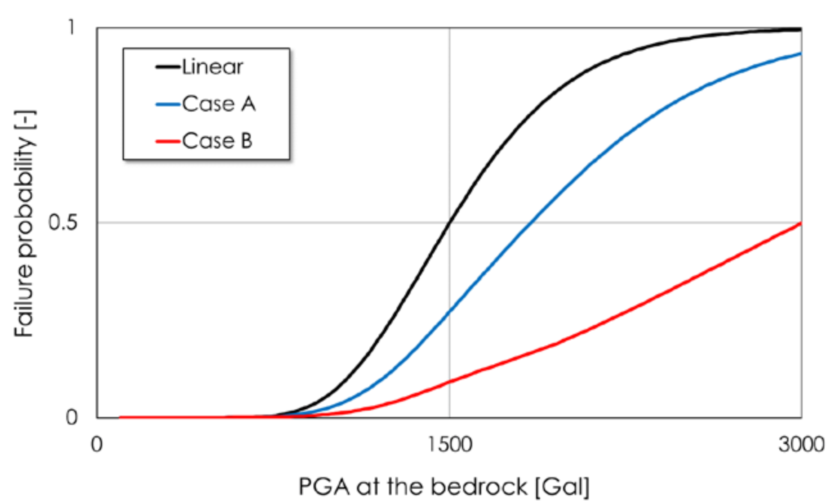

Fig. 7 – Evaluation example results of the composite fragility curve

3.6 Considerations and challenges for implementation to actual plant

Generally speaking, a major important safety component of the nuclear power plant has a natural period shorter than the main structures of the building. The acceleration input level of the component reduced in a qualitative manner by introducing the realistic response considering dynamic nonlinear characteristics of the building. However, we have to consider the possibility that the evaluated result of peak floor acceleration value by the dynamic nonlinear analysis is higher than linear evaluation due to resonance with the predominant higher mode of the building and other contributing factors regarding physical phenomena.

Moreover, lifting of the building in the high ground motion level has an influence on the characteristics of the acceleration response spectrum in the short period regarding the component natural period range. Therefore, development of the dynamic nonlinear seismic response analysis model with a high degree of accuracy on the short period is required.

Hereafter, a study with the actual plant regarding the quantitative evaluation in terms of the dynamic non-linear characteristics of building take effect with influence a natural period zone of the nuclear component is required.

4. Conclusion

In this study, the novel component fragility evaluation method on the seismic PRA that contributes in establishing a more realistic component fragility evaluation in terms of building response considering dynamic nonlinear characteristics for nuclear power plants was developed.

The major characteristics of proposed method are as follows. The PDF of seismic response of component provides combination of the floor acceleration response spectra in the component natural period and component response factor, which includes uncertainty expressed in the logarithmic standard deviations. The PDF of component capacity is evaluated in the same manner as the SSMRP method. Failure probability is evaluated by the conditional probability of failure in the fragility evaluated in each peak ground acceleration level, which is obtained as PDF of realistic response exceeding the PDF of realistic capacity. In other words, proposed method is a hybrid method, which consists of building response evaluated by the time history response analysis of building based on the nonlinear lumped mass model and component response analysis evaluated by the response factor method.

The presented method can be expected to provide a more realistic and reasonable solution to obtain the fragility curve of component in a SPRA on nuclear power plant.

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