IMPROVEMENT OF THE COMPONENT FRAGILITY EVALUATION CONSIDERING DYNAMIC NON LINEAR CHARACTERISTICS OF BUILDING ON SEISMIC PRA

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The objective of this study is to improve the component fragility evaluation method on the seismic PRA which is contribute to establish a more realistic component fragility evaluation in terms of building response considering dynamic nonlinear characteristics as well as improve the response factor regarding component. 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 reasonable 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. Moreover, a latest information of the uncertainty of the component fragility evaluation was investigated regarding the median and logarithmic standard deviation (βr, βu) of the response factor. The presented method and basic concept regarding median and uncertainty on the component response factor can be expected to provide a realistic and reasonable solution to obtain the fragility curve of components in NPPs.

I. 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 based on the incorporation with nuclear industry such as electric utility and vender of nuclear power plant, etc.

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.

The couple of component seismic fragility methods have been carried out for nuclear power plants in downing of seismic PRA studies in United States more than 30 years ago. There are SSMRP (Summary Report on the Seismic Safety Margins Research Program) method which is required for detailed seismic response analysis and realistic capacity data of component, and Separation of Variable Method (Zion Method) which is simple method based on the simple lognormal distribution model.

The practical level of seismic PRA in Japan have always been done by the Zion Method in regard to conventional evaluation of NPP.

In the current situation of Japan, seismic response analysis regarding buildings has been conducted by using nonlinear lumped mass analysis model. Taking into account dynamic nonlinear characteristics, the Zion Method is not a method for dealing reasonably with building response, this method is treated by single probability density function (PDF). On the other hand, SSMRP method has an availability of building response considering dynamic nonlinear characteristics. 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 regarding 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. Moreover, the uncertainty of the component fragility evaluation regarding a rational definitions of median and logarithmic standard deviation (βr, βu) of the response factor and capacity factor was investigated based on the state of the practice in the United States.

II. CONVENTIONAL METHOD OF COMPONRNT 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 (Ref.1). The first complete SPRA of a commercial nuclear power plant was during 1981 at the Zion Nuclear Power Plant (Ref.2). 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 (Ref. 3, 4 and 5). The lognormal distribution has been observed as a suitable representation of numerous random processes 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.

Generally, true failure acceleration is expected to be greater than the design-basis level for ground motion. If the individual impacts of these assumptions on the final failure acceleration were judged to be independent of each other, with some uncertainty, based on the above properties, a choice of these uncertainties being normally or lognormally distributed would be convenient. 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 independent random variables, each following any PDF, 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 (Ref.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.

II.A. Basic equation of failure probability

Failure probability $F(\alpha)$ of component evaluates as conditional failure probability, which is obtained the PDF of realistic response $f_R(\alpha, x)$ exceeds the PDF of realistic capacity $f_S(x)$. Both PDF of realistic response and capacity are assumed to the logarithmic standard distribution that consists of median and logarithmic standard deviation. $F(\alpha)$ is represented by the following Eq. (1) that evaluates each acceleration level of α .

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

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.

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

II.B. Conventional simple method

A common simple method is the Zion 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 Zion Method.

The median factor of safety, *Fm*, 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 (Ref. 7.). This method assumes a linear response when evaluating the realistic response. The realistic 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 Zion 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).

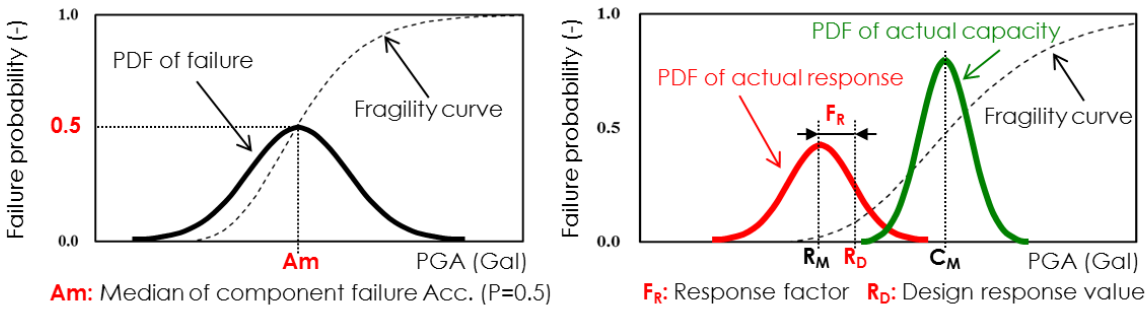

Fig. 1 – PDF of conventional simple method (left side: Zion Method, right side JAERI Method)

III. PROPOSAL OF COMPONENT FRAGILITY EVALUATION CONSIDERING DYNAMIC NONLINEAR BUILDING RESPONSE

In this study proposed component fragility evaluation method which is consider the dynamic nonlinear building response. As shown below, III.A and III.B are described characteristics of the nonlinear building response data and procedure of the proposed method.

III.A. Investigation 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.

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.

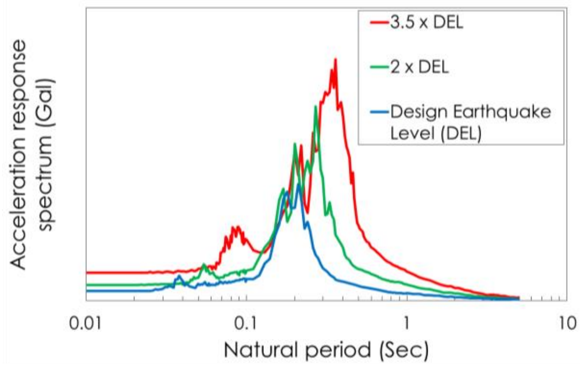

Fig. 2 – Example of the floor response spectrum considering dynamic nonlinear characteristics of the building

III.B. Procedure of the component fragility evaluation method considering dynamic nonlinear building floor response

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 (Zion 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.

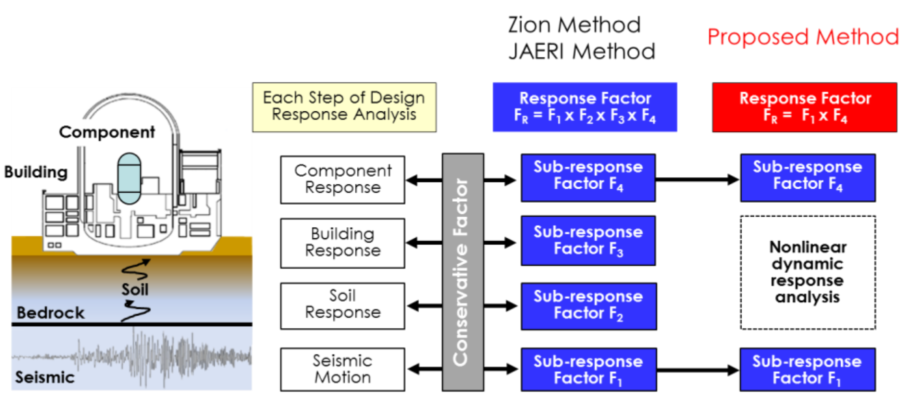

Fig. 3 – Uncertainty factors related to design response analysis with conventional and proposed method

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 fragility evaluation 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 Zion Method and JAERI 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 uncertainty 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.

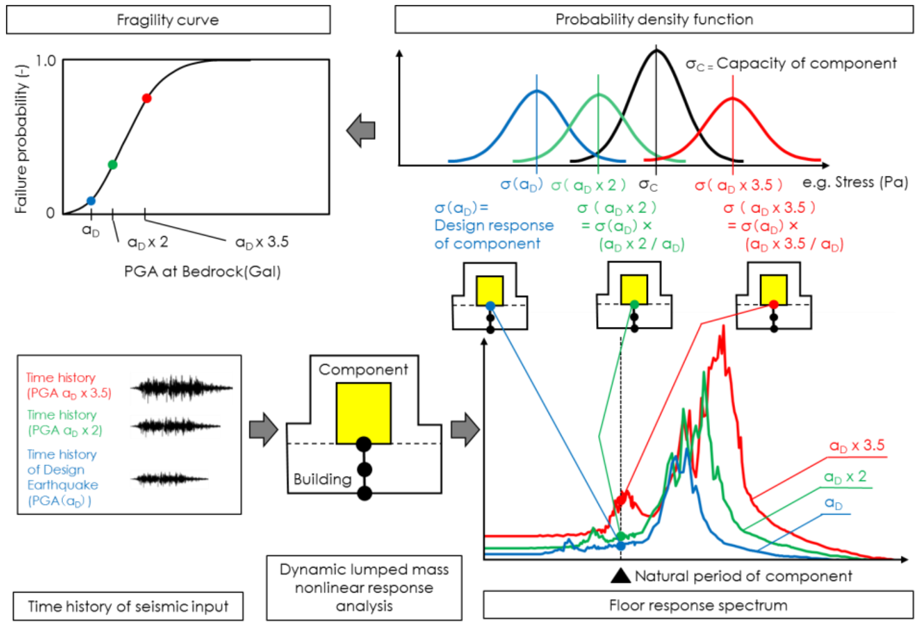

Fig. 4 – Concept of component fragility evaluation considering dynamic nonlinear building response

III.C. 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.5.

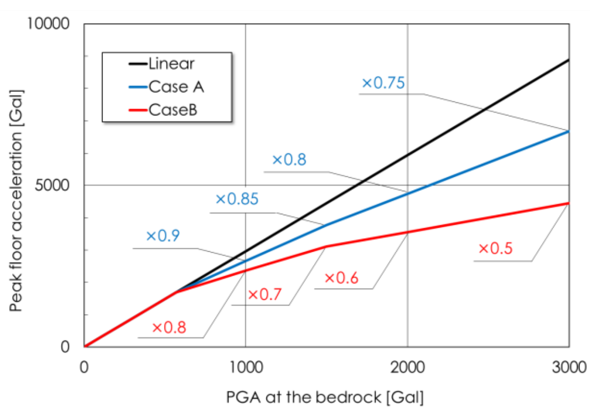

Fig. 5 – Relationship of peak acceleration between floor response and PGA at the bedrock in the example case

Relationship between the peak ground acceleration at the engineering bedrock and peak acceleration of floor response assumed to the linear that is represented by the straight line as shown in black line of Fig. 5. 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.5 in consideration of the nonlinear characteristics of the building are shown in Fig.6. 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 has the same value as a precondition to evaluate the composite fragility curve.

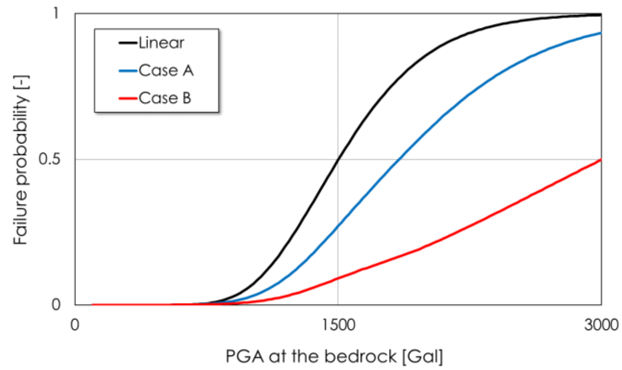

Fig. 6 – Evaluation example results of the composite fragility curve

IV. INVESTIGATION OF THE COMPONENT RESPONSE FACTOR

The uncertainty factor regarding component response (F4) are mainly consist of sub response factor such as spectral shape factor(F_{ESS}), damping factor(F_d), modeling factor(F_{EM}), mode combination factor(F_{EMC}), and ductility factor. We have considered rationality of fragility evaluation in Japan according to the state of the practice regarding US reports, such as technical report of EPRI (Ref. 3. 4. 6. 8. and 9.). Therefore, obtaining knowledge regarding the handling of uncertainties in terms of deriving a realistic response as well as capacity was basically the same in Japan and the US.

In this study, concept and challenges regarding median and uncertainty on the component response factor was organized. A generalized concept and challenges are shown in Table.I.

TABLE I. Generalized concept and challenges regarding median and uncertainty on the component response factor

Response factor	Median /Uncertainty	Generalized concept of evaluation and challenges
Spectral shape factor (F_{ESS})	Median	Design margin (10% widening of floor response spectra)
	βr	If a value is simply integrated as a design margin, consideration of uncertainty is not required. Future discussions are expected to focus on the frequency characteristics of seismic, etc.
	βu	If a value is simply integrated as a design margin, consideration of uncertainty is not required. However, future discussions are expected to the consideration of the lack of knowledge regarding the 10% widening of floor response spectra.
Damping factor (F_d)	Median	Uncertainty of design damping facture is defined as a structural damping factor.
	βr	Take no thought of uncertainty. (description as "-")
	βu	Uncertainty is calculated based on the response of design damping factor defined 99% confidence value. Future discussions are expected to the consideration in terms of a lack of knowledge and data regarding structural damping factor
Modeling factor (F_{EM})	Median	Take no thought of uncertainty. Future discussions are expected to the consideration of uncertainty of parameter setting such as second moment of area, Young's modulus and Poisson's ratio regarding the stiffness of vibration model.
	βr	Take no thought of uncertainty. (description as "-")
	βu	0.15 (Ref. 7.) except for the rigid model and time historical analysis. Future discussions are expected to the consideration of the lack of knowledge regarding cross-section and axle distribution.
Mode combination factor (F_{EMC})	Median	Take no thought of uncertainty. Future discussions are expected to the consideration of repeatability of actual phenomena.
	βr	0.15 (Ref. 7.) except for the rigid model and time historical analysis. Future discussions are expected to the consideration regarding the frequency characteristics of seismic, etc.
	βu	Take no thought of uncertainty. (description as "-")

Uncertainty factors for realistic response were similar in general between Japan and US. The numerical difference between Japan and US is caused by the type of foundation ground. The large segment of the nuclear facilities in the US are built on soil foundation, on the other hand Japanese important facilities are built on bed rock according to the nuclear regulation. Therefore, component design such as natural period and damping property are different due to installation environment of component.

A latest information of the US, uncertainty of the response factor which represented by logarithmic standard deviation (βr, βu) are determined rationally. It is often the case that if the uncertainty can not exactly divided into βr and βu, uncertainty of sub response factor is integrated into as the predominant side. On the other hand, not predominant side is treated "-".

Meanwhile, a conventional treatment in Japan regarding not predominant side of the sub factor uncertainty was defined numerical zero value. In the consideration of philosophical deliberation on zero value, it should be used the "-" except for the represent for the calculation input data.

V. CONCLUSIONS

In this study, the component fragility evaluation method on the seismic PRA that evaluate building response considering dynamic nonlinear characteristics for nuclear power plants was developed. Moreover, the concept regarding median and uncertainty on the component response factor was organized. 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 acceleration level, which is obtained as PDF of realistic response exceeding the PDF of realistic capacity.

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.

The presented method and generalized concept regarding median and uncertainty on the component response factor 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.

NRRC will provide the example of the application of present methods for the nuclear operators and nuclear industry to continually improve the safety of nuclear facilities.

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