SMiRT-12 / K. Kussmaul (Editor)

MK04/1

EVALUATION OF COMPONENT FRAGILITY IN ISOLATED STRUCTURE

K. Hirata[1], A. Yamamoto[2] and K. Ishida[1]

[1]CRIEPI Abiko Lab., 1646 Abiko, Abiko-city, Chiba 270-11, Japan
[2]Hitachi Eng. Co. Ltd., 3-2-1 Saiwai-chou, Hitachi-city, Ibaraki 317, Japan

ABSTRACT

This paper deals with a methodology evaluating seismic fragility of components in base isolated structure in terms of both ZPA and ground motion parameter, in which functional relationship between both input parameters are made use of, and response non-linearity of the base isolated structure is taken into account. The proposed method is applied to fragility evaluation of FBR reactor vessel.

1 INTRODUCTION

Seismic fragility of components in nuclear power plant is evaluated in terms of zero period acceleration (ZPA) at the floor and/or ground motion parameter (e.g., peak ground acceleration). The former one is advantageous to the latter one in that fragility of various components can be evaluated independent of the response of the structure, especially in the case where the fragilities are applied to design procedure. However, to evaluate annual probability of failure of the component in connection with seismic hazard, or for comparative study of the fragilities regarding the structure and the component, the component fragility should be evaluated with the ground motion parameter.

For base isolated reactor building (R/B) where isolation device shows inelastic response under design earthquake motion, linear relationship between ground motion intensity and the structural response does not hold, and the application of the methodology developed in past seismic PSA's is difficult. In this paper proposed is a method evaluating seismic fragility of the component in the base isolated structure in terms of ground motion parameter considering the response non-linearity of the structure.

2 EVALUATION METHOD

2.1 Formulation of fragility in terms of ZPA

In the fragility analysis of the component, below formulation proposed by Kennedy and Ravindra[1] is widely used.

$$Pf(a) = \Phi\left[\frac{ln(a/Am) + \beta u\Phi^{-1}(Q)}{\beta r}\right] \qquad (1)$$

where, Pf(·) is the failure probability of the component, a is the maximum acceleration of input earthquake motion, Φ(·) is the cumulative normal distribution function, Am is the median of the acceleration capacity A of the component, βu and βr are log-standard deviations respectively accounting for the system uncertainty and the inherent randomness. When desired to evaluate the fragility in terms of ZPA, a and Am in the above equation correspond to ZPA and the acceleration capacity evaluated in terms of ZPA. Acceleration capacity A is expressed as a product of ZPA of design floor response, Ad, component response factor Fre and component capacity factor Fc as

$$A = Ad \cdot Fre \cdot Fc \qquad (2)$$

where, Fre and Fc respectively evaluating randomness, uncertainty and estimation error of the median included in estimated response and capacity. These factors are expressed as products of sub-factors, e.g., capacity factor Fc is expressed as follows.

$$Fc = Fs \cdot F\mu \qquad (3)$$

where, Fs is the ratio of the ultimate strength to the stress response for design floor response, Fμ is the inelastic energy absorption factor that accounts for the reduction of the response in the inelastic region of the component.

2.2 Evaluation of Fμ for reactor vessel

High frequency contents of input earthquake motion to the base isolated structure are filtered off, and the components in the structure are subjected to long period motion compared to their natural frequencies. The base isolated R/B considered herein has natural period of 1~2 second, and for example, the natural period of the reactor vessel is around 0.2 second. In such a case, seismic load could be considered static rather than dynamic, and Fμ is overestimated if one uses Newmark's formula[3] in which Fμ is expressed as a function of allowable ductility ratio μ as

$$F\mu = \sqrt{2\mu - 1} \qquad (4)$$

In this study, Fμ for reactor vessel of planned fast breeder reactor (FBR) is evaluated by inelastic response analysis of a single degree of freedom system modelling the reactor vessel, and considering shear buckling as a failure mode. Hysteresis rule of the reactor vessel[2] is used as shown in Fig. 1. Three kinds of floor response waves are used which are obtained from the response analyses of the base isolated R/B for artificial earthquake waves satisfying the target design response spectrum. Each floor response wave is scaled up and used for the response analysis. Fμ, in this case, is given as

$$F\mu = Acr/Ae \qquad (5)$$

where, Acr and Ae are respectively ZPA, where buckling occurs for inelastic system (Fig. 1 (a)) and elastic system (Fig. 1 (b)). Fig. 2 shows an example of the relationship between ZPA and the response displacement of the reactor vessel. As shown in this figure, for the reactor vessel in the base isolated structure, after response displacement exceeds the buckling displacement (Dcr), the response increases steeply with the increase of ZPA, implying the value of Fμ small. Median value of Fμ thus estimated is shown in Table 1.

2.3 Formulation of component fragility using ground motion parameter

Using Eq. (1), one can evaluate component fragility in the base isolated R/B in terms of ZPA. For the base isolated structure, due to its inelastic response for the design earthquake motion (due to damping device) and hardening effect of the isolation device (elastomer bearing) in the ultimate state, linear relationship between the ground motion parameter and the response does not hold. Here, non-linear functional relationship between the ground motion parameter and the response is estimated by regression analysis, and the result is incorporated into Eq. (1).

As to the ground motion parameter for the base isolated structure, it is pointed out that the spectral response at its natural period is highly correlated with the response[4]. Figs. 3 and 4 show the relationship between the velocity spectral response Sv(T=2sec, h=5%) and the maximum response displacement of the isolation device, and ZPA at the floor level of the base isolated R/B where the reactor vessel is installed. In these response analyses, artificial earthquake motions are used generated from 12 different power spectra with 25 different random phase characteristics for each spectrum, i.e., 300 waves in all. In this case study, linear limit of 50 cm for the isolation device is assumed, and maximum displacement response of the isolation device for design earthquake motion (Amax = 483cm/sec^2, Sv(T=2sec, h=5%) = 150cm/sec)) is 31.2cm having enough margin for the linear limit of the rubber bearing.

Multiple regression analysis between Sv(T=2sec, h=5%) and the maximum response acceleration (ZPA) is conducted using trilinear function as

$$Zm(s) = \beta 0 + \beta 1 \cdot s1 + \beta 2 \cdot s2 + \beta 3 \cdot s3 \qquad (6)$$

where, Zm(·) is the median of ZPA for given s, s is Sv(T=2sec, h=5%) of the ground motion, β0, β1, β2 and β3 are the regression coefficients. s1, s2 and s3 are defined as

$$\begin{aligned} s1 &= s \\ s2 &= 0(s < sH1),\ s - sH1(s > sH1) \\ s3 &= 0(s < sH2),\ s - sH2(s > sH2) \end{aligned} \qquad (7)$$

with sH1 and sH2 being corner points of the trilinear function. The first corner point sH1 corresponds to the elastic limit of the isolation device above which isolating function decreases, and sH2 corresponds to the yield point of the super structure above which owing to the energy absorption of the super structure gradient of the regression line decreases (Fig. 4). Also the variance of the response around the regression curve is evaluated. Substituting Eq. (6) into Eq. (1) one can obtain

$$Pf(s) = \Phi\left[\frac{ln(Z(s)/Am) + \beta' u \Phi^{-1}(Q)}{\beta' r}\right] \qquad (8)$$

in which β'u and β'r are the revised values where the uncertainty and the randomness regarding the structural response are taken into account.

3 NUMERICAL EXAMPLE

Using Eqs. (1) and (8), seismic fragility of the reactor vessel for shear buckling mode is evaluated. Parameters regarding randomness and uncertainty on the response and the capacity used in the analysis are shown in Table 1. Some of these parameters are evaluated from the experimental study and the numerical simulation, some are quoted from PRA study conducted for LWR (non-isolated)[1], and the rest are assumed. Figs. 5 and 6 respectively show fragilities evaluated in terms of ZPA and Sv of the ground motion. Effect of change in the tendency of the structural response with the increase of the ground motion intensity appears in the fragility curve evaluated in terms of Sv, whereas in the fragility curve in terms of ZPA such singular points do not appear.

For the earthquake motion intensity corresponding to that of the design earthquake (Sv(T=2sec, h=5%) = 150cm/sec) and the response (ZPA = 0.36G) probability of failure (Pf) of the reactor vessel for the shear buckling mode is evaluated as follows.

[Probability of failure in terms of ZPA]
Pf = 4.7×10^{-23} (Q: Non-exceedence probability = 50%)
1.5×10^{-11} (Q = 95%)
HCLPF = 0.69G

[Probability of failure in terms of Sv(T=2sec, h=5%)]
Pf = 2.1×10^{-6} (Q = 50%)
1.3×10^{-3} (Q = 95%)
HCLPF = 203cm/sec

As can be expected Pf in terms of Sv, in which the effect of the response randomness of the structure is considered, increases compared to Pf in terms of ZPA. Considering the probability of the occurrence of the earthquake with the intensity of the design earthquake (it is considered less than 10^{-4}/year), reliability level of the reactor vessel for earthquake is shown considerably high.

4 Conclusions

Conclusions of this study are summarized as follows.

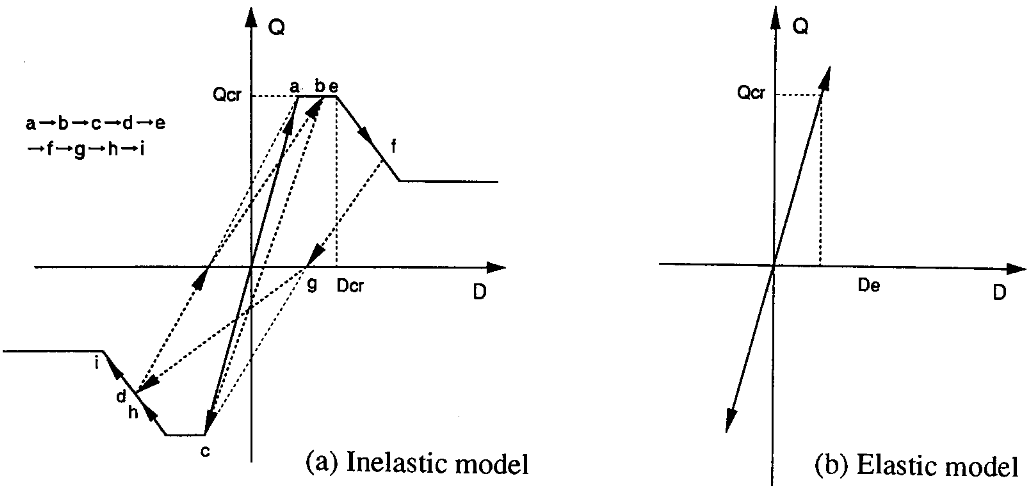
1) A method for fragility evaluation of components in base isolated structure in terms of ground motion parameter is proposed.
2) For the base isolated structure, spectral response around its fundamental frequency (e.g., Sv(T=2sec, h=5%)) is proper as a ground motion parameter.
3) For the shear buckling of the reactor vessel, which is the dominant failure mode, seismic fragility is evaluated both in terms of ZPA and Sv(T=2sec, h=5%) by the proposed method.

5 Acknowledgment

This study was carried out as part of the project of the Ministry of International Trade and Industry titled "Verification Tests of Fast Breeder Reactor Technology", which has been conducted since 1987.

REFERENCES

[1] Kennedy, R.P. and Ravindra, M.K. 1984. Seismic Fragilities for Nuclear Power Plant Risk Studies, Nuc. Eng. and Design 79, pp. 47-68
[2] Hagiwara, Y., Akiyama, H., et al. 1991. Post-buckling Behavior during Earthquakes and Seismic Margin of FBR Main Vessels, Int. J. Pres. Ves. & Piping 45, pp.259-271
[3] Newmark, N. M. 1977. Inelastic Design of Nuclear Reactor Structures and Its Implications on Design of Critical Equipment, Trans. SMiRT K4/1, San Francisco
[4] Hirata, K. and Ohtori, Y. 1992. Seismic Reliability Analysis of Isolated Structure and its Application to Reliability-based Design (in Japanese), CRIEPI Report, No. U92021



(a) Inelastic model

(b) Elastic model

Fig. 1 Hyteresis Rule used for S-D-O-F Model

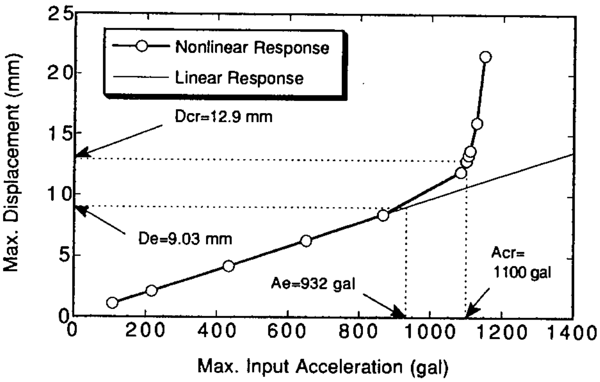


Fig. 2 Max. Input Acceleration vs. Max. Displacement
(Comparison of Response between Liear and Non-linear System)

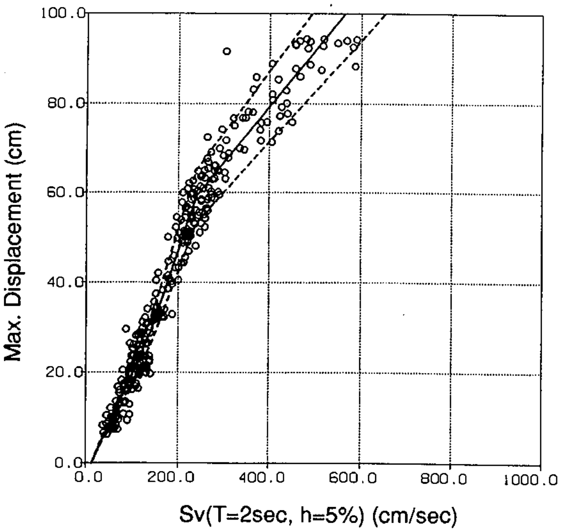


Fig. 3 Sv(T=2sec, h=5%) vs. Displacement Response of Isolation Device

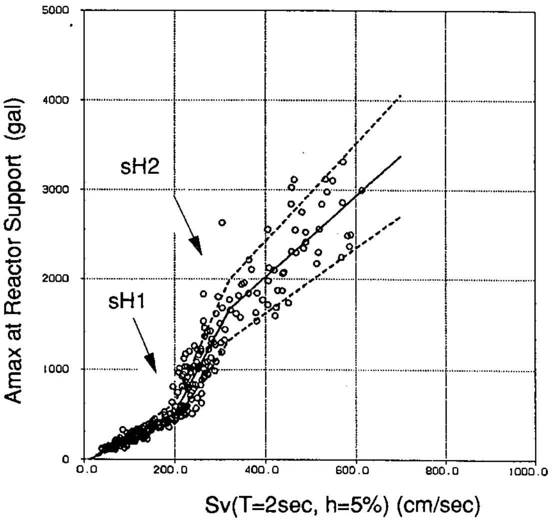


Fig. 4 Sv(T=2sec, h=5%) vs. ZPA

Table 1 Parameters used for Fragility Analysis

Factors	Median	Random βr	Unceratain βu
Response (Fr)e			
Component	0.82	0.11	0.23
Structure	1.00	0.23	0.0
Capacity (Fc)			
Fs	3.71	0.06	0.10
Fμ	1.18	0.0	0.0

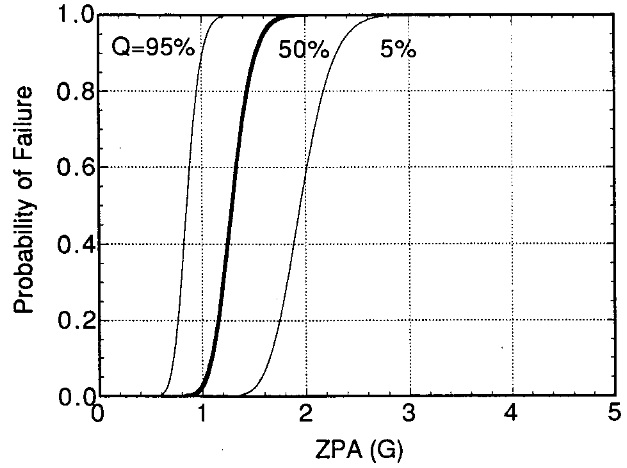


Fig. 5 Prbability of Failure for Reactor Vessel (Pf - ZPA Relationship)

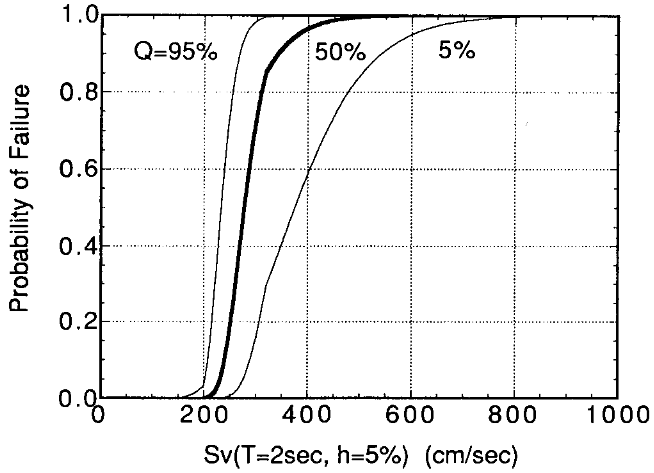


Fig. 6 Prbability of Failure for Reactor Vessel (Pf - Sv Relationship)