Fragility Estimation of Isolated FBR Structure

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ABSTRACT

This paper presents a methodology and some results on fragility estimation of isolated reactor building for FBR(Fast Breeder Reactor). The methodology is based on regression analysis between intensity of input earthquake motion and response obtained from non-linear response analysis in which the effect of non-linear restoring characteristics regarding isolators and super structure are taken into account. And also the result of probabilistic estimation on the ultimate capacity of isolation layer is made use of in the fragility estimation.

1. INTRODUCTION

Method of seismic PSA(Probabilistic Safety Assessment) for NPP(Nuclear Power Plant) has been developed in the past decade[1][2], especially in U.S.A. a number of utility-based seismic PSA's using so called "simplified method" for LWR(Light Water Reactor) has been conducted so far.

In Japan, application of seismic isolation system to demonstration FBR plant is planned. In the case of isolated structure it is difficult to estimate response for earthquake motion with arbitrary intensity from the response with design earthquake, as under design earthquake motion isolated structure behaves inelastically. Here the method proposed by authors[3] is extended and made use of, and the effect of hardening of rubber bearing and the non-linearity of the super structure as well as the "group effect of rubber bearings" are taken into account.

2. CORRELATION OF EARTHQUAKE INTENSITY AND RESPONSE

The proposed method is based on the regression analysis between the response and the intensity of the input motion. As mentioned in the previous paper[3], response of the isolated structure has strong correlation with peak ground velocity Vmax. And the regression of the response is conducted with Vmax as explanatory variable. Non-linear response analyses are conducted for reference FBR building shown in Fig. 1 with observed and artificial earthquake waves which are scaled up.

Figs. 3 and 4 show the relationship between Vmax and the response of the

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isolation layer and a member of super structure respectively. The response of the super structure is transformed into "equivalent linear response" as shown in Fig. 2 whereas that of the isolation layer is not. Trend of the relationship between Vmax and the response changes before and after the certain level of Vmax due to the hardening effect of the rubber bearing. Multiple linear regression analyses are conducted for these relationships with bi-linear function. Bi-linear regression is given as

$$Q = \beta_0 + \beta_1 x_{01} + z \cdot \beta_2 x_{02} \tag{1}$$

where β_0, β_1, β_2 = regression coefficients, x_{01} and x_{02} are independent variables given as

$$\begin{aligned} x_{01} &= \text{Vmax} \\ x_{02} &= 0 && \text{if} \quad (\text{Vmax}) \leq (\text{Vmax})_h \\ &= (\text{Vmax})-(\text{Vmax})_h && \text{if} \quad (\text{Vmax}) > (\text{Vmax})_h \end{aligned} \tag{2}$$

where $(\text{Vmax})_h$ is the value of Vmax at the intersection of two lines, which is so determined that it will give largest multiple correlation coefficient largest. And z = dummy variable which is given as

$$\begin{aligned} z &= 0 && \text{if} \quad (\text{Vmax}) \leq (\text{Vmax})_h \\ z &= 1 && \text{if} \quad (\text{Vmax}) > (\text{Vmax})_h \end{aligned} \tag{3}$$

3. METHOD OF FRAGILITY ESTIMATION

Safety margin Sf for the isolation layer and the member of the super structure is given as

$$Sf = R/Q \quad \text{or} \quad Sf = R^*/Q^* \tag{4}$$

where R = ultimate capacity expressed in terms of "ultimate displacement" for isolation layer and "ultimate strain" for the structure member of the upper structure, Q = maximum responses, R^* and Q^* are "equivalent elastic"quantities converted from inelastic value giving the same amount of potential energy(Fig. 2). Estimation of the response for given intensity of earthquake motion is made using functional relationship obtained from the regression analysis given by Eq. (1), where the maximum response Q(or Q^*) is given as a function of peak ground velocity Vmax.

Assuming that the ultimate capacity of the isolation layer and the member of the super structure are lognormally distributed as well as the response Q(or Q^*), reliability index β for each component is given as function of Vmax as

$$\beta(\text{Vmax}) = \frac{E[\ln R - \ln Q(\text{Vmax})]}{\sqrt{D^2[\ln R] + D^2[\ln Q(\text{Vmax})]}} \tag{5}$$

where $E[\cdot]$ and $D[\cdot]$ respectively mean expectation and standard deviation. Here uncertainty of response Q(or Q^*) is assumed resulting from (i)randomness of response due to material randomness, (ii)modelling uncertainty and (iii)randomness of response due to random characteristics of earthquake wave. As for (i), it is considered as D[ln Q(Vmax)] in Eq. (5). As for (ii), its effect is not considered here since non-linear response analyses are performed using multi-dimensional stick model and its effect is considered negligible small. As for (iii), its effect is estimated from the estimate interval of the dependent variable(response Q) in the regression analysis.

In the multiple regression given by Eq.(i), a% non-exceedence value of response (Q)a is given as

$$(Q)a = \hat{\beta}_0 + \hat{\beta}_1 x_{01} + z\cdot\hat{\beta}_2 x_{02} + t(n-p-1,a)\sqrt{[1+1/n+D_0^2/(n-1)]V_e} \tag{6}$$

where $\hat{\beta}_0$, $\hat{\beta}_1$, $\hat{\beta}_2$ = least square estimates of regression coefficients, t(n-p-1,a) = a-percentile value of the t-distribution with n-p-1 degree of freedom(n:number of data(waves), p:number of explanatory variables in regression analysis), D_0 = Mahalanobis' distance defined by Eq. (7) and V_e = unbiased estimate of conditional variance given by Eq. (8)

$$D_0^2 = \sum_{i=1}^{2}\sum_{j=1}^{2}(x_{0i}-x_i)(x_{0j}-x_j)S^{ij} \tag{7}$$

where S^{ij} is the component of inverse of matrix of sum of product of deviation.

$$V_e = \sum_{i=1}^{n}[Q_i-\{\hat{\beta}_0+\hat{\beta}_1(x_{01})_i+z\cdot\hat{\beta}_2(x_{02})_i\}]^2/(n-p-1) \tag{8}$$

Fragility, defined as conditional probability of failure under given peak ground velocity is given as

$$Pf(Vmax) = 1 - \Phi(\beta(Vmax)) \tag{9}$$

where Pf = probability of failure, Φ = cumulative standard normal distribution function. Substituting Eq. (6) into Eq. (5) and further into Eq. (9), one can obtain confidence interval of fragility.

4. PROBABILISTIC ESTIMATION ON ULTIMATE CAPACITY OF ISOLATION LAYER

For the isolated structure, reliability of the rubber bearing is of the matter of great concern. From the experimental data[4], statistical data of mechanical characteristics for rubber bearing are accumulated. Here effect of the randomness of the strength of the rubber bearing on the ultimate capacity of the isolation layer is investigated by M.C.S.

Procedure of the M.C.S. is as follows.

(i)Model the super structure of the reference reactor building as a rigid body with underlying 272 rubber bearings (Fig. 1).
(ii)Suppose randomness of the strength of the rubber bearing, which is given as two-dimensional rupture surface, is normally distributed around its mean as shown in Fig. 5.

(iii)Strength of each rubber bearing is given from normal random number according to the assumption above.
(iv)Simulations of static loading are carried out where different set of random numbers are assigned for the strength of the rubber bearings in each simulation.
(v)From the simulations above, estimate statistical characteristics such as mean, c.o.v.(coefficient of variation) concerning the ultimate displacement and the load at ultimate state.

In the M.C.S. c.o.v. of the bearing capacity is taken as a parameter, ranging 0.1-0.4, and the number of the sample of each M.C.S. is 100.

Figs. 6 and 7 show the results of the M.C.S. From these results it is made clear that as the c.o.v. of the bearing capacity increases the mean of the ultimate capacity of the isolation layer decreases, although their standard deviations do not. In the case where c.o.v. = 0.2, mean and c.o.v. of the ultimate displacement of the isolation layer are estimated 65cm and 0.062.

5. ESTIMATION OF FRAGILITY

Using the method and results shown in section 3 and 4, fragility estimation for respective isolation layer and super structure is carried out. Fig. 8 shows fragility for the isolation layer and the 1st layer of the super structure with confidence interval of 90%. Fig. 9 shows mean fragilities for the isolation layer and each layer of the super structure, showing that in the case of the reference FBR structure, probability of failure for the isolation layer is larger than that for the super structure.

6. CONCLUSIONS

A method of fragility estimation for the isolated structure is proposed, and for the reference FBR structure, fragility is estimated in terms of peak ground velocity. As future scope of this research, estimation of the randomness of response due to random nature of earthquake waves or method of selecting earthquake waves for the regression analysis should primarily be included.

7. ACKNOWLEDGEMENTS

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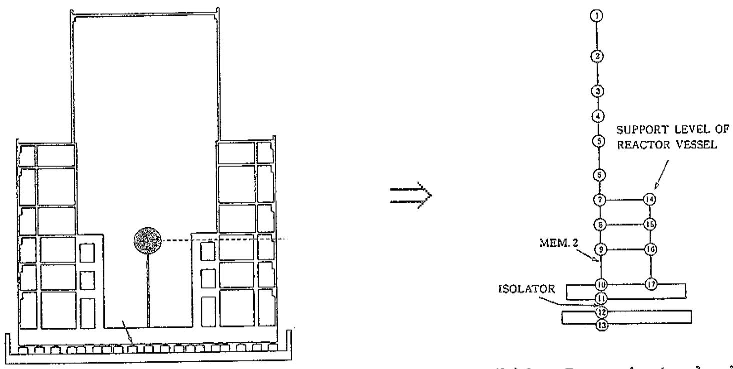
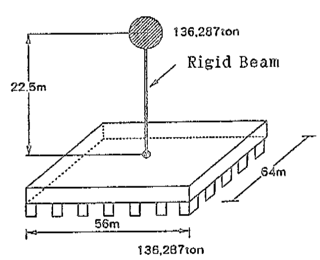
REFERENCES

[1]R. P. Kennedy and M. K. Ravindra: Seismic Fragilities for Nuclear Power Plant Risk Studies, Nuclear Engineering and Design 79(1984), pp.47-68
[2]An Approach to the Quantification of Seismic Margins in Nuclear Power Plants, NUREG/CR-4334, 1985
[3]K. Hirata, Y. Kobayashi, et al.: Reliability Analysis for Seismically Isolated FBR system, Trans. 10th SMiRT, M pp.115-120, 1989
[4]T. Mazda, H. Shiojiri, et al.:Test on Large-Scale Seismic Isolation Elements, Trans. 10th SMiRT, K2 pp.679-684, 1989



(a)Reference FBR Building

(b)for Dynamic Analysis



(c)for Static M.C.S.

Fig. 1 Modelling of Isolated Reactor Building

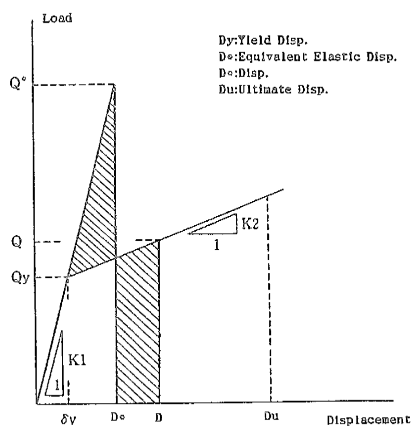


Fig. 2 Load-displacement Relation for Isolator and
Concept of Equivalent Linear Response

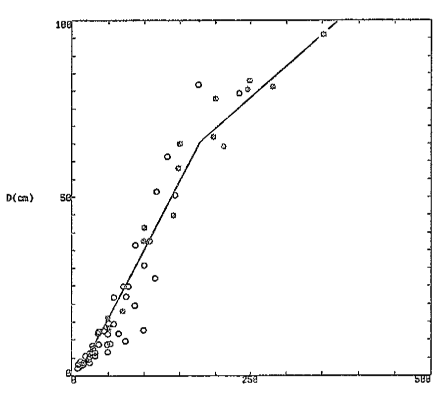


Fig. 3 Vmax vs. Max. Displacement of Isolation Layer

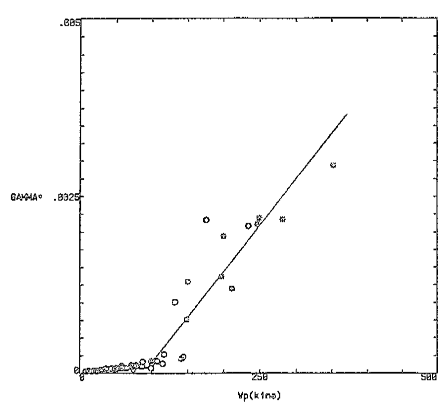


Fig. 4 Vmax vs. Equivalent Max. Shear Strain of
1st-layer of Super Structure

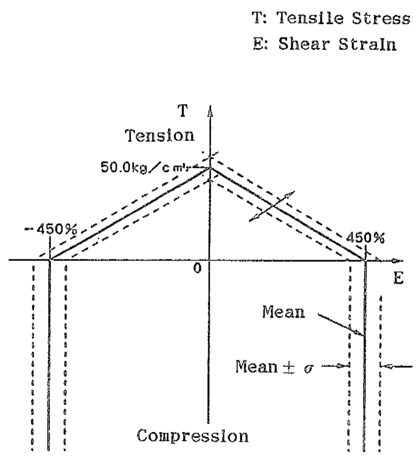


Fig. 5 Rupture Surface of Rubber Bearing

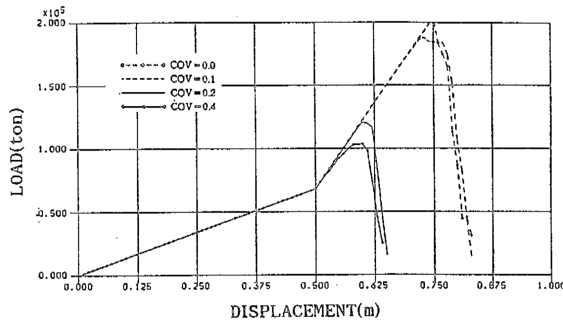


Fig. 6 Sample of M.C.S. (Load vs. Disp. of Isolation Layer)

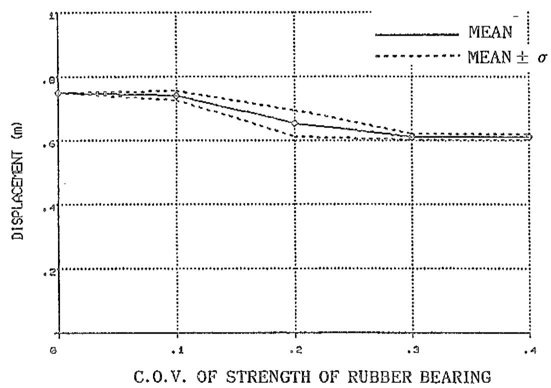
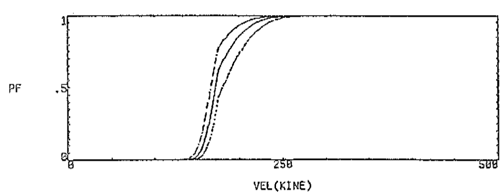
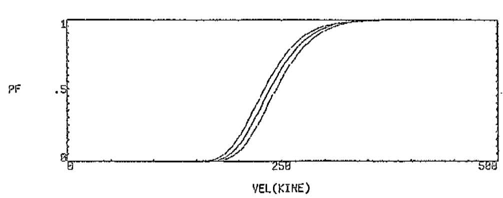


Fig.7 Mean and Standard Deviation of Ultimate Disp. of Isolation Layer



(a)Isolation Layer



(b)1st-layer of Super Structure

Fig. 8 90% Confidence Interval of Fragility

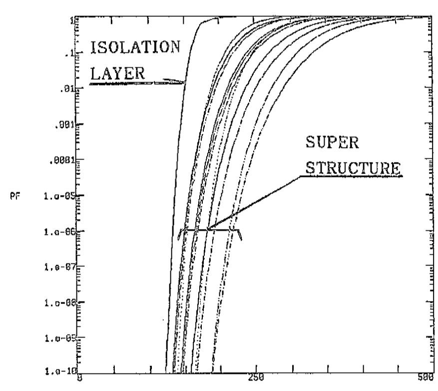


Fig. 9 Mean Fragility for Isolation Layer and Super Structure