SMiRT-12 / K. Kussmaul (Editor)

K07/1

EFFECTS OF UNCERTAINTIES IN SOIL-STRUCTURE INTERACTION MODELS ON NONLINEAR SEISMIC RESPONSES OF NUCLEAR REACTOR BUILDINGS

J. Mizuno[1], H. Namba[2], T. Komura[3], Y. Tuchiya[4] and M. Saitoh[4]

[1]Nuclear Structures Engineering Dept, Kajima Corp., [2]Office of Energy and Nuclear Engineering, Takenaka Corp., [3]Nuclear Power Division, Shimizu Corp., [4]Nuclear Power Plant Construction Dept., Tokyo Electric Power Company (Japan)

1. INTRODUCTION

Effects of uncertainties in materials and modeling on seismic responses of nuclear reactor buildings are relatively small if responses remain in the elastic range of structures. However, under extremely severe earthquakes, responses are expected to go into nonlinear ranges, and responses may exhibit wider scatters due to the uncertainties and variabilities in materials and nonlinear characteristics of shear walls. Thus, it may be quite important to evaluate the effects of the uncertainties on nonlinear responses, especially, the maximum shear strain response, which is one of the most critical responses to the seismic safety of reinforced concrete shear walls and to reactor buildings as a whole.

To this end, the sensitivities of nonlinear responses, mainly shear strain responses, to the uncertainties and variabilities of materials and nonlinear characteristics of shear walls are evaluated for a reactor building of BWR Mark I type; then, the variabilities of nonlinear responses due to the uncertainties and variabilities are evaluated on the basis of the first-order approximation of response statistics as well as numerical simulations.

2. SOIL STRUCTURE INTERACTION MODEL FOR BWR MARK-I REACTOR BUILDING

A soil-structure interaction (SSI) model for evaluating seismic responses is shown in Fig. 1. The reactor building model is constructed, considering the symmetrical condition; the main reinforced concrete shear walls such as the outer box wall (OW), the inner box wall (IW), the shell wall (SW) are represented by beam elements; the masses are lumped at each floor level; the base mat slab is assumed to be rigid. The soil stiffness and damping for sway and rocking motion of the base mat slab are evaluated as a function of vibration frequency on the basis of the vibration admittance theory /1/, considering an elastic half space of soil. However, to evaluate the seismic responses in the time domain, the soil stiffness is approximated by the value at the zero-frequency, as a constant value with regard to vibration frequencies; the soil damping is approximated by the secant line of the imaginary function from the origin (0 Hz) to the fundamental frequency of the SSI model as shown in Fig. 3 /2/.

The nonlinearities in both the shear stress-strain relationships and the moment-curvature relationships of reinforced concrete shear walls, shown in Fig. 2 /2/, are considered under the S2 earthquake motion.

3. EFFECTS OF UNCERTAINTIES OF MODEL PARAMETERS ON NONLINEAR RESPONSES

3.1 Variabilities and Uncertainties of Model Parameters

Variabilities and uncertainties considered in the essential model parameters of the SSI model are listed in terms of coefficient of variation (cov) in Table 1. The statistics of concrete strength, damping factor of the building and the shear wave velocity of soil are determined on the basis of related previous studies. The statistics of soil spring and damping, Young's modulus and shear modulus of concrete and the envelope curve of shear stress-strain relationships are determined by the first-order approximation of the functions of basic variables.

The input earthquake motion is the S2 earthquake shown in Fig. 4, which is treated in a deterministic way.

3.2 Evaluation of Response Statistics

The first two moments (mean and variance) of maximum responses of the reactor building are main concerns in this study. Maximum responses may be expressed as a function of basic random variables; thus a maximum response, say maximum shear stress response, is expressed as

$$D(\mathbf{x}) = D(x_1 \cdots\cdots x_n) \tag{1}$$

Expanding Eq. 1 into Taylor series at the mean values of **x**, and truncating the series at the linear terms, the first-order approximate mean and variance can be obtained as,

$$D(\overline{\mathbf{x}}) = D(\overline{x}_1 \cdots\cdots \overline{x}_n) \tag{2}$$

$$\mathrm{Var}(D) = \sum \mathrm{Var}(x_i)\left(\frac{\partial D}{\partial x_i}\right)^2 + \sum_{i \neq j}\sum \mathrm{Cov}(x_i, x_j)\left(\frac{\partial D}{\partial x_i}\right)\left(\frac{\partial D}{\partial x_j}\right) \tag{3}$$

where $\overline{x}_i$, $\mathrm{Var}(x_i)$, $\mathrm{Cov}(x_i,x_j)$ are the mean, variance and covariance of basic random variables, respectively, and the partial derivatives are evaluated at the mean value of each basic random variable. With the following transformation, $\partial D = \partial\Omega_D \cdot \overline{D}$ and $\partial x_i = \partial\Omega_{x_i} \cdot \overline{x}_i$, Eq.3 can be rewritten in terms of coefficient of variation (cov) as,

$$\mathrm{cov}(D) = \sqrt{\sum\left(\frac{\partial\Omega_D}{\partial\Omega_{x_i}}\right)^2 \mathrm{cov}(x_i)^2 + \sum_{i \neq j}\sum \rho_{ij}\,\mathrm{cov}(x_i)\mathrm{cov}(x_j)\left(\frac{\partial\Omega_D}{\partial\Omega_{x_i}}\right)\left(\frac{\partial\Omega_D}{\partial\Omega_{x_j}}\right)} \tag{4}$$

where ρ_{ij} is the correlation coefficient between x_i and x_j.

3.3 Sensitivity Analysis

The sensitivities of responses against the model parameters listed in Table 1 may be evaluated by the partial derivative, $\partial\Omega_D / \partial\Omega_{x_i}$, at the mean value of x_i. However, taking into account the effects of degree of dispersion of each model parameter, the variability of response due to the variability of each model parameter may be evaluated by $\partial\Omega_D / \partial\Omega_{x_i} \bullet \mathrm{cov}(x_i)$

The partial derivatives of maximum shear strain responses of the shear walls are evaluated numerically by the central difference scheme, and the values of representative three inner box walls are shown in Fig. 5. The inner box wall of the 4th floor (IW4F) is the most severely damaged walls and shows the highest sensitivity to the shear stress-strain relationships. Also the sensitivities to the shear modulus of concrete (G) and the sway soil spring (Ks) to the maximum shear strain response of IW4F are relatively high. The responses of IWB2F remain in the elastic range, and shows much smaller sensitivities than those of IW4F.

In Fig. 6, the values of $\partial\Omega_D / \partial\Omega_{x_i} \bullet \mathrm{cov}(x_i)$ of each model parameters are plotted. Although the value corresponding to the shear stress-strain relationships is still large due to the high sensitivity, the values corresponding to the damping factor (h) and soil springs (Ks and Kr) are relatively high for the critical shear walls, reflecting the large coefficients of variation of those parameters.

3.4 Variabilities of Maximum Responses

The variabilities of maximum responses as well as the mean maximum responses due to the variabilities of model parameters are evaluated on the basis of both the first-order approximation of nonlinear responses (Eqs. 1 and 4) and a numerical simulation technique, i.e. the two point estimate method /3, 4/.

In Fig. 7 and 8, the mean maximum acceleration responses and mean maximum shear strain responses are plotted respectively for each shear wall at each floor level. The first order approximation of mean maximum responses shows good agreement with the simulated results.

The coefficients of variation of maximum acceleration responses and maximum shear strain responses are plotted in Figs. 9 and 10, respectively. In Fig. 9, the covs from B2F up to 3F are about 0.05, however the values of 3F and 4F are about two to three times larger than those of lower floor levels due to severer nonlinearity of IW3F and IW4F.

In Fig. 10, the covs of shear strain show larger values than those of the acceleration responses. Especially, the covs of IW3F and IW4F are as high as 0.45, which is about five times larger than those of shear walls at the B2F.

Thus, it may be pointed out that (1) the damages are concentrated in the inner box walls at 3rd and 4th floor, which are found to firstly go into nonlinear range; (2) variabilities of responses, especially shear strain responses, increase significantly in shear walls where damages are concentrated; (3) in nonlinear responses, strain responses are more sensitive to the variabilities of model parameters due to stiffness degradation than acceleration responses.

4. CONCLUDING REMARKS

Effects of uncertainties and variabilities in materials and modeling of a SSI model on seismic nonlinear responses of nuclear reactor buildings are evaluated. In nonlinear seismic responses, seismic damages tend to concentrate in some critical shear walls in a reactor building: in those critical walls, the sensitivities to model parameters, particularly the nonlinear characteristics of the shear walls, increase significantly; thus the variabilities of responses, especially shear strain response, increase considerably as high as 0.45 in terms of cov.

Thus the variabilities of responses due to the uncertainties and variavilities of materials and nonlinear characteristics of shear walls should be taken into account for evaluating the seismic safety of a reactor building.

The means and variances of responses evaluated by Eqs. 2 – 4 reasonably agree with the results of numerical simulation.

Acknowledgment

This work was carried out as a part of the cooperative joint study, " Research on the Overall Seismic Safety Evaluation of Nuclear Power Facilities" under the sponsorships of 10 electric power companies in Japan. The sponsorships and efforts made by all of the members in the joint study are greatly acknowledged.

References

/1/ Tajimi, H., "Basic Theories on Aseismic Design of Structures", Report of the Institute of Industrial Science, Univ. of Tokyo, Vol. 8, No.4, March 1959

/2/ JEAG 4601-1987, "Electrical Technical Guidelines, Nuclear Edition: Technical Guidelines for Aseismic Design of Nuclear Power Plants", Electrical Technical Standard Survey Committee, Electrical Society of Japan, 1987

/3/ Shimizu, A., Ugata, T., Kobayashi, Y., Hirota, M., and Saito, M., "Analytical Study of Analysis Methods of Several Random Variables for Seismic Nonlinear Responses of Reactor Buildings", Proc. the 12th SMiRT Conference, Stuttgart, FRG, Paper K14/4, 1993

/4/ Rosenblueth, E., " Two-point estimates in probabilities", Applied Mathematical Modeling, Vol. 5, pp. 329-335, 1981

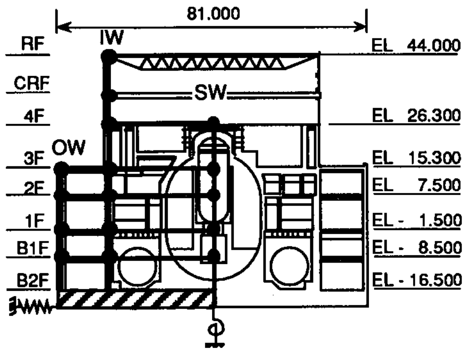
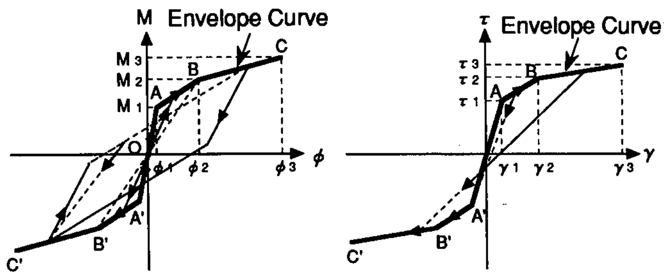


Fig. 1 SSI Model for BWR Mark-I Reactor Building



a. Moment-Curvature Relationships

b. Shear Stress-Strain Relationships

Fig. 2 Nonlinear Characterestics of Shear Walls

Table 1 Analytical Conditions

Model Parameters		Mean Value	cov
Soil			
Shear Wave Velocity	Vs	1000 m/s	10%
Soil Spring Sway	Ks *1	4.71×10^{5} tf/cm	20%
Rocking	K_θ *1	9.04×10^{12} tf·cm/rad	20%
Soil Damping Sway	Cs *1	1.30×10^{4} tf·rad/cm·s	10%
Rocking	C_θ *1	7.09×10^{10} tf·cm/s	5%
Reactor Building			
Concrete			
Concrete Strength	fc'	460 kgf/cm^2	13%
Young's Modulus	Ec *2	320 tf/cm^2	6.5%
Shear Modulus	Gc *2	137 tf/cm^2	6.5%
Damping Factor	h	5% to the critical damping	25%
Mass			Deterministic
Force-Deflection Relationships			
Shear stress vs. strain		Mean Envelope Curve	5%
Moment vs. curvature			Deterministic
Input Motion			
S2 Earthquake Motion			
Maximum Acceleration		407.1gal	Deterministic

Notes: *1 Soil springs and damping coefficients are assumed to be perfectly correlated with the shear wave velocity, Vs

*2 Young's modulus and shear modulus of concrete are assumed to be perfectly correlated with the concrete strength, fc'

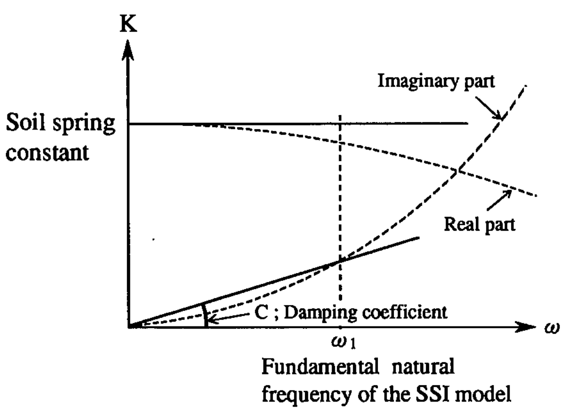


Fig. 3 Soil Spring and Damping Coefficient

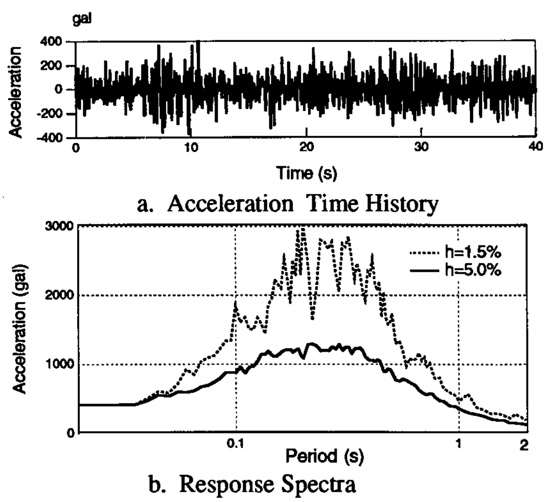


Fig. 4 Input S2 Earthquake Motion

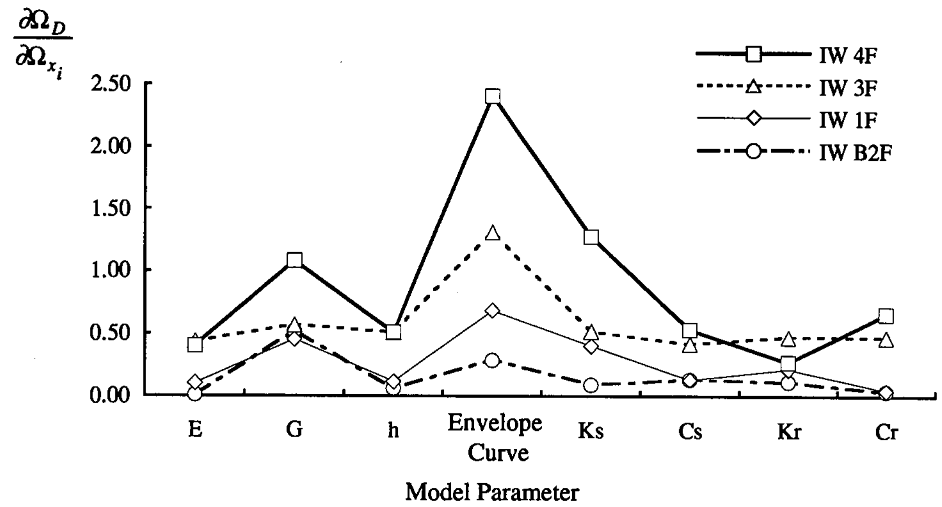


Fig. 5 Sensitivity of Shear Strain Response to Model Parameters

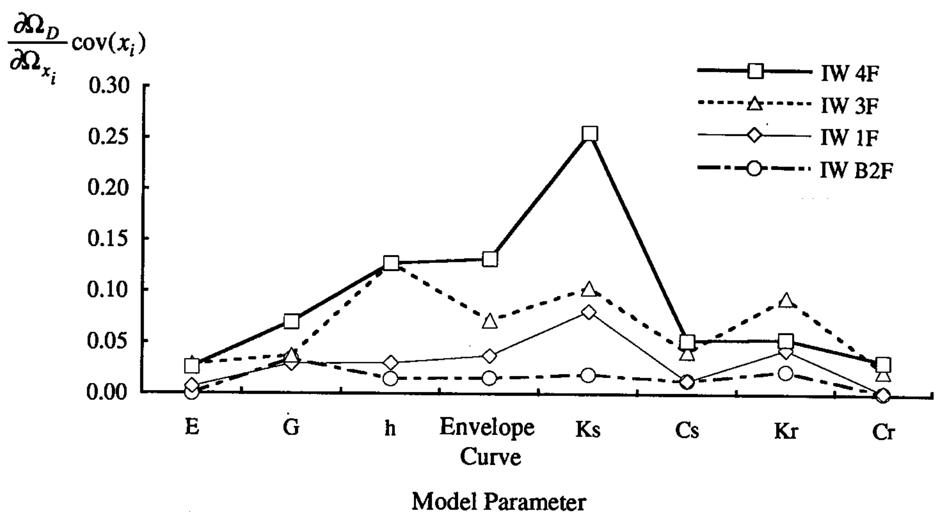


Fig. 6 Variability (cov) of Shear Strain Response due to Variabity of Each Model Parameter

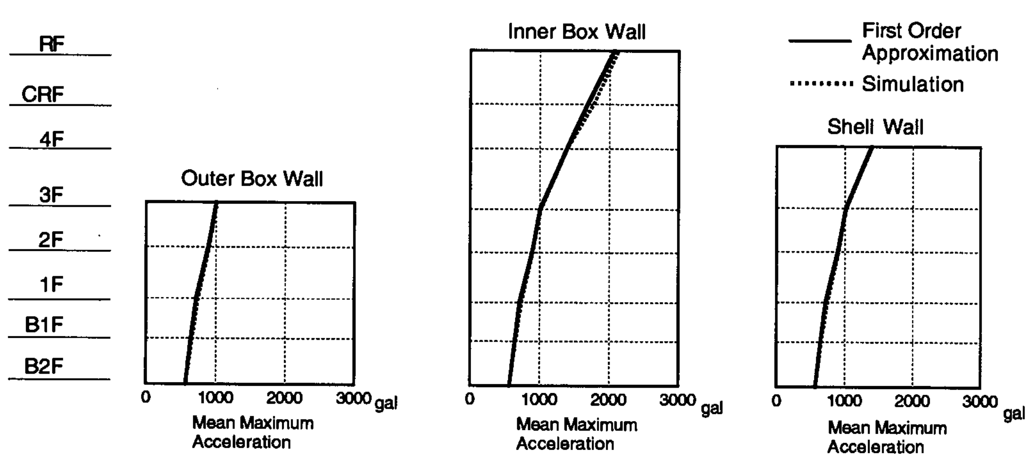


Fig. 7 Mean Maximum Acceleration

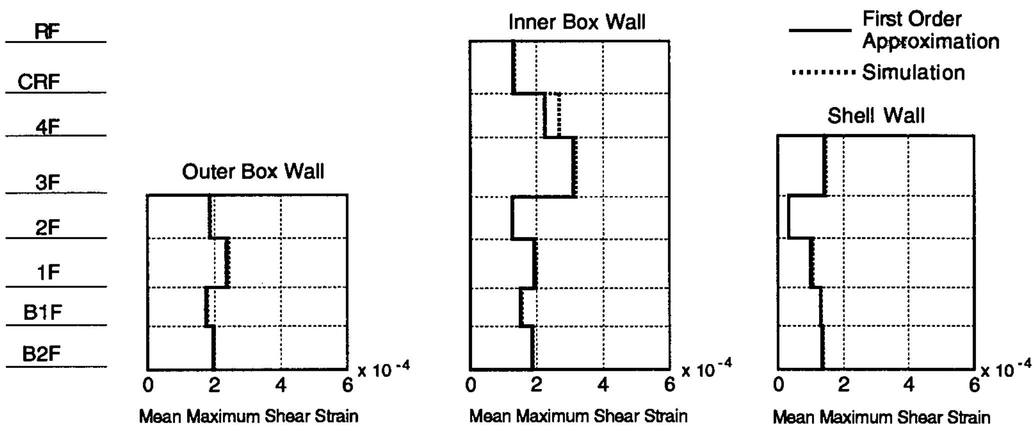


Fig. 8 Mean Maximum Shear Strain

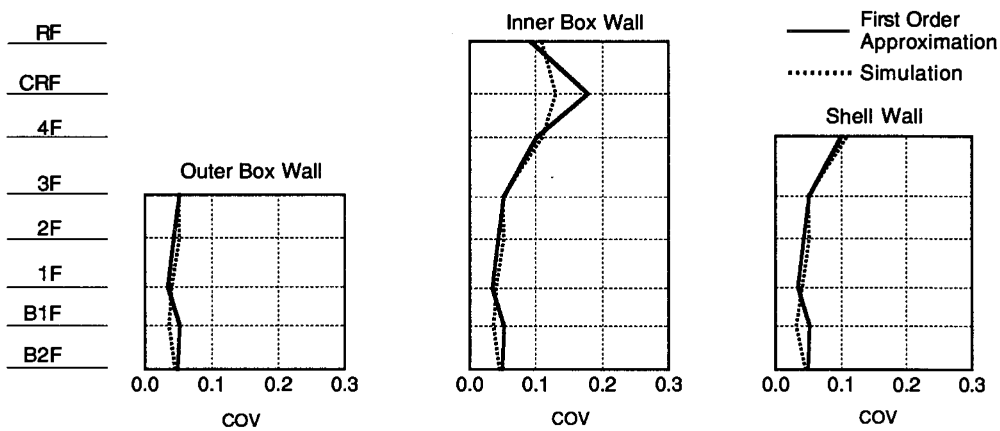


Fig. 9 Coefficient of Variation of Maximum Acceleration

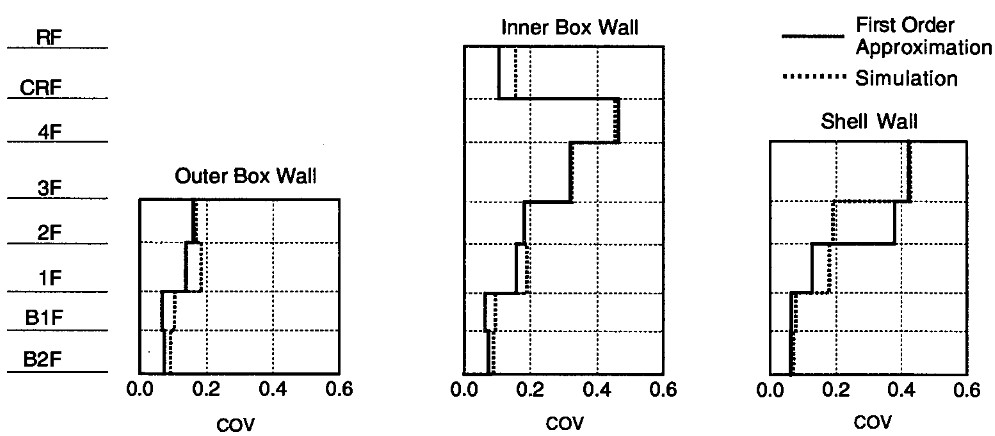


Fig. 10 Coefficient of Variation of Maximum Shear Strain