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Failure probability evaluation for a reactor building using linear response

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1. INTRODUCTION

A fragility analysis for a PWR nuclear power plant is evaluated. The fragility evaluation is for structure seismicity, and is intended to demonstrate a method for representing non-linear variability effects on the structure through linear response analysis. The linear response analysis is coupled with a coefficients method to obtain the structure fragility. In the coefficients method the structure's reference response and capacity are factored by various coefficients to obtain an expected response and capacity, and from these results the evaluation of structure fragility is determined. Failure mode for the fragility evaluation is shear wall failure. Figure 1 displays a flowchart of the fragility evaluation study.

2. STRUCTURE MODEL AND EARTHQUAKE INPUT MOTION

2.1 Analysis model

The PWR nuclear reactor building is modeled as a multi-stick lumped mass with soil sway and rocking springs (Figure 2). The building stiffness variability is assumed to lie within the structure's inherent uncertainties of concrete strength, damping, and ultimate strain of the shear walls. Additionally, uncertainties in rebar yield strength and soil shear wave velocity are considered. All variabilities are assumed as log-normal distributions. Variation in the building weight is not assumed. The stiffness variability is then used in the structure response evaluation model, which employs the following two models.

1. *Median model-* uses the property median values
2. *Variability analysis model-* considers the property variabilities

Both these models are used in determining the expected (factored) structure response, and additionally, the median model is used when determining the structure shear stress capacity.

2.2 Earthquake Input motion description

Variability in the earthquake input motion is also considered to determine the building failure probability. More specifically, the input motion spectral shape variability and phase differences effects on the expected structure response and capacity are investigated. Three types of earthquake waves are used to carry out such an investigation.

1. Es wave: At 5% damping, this is a median spectral shape earthquake wave based on the Japanese S1 design earthquake with a maximum acceleration of 270 gal.
2. ESA wave: Based on the Es wave median, this wave (10 waves) considers spectral shape variability from actual earthquake data, for a period of 0.1 to 0.3 seconds, with a fixed logarithmic standard deviation of 0.33. The ESA spectra is shown in Figure 3.

3. E_{NL} wave: This wave (4 waves) has the same spectral shape of the Es wave, but of different phase The E_{NL} earthquake input motion waves for evaluation are displayed in Figure 4.)

3. COEFFICIENT COMPOSITION

The structure fragility evaluation is carried out from the probabilistic estimations in expected structure response, R(a), and the structure ultimate shear stress capacity, C. The expected response, which is defined as a function of *a*, the acceleration input level, is obtained from a reference response, r(a), which is factored by various coefficients to account for variability in the response. Similarly, the capacity is determined by factoring the ultimate shear stress, S, to account for variability in capacity. R(a) and C are determined by the composition of the coefficients in the following equations.

$$\text{Expected response, } R(a) = r(a) \bullet F_{SA} \bullet F_{SS} \bullet {}_{R}F_{M}$$

$$\text{Capacity, } C = S \bullet F_{NL} \bullet {}_{C}F_{M}$$

where

- r(a) is the reference response (fixed value) defined as the median response (maximum shear stress) based on the Es wave input to the median model.
- F_{SA} is the coefficient for effects on the structure response variability due to variability in the input motion spectral shape, and is realized from the variability in the structure response (maximum shear stress) when the E_{SA} waves (10) are input to the median model.
- F_{SS} is the coefficient for effects on the structure response variability due to uncertainty in the element properties, and is obtained from applying the Es wave to the variability analysis model.
- ${}_{R}F_{M}$ is primarily the coefficient for effects on the structure response variability due to response evaluation procedure uncertainty, but is also used here to include the variability in the soil spring evaluation equation which is obtained from literature.
- S is the structure ultimate shear stress capacity, and is based on Japanese nuclear power plant design guidelines considering property uncertainties. Ultimate shear strength is evaluated from first-order second moment method (FOSM) which comes from a Taylor series expansion about the mean.
- F_{NL} is the coefficient for effects on the capacity variability due to variability in linearization non-linear effects using ultimate shear strain.
- ${}_{C}F_{M}$ is the coefficient for effects on the capacity variability due to capacity evaluation method uncertainty, and is obtained from literature.

The relationships among the coefficents, structural model, and earthquake input motions are shown in Table 1.

4. EVALUATION OF NON-LINEAR EFFECTS

The coefficient F_{NL} primarily represents the difference between the linear and non-linear responses. More specifically, the coefficient is for effects on the capacity variability due to variability in linear representation of non-linear effects using ultimate shear strain. Hence, F_{NL} is a function of the ultimate shear strain, and therefore includes variability of the ultimate shear strain. Accordingly, F_{NL} also includes procedural effects of the linearization. The evaluation flowchart is shown in Figure 5.

4.1 FNL Evaluation

With the same input acceleration for a linear and non-linear analysis, F_{NL} can be expressed as the ratio of the linear response stress (τ_L) to the non-linear response stress (τ_{NL}) (see Figure 6).

For evaluating F_{NL} as a function of the ultimate shear strain, the following calculations are carried out using the analysis mean model and the 4 E_{NL} input motion waves.

The input motion level magnitude is at structure maximum shear strains of $9x10^{-3}$, $5x10^{-3}$, $4x10^{-3}$, and $2x10^{-3}$, which correspond to maximum accelerations of 2700, 2000, 1100, and 800 gal respectively. Calculating the response stresses (τ_L and τ_{NL}) for each combination of input motion wave and maximum shear strain, a total of 16 cases of F_{NL} are obtained, and plotted for the various shear strains. A linear regression is then carried out (Figure 7). For both a cylindrical and box wall, the regressions are as follows.

Cylindrical wall: $F_{NL}=1.26+0.18\gamma\,(x10^3)$ (1)

Box wall: $F_{NL}=1.63+0.16\gamma\,(x10^3)$ (2)

Applying the 2-point estimation method to the above two equations, F_{NL} is obtained from the variability of ultimate shear strain. As an example, for the cylindrical wall, inputting the experimental median ultimate shear strain $\gamma=9.5x10^{-3}$ and logarithmic standard deviation $\beta=0.32$ yields 3.0 and 0.19 for the median β of F_{NL} respectively. Additionally, F_{NL} due to the linearization procedural effects is assigned a median of 1.0 and β of 0.3, which are obtained from literature.

Thus, the total F_{NL} becomes the combination of F_{NL} from the ultimate shear strain variability and the F_{NL} for procedural effects. The medians of these two F_{NL} components are combined multiplicatively while their logarithmic standard deviations are combined by SRSS. Once again, as an example, for the cylindrical wall, the total F_{NL} now becomes 3.0 with a logarithmic standard deviation of 0.36.

5. COEFFICIENT ANALYSIS RESULTS

Table 2 displays the analysis results for the analysis model elements OS06 (cylindrical wall) and EB15 (box wall) which correspond to the damage concentration levels.

6. FRAGILITY EVALUATION OF THE STRUCTURE

The structure fragility is evaluated with reference to maximum seismic acceleration. From the expected response, R(a), and capacity, C, the median and logarithmic standard deviation of seismic capacity for the structure can be evaluated as follows.

$$\hat{A} = \left(\hat{C} / \hat{R}\right) \bullet 270 \text{ (Gal)} \quad (3)$$

where

$\hat{A}$ = structure's median seismic capacity referenced to maximum seismic acceleration(Gal)

$\hat{C}$ = median structure strength capacity $(\mathrm{Kg/cm^2})$

$\hat{R}$ = median of expected response, R(a = 270) $(\mathrm{Kg/cm^2})$

$$\beta = \sqrt{\beta_R^2 + \beta_C^2} \quad (4)$$

where

β = logarithmic standard deviation of the structure's seismic capacity

β_R = logarithmic standard deviation of expected response R(a = 270)

β_C = logarithmic standard deviation of capacity C

The results calculated from equations (3) and (4) are shown in Figure 8. Overlaid on the same plot are the results from a non-linear fragility evaluation. Both evaluations are in good agreement.

7. CONCLUSION

For a structure seismic fragility evaluation, a method has been proposed for defining non-linear variability effects through use of a linear response analysis. More specifically, a coefficient, FNL(γ), has been proposed to account for effects on the capacity variability due to variability in linearization non-linear effects, and a reasonable attempt to evaluate the variability of FNL was carried out.
The non-linear and linear fragility evaluations were in good agreement.
Additionally, it is important to note that if the structure type is changed, accordingly, the FNL changes. Therefore, there exist a need to carry out similar studies for various structures, with intentions to accumulate a data base for FNL.

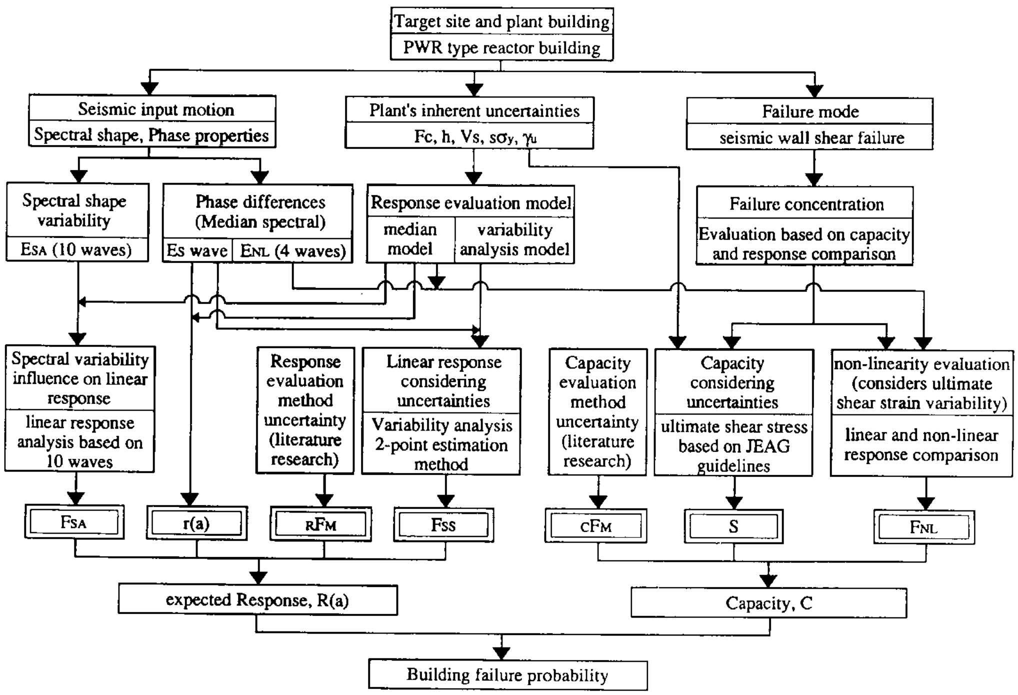

Figure 1. Flowchart for method and evaluation based on linear response

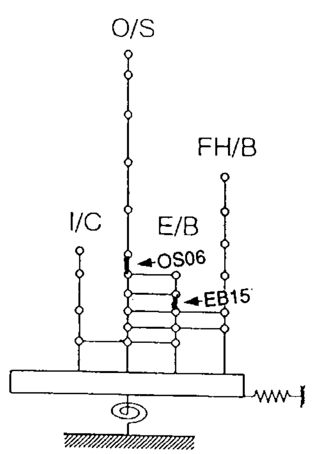

Figure 2. Analysis model

Table 1. Relationships among the coefficients, structural model, and earthquake input motions

coefficient	Uncertainty variable(s)	Structure model	Earthquake input motion
r(a)	-	median value	Es wave
FSA	earthquake input motion spectral shape	median value	ESA wave
FSS	Fc, Vs, h	variability analysis	Es wave
RFM	evaluation method	-	
S	stress: Fc, sσy strain: literature	-	
CFM	evaluation method	-	
FNL	non-linear effect	median value	ENL wave

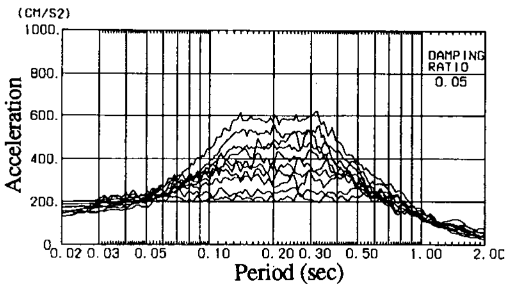

Figure 3. ESA Spectra (200 Gal)

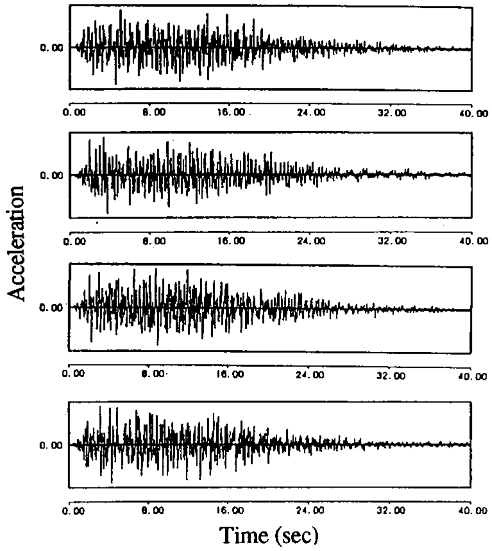

Figure 4. ENL earthquake input motion waves for evaluation

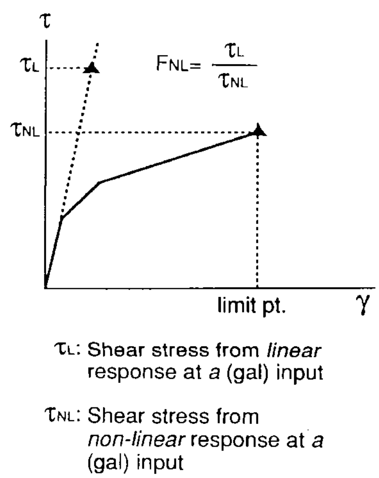

Figure 6. Linear and non-linear response stress

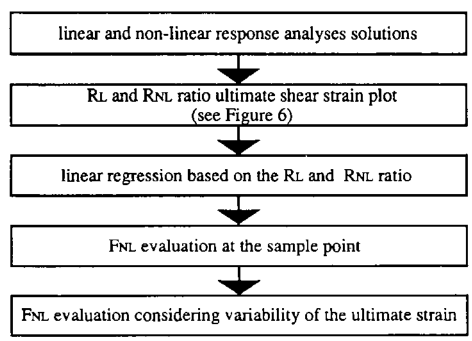

Figure 5. Evaluation flowchart

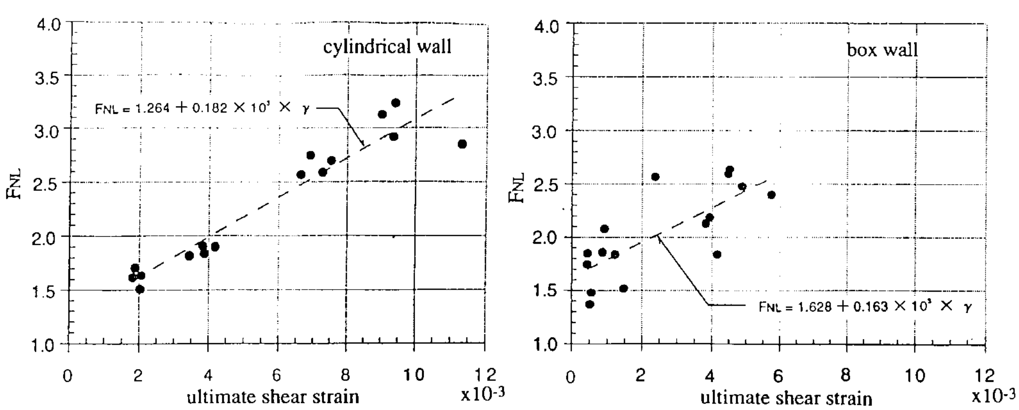

Figure 7. Relationship between ultimate shear strain and non-linearity

Table 2. Coefficient analysis results

	OS06 (cylindrical wall)		EB15 (box wall)	
	Median	Logarithmic standard deviation β	Median	Logarithmic standard deviation β
r(a)	19.8 (kg/cm^2)	-	14.8 (kg/cm^2)	-
F_{SA}	1.0	0.30	1.0	0.29
F_{SS}	0.98	0.07	1.00	0.05
$_RF_M$	1.0	0.06	1.0	0.06
R(a)	19.4	0.31	14.8	0.30
S	64 (kg/cm^2)	0.04	61 (kg/cm^2)	0.06
F_{NL}	3.0	0.36	2.5	0.32
$_CF_M$	1.02	0.18	1.02	0.18
C	196 (kg/cm^2)	0.40	156 (kg/cm^2)	0.37

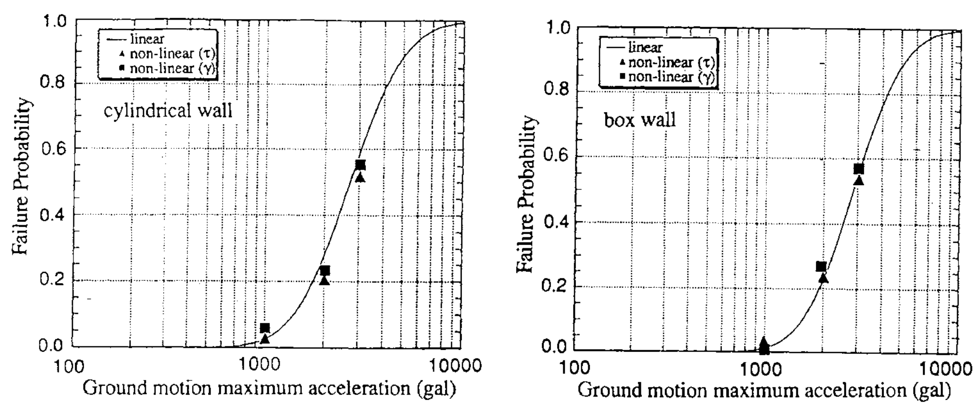

Figure 8. Structure fragility analysis results

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