The case study of the multiple seismic failure modes for SPRA

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1. Introduction

The conventional seismic probabilistic risk assessment usually was modeled with one governing failure mode of SSCs. The CDF or LERF of SPRA [1], [2], [3] was not a major contributor event before 1990's because it is generally much lower than the other event. However, the earthquake records are getting accumulated, the seismic event become the one of the affective events to the total CDF or LERF. Consequently, the more detailed assessment approach is required for the SPRA. The governing failure mode from fragility analysis used to consider when the seismic event quantification model is developed. But, some of second failure modes in SSCs have the little capacity differences, the final fragility curve from combining the similar capacity failure modes with the governing failure mode could be different from the single failure mode fragility curve. In accordance with this matter, the effect of multiple failure mode from one component in the risk dominant SSCs are examined in this paper.

2. Multiple Failure Modes

In this section, the effectiveness of the multiple failure modes in the SPRA is going to be reviewed. There are two ways to consider the multiple failure modes; first is providing the possible failure modes to the system analysis for exclusively including them in SPRA model, second is combining more than two fragilities into a single fragility representing the overall probability of failure for the SSC. In this paper, the second approach is used to review the effect.

2.1 Seismic Fragility

The entire family of fragility curves for an element corresponding to a particular failure mode can be expressed in terms of the best estimate of the median ground acceleration capacity, Am, and two variables. Thus, the ground acceleration capacity, A, is given by:

$$A = A_m e_R e_U \qquad (1)$$

At each acceleration value, the fragility f can be represented by a subjective probability density function. The subjective probability, Q(confidence) of not exceeding a fragility f' is related to f' :

$$f' = \Phi\left[\frac{\ln\left(\frac{a}{A_m}\right) + \beta_U \Phi^{-1}(Q)}{\beta_R}\right] \qquad (2)$$

2.2 Correlation of failure mode

The different failure mode from same equipment usually is affected by similar seismic response, so there might exist the correlation between the failure modes. To take into consideration of the failure mode correlation, the 'split fraction' which is in NUREG/CR-7237 [4] was adopted to calculate the combined fragility calculation. When two failure modes A and B fail, the likelihood that the failure of A is dependent on B's failure can be expressed by a "Spit Fraction", SF such that SF is the likelihood (or probability) that the two failures are dependent, and (1-SF) is the likelihood that are independent. Based on NUREG report [4], the joint probability of failure can be defined such as following;

A-IND = Independent Failure Probability of A
B-IND = Independent Failure Probability of A
AB-DEP = Dependent Failure Probability of A and B
AB-Fail = joint probability of failure of A and B, that is, the probability that they both fail. Then:
AB-FAIL = A-IND* B-IND*(1-SF) + AB-DEP*SF
SF = Split Fraction

2.3 Combination of the multiple failure modes

When a component has the multiple failure modes but each capacity has little differences then it could affect the CDF or LERF. In this case, the second failure mode need to be combined into its failure probability. The failure modes from the fragility analysis are independent but not mutually exclusive. Therefore, the probability from two failures can be expressed by the union events A and B or P(AUB) and is calculated using following demand equation.

$$P(A \cup B) = P(A) + P(B) - P(A \cap B)$$

Where, $P(A \cap B) = P(A) \times P(B)$

Therefore,

$$P(A \cup B) = P(A) + P(B) - P(A) \times (B) \qquad (3)$$

$$R_T = \frac{S_{ARE}}{G_{SSE}} R_{SSE} + R_N \qquad (4)$$

R_T : Total Response to the RE plus normal operating loads
G_{SSE}: Equivalent static g force used for the SSE qualification
S_{ARE} : Peak Spectral Acceleration from the RE response spectrum
R_N : Computed load or response to normal operating loads
R_{SSE} : Computed load or response to the G_{SSE} loading

The approach develops the mean fragility curves for each failure mode and then calculates the mean curve for at least one failure occurring. When calculating combined failure fragility, the demand load by Eq. (4) was used and the correlation of demand also take into consideration in this calculation. Table 1 shows HCLPF of different failure modes, each has the small differences to see the combined failure probability.

Table 1. Assumed HCLPF for different failure mode

Failure	HCLPF	Am	βr	βu	βc
P(A)	0.40	1.00	0.24	0.32	0.40
P(B1)	0.41	1.04	0.24	0.32	0.40
P(B2)	0.43	1.08	0.24	0.32	0.40
P(B3)	0.45	1.12	0.24	0.32	0.40
P(B4)	0.46	1.17	0.24	0.32	0.40
P(B5)	0.48	1.22	0.24	0.32	0.40

The demand failure modes are assumed to have the same variables and the seismic response to each failure mode is also similar. Table 2 shows the result of combined failure mode probability and Figure 1 depicts the combined fragility curve. The combined probability tends to be closed to the single failure probability when HCLPF is approaching to about 20% differences from single failure capacity.

Table 2. Result of Combined failure mode probability

%G Level	P(A)	P(AUB1)	P(AUB2)	P(AUB3)	P(AUB4)	P(AUB5)
0.05	3.46E-14	3.36E-14	2.49E-14	2.08E-14	1.89E-14	1.80E-14
0.20	2.87E-05	3.31E-05	2.66E-05	2.22E-05	1.94E-05	1.75E-05
0.40	1.10E-02	1.39E-02	1.19E-02	1.03E-02	9.12E-03	8.19E-03
0.60	1.01E-01	1.31E-01	1.17E-01	1.06E-01	9.55E-02	8.70E-02
0.80	2.88E-01	3.63E-01	3.37E-01	3.13E-01	2.91E-01	2.70E-01
1.20	6.76E-01	7.61E-01	7.37E-01	7.11E-01	6.86E-01	6.60E-01
1.50	8.45E-01	8.96E-01	8.81E-01	8.64E-01	8.46E-01	8.26E-01
1.80	9.29E-01	9.54E-01	9.46E-01	9.36E-01	9.25E-01	9.12E-01

2.4 Converting Probability to HCLPF

The quantification of SPRA use the median acceleration capacity and its variabilities to construct model. However, the combined mean curve may not be lognormal, but an approximate lognormal combined fragility can be approximated from this combined mean curve. From the combined mean curve, the 1% probability gives the new $A_{1\%}$ capacity, and the 50% probability gives the new median capacity.

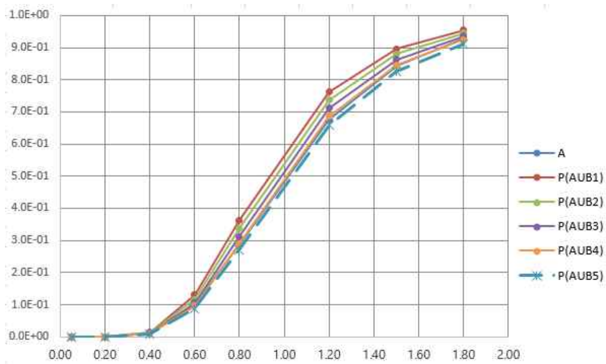

Figure 1. Comparison between Single Failure and Combined Failure Fragility Curve

From these two values, the composite variability βc can be calculated using Equation (5).

$$A_{1\%} = Am\ e^{-2.33(\beta c)} \tag{5}$$

βr and βu can then be assigned proportionately, i.e, corresponding to the βr and βu of the dominant failure mode such that their SRSS equals βc.

Table 3. Converted HCLPF from Combined Probability

Com. Prob.	Am	βr	βu	βc	HCLPF
P(AUB1)	0.94	0.24	0.32	0.40	0.37
P(AUB2)	0.96	0.24	0.32	0.40	0.38
P(AUB3)	0.99	0.24	0.32	0.40	0.39
P(AUB4)	1.01	0.24	0.32	0.40	0.40
P(AUB5)	1.04	0.24	0.32	0.40	0.41

The converted fragility curve is not a lognormal, so the median acceleration is obtained by linear interpolation with adjacent point. The variability is assumed based on "Table 3-11. Recommended logarithmic standard deviation to use in the hybrid fragility approach" by referred to EPRI [5]. HCLPF is getting increased when the difference is close about 20%, it means that the HCLPF for the governing failure modes would not affect the CDF and LERF.

3. Conclusions

According to EPRI 3002012994 [5], the combined fragility curve will be close to the dominant failure mode fragility curve (i.e., with the lowest capacity), if HCLPF capacity next to the governing failure is higher than about 20% with similar variabilities. As the result of the case study, the final combined probability could affect the SPRA result, so it needs to take a caution when conducting the calculation. All of SSCs in SPRA did not need to take a consideration of this combined capacity probability, only few risk dominant contributor is needed to have the detail analysis by the expert who have the enough experience.

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