Fragility Analysis of a Seismically-Isolated Emergency Diesel Generator

Young-Sun Choun[a], Yasuki Ohtori[b], and In-Kil Choi[a]
a *Korea Atomic Energy Research Institute, sunchun@kaeri.re.kr*
b *Central Research Institute of Electric Power Industry, ootori@criepi.denken.or.jp*

1. Introduction

The seismic capacity of an Emergency Diesel Generator (EDG) in nuclear power plants influences the seismic safety of the plants significantly. A recent study showed that the increase of the seismic capacity of the EDG could reduce the core damage frequency (CDF) remarkably [1,2]. It is known that the major failure mode of the EDG is a concrete coning failure due to the pulling out of the anchor bolts [3]. The use of base isolators instead of anchor bolts can increase the seismic capacity of the EDG without any major problems.

The fragility curves for a base-isolated EDG should be different from those for a conventional type because the major failure mode of the base-isolated EDG will not be a concrete coning one any more. The governing failure mode of the base-isolated EDG must be the damage of the isolators.

This study introduces a fragility evaluation method for an isolated EDG, and evaluates the fragilities for the isolated EDG and compares them with those for the conventional one. Evaluation of the ground motion index is also carried out to determine the governing parameter suitable for representing the seismic responses of the base isolator.

2. Analytical Models for an Isolated EDG

The analytical model for the base-isolated EDG is shown in Figure 1. The weight of the EDG, 172,000 kgf, is modeled as a lumped mass at the mid-height. At the base of the EDG, spring elements are introduced to represent the behavior of the isolators. The spring elements consist of two springs for the horizontal direction and one spring for the vertical direction. For the horizontal springs, a bilinear hysteretic model as shown in Figure 2 is used. For the vertical spring, a linear model with a stiffness of 20Hz is used. In the case of the conventional EDG, the stiffnesses of the springs are determined in order to have a natural frequency of 20Hz in the horizontal and vertical directions.

For the fragility analysis, 38 input motions - 26 earthquake records and 12 artificial motions - are used.

3. Evaluation of Fragility Curves

The probability of failure can be determined by using the relationship between the response and the intensity of a ground motion as shown in equation (1).

$$R(S) = \alpha \cdot S^{\beta} \cdot \varepsilon \tag{1}$$

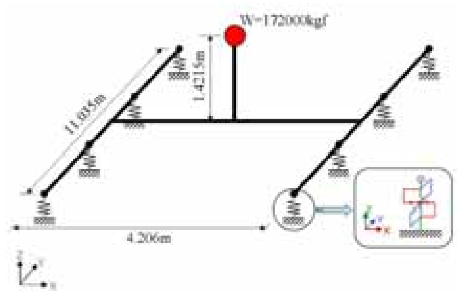

Figure 1 Analytical model for a base isolated EDG

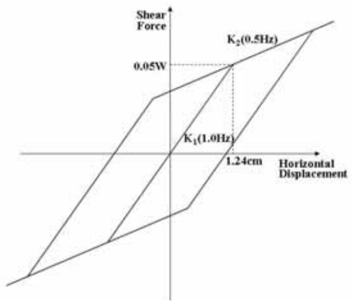

Figure 2 Hysteretic model for isolators

where, R is the response, S is the intensity of a ground motion, α and β are the regression coefficients, and ε represents the factor for response regression.

The probability of failure can be calculated by equation (2).

$$\begin{aligned} P_f &= \Phi\left[\frac{\mu_R(S) - R_{CR}}{\sigma_R}\right] \\ &= \Phi\left[\frac{\mu_R(S)/R(S) - R_{CR}/R(S)}{\sigma_R/R(S)}\right] \\ &= \Phi\left[\frac{E[\varepsilon] - R_{CR}/R(S)}{\beta_C}\right] \end{aligned} \tag{2}$$

where, R_{CR} is the critical response, $E[\varepsilon]$ is the expected value for ε, and β_C is given by the standard deviation due to structural randomness, β_r, and the standard deviation of ε, β_ε, as

$$\beta_C = \sqrt{\beta_r^2 + \beta_\varepsilon^2} \tag{3}$$

The fragility curves can be obtained by calculating equation (2) for each intensity level of the ground motion.

In general, the seismic response of structures depends on the peak ground acceleration (PGA). However, for flexible structures such as a base isolated structure, their seismic responses depend on the spectral intensity for a displacement response (SI_d), which is expressed as equation (4), or a spectral velocity (S_V) [4].

$$SI_d = \frac{1}{2.4}\int_{0.1}^{2.5} S_d(T,h)dT \qquad (4)$$

where, S_d is the spectral displacement, T and h are the period and damping value of the structures, respectively.

Figures 3 and 4 show the acceleration responses of the conventional and isolated EDG for a PGA and SI_d, respectively. It is demonstrated that the seismic response of the isolated EDG is more sensitive to SI_d than PGA.

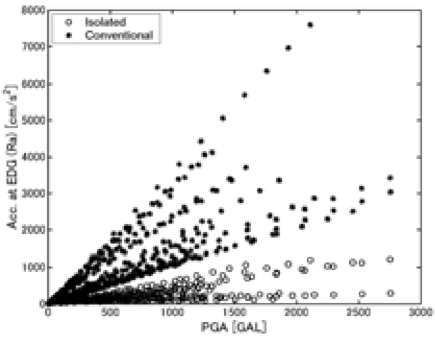

Figure 3 Relationship between PGA and acceleration response at the mass center of the conventional and isolated EDG

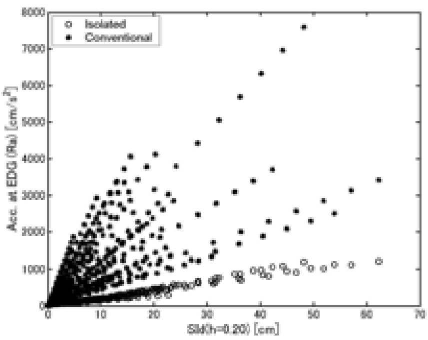

Figure 4 Relationship between SI_d and acceleration response at the mass center of the conventional and isolated EDG

Table 1 Regression curves for the responses of EDG

Type	Response	Index	α	β	E[ε]	c.o.v. of ε
Isolated	Displ.	SI_d	1.326	1.036	0.953	0.222
	Accel.	SI_d	38.31	0.694	0.952	0.226
Conven-tional	Accel.	PGA	2.758	0.887	0.864	0.397

Table 1 summarizes the regression coefficients for the responses of the isolated and conventional EDG. Substituting these values into equation (1) - (4), the probability of failure can be calculated for a given intensity of the ground motion. Finally, after converting the ground motion index from SI_d to PGA for the isolated one, the fragility curves for the isolated and conventional EDG are obtained as in Figure 5

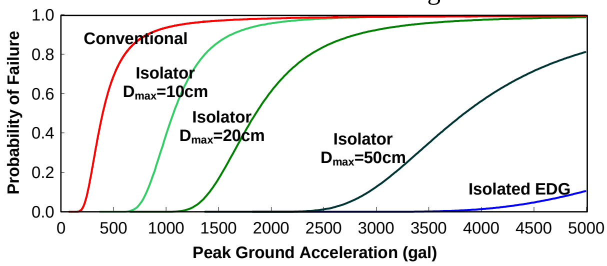

Figure 5 Fragility curves for the conventional and isolated EDG

Table 2 HCLPF values for the conventional and isolated EDG

Type	HCLPF (gal)
Conventional	192.6
Isolated, D_{max}=10 cm	687.3
Isolated, D_{max}=20 cm	1,192.6
Isolated, D_{max}=50 cm	2,470.0
Isolated, no failure at isolators	3,903.4

Table 2 shows the HCLPF (High Confidence Low Probability of Failure) values for the conventional and isolated EDG. When the maximum displacement of the isolators is limited to 10 cm, the HCLPF value increases by 3.5 times the HCLPF value for the conventional EDG.

4. Conclusion

A fragility analysis method for an isolated EDG is developed. Using the method, the fragility curves for the conventional and isolated EDG are obtained. It is demonstrated that the application of an isolation system to the EDG increases its seismic capacity significantly. It is also demonstrated that the seismic response of an isolated EDG is more sensitive to SI_d than PGA.

Acknowledgement

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