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Division V

EVALUATION OF THE EFFECT OF EARTHQUAKE GROUND MOTIONS ON INELASTIC ENERGY ABSORPTION FACTOR

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ABSTRACT

To consider the effect of earthquake ground motions on inelastic energy absorption factor, F_μ, 151 earthquake ground motion records were classified into four groups based on epicentral distance and strong motion duration and SDOF time-history analyses were performed for each group. The analysis results showed that one current approximate method based on Riddell-Newmark method underestimated the actual inelastic energy absorption factor because the method cannot effectively represent the inelastic energy absorption capacity of NPP structures founded on rock site in moderate to low seismicity regions.

Stochastic properties of the inelastic energy absorption factor were presented using the concept of up-crossing event and first-passage probability. Near-fault earthquakes measured within 30 km with short strong motion duration showed the greatest mean inelastic energy absorption factor at shorter periods less than 0.5 sec. However, due to the greater standard deviations at the periods, probability that the mean inelastic energy absorption factor will be over-estimated was higher than other earthquake groups.

For practical use of inelastic energy absorption factor, simplified bi-linear estimate was proposed. The bi-linear estimate of inelastic energy absorption factor was greater than those of previous studies as considered in the study were earthquake ground motions recorded only on rock site. Variations of the factor between earthquake groups classified by epicentral distance and strong motion duration were negligible due to similar site conditions.

INTRODUCTION

Structure deformation and corresponding inelastic energy absorption capacity beyond elastic limit state can be simply estimated by the use of an inelastic energy absorption factor, F_μ. EPRI reports (TR-103959, 1994 & TR-3002012994, 2018) provide approximate estimates of F_μ factor. One of the methods is based on Riddell-Newmark method (Riddell and Newmark, 1979) which has an advantage in that the method can directly consider the effect of earthquake ground motions on structures. Riddell-Newmark methods considered 10 earthquake ground motions recorded on rock and alluvium site. Other studies done by Nassar and Krawinkler (1991), Vidic et al. (1992), and Miranda (1993) also proposed empirical estimates of F_μ as earthquake records were accumulated. In the studies of Nassar and Krawinkler (1991) and Vidic et al. (1992), the factor was proposed based on Western United States ground motion records and Miranda (1993) considered local site conditions (rock, alluvium, and very soft soil). Considering the fact that most of NPPs are founded on rock site in moderate to low seismicity regions, there is a possibility that the previous methods can underestimate the inelastic energy absorption capacity.

An earthquake of moment magnitude 5.4 (Richter magnitude 5.8) occurred 27 km away from Wolsong nuclear power plant, in Korea in 2016. The earthquake was characterized by short strong motion duration ($D_{5\text{-}75\%}$=1.6 sec) and high-frequency components. As described in the EPRI report TR-103959(1994), inelastic energy absorption factor, F_μ, tends to decrease as strong motion duration increases. Also, NUREG/CR-3805(1986) states that high-frequency earthquake can cause greater F_μ factor of NPP structures having elastic frequencies in the 1.8 to 10 Hz range. Furthermore, high amplitude velocity pulse was observed in the earthquake causing sudden energy dissipation in a short period of time as in the studies of near-fault earthquake response (Kalkan and Kunnath, 2006 and Huang and Chen, 2000). Accordingly, simple numerical analyses were performed to evaluate the effect of epicentral distance, strong motion duration on inelastic energy absorption factor, F_μ. Approximate estimate of F_μ was presented and compared to previous studies as well as the stochastic properties of F_μ depending on the earthquake groups classified by epicentral distance and strong motion duration.

EVALUATION OF INELASTIC ENERGY ABSORPTION FACTOR

In the present study, simple non-linear (elasto-plastic) SDOF analyses were performed for several earthquake ground motions to calculate the inelastic energy absorption factor. To verify the effect of epicentral distance and strong motion duration on inelastic response of a structure, F_μ was calculated for four classified earthquake ground motion groups and the mean and standard deviation of each group were compared each other.

Earthquake ground motion records

151 earthquake ground motions were selected and classified based on epicentral distance and strong motion duration (Table 1).

Table 1: Classification of earthquake ground motions

	Group 1	Group 2	Group 3	Group 4	Group 5
Number of GMs	21	41	4	68	16
Mean {Epicentral distance} (km)	12.19	19.39	81.94	90.15	56.18
Mean {$D_{5\text{-}75\%}$} (sec)	1.96	4.91	1.31	5.42	10.80
Mean {$D_{5\text{-}95\%}$} (sec)	3.90	9.87	4.88	10.81	27.26
For all earthquake ground motions $V_{S,30}$ > 760 m/s , M_w > 4.0					

The maximum epicentral distance of Group 1 and Group 2 was shorter than 30 km (near-fault), while that of the earthquake ground motions of Group 3 and Group 4 was longer than 80 km(far-fault). The longest strong motion duration ($D_{5\text{-}95\%}$) calculated based on Arias intensity(I_A) was shorter than 5 seconds in the case of Group 1 and Group 3 earthquake ground motions, while Group 2 and Group 4 showed relatively longer strong motion duration (at least over 6 seconds). Group 5 represents 16 earthquake ground motions recorded in CEUS. For all earthquake ground motions in Table 1, shear wave velocity, $V_{S,30}$, was greater than 760m/s to minimize the effect of soil conditions. Group 3 ground motions were excluded from the study due to few records.

Evaluation of inelastic energy absorption factor

An elasto-perfectly plastic SDOF model with 5% damping ratio was assumed to verify the variation of F_μ depending on the different earthquake ground motion groups. Figure 1 shows the mean and standard deviation of F_μ for each group. Ductility demand, μ, was 2.0, 4.0, 6.0, 8.0 from the bottom in order.

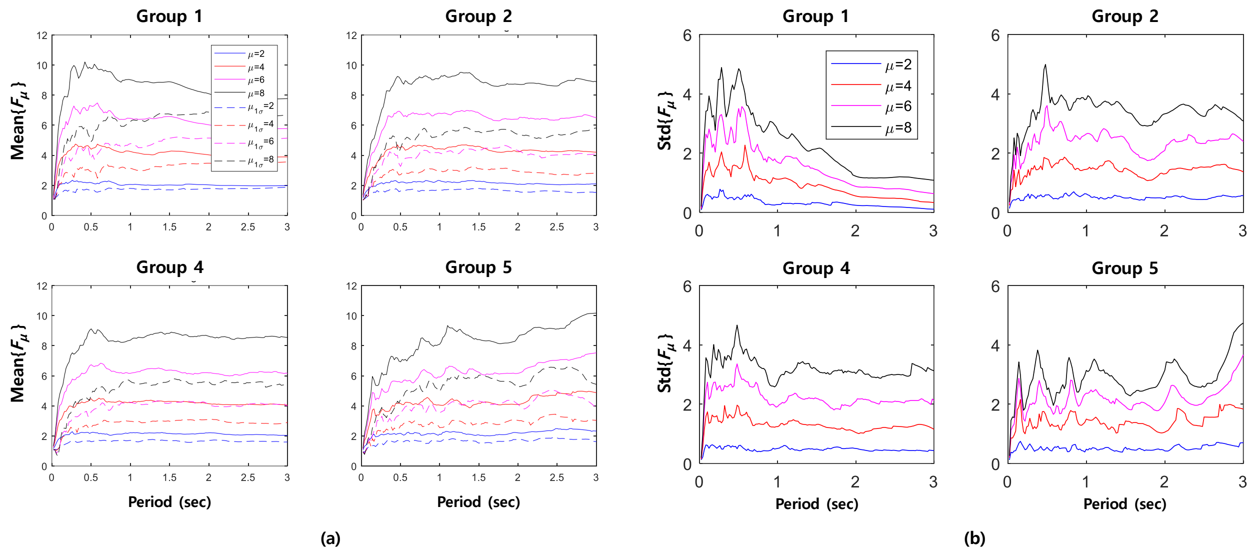

Figure 1 F_μ for different types of earthquake ground motions: (a) mean (b) standard deviation

As empirically observed in many previous studies, at very short periods, F_μ is close to one showing rigid body motion. At acceleration sensitive region, where equal energy absorption principle holds, F_μ was close to $\sqrt{2\mu - 1}$. Over velocity sensitive region, F_μ converged to μ as a structure become flexible.

Group 1 earthquakes showed the greatest F_μ in shorter periods less than 0.5 sec. Group 2 and Group 4 earthquakes showed relatively less steep increase of F_μ in shorter periods, and little difference was observed between the two groups due to the similar frequency components. On the other hand, Group 1 and Group 5 earthquakes which generally show narrow-banded frequency spectrum (high-frequency), gave greater F_μ as in NUREG/CR-3805(1986). The standard deviation of F_μ of Group 1 decreased over 0.5 sec while the other groups showed relatively constant standard deviations. Accordingly, for earthquake ground motions of shorter strong motion duration (Group 1), the reliability of the predicted F_μ increases as the natural period increases.

Stochastic properties of F_μ

To evaluate the conservatism of the mean F_μ, stochastic properties of F_μ was evaluated in three steps as follows.

Step 1. Definition of failure

The failure of a structure due to ductility demand and corresponding hysteretic energy dissipation can be defined by up-crossing events(N+) as follows.

$$\text{upcrossing event(fail)}: F_{\mu,m}(T) - F_{\mu,i}(T) > 0 \tag{1}$$

Where T is natural period of a structure, $F_{\mu,m}(T)$ is the mean inelastic energy absorption factor at period T, and $F_{\mu,i}(T)$ is the inelastic energy absorption factor of i-th earthquake ground motion at period T. The up-crossing event occur when the inelastic energy absorption factor of a certain earthquake ground motion is greater than the mean inelastic energy absorption factor. Therefore, the number of up-crossing events indicates the minimum number of natural periods of a structure where inelastic energy absorption factor was over-estimated.

Figure 2 shows an example of the mean of the cumulative number of up-crossings(N+) for the two earthquake groups. The cumulative number of up-crossing events increases as natural period increases. Both Group 1 and Group 4 earthquakes showed more than 2.5 times of up-crossing events less than 1.0 second, on average. Group 1 showed relatively rapid increase of the number of up-crossing events until the period of 1.0 second, while the number of up-crossing events of Group 4 increased gradually. This result accords with the standard deviations in Figure 1-(b) where Group 1 showed greater standard deviation of inelastic energy absorption factor in shorter periods than Group 4.

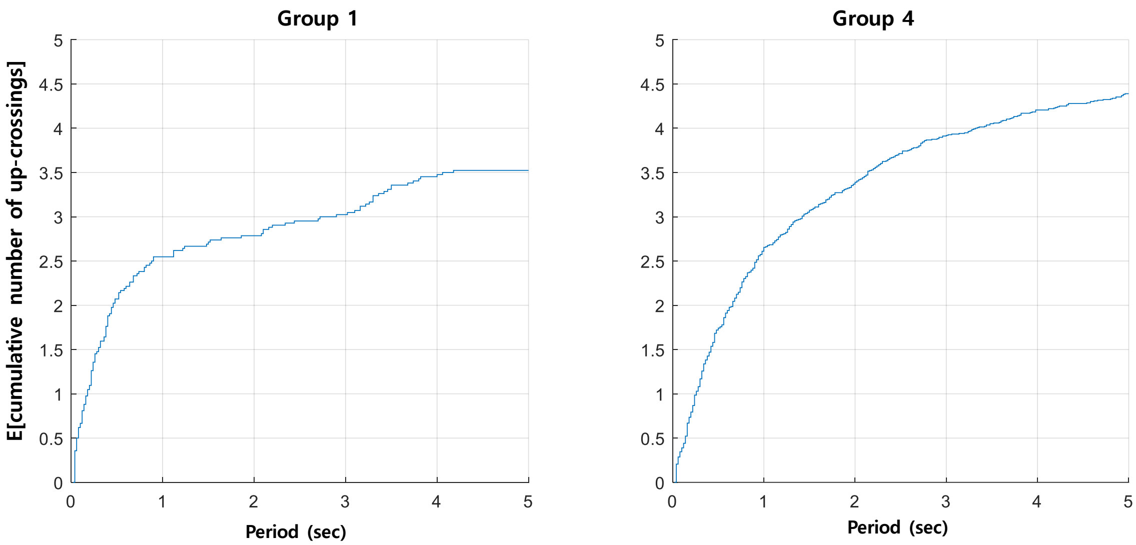

Figure 2 The mean of the cumulative number of up-crossings

Step 2. First-passage probability of F_μ

Based on the up-crossing events, or failure events, defined in Step 1, first-passage probability can be calculated as follows (Eq. (2)).

$$p_x(a;\tau) = 1 - F_x(a;0) \cdot \mathrm{P}(\text{zero upcrossings above level a in } (0,\mathrm{T}]) \quad (2)$$

Where, $p_X(a;\tau)$ is the first-passage probability of F_μ and $F_X(a;0)$ is probability of safe start. Probability of safe start was assumed to 1.0, because at period close to zero, a structure is very stiff and shows rigid body motion (elastic response) regardless of ground motions. P(zero up-crossings above level a in (0,T]) was assumed to follow Poisson process. Accordingly, first-passage probability can be given by Eq. (3) from Eq. (2).

$$\mathrm{p_x}(a;\tau) = 1 - 1.0 \cdot \exp[-\int_0^\tau \nu^+(a;T)dT] \quad (3)$$

Figure 3 shows an example of first-passage probability of F_μ. In the case of Group 1 earthquakes, the possibility that the mean F_μ over-estimates the actual F_μ derived from a certain earthquake ground motion reaches 90% at natural period of 0.5 second, while Group 4 earthquakes shows lower possibility near 0.5 second (80%).

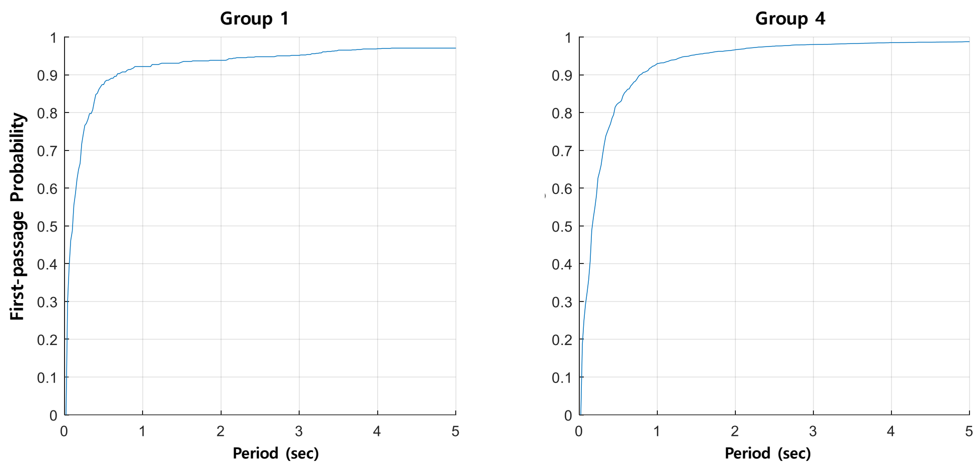

Figure 3 First-passage probability for Group 1 and Group 4

The overestimate (or unconservatism) of F_μ can be determined by applying the concept of first-passage probability. As shown in Figure 4, the number of up-crossing events and the corresponding first-passage probability decrease as the reference value decreases from the mean. For example, if mean minus one standard deviation level is used instead, the possibility of the over-estimation until 0.5 sec is about 57% for Group 1 earthquake, and about 50% for Group 4 earthquake, respectively. If mean minus two standard deviation level is used instead, the possibility is less than 5% for both groups. Depending on the purpose of the use of F_μ or the method (e.g., CDFM or SOV), the F_μ can be determined based on the first-passage probability of F_μ.

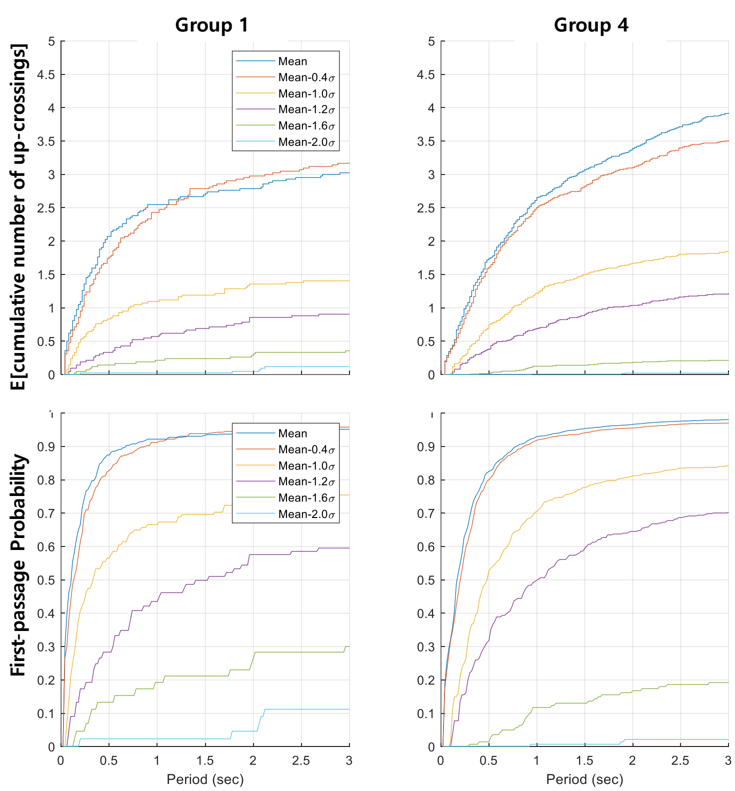

Figure 4 Number of up-crossing events and first-passage probability ranging from mean to mean minus two standard deviations (Group 1 and Group 4)

Once the first-passage probability is decided, F_μ corresponding to the first-passage probability also can be determined. Figure 5 shows a comparison of mean and mean minus one standard deviation level of F_μ. Due to the difference of standard deviations between the groups (Figure 1), the difference of mean minus one standard deviation level of F_μ between the two groups was increased.

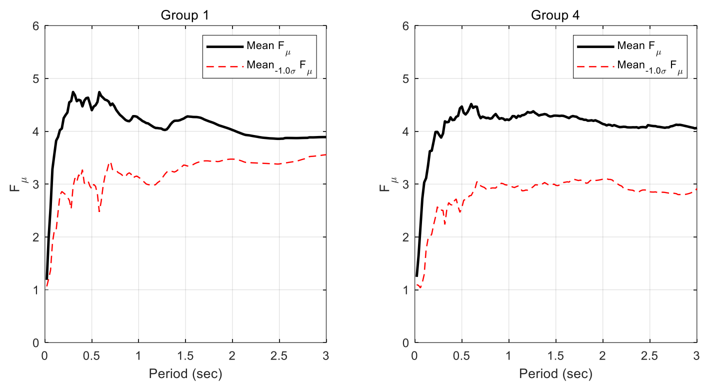

Figure 5 Mean and mean minus one standard deviation F_μ (μ=4.0)

Step 3. Approximate estimate of F_μ (optimization method)

For practical use of F_μ factor in seismic fragility analysis, approximate estimate (bilinear) using optimization method was introduced as shown in Eq. (4).

$$\mathrm{Min}\Pi = \frac{1}{2}\int_{T_u}^{T_l}\left(F_{\mu,0}(a,T) - F_{\mu,m}\right)^2 dT$$
$$\rightarrow \delta\Pi = \delta_{\mathrm{a}}[\int_{T_u}^{T_0}\left(F_{\mu,0}(a,T) - F_{\mu,m}\right)dT + \int_{T_0}^{T_u}\left(F_{\mu,0}(a,T) - F_{\mu,m}\right)dT] = 0 \quad (4)$$

Where T_l and T_u are the period of the lower and the upper bound, respectively. T_0 is the intersection point of the two linear equation. $F_{\mu,0}$ is the simplified(bilinear) estimate of F_μ and $F_{\mu,m}$ is the mean of F_μ for each earthquake group. a is the slope of the simplified bilinear equation. Figure 6 shows the approximate estimate of mean F_μ for each earthquake group (ductility demand, μ=4.0).

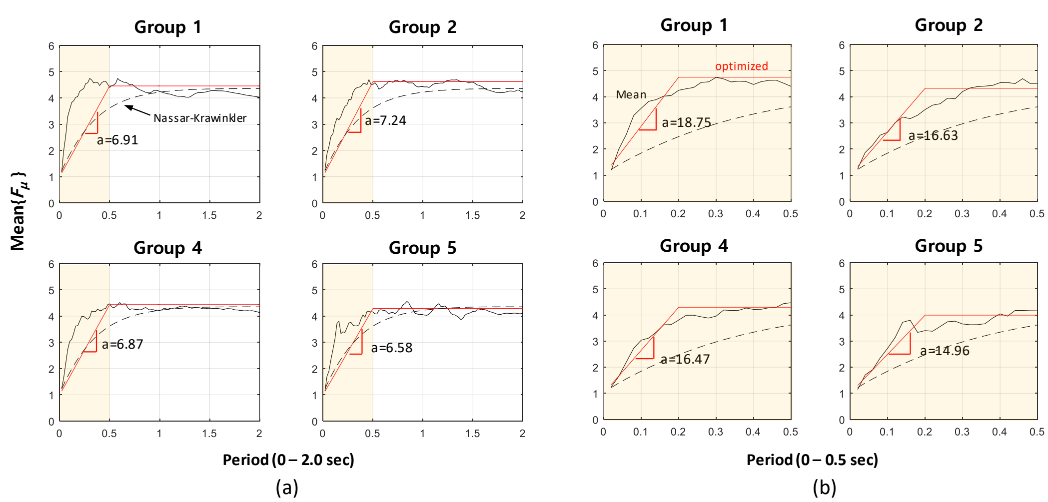

Figure 6 Approximate estimate of $F_{\mu,m}$ (μ=4.0) (a) T_l =0, T_u =2.0, (b) T_l =0, T_u =0.5

In Figure 6, the black solid line shows the mean of F_μ, $F_{\mu,m}$, the red solid bilinear line shows the approximate estimate of $F_{\mu,m}$, $F_{\mu,0}$, and the dashed line shows the estimate of F_μ proposed by Nassar and Krawinkler (1991) which gives greater estimate of F_μ than that of Riddell and Newmark (1979) as mentioned by Miranda and Bertero(1994).

In the case of upper bound period of 2.0 (Figure 6-(a)), little difference of the approximate estimate of $F_{\mu,m}$, $F_{\mu,0}$, was observed among the four earthquake groups. Due to the longer period of interest (0-2.0sec), $F_{\mu,0}$ underestimated the F_μ in the period of 0-0.5 sec. Figure 6-(b) shows the $F_{\mu,0}$ optimized for the period of 0-0.5 sec. The slope, a, in Figure 6-(b) is better matched to the $F_{\mu,m}$, and is more than two times greater than the slope in Figure 6-(a). Still, little difference was observed between the four earthquake groups. It attributes to the similar soil condition of each ground motion in this study (Rock, $V_{S,30}$ > 760m/s) and corresponding high-frequency component as mentioned in Chapter 2, NUREG/CR-3805(1986). However, considering the fact that NPP structures are generally constructed on rock site, estimation of F_μ based on previous studies (e.g., Riddell and Newmark, 1979) can under-estimate the inelastic energy absorption capacity of a structure in SOV approach of seismic fragility analysis, especially for shorter periods (< 0.5 sec).

CONCLUSION

The effect of earthquake ground motions on inelastic energy absorption factor, F_μ, and the stochastic properties were evaluated for four earthquake groups classified by epicentral distance and strong motion duration. The major findings of the present study are summarized as follows.

1. Group 1 earthquake (near-fault & short strong motion duration) showed the greatest mean F_μ in shorter periods less than 0.5 sec. However, the difference of mean F_μ between earthquake groups was negligible due to similar soil conditions (rock, $V_{S,30}$>760m/s).

2. Using the concept of up-crossing events and first-passage probability, stochastic properties of F_μ were evaluated. Accordingly, a certain level of conservatism of F_μ can be determined quantitatively and can be used in seismic risk assessment of a structure.

3. For practical use of F_μ in seismic fragility analysis, approximate estimate of F_μ was introduced using optimization method. It was found that mean F_μ based on 151 earthquake ground motions showed greater value than that of previous studies (Riddell and Newmark, 1979 and Nassar and Krawinkler, 1991). Considering the fact that most of NPPs are found on rock site, using mean F_μ based on 151 earthquake ground motions recorded on rock site can be more appropriate in seismic fragility analysis.

It should be noted that F_μ factor in this study is based on idealized elasto-perfectly plastic SDOF model and can over-estimate the actual inelastic energy absorption capacity of RC structures in NPPs which are characterized by stiffness degradation and pinched hysteresis loop. Accordingly, experimental studies of RC shear wall of NPP structures are in progress and will be incorporated in the study to evaluate more accurate inelastic energy absorption capacity based on test based post-yield stiffness ratio, ductility capacity, and hysteretic energy dissipation.

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