Seismic Fragility Analysis of RC Shear Wall with Age-Related Degradation for Different Failure Criteria

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1. Introduction

Reinforced concrete (RC) shear wall has been used various structures because it has excellent resistant capacity under seismic load. Especially shear wall system has been used at the containment and auxiliary building of nuclear power plants (NPPs) due to safety and shielding effectiveness.

The degradation of concrete is often caused by aggregate expansion and chemical damage. Degradation leads to reduction of strength and ductility. Various failure criteria must be therefore considered for seismic fragility analysis of degraded shear walls.

In this study, we deal with seismic safety of RC shear wall with age-related degradation considering different failure criteria.

2. Failure criteria for RC shear wall

2.1 Shear force failure criteria

The ultimate strength capacity of RC shear wall is a function of the material strength, the geometry of the wall, including the amount of reinforcement and reinforcement detailing. According to technical report [1], the RC shear wall of NPPs is governed by in-plane load that can result in shear friction, diagonal shear cracking, flexural reinforcement yielding. When properly designed, diagonal shear cracking is most likely failure mode in RC shear wall under seismic load. In this study the flowing equation proposed by ACI-349 [2] was used to calculate ultimate shear strength.

$$V_u = V_{conc} + V_{steel} \tag{1}$$

$$V_{conc} = \Phi\left[8.3\sqrt{f'_c} - 3.4\sqrt{f'_c}\left(\frac{h_w}{l_w} - 0.5\right) + \frac{N_A}{4 l_w h}\right] hd \tag{2}$$

$$V_{steel} = \left[a\rho_h + b\rho_v\right] f_y hd \tag{3}$$

where $f_c^{'}$ =concrete compressive strength, h_w =wall height, l_w =wall width, h =wall thickness, d = effective wall width, N_A =axial load, f_y =steel yield strength, ρ_v =vertical reinforcing steel ratio, ρ_h =horizontal reinforcing steel ratio, a,b = factors that relate the shear capacity of the horizontal and vertical reinforcement to the aspect ratio of the wall

2.2 Displacement failure criteria

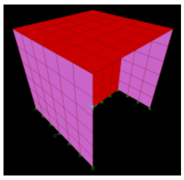
RC shear walls of NPPs are usually considered to have large capacity against seismic load because of their heavy construction. Therefore, in seismic probabilistic risk assessments, structural failure of RC shear wall is generally defined to occur when deformation are sufficient impair the functionality of attached equipment. The limit state was defined as the drift ratio equal to 4 times yield displacement, a point where significant damage to attachments and penetrations may occur.

3. Modeling of RC shear wall

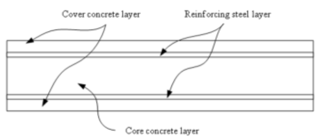
RC shear wall is an H-shaped wall with two flange walls and one center wall. Figure 1 a) represents the finite element model for seismic analysis. The layered shell element was used to model concrete and steel.

The thickness of the wall is 2' throughout. The length of the center wall is 20', the length of the flange wall is 20', and the height of the wall is 24'.

The reinforcement consist of #5(15.9mm) bars spaced at 8.5' (21.6cm) at each face in each direction resulting in a horizontal and vertical reinforcing ratio equal to 0.003. A vertical load equal to 300psi applied in the wall.



a) Finite element model



b) Multi-layered shell element

Fig. 1. Analytical model

The compressive strength of concrete increases usually due to concrete hardening. According to the SAG material DB [3] and previous research result, the compressive strength of concrete after 10 year is higher about 50% than initial strength. On the other hand, the steel section reduces due to the rust. And it was assumed that concrete spalling at cover concrete of RC shear wall occurred 0.03in/yr. A summary of analysis variables is provided in table 1.

Table 1. Variation of variables over time

Time (year)	f'$_c$ (ksi)	E (ksi)	A (in^2)	F$_y$ (ksi)	T (in)
0	4.40	3834	0.3	71.00	24.0
10	6.55	5152	0.30	71.00	23.7
20	6.87	5370	0.29	68.68	23.4
40	7.19	5587	0.27	65.24	22.8
60	7.38	5714	0.25	62.53	22.8
100	7.62	5874	0.23	57.94	22.8

(f'_c: compressive strength of concrete, E: elastic modulus of concrete, A: steel area, F_y: steel yield strength, T: wall thickness)

4. Seismic fragility analysis of RC shear wall

4.1Time-dependent seismic fragility

20 ground motion used in SAC-steel project were selected for dynamic analysis of shear wall.

Among seismic fragility parameter, the median capacity and uncertainties (e.g. aleatory, epistemic) will change as age. In this study the seismic fragility of analytical model was calculated using the equation (4). The lognormal standard deviation on randomness and uncertainty considering material strength was assumed to be 0.15.

$$f'(t) = \Phi\left[\frac{\ln(a/A_m(t)) + \beta_U(t)\cdot\Phi^{-1}(Q)}{\beta_R(t)}\right] \qquad (4)$$

where $A_m(t)$, $\beta_R(t)$, and $\beta_U(t)$, represent median capacity, randomness and uncertainty at time "t".

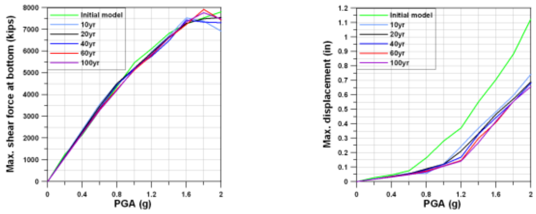
4.2 Response for different failure criteria

Because there is little different on natural frequency of initial model and other model the base shear of analytical model at a given PGA is similar each other as shown in fig. 2a). The stiffness of aged shear wall was increased by concrete hardening. The stiffness reduction of shear wall due to degradation was offset by the stiffness increase due to concrete hardening. For this reason, lateral displacement of shear wall with time was reduced as shown in fig. 2b).

4.3 Fragility curves

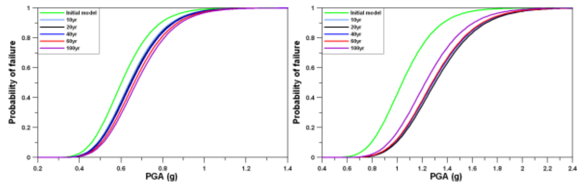
Ultimate shear strength of RC shear wall using equation proposed by ACI-349 changed due to concrete hardening and degradation. While ultimate displacement of RC shear wall reduced due to ductility reduction of steel.

When shear force is applied as failure criteria, it can be observed high confidence low probability failure (HCLPF) of RC shear wall increase. On the other hand, when top displacement is applied as failure criteria, HCLPF of RC shear wall increase until 20 year and it decrease after 40 year. HCLPF of RC shear wall using top displacement as failure criteria was higher about 1.7~1.9 times than that using shear force as failure criteria.



a) Shear force b) Top displacement

Fig. 2. Median response of RC shear wall according to failure criteria



a) Shear force b) Top displacement

Fig. 3. Fragility curve of RC shear wall according to failure criteria

5. Conclusion

The failure criteria of low-rise shear wall in NPPs was usually defined by force and displacement. In this study, seismic fragility analysis of RC shear wall was carried out using different failure criteria. It can be concluded that seismic fragility of low-rise RC shear wall was governed by shear force failure criteria. If shear wall differs from analytical model in aspect ratio, steel ratio and degradation condition, the dominant failure criteria can be changed. Although the capacity of shear wall was reduced by age-related degradation, seismic safety of shear wall with time will be seldom reduced due to concrete hardening.

Acknowledgement

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