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Investigation on Shear Strength Prediction of Nuclear Power Plant RC Walls for Seismic Probabilistic Risk Assessment

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1. Introduction

In Methodology for Developing Seismic Fragilities [1] reported by Electric Power Research Institute (EPRI), a diagonal shear cracking equation by Barda et al. [2] has been traditionally used to develop fragility curves for shear walls in Nuclear Power Plants (NPP). However, due to the limited number of experimental data when the equation was first adopted to the EPRI report, the median strength and logarithmic standard deviation by this equation was roughly determined. To investigate the accuracy of the current fragility curves for NPP shear walls, the equation was re-evaluated on the basis of a large number of database accumulated by many researchers. Other equations including ACI methods were also evaluated and compared.

2. Wall Database

A wall database consisting of 319 flanged walls was used for this study [3]. To focus on the evaluation of walls that failed by shear (i.e. diagonal shear cracking and web crushing), the walls with flexural yielding, shear-friction failure, or local failures such as re-bar buckling and fracture were excluded. Considering typical shapes of NPP walls, walls with rectangular cross-sections were not considered and the aspect ratio of walls was smaller 2.0. As a result, the number of 293 flanged walls was examined in this investigation.

3. Shear Strength Equations of RC Walls

3.1 ACI General Provision

The shear strength of walls is defined as the sum of the contributions of concrete V_c, and shear reinforcement V_s based on the work of Cardenas et al. [4] as follows.

$$V_n = V_c + V_s \tag{1}$$

$$V_c = min\begin{cases} 0.27\sqrt{f_c'}hd + N_u d/4l_w \\ \left[0.05\sqrt{f_c'} + \frac{l_w\left(0.1\sqrt{f_c'}+0.2\frac{N_u}{l_w h}\right)}{\frac{M_u}{V_u}-\frac{l_w}{2}}\right]hd \end{cases} \tag{2}$$

$$V_s = A_v f_{yh} d/s \tag{3}$$

where f_c' = compressive strength of concrete, l_w = length of wall, h = thickness of wall, d = distance from the extreme compression fiber to the centroid of longitudinal tension reinforcement (= $0.8l_w$ in ACI 349), V_u = applied shear force, N_u = axial force (positive sign in compression), M_u = applied moment, A_v = area of transverse reinforcement within spacing s, and s = center-to-center spacing of transverse reinforcement. Unless a more detailed calculation is made in accordance with Eq. (2), the concrete shear strength shall not exceed $V_c = 0.17\sqrt{f_c'}hd$. Eq. (2) corresponds to the occurrence of web shear cracking and flexural-shear cracking.

3.2 Barda Equations

The capacity given in Section 3.1 for low-rise concrete shear walls with boundary elements were known very conservative. In Methodology for Developing Seismic Fragilities [1], the shear strength of low-rise walls with diagonal shear cracking is determined using the following equations based on the work of Barda et al. [2].

$$V_u = v_u h d' \tag{4}$$

$$v_u = v_c + v_s \tag{5}$$

$$v_c = 0.69\sqrt{f_c'} - 0.28\sqrt{f_c'}\left(\frac{h_w}{l_w} - 0.5\right) + \frac{N_u}{4l_w t_n} \tag{6}$$

$$v_s = \rho_{se} f_y \tag{7}$$

$$\rho_{se} = A\rho_v + B\rho_h \tag{8}$$

where h_w = height of wall, ρ_v = vertical steel reinforcement ratio, ρ_h = horizontal steel reinforcement ratio, d' = distance from extreme compression fiber to center of force of all reinforcement in tension (=$0.6l_w$ in Barda equations), and A, B = constants as follows.

$$A = 0, B = 1\ (h_w/l_w \le 0.5)$$
$$A = \frac{-h_w}{l_w} + 1.5, B = \frac{h_w}{l_w} - 0.5\ \left(0.5 \le \frac{h_w}{l_w} \le 1.5\right)$$
$$A = 1, B = 0\ (h_w/l_w \ge 1.5)$$

3.3 ACI Seismic Provision

In special structural wall provision, the nominal shear strength recognizes the higher shear strength of walls with high strength to moment ratios.

$$V_n = A_{cv}\left(\alpha_c\sqrt{f_c'} + \rho_h f_{yh}\right) \tag{9}$$

where A_{cv} is the total sectional area, and the coefficient α_c is 0.25 for $h_w/l_w \le 1.5$, is 0.17 for $h_w/l_w \ge 2.0$, and varies linearly between 0.25 and 0.17 for h_w/l_w between 1.5 and 2.0.

3.4 Gulec et al.

Gulec and Whittaker [5] developed empirical equations to predict the shear strength of low-rise walls ($h_w/l_w \leq 2.0$) with a rectangular cross-section and flanged cross-section. In this study, the empirical equation for flanged sections was presented as follows.

$$V_{Gulec} = \frac{0.04 f_c' A_{eff} + 0.4 F_{vw} + 0.15 F_{vbe} + 0.35 P}{\sqrt{h_w/l_w}} \leq 1.25 A_{cv} \sqrt{f_c'} \quad (10)$$

where F_{vw} and F_{vbe} = the forces developed in vertical web and vertical boundary element reinforcement, respectively, and A_{eff}= the effective area for flanged walls.

4. Investigation on Shear Strength using Wall Database

Figs. 1(a)-1(d) show test strength ratios of the wall database predicted by ACI General Provision [Eqs. (1)-(3)], Barda equations [Eqs. (4)-(8)], ACI Seismic Provision [Eq. (9)], and Gulec equation [Eq. (10)], respectively. Logarithmic statistical values for the strength ratios of the wall database were also presented in Table I. The strength ratios predicted by ACI General Provision (Fig. 1(a)) were significantly conservative, particularly for small h_w/l_w, as pointed out in the EPRI report [1]. This conservatism was reduced by Barda equations (Fig. 1(b)), resulting in much smaller logarithmic median ($\mu \approx 0.20$) than that of ACI General Provision ($\mu \approx 0.60$) (Table I). However, the logarithmic standard deviation was greater than the recommendation value by EPRI report ($\beta_{EPRI} = 0.2 < \beta = 0.312$). On the other hand, μ by ACI Seismic Provision (=0.133) and β by Gulec equation (=0.29) was closer to zero than those by Barda equation ($\mu = 0.201$ and $\beta = 0.312$), respectively.

Table I: Logarithmic statistics of $V_{test}/V_{pred.}$

$V_{test}/V_{pred.}$	Logarithmic Median (μ)	Logarithmic standard deviation (β)
ACI General	0.596	0.329
Barda equations	0.201	0.312
ACI Seismic	0.133	0.336
Gulec equation	-0.213	0.290

5. Conclusions

To investigate the accuracy of the current fragility curves for NPP shear walls, design shear strength equations including Barda equation were re-evaluated using a wall database consisting of 293 flanged walls.

The predictions by Barda equations showed that the logarithmic median was 0.201 and the logarithmic standard deviation was 0.312, which did not agree with the recommended values in the EPRI report ($\mu_{EPRI} = 0$, $\beta_{EPRI} = 0.2$). Further study is required to develop a new equation to improve the accuracy of median value and to narrow logarithmic standard deviation.

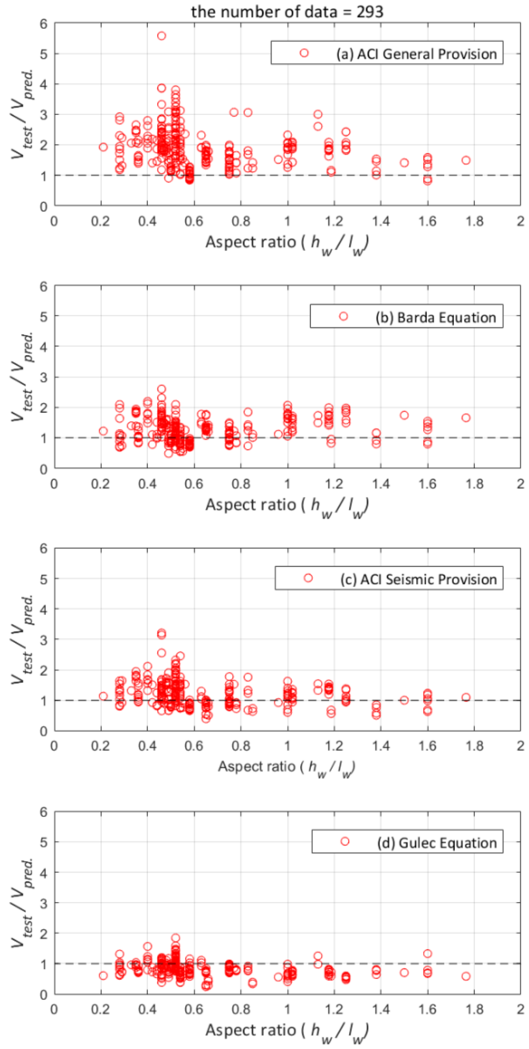

Fig. 1. Test strength divided by shear equations versus aspect ratio using a database with 293 flanged walls

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