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Design and Analysis of Rectangular Squat RCC Wall with Different Design Code

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ABSTRACT - Reinforced concrete walls with a ratio of height to length of less than two are important structural components in many commercial buildings and nearly all safety-related nuclear structures. The performance of these short (squat) walls is most important during earthquake shaking because they are designed and detailed to provide most of the lateral stiffness and strength in a building or structure. Current design provisions in codes and standards for reinforced concrete walls focus on tall (flexure-critical) walls and pay less attention to squat walls, although squat walls are far more common in practice. Squat wall failure is generally shear-related and non-ductile. The deformation modes are investigated which develop in critical region of reinforced concrete walls subjected to in elastic cyclic loading. A database of information from tests of 202 squat walls is assembled with the objective of improving the current state of knowledge on squat wall response. Predictive equations are available in literature to compute the shear strength of squat wall but the scatter in the results for a given set of design variables is large. The utility of seven predictive equations is evaluated using the data from test of 202 rectangular squat walls. The equation proposed by Wood in 1990 resulted in a median ratio of the predicted to measured strengths close to 1.0 with a small coefficient of variation. Improved empirical equations are developed for peak shear strength for rectangular walls and walls with boundary elements in a format suitable for inclusion in standards and codes of practice. These codes are used to predict the monotonic and cyclic response of squat walls. Information from the database is used to develop fragility functions, damage states, and scopes of repair for seismic performance assessment of buildings and safety-related nuclear structures incorporating squat reinforced concrete.

Key Words: Squat RRC Wall, Design Code, Peak Shear Strength, Predictive Equations,

I. INTRODUCTION

Shear Wall:

Shear walls are the vertical structural element which resists the horizontal forces acting on a building structure. Shear wall can also be defined as a wall which are reinforced & made of braced panels to carry lateral forces. Squat walls are generally grouped by plane geometry, namely, rectangular, barbell, and flanged. They provide much or all of a structure’s lateral strength and stiffness to resist earthquake and wind loadings. Code provisions for seismic design of reinforced concrete walls were drafted primarily for slender walls although most reinforced concrete walls in building structure around the world are squat. A desirable earthquake resistant philosophy for reinforced concrete walls is to suppress shear failure in design earthquake shaking. Experiments studies have shown that well designed and detailed tall (or slender) walls will yield in flexure and not fail in shear. On the contrary, squat walls are prone to shear failure that is generally associated with rapid loss of strength and stiffness under cyclic loading. The thickness of the shear wall for regular buildings can be generally in the range of 150 mm to 400 mm.

Fig. 1.1: Shear Wall in a Building

II. AIM AND OBJECTIVE

The objectives of the research project presented in this report are six-fold, namely,

1. To collect metadata and response data for all tests of squat reinforced concrete walls

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reported in the literature since the 1950s to till date.

2. To compare experimental and calculated peak shear strength by using predictive equations.
3. To evaluate the utility of equations used to predict the shear strength of squat reinforced concrete walls of different cross sections.
4. To check effect of different design parameters such as wall geometry, reinforcement ratios and applied axial loads on peak shear strength of specimens.
5. To provide best predictive equation for calculation of peak shear strength from the different codes used.

Collectively, the goal is to improve substantially the state of knowledge on the seismic response of squat (short) reinforced concrete walls.

III. LITERATURE REVIEW OVERVIEW

This chapter provides a review of the literature on experimental and analytical studies of squat reinforced concrete walls. The following section presents a summary of the experimental programs conducted on squat reinforced concrete walls.

2.2 Review of Experimental Programs

A significant number of tests of squat reinforced concrete walls were conducted from 1950 to the time of this writing in countries including the United States, Canada,Chile, England, France, Germany, Japan, New Zealand, Switzerland, Portugal, Mexico, Australia, and Taiwan. These tests were conducted mainly at the component level andmainly on walls with three types of cross sections, namely, rectangular, barbell (rectangular section with columns at wall ends), and flanged (rectangular section with cross walls at the ends).

Table 2.1 presents summary information on the experimental programs conducted on squat reinforced concrete walls without openings (solid walls).

Table 2.1 Review of experimental programs on squat reinforced concrete wall

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Program ID/ Reference	Information
Alexander / Alexander et al. (1973)	Five walls with rectangular cross-sections were loaded cyclically (quasi-static). Wall aspect ratios ranged between 0.50 and 1.50. Three walls were tested with coexisting axial forces that ranged between 0.046 $A_g f'c$ and 0.093 $A_g f'c$. Four walls included additional reinforcement at the interface between the wall-web and foundation.
Cardenas / Cardenas et. al. (1980)	Seven walls with rectangular cross-sections were tested. The moment-to-shear ratio of each wall was 1.08. None of the walls was tested with coexisting axial force. Six walls were loaded monotonically and one wall was loaded cyclically (quasi-static).
Pilakoutas / Pilakoutas (1991)	Six walls with rectangular cross-sections were tested using cyclic loading (quasi-static). The moment-to-shear ratio of each wall was 2.13. None of the walls was tested with a coexisting axial force.

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Luna et al. (2015)	Twelve large scale squat walls with rectangular cross section were tested under reversed cyclic loading and without axial load at the University at Buffalo, New York. All wall specimens' cross section measured 20.3 cm x 305 cm. All wall specimens were reinforced with two curtains of No. 13 (12.7 mm nominal diameter) mild rebars. Yield stress between 434 MPa and 462 MPa and reinforcement ratios ranging from 0.33% to 1.5% were used. Aspect ratios varied from 0.33 to 0.94 and concrete strength varied from 24.1 MPa to 53.8 MPa.
Park et al. (2015)	Seven walls with rectangular cross section and one with barbell cross section were tested. High strength reinforcing steel with yield stress ranging from 477 MPa to 667 MPa was used. Wall aspect ratio was set to 1.0 (M/Vlw=1.17), constant axial load ratio was set to 7%, and thickness was 200 mm for all the specimens. Concrete strength was varied from 46.1 MPa to 70.3 MPa.
Cheng et al. (2016)	Results are reported from reversed cyclic tests of five large-scale squat wall specimens reinforced with steel bars having specified yield strength of either 60 or 115 ksi (413 or 792 MPa). Two specimens were designed for a shear stress of $5\sqrt{fc'}$ psi ($0.42\sqrt{fc'}$ MPa) and the other three $9\sqrt{fc'}$ psi ($0.75\sqrt{fc'}$ MPa).
Hube et al. (2017)	The test program consisted on nine full scale specimens subjected to lateral cyclic displacements and no axial loads. The length and height of the walls were 1600 mm, and the aspect ratio 1.0. The thickness of the reference wall (WSL1) was 100 mm, and it was designed with a single layer of reinforcement. A welded-wire mesh with vertical and horizontal reinforcement ratios of 0.002 was used for the reference wall.

IV. SQUAT WALL DATABASE

A significant number of tests of squat reinforced concrete walls were conducted From 1950 to date in countries including the U.S., Canada, Chile, England, France, Germany, Japan, New Zealand, Switzerland, Portugal, Mexico, and Taiwan. Most of These studies have focused on the peak shear strength of squat walls and included tests On three types of cross sections, namely rectangular, barbell (rectangular section with Columns at wall ends), and flanged (I-shaped cross section). The data from the 202 Rectangular wall tests were assembled from Alexander et al. (1973), Hirosawa (1975), Cardenas et al. (1980), Hernandez (1980), Synge (1980), Endebrock et al. (1985), Maier And Thürlimann (1985), Wiradinata (1985), Pilette (1987),

Wasiewicz (1988), Huang And Sheu (1988, 1994), Lefas et al. (1990), Lefas and Kotsovos (1990), Rothe (1992), Maier (1992), Cheng et al.(1994), Cheng and Yang (1996), Mohammadi-Doostdar (1994), Pilakoutas and Elnashai (1995a,b), Hidalgo et al. (1998, 2002), Salonikios et Al. (1999), Xie and Xiao (2000), and Greifenhagen and Lestuzzi (2005), Massone/Massone (2006), Kuang/Kuang and Ho (2008), Terzioglu (2011), Carrillo Alcocer (2013), Luna et al. (2015), Cheng et al. (2016), Hube et al. (2017).

This study addresses the responses of rectangular walls only. Test specimens were selected based on The following criteria:

1) A minimum web thickness of 2 in. (51 mm)
2) Symmetric reinforcement layout
3) No diagonal reinforcement or additional wall-to- foundation reinforcement to

Control sliding shear

4) Aspect ratios (hw/lw) less than or equal to 2.0, corresponding to a maximum Moment-shear ratio (M/Vlw) of 2.13.

Table 3.1 presents summary information on the 202 rectangular walls earthquake Shaking, and nuclear safety-related structures are likely to be subject to multiple cycles of loading to peak strength in safe shutdown earthquake shaking. Building codes, Manuals of practice, guidelines and the literature provide a number of equations for the Peak shear strength of reinforced concrete walls. However, these equations significantly Vary in structure and there is substantial scatter in the peak shear strength predicted by These equations as indicated by prior studies [Wood (1990), Gulec (2005)]. The Following sections aim to assess the performances of widely used peak shear strength Equations using the 202 specimen squat wall database presented in Section 3. The

Experimentally measured peak shear strengths of the walls are compared with nominal Shear strengths predicted by seven equations:

1) Section 21.7 of ACI 318-05;
2) Section 11.10 of ACI 318-05;
3) Barda et al. (1977);
4) ASCE 43-05 [ASCE (2005)];
5) Wood (1990);
6) Mexican Code (2004); 7) IS Code 456:2000

V. PREDICTIVE EQUATIONS FOR PEAK SHEAR STRENGTH

Peak shear strength is the key variable for force- based design and performance Assessment of reinforced concrete squat walls. Accurate evaluation of the peak shear Strength of squat walls is important because conventional buildings are likely to Experience multiple deformation cycles well beyond yield in maximum

1) Section 21.7 of ACI 318-05

One equation is provided in ACI 318-05, Section 21.7(Special reinforced concrete structural walls and coupling beams) for seismic design. The equation in Section 11.10 (Special provisions for walls) is used for general design. Equation Set I (Eq. (1)) is from Section 21.7 of ACI 318-05

$Vn1 = (\alpha c \sqrt{f'c} + \rho h\ fyh)\ Aw \leq 10 \sqrt{f'c}$ (1)

Chapter 21 of ACI 318-05 imposes an upper limit of 10 psi (0.83 MPa) on peak shear stress; the limit is intended to prevent diagonal compression failure. A lower limit of 0.25% is imposed on the horizontal and vertical web reinforcement ratios. For walls with aspect ratios less than or equal to 2.0, ACI 318-05, Chapter 21 requires that the vertical web reinforcement ratio be no less than the horizontal web reinforcement ratio.

2) Section 11.10 of ACI 318-08

The procedure to predict the peak shear strength in Section 11.10 of ACI 318-08 is given by Eq. (2) through (5) (Equation Set II)

$Vn2 = Vc + Vs \leq 10 \sqrt{f'c}\ tw\ d1$ (2)

$Vc = 3.3 \sqrt{f'c}\ tw\ d1 + Nu\ d14\ lw$ (3)

$$Vc = \left[0.6\sqrt{f'c} + \frac{lw\left(1.25\sqrt{f'c} + \frac{0.2\ Nu}{lw\ tw}\right)}{\frac{Mu}{Vu} - \frac{lw}{2}}\right] \quad (4)$$

$$Vs = \frac{Av\ fyh\ d1}{s} \quad (5)$$

Per Section 11.10.6 of ACI 318-05, the shear strength provided by concrete is taken as the lesser of the values provided by Eq. (3) and (4), Eq. (4) does not apply if $Mu/Vu - lw/2 \leq 0$, and the peak shear stress is limited to $10\sqrt{f'c}$ psi (0.83 MPa). The minimum horizontal web reinforcement ratio is 0.25%. The minimum vertical web reinforcement ratio is given by

$$\rho v = 0.0025 + 0.5\,(2.5 - hw/lw)\,(\rho h - 0.0025) \quad (6)$$

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3) Barda et al. (1977)

Equation Set III (Eq. (7)) was proposed by Barda et al. 1977 to predict the peak shear strength of squat walls

$$Vn3 = \left(8\sqrt{f'c} - 2.5\sqrt{f'c}\,\frac{hw}{lw} + \frac{Nu}{4\,lw\,tw} + \rho v\,fyv\right) tw\,d2 \quad (7)$$

4) ASCE 43-05 [ASCE (2005)]

Equation Set IV is those of Eq. 4.2-4 and 4.2-3 of ASCE/ SEI 43-05 (Eq. (8) through (10)) to predict the peak shear strength of squat walls with barbells or flanges. This equation set can also be used for near-rectangular walls with small barbells or flanges when the total plan area of the wall is only slightly greater than that of the web alone. This equation set is applicable for walls with aspect ratios $hw/lw \leq 2$ and vertical and horizontal web reinforcement ratios less than or equal to 1%. If the reinforcement ratios exceed 1%, the combined reinforcement ratio ρse (calculated using Eq. (10)) is limited to 1%.

ASCE/SEI 43-05 (ASCE 2005) imposes an upper limit of $20\sqrt{f'c}$ psi ($1.66\sqrt{f'c}$MPa) on the peak shear stress.

$$Vn4 = Vn\,d3\,tw \quad (8)$$

$$Vn = 8.3\sqrt{f'c} - 3.4\sqrt{f'c}\left(\frac{hw}{lw} - 0.5\right) + \frac{Nu}{4\,lw\,tw} + \rho se\,fy1 \leq 20\sqrt{f'c} \quad (9$$

5) Wood (1990).

Equation Set V (Eq. (11)) was proposed in Wood (1990) to calculate the peak shear strength of squat walls

$$6\sqrt{f'c}\,Aw \leq Vn5 = \frac{Avf\,fy2}{4} \leq 10\sqrt{f'c} \quad (11)$$

6) Mexican Code (2004)

Section 6.5 of Complementary Technical Standards for Design and Construction of Concrete Structures (hereafter referred as NTC 2004) provides a set of semi-empirical equations, based on the modified truss analogy, to predict the peak shear strength of reinforced concrete walls. The modified truss analogy computes peak shear strength as the sum of the shear forces resisted by the concrete and the transverse (horizontal) web reinforcement. The following five equations are used to predict peak shear strength:

$$Vn1 = Vc + Vs \leq 2\, Aw \sqrt{f'c} \quad (12)$$

$$Vc = 0.85 \sqrt{f'c}\, lw\, tw \quad (13)$$

$$Vc = tw\, d2\, (0.2 + 20\, \rho vt)\, f'c \quad (14)$$

$$Vc = 0.5\, tw\, d2 \sqrt{f'c} \quad (15)$$

$$Vs = \rho h\, fyh\, Aw \quad (16)$$

7) IS CODE 456:2000 EQUATION

Nominal Shear strength

$$Vn7 = Vc + Vs \quad (17)$$

$$Vc = \tau c\, b\, d \quad (18)$$

Where bent-up bars are provided. their contribution towards shear resistance than not

Be more than half that of the total shear reinforcement.

The strength of shear reinforcement Vs shall be calculated as below:

A) For vertical stirrup:

$$Vs = \frac{0.87\, fy\, Asv\, d}{Sv} \quad (19)$$

For inclined stirrups or series of bar l bent-up at different cross-sections:

$$Vs = \frac{0.87\, fy\, Asv\, d}{Sv}(sin\alpha + cos\alpha) \quad (20)$$

Asv = total cross-sectional area of stirrup legs or bent-up ban within a distance Sv

Sv = spacing of the stirrups or bent-up bars along the length of the member

τc = nominal shear Stress

τv = design shear strength of the concrete.

b = breadth of the member which for flanged beams, shall be taken as the breadth of the web b.

fy = characteristic strength of the stirrup or bent-up reinforcement which shall not be taken greater than 415 N/mm2.

α = angle between the inclined stirrup or bent- up bar and the axis of the member

d = effective depth (taken as 0.8 lw)

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STATISTICAL ANALYSIS OF PREDICTIVE EQUATIONS

A statistical summary of the ratios of the predicted to measured peak shear strength for the 202 walls is presented in Table 5.1 for each of the seven equation sets. The ratios of predicted to measured strength tagged with an asterisk (e.g., Vn1*) present statistics for the equation set without the corresponding upper shear stress limits.

Values in columns 2 (arithmetic mean) or 3 (median or 50th percentile) in Table greater than 1.0 indicate that the predictive equation is unconservative in a mean or median sense, respectively, namely, the equation overestimates the measured peak shear strength. The last column in the table reports the percentage of unconservative predictions for the 202 specimens in the group. The standard deviation (column 4) and coefficient of variation (column 5 – COV) are also reported to provide supplemental information on the dispersion in the ratios.

	Mean	Median	Standard deviation	COV	Minimum	Maximum	Percent over predictions
Vn1/ Vpeak	1.24	1.14	0.50	0.41	0.36	3.53	66
Vn1*/ Vpeak	1.38	1.22	0.61	0.45	0.36	3.53	70
Vn2/ Vpeak	1.05	0.95	0.40	0.38	0.36	2.74	47
Vn2*/ Vpeak	1.19	1.11	0.50	0.50	0.36	2.74	56
Vn3/ Vpeak	1.35	1.30	0.44	0.33	0.53	2.96	77
Vn4/ Vpeak	1.25	1.18	0.45	0.36	0.53	2.72	67
Vn4*/ Vpeak	1.26	1.20	0.46	0.37	0.53	3.07	68
Vn5/ Vpeak	1.04	0.97	0.33	0.32	0.48	2.24	47
Vn6/ Vpeak	1.09	1.01	0.40	0.37	0.39	2.81	51
Vn6*/ Vpeak	1.39	1.24	0.63	0.45	0.39	3.60	71
Vn7/ Vpeak	0.63	0.55	0.44	0.69	0.06	2.41	15

VI. CONCLUSION

The key conclusions of this study are listed below:

1. The scatter in the values of peak shear strength predicted by the seven equations evaluated in this study is substantial. The utility of these equations is affected significantly by wall geometry.
2. The best predictions of peak shear strength (i.e., median ratio of predicted to measured peak shear strength close to 1.0 and a small coefficient of variation) are obtained using the equation of Wood (1990) for walls with rectangular cross sections. Most of Wood's (1990) estimates of peak shear strength were governed by the lower limit on wall shear stress.
3. The nominal strength equations of Chapter 11 of ACI 318-05 generally provided the most conservative (lowest) estimates of peak shear strength.
4. Mexican code equation is third most reliable equation for peak shear strength calculation after Wood's equation and equation of Chapter 11 of ACI 318-05 respectively.

5. The procedures of Barda (1977) and ASCE/SEI 43-05 consistently overestimated the peak shear strength of the rectangular walls in the database and should not be used to proportion shear walls with rectangular cross sections.
13. The 20 $\sqrt{f'c}$ psi (1.66$\sqrt{f'c}$ MPa) shear stress limit in ASCE/SEI 43-05 was achieved by very less number of walls in the database and should be revised.
14. Though overprediction value provided by equation set VII is very less, coefficient of variation is large hence this equation is not as reliable as other equations. Lower and upper limit should be imposed on the above set of equation to get
15. Vn7/Vpeak values equal to 1.

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