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An Alternative Shear Strength Equation of Reinforced Concrete Squat Walls for Ensuring the Deformation Capacity

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Abstract: Low aspect ratio reinforced concrete walls are important structural components of both conventional buildings and safety-related nuclear structures because they may provide much or all of a structure's lateral strength and stiffness to resist earthquake loadings. Building codes, manuals of practice, guidelines and standards provide a number of equations for peak shear strength of reinforced concrete walls and give reasonable predictions. However, deformation capacity is also a key factor in seismic design and these equations do not account for the factor during design. In this paper, the performance of five equation sets is evaluated using data from tests of 250 solid squat walls. According to the evaluation results, one equation set with best performance is selected for developing alternative expressions.

***Keywords:** shear strength equation, squat wall, deformation capacity, reinforced concrete*

1. Introduction

The reinforced concrete squat walls have been widely used in low-rise economic housing, conventional buildings and safety-related nuclear structures in recent years, due to their efficiency and economy. In general, these walls have a height to width ratio of 2.0 or lesser and the predominant action is shear.

Since the 1950s, many researches have studied the shear behavior of squat reinforced concrete walls [1]-[2][3][4][5]and various equations have been developed (based on the statistical analysis of the squat walls test results) and been applied in building codes, manuals of practice and guidelines to predict the peak shear strength of reinforced concrete walls[6-10]. In addition, these equations (such as ACI, ASCE/SEI , AIJ and EC8) for peak shear strength of squat walls have been evaluated and improved by researchers since shear strength is the key variable for force-based design and performance assessment. In 1900, ACI model has been evaluated by woods[10] and alternative design provisions were developed to improve the predictions of peak shear strength. Sanchez-Alejandre and Alcocer [11], based on the comparison results of seven equations for shear strength of squat walls, to study the trends of shear strength behavior and a design model for squat wall is proposed. After several years, five predictive equations (ACI, Barada, woods and ASCE) are comprehensively evaluated using data from tests of 120 rectangular walls and 247 squat walls with barbell or flange boundary elements by Gulec [12]. The results show that the best predictions of peak shear strength of rectangular squat walls and walls with boundary barbells or flanges were obtained using Wood's equation and ASCE/SEI 43-05, respectively. In 2011[13-14], improved empirical equations were developed by Gulec using the data from tests of 227 low aspect ratio walls. The equations can accurately predict the experimentally measured values of peak shear strength with low coefficients of variation.

Besides, many scholars have studied deformation capacity of shear wall. In 1999, Qian Jiaru[15] researched the shear wall deformation capacity (dominate by bending) and developed model for calculating the capacity. 6 years later, numerical analysis were conducted by Qian[16] to study the effects of axial load ratio, edge constraint length and characteristic value of stirrup content on the deformation capacity of shear wall, which is subject to bending failure. In 2008, based on the tested results of shear wall under cyclic loading, one model was proposed by Lu[17] for predicting the ultimate drift of shear wall predominant by bend. Cao et al[18]., compared test results of seismic performance for common shear wall and shear wall with diagonal bracing, and found that adding diagonal bracing to member can effectively improve the deformation capacity of squat wall. The cyclic loading test of Six shear walls was conducted by Alessandro Dazio[19]. According to the results, it is concluded that reinforcement ratio of edge constraint area and constraint form will significant affect the deformation capacity of high aspect ratio RC walls. Furthermore, the strain limits value of material corresponding to different limit states were derived by Alessandro Dazio. John.H Thomsen and John.W[20]. Wallace applied experiment result to verify validity of calculation method of appraising deformability of shear wall.

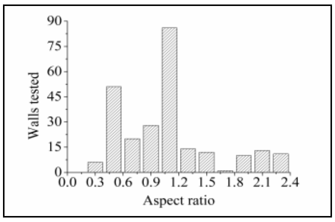
It can be clearly seen that the above predictive equations are able to reasonably predict the peak shear strength of squat reinforced concrete walls. The deformation of walls is rarely focused by researchers, especially squat walls. In the modern seismic design concept[21], however, an adequate design of structural wall requires that the wall should have not only enough bearing capacity but also deformation capacity to resist the horizontal seismic loading. According to the previous studies, many researchers only focus their study on the former (load carrying capacity) but ignored the latter. For better understanding of the predictive equations for seismic shear strength of squat RC walls, it is necessary to further evaluate performance of the equations from the aspect that whether the equations can ensure the deformation capacity of squat walls.

In this paper, the results of tests of 266 squat walls are compiled and reduced to evaluate the performance of five equation sets, which are widely used to predict the shear strength of reinforced concrete walls (1),2),3),4),5)). The walls in the database are rectangular, barbell and flanged. One equation is identified as the most reliable of the five. Based on the most reliable equation set, as well as the trends that relevant parameters effects, an alternative expressions that provide improved the ability to assurance deformation capacity are proposed.

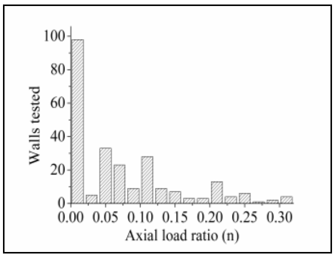
2. Experimental data of RC walls

Aimed at assessing the adequacy of shear strength equations from the aspect of assurance deformation capacities, a database with relevant information from tests was constructed. Data from 266 tests available in the literature were gathered, revised and organized. Database includes tests carried out in U.S, Canada, New Zealand, China, England, Japan and Mexico[22-56]53]56]. 56]The walls in the database with three different cross sections, namely, rectangular, barbell, and flanged. The population of test specimens were considered in this study based on the following criteria: 1) the lateral load was applied statically in the plane of the wall; 2) the walls were reported to have failed in shear; 3) symmetric reinforcing bar layout; 4) no diagonal reinforcement or additional wall-to-foundation reinforcing bar to control sliding shear and 5) aspect ratio of less than or equal to 2.0. The data for the 16 walls of the 266 that did not meet all of the aforementioned criteria were excluded from the analysis that is presented herein.

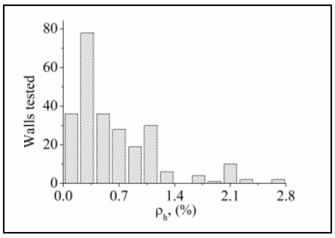
The frequency distributions of walls' summary information are shown in fig 1. The aspect ratio of walls ranged from 0.2 to 2.39; Axial load, in addition to self weight of the walls, was applied 152 specimens with axial load ratio(n) varying from 0.03 to 0.3; walls with concrete compressive strengths varied from 13.66 to 66.33MPa; In addition, the web thickness ranged from 45 to 200 mm; Both the horizontal and vertical web reinforcement ratio ranged between 0.00 and 0.024; Boundary element reinforcement was provided in 217 of the 250 walls with boundary element reinforcement ratio up to 0.133. Eleven of the 250 walls in the dataset had neither horizontal nor vertical web reinforcement. Six walls with only horizontal web reinforcement and four walls with only vertical web reinforcement were tested. The reported yield stress of reinforcement ranged between 203 to 667MPa.



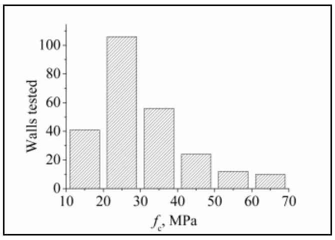
(a) Wall aspect ratio



(b) Normal stress/compressive strength ratio



(c) Horizontal web reinforcement ratio



(d) Concrete compressive strength

Fig. 1 *Histograms of the main input parameters of walls studied*

3. Equations for calculating shear strength of squat reinforced concrete walls

Five code equations for shear strength provided in GB 50010-2010 (China building code), Chapter 18 of ACI 318-14 (ACI Committee 318 2014), Chapter 11 of ACI 318-14 (ACI Committee 318 2014), EC08 (European code), and CSA A23.3-04 (Canada code) are used to evaluate the ability to ensure deformation capacity of 250 squat walls. The five equations for predicting shear strength of RC walls consider nominal strength to be the addition of the contributions of concrete Vc and steel reinforcement within the web Vs.

Equations set I is that of Eq. 11.7.4 of GB 50010-2010 (eq. (1)) [8]to calculate the peak strength of squat walls. In the equation Vc depends on the aspect ratio λ and axial load *N*.The larger the aspect ratio is, the lower the concrete contribution is. In contrast, with the increase of axial load, the concrete contribution is increased. An upper limit of $(0.15\beta_c f_c)/\gamma_{RE}$ (peak shear stress) is imposed in equation (1); the limit is intended to prevent diagonal compression failure. The reinforcement ratio of horizontal and vertical web reinforcement must be more than 0.3%.

$$V_1 = \frac{1}{\gamma_{RE}}[\frac{1}{\lambda - 0.5}(0.4 f_t bh_0 + 0.1N\frac{A_w}{A}) + 0.8 f_{yv}\frac{A_{sh}}{S}h_0] \quad (1)$$

$$\le \frac{1}{\gamma_{RE}}(0.15\beta_c f_c bh_0)$$

$$V_{c1} = \frac{1}{\lambda - 0.5}(0.4 f_t bh_0 + 0.1N\frac{A_w}{A}) \quad (2)$$

$$V_{s1} = 0.8 f_{yv}\frac{A_{sh}}{S}h_0 \quad (3)$$

Where γ_{RE} is equal to 0.85; λ equal to 1.5 for $\lambda \le 1.5$, 2.2 for $\lambda \ge 2.2$, and varies linearly for $1.5 \le \lambda \le 2.2$; f_t is assumed equal to $0.1 f_c$; h_0 is assumed equal to $0.8\, l_w$; A_w is the area of web cross section, it is equal to A for rectangular wall; The range of $\frac{A_w}{A}$ is (0,1); β_c equal to 1.0 for $f_c \le 50MPa$, 0.8 for $f_c \ge 80MPa$, and varies linearly for $50 \le f_c \le 80$.

ACI 318-14[6] provided two semi-empirical equations to calculate the peak shear strength of reinforced concrete walls. The two equations are based on the modified truss analogy approach. One equation is provided in ACI 318-14, section 18 for seismic design. The equation in section 11, special provisions for walls, is used for general design. Equation set Ⅱ(eq.(4) is from section 11 of ACI 318-14. Equation set Ⅱ imposes an upper limit of $0.83\sqrt{f_c^{'}}$ on peak shear stress. A lower limit of 0.25% is imposed on the horizontal and vertical web reinforcement ratios. The equation set is shown in the following four equations:

$$V_2 = V_c + V_s \le 0.83 A_{cw}\sqrt{f_c^{'}} \quad (4)$$

$$V_{c2} = (0.274\lambda^{'}\sqrt{f_c^{'}} + \frac{N_u}{4 l_w d})bd \quad (5)$$

$$V_{c2} = [0.05\lambda^{'}\sqrt{f_c^{'}} + \frac{(0.104\lambda\sqrt{f_c^{'}} + 0.2\frac{N_u}{l_w h})}{\frac{M_u}{V_u l_w} - \frac{1}{2}}]bd \quad (6)$$

$$V_{s2} = \frac{A_v f_{yt} d}{S} \quad (7)$$

Where d is assumed equal to $0.8\, l_w$; λ' equal to 1.0 in the paper.

The procedure to calculate the shear strength in section 18 of ACI 318-14, Equation set Ⅲ, is shown in the following. The equation ignored the effect of axial load, the main reason is that axial load applied on the cross section of shear wall is continues changed during the seismic excitation. However axial load benefit for shear strength, for security consideration, the seismic design of equation sets Ⅲ ignores the effect of axial load.

$$V_3 = A_{cw}(\alpha_c\lambda'\sqrt{f_c^{'}} + \rho_t f_y) \le 0.83 A_{cw}\sqrt{f_c^{'}} \quad (8)$$

α_c is equal to 2.0 for aspect ratio ≥ 2.0, 3.0 for aspect ratio ≤ 1.5, and varies linearly for $1.5 \le \lambda \le 2.2$.

Equation set Ⅳ is those of eq. (9) through (11) (EC08) [7] to predict the shear strength of squat walls. Differently from GB and ACI, the calculate equation includes both vertical and horizontal reinforcement. Besides, this equation applies variable angle truss model to predict carrying capacity and gives lower limit value of shearing force.

$$V_4 = V_{c4} + V_{s4} \quad (9)$$

$$V_c = [C_{Rd,c}k(100\rho_l f_{ck})^{\frac{1}{3}} + k_1\sigma_{cp}]b_w d \quad (10)$$

$$\ge (v_{\min} + k_1\sigma_{cp})b_w d$$

$$V_{s4} = \frac{A_{SW}}{s} z f_{ywd}\cot\theta \quad (11)$$

$$v_{\min} = 0.035 k^{\frac{2}{3}} f_{ck}^{\frac{1}{2}} \quad (12)$$

Where $C_{Rd,c}$ equals to $0.18/\gamma_c$; γ_c is equal to 0.15; $k = 1 + \sqrt{\frac{200}{d}} \le 2.0$; k_1 is 0.15; z is assumed equal to 0.9d; The recommended limits of $\cot\theta$ is from 1 to 2.5; In this paper, the value of $\cot\theta$ is assumed equal to 1.

Equation set Ⅴ is shear strength equation of CSA A23[9]. The equation set also adopts variable angle truss model to calculate peak shear strength. The expression is shown in equation (13). In equation sets Ⅴ, the form of equation is similar to that of formula group III. The effect of axial compressive ratio on shear capacity is also ignored.

$$V_5 = \phi_c \lambda' \beta \sqrt{f_c'} b_w d_v + \frac{\phi_s A_v f_y d_v \cot\theta}{S} \qquad (13)$$

Where ϕ_c is resistance factor of concrete, which is equal to 0.65; β is a factor accounting for the shear resistance of cracked concrete and taken as 0.18; $\phi_s = 0.18$; In equation (13), the value of θ is equal to 45°for axial load ratio ≤ 0.1, 35°for axial load ratio ≥ 0.2, and varies linearly for axial load ratio varied from 0.1 to 0.2.

The symbols of all the five equations are listed in table 1.

Table 1.*Symbols of shear strength equations*

Symbol	Meaning	Symbol	Meaning
γ_{RE}	the seismic action coefficient	λ	aspect ratio coefficient
f_t	tensile strength of concrete	f_c	the compressive strength of prism concrete
b	thickness of wall	h_0	the effective depth of cross section
l_w	the length of wall	A	the gross area of cross section
A_w	the area of web cross section	β_c	the effect coefficient of concrete
S	spacing of horizontal distribution bar	A_{sh}	the area of horizontal reinforcement within distance of S
d	effective depth of cross section	A_v	the area of horizontal reinforcement within distance of S
N_u	axial load	M_u	moment at section
V_u	shear force at section	λ'	modification factor to reflect the reduced mechanical properties of lightweight concrete relative to normalweight concrete of the same compressive strength
f_c'	compressive strength of cylinder concrete	A_{cw}	the area of wall bounded by web thickness and wall length
α_c	aspect ratio coefficient	ρ_t	horizontal reinforcement ratio
$C_{Rd,c}$	Determined by γ_c	γ_c	Concrete partial coefficinets
k_1	A coefficient considering the effects of axial load forces on the stress distribution	σ_{cp}	axial compress stress
f_{ck}	compressive strength of cylinder concrete	ρ_l	reinforcement ratio for longitudinal reinforcement
z	lever are of internal forces	θ	the angle between concrete compression strut and the wall axis perpendicular to the shear force
A_{SW}	ross-sectional area of shear reinforcement within S	f_{ywd}	the yield strength of shear reinforcement
ϕ_c	resistance factor of concrete	β	a factor accounting for the shear resistance of cracked concrete
b_w	the web thickness of wall	d_v	effective depth of the section of wall
ϕ_s	resistance factor for non prestressed reinforcing bars	A_v	the area of tranverse reinforcement within s
f_y	yield strength of tranverse reinforcement		

In the study, one of the aims was made to evaluate the performance of calculating expressions for the shear strength of squat RC walls from the aspect of assuring deformation capacities. To do this, firstly, average compressive strength of concrete was used in shear strength equations and the compression strength of concrete was standardized. Since f_c is the compressive strength of prism concrete, f_c' is, however, compressive strength of cylinder concrete. According to the reference **Error! Reference source not found.**, the f_c' can be similarly translated as f_c using equation (14):

$$f_c^{'} = 1.194 \times f_c \qquad (14)$$

Secondly, all five equation sets were normalized through the transformation of shear strength calculating expressions. During transformation, the Shear-Bearing Capacity (V_1, V_2, V_3, V_4 and V_5) were expressed by shear-compression ratio (v / f_c) and the horizontal steel reinforcement ratio was transformed into horizontal reinforcement characteristic value ($\rho_t f_y / f_c$), Where v is shear stress. After being normalized, both the shear-compression ratio and horizontal reinforcement characteristic value of all the equation sets were varied between (0,1). The normalized results of the five equation sets are listed in table 2.

In table 2, the equation of horizontal reinforcement ratio (ρ_{sh} for sets I and Ⅳ, ρ_t for sets Ⅱ and Ⅲ, ρ_h for sets Ⅴ) are shown in equation (15).

$$\rho_h = \frac{A_{sh}}{bS} \qquad (15)$$

The symbols' interpretation of equation (15) are listed in table 1

Table 2.*Normalized equation for calculating the shear strength of RC squat walls*

Model	Equation sets	Normalized expression
GB 50010-2010	I	$\frac{V_1}{f_c b h_0} = \frac{0.8\rho_{sh} f_{yv}}{f_c} + \frac{1}{10\times\gamma_{RE}}[\frac{1}{\lambda-0.5}(0.4+\frac{n}{0.8}\times\frac{A_w}{A})]$
ACI 318-14,Ch 18	Ⅱ	$\frac{V_2}{f_c hd} = \min\begin{cases} \rho_t \frac{f_{yt}}{f_c} + \frac{0.2994\lambda^{'}}{\sqrt{f_c}} + \frac{n}{4} \\ \frac{\rho_t f_{yt}}{f_c} + \left[\frac{0.0546\lambda^{'}}{\sqrt{f_c}} + \frac{0.1136\lambda}{(\frac{M_u}{V_u l_w}-0.5)\sqrt{f_c}} + \frac{0.2n}{(\frac{M_u}{V_u l_w}-0.5)}\right] \end{cases}$
ACI 318-14,Ch 11	Ⅲ	$\frac{V_3}{f_c hd} = \frac{0.0906\alpha_c \lambda^{'}}{\sqrt{f_c}} + \frac{\rho_t f_y}{f_c}$
EC08	Ⅳ	$\frac{V_4}{f_c d b_w} = \min\begin{cases} (0.9\cot\theta)\frac{\rho_{sh} f_{ywd}}{f_c} + \left[\frac{0.0406k^{\frac{3}{2}}}{(f_c)^{\frac{1}{6}}} + k_1 \times n\right] \\ (0.9\cot\theta)\frac{\rho_{sh} f_{ywd}}{f_c} + \left[\frac{C_{Rd,c}k(119.3\rho_l)^{\frac{1}{3}}}{(f_c)^{\frac{2}{3}}} + k_1 \times n\right] \end{cases}$
CSA A23	Ⅴ	$\frac{V_5}{f_c b_w d_v} = \cot\theta \frac{\rho_h f_y}{f_c} + \frac{1.0922\phi_c \lambda^{'}\beta}{\sqrt{f_c}}$

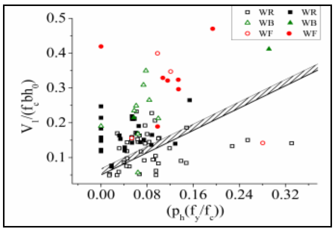
4. Performance evaluation of existing shear expressions

The above equation sets were analyzed to test their performance from the aspect of assuring the deformation capacity of squat RC walls. For this, the performances of each shear expression were correlated with the collected experimental results described in section 2. In order to assess the performance of squat wall, 1/120 drift angle demand during seismic excitation was selected as the criteria.The criteria was determined according to the code of "Technical specification for concrete structures of tall building". In the code the drift limits value of frame-shearwall structure and shearwall structure are 1/100 and 1/120 respectively. The paper mainly focuses on the performance of shear strength equations of squat walls in shearwall structure, so 1/120 was chosen as criteria. If ultimate drift angle of experimental results (the ultimate drift angle is determined when the squat walls bearing capacity falls to 85% of the peak bearing capacity) greater or equal to the criteria (1/120), the deformation capacity of the wall satisfy the requirements; otherwise the wall dissatisfy the requirements. To assess the performance of squat walls accurately, choosing correct parameters that affect the performance is important. According to the normalized results of five equation sets in table 1, it can be seen that most codes consider the influence of axial load ratio and aspect ratio on shear capacity. Besides, reference [20] applied diagonal compression field theory to simulate squat wall. The simulation results indicate that aspect ratio and axial compressive ratio will significant affect the deformation capacity of squat wall. Thus, the above two factors were selected as the relevant parameters in the research. The database of 250 squat walls was divided into three groups with axial load ratio and aspect ratio as variables, respectively. Due to the ultimate drift angle of almost walls, that aspect ratio larger than 1.5, can reach 1/120, this paper will not evaluate performance of the equation sets in the region. The database was equally divided into three groups according to distribution scope of relevance parameters (axial load ratio and aspect ratio) and distribution frequency of specimens. The grouping result is listed in table 3.

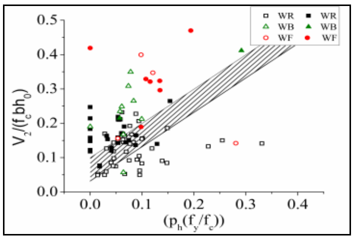
***Table 3** Grouping results*

	Axial load ratio	Aspect ratio
Group 1	$n=0$	$0<\lambda\leq 0.6$
Group 2	$0<n\leq 0.15$	$0.6\leq\lambda<1.0$
Group 3	$0.15<n\leq 0.3$	$1.0\leq\lambda<1.5$

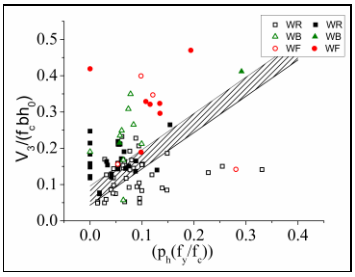
Comparison for the five equation sets when axial load equal to 0 and aspect ratio varied from 0 to 0.6 are shown in fig.2 and 3, respectively. In the figures, empty marks represent deformation capacity of walls satisfies the deformation demands (1/120); solid marks are for deformation capacity dissatisfies the deformation demands. Rectangular markers, triangle markers and circle markers represent rectangle (WR), barbell (WB) and flange (WF) cross section of walls, respectively. The bounds of shadow area were defined by the upper and lower bound limits of each equation sets in the figure. For axial load parameters, the upper bound of each equation sets was obtained by assuming the value of aspect ratio and compression strength of concrete (f_c) is equal to 0.46 and 60.3 (MPa), respectively; the lower bounds were determined by assume aspect ratio and compression strength of concrete (f_c) is equal to 1.5 and 13.66 (MPa), respectively. Similarly, the upper bound for aspect ratio parameters is defined by assuming axial load ratio and compression strength of concrete equal to 0.3 and 60.3(MPa), respectively; The lower bound is calculated by assuming axial load ratio and compression strength of concrete equal to 0 and 13.66(MPa), respectively. All the parameters' value to calculate the bound limits of equation sets is determined according to maximum and minimum value bound of basic information distribution of database (in fig.1.)



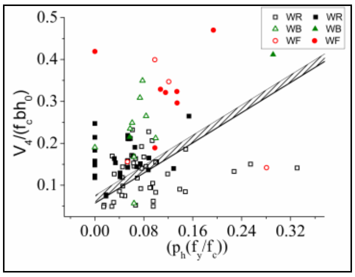
(a) GB 5001-10



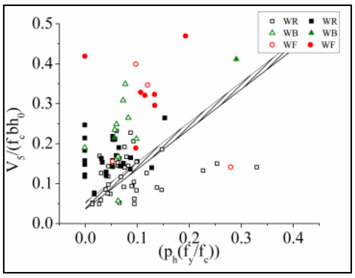
(b) ACI 318-14, Ch 11



(c) ACI 318-14, Ch 18



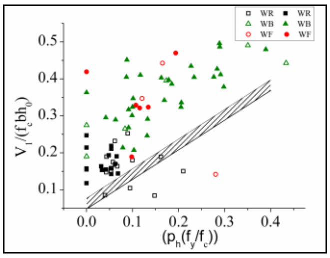
(d) EC 08



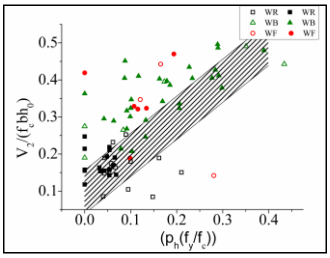
(e) CSA A23

***Figure 2.**Comparison of measured results and five equation sets (n=0)*

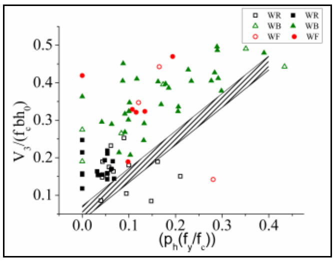
Both in figure 2 and 3, the performance of the five equation sets is evaluated by the percent of numbers of solid marks below upper bound line. The lower the percent is, the better the performance is. The comparative analysis of the percent of the five equation sets is conducted by means of statistic parameters such as mean, maximum and minimum. If all the solid marks are above the upper bound line, which means that the percent is equal to zero and the shear strength equation set has the best performance. Otherwise, if all the solid markers are below upper bound line, the percent is equal to 1 and the shear strength equation set has the worst performance.



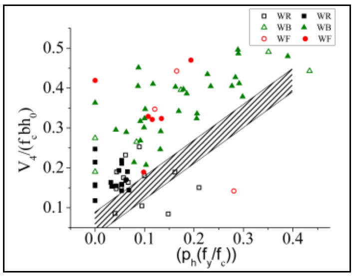
(a) GB 5001-2010



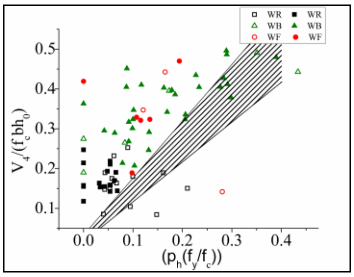
(b) ACI 318-14, Ch 11



(c) ACI 318-14, Ch 18



(d) EC 08

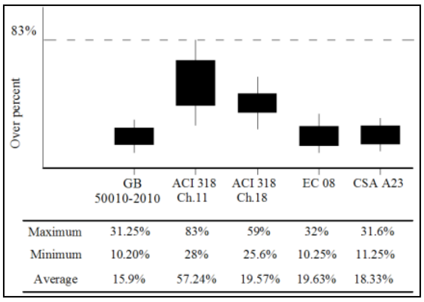


(e) CSA A23

Figure 3.*Comparison of measured results and five equation sets (aspect ratio=0-0.6)*

Maximum and minimum, as well as average of the percent of six groups' (three groups for axial load parameters and the other for aspect ratio parameters) solid marks below upper bound line are compared in fig.3 for walls in database. Results were derived from calculations similar to those that led to the development of fig.3. In the graph, minimum and maximum percents correspond to the lower and upper ends of the vertical line, respectively. Average value of percent is related to the height of the marker. It is readily apparent that the largest maximum percent corresponda to equation set Ⅱ. Results for equation sets Ⅰ,Ⅲ,Ⅳ and Ⅴ are comparable. Furthermore, the average values of percent in graph 3 are smaller for equation set Ⅰ. The average percents of equation set Ⅱ (ACI 318-14, Ch 11), EC 08 and CSA A23 were 57.24%, 19.63% and 18.33%, respectively. It also can be observed that the average values of percent in graph 3 for equation set Ⅰ are smaller than others.

Based on the comparison results, it is indicate that equation set Ⅰ is the beste performance of the five because the average value for the equation set is closer to 0% and the maximum and minimum values are both relatively small. In all cases, minimum and average percent were larger than 10%, considerable insecurity of the equation sets assuring deformation capacity still exists. According to these conclusions, it was deemed necessary to develop a alternative expression (based on the equation set Ⅰ) that would better assure the deformation capacity of squat walls.



	GB 50010-2010	ACI 318 Ch.11	ACI 318 Ch.18	EC 08	CSA A23
Maximum	31.25%	83%	59%	32%	31.6%
Minimum	10.20%	28%	25.6%	10.25%	11.25%
Average	15.9%	57.24%	19.57%	19.63%	18.33%

Figure 4.*Statistical values of over percent*

5. Alternative expressions for shear strength based on deformation capacity

As indicated previously, the research reported herein aimed at better understanding of the performance (from the aspect of deformation capacity) of existing shear strength expressions for RC squat walls, as well as developing an alternative expressions for such elements. In the previous section the performance of each equation sets was evaluated. Evaluation results indicate that equation sets Ⅰ (GB 50010-2010) has better performance than others. Based on equation set Ⅰ, as well as trends observed (axial load and aspect ratio effects), an alternative formulation for shear strength that improved the performance of deformation capacity is proposed.

5.1. The transformed form of equation set Ⅰ

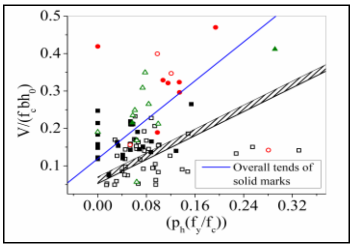
For developing the alternative expression according to equation set Ⅰ, it is necessary to make the functional form of the equation clear. After being normalized, the equation set Ⅰ is shown in table 2. Due to the horizontal and vertical coordinates of figure (e.g. figure 2) of evaluation performance in section 4 respectively represents the horizontal distribution bar and shear compression ratio, thus, $\frac{\rho_{sh} f_{yv}}{f_c}$, $\frac{V_1}{f_c b h_0}$ (equation set Ⅰ) are independent variable and dependent variable of equations, respectively. In addition, the effects of axial load and aspect ratio on equation sets Ⅰ can be acted as constant, so this equation set can be regarded as a linear function. Its expression can be simply expressed as follows:

$$y = Kx + B \qquad (14)$$

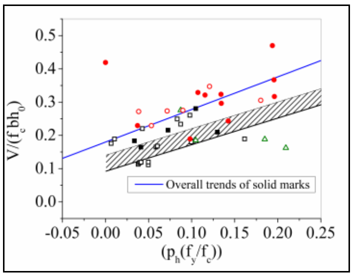
Where y is corresponding to $\frac{V_1}{f_c b h_0}$; K is reduction factor (=0.8) of horizontal reinforcement characteristic value $\frac{\rho_{sh} f_{yv}}{f_c}$; x is $\frac{\rho_{sh} f_{yv}}{f_c}$ and B is relevant with axial load and aspect ratio. For safe consideration, the value of $\frac{A_w}{A}$ is assumed equal to 1 in the research.

Based on the form of equation (14), two ways can be used to improve the performance of the equation. First of all, modify the reduction factor K; secondly, modify the contribution of B. However, the comparison of equation (14) and trends of solid marks with increase of $\rho_{sh} f_{yv} / f_c$ (shown in fig. 5) indicate that, in general, the reduction factor K of equation set I is no more than the overall trends. That means the reduction factor is conservative and second method (adjust B) should be used to improve the performance of equation (14). As previous description indicate that B is relevant with two parameters (axial load ratio (n) and aspect ratio (λ)). For improving the performance of equation (14) by modifying the contribution of B, it is necessary to research the relevance between B and the two parameters.

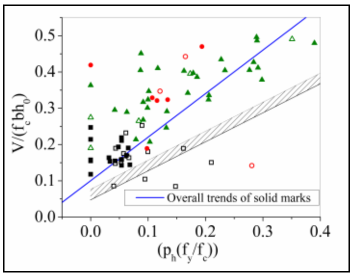
In this paper, the relevance of B with the two parameters is assumed as $B = B_n \times B_\lambda$. B_n and B_λ is the function of axial load ratio(n) and aspect ratio(λ), respectively. In addition, the two functions are assumed independent. The steps of improving B are as follows: (1) based on equation set I, keep B_λ unchanged, calculate modification value corresponded to B_n under action of different axial load ratios, then fit function B_n with this independent variable. (2) in equation set I, B_n is unchanged, derive corresponding B_λ modification value with aspect ratio, and fit B_λ. (3) make B_n and B_λ fit respectively in step (1) and (2) multiply to get final modification function $B = B_\lambda \times B_n$. The two functions (B_n and B_λ) will be separately fitted in the next two sections.



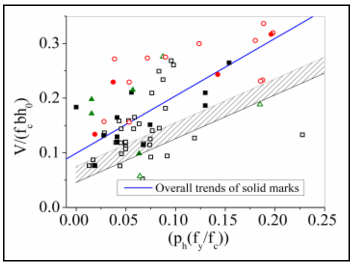
(a) n=0



(b) n=0.15-0.3



(c) $\lambda = 0 - 0.6$



(d) $\lambda = 1.0 - 1.5$

Figure 5.*Trends comparison of solid mark and equation set I*

5.2. Effect of axial load on B_n

Code equations for shear strength acknowledge the contribution of axial load by adding a term that is a function of the axial load stress. In addition, axial load can also affect the deformation capacity of walls. The comparison of equation set I with solid markers are shown in fig.1 (a), based on previous analysis improving the performance of equation set I should adjust the contribution of B. For improving the performance, the upper bound line of equation set I in fig.1 (a) should be shifted a distance by modifying B_n. After shifting, all solid marks above the upper bound line are shown in fig.6. In the case (n=0), the value of B_n is 0.033. Similar method was used to obtain the value in different axial load ratio (n=0.075, 0.15, 0.22 and 0.3). B_n's value is plotted against axial load ratio in fig 7. In the graph, Rhombus solid marks represent the value of B_n. Also plotted in the graph it is simple linear function developed for the trends of B_n vary with axial load ratio. The Matlab commercial software was used to fit the linear function in figure 7. The fitting function is given in equation (15).

$$B_n = 0.23333\times n + 0.025 \qquad (15)$$

Combining Eq.(14) and equation set Ⅰ, the improved function by fitting B_n are given as:

$$\frac{V_1}{f_c b h_0} = \frac{0.8\rho_{sh} f_{yv}}{f_c} + B_\lambda(0.2333\times n + 0.025) \qquad (16)$$

In Eq.(16), $B_\lambda = 0.1176/(\lambda - 0.5)$ is the same as corresponding function terms of equation set Ⅰ.

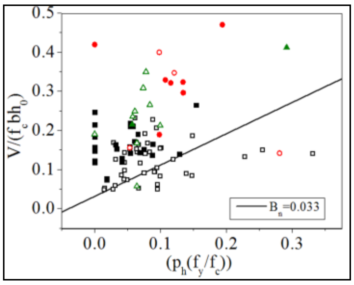


Figure 6.*Comparison results of* $B_n = 0.033$

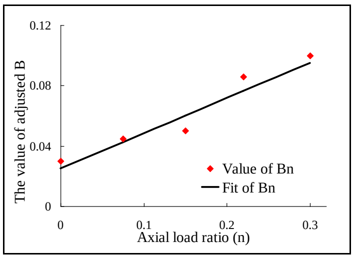
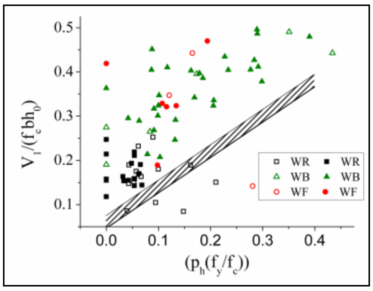


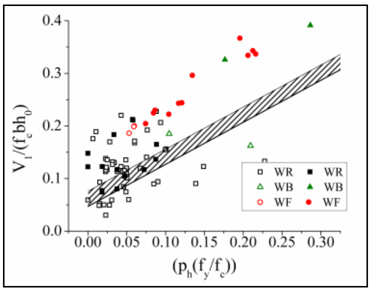
Figure 7.*Fitting function of* B_n

5.3. Effect of aspect ratio on B_λ

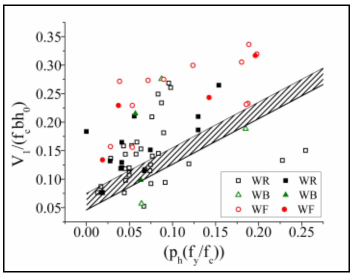
Use solid marks to assess the performance of equation set Ⅰ, in the case λ is used as variables. The comparison results are shown in fig.8.



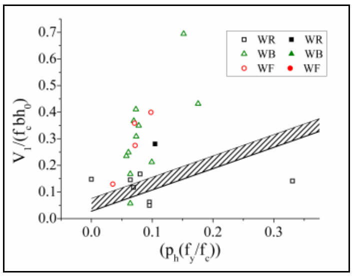
(a) $\lambda = 0 - 0.6$



(b) $\lambda = 0.6 - 1.0$



(c) $\lambda = 1.0 - 1.5$



(d) $\lambda > 1.5$

Figure 8.*Comparison of equation set Ⅰ and solid marks with different aspect ratio(* λ *)*

Compared with the results of equation set Ⅰ with different axial load ratios (fig. 2(a)), the performance of equation set Ⅰ (λ as variables) shown in fig.8 are better. Because in figure 8, all the solid marks are above the upper bound line of equation set Ⅰ (except fig.8(b) and 8(c)). However, insecurity of the equation still exists. Therefore, it is needed to improve the performance of equation set Ⅰ by modified B_λ. Due to equation set Ⅰ satisfied the requirements of deformation capacity when the aspect ratio ranged between 0-0.6 and more than 1.5. It is not necessary to improve the equation of the two regions. The method for fitting B_λ in section 5.3 is similar to section 5.2. The alternative equation was proposed based on equation set Ⅰ, thus aspect ratio as variable, the paper references function form of equation set Ⅰ($B_\lambda = \frac{a}{\lambda} + b$). In the function, two coefficients need to be determined (a and b) through fitting. The corrected values of B_λ corresponding to different aspect ratio are shown in figure 9.

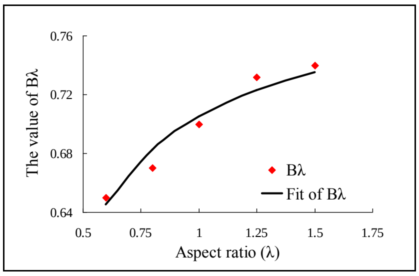


Figure 9.*Fitting function of* B_λ

Fitting result is shown in equation (17). This equation is only applied in the range between 0.6 and 1.5 of aspect ratio. In the otherwise scope, the contribution of aspect ratio on shear capacity is equal to GB50010-2010. The improved B_λ expression is given by equation 18.

$$B_\lambda = \frac{-0.074}{\lambda} + 0.82 \qquad (17)$$

$$B_\lambda = \begin{cases} 0.1176 & 0 < \lambda < 0.6 \\ \dfrac{-0.09}{\lambda} + 0.79 & 0.6 \le \lambda \le 1.5 \\ \dfrac{0.1176}{\lambda - 0.5} & 1.5 < \lambda \end{cases} \qquad (18)$$

In equation (18), B_λ is a step function. The function of B_λ is the same as corresponding function term of equation set I for aspect ratio ranged between $0 < \lambda < 0.6$ and $1.5 < \lambda$.

5.4. Alternative shear strength expressions for assuring deformation capacity

In the previous sections, the performance of five equation sets was studied in terms of deformation demands criteria, equation set I (GB 50010-2010) shows better performance than that of others. Based on equation set I, an alternative shear strength formulation for assuring deformation capacity is proposed. Such formulation is consistent with the well accepted formulation in performance. The expression can be expressed as:

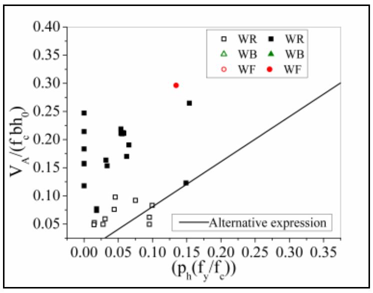
$$\frac{V_A}{f_c b h_0} = \frac{0.8\rho_{sh} f_{yv}}{f_c} + B_\lambda B_n \qquad (19)$$

The value of B_λ can be obtained from equation (18):

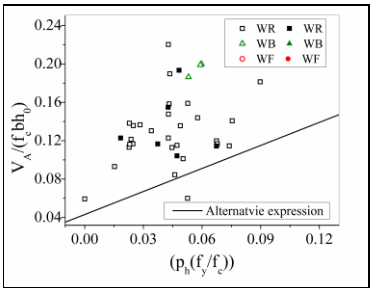
(1) For $0 < \lambda < 0.6$, the effects of aspect ratio is ignored; (2) For $0.6 \le \lambda \le 1.5$, which is a function of aspect ratio and is shown in fig.9; and (3) For $1.5 < \lambda$, the function is the same as the contribution of aspect ratio in equation set I .The contribution of axial load, B_n, is calculated with Eq.(15), which was plotted in fig.7.

To assess the performance of the alternative expressions (Eq. (19)) to ensure the deformation capacity of RC squat walls, some typical comparison results are shown in fig. 10.

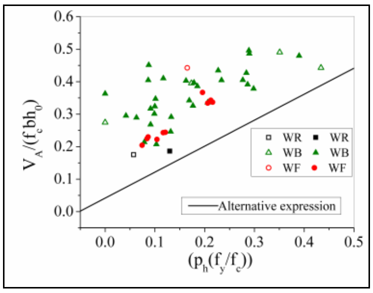
A comparison of fig.10 indicates that almost data points of solid mark are above the calculation result of eq. (19). As can be observed, the performance of the alternative expressions is better than the other equation sets studied here (Fig 2 to 4), including GB 50010-2010, ACI 318-14 Ch.11, ACI 318-14 Ch.18, EC 08 and CSA A23.



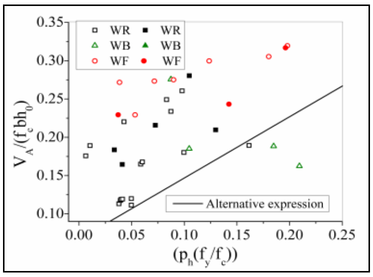
(a) n=0 $0.6 \le \lambda \le 1.0$



(b) n=0-0.15 $0.6 \le \lambda \le 1.0$



(c) n=0-0.15 $0 \le \lambda \le 0.6$



(d) n=0.15-0.3 $1 \le \lambda \le 1.5$

Figure 10.*Performance evaluation of alternative expression*

An improvement of performance is obtained. The over percent is smaller than 10%. This demonstrates that the alternative expressions can ensure the deformation capacity of squat walls is more than existing calculation equations. Although the performance of alternative expression is better than others. It should be noted that the proposed expressions are valid only in the parameter range used in this study (listed in fig.1).Furthermore in equation (19), the upper limit of V_A and the lower limit of horizontal reinforcement ratio is same as GB 50010-2010.

6. Conclusion

Five equations' performance is evaluated using data from tests of 250 solid squat walls. Based on evaluation results, an alternative shear strength expression for ensuring deformation capacity is proposed. In this paper, following conclusions can be obtained:

1. From the statistical comparison performed with the available expressions, those proposed by GB50010-2010 for squat RC walls with the better performance for ensuring deformation capacity.
2. Based on equation set I (GB 50010-2010), robust, yet simple shear strength expressions were developed and calibrated. Expression is applicable to walls with the features presented fig.1. The expression is a linear function considering the effects of axial load and aspect ratio. Such expression is consistent with the well accepted formulation in performance.
3. From the comparison of performance in alternative expressions and five equation sets, it is clear that the expression is reliable. The over percent is low.

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