17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 27th to October 2nd, 2021

STRUT AND TIE MODEL TO ESTIMATE THE SHEAR STRENGTH OF REINFORCED CONCRETE SQUAT WALLS

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Abstract

A strut and tie model-based equation was proposed to predict the shear strength of rectangular reinforced concrete squat walls. The results of 54-tested squat shear walls in the literature were investigated to evaluate the accuracy of the proposed equation in addition to other commonly used equations such as ACI 318-19, Wood 1990, and Gulec 2011. The investigation revealed that the proposed equation has an excellent prediction accuracy, where the average of experimental-to-predicted shear strength ratio is 1.137 and Coefficient of Variance 0.22. Based on the analyzed 54 wall results, the ACI 318-19 tends to overpredict the shear strength of squat walls.

Keywords: Squat Walls, ACI, Shear Strength, Strut and Tie Model.

1. Introduction

Shear walls with height-to-length ratio less than two are classified as squat shear walls. They are the main components in lateral-resisting systems in low-rise reinforced concrete buildings and nuclear structures. The American Concrete Institute code (ACI 318-19) [1] requires vertical and horizontal steel bars on the wall web and two boundary elements at the wall ends. Numerous squat walls designed according to the ACI provisions were tested, and the results demonstrate sudden drop in shear strength at low drift ratio is the most common type of failure, (Cheng et al., 2016 [2]; Baek et al., 2017 [3]). Therefore, the behavior of squat walls is considered brittle, but the ACI 318-19 design equation was derived based on empirical analysis for beams which does not reflect the brittle behavior of squat walls. Several studies were devoted to predicting the shear strength of squat walls; however, the predicted strength is scattered and does not match the experimental results. Yu and Hwang 2005 [4], Hwang et al 2001 [5], Chandra et al 2018 [6], Kassem 2014 [7], proposed the Strut and Tie model (STM) to predict the shear strength of squat walls. Although they fairly predict the shear strength, the procedure to calculate the wall shear strength is complicated and time consuming.

Several equations are available to estimate the shear strength of squat walls, Wood 1990 [8] investigated the results of tested 143 squat walls in literature, based on the shear-friction model, the following empirical equation was proposed to estimate the squat wall shear strength:

$$0.5\sqrt{f_c'}A_{cv} \le V_n = \frac{A_{vf}\, f_y}{4} \le 0.83\sqrt{f_c'}A_{cv} \tag{1}$$

Where V_n is the wall shear strength (N), f'_c is the concrete compressive strength (MPa), A_{cv} is the wall web area (mm^2).

Similar to ACI 318-08 Chapter 21 equation, ACI 318-19 Chapter 18 section 18.10.4.3 requires vertical reinforcement at least equals to the horizontal reinforcement ratio for squat walls, the minimum reinforcement ratio for vertical and horizontal reinforcement is 0.25%. The wall shear strength, section 18.10.4.1, shall be estimated by:

$$\begin{aligned} &V_n = A_{cv}\left(0.083\alpha_c\lambda\sqrt{f_c'} + \rho_t f_y\right) \le 0.83\sqrt{f_c'} \\ &\alpha_c = 0.25 \text{ for } \mathrm{h}_w / l_w \le 1.5 \\ &\alpha_c = 0.17 \text{ for } \mathrm{h}_w / l_w \ge 2.0 \\ &\alpha_c \text{ varies linearly between 0.25 and 0.17 for } 1.5 \le \mathrm{h}_w / l_w \le 2.0 \end{aligned} \tag{2}$$

Where V_n is the wall shear strength (N), ρ_t is the horizontal reinforcement ratio, f'_c is the concrete compressive strength (MPa), A_{cv} is the wall web area (mm^2), h_w/l_w is the wall height to length ratio and λ is a reduction factor to reflect the reduced lightweight concrete strength.

However, the ACI 318-19 Chapter 18 equation only considers the concrete compressive strength and the horizontal reinforcement to estimate the wall shear strength, no credits are given for the vertical reinforcement also wall aspect ratio is not significantly affect on shear strength.

Gulec and Whittaker 2011 [9] investigated the squat walls database to build a new predicting shear strength model for rectangular squat walls with aspect ratio 1.0 or less,

$$V_{rec} = \frac{1.5\sqrt{f_c'}A_w + 0.25F_{vw} + 0.2F_{vbe} + 0.4P}{\sqrt{h_w / l_w}} \le 10\sqrt{f_c'}A_w \tag{3}$$

A_w (in.^{2}) is the wall web area; F_{vw} and F_{vbe} (Ib) are the forces developed due to longitudinal and boundary reinforcements, respectively; The forces are calculated by multiplying the reinforcement area by yielding steel stress; h_w (in.) is wall height; l_w (in.) is wall length; P (lb) is the applied external axial force. (Note: 1 in. = 25.4 mm and 1 lb = 4.45 N).

In this study, a simple strut-and-tie (STM) model was derived to estimate the shear strength of squat walls, the model was compared to the results of 54 tested squat wall specimens in literature.

2. Strut and Tie Model

The shear force transfer was derived based on extensive data of experimental program discussed in Almasabha G. 2019 [10]. Overall, the shear force transfer throughout a strut which is designated by yellow strip as shown in Fig. 1. To maintain static equilibrium, sufficient tensile forces in ties must balance the compressive forces in the strut, the ties consist of several vertical steel bars. The tie width and strut width are designated by Y_1 and Y_2 which mainly depend on the wall aspect ratio. The horizontal steel bars are critical to reinforce the strut, the contribution of horizontal reinforcement is given by Y_3. The proposed shear strength of squat walls is the minimum value of the tie strength and the strut strength. Eq. (4) represents the shear strength of squat walls with aspect ratio less than 0.75, and Eq. (5) shows the shear strength of squat walls with aspect ratio of 0.75 and less than 2.0.

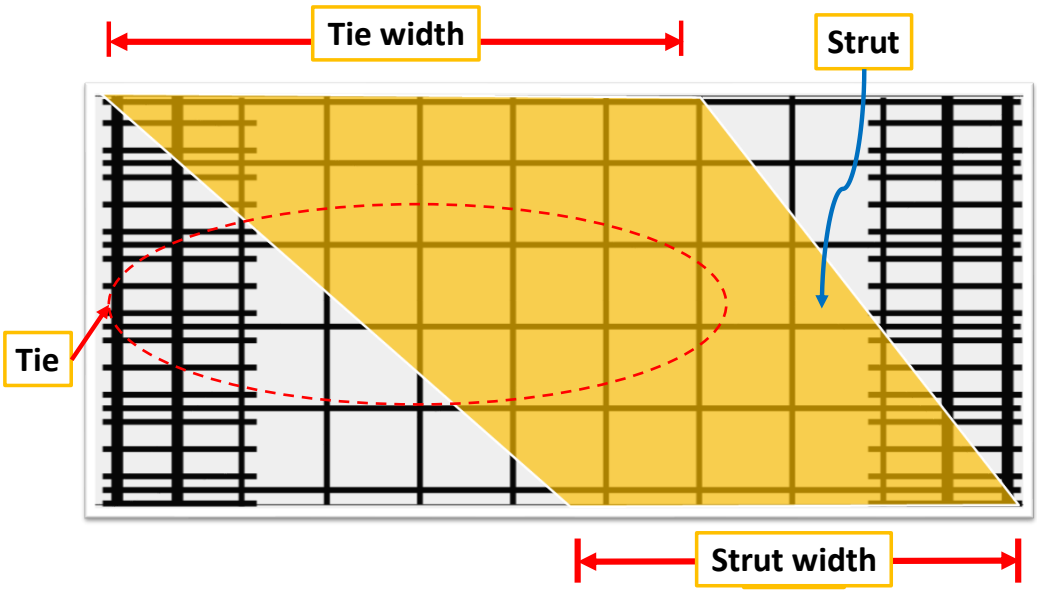

Fig. 1– General strut and tie componentes

The following proposed Eq. (4) valid for wall aspect ratios less or equal 0.75:

$$V_{proposed} = \text{minimum of} \begin{cases} V_{tie} = Y_1 A_{sv} F_{yv} \\ V_{strut} = 0.6(0.85) Y_2 A_w f_c' \cos(45°) + Y_3 A_{sh} F_{yh} \end{cases} \quad (4)$$

The following proposed Eq. (5) valid for wall aspect ratio more than 0.75 and less than 2.0:

$$V_{proposed} = \text{minimum of} \begin{cases} V_{tie} = \dfrac{A_{sb} F_{yb}}{aspect\ ratio} \\ V_{strut} = 0.6(0.85) \dfrac{A_w}{4} f_c' \cos(\alpha°) + 0.5 A_{sh} F_{yh} \end{cases} \quad (5)$$

$$\alpha = \tan^{-1}(aspect\ ratio)$$

α is the strut inclination angle (degrees)

Where:

Y_1 is the tie width and calculated by:

$$\frac{3L}{4} \geq Y_1 = \frac{4}{3}(1 - aspect\ ratio) \geq \frac{L}{3}$$

Y_2 is the strut width and calculated by:

$$\frac{3L}{4} \geq Y_2 = \frac{1}{4(aspect\ ratio)} \geq \frac{L}{3}$$

Y_3 is the horizontal reinforcement contribution of strut strength and calculated by:

$$0.5 \geq Y_3 = \frac{aspect\ ratio}{2} \geq 0.25$$

$V_{proposed}$: the wall shear strength (N).

A_{sb}: summation of steel bars area located at one boundary.

F_{yv}: actual steel yield strength of vertical reinforcements, MPa.

F_{yh}: actual steel yield strength of horizontal reinforcements, MPa.

F_{yb}: actual steel yield strength of boundary reinforcements, MPa.

f'c: concrete compressive strength (MPa)

3. Database of tested squat shear walls

The database of 54 tested squat walls were used to evaluate the accuracy of the proposed strut-and-tie model-based equation compared to the equations of Wood 1990 [8], Gulec 2011[9], and ACI 318-19 [1]. The database is summarized in Table 1 which consists of rectangular squat walls with aspect ratio range from 0.33 to 1.0.

Table 1 – Database of tested rectangular squat walls

Reference	Number of tests	Aspect ratio
Whyte and Stojadinovic [11]	2	0.53
Alexender [12]	1	0.5
Sheu [13]	16	0.5
Baek et al. (2017) [3]	9	0.5 and 1.0
Baek et al. (2018) [14]	12	0.33 and 0.5
Cheng et al. [2]	5	1.0
Synge [15]	1	0.5
Yoshizaki [13]	5	0.5
Wiradinata [16]	1	0.5
Almasabha G. 2019 [10]	2	0.5 and 1.0
Total	54	

4. Database Analysis

The tie, strut and the proposed strength were calculated according to Eq. (4) and Eq. (5), the predicted shear strength by proposed equation of the squat walls listed in the database is illustrated in Fig. (2). The predicted shear strength by Wood 1990, ACI 318-19, and Gulec 2011 were also calculated using Eq. (1), Eq. (2) and Eq. (3), respectively, the calculated shear strength of squat walls are illustrated in Fig. (3), Fig. (4), and Fig. (5), respectively. Table 2 summarizes the ratio of experimental to the predicted shear strength by other equations, the dispersion parameters (Average, Standard deviation, and Coefficient of variance) of the evaluated database. The results emphasize the accuracy of the proposed equation to predict shear strength of squat walls compared to the other available equations. Where the average predicted strength is 1.137 with coefficient of variance 0.22. The ACI 318-19 overpredicts the shear strength.

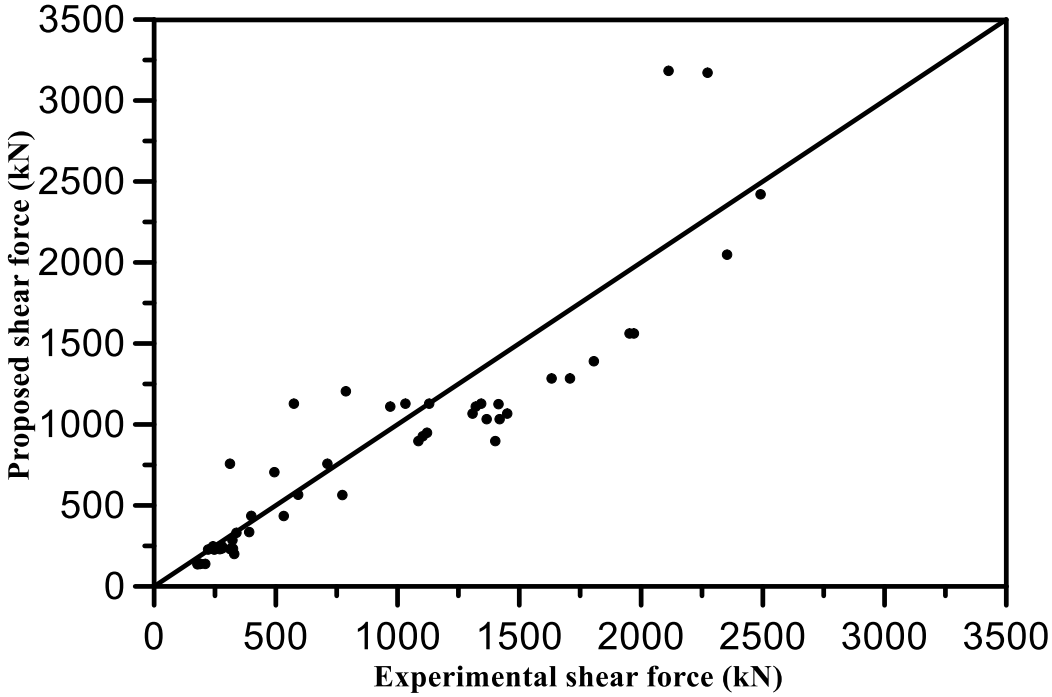

Fig. 2– Experimental and Proposed shear strength.

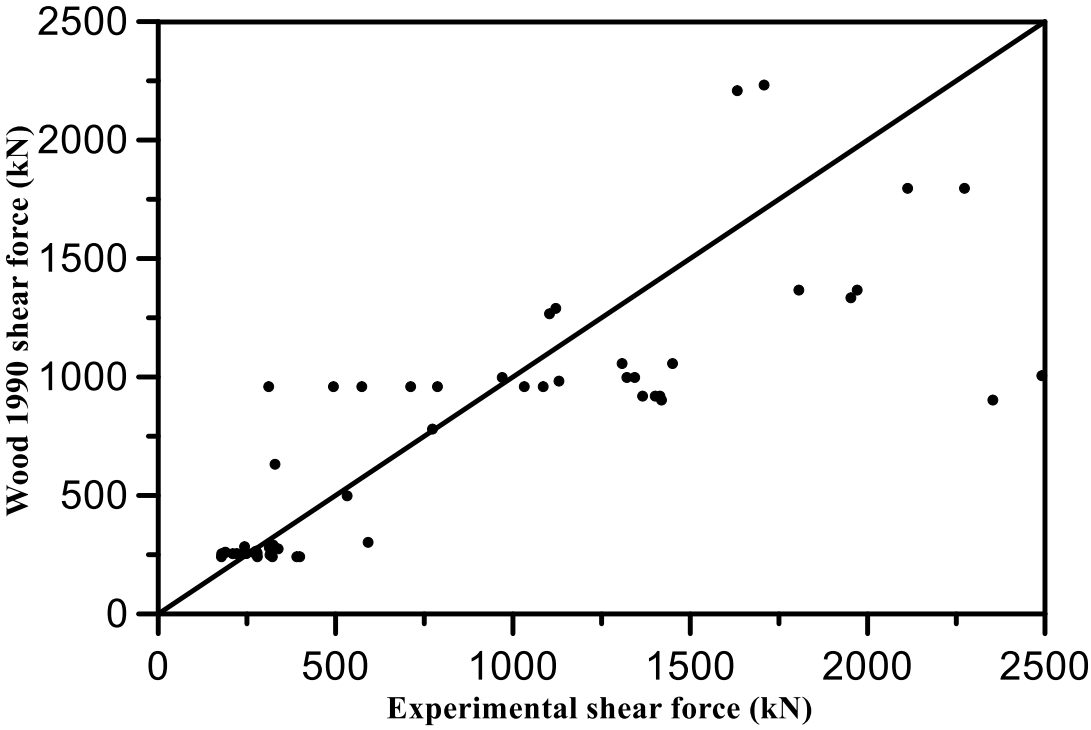

Fig. 3– Experimental and Wood 1990 shear strength.

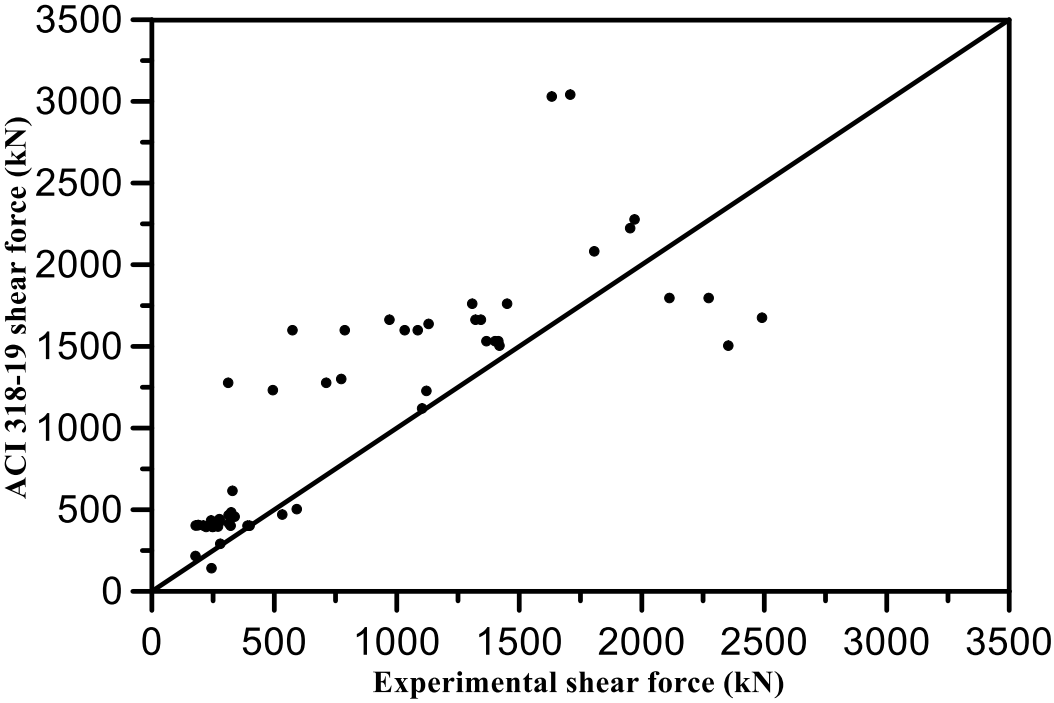

Fig. 4– Experimental and ACI 318-19 shear strength.

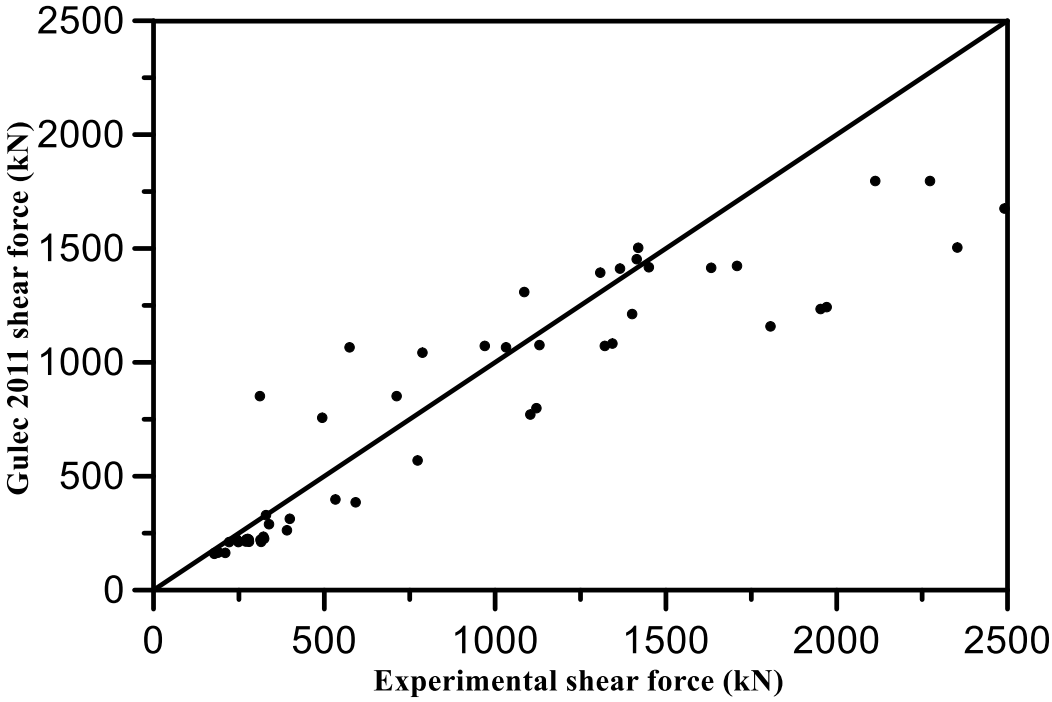

Fig. 5– Experimental and Gulec 2011 shear strength.

Table 2 – Average, Standard deviation, and Coefficient of variance of database.

Dispersion	Wood (1990)	Gulec (2011)	ACI 318-19	$V_{proposed}$
Average	1.135	1.172	0.778	1.137
Standard deviation	0.429	0.262	0.294	0.250
Coefficient of variance	0.378	0.224	0.378	0.220

5. Conclusions

A Strut and Tie Model-based Proposed Equation was presented to predict the squat wall shear strength, the equation was derived based on experimental results of this study. Compared to the results of tested 54 rectangular squat walls in the literature, the equation has an excellent prediction accuracy, where the average of experimental-to-predicted shear strength ratio is 1.137 and Coefficient of Variance 0.22. Based on the analyzed database, the ACI 318-19 tends to overpredict squat walls shear strength.

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