Assessment of Shear Strength Models for Squat Rectangular Reinforced Concrete Shear Walls

Duc-Xuan Nguyen
Department of Civil Engineering, Vinh University, Vinh, Vietnam
ducxuankxd@vinhuni.edu.vn

Xuan-Hung Vu
Department of Civil Engineering, Vinh University, Vinh, Vietnam
xuanhungkxd@vinhuni.edu.vn

Kieu-Vinh T. Nguyen
Department of Civil Engineering, Vinh University, Vinh, Vietnam
kieuvinhkxd@vinhuni.edu.vn

Duy-Duan Nguyen
Department of Civil Engineering, Vinh University, Vinh, Vietnam
duyduankxd@vinhuni.edu.vn (corresponding author)

Received: 16 August 2024 | Revised: 16 September 2024 | Accepted: 19 September 2024

ABSTRACT

The shear strength is a critical parameter in the design of Reinforced Concrete (RC) shear walls subjected to lateral loads. Numerous design codes and published studies have proposed formulas for calculating the shear strength of squat RC walls. However, there is a discrepancy between the calculated and experimental results. This study aims to evaluate various models for the calculation of the shear strength of rectangular squat RC walls using 312 databases collected from the literature. The shear strength of the RC walls was calculated using eight code- and empirical-based models, while the input parameters were obtained from the experimental database. The results were evaluated utilizing two statistical indicators: coefficient of determination and root-mean-squared error. The analysis of the results revealed that the model of C. K. Gulec and A. S. Whittaker is the optimal model, followed by the models of S. L. Wood and Eurocode-8 (EC8).

Keywords-design code; empirical formula; experimental data; rectangular squat RC wall; shear strength

I. INTRODUCTION

RC walls have been widely used in buildings and nuclear power plants because of their large capacity for lateral loading [1]. In addition to columns, walls are key members of the lateral structural system of RC buildings [2]. There are two typical cross-section types of RC walls: rectangular and flanged. Based on previous experimental results, three common failure modes of RC walls have been identified: flexure, shear, and flexure-shear combination [3]. Flexural failure normally occurs in slender walls (i.e., when the aspect ratio is larger than 2.5) with a ductile failure mechanism, such as flexural yielding near the base. Shear failure is governed by low-aspect-ratio walls or squat walls (aspect ratio less than 1.5) with typical diagonal tension failure or diagonal web crushing. Flexure-shear failure can occur for walls with an aspect ratio from 1.5 to 2.5. In this case, the wall experiences a yield in the flexure followed by shear failure, typically a diagonal tension failure after concrete spalling, diagonal compression after crushing at boundary elements, or shear sliding after flexural yielding.

The shear strength is a crucial parameter in the design of RC walls when seismic loading is considered. In the last decades, numerous experiments have been conducted to propose equations for calculating the shear strength of rectangular RC walls [3-8]. For instance, authors in [3] tested eight squat RC walls with boundary elements, considering various reinforcement and aspect ratios. They pointed out that the current design underestimated the shear strength of the squat RC walls. A formula was proposed based on the experimental results. In [4], the equations of the ACI 318-83 code were re-evaluated using 143 experimental datasets for squat RC walls. Authors in [5] proposed a strut and tie-based model for predicting the shear strength of squat RC walls subjected to earthquake. In [6], an equation was presented to estimate the shear strength of squat RC walls based on 277 experimental databases. In [7], an analytical formula was provided to calculate the shear strength of RC walls based on the calibration of 664 datasets. Moreover, some codes and standards, such as ACI 318 [9], ASCE/SEI-43 [10], and EC8 [11], provide equations for estimating the shear strength of rectangular RC walls. Nevertheless, there is disagreement between the code- and empirical-based models and experimental results. Therefore, it is necessary to evaluate the different models using large amounts of experimental data.

The objective of this study is to evaluate various models for determining the shear strength of rectangular RC squat walls. Eight models, including both code- and empirical-based approaches, were examined. A comprehensive database comprising 312 experimental results was compiled from the existing literature. Subsequently, the shear strength of the rectangular RC squat walls was computed employing these eight models for all 312 data points. The performance of each model was then evaluated utilizing statistical metrics, specifically the coefficient of determination and root-mean-squared error.

II. MODELS FOR CALCULATING THE SHEAR STRENGTH OF RECTANGULAR RC COLUMNS

Eight code- and empirical-based equations were deployed for calculating the shear strength of rectangular RC squat walls. The code-based models were ACI 318 Chapter 11 and 18 [9], ASCE/SEI-43 [10], and EC8 [11]. Additionally, the empirical models were acquired from [3, 4, 6, 8]. The expressions of the models are described in Table I.

TABLE I. SHEAR STRENGTH MODELS CONSIDERED IN THIS STUDY

Model	**Equation**	
ACI 318 Ch. 11	$V = V_c + V_s \leq 0.83\sqrt{f_c'}t_w d;\ d = 0.8l_w$ $V_c = 0.27\lambda\sqrt{f_c'}t_w d + \frac{Pd}{4l_w}$ or $V_c = \left[0.05\lambda\sqrt{f_c'} + \frac{l_w\left(0.1\lambda\sqrt{f_c'}+0.2\frac{P}{l_w t_w}\right)}{\frac{M}{V}-\frac{l_w}{2}}\right]t_w d$ $V_s = \frac{A_v f_y d}{s}$ where V_c is the shear strength provided by concrete; V_s is the shear strength contributed by lateral reinforcements; f_c' is the compressive strength of concrete; t_w is the wall thickness; P is the axial load; A_v is the area of the lateral reinforcement; f_y is the yield strength of reinforcement; s is the spacing of lateral reinforcements; λ is the factor considering the reduction of concrete characteristics; l_w is the wall length; h_w is the wall height; M/V is the ratio of moment and shear force.	(1)
ACI 318 Ch. 18	$V = A_{\text{cv}}\left(\alpha_c\lambda\sqrt{f_c'} + \rho_h f_y\right) \leq 0.83A_{\text{cw}}\sqrt{f_c'}$ where A_{cw} is the cross-sectional area of the web of the RC wall along with the shear force direction; ρ_h is the lateral reinforcement ratio; α_c is the coefficient representing the portion of shear strength provided by the concrete and the entire wall.	(2)
ASCE43	$V = v_n d t_w, (d = 0.6l_w)$ $v_n = 0.69\sqrt{f_c'} - 0.28\sqrt{f_c'}\left(\frac{h_w}{l_w} - 0.5\right) + \frac{P}{4l_w t_w} + \rho_{\text{se}}f_y \leq 1.67\sqrt{f_c'}$ $\rho_{\text{se}} = A\rho_v + B\rho_h$ if $h_w/l_w < 0.5, A = 1\ ; B = 0$ if $0.5 < h_w/l_w < 1.5, A = -h_w/l_w + 1.5\ ; B = h_w/l_w - 0.5$ if $h_w/l_w \geq 1.5, A = 0\ ; B = 1$ where ρ_v is the longitudinal reinforcement ratio.	(3)
EC8	$V = \left[\rho_h f_{yh}\left(\frac{M_n}{V_n l_w} - 0.3\right) + \rho_v f_{yv} * \left(1.3 - \frac{M_n}{V_n l_w}\right)\right]t_w d_w$ if $\frac{1.5P}{A_w f_c'} < 0.1$ $V = \left[0.15\sqrt{f_c'} + \rho_h f_{yh}\left(\frac{M_n}{V_n l_w} - 0.3\right) + \rho_v f_{yv} * \left(1.3 - \frac{M_n}{V_n l_w}\right)\right]t_w d_w$ if $\frac{1.5P}{A_w f_c'} > 0.1$ $d_w = 0.8l_w$; f_{yh} is the yield strength of horizontal reinforcements; f_{yv} is the yield strength of vertical reinforcements; A_w is the cross-sectional area of the wall;	(4)
[3]	$V = \left(0.67\sqrt{f_c'} - 0.21\sqrt{f_c'}\frac{h_w}{l_w} + \frac{P}{4l_w t_w} + \rho_v f_y\right)t_w d$ $(d = 0.6l_w)$	(5)
[4]	$0.5A_{\text{cv}}\sqrt{f_c'} \leq V = \frac{A_{\text{vf}}f_y}{4} \leq 0.83A_{\text{cv}}\sqrt{f_c'}$ A_{vf} is the area of the shear lateral reinforcements.	(6)
[6]	$V = \frac{1.5\sqrt{f_c'}A_w + 0.25F_{\text{vw}} + 0.2F_{\text{vbe}} + 0.4P}{\sqrt{h_w/l_w}} \leq 10A_w\sqrt{f_c'}$ (Applied for $h_w/l_w \leq 1.0$) where F_{vw} is the strength provided by the longitudinal reinforcement in the web; F_{vbe} is the strength provided by the longitudinal reinforcement in the boundary elements.	(7)
[8]	$V = \left(0.35 + 0.068f_c' - 0.08f_c'\frac{h_w}{l_w} + 0.41\frac{P}{A_g} + 0.47\rho_{\text{se}}f_{\text{yse}} + 0.39\rho_{\text{be}}f_{\text{ybe}}\right)A_{\text{cv}}$ $f_{\text{yse}} = Af_{\text{yv}} + Bf_{\text{yh}}$ $\rho_{\text{se}} = A\rho_v + B\rho_h$ $\rho_{\text{be}} = A_{\text{sbe}}/A_{\text{cv}}$ if $h_w/l_w \leq 0.5, A = 1;\ B = 0$ if $0.5 < h_w/l_w < 1.5, A = -h_w/l + 1.5;\ B = h_w/l - 0.5$ if $h_w/l_w \geq 1.5,\ A = 0;\ B = 1$ f_{ybe} is the yield strength of the reinforcements of boundary elements.	(8)

III. COLLECTED DATABASE

A database including 312 experimental results for squat rectangular RC walls was collected from the literature [3, 6, 8, 12-45]. Figure 1 shows the configuration and reinforcement details of the rectangular RC squat wall.

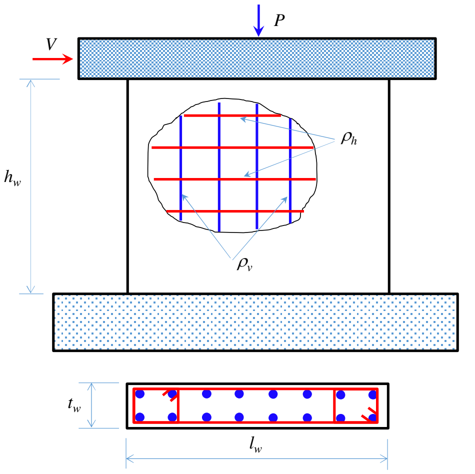


Fig. 1. Configuration and properties of rectangular RC wall.

The distributions of the input parameters from the 312 datasets are depicted in Figure 2. The correlations between the input parameters are portrayed in Figure 3.

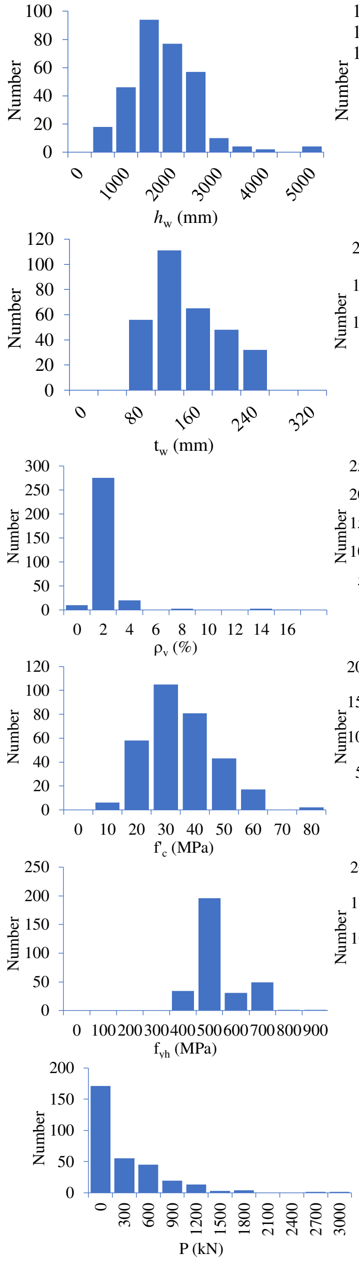
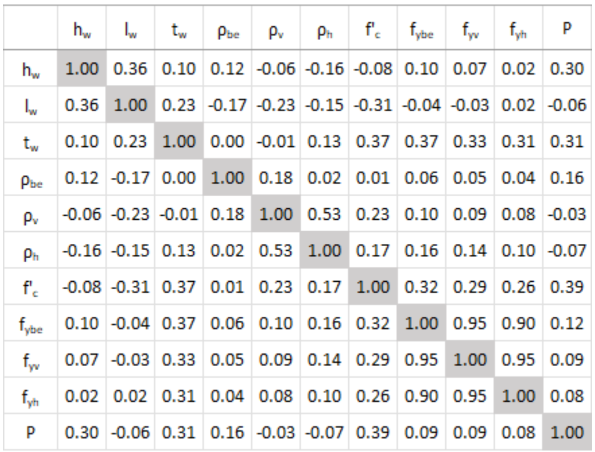


Fig. 2. Distribution of the input parameters in the database.

It should be noted that the datasets cover a wide range of input design parameters, such as the aspect ratio, axial compression ratio, and material strength. The high strength concrete and reinforcement were also considered in the data in which the compressive strength of concrete was up to 70 MPa and the yield strength of rebar was up to 806 MPa. The ranges of the input parameters are:

- Wall height: 500 mm ≤ h_w ≤ 4691 mm.
- Wall length: 600 mm ≤ l_w ≤ 5415 mm.
- Wall thickness: 60 mm ≤ t_w ≤ 240 mm.
- Aspect ratio: 0.3 ≤ h_w/l_w ≤ 2.2.
- Axial compression ratio: 0 ≤ $P/f_c'A_g$ ≤ 0.50.
- Longitudinal reinforcement ratio at the boundaries: 0.0% ≤ ρ_{be} ≤ 14.3 %.
- Vertical reinforcement ratio: 0.00% ≤ ρ_v ≤ 14.3%.
- Horizontal reinforcement ratio: 0.00% ≤ ρ_h ≤ 6.7%.
- Compressive strength of concrete: 5.2 MPa ≤ f_c' ≤ 70.3 MPa.
- Yield strength of the reinforcing bar at the boundary: 300 MPa ≤ f_{ybe} ≤ 770 MPa.
- Yield strength of vertical reinforcement: 300 MPa ≤ f_{yv} ≤ 770 MPa.
- Yield strength of horizontal reinforcement: 314 MPa ≤ f_{yh} ≤ 806 MPa.



	h_w	l_w	t_w	ρ_{be}	ρ_v	ρ_h	f'_c	f_{ybe}	f_{yv}	f_{yh}	P
h_w	1.00	0.36	0.10	0.12	-0.06	-0.16	-0.08	0.10	0.07	0.02	0.30
l_w	0.36	1.00	0.23	-0.17	-0.23	-0.15	-0.31	-0.04	-0.03	0.02	-0.06
t_w	0.10	0.23	1.00	0.00	-0.01	0.13	0.37	0.37	0.33	0.31	0.31
ρ_{be}	0.12	-0.17	0.00	1.00	0.18	0.02	0.01	0.06	0.05	0.04	0.16
ρ_v	-0.06	-0.23	-0.01	0.18	1.00	0.53	0.23	0.10	0.09	0.08	-0.03
ρ_h	-0.16	-0.15	0.13	0.02	0.53	1.00	0.17	0.16	0.14	0.10	-0.07
f'_c	-0.08	-0.31	0.37	0.01	0.23	0.17	1.00	0.32	0.29	0.26	0.39
f_{ybe}	0.10	-0.04	0.37	0.06	0.10	0.16	0.32	1.00	0.95	0.90	0.12
f_{yv}	0.07	-0.03	0.33	0.05	0.09	0.14	0.29	0.95	1.00	0.95	0.09
f_{yh}	0.02	0.02	0.31	0.04	0.08	0.10	0.26	0.90	0.95	1.00	0.08
P	0.30	-0.06	0.31	0.16	-0.03	-0.07	0.39	0.09	0.09	0.08	1.00

Fig. 3. Correlation between input parameters.

IV. EVALUATION OF CALCULATED SHEAR STRENGTH FOR RC SQUAT WALLS

To evaluate the shear strength calculated from the different models listed in Table I, two statistical properties were used: the coefficient of determination (R^2) and the Root-Mean-Squared Error (*RMSE*). It should be noted that the R^2 value indicates the percentage of data close to the regression line. The higher the R^2 is, the more accurate is the calculated model, and vice versa. The *RMSE* is employed to quantify the error between the calculated and experimental values; thus, the lower the RMSE is, the better is the calculated model, and vice versa. The definitions of R^2 and *RMSE* values are expressed as:

$$R^2 = 1-\left(\frac{\sum_{i=1}^{n}(t_i-o_i)^2}{\sum_{i=1}^{n}(t_i-\bar{o})^2}\right) \quad (9)$$

$$RMSE = \sqrt{\left(\frac{1}{n}\right)\sum_{i=1}^{n}(t_i - o_i)^2} \quad (10)$$

where t_i and o_i are the test and calculated results of the i sample; n is the count of the data points; $\bar{o}$ is the mean of the calculated results.

Figure 4 shows a comparison between the shear strength of the rectangular RC squat walls calculated using the eight models and the experimental results. The dashed line represents the true results (i.e., the calculated values are equal to the experimental values).

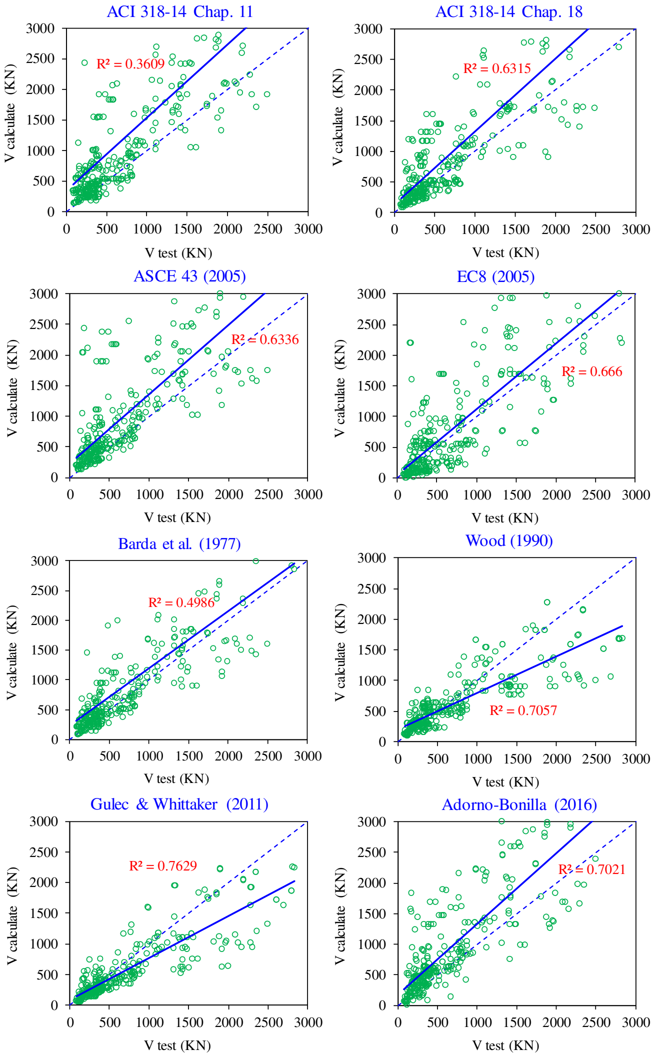


Fig. 4. Comparison between the eight models and experimental results.

The blue line in Figure 4 represents the linear regression. Among the investigated models, the C. K. Gulec and A. S. Whittaker model [6] is the best one exhibiting the lowest scattering, followed by the S. L. Wood model [4] and EC8 [11]. The calculated results based on the C. K. Gulec and A. S. Whittaker [6] and S. L. Wood models [4] were smaller than the experimental results, implying a conservative estimation. Moreover, the results obtained from ACI-318 [9] and ASCE/SEI 43 [10] demonstrated larger scattering. These deviations may be due to the influence of axial compression and boundary elements.

Table II summarizes the calculated R^2 and $RMSE$ values obtained from the eight models. Additionally, the statistical properties of the ratio, $V_{calculate}/V_{test}$, are also calculated in which Minimum (Min), Maximum (Max), mean, Standard Deviation (SD), and Coefficient of Variation (CV) are quantified. The results display that the C. K. Gulec and A. S. Whittaker model [6] is the most reliable model with the highest R^2 value (0.763) and the smallest $RMSE$ (351 kN). This can be attributed to the fact that the equation utilized in [6] considers the effects of the squat RC walls. Besides, the models of S. L. Wood [4] and EC8 [11] are also good options with R^2 values of 0.705 and 0.666, and $RMSE$ values of 373 kN and 505 kN, respectively. Moreover, the mean values of the ratio $V_{calculate}/V_{test}$ of the C. K. Gulec and A. S. Whittaker model [6], S. L. Wood model [4], and EC8 [11] models are 0.90, 1.10, 1.23, respectively. This implies that the mean calculated results were close to the experimental results. Meanwhile, the ACI 318 [9] and ASCE 43 [10] models provided lower accuracy than the other models. Consequently, this study suggests using the models of C. K. Gulec and A. S. Whittaker [6], S. L. Wood model [4], and EC8 [11] models for predicting the shear strength of rectangular RC squat walls.

TABLE II. STATISTICAL PROPERTIES FOR EVALUATING SHEAR STRENGTH OF RC COLUMNS

Model	**R^2**	**RMSE**	**Statistical properties of ratio $V_{calculate}$ / V_{test}**				
			Min	**Max**	**Mean**	**SD**	**CV**
ACI 318 Ch. 11 [9]	0.361	1145	0.52	2.29	42.26	4.43	1.93
ACI 318 Ch. 18 [9]	0.631	660	0.47	1.15	18.68	1.33	0.86
ASCE 43 [10]	0.633	651	0.62	1.79	23.93	1.94	1.08
EC8 [11]	0.666	505	0.01	1.23	13.98	1.36	1.11
[3]	0.498	661	0.47	1.66	25.47	2.63	1.58
[4]	0.705	373	0.39	1.10	3.41	0.49	0.45
[6]	0.763	351	0.32	0.90	3.02	0.41	0.46
[8]	0.702	574	0.03	1.62	18.43	1.49	0.92

V. CONCLUSIONS

This study evaluated eight different models for calculating the shear strength of rectangular Reinforced Concrete (RC) squat walls using a comprehensive database of 312 experimental. Eight code- and empirical-based models were considered. The accuracy of the calculated models was assessed using statistical properties.

The analysis revealed that the shear strength of rectangular RC squat walls depends not only on the cross-sectional configurations and material properties, but also on the lateral reinforcement spacing, aspect ratio, axial compression, and boundary elements.

The C. K. Gulec and A. S. Whittaker model demonstrated the highest accuracy, followed by the S. L. Wood model and Eurocode 8 (EC8). These models displayed the best performance in terms of coefficient of determination (R^2) and

Root-Mean-Squared Error (RMSE). The C. K. Gulec and A. S. Whittaker model, in particular, exhibited the highest R^2 value of 0.763 and the lowest RMSE of 351 kN. In contrast, the ACI 318 and ASCE 43 code-based models provided a lower estimation of the shear strength. Based on these findings, it is recommended to use the C. K. Gulec and A. S. Whittaker, S. L. Wood, or EC8 models for predicting the shear strength of rectangular RC squat walls.

It should be noted that the findings of this study were applied only to rectangular RC squat walls. For other RC wall types, further investigation is necessary. This study provides valuable insights for engineers and researchers in selecting appropriate models for shear strength calculations in RC wall design and analysis.

REFERENCES

[1] C. K. Gulec, A. S. Whittaker, and B. Stojadinovic, "Shear Strength of Squat Rectangular Reinforced Concrete Walls," *Structural Journal*, vol. 105, no. 4, pp. 488–497, Jul. 2008, https://doi.org/10.14359/19863.

[2] T. A. Nguyen, N. M. Pham, T. C. Vo, and D. D. Nguyen, "Assessment of Shear Strength Models of Reinforced Concrete Columns," *Engineering, Technology & Applied Science Research*, vol. 12, no. 6, pp. 9440–9444, Dec. 2022, https://doi.org/10.48084/etasr.5248.

[3] F. Barda, J. M. Hanson, and W. G. Corley, "Shear Strength of Low-Rise Walls with Boundary Elements," *Reinforced Concrete Structures in Seismic Zones, SP-53*, vol. 21, no. 46, pp. 149–202, 1977.

[4] S. L. Wood, "Shear Strength of Low-Rise Reinforced Concrete Walls," *Structural Journal*, vol. 87, no. 1, pp. 99–107, Jan. 1990, https://doi.org/10.14359/2951.

[5] A. Sánchez-Alejandre and S. M. Alcocer, "Shear strength of squat reinforced concrete walls subjected to earthquake loading — trends and models," *Engineering Structures*, vol. 32, no. 8, pp. 2466–2476, Aug. 2010, https://doi.org/10.1016/j.engstruct.2010.04.022.

[6] C. K. Gulec and A. S. Whittaker, "Empirical Equations for Peak Shear Strength of Low Aspect Ratio Reinforced Concrete Walls," *Structural Journal*, vol. 108, no. 1, pp. 80–89, Jan. 2011, https://doi.org/10.14359/51664205.

[7] W. Kassem, "Shear strength of squat walls: A strut-and-tie model and closed-form design formula," *Engineering Structures*, vol. 84, pp. 430–438, Feb. 2015, https://doi.org/10.1016/j.engstruct.2014.11.027.

[8] C. M. Adorno Bonilla, "Shear strength and displacement capacity of squat reinforced concrete shear walls," PhD dissertation, Department of Civil Engineering, University of Puerto Rico, Mayaguez, Puerto Rico, 2016.

[9] *ACI CODE-318-14: Building Code Requirements for Structural Concrete and Commentary*. American Concrete Institute, 2014.

[10] *ASCE/SEI 43-05: Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities*. Reston, Virginia, USA: American Society of Civil Engineers, 2005.

[11] *Eurocode 8: Design of Structures for Earthquake Resistance - Part 1: General Rules, Seismic Actions and Rules for Buildings*. Brussels: European Committee for Standardization, 2004.

[12] A. R. Khoso, J. S. Khan, R. U. Faiz, M. A. Akhund, A. Ahmed, and F. Memon, "Identification of Building Failure Indicators," *Engineering, Technology & Applied Science Research*, vol. 9, no. 5, pp. 4591–4595, Oct. 2019, https://doi.org/10.48084/etasr.2872.

[13] H. Ullah, M. Rizwan, M. Fahad, and S. a. A. Shah, "Seismic Evaluation of the RC Moment Frame Structure using the Shake Table," *Engineering, Technology & Applied Science Research*, vol. 11, no. 1, pp. 6674–6679, Feb. 2021, https://doi.org/10.48084/etasr.3959.

[14] L. Hamzaoui and T. Bouzid, "The Proposition of an EI Equation of Square and L–Shaped Slender Reinforced Concrete Columns under Combined Loading," *Engineering, Technology & Applied Science Research*, vol. 11, no. 3, pp. 7100–7106, Jun. 2021, https://doi.org/10.48084/etasr.4048.

[15] K. I. Christidis, E. Vougioukas, and K. G. Trezos, "Strengthening of non-conforming RC shear walls using different steel configurations," *Engineering Structures*, vol. 124, pp. 258–268, Oct. 2016, https://doi.org/10.1016/j.engstruct.2016.05.049.

[16] K. I. Christidis and K. G. Trezos, "Experimental investigation of existing non-conforming RC shear walls," *Engineering Structures*, vol. 140, pp. 26–38, Jun. 2017, https://doi.org/10.1016/j.engstruct.2017.02.063.

[17] N. C. Mickleborough, F. Ning, and C.-M. Chan, "Prediction of Stiffness of Reinforced Concrete Shearwalls under Service Loads," *Structural Journal*, vol. 96, no. 6, pp. 1018–1026, Nov. 1999, https://doi.org/10.14359/778.

[18] J. Ma and B. Li, "Experimental and Analytical Studies on H-Shaped Reinforced Concrete Squat Walls," *Structural Journal*, vol. 115, no. 2, pp. 425–438, Mar. 2018, https://doi.org/10.14359/51701144.

[19] F. E. Farvashany, S. J. Foster, and B. V. Rangan, "Strength and Deformation of High-Strength Concrete Shearwalls," *Structural Journal*, vol. 105, no. 1, pp. 21–29, Jan. 2008, https://doi.org/10.14359/19065.

[20] D. Palermo and F. J. Vecchio, "Behavior of Three-Dimensional Reinforced Concrete Shear Walls," *Structural Journal*, vol. 99, no. 1, pp. 81–89, Jan. 2002, https://doi.org/10.14359/11038.

[21] Y. L. Mo and J. Chan, "Behavior of reinforced-concrete-framed shear walls," *Nuclear Engineering and Design*, vol. 166, no. 1, pp. 55–68, Oct. 1996, https://doi.org/10.1016/0029-5493(96)01244-7.

[22] A. C. Birely, "Seismic Performance of Slender Reinforced Concrete Structural Walls," PhD dissertation, University of Washington, Seattle, USA, 2013.

[23] J. W. Wallace, K. J. Elwood, and L. M. Massone, "Investigation of the Axial Load Capacity for Lightly Reinforced Wall Piers," *Journal of Structural Engineering*, vol. 134, no. 9, pp. 1548–1557, Sep. 2008, https://doi.org/10.1061/(ASCE)0733-9445(2008)134:9(1548).

[24] Y. Zhang and Z. Wang, "Seismic Behavior of Reinforced Concrete Shear Walls Subjected to High Axial Loading," *Structural Journal*, vol. 97, no. 5, pp. 739–750, Sep. 2000, https://doi.org/10.14359/8809.

[25] J. P. Rivera and A. S. Whittaker, "Damage and Peak Shear Strength of Low-Aspect-Ratio Reinforced Concrete Shear Walls," *Journal of Structural Engineering*, vol. 145, no. 11, Nov. 2019, Art. no. 04019141, https://doi.org/10.1061/(ASCE)ST.1943-541X.0002364.

[26] L. M. Massone Sanchez, "RC wall shear - flexure interaction: analytical and experimental responses," PhD dissertation, California, Los Angeles, USA, 2006.

[27] M.-Y. Cheng, S.-C. Hung, R. D. Lequesne, and A. Lepage, "Earthquake-Resistant Squat Walls Reinforced with High- Strength Steel," *Structural Journal*, vol. 113, no. 5, pp. 1065–1076, Sep. 2016, https://doi.org/10.14359/51688825.

[28] J.-W. Baek, H.-G. Park, J.-H. Lee, and C.-J. Bang, "Cyclic Loading Test for Walls of Aspect Ratio 1.0 and 0.5 with Grade 550 MPa (80 ksi) Shear Reinforcing Bars," *Structural Journal*, vol. 114, no. 4, pp. 969–982, Jul. 2017, https://doi.org/10.14359/51689680.

[29] H.-G. Park, J.-W. Baek, J.-H. Lee, and H.-M. Shin, "Cyclic Loading Tests for Shear Strength of Low-Rise Reinforced Concrete Walls with Grade 550 MPa Bars," *Structural Journal*, vol. 112, no. 3, pp. 299–310, May 2015, https://doi.org/10.14359/51687406.

[30] P. Riva and A. Franchi, "Behavior of Reinforced Concrete Walls with Welded Wire Mesh Subjected to Cyclic Loading," *Structural Journal*, vol. 98, no. 3, pp. 324–334, May 2001, https://doi.org/10.14359/10221.

[31] K. Pilakoutas and A. Elnashai, "Cyclic Behavior of RC Cantilever Walls, Part I: Experimental Results," *Structural Journal*, vol. 92, no. 3, pp. 271–281, 1995, https://doi.org/10.14359/1128.

[32] T. N. Salonikios, A. J. Kappos, I. A. Tegos, and G. G. Penelis, "Cyclic Load Behavior of Low-Slenderness Reinforced Concrete Walls: Design Basis and Test Results," *Structural Journal*, vol. 96, no. 4, pp. 649–660, Jul. 1999, https://doi.org/10.14359/703.

[33] L. M. Massone, "Strength prediction of squat structural walls via calibration of a shear–flexure interaction model," *Engineering Structures*, vol. 32, no. 4, pp. 922–932, Apr. 2010, https://doi.org/10.1016/j.engstruct.2009.12.018.

[34] P. A. Hidalgo, C. A. Ledezma, and R. M. Jordan, "Seismic Behavior of Squat Reinforced Concrete Shear Walls," *Earthquake Spectra*, vol. 18, no. 2, pp. 287–308, May 2002, https://doi.org/10.1193/1.1490353.

[35] J. Ma, C.-L. Ning, and B. Li, "Peak Shear Strength of Flanged Reinforced Concrete Squat Walls," *Journal of Structural Engineering*, vol. 146, no. 4, Apr. 2020, Art. no. 04020037, https://doi.org/10.1061/(ASCE)ST.1943-541X.0002575.

[36] M. Del Carpio Ramos, A. S. Whittaker, and C. K. Gulec, "Predictive Equations for the Peak Shear Strength of Low-Aspect Ratio Reinforced Concrete Walls," *Journal of Earthquake Engineering*, vol. 16, no. 2, pp. 159–187, Feb. 2012, https://doi.org/10.1080/13632469.2011.613529.

[37] B. N. Luna, J. P. Rivera, J. F. Rocks, C. Goksu, and A. S. Whittaker, "Seismic behavior of low aspect ratio reinforced concrete shear walls," presented at the 22nd International Conference on Structural Mechanics in Reactor Technology, San Francisco, California, USA, 2013.

[38] B. N. Luna, "Seismic response of low aspect ratio reinforced concrete walls for buildings and safety-related nuclear applications," PhD dissertation, Department of Civil, Structural and Environmental Engineering, State University of New York, Buffalo, USA, 2015.

[39] M. Hirosawa, *Past experimental results on reinforced concrete shear walls and analysis on them*. Building Research Institute, Ministry of Construction, 1975.

[40] M. J. Moradi and M. A. Hariri-Ardebili, "Developing a Library of Shear Walls Database and the Neural Network Based Predictive Meta-Model," *Applied Sciences*, vol. 9, no. 12, Jan. 2019, Art. no. 2562, https://doi.org/10.3390/app9122562.

[41] T. Terzioglu, K. Orakcal, and L. M. Massone, "Cyclic lateral load behavior of squat reinforced concrete walls," *Engineering Structures*, vol. 160, pp. 147–160, Apr. 2018, https://doi.org/10.1016/j.engstruct.2018.01.024.

[42] A. E. Cardenas, H. G. Russell, and W. G. Corley, "Strength of Low-Rise Structural Walls," *Special Publication*, vol. 63, pp. 221–242, Aug. 1980, https://doi.org/10.14359/6653.

[43] S. Epackachi and A. S. Whittaker, "A validated numerical model for predicting the in-plane seismic response of lightly reinforced, low-aspect ratio reinforced concrete shear walls," *Engineering Structures*, vol. 168, pp. 589–611, Aug. 2018, https://doi.org/10.1016/j.engstruct.2018.04.025.

[44] I. D. Lefas, M. D. Kotsovos, and N. N. Ambraseys, "Behavior of Reinforced Concrete Structural Walls: Strength, Deformation Characteristics, and Failure Mechanism," *Structural Journal*, vol. 87, no. 1, pp. 23–31, Jan. 1990, https://doi.org/10.14359/2911.

[45] T. A. Tran and J. W. Wallace, "Cyclic Testing of Moderate-Aspect-Ratio Reinforced Concrete Structural Walls," *Structural Journal*, vol. 112, no. 6, pp. 653–665, Nov. 2015, https://doi.org/10.14359/51687907.