ENGINEERING RESEARCH JOURNAL (ERJ)
Vol. 1, No. 28 Apr. 2016, pp. 104-115.
Journal Homepage: www.feng.bu.edu.eg

SEISMIC SHEAR STRENGTH OF REINFORCED CONCRETE BRIDGE COLUMNS

Fouad B. A. Beshara[1], Ahmed A. Mahmoud[2], Ahmed N. Khater[3]
[1]Associate Professor, [2]Professor and Head of Civil Eng. Department, [3]Demonstrator.
Civil Engineering Department, Faculty of Engineering at Shoubra, Benha University.

AbstractThis paper presents a design method for the seismic shear strength of RC bridge columns. The design approach is based on the principle tensile stress for the diagonally-cracked concrete column with empirical modifications. The proposed method accounts for the effects of concrete compressive strength, axial load level, shear span to depth ratio, longitudinal reinforcement ratio, and displacement ductility ratio. The analytical predicted results of shear strength for forty seven rectangular columns and thirty eight circular columns are in a good agreement with the experimental results. The average ratio between experimental shear strength to predicted strength is 1.21 for circular columns and 1.25 for rectangular columns. The proposed model is compared with the ACI 318-11 and ECP-203 codes, as well as the design approaches of the Caltrans SDC and modified UCSD model. Also, the parametric studies show the reliability of the method for calculating shear strength of bridge columns with different geometrical and material parameters.

Key words: Concrete bridge columns; RC design; cyclic loads; seismic; shear strength.

1. Introduction

Due to its brittle nature, shear is regarded as a mode of failure that should be avoided in reinforced concrete bridge column design [1]. To provide a reinforced concrete bridge column with sufficient shear strength, it is domineering that the shear strength be predicted in an accurate and dependable manner. The available experimental results, e.g. [2-9] indicate that the column shear strength is influenced by several variables, such as the concrete compressive strength, axial load level, shear span to depth ratio, longitudinal steel ratio and transverse reinforcement content and yield strength. Various existing shear strength models such as the ACI 318-11 [10], ECP-203 [11] Caltrans SDC [12], and Modified UCSD model [1] incorporate some of these variables. Hence, there is a need for development of a new model that consider most of the noticeable shear strength variables.

The objective of this paper is to develop a simple design model for seismic shear strength of concrete columns. The proposed design approach is developed by revising and modifying Sezen and Moehle model [14]. The proposed design method account for the effects of concrete compressive strength, shear span to depth ratio, longitudinal steel ratio, compression load level, and displacement ductility on shear strength of bridge columns.

2. Previous Shear Strength Models for Concrete

For American code ACI 318-11 [10], the shear strength of concrete is given by:

$$v_c = 0.17\left[1+\frac{P}{13.8\,A_g}\right]\sqrt{f_c`} \tag{1}$$

P is the axial compression load, A_g is the gross area of the section, and fc`is the concrete cylinder compressive strength (MPa).

For Egyptian code ECP-203 [11], the concrete shear strength v_C is given as a function of concrete cube compressive strength (f_{cu}) (MPA).

$$v_c = 0.24\sqrt{f_{cu}/\Upsilon_c}\ [1+0.07(P/A_g)] \tag{2}$$

Where Υ_c is the strength reduction factor of concrete =1.5

For Caltrans seismic design criteria (SDC) [12], the concrete shear strength v_c inside the plastic hinge of members as follows:

$$v_c = F_1\ F_2\ \sqrt{f_c`} \le 0.33\sqrt{f_c`} \tag{3}$$

$$F_1 = 0.025 \le \frac{\rho_s\, f_{yt}}{12.5} + 0.305 - 0.083\,\mu_\Delta < 0.25 \tag{4}$$

$$F_2 = 1 + \frac{P}{13.8\,A_g} < 1.50 \tag{5}$$

μ_Δ is defined as the displacement ductility demand, and equal to column displacement divided by yielding displacement. ρ_s is the volumetric ratio of spiral or hoop reinforcement.

In university of California USCD [1], the concrete shear strength is given as:

$$v_c = \alpha\beta\Upsilon\sqrt{f_c`} \tag{6}$$

$$1 \le \alpha = 3 - \frac{a}{d} \le 1.50 \tag{7}$$

$$\beta = 0.50 + 20\ \rho_L \le 1$$

(8) $0.05 \le \Upsilon = 0.37 - 0.04\,\mu_\Delta \le 0.29$ for uni − axial bending (9)

$$0.05 \le \Upsilon = 0.33 - 0.04\,\mu_\Delta \le 0.29 \text{ for bi − axial bending} \tag{10}$$

ρ_L is the longitudinal reinforcement ratio, and a is the column height.

3. Mathematical Formulation of the Proposed Shear Model

The majority of available column shear strength models estimates the shear strength as the summation of shear carried by concrete V_C, and shear carried by transverse reinforcement V_S. The proposed shear strength equation follows the same trend by combining concrete and transverse reinforcement contributions.

3.1 Concrete and Axial Load Contributions

In order to determine the concrete contribution to the shear strength of RC columns with inclined cracks, Sezen [14] assumed that onset of diagonal tension cracking in an element under uniform stress state can be related to the nominal principal tension stress acting on the element. Assuming loading within the x-y plane, the limiting shear stress in concrete τ_{xy} can be defined from equilibrium as:

$$\tau_{xy} = \sqrt{\left(\sigma_1 - \frac{\sigma_x + \sigma_y}{2}\right)^2 - \left(\frac{\sigma_x - \sigma_y}{2}\right)^2} \quad (11)$$

τ_{xy} , shown in Fig (1) is the shear stress on planes perpendicular to member transverse and longitudinal axes, σ_1 is the principal tension stress, σ_x is the normal stress on plane parallel to longitudinal axis, and σ_y is the normal stress on plane perpendicular to member longitudinal axis. Considering no normal stress applied in the direction perpendicular to the axial load direction (σ_x = 0), equation (11) is rewritten as:

$$\tau_{xy} = \sigma_1 \sqrt{1 - \left(\frac{-\sigma_y}{\sigma_1}\right)} \quad (12)$$

The inclined cracking is assumed to occur when the principle tensile stress of concrete reaches its tensile strength [14].

$$\tau_{xy} = f_t \sqrt{1 - \left(\frac{-\sigma_y}{f_t}\right)} \quad (13)$$

The tensile strength of concrete f_t is given as function of concrete compressive strength.

For ACI 318-11 [10], $f_t = 0.50\sqrt{f_c`}$ (14-a)

For ECP-203 [11 $f_t = 0.60\sqrt{f_{cu}}$ (14-b)

The axial stress is defined by ($\sigma_y = -P/A_g$), negative sign indicates the compression axial force, so the concrete shear stress in equation (13) can be rewritten ($\tau_{xy} = v_C$) as:

$$v_c = f_t \sqrt{1 + \left(\frac{P}{f_t A_g}\right)} \quad (15)$$

3.2 Shear Span to Depth Ratio, Longitudinal steel ratio and Displacement ductility Factors

The existing experimental results [1,5,8,13] indicate that the shear strength is greater for columns with smaller shear span to depth ratios, as the confinement effect of the adjacent members is greater in these situations. In the present study, the concrete contribution v_c is reduced with the increase of (a/d) ratio by a factor named

F_1.

$$v_c = \frac{f_t}{F_1}\sqrt{1+\left(\frac{P}{f_t\,A_g}\right)} \qquad (16)$$

In order to determine the factor F_1, a linear regression analysis data fit [16] is used to solve nonlinear models with all variables. Several experimental results of column tests are used in the regression analysis. The plot of the proposed linear expression is shown in Fig (2-a) together with the associated proposed shear strength predictions and the experimental shear results. The predicted equation for factor F_1 is derived as:

$$F_1 = 1 + 0.35\,\frac{a}{d} \qquad (17)$$

The experimental results [1,5,8,13], show that a smaller longitudinal reinforcement ratio results in a decrease in the strength of concrete shear resisting mechanism due to three reasons. First, dowel action from the longitudinal reinforcement is smaller if there are fewer numbers of small diameter bars. Second, crack distribution is characterized by fewer widely-spaced cracks, which, in turn, results in a decrease of aggregate interlock resistance. Third, the smaller compression zone resulting from the reduced longitudinal steel ratio, in turn, reduces the compression zone shear transfer. On the basis of these considerations, the concrete mechanism strength is revised to give the following:

$$v_c = F_2\,\frac{f_t}{F_1}\sqrt{1+\left(\frac{P}{f_t\,A_g}\right)} \qquad (18)$$

Again, the regression analysis data fit [16] of experimental results was used to evaluate the factor F_2 for the effect of longitudinal reinforcement ratio (ρ_l). Fig (2-b) shows the correlation of the proposed shear strength and the experimental shear results. The predicted equation for factor F_2 is:

$$F_2 = 0.50 + 10\;\rho_l \qquad (19)$$

It was reported in [1,6,14], that the shear strength is degraded with increasing the displacement ductility demand. Sezen [14] stated that the proposed shear strength model can be improved by introducing a displacement ductility-related factor F_3 for both concrete and transverse reinforcement contributions to the shear strength. Following the same approach in the present study, the factor F_3 is given as follows:

$$F_3 = 1.0 \text{ for } \mu_\Delta \le 2.0 \qquad (20\text{-a})$$

$$F_3 = 1.0 - 0.3\left(\frac{\mu_\Delta - 2.0}{4.0}\right) \text{ for } 2.0 \le \mu_\Delta \le 6.0 \qquad (20\text{-b})$$

$$F_3 = 0.7 \text{ for } \mu_\Delta \ge 6.0 \qquad (20\text{-c})$$

3.3 Proposed Nominal Shear Strength for Bridge Columns

The nominal shear strength (V_n) is evaluated as the sum of nominal concrete shear strength (V_C) and nominal shear strength provided by shear reinforcement (V_S).

$$V_n = V_C + V_S \tag{21}$$

The shear force carried by concrete V_C, is related to shear stress , and effective cross sectional area A_{eff} which is taken as 80 % of the gross sectional area (A_g) [1,10,13,14].

$$V_C = v_c\, A_{eff} \tag{22}$$

$$A_{eff} = 0.80\ Ag \tag{23}$$

The contribution of transverse reinforcement to shear strength is based on a truss mechanism using a 45° angle between the diagonal compression struts and the column longitudinal axis [10,11].

$$V_S = \frac{A_v\, f_{yt}\, d}{s} \tag{24}$$

A_v is the area of shear reinforcement, f_{yt} is the yield strength of web reinforcement and s is the spacing of shear reinforcement. For circular members with circular ties, hoops, or spirals; used as shear reinforcement, it is permitted to take the effective depth, d, as 0.80 times the diameter of the concrete section, and A_v can be taken as two times the area of the bar cross section used as the spiral [11].

From equations (22) to (24), the nominal proposed shear strength is given as:

$$V_{Proposed} = v_c\ 0.80\ A_g + \frac{A_v\, f_{yt}\, d}{s} \tag{25}$$

Introducing the effects of displacement ductility level, shear span to depth ratio, longitudinal steel ratio, and in equation (25), the design equation is rewritten in the final form as:

$$V_{Proposed} = F_3\ F_2\ \frac{f_t}{F_1}\sqrt{1 + \left(\frac{P}{f_t\, A_g}\right)}\ 0.80\, A_g + F_3\ \frac{A_v\, f_{yt}\, d}{s} \tag{26}$$

4. Validation and Comparative Studies

4.1 Validation Studies

In order to validate the proposed shear model, the experimental results of forty-seven rectangular columns [2,3,4,5,14], and thirty-eight circular columns [6,7,8,9] are used. Shear results are presented in the form of graphs relating the experimentally recorded strengths to the strengths obtained from the proposed model. The analyzed columns have shear span to depth ratio (a/d) ranging from 1.10 to 4.10, axial load level from 0.00 to 0.61. The longitudinal and transverse reinforcement ratios ranging from 0.00 % to 4.00 % and 0.00 % to 1.02 % respectively. The concrete compressive strength ranged from 13.10 to 49.30 MPa.

The predicted shear force ($V_{proposed}$) versus the obtained experimental shear force (V_{exp}) for 85 columns is plotted in Fig. (3). The overall average value of the ratio between the experimental shear force (V_{exp}) and the predicted shear force ($V_{proposed}$) is of value 1.21 for circular columns with standard deviation of 0.16, while the ratio is 1.25 with standard deviation of 0.19 for rectangular columns. These values indicate that the proposed shear model gives good predictions with consistent results. Generally speaking, the proposed shear model is on the safe side and gives consistent predictions.

4.2 Comparative Studies with Design Codes and Equations

The shear strengths of circular and rectangular columns were re-calculated using the design codes ACI 318-11 [10] and ECP-203 [11]. Fig. (4) and Fig. (5). provide quick judgment of the results. For circular columns, the mean ratio of the experimental to the predicted strength and its standard deviations are 1.37 and 0.27 for American code, and 1.44 and 0.29 for Egyptian code. For rectangular columns, the average ratio of the experimental to the predicted shear strength and its standard deviations are 1.47 and 0.29 for ACI 318-11 [10], and 1.82 and 0.36 for ECP-203 [11]. Generally, the predictions of design codes for shear strength of columns are more conservative as the effects of shear span to depth ratio, longitudinal steel ratio and displacement ductility ratio are neglected in the design equations.

Using design criteria of Caltrans [12] and USCD [1], the shear strengths of circular and rectangular columns were re-evaluated. The predicted ultimate shear strengths by the first method (V_{CALTR}) and second model (V_{USCD}) versus the obtained experimental shear strength (Vexp) are plotted in Fig. (6) and Fig. (7), respectively. For circular columns, the average ratio of the experimental to the predicted strength and its standard deviations are 1.05 and 0.22 for Caltrans method, and 1.02 and 0.10 for USCD approach. For rectangular columns, the mean ratio of the experimental to the predicted shear strength and its standard deviations are 1.22 and 0.25 for the first approach, and 1.08 and 0.23 for the second approach. From Figs. (6) and (7), it is clear that a reasonable portion of the predicted results are on the unsafe side, especially for rectangular columns.

4.3 Reliability Studies

In order to investigate the validity and applicability of the proposed shear model across the range of several key parameters, Fig. (8) and Fig. (9), show the effect of concrete compressive strength (f_c\`) and axial load level ($P/f_c`A_g$) on ultimate shear predictions. The effects of stirrups volumetric ratio (ρ_s) and stirrups yield stress (f_{yt}) on ultimate shear predictions are plotted in Fig. (10) and Fig. (11). Shear span to depth ratio (a/d) and longitudinal reinforcement ratio (ρ_L) effects on ultimate shear predictions are shown on Fig. (12) and Fig. (13). In these figures, the ratios of experimental ultimate shear strength, (V_{exp}) to analytical shear strength ($V_{proposed}$) versus the studied parameters were plotted for both circular and rectangular reinforced concrete columns. The figures show that the scatter is low and uniform for the entire set of all variables, and there are good correlation between the experimental and predicted strengths. It also presents a strong evidence for the reliability of the proposed model to calculate seismic shear strength of bridge columns with different geometrical properties, concrete compressive strengths and total reinforcement ratios.

5. Conclusions

From the validation, parametric, and comparative studies for the proposed shear design method for RC bridge columns the following conclusions are made:

1- The proposed seismic shear design method for RC columns is successful in predicting the strength of 38 circular columns and 47 rectangular columns with different material, geometrical, loading, and steel parameters. The overall average value of the ratio between the experimental shear strength to the predicted strength is of value 1.21 for circular columns, while the ratio is 1.25 for rectangular columns.

2- The predictions of American and Egyptian design codes for shear strength of columns are more conservative as the effects of shear span to depth ratio, column axial load, longitudinal steel ratio and displacement ductility ratio are neglected in the design equations. For ACI 318-11 and ECP-203, the overall mean ratio of the experimental to the predicted strength is respectively 1.37 and 1.44 for circular columns, and 1.47 and 1.82 for rectangular columns.

3- Using design criteria of Caltrans and USCD, the predicted shear strengths of RC columns are less-conservative. A portion of the predicted results are on the unsafe side, especially for rectangular columns. For Caltrans SDC and Modified UCSD approaches, the overall average ratio of the experimental to the predicted strength is respectively 1.05 and 1.02 for circular columns, and 1.08 and 1.02 for rectangular columns.

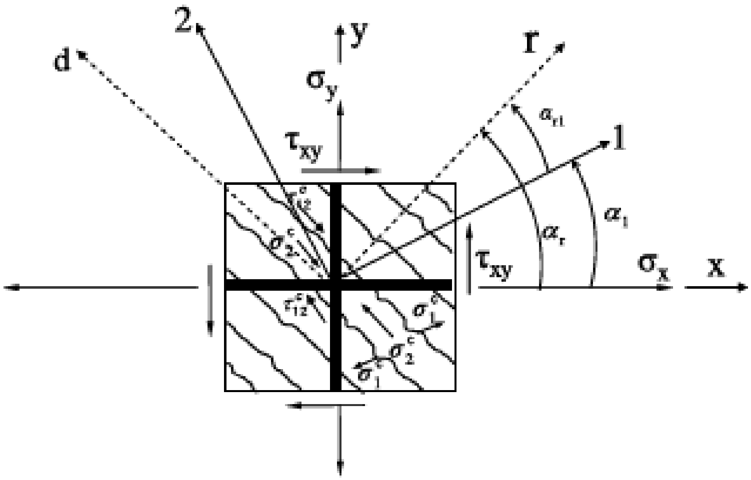

Fig. 1. Principle Stresses of R.C Element

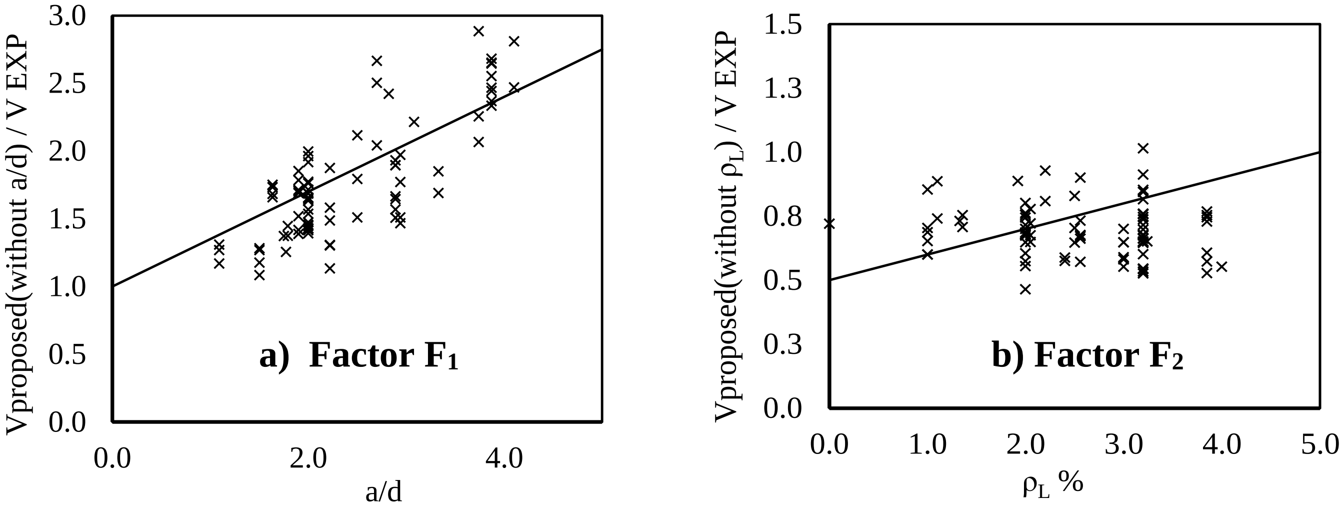

Fig. 2. Normalized Shear Strength versus Shear Span to Depth Ratio and Longitudinal Reinforcement Ratio.

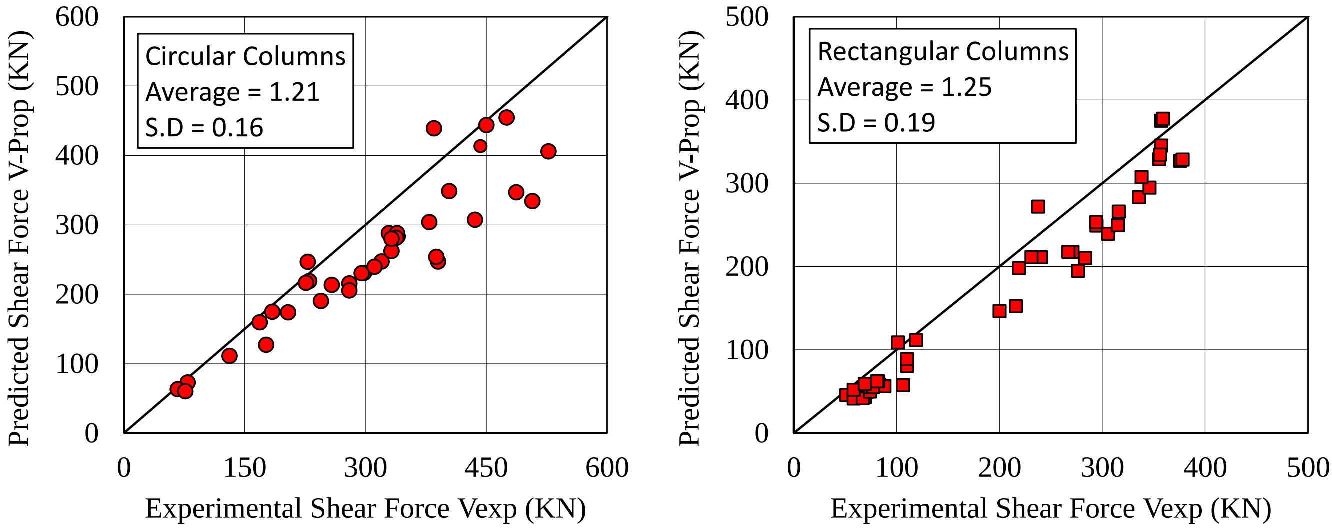

Fig. 3. Shear Force Predictions by the Proposed Model

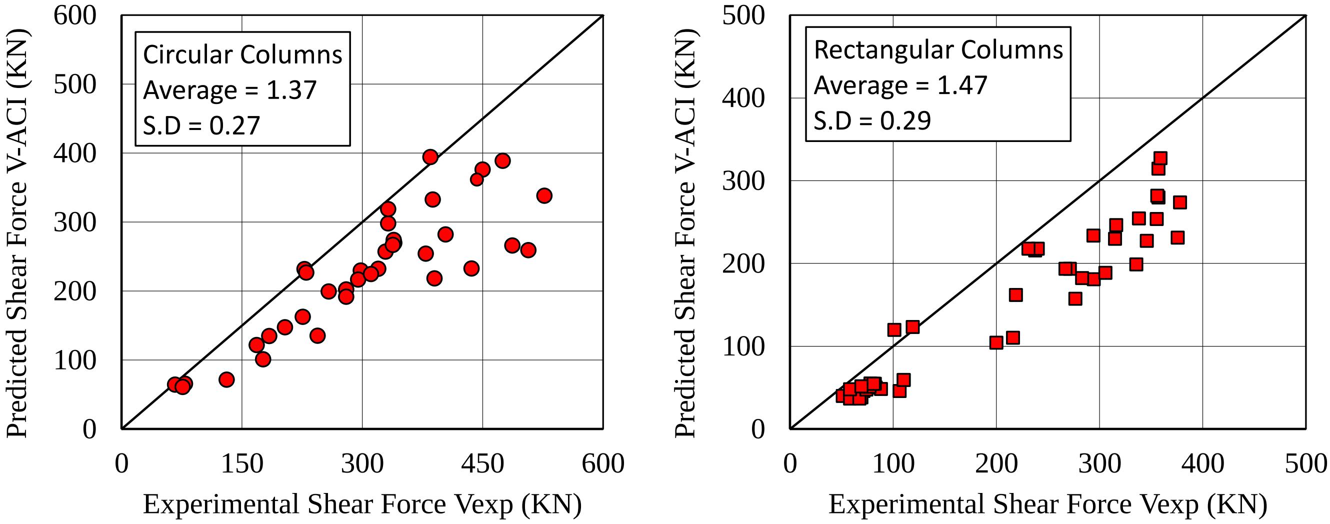

Fig. 4. Shear Force Predictions by ACI 318-11 [10]

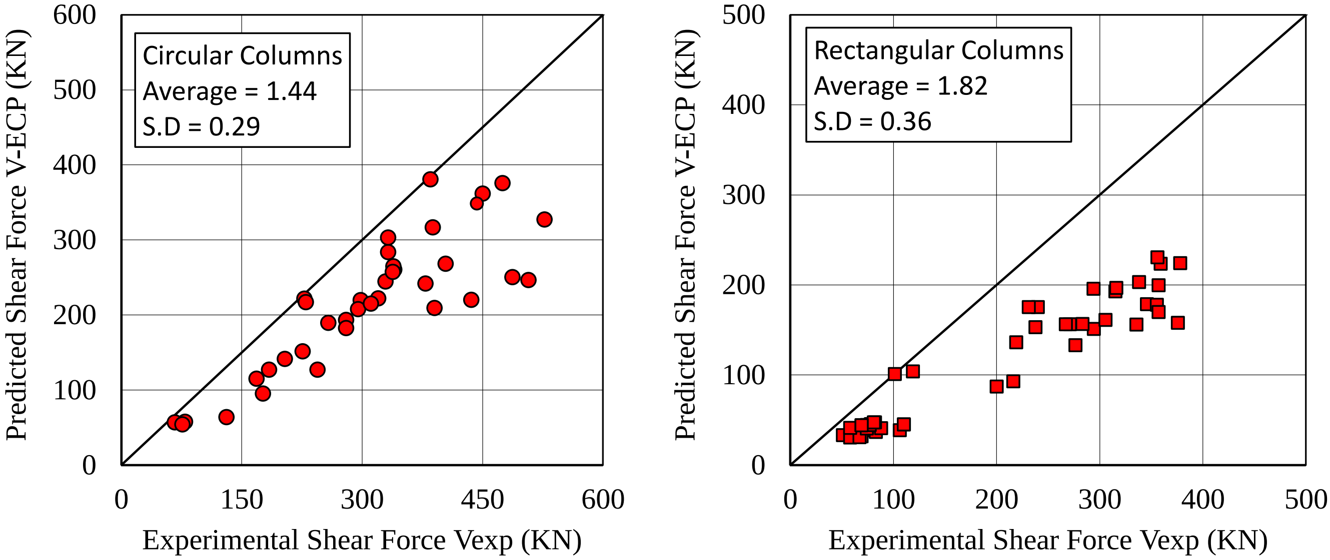

Fig. 5. Shear Force Predictions by ECP-203 [11]

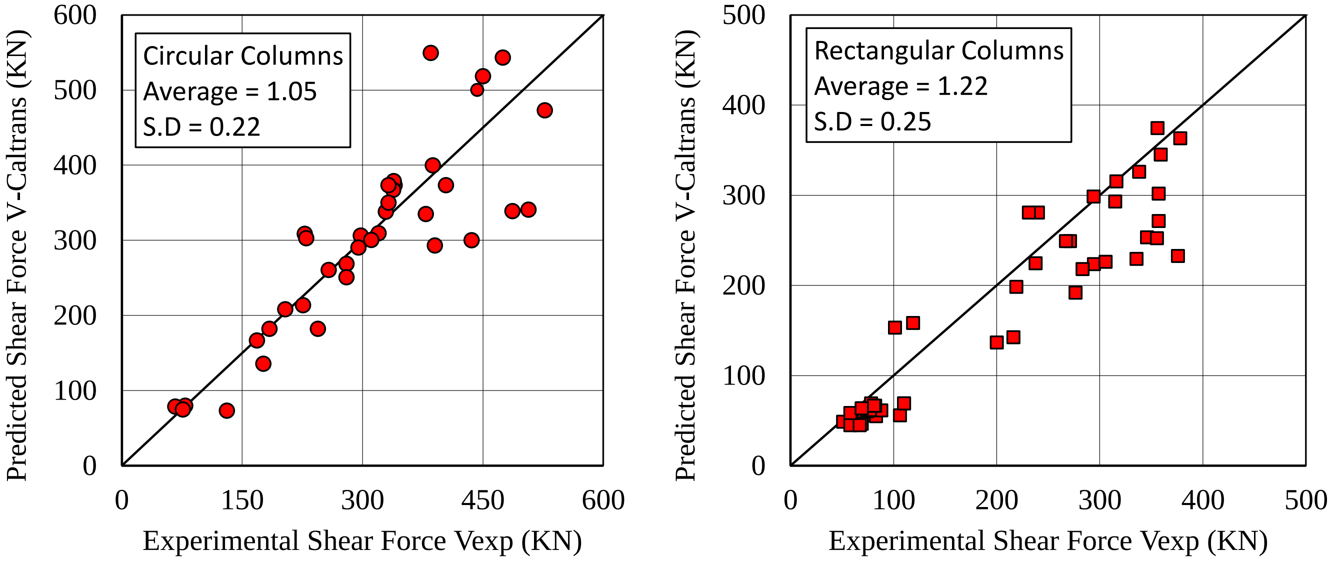

Fig. 6. Shear Force Predictions by Caltrans SDC [12]

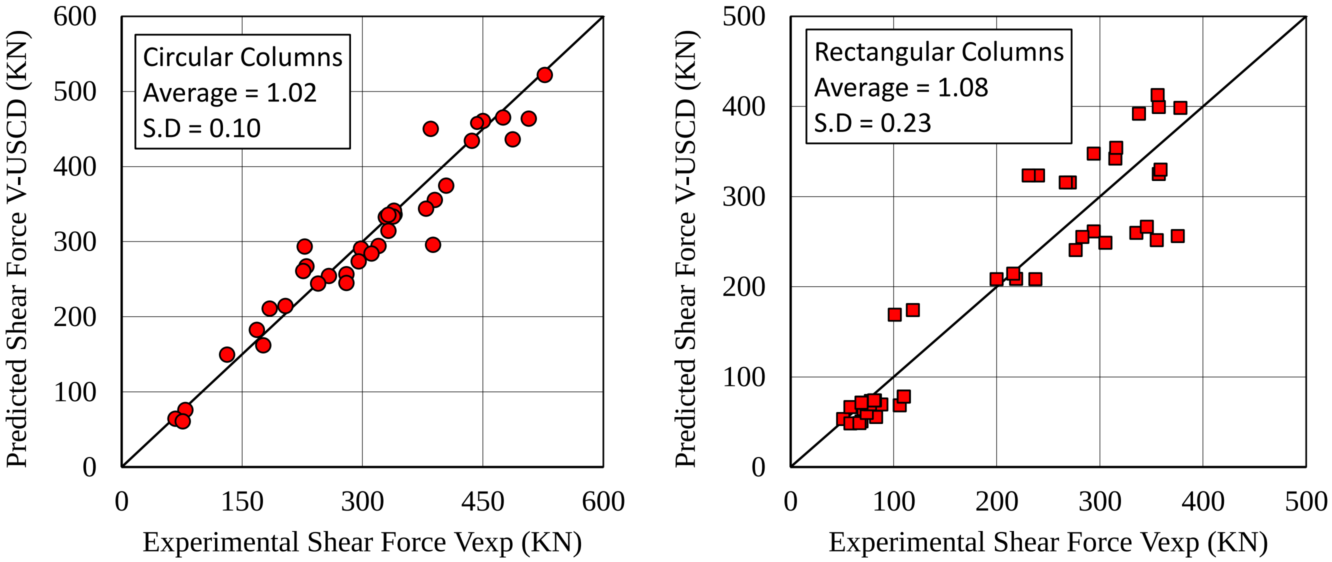

Fig. 7. Shear Force Predictions by UCSD model [1]

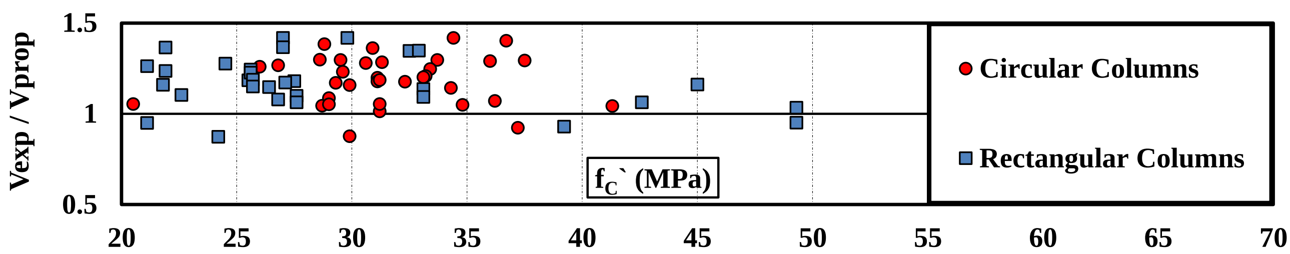

Fig. 8. Effect of Concrete Compressive Strength on Ultimate Shear Predictions

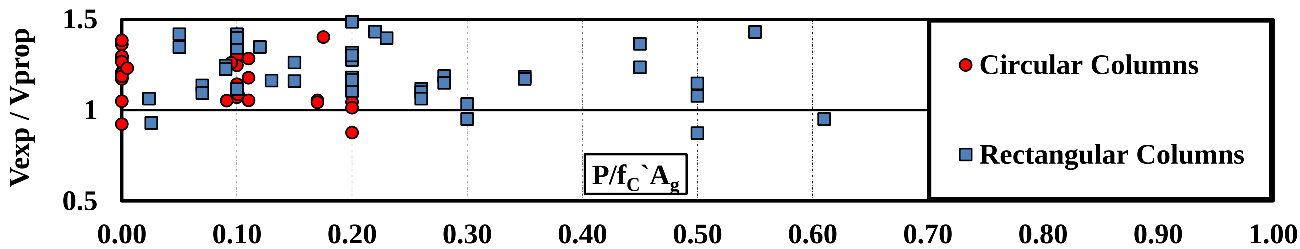

Fig. 9. Effect of Axial Load Level on Ultimate Shear Predictions

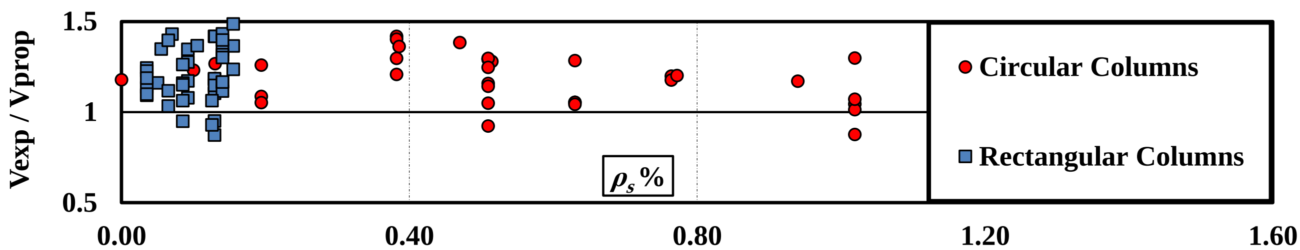

Fig. 10. Effect of Stirrups Volumetric Ratio on Ultimate Shear Predictions

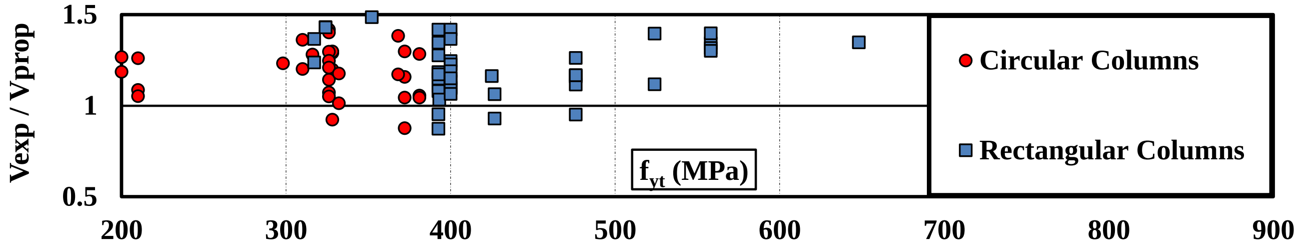

Fig. 11. Effect of Stirrups Yield Strength on Ultimate Shear Predictions

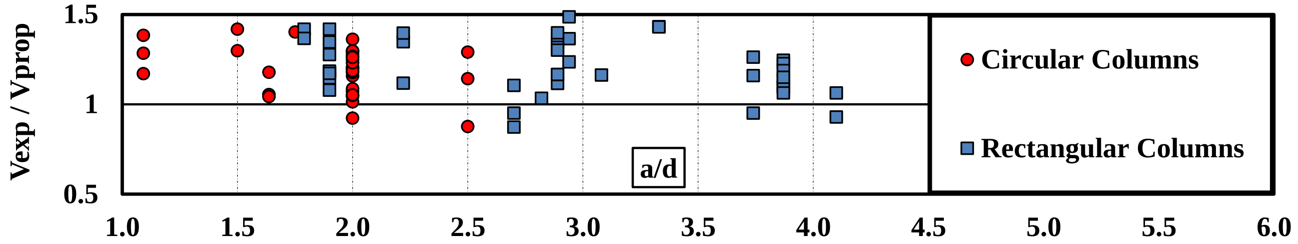

Fig. 12. Effect of Shear Span to Depth Ratio on Ultimate Shear Predictions

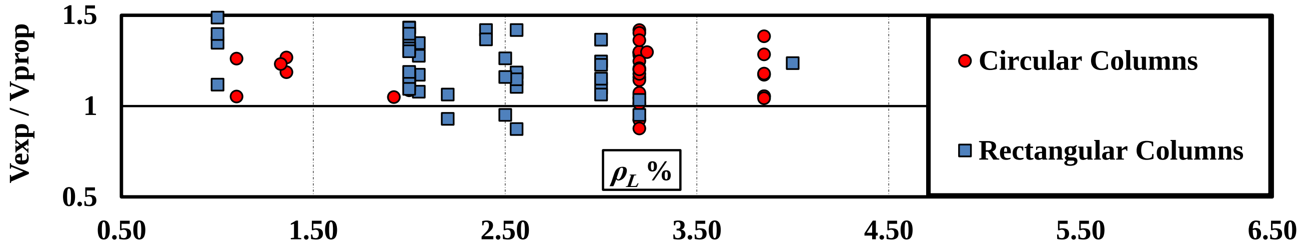

Fig. 13. Effect of Longitudinal Reinforcement Ratio on Ultimate Shear Predictions

REFERENCES

1. Mervyn J. K. and Nigel P.M.J. (2000). "Improved Analytical Model for Shear Strength of Circular Reinforced Concrete Columns in Seismic Regions" ACI Structural Journal, V. 97, No. 3. May-June 2000.
2. Cao T., and Bing L., (2014). "Shear Strength Model for Reinforced Concrete Columns with Low Transverse Reinforcement Ratios" Advances in Structural Engineering Vol. 17 No. 10
3. Zuanfeng, P., and Bing, Li., (2013). "Truss-Arch Model for Shear Strength of Shear-Critical Reinforced Concrete Columns" Journal of Structural Engineering ASCE.
4. Lee, H.H. (2006). "Shear Strength and Behavior of Steel Fiber Reinforced Concrete Columns under Seismic Loading", Engineering Structures, Vol. 29, No. 7, pp. 1253–1262.

5. Govinda, P., and Hiroshi, M., (2005). “Seismic Performance of Reinforced Concrete Piers with Bond-Controlled Reinforcements” ACI Structural Journal, V. 102, No. 2.
6. Ang, B.G., Priestley, M.J.N. and Paulay, T. (1989), “Seismic shear strength of circular reinforced concrete columns,” ACI Structural Journal, V.86, pp. 45-59.
7. Arakawa, T.H., Ming, X., Arai, Y.; and Mizoguchi, M., "Ultimate Shear Strength of Spirally-Confined Concrete Columns", Transactions of the Japan Concrete Institute, Vol.9, 1987, pp. 305-312.
8. Ohtaki, T.; Benzoni,G., Priestley, M.J.N., "Seismic Performance of a Full-Scale Bridge Column - As Built and As Repaired," University of California, San Diego, Structural Systems Research Project, Report No. SSRP-96/07, November, 1996.
9. Omar, A., David I. McLean, and M. Lee “Performance of Existing Bridge Columns under Cyclic Loading-Part 2: Analysis and Comparisons with Theory” ACI Structural Journal, V. 96, No. 1, January-February 1999.
10. ACI 318 (2011). Building Code Requirements for Structural Concrete and Commentary, American Concrete Institute, Michigan, USA
11. Egyptian Code of Practice: ECP 203-(2007), “Design and Construction for Reinforced Concrete Structures,” Ministry of Building Construction, Research Center for Housing, Building and Physical Planning, Cairo, Egypt.
12. Caltrans (2013), "Seismic Design Criteria", SDC-2013, California Department of Transportation, Sacramento, CA.
13. Priestley, M.J.N., Calvi, M.C., and Kowalsky, M.J. (2007),"Displacement-Based Seismic Design of Structures", IUSS Press, Pavia, 670 pp.
14. Sezen, H. and Moehle, J. (2004). “Shear Strength Model for Lightly Reinforced Concrete Columns”, Journal of Structural Engineering, ASCE, Vol. 130, No. 11, pp. 1692–1703.
15. Ascheim, A., and Moehle, J. P. (1992), "Shear Strength and Deformability of RC Bridge Columns Subjected to Inelastic Cyclic Displacements." Rep. No. UCB/EERC-93/04, Earthquake Engrg. Res. Ctr., University of California Berkeley.
16. Oakdale Engineering: Data Fit User’s Manual, Oakdale Engineering, Oakdale, PA, USA, 2005.