A study on precdiction of shear strength of RC shear-wall with openings

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ABSTRACT

Reinforced Concrete (RC) walls with openings are widely used in modern buildings due to their shear stiffness and effectiveness in implementing architectural ideas and solutions such as traffic flow, ventilation, lighting, etc. However, design practices often overlook the effects of openings, especially in designs in Vietnam. This study proposes to examine 3 simplified methods for calculating the shear capacity of this type of wall using approximate methods with reduced strength coefficients: Ono, AIJ, and Kitano modification. Verification results with 83 experimental samples, expressed as the ratio between the experimental critical shear force and the calculated value, show that the Ono and Kitano modification methods give higher calculated values compared to experiments, with average ratios of (0.95; 0.98) and (0.92, 0.90) for push and pull load directions respectively. The AIJ calculation results are lower than experimental results with the average ratio of (1.11; 1.10). The CoV coefficient shows that the Kitano modification method has the lowest result dispersion with a CoV of 0.16 for both force directions. Based on the survey and evaluation of the 3 methods, the author proposes a strength reduction factor of 0.708 when calculating the critical strength of RC walls using the AIJ method in design problems. The average ratio for the proposed coefficient is 1.56 and 1.55 for push and pull directions. The CoV value of 0.18 indicates that the results are entirely suitable for practical structural design problems.

Keywords: *AIJ method, Modified Kitano method, Ono method, RC Wall with openings, Shear strength.*

1. INTRODUCTION

The design of modern buildings, both low-rise and high-rise, has become increasingly focused on providing adequate lateral load resistance, particularly against wind and earthquake forces, with shear walls commonly used to provide the necessary strength and stiffness. In seismic design, the architectural design of low-rise housing has trended towards using reinforced concrete walls with openings (RCWO) to accommodate requirements such as passageways, lighting, and ventilation. However, this design approach has been observed to be vulnerable during earthquakes, with the first floors of these buildings often sustaining the most damage or even collapse, as evidenced by the destruction caused by previous seismic events, a phenomenon also observed in other high-seismic regions around the world that have adopted similar design approaches. As a result, the seismic behavior of these perforated walls has attracted significant research interest, particularly since the 1980s, with previous research showing that the strength and ductility of PRCW are influenced by the size and location of the openings within the wall, leading to a better understanding of the factors that affect the performance of these structural elements under lateral loading conditions, which must inform the development of more robust and reliable design approaches for these types of buildings, especially in seismic-prone areas.

The seismic performance of low-rise buildings, particularly those with reinforced concrete walls with openings, has been a serious concern for researchers and designers, with the damage and collapse of street houses during earthquakes highlighting the vulnerability of this type of structural system. While the current ACI code [1] provides provisions to determine the strength capacity of vertical and horizontal segments of walls with openings, it may not directly present a straightforward procedure to evaluate the strength capacity of framed structural walls with openings, necessitating the need to find a more comprehensive method to evaluate the strength and apply it to the design of perforated RC walls. Julian Carrillo [2], a wall specimen with one door and one window, as shown in Figure 2.10, was tested to propose a modified shear strength equation for Section 18.10 of ACI 318-14. More experiments need to be conducted better to understand the behavior of this type of wall. However, only a limited number of experimental studies have been carried out to investigate the structural behavior of this specific type of perforated wall.

C.P. Taylor [3] applied the Strut-and-Tie model to design slender reinforced concrete walls, which showed a highly complex configuration due to the presence of several steep strut elements. To simplify the approach, Bing Li [4] modified and applied a simplified Strut-and-Tie model based on the behavior of a slender RC wall, and the yielding strength is predicted by determining the yield strength in the tie member, corresponding to the peak yielding strength of the reinforcement bars. While the Strut-and-Tie model can provide insights into the behavior of RC walls, their applications may be complex and necessitate simplifications, but it can be used to evaluate the shear strength of RC walls with openings.

The earliest research to develop a simplified method to predict the shear capacity of reinforced concrete walls with openings was proposed by Ono [5] in the 1980s and AIJ (Architectural Institute of Japan) [6], which used a reduction factor, r, to predict the peak shear strength. In a similar method proposed by Kitano's method [7], Kitano introduced another reduction factor, γ, to account for the effect of the opening zone on the Diagonal Compression Strut in the presence of openings, all aiming to provide more accurate and reliable ways to evaluate the strength of perforated RC walls that can be applied in the design of low-rise buildings in seismic-prone areas.

To support engineers in the simple calculation and design of reinforced concrete walls with openings, this study will discuss and evaluate the simplified calculation methods of Ono, Kitano, and AIJ. Finally, we suggested an effective method that can be used to predict the shear capacity of walls for practical design.

2. MATERIALS AND METHOD

This study on the shear capacity of reinforced concrete walls with openings will introduce and discuss simplified methods using reduction factors. At the same time, 83 test specimens of RC walls with openings [5, 8-28], that failed in shear have been compiled. These data were used to validate the methods proposed by Ono, Kitano, and AIJ. Among them, the author has modified the Kitano method using the compression depth of the Diagonal Compression Strut.

The reinforced concrete wall with openings walls are important structural components that provide serviceability, building safety, and architectural benefits, particularly in low-rise housing where they are commonly used as the main lateral load-resisting systems, and the evaluation of their shear strength has attracted significant research interest since the 1980s, though the earliest work did not directly determine the shear strength of walls with openings but rather predicted the approximate ultimate strength based on experimental evidence, such as the approach proposed by Ono and Tokuhiro, this method assumed that the shear distribution is contributed only by the effective concrete compressive field with a cracking angle of 45 degrees and used a shear strength reduction factor to approximate the ultimate strength, with the predicted shear strength found to be close to experimental results, which showed that the opening size affects the shear strength and failure mode of perforated RC walls, though the weakness of their approach was the limited upper limit of the opening size in the available experimental specimens and the assumption of a 45-degree diagonal compressive field, indicating the need for further research to develop more comprehensive and accurate methods for evaluating the shear strength of RC walls with openings, particularly in addressing the limitations of the earlier approaches and expanding the range of applicability. Equations 1, 2, and Figure 1 present the Ono proposition.

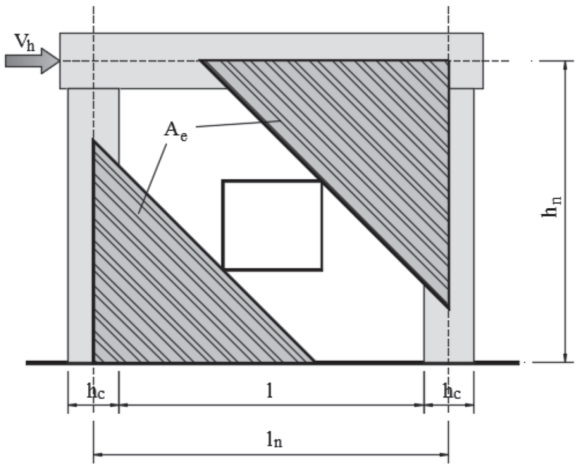


Figure 1. Approximated method using shear strength reduction factor by Ono

$$V_o = r_u V \quad \text{(Eq. 1)}$$

$$r_u = \sqrt{\frac{\Sigma A_e}{A}} = \sqrt{\frac{\Sigma A_e}{l_n h_n}} \quad \text{(Eq. 2)}$$

Where A_e is the total area of the effective concrete compressive field (cm^2); A is the effective area of the wall (cm^2), defined as the area of l_n and h_n; V is the shear strength of RC wall without opening, can be estimated by Hirosawa's equation [8] (kgf).

The AIJ standard presents a simplified approximated equation using a shear strength reduction factor, r, to predict the peak shear strength of walls with openings, expressed in Figure 2 and Equations 3 to 6. However, the AIJ provision seems to have a limitation in that it does not consider the effects of the opening location on the shear strength, accounting only for the geometrics of the openings, such as the length, l_{oi}, and height, h_{oi}, of the openings relative to the total length (l_w) and height (h_w) of the wall. At the same time, the search results indicate that the location of the openings within the wall can also influence the shear strength, which is not captured by the AIJ equation, necessitating the need for more comprehensive methods to evaluate the shear strength of perforated RC walls by considering the effects of both the opening size and location, in order to provide more accurate assessments of the shear capacity of this type of structural system.

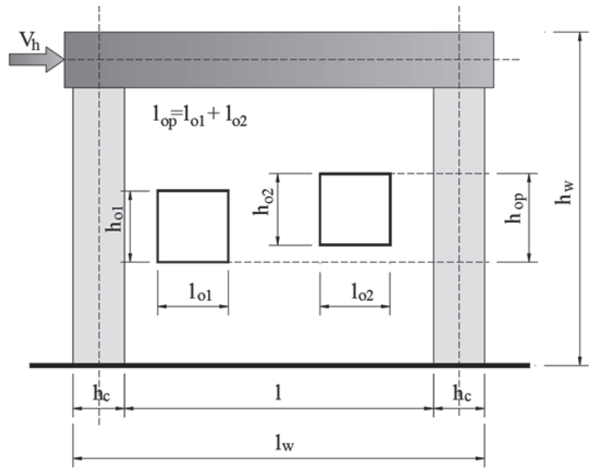


Figure 2. Approximated method using shear strength reduction factor by AIJ

$$V_{AIJ} = rV \quad \text{(Eq. 3)}$$

$$r = \min\{r_1, r_2, r_3\} \quad \text{(Eq. 2)}$$

$$r_1 = 1 - 1.1\frac{l_{op}}{l_w} \quad \text{(Eq. 4)}$$

$$r_2 = 1 - 1.1\sqrt{\frac{l_{op} h_{op}}{l_w h_w}} \quad \text{(Eq. 5)}$$

$$r_3 = 1 - \frac{\sum h_o}{h_w} \quad \text{(Eq. 6)}$$

Where: l_{op} and h_{op} are the effective length and height of the openings, respectively (cm); l_w and h_w are the effective length and height of the RCWO, respectively (cm); V_{AIJ} is the shear strength of RCWO based on the AIJ method (kgf);

Based on the assumption that the shear strength is provided by the Diagonal Compression Strut within the wall, Kitano [7] proposed a method to estimate the shear capacity of reinforced concrete wall specimens with openings. This method assumed a 45-degree inclined crack angle and introduced a reduction factor, γ, to account for the effect of the opening zone on the Diagonal Compression Strut. However, this method proposes using a Diagonal Compression Strut, so the influence of the axial force needs to be considered further. To address this limitation, a modified Kitano method was proposed by using the Diagonal Compression Strut model of Zhang and Jirsa [29] and the Simplified depth of the wall compression zone as is approximated with Paulay and Priestley equation [30], in addition to the reduction factor, γ, to estimate better the shear capacity of RC walls with multiple openings, aiming to provide a more accurate assessment of the shear strength of perforated RC walls by accounting for the effects of the opening size, location, and the compression depth of the diagonal strut as shown in Figure 3 and Equation 7 to 9

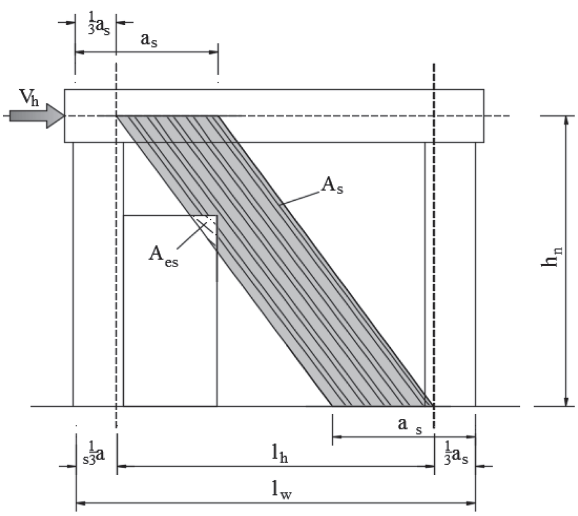


***Figure** 3. Modified Kitano model for the RC wall's shear strength reduction factor with openings.*

$$V_{MKitano} = \gamma V \quad \text{(Eq. 7)}$$

$$\gamma = \frac{A_s - A_{es}}{A_s} \quad \text{(Eq. 8)}$$

$$a_s \approx \left(0.25 + 0.85\frac{N_u}{l_w t_w f_c^{`}}\right) l_w \quad \text{(Eq. 9)}$$

Where: $V_{MKitano}$ is the shear strength of RCWO based on the Modified Kitano method (kgf); V is the shear strength of the wall without opening and can be estimated by Hirosawa's equation (kgf); N_u is the axial load (kgf); f'_c is the compressive strength of the concrete (kgf/cm²); l_w and t_w are the length and thickness of the section in the direction of the shear force (cm).

Finally, the shear strength of shear walls without opening can be predicted by Hirosawa's equation, also called Modified-Arakawa's equation. Hirosawa's formula (Eq. 10) is an empirical equation that is extensively used in Japan [6] to calculate the ultimate shear strength of shear walls.

$$V = Q_u = \left\{ \frac{0.0679\rho_t^{0.23}\left(F_c + 180\right)}{\sqrt{M/VD + 0.12}} + 2.7\sqrt{f_{yw}\rho_w} + 0.1\sigma_o \right\} b_e j \quad \text{(Eq. 10)}$$

Where: $b_e = \left(\Sigma b_c h_c + l t_w\right)/\left(l + \Sigma h_c\right)$ is the effective thickness of wall (cm); b_c and h_c are the depth and the width of boundary columns (cm), respectively; j is the distance between centers of tension and compression, $j = 7l_w/8$ (cm); ρ_t is the tension axial steel ratio considering a wall as a column; $_t = 100A_t / b_e j$ (%); A_t is the total tension steel area in a flange (cm²); *M/VD* is the shear span ratio; ρ_w is the horizontal steel ratio using the effective thickness; F_c is the compressive strength of concrete (kg/cm²); f_{yw} is the horizontal steel yield stress (kg/cm²); σ_o is the average axial stress (kg/cm²).

3. RESULTS AND DISCUSSION

3.1. Experimental verification

To provide a comprehensive perspective, this study compared three sets of shear strength equations predicated on the Ono method, the AIJ method, and the Modified Kitano method against empirical test results, leveraging a corpus of eighty-three extant experimental datasets about reinforced concrete walls with openings to validate the predicted shear strengths derived from these three methodologies, with this multifaceted approach engendering a more nuanced understanding of the relative merits and limitations of each method, ultimately facilitating the selection of the most efficacious technique for practical design applications. The typical reinforced concrete wall with opening specimens is shown in Figure 1, in which the ratio γ_r is defined as $\gamma_r = l_{op}h_{op}/l_n h_n$.

Three methods for predicting the shear strength of reinforced concrete squat walls were evaluated in this study: the Ono method, which considers the effect of the opening zone on the contributed area; the AIJ method, which accounts for the effect on the area of transferred loading; and the Modified Kitano method, which incorporates the impact on the diagonal strut area. These three methods were compared against the measured peak shear strengths of 83 RC wall specimens [5, 8-28].

Table 1: Summary of Experimental Data

		From the value of	To the value of
Aspect ratio (h_w/l_w)		0.38	1.01
Compressive strength of concrete (kg/cm²)		178.5	828.0
Axial compression stress (kg/cm²)		0	110
Flange	Thickness t_w (cm)	3.0	10
	Longitudinal bars ratio	0.785	3.980
	Longitudinal bars yielding strength (kg/cm²)	3306	4069
	Transverse bars ratio	0.111	1.713
	Transverse bar yielding strength (kg/cm²)	1632	5537
Web	Column width b_c (cm)	15	35
	Column depth h_c (cm)	15	35
	Vertical bars ratio	0.223	2.261
	Vertical bars yielding strength (kg/cm²)	1632	5537
	Horizontal bars ratio	0.223	2.261
	Horizontal bars yielding strength (kg/cm²)	1632	5537

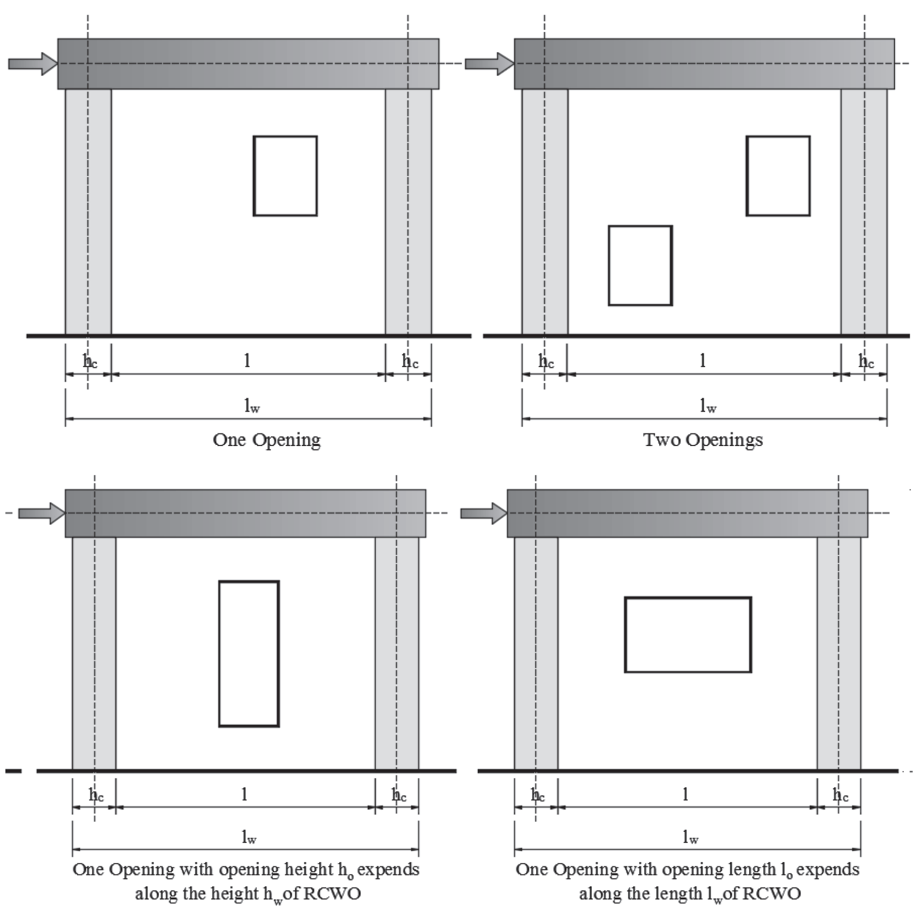
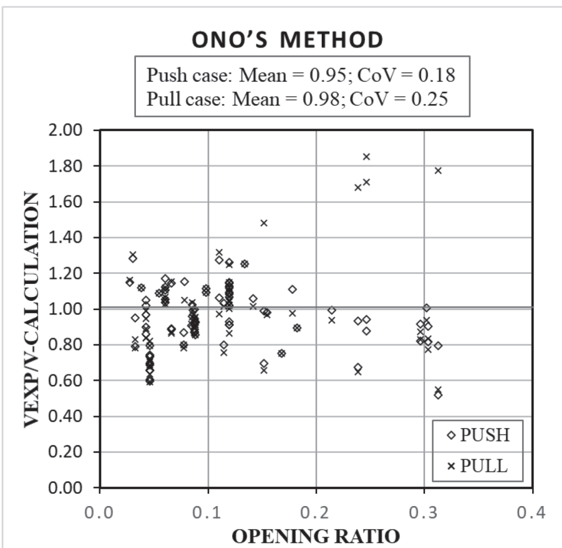
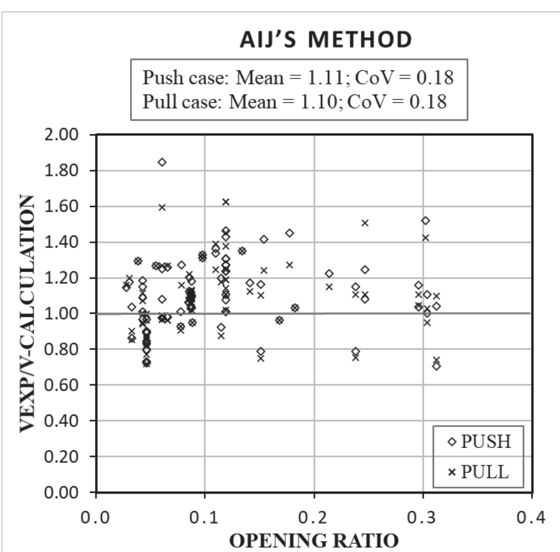


***Figure** 4. The typical reinforced concrete wall with openings specimens.*

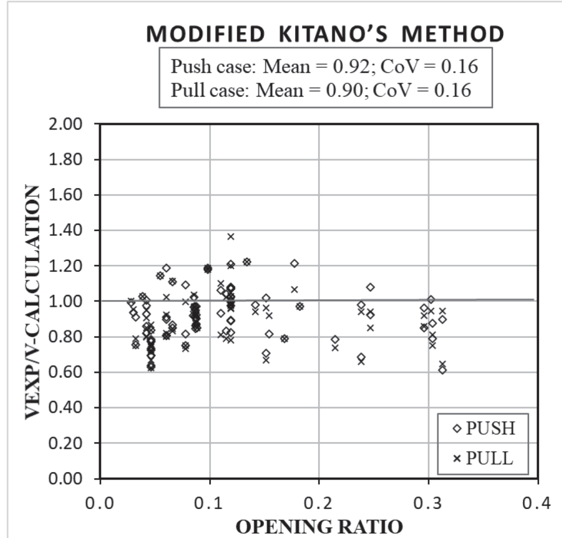
Figure 4 presents the examination of the existing experimental data, and it is worth mentioning that the application of reduction factors in this study discussion has a good prediction. The results showed that the Ono method yielded Mean values of 0.95 and 0.98 with Coefficient of Variation (CoV) of 0.18 and 0.25 for push and pull load directions, respectively. The AIJ method had better Mean values of 1.11 and 1.10 with a CoV of 0.18 for both push and pull load directions. The Modified Kitano method had the lowest Mean values of 0.92 and 0.92 with the lowest dispersion, as indicated by the CoV coefficients 0.16 for both load directions.



a) Ono's method



b) AIJ method



c) Modified Kitano method

***Figure** 5. Calculated shear strength by discussed methods*

*3.2. The proposed factor for Technical designer*The comparative results showed that the Kitano method with the lowest ratio coefficients means that the predicted shear strength values calculated are higher than the actual values; however, this method only considers the Diagonal Compression Strut, so in some cases where the opening locations are outside the influence zone of the diagonal strut, it will be a significant limitation. Therefore, the Modified Kitano method is not suitable for recommendation in design. The Ono method, which considers the stress distribution zone but does not account for the effect of openings, has a ratio coefficient of less than 1 and the highest dispersion, so it also has a similar meaning to the Modified Kitano method. Additionally, calculating the areas of the stress distribution zones requires using complex geometric factors, which will be time-consuming.

In contrast, although the AIJ method still has limitations, it does not consider the difference in shear strength reduction factors between the push and pull load direction. However, the AIJ method showed the most conservative result with mean values greater than 1 and an appropriate dispersion coefficient (CoV = 0.18) for both load directions. Therefore, this study proposes using a total strength reduction factor g_s in calculating shear strength according to the AIJ method, as shown in equation 11. Examining the change in g_s values from 0.1 to 1.0 indicates that a g_s value of 0.708 is appropriate, achieving coefficients greater than one in most calculation cases.

The results when applying the $\gamma_s = 0.708$ factor to the AIJ design method demonstrated that the shear strength prediction is completely suitable, simple yet effective, and safe (Eq. 11). The result shows that the mean values of this study proposed factor are 1.56 và 1.55 for push and pull load directions, with the CoV is 0.18 for both of load directions. Consequently, the AIJ method combined with the 0.708 reduction factor is the optimal choice for engineers to use in practical design applications.

$$V_{opening} = \gamma_s V_{AIJ} \quad \text{(Eq. 11)}$$

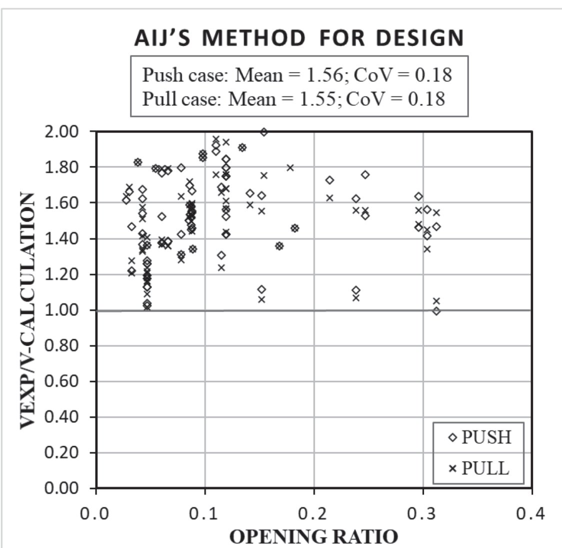


***Figure** 6. The result of the suggested method*

4. CONCLUSION

This comprehensive study evaluated three methods for predicting the shear strength of reinforced concrete squat walls with openings: the Ono, AIJ, and Modified Kitano. These three approaches were compared against the measured peak shear strengths of 83 RC wall specimens, with the application of reduction factors demonstrating good predictive capability.

The Coefficient of Variation analysis showed that the AIJ and Modified Kitano methods exhibited more uniform predictions than the Ono method. Specifically, the Ono method yielded Mean values of 0.95 and 0.98 with CoV coefficients of 0.18 and 0.25 for push and pull load directions, respectively. The AIJ method had better Mean values of 1.11 and 1.10 with a CoV of 0.18 for both load directions. The Modified Kitano method had the lowest Mean values of 0.92 and 0.92 with the lowest dispersion, as indicated by the CoV coefficients of 0.16.

However, the existing experimental data used in this study were limited to walls with an opening ratio (opening area/wall area) smaller than 0.4. Therefore, these approaches are recommended for shear walls with an opening ratio of less than 0.4.

The results indicated that the Modified Kitano method, which considers the effect of the opening zone on the assumed Diagonal Compression Strut area, provides the most accurate and uniform predictions. Nonetheless, this method has a limitation in that it only accounts for the diagonal strut, and in some cases, the opening locations may fall outside the influence zone of the strut.

With the same Mean value as the Modified Kitano method, the Ono method predicts the Mean values smaller than 1, which implies a lack of safety. Additionally, calculating the areas of stress-distribution regions was complicated, and in some cases, these areas were minimal, making the results inconsistent with experimental results.

In contrast, the AIJ method exhibited Mean values greater than 1 and an appropriate dispersion coefficient (CoV = 0.18), suggesting its suitability for design applications. This study suggests using a 0.708 total strength reduction factor for the calculated V_{AIJ} value when designing. Applying the 0.708 factor to the AIJ design method demonstrated that the shear strength prediction is completely suitable, simple, effective, and safe.

In conclusion, the AIJ method combined with the 0.708 reduction factor is the optimal choice for engineers to use in practical design applications involving reinforced concrete walls with openings, particularly for walls with an opening ratio of less than 0.4.

REFERENCES

[1] American Concrete Institute, *ACI 318-14 Building Code Requirements for Structural Concrete and Commentary (Metric)*, American Concrete Institute, 2019.

[2] C. Julian and M. A. Sergio, *Shear Strength of Reinforced Concrete Walls for Seismic Design of Low-Rise Housing*, Structural Journal, 110(3) 2013.

[3] C. P. Taylor, P. A. Cote, and J. W. Wallace, *Design of Slender Reinforced Concrete Walls with Openings*, ACI Structural Journal, vol. 95, no. 4, pp. 420-433, 1998.

[4] B. Li and W. Hui, *Design of reinforced concrete walls with openings - strut-and-tie approach*, Nanyang Technological University, 2005.

[5] M. Ono and I. Tokuhiro, *Experimental Studies on Elasto-Plastic Behaviors of Reinforced Concrete Framed Shear Walls with Various Kinds of Openings*, Reports of the Faculty of Engineering, Kinki University in Kyushu. Science and technology section, vol. 14, pp. 33-63, 1985.

[6] Architectural Institute of Japan, *Standard for Structural Calculation of Reinforced Concrete Structures,* 8th ed., 2010.

[7] A. Kitano, O. Joh, and Y. Goto, *Experimental study on the strengthening and repair of R/C wall-frame structures with an opening by CF-Sheets or CF-Grids*, in CICE 2004, 2004, pp. 631-642.

[8] M. Ono, *Effects of Parameters of Framed Shear Walls with an Opening on Failure Behaviors*, in Summaries of technical papers of Annual Meeting Architectural Institute of Japan. Structures II, 1994, pp. 283-284.

[9] M. Ono and I. Tokuhiro, *Study on Estimate of the Shear Strength of Reinforced Concrete Framed Shear Walls with Opening*, Concrete Research and Technology, vol. 7, no. 2, pp. 53-64, 1996.

[10] M. Ono and I. Tokuhiro, *Experimental Studies on Elasto-Plastic Behaviors Reinforced Concrete Framed Shear Walls of Different Wall Thickness with Opening*, in Summaries of technical papers of Annual Meeting Architectural Institute of Japan. Structures II, 1989, pp. 599-600.

[11] M. Ono and I. Tokuhiro, *Experimental Studies on Elasto-Plastic Behaviors of Shear Walls with Different Wall Thickness*, Reports of the Faculty of Engineering, Kinki University in Kyushu. Science and technology section, 1989.

[12] I. Tokuhiro and M. Ono, *Experimental Studies on Elasto-Plastic Behaviors of Reinforced Concrete Shear Walls with Opening Except in Center*, in Proceedings of the Japan Concrete Institute, vol. 9, no. 2, 1987, pp. 385-390.

[13] M. Ono and I. Tokuhiro, *A proposal of reducing rate for strength due to opening effect of reinforced concrete framed shear walls*, Journal of structural and construction engineering, 435, 119-129, 1992.

[14] M. Ono and I. Tokuhiro, *Study on Estimate of the Shear Strength of Reinforced Concrete Framed Shear Walls with Opening*, Concrete research and technology, Japan Concrete Institute, vol. 7, no. 2, pp. 53-64, 1996.

[15] M. Ono and I. Tokuhiro, *Study on Estimate of the Shear Strength of Reinforced Concrete Framed Shear Walls with Opening (in Japanese),*" Concrete Research and Technology, 7(2), pp. 53-64, 1996.

[16] A. Urabe, *Experimental Study on shear strength of RC wall with a large opening,* in Proceedings of the Japan Concrete Institute, 2009.

[17] C. Yamazaki, *A Study on the reinforcement for new openings, in the existing wall*, in Proceedings of the Japan Concrete Institute, Japan, 2005.

[18] K. Fuzii, *Mechanical behavior of R/C framed shear walls with reinforced wall panel beside an opening*, in Proceedings of the Japan Concrete Institute, Japan, 2002.

[19] Y. Matsuoka, F. Esaki, and M. Ono, *Effect of loading rate on mechanical behavior of R/C framed shear walls with an opening*, in

Proceedings of the Japan Concrete Institute, Japan, 2003.

[20] T. Kabeyasawa, Y. Kikai, and T. Kimura, *Experimental study on reinforcement details of reinforced concrete shear walls with opening*, in Proceedings of the Japan Concrete Institute, Japan, 1988.

[21] T. Kabeyasawa and T. Kimura, *Ultimate strength reduction of reinforced concrete shear walls with an opening*, in Proceedings of the Japan Concrete Institute, Japan, 1989.

[22] H. Takeda and K. Ohtsuki, *Reinforcement concrete slender wall: experimental study on the shear stiffness of reinforced concrete slender walls with vertical opening*, Architectural Institute of Japan, pp. 455-459, 1991.

[23] M. Ono, I. Tokuhiro, and K. Kuratomi, *Experimental study on ultimate shear strength of reinforced concrete shear walls with vertical opening*, Architectural Institute of Japan, pp. 385-356, 1992.

[24] T. Nisiyama and M. Ono, *Experimental study on reinforced concrete opening wall above opening periphery ratio 0.4,* Architectural Institute of Japan, pp. 47-148, 1995.

[25] Y. Kanehira and M. Mochizuki, *Degradation behaviors of framed shear walls with an opening subjected to a repeated load at a high speed*, in Proceedings of the Japan Concrete Institute, Japan, 2000.

[26] H. Kumagai, *Structural behavior of high strength concrete shear walls*, Architectural Institute of Japan, pp. 611-612, 1990.

[27] H. Minoda, *Effect of loading rate on elasto-plastic behaviors of shear walls with opening (part1 and 2)*, Architectural Institute of Japan, 385-392, 1998.

[28] H. Aoyama, *Strength and behavior of post-cast shear walls for strengthening of existing reinforced concrete building*, in Proc. Of 8th WCEE, 1984.

[29] Zhang, L., J.O. Jirsa, and P.M.F.S.E. Laboratory, *A Study of Shear Behavior of Reinforced Concrete Beam-column Joints*. Phil M. Ferguson Structural Engineering Laboratory, University of Texas at Austin, 1982.

[30] Robert Park and Thomas Paulay, *Reinforced Concrete Structures,* John Wiley & Sons, Inc, 1975