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Ultimate Axial Strength Equation of RC Thin Walls with Openings

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Abstract: - An experimental test of RC thin wall specimens with high strength concrete up to 100 MPa had been undertaken to investigate the ultimate axial strength of reinforced concrete wall panels with various opening configurations. Background and test rig are stated briefly. An empirical equation using regression analysis based on the test results is proposed. An opening index of the equation is described in detail with respect to opening size and location considering both vertical and horizontal directions.

Keywords: - Ultimate axial strength, RC thin walls, Opening configuration index, Empirical equation

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I. INTRODUCTION

A structural behavior of axially loaded thin walls with openings is more complex than those without opening. The opening configuration leaded to reduce axial strength of the thin walls inhibits the natural bending and buckling failure effect as well as post-buckling behavior. Opening variables; size and location are incorporated in the opening configuration. The other more obvious variables that significant affect for the ultimate strength of thin walls (such as concrete compressive strength, height to thickness ratio, restraint condition and et.al) are also incorporated. The wall axial strength does not increase linearly at the high concrete strength range over 65 MPa. Especially the axial strength of high strength thin walls shows lower than the one predicted by existing national code methods (Korean concrete Institution; KCI-2012, Eurocode2-2009, American concrete Institution; ACI318-2014) and Eq. (1) proposed by Saheb and Desayi(1989)[1].

$$P_{uc} = 0.55\,\phi[A_g f_c^{'} + (f_y - f_c^{'})A_{st}][1 - (\frac{kh}{32\,t_w})^2] \tag{1}$$

where ϕ = 0.7 for compression members; f'_c is specified compressive strength of concrete; A_g is gross sectional area of the wall; f_y is yield strength of rebar; A_{st} is sum of sectional area of rebar; h is vertical distance between supports; t_w is overall thickness of wall member; k is the effective length factor for end conditions.

The ultimate axial strength in high strength concrete thin walls was successfully predicted using the strength function $(f'_c)^{0.7}$ instead of (f'_c) by Doh and Fragomeni (2005)[2]. Furthermore, the predicted strength by the existing code equations and Eq. (1) is eliminated when the height to thickness ratio H/t_w is greater than 25, whereas the actual capacity revealed by the test results can be reasonably predicted as shown by the empirical Eq. (2) proposed by Doh and Fragomeni (2005).

$$N_u = 2.0\,f_c^{'0.7}(t_w - 1.2e - 2e_a) \tag{2}$$

where N_u is the design axial strength per unit length of the wall (N/mm); e is the eccentricity of the load; e_a is an additional eccentricity due to lateral deflection; or $e_a = H_{we}^2/2500t_w$, where H_{we} is an effective wall height of a braced wall shall be taken the unsupported height of the wall where it is not restrained against rotation at both ends.

A decrease of ultimate axial strength due to opening size and location is suggested by Saheb and Desayi (1990)[3] and Doh and Fragomeni (2006)[4] based on their experimental test results of walls with openings. The decrease of ultimate strength between solid walls and walls with openings is defined by a linear extrapolation using regression analysis based on geometrical properties of opening size and location. From experimental program carried out in this research, newly derived decreasing functions incorporating various opening configurations (opening size and location for window and door type openings) are utilized in the empirical equation.

II. METHODS

In the experimental program, reinforced concrete thin walls with openings were tested to failure. Typical details of the testing walls with one or two openings showed in Fig. 1 had three types of height to thickness ratios; 30, 35, and 40. The dimensions and material properties of the walls and failure loads are recoded, where O and T indicate One and Two-way action tests. The two digital numbers in the second column denote the nominal concrete strength, followed by W1, W2 or D1 denoting one or two Window or Door type openings respectively. The final part of the panel description refers to location (Left, Upper, Bottom, Wide or Small) and length of panel, so C1.6 refers to Center opening for 1.6m long square panel.

Figure 1 Various opening configurations

A single F41 mesh layer of steel reinforcement was incorporated into the concrete wall panels. The F41 mesh had design yield strength of 450 MPa and the minimum tensile strength was 500 MPa. The reinforcement ratios ρ_v and ρ_h were 0.0031 for all panels, satisfying the minimum requirements to prevent shrinkage cracks occurring during the curing process and not to add strength to the walls. As current simplified wall design equations only require minimum reinforcement, it was decided that investigating the effect of increasing reinforcement ratios would not be investigated. The concrete compressive strengths of the various wall panels at day of testing varied between 32.0 MPa and 99.3 MPa are recorded. This indicates a very good range of concrete strengths were obtained for both normal and high strength concrete walls.

The testing geometry of walls was decided considering as common practical situation such that 3,000 mm story height and 100 mm thickness lead to the height to thickness ratio 30 as well as D10 single layer reinforced concrete walls is not counted the axial strength as a structural member. The typical test panels designated as a 40 % reduced model as 1200 mm square panel and 40mm thickness (H/t_w=30). Two more high thin wall specimens (H/t_w=35 and 40) were tested and the opening size of the specimens was designated 25% of the wall height. The top and bottom hinged support conditions were each simulated by placing a high strength steel rod on a thick steel plate welded along the steel plate at an eccentricity of $t_w/6$ from the section center line for one-way action. To achieve the hinged side support conditions for two-way action, the side edges of the walls had to be effectively stiffened in the perpendicular direction to prevent rotation about the x-axis while allowing rotation about the y-axis. Load increments control test was carried out, utilizing the load cell positioned between the center hydraulic jack and upper loading beam, were applied to the wall panel at approximately 5 kN per hydraulic jack. The walls were therefore loaded at approximately 14.7 kN increments measured by the load-cell up to failure. At each load increment, crack patterns and deflections were recorded. Most of the panels with high strength concrete failed in a brittle mode and the sudden failure of these panels made it sometimes difficult to record the maximum deflection precisely at failure.

The following were considered in the development of the wall design equation:

(1) The wall contains at least the minimum amount of reinforcement in the vertical and horizontal directions to protect shrinkage cracks during concrete wall curing period only.

(2) A percentage increase in concrete strength did not result in the same percentage increase in wall strength. For example of test results, for one-way walls (OW1C1.2) an increase in concrete strengths from 53 MPa to 96 MPa (81% increase) results in a corresponding increase in wall strength of 58% and for another example of two-way walls (TW1C1.6) an increase in concrete strengths from 50 MPa to 94 MPa (87% increase) also results in a corresponding increase in wall strength of 54%.

(3) Eq. (2) by Doh and Fragomeni (2005) is utilized for the calculation of N_u as it is considered most reliable for the test range and variables used.

(4) An increase in wall strength due to side restraints is approximately between 2.5 to 3.5 times with high slenderness ratio ($30\leq H/t_w \leq 40$).

(5) The reduced axial strength ratio of walls due to asymmetric opening location is approximately 25% smaller as well as the ratio due to door type opening is 30% reduced in both one-and two-way actions.

(6) The opening index of horizontal direction is more critical than the index of vertical direction in both actions. The index of spacing between the openings in one-way action is negative whereas positive in two-way action.

The proposed equation for the ultimate strength of walls with openings is:

$$N_{uo} = (k_1 - k_2 \cdot \chi_{xys}) \cdot N_u \qquad (3)$$

where N_u is an ultimate strength of solid walls without opening per unit length as defined by Eq. (2); χ_{xys} is the opening index defined by the opening size and location in both horizontal and vertical directions and the spacing between two openings (if applicable); k_1= 1.386 and k_2=2.014 for walls in one-way action; and k_1 = 1.023 and k_2 = 0.837 for walls in two-way action, which were derived by the method of least squares using the experimental data obtained

III. OPENING INDEX

The calculation of N_u chosen as Eq.(2) differs to current Code wall design equation in that the wall strength increases in an indirect proportion for concrete strengths up to 100 MPa and the variation is with respect to the concrete compressive strength $(f'_c)^{0.7}$.

The opening parameter (χ_{xys}) of Eq.(3) is equal to:

$$\chi_{xys} = \frac{\left(\frac{A_{ox}}{A_x} + \frac{\eta_x \pm s_x/2}{L}\right) + \lambda \cdot \left(\frac{A_{oy}}{A_y} + \frac{\eta_y}{H}\right)}{(1+\lambda)} \qquad (3a)$$

Where, χ_{xys} was formulated by χ_x, χ_y and s_x with a weight ratio (λ). That is $(\chi_x \pm s_x/2+\lambda\ \chi_y)/(1+\lambda)$ and is derived herein.

(1) The opening index of horizontal direction, χ_x with respect to the influence of opening size and location was proposed by Saheb and Desayi (1990). It is defined as:

$$\chi_x = \left(\frac{A_{ox}}{A_x} + \frac{\eta_x}{L}\right) \qquad (3b)$$

where, $A_{ox}=L_o \times t_w$, L_o is opening length, $A_x=L \times t_w$, L is wall length,

$$\eta_x = \frac{L}{2} - \left(\frac{\frac{1}{2}t_w L^2 - t_w L_o \eta_{ox}}{Lt_w - L_o t_w}\right) \qquad (3c)$$

where, η_{ox} is a distance from the left edge to opening center.

(2) Similarly, for opening size and location in vertical direction, χ_y is defined as:

$$\chi_y = \left(\frac{A_{oy}}{A_y} + \frac{\eta_y}{H}\right)$$

where $A_{oy} = H_o \times t_w$, H_o is opening height, $A_y = H \times t_w$, H is wall height,

$$\eta_y = \frac{H}{2} - \left(\frac{\frac{1}{2}t_w H^2 - t_w H_o \eta_{oy}}{Ht_w - H_o t_w}\right)$$

where η_{oy} is a distance from the top edge to opening center.

(3) When the wall panels have two openings located side by side, χ_{xs} is used to consider the spacing effect instead of χ_x. For the opening spacing parameter s_x for walls with two openings located side by side. χ_{xs} and χ_y are given as follows;

$$\chi_{xs} = \left(\frac{A_{ox}}{A_x} + \frac{\eta_x - s_x/2}{L}\right), \text{ or } \quad \chi_y = \left(\frac{A_{oy}}{A_y} + \frac{\eta_y}{H}\right) \quad \text{for one-way action} \qquad (3d)$$

$$\chi_{xs} = \left(\frac{A_{ox}}{A_x} + \frac{\eta_x + s_x/2}{L}\right), \text{ or } \quad \chi_y = \left(\frac{A_{oy}}{A_y} + \frac{\eta_y}{H}\right) \quad \text{for two-way action} \qquad (3e)$$

(4) Therefore, the opening index, $\chi = \chi_{xys}$, which is a combination index of each directions with a weight ratio, λ, becomes:

$$\chi_{xys} = (\chi_{xs} + \lambda \times \chi_y) / (1+\lambda) \qquad (3e)$$

where the weight ratio (λ) applies to χ_y to ensure its influence rating in calculation of χ_{xs}.

(5) Eventually, the reduced strength due to openings is equal to:

$$k_1 - k_2 \cdot \chi_{xys} = k_1 - k_2 \cdot \left\{ \frac{\left(\frac{A_{ox}}{A_x} + \frac{\eta_x \pm s_x/2}{L}\right) + \lambda \times \left(\frac{A_{oy}}{A_y} + \frac{\eta_y}{H}\right)}{1+\lambda} \right\} \qquad (3g)$$

Note s_x is zero for walls with one opening.

Table 1 Opening index of test specimen

	$\left(\frac{A_{ox}}{A_x}\right)$	$\left(\frac{\eta_x}{L}\right)$	$\left(\frac{s_x/2}{L}\right)$	χ_{xs}, one-/two-way	$\left(\frac{A_{oy}}{A_y}\right)$	$\left(\frac{\eta_y}{H}\right)$	χ_y	χ_{xys}, λ=1 (χ_{xs}+χ_y)	χ_{xys}, λ=0.17 for one-way	χ_{xys}, λ=0.39 for two-way
(a) Stage one for only one-way walls										
W1C1.2	0.25	0	0	*0.25*	0.25	0	*0.25*	0.25	0.25	
W1C1.4	0.25	0	0	*0.25*	0.25	0	*0.25*	0.25	0.25	
W1C1.6	0.25	0	0	*0.25*	0.25	0	*0.25*	0.25	0.25	
W2C1.2	0.5	0	-0.08	*0.42*	0.25	0	*0.25*	0.33	0.392	
W2C1.4	0.5	0	-0.08	*0.42*	0.25	0	*0.25*	0.33	0.392	
W2C1.6	0.5	0	-0.08	*0.42*	0.25	0	*0.25*	0.33	0.392	
(b) Stage two for only two-way walls										
W1C1.2	0.25	0	0	*0.25*	0.25	0	*0.25*	0.25		0.25
W1C1.4	0.25	0	0	*0.25*	0.25	0	*0.25*	0.25		0.25
W1C1.6	0.25	0	0	*0.25*	0.25	0	*0.25*	0.25		0.25
W2C1.2	0.5	0	0.08	*0.58*	0.25	0	*0.25*	0.42		0.490
W2C1.4	0.5	0	0.08	*0.58*	0.25	0	*0.25*	0.42		0.490
W2C1.6	0.5	0	0.08	*0.58*	0.25	0	*0.25*	0.42		0.490
(c) Stage three										
W1W1.2	0.5	0	0	*0.5*	0.25	0	*0.25*	0.375	0.464	0.430
W1L1.2	0.25	0.07	0	*0.32*	0.25	0	*0.25*	0.285	0.309	0.300
W1U1.2	0.25	0.07	0	*0.32*	0.25	0.042	*0.292*	0.306	0.315	0.312
D1C1.2	0.25	0	0	*0.25*	0.625	0.313	*0.938*	0.594	0.350	0.443
D1L1.2	0.25	0.07	0	*0.32*	0.625	0.313	*0.938*	0.628	0.409	0.493
W1SB1.2	0.2	0	0	*0.2*	0.2	0.025	*0.225*	0.213	0.204	0.207
W1SL1.2	0.2	0.025	0	*0.225*	0.2	0	*0.2*	0.213	0.221	0.218

IV. DRIVE EQUATION

The reduced strength ratios between experimental ultimate load and predicted load by Eq.(2) for corresponding wall without opening was indicated with the opening index in Table 1 to derive a best fitting line as expressed intersection (k_1) and indirect slope (k_2) shown in Fig. 2 for one-way walls and Fig. 3 for two-way walls. The weight ratios (λ) was controlled using iteration method to converge the maximum R^2 value.

Eq.(3) can be rewritten according to the test properties shown in Table 2 including H/t_w>27 for RC thin walls with openings in one-way action,

$$N_{uo,one-way} = 1.6\phi f_c'^{0.7} A_g \left[1-\left(\frac{H}{109.5t_w}\right)^{0.24}\right]\cdot\left[1.386 - 2.014\left(\frac{\chi_{xs}+0.17\chi_y}{1.17}\right)\right] \quad (3a)$$

Table 2 Regression analysis to determine λ of one-way walls

One-way	$N_{u,Eq.(2.)}$ (kN)	$N_{uo,test}$ (kN)	$N_{uo,test}/N_{u,Eq.(2.)}$	χ_{xys} λ=0.16	λ=0.17	λ=0.18
(a) Stage one						
OW1C1.2	425.4	378.9	**0.890**	0.250	0.250	0.250
OW2C1.2	427.7	256.7	**0.549**	0.394	0.392	0.391
(b) Stage three						
O65W1W1.2	361.6	176.0	**0.487**	0.466	0.464	0.462
O65W1L1.2	361.6	258.4	**0.715**	0.310	0.309	0.309
O65W1U1.2	361.6	257.8	**0.713**	0.316	0.315	0.315
O65D1C1.2	361.6	243.7	**0.674**	0.345	0.350	0.355
O65D1L1.2	361.6	206.0	**0.570**	0.405	0.409	0.414
R-square				98.77%	**98.83%**	98.79%
Intersection, k_1				1.383	**1.386**	1.388
Slope, k_2				-2.005	**-2.014**	-2.021

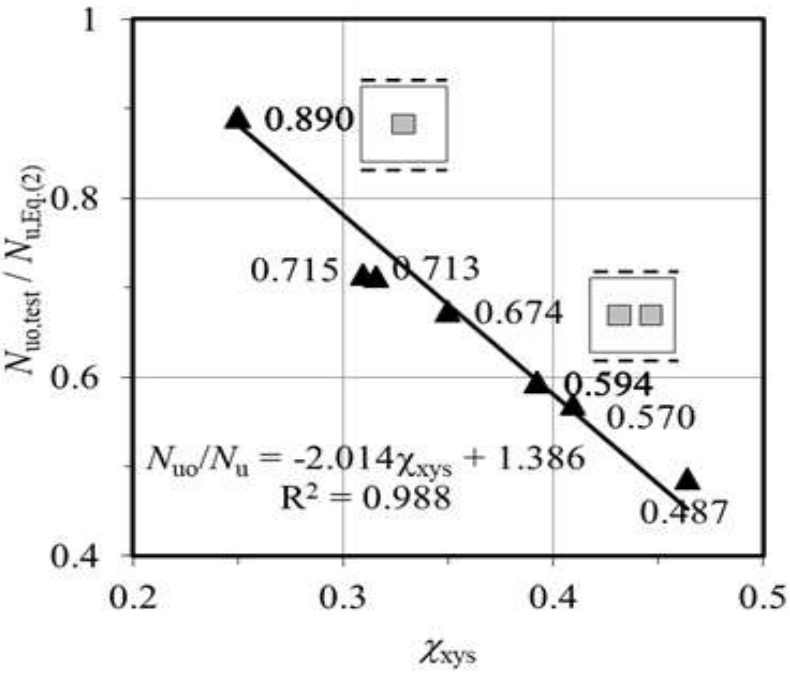

Figure 2 Derivation of k1, k2, and λ of walls in one-way action

Eq.(3) also can be rewritten according to the test properties shown in Table 3 including H/t_w>27 for RC thin walls with openings in two-way action,

$$N_{uo,two-way} = 1.6\phi f_c'^{0.7} A_g \left[1-\left(\frac{H}{7729.2t_w}\right)^{0.24}\right]\cdot\left[1.023 - 0.837\left(\frac{\chi_{xs}+0.39\chi_y}{1.39}\right)\right] \quad (3b)$$

Table 3 Regression analysis to determine λ of two-way walls

Two-way	$N_{u,Eq.(2)}$ (kN)	$N_{uo,test}$ (kN)	$\frac{N_{uo,test}}{N_{u,Eq.(2.)}}$	χ_{xys}		
				λ =0.38	**λ =0.39**	λ =0.40
(a) Stage two						
TW1C1.2	1319.8	1124.8	**0.847**	0.250	0.250	0.250
TW2C1.2	1305.5	792.1	**0.609**	0.492	0.490	0.488
(b) Stage three						
T65W1W1.2	951.1	682.2	**0.717**	0.431	0.430	0.429
T65W1L1.2	1050.4	737.5	**0.702**	0.300	0.300	0.300
T65W1U1.2	1020.8	715.7	**0.701**	0.312	0.312	0.312
T65D1C1.2	1050.4	676.9	**0.644**	0.439	0.443	0.446
T65D1L1.2	951.1	582.7	**0.613**	0.490	0.493	0.496
T65W1SB1.2	1020.8	794.6	**0.778**	0.207	0.207	0.207
T65W1SL1.2	951.1	721.0	**0.758**	0.218	0.218	0.218
R-square				87.61%	**87.62%**	87.61%
Intersection, k_1				1.022	**1.023**	1.023
Slope, k_2				-0.833	**-0.837**	-0.840

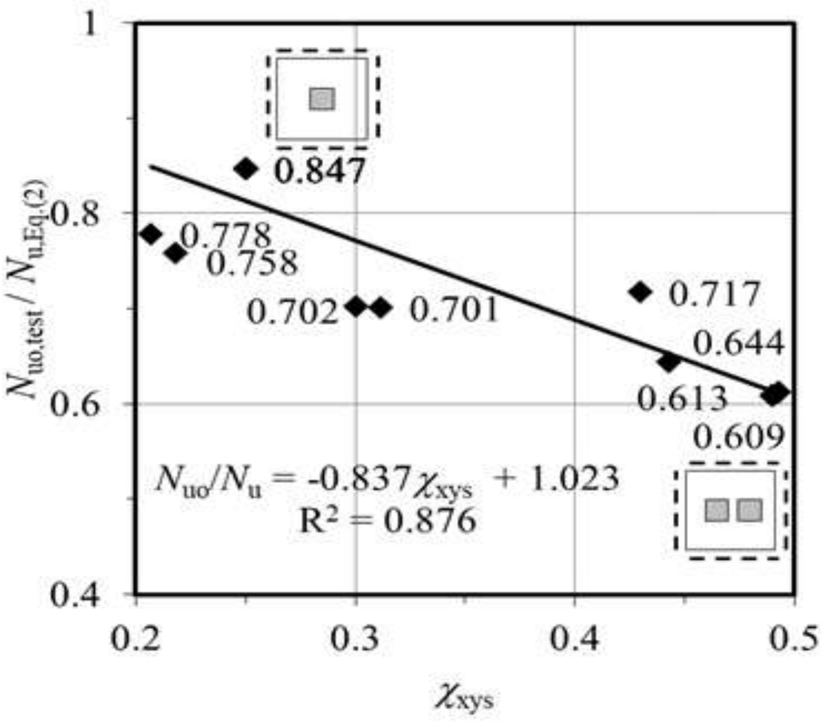

Figure 3 Derivation of k1, k2, and λ of walls in two-way action

The ultimate loads(N_{uo}) of RC thin walls with various openings subjected axial load in plane with an eccentricity between measured test results and predicted by Eq.(3) are indicated in Fig. 4 to verify the proposed empirical equation. Those are presented comprehensive result and further achieved with good coefficient of variation within 10%. Most higher ultimate loads over 1000 kN (high compressive strength over 75 MPa) by the test are slightly greater than predicted loads indicates that the Eq.(3) might be conservative and safe prediction will be respected.

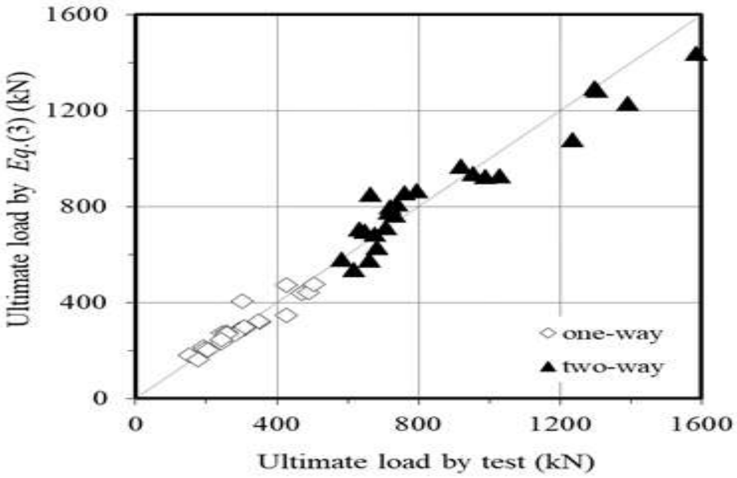

Figure 4 Comparison between test result and corresponding prediction by Eq.(3)

V. CONCLUSION

To upgrade simplify national code equations, an experimental procedure including various opening configurations is carried out. Incorporating the experimental test, the ultimate axial strength equation of walls with openings is developed. The linear reduction strength due to openings is expressed by intersection(k_1) and proportional slope(k_2) as 1.386 and -2.014 for one-way walls and 1.023 and -0.837 for two-way walls respectively. The weight ratios (λ) also derived from the experimental results tested are 0.17 for one-way walls and 0.39 for two-way walls.

Exist the national codes had limitations; concrete strength under 65 MPa, height to thickness ratio under 30, walls restraint condition is simply supported on top and bottom edge only and omittable opening sectional area within 20%. The limitations are extended by the proposed empirical equation such that concrete strength up to 100 MPa, height to thickness ratio up to 40, restraint condition included simply supported on all side edge, and opening sectional area up to 50%. Particularly, opening index considering opening size and location in x- and y- both direction combined weight ratio λ. The equation and opening index are derived by testing results and regression analysis.

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REFERENCES

[1]. J.H. Doh, and S. Fragomeni, Evaluation of experimental work on concrete walls in one and two-way action, *Australian Journal of Structural Engineering, 6(1)*, 2005, 37-51.
[2]. S.M. Saheb and P. Desayi, Ultimate strength of RC wall panels in one-way in-plane action, ASCE *Journal of Structural Engineering, 115(10),* 1989, 2617-2630.
[3]. J.H. Doh, and S. Fragomeni, Ultimate load formula for reinforced concrete wall panels with openings, *Advances in Structural Engineering, 9(1)*, 103-115.
[4]. S.M. Saheb and P. Desayi, Ultimate strength of RC wall panels with openings, ASCE *Journal of Structural Engineering, 116(6),* 1990, 1565-1578.

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