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Ultimate Axial Strength of RC Slender Walls with Openings

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***Abstract*— An experimental test of 47 slender 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 in detail. A new design equation is proposed as the empirical formula based on the test results. An opening parameter of the formula is described in detail with respect to opening size and location both vertical and horizontal directions.**

***Index Terms*— Axial strength, empirical formula, opening configurations, RC slender walls.**

I. BACKGROUND/ OBJECTIVE AND GOALS

The analysis of axially loaded wall panels with openings is more complex than walls without openings. The effect of opening size causes a reduction in axial strength to a wall system and the origin of the opening location inhibits the natural bending and buckling failure exhibited. Opening variables; size and location are incorporated in a new empirical formula. The other more obvious variables that significantly affect the ultimate strength of wall panels (such as the concrete strength, slenderness ratio and boundary condition) will also be incorporated. The wall strength does not increase linearly in high concrete strength range. In particularly, when high concrete strengths over 65 MPa are used, wall strengths show lower capacities than the predicted wall strengths using existing code methods (Korean Concrete Institution: KCI-2012[8], Eurocode2-2009[3], Australian Standards: AS3600-2009[2] and American Concrete Institution: ACI318-2014[1]) and Eq.(1) proposed by Saheb and Desayi [9].

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

where ϕ = 0.7 for compression members; f'c is specified compressive strength of concrete; Ag is gross sectional area of the wall panel; fy is yield strength of rebar; Ast is sum of sectional area of rebar; h is vertical distance between supports; tw is overall thickness of wall member; k is the effective length factor for end conditions.

The ultimate strengths in high strength concrete solid walls were successfully predicted using the strength function $(f'_c)^{0.7}$ instead of (f'_c) by Doh and Fragomeni [5]. Further according to existing code equations and Equation 1, the predicted wall strengths are close to zero when slenderness H/t_w is greater than 30, whereas the actual capacity can be reasonably predicted as shown by the empirical Eq. (2) proposed by Doh[4].

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

where N_u = the design axial strength per unit length of the wall (N/mm); e = the eccentricity of the load; e_a = 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 strength due to opening size and location is suggested by Saheb and Desayi[10] and Doh and Fragomeni[6] using their limited 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 wide and door type openings) are utilized in the new empirical formula.

II. METHODS

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

(1) The wall contains at least the minimum amount of steel as specified by AS 3600[2] in the vertical and horizontal directions to protect shrinkage cracks during concrete wall curing period.

(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 [5] 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 ratios of walls due to asymmetric opening location are approximately 25% in both one-and two-way actions.

(6) The reduced wall strengths due to door type openings compared to window type openings tested (the opening parameters in horizontal direction are identical) are 30% in both one- and two-way action.

(7) The opening parameters in horizontal direction are more critical than in vertical direction [7].

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

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

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 parameter 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. TEST PANELS AND RIG

In the experimental program, forty-five reinforced concrete wall panels with openings were tested to failure. Typical details of the test panels with one and two. The dimensions and material properties of the test panels 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.

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 in the Australian Standard to prevent shrinkage cracks occurring during the curing process and not to add strength to the wall panels. 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 was supplied by a local concrete ready-mix company. General purpose cement, sand and 10 mm aggregates were used to produce concrete. No admixtures were used for the normal strength mixes. The typical high strength concrete mixes consisted of fly ash, water reducing agent and super-plasticizer in addition to the major components. 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 panels.

Wall panel size for testing were decided common practical situation such that 3,000 mm story height, 100 mm thickness, 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 slender specimens (H/t_w=35 and 40) were tested and the opening size of wall panels were designated 25% of the wall length. The test frame was designed to support three independent hydraulic jacks each of 800 kN capacity. The rig was originally built by Doh[4] consisting of two main steel 310 UC 118 columns each 4000 mm high and 2 steel 380 PFC cross beams that support the jacks. The jacks were required to transmit a uniformly distributed load across the top through a steel 250 UC loading beam at an eccentricity of t_w/6. The 250 UC supporting beam on the strong floor was identical to the loading beam. The top and bottom hinged support conditions were each simulated by placing a high strength steel rod on a thick steel plate and varying lengths which corresponded to the different test panel dimensions. The steel rod was welded along the steel plate at an eccentricity of t_w/6 from the section center line. To achieve the hinged side support conditions for two-way action, the edges of the wall panels had to be effectively stiffened in the perpendicular direction to prevent rotation about the x-axis while allowing rotation about the y-axis. To achieve this, two 150 PFC's separated by a square hollow section extending along the height of both sides of the test panel were used.

A static loading regime was adopted for the testing. Load increments, 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.

IV. OPENING PARAMETER

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

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

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 parameter, χ_x with respect to the influence of opening size and location in the horizontal direction only was proposed by Saheb and Desayi[10]. It is defined as:

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

where $A_{ox} = L_o \times t_w$, L_o = opening length, $A_x = L \times t_w$, L= wall length, $\eta_x = \frac{L}{2} - \left(\frac{\frac{1}{2} t_w L^2 - t_w L_o \eta_{ox}}{L t_w - L_o t_w} \right)$

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

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

$$\chi_y = \left(\frac{A_{oy}}{A_y} + \frac{\eta_y}{H}\right) \qquad (3c)$$

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

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

where η_{oy}= 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;

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

for one-way action (3d)

$$\chi_{xs} = \left(\frac{A_{ox}}{A_x} + \frac{\eta_x + s_x/2}{L} \right), \text{ or } \quad \chi_y = \left(\frac{A_{oy}}{A_y} + \frac{\eta_y}{H} \right)$$

for two-way action (3e)

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

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

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=0 for walls with one opening.

V. RESULTS

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

Table 1 Comparison between predicted loads by Eq.(2) and test results of walls in one-way action

One opening	$N_{u,Eq.(2)}$ (kN)	$N_{uo,test}$ (kN)	$\frac{N_{uo,test}}{N_{u,Eq.(2)}}$	Two openings	$N_{u,Eq.(2.6a)}$ (kN)	$N_{uo,test}$ (kN)	$\frac{N_{uo,test}}{N_{u,Eq.(2)}}$
O50W1C1.2	330.6	309.0	0.935	O50W2C1.2	318.5	191.3	0.601
O70W1C1.2	392.0	426.7	1.089	O70W2C1.2	392.0	242.8	0.619
O90W1C1.2	497.4	470.9	0.947	O95W2C1.2	501.5	308.1	0.614
O95W1C1.2	501.5	488.5	0.974	O45W2C1.4	305.8	150.7	0.493
O45W1C1.4	242.8	191.3	0.788	O90W2C1.4	461.0	244.3	0.530
O90W1C1.4	461.0	300.2	0.651	O95W2C1.4	536.3	350.8	0.654
O95W1C1.4	536.3	426.1	0.795	O50W2C1.6	345.3	195.7	0.567
O50W1C1.6	325.6	294.3	0.904	O70W2C1.6	447.6	279.0	0.623
O90W1C1.6	541.0	503.3	0.930	O90W2C1.6	541.0	347.3	0.642
Average			0.890				0.594
CV(%)			14				9

Table 2 Comparison between predicted loads by Eq.(2) and test results of walls in two-way action

One opening	$N_{u,Eq.(2)}$ (kN)	$N_{uo,test}$ (kN)	$\frac{N_{uo,test}}{N_{u,Eq.(2)}}$	Two openings	$N_{u,Eq.(2)}$ (kN)	$N_{uo,test}$ (kN)	$\frac{N_{uo,test}}{N_{u,Eq.(2)}}$
T50W1C1.2	877.9	706.3	0.805	T50W2C1.2	877.9	618.0	0.704
T70W1C1.2	1151.0	953.5	0.828	T70W2C1.2	1151.0	633.4	0.550
T45W1C1.4	941.8	732.8	0.778	T90W2C1.2	1391.2	665.1	0.478
T90W1C1.4	1578.0	1303.7	0.826	T45W2C1.4	941.8	662.2	0.703
T95W1C1.4	1590.7	1298.4	0.816	T90W2C1.4	1578.0	918.2	0.582
T50W1C1.6	1140.5	1030.1	0.903	T95W2C1.4	1398.1	759.9	0.544
T70W1C1.6	1509.6	1390.6	0.921	T50W2C1.6	1140.5	647.5	0.568
T90W1C1.6	1769.0	1583.3	0.895	T70W2C1.6	1509.6	988.8	0.655
				T90W2C1.6	1761.5	1236.1	0.702
Average			0.847				0.609
CV(%)			6				14

Table 3 Regression analysis of walls in one-way action

One-way	$N_{u,Eq.(2)}$ (kN)	$N_{uo,test}$ (kN)	ratio	χ_{xys}		
				λ =0.16	**λ =0.17**	λ =0.18
(a) Stage one						
OW1C1.2	See Table 1		**0.890**	0.250	0.250	0.250
OW2C1.2			**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

Table 4 Regression analysis of walls in two-way action

Two-way	$N_{u,Eq.(2)}$ (kN)	$N_{uo,test}$ (kN)	ratio	χ_{xys}		
				λ =0.38	**λ =0.39**	λ =0.40
(a) Stage two						
TW1C1.2	See Table 2		**0.847**	0.250	0.250	0.250
TW2C1.2			**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

From the regression analysis, Eq.(3) can be rewritten, including $e=t_w/6$, $H=L$ and $H/t_w>27$ as follows;

$$N_{uo,one-way} = 1.6\phi f_c'^{0.7} A_g \left[1-\left(\frac{H}{109.5t_w}\right)^{0.24}\right]\cdot\left[1.386-2.014\left(\frac{\chi_{xs}+0.17\chi_y}{1.17}\right)\right] \quad (3.1)$$

$$N_{uo,two-way} = 1.6\phi f_c'^{0.7} A_g \left[1-\left(\frac{H}{7729.2\ t_w}\right)^{0.24}\right]\cdot\left[1.023-0.837\left(\frac{\chi_{xs}+0.39\chi_y}{1.39}\right)\right] \quad (3.2)$$

Table 5 Comparison of ultimate loads of walls

One-way	$N_{uo,test}$ (kN)	$N_{uo,Eq.(3.1)}$ (kN)		Two-way	$N_{uo,test}$ (kN)	$N_{uo,Eq.(3.2)}$ (kN)	
(a) walls with one opening							
O50W1C1.2	309.0	291.8	0.94	T50W1C1.2	706.3	714.4	1.01
O70W1C1.2	426.7	345.9	0.81	T70W1C1.2	953.5	936.6	0.98
O90W1C1.2	470.9	439.0	0.93	T45W1C1.4	732.8	766.4	1.05
O95W1C1.2	488.5	442.6	0.91	T90W1C1.4	1303.7	1284.1	0.98
O45W1C1.4	191.3	214.3	1.12	T95W1C1.4	1298.4	1294.4	1.00
O90W1C1.4	300.2	406.8	**1.36**	T50W1C1.6	1030.1	928.1	0.90
O95W1C1.4	426.1	473.3	1.11	T70W1C1.6	1390.6	1228.4	0.88
O50W1C1.6	294.3	287.3	0.98	T90W1C1.6	1583.3	1439.5	0.91
O90W1C1.6	503.3	477.4	0.95				
(b) walls with two openings							
O50W2C1.2	191.3	189.7	0.99	T50W2C1.2	618.0	538.2	0.87
O70W2C1.2	242.8	233.5	0.96	T70W2C1.2	633.4	705.6	1.11
O95W2C1.2	308.1	298.7	0.97	T90W2C1.2	665.1	852.8	**1.28**
O45W2C1.4	150.7	182.1	**1.21**	T45W2C1.4	662.2	577.4	0.87
O90W2C1.4	244.3	274.6	1.12	T90W2C1.4	918.2	967.3	1.05
O95W2C1.4	350.8	319.4	0.91	T95W2C1.4	759.9	857.1	**1.13**
O50W2C1.6	195.7	205.6	1.05	T50W2C1.6	647.5	699.2	1.08
O70W2C1.6	279.0	266.6	0.96	T70W2C1.6	988.8	925.4	0.94
O90W2C1.6	347.3	322.2	0.93	T90W2C1.6	1236.1	1079.9	0.87
(c) walls with various openings							
O65W1W1.2	176.0	163.5	0.93	T65W1W1.2	682.2	630.8	0.92
O65W1L1.2	258.4	275.9	1.07	T765W1L1.2	737.5	810.9	1.10
O65W1U1.2	257.8	271.5	1.05	T65W1U1.2	715.7	778.0	1.09
O65D1C1.2	243.7	246.4	1.01	T65D1C1.2	676.9	685.2	1.01
O65D1L1.2	206.0	203.1	0.99	T65D1L1.2	582.7	580.6	1.00
				T65W1SB1.2	794.6	867.4	1.09
				T65W1SL1.2	721.0	799.4	1.11
Average			1.01				1.01
CV(%)			12				10

Note that only four of forty-seven specimens, the strength ratio shows slightly overpredicted values which is out of CV range. It is possibly happened in experimental test due to lower test result estimated on the whole test result trend by human error.

VI. VALIDATION

To further validate the proposed formula *Eq.*(3), predicted ultimate are compared to actual failure loads of previous tested data by Saheb and Desayi[10] and Wong[11].

Saheb and Desayi tested a total of 12 wall panels with openings (6 opening types in one- and two-way action each). All tested wall panels had an identical material property and double layered minimum steel. All walls were made of normal strength concrete and a constant slenderness ratio of 12.

For the six opening types of concrete wall panels, the predicted ultimate loads using proposed formula *Eq.*(3) are presented and compared to the test results in Table 6. *Eq.*(3) can be rewritten for these stocky rectangular walls with openings according to the test properties including eccentricity $e=t_w/6$, $H/L=2/3$ and $H/t_w=12$, using the effective height of H_{we} ($=\beta H$; $\beta=1$ and 54/65 for one- and two-way walls respectively) as follows:

$$N_{uo,one-way} = 1.6 f_c'^{0.7} A_g \left[1-\left(\frac{H}{31.6t_w}\right)^{2}\right]\cdot\left[1.386-2.014\left(\frac{\chi_{xs}+0.17\chi_y}{1.17}\right)\right] \quad (4)$$

$$N_{uo,two-way} = 1.6 f_c'^{0.7} A_g \left[1-\left(\frac{H}{38.1t_w}\right)^{2}\right]\cdot\left[1.023-0.837\left(\frac{\chi_{xs}+0.39\chi_y}{1.39}\right)\right] \quad (5)$$

The comparison shows an average ratio of 0.83 with good coefficient of variation of 12% which indicates very good prediction using the new equation. The comparisons of wall panels with door type openings, WWO-4 WWO-5 and WWO-6 in both one- and two-way action, indicate conservative results from 0.78 to 0.70 but are considered safe.

This is good evidence to suggest that the door type openings in walls to overestimate were sufficiently considered in the new equation. Highlighted numbers by bold font indicate considering spacing effects.

Table 6 Comparison with test results by Saheb and Deasyi

	f_c (MPa)	$N_{uo,test}$ (kN)	Opening parameter, χ				$N_{uo,Eq.(4\sim5)}$ (kN)	ratio
			χ_x	χ_{xs}	χ_y	χ_{xys}		
one-way							λ_{one} =0.17	
WWO-1	35.3	672.56	0.267	0.267	0.4	0.286	604.9	0.90
WWO-2	35.3	568.90	0.360	0.360	0.4	0.365	485.4	0.85
WWO-3	35.3	433.47	0.533	**0.411**	0.4	0.409	419.2	0.97
WWO-4	35.3	652.65	0.233	0.233	1.050	0.352	505.7	0.77
WWO-5	35.3	548.02	0.316	0.316	1.050	0.423	399.2	0.73
WWO-6	35.3	423.47	0.509	**0.370**	1.050	0.469	329.5	0.78
two-way							λ_{two} =0.39	
WWO-1(p)	35.3	692.47	0.267	0.267	0.4	0.306	589.1	0.85
WWO-2(p)	35.3	592.83	0.360	0.360	0.4	0.372	550.3	0.93
WWO-3(p)	35.3	448.38	0.533	**0.656**	0.4	0.580	426.4	0.95
WWO-4(p)	35.3	697.47	0.233	0.233	1.050	0.475	488.9	0.70
WWO-5(p)	35.3	587.83	0.316	0.316	1.050	0.533	454.2	0.77
WWO-6(p)	35.3	448.38	0.509	**0.648**	1.050	0.767	315.3	0.70
Average								0.83
C.V.(%)								12

Wong[11] tested a total of 10 wall panels with openings (5 opening types in one- and two-way action each). All tested wall panels had an identical material property and double layered minimum steel.

For the five opening types of concrete wall panel tests, the predicted ultimate loads using proposed formula *Eq.*(3) are presented and compared to test results in Table 6. *Eq.*(3) can be rewritten for slender rectangular walls with openings according to the test properties including eccentricity $e=t_w/6$, $H/L=3/4$ and $H/t_w=30$, using the effective height of H_{we} ($=\beta H$; $\beta=18/(H/t_w)^{-0.88}$ and $1728/125(H/t_w)^{-0.88}$ for one- and two-way walls respectively) as follows,

$$N_{uo,one-way}=1.6f_c^{\prime 0.7}A_g\left[1-\left(\frac{H}{109.5t_w}\right)^{0.24}\right]\cdot\left[1.386-2.014\left(\frac{\chi_{xs}+0.17\chi_y}{1.17}\right)\right] \quad (6)$$

$$N_{uo,two-way}=1.6f_c^{\prime 0.7}A_g\left[1-\left(\frac{H}{987.9t_w}\right)^{0.24}\right]\cdot\left[1.023-0.837\left(\frac{\chi_{xs}+0.39\chi_y}{1.39}\right)\right] \quad (7)$$

The comparison shows an average of 0.68 with coefficient of variation of 20% which indicates conservative prediction. This indicates the new equation can reasonably predict failure of walls with openings with high strength concrete of greater than 65 MPa and slenderness ratio of 30 which were variables used in Wong's tests. It should be noted the prediction does not consider the additional capacity due to reinforcement.

This conservatism is particularly evident in the wall panels with asymmetry window and door type openings, WWO-2 and WWO-4(p) which indicates minimum ratios of walls in one- and two-way action by 0.40 and 0.61 respectively, but they are considered safe.

Table 7 Comparison with test results by Wong

	f_c (MPa)	$N_{uo,test}$ (kN)	Opening index				$N_{uo,Eq.(6\sim7)}$ (kN)	ratio
			χ_x	χ_{xs}	χ_y	χ_{xys}		
one-way							λ_{one}=0.17	
WWS	90.0	1495				0	997.1	0.67
WWO1	68.1	880	0.300	0.300	0.40	0.315	617.3	0.70
WWO2	92.0	1421	0.407	0.407	0.40	0.406	575.3	0.40
WWO3	70.9	540	**0.478**	**0.478**	0.40	0.467	376.4	0.70
WWO4	74.0	935	0.263	0.263	1.05	0.377	545.0	0.58
two-way							λ_{two}=0.39	
WWS-(p)	72.0	2200				0	1812.9	0.82
WWO-1(p)	74.6	1765	0.300	0.300	0.40	0.330	1358.9	0.77
WWO-2(p)	65.0	1760	0.407	0.407	0.40	0.405	1137.5	0.65
WWO-3(p)	84.8	1175	**0.720**	**0.720**	0.40	0.627	1028.5	0.88
WWO-4(p)	88.0	2065	0.263	0.263	1.05	0.495	1263.2	0.61
Average								0.68
C.V.(%)								20

VII. CONCLUSION

An empirical equation was derived using the experimental tests on forty-seven reinforced concrete wall panels with openings in one- and two-way action. The specimens used were axially loaded with an eccentricity of $t_w/6$ and slenderness between 30 and 40 and concretes between 50MPa and 100MPa as well as various opening configurations.

The practical code equations of wall panels, given in as the Australian Standard and the American Concrete Institute, were found to have several limitations, not applicable to walls with high concrete strength, high slenderness, simply supported on all side edges and with openings. In view of the significant short comings, the more appropriate formula derived in this study was required.

Incorporating the experimental test results from the previous studies, the new ultimate load formulae (one- and two-way action) were developed using regression analysis for reinforced concrete wall panels with openings. The linear relations of reduced strengths of walls are expressed by the intersection (k_1) and indirect proportion 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.

Comparisons of predicted ultimate loads using the new equation to the test results of corresponding wall panels with openings indicate an excellent average ratio of 1.01 in both one- and two-way actions. Comparisons to previous experimental data tested by Saheb and Desayi and Wong showed good agreement. Saheb and Desayi focused on normal strength stocky walls with openings while Wong had high strength concrete slender walls with openings. This indicates the versatility of new equation.

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