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Numerical Modelling of Precast Wall Panel with Opening to Determine Effect of Slenderness, Aspect Ratio and Opening Ratio to the Ultimate Load Capacity

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Abstract

The primary advantage of using prefabricated concrete in a building is enhancing building completion speed. Renovation works are then carried out, introducing opening to the wall to provide new access. Without the option of providing opening on the precast load-bearing wall, this would cause a significant impact on structural integrity. This paper presents numerical modelling of the precast wall panel with opening. The ultimate load of the precast wall panel is evaluated where the slenderness of the panel, the aspect ratio and the opening ratio are taking into consideration. The ultimate load capacity of the wall with an opening (Nu,o) which was derived from the numerical analysis using Finite Element Model is compared with design equations for the precast wall in the ACI 318-14, AS3600-2009 and EN1992-1-1. The proposed design equations by other researchers are compared as well. It is found that the relationship between geometry properties and ultimate load are determined under the specified condition. When buckling type failure is imminent, a non-linear relationship can be observed which significantly reduce the ultimate load. On the other hand, under bending type failure, a linear relationship can be observed. It is observed that the code design equations are not applicable in determining the ultimate load of the wall with opening where the mean values of the differences are 9.79, 1.39 and 2.12 respectively observed. The value of Nu,o from the numerical

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model found a good comparison with the proposed equation from other researchers with a mean difference 0.15.

Keywords: Precast wall with opening, ultimate load capacity, slenderness ratio, aspect ratio, opening ratio.

1 Introduction

More than half of the population of the world lives in urban areas since 2007 (i.e. 50.14%). In Malaysia, since 1991, half of the population already lives in the urban area. The number will keep increasing and projected in 2050 two-third of the world population will be urban. The Sustainable Development Goal 11 (SDG 11) highlights the cities as the essential roles in global political agenda. The SDG 11.1, which focuses on affordable housing, has targeted by 2030 to ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums [1]. The achievement indicator is to measure the proportion of the urban population living in informal settlements or inadequate housing. There were 30,917 houses constructed or repaired for the poor households and 139,329 houses developed for low- and middle-income families between 2016 – 2017 in Malaysia [2]. As the Malaysia current achievement in 2017 alone, the number of completed low-cost housing units and low-cost flats is 2,771 and 4,052 respectively [2].

Reinforced concrete is still commonly used as building materials. By adopting the Industrialized Building System (IBS), Malaysia's construction industry is increasing towards industrialisation. The primary advantages of using prefabricated concrete in a building are the chance of enhancing building completion speed, high-quality product, improved durability, reduced shaping and fieldwork, and, more importantly, social and environmental benefits [3], [4]. It can offer alternatives to shorten affordable houses in many regions [5]. There is an excellent potential for using this type of the panel in building construction. A precast component such as beams, columns and walls are manufactured in factories then assemble and install to the final position. In a prefabricated load-bearing wall, an opening is often found in the means of giving access. In a structural sense, opening is considered as a source of weakness since it reduces the ultimate load capacity of the wall.

A building often experiences renovation throughout its service life. Renovation works are then carried out involving providing new access by introducing opening to the wall for windows or door installation. The most pronounced example can be seen from shop lots. Typical business premises found in Malaysia are shop lots restaurant, mini hotel, market and banks which require space to operate and in some case by adjoining two adjacent units. Without the option of providing opening with the precast load-bearing wall, this would cause a huge impact on the value of the structure in terms of investments and commercial. Besides, precast façade often designs as a non-structural component where the wall section of the element does not account for any load instead design as a beam structure integrated on top of the façade acting as a frame.

Since the last century, many studies have contributed to understanding the behaviour of the structural wall under different condition. Some properties of structural walls have been well understood however there are still some unexplored filed to complete the whole picture. One of the very first systematic studies of the effect of eccentric load on the concrete wall was carried out by Seddon in 1956. It was stated that every opening present in a wall is considered as the source of weakness since it reduces the load-carrying capacity. The study concluded that small opening in concrete plays only a minor role in the load-carrying capacity and it is generally accepted until now. Moreover, the study also emphasis on a significant reduction of the load-carrying capacity of a wall when a large opening is present but with not well-defined classification of a large and small opening. Recent studies in [6], [7], [8] and [9] summaries the studies and the current gap are well stressed where the effect on contribution in eccentricity, the orientation of reinforcement and reinforcement ratio to other variables is still unknown. The safe and reliable design model cover all variables are yet available.

Furthermore, two way supported wall under high strength concrete, and geometry properties greater than 1000 mm are less intensively studied [6]. In the present, there are no recommendation or philosophies on design load-bearing wall with opening given by design codes and guidelines. Besides that, studies have concluded that the method suggests by code and guidelines are leaning towards the conservative side. Some of the general relationships of properties affecting the behaviour of the wall with opening are investigated by using the finite element method in Ansys. Through the years, the various equation has been proposed by researchers to address the lack of procedure in the design equation.

Geometry property is one of the main factors on determining how structural wall with opening behaves. Geometry properties cover the size of the wall, size of the opening and also the shape and symmetry. General parameters used to describe geometry properties in wall with opening are height of wall (H_w), thickness of wall (t_w), length of wall (L_w), height of opening ratio (H_o) and length of opening ratio (L_o) to form slenderness ratio (λ), aspect ratio (δ), opening height ratio (O_h), opening length ratio (O_l) and opening area ratio (O_a).

Where:

Slenderness ratio, $\lambda = H_w / t_w$

Aspect ratio, $\delta = H_w / L_w$

Opening height ratio, $O_h = H_o / H_w$
Opening length ratio, $O_l = L_o / L_w$
Opening area ratio, $O_a = A_o / A_w$
Axial strength ratio, $N_c / (f_c'. L_w . t_w)$

In a structural wall, other than the geometrical parameters, the boundary condition playing its role in providing the ultimate load capacity as well.

1.1 Boundary Condition and Failure Type

The number of supports on the wall affects significantly on how the load is transferred and distributed. Boundary condition can be classified into two types, One Way (OW) where the wall is supported on top and bottom or Two Way (TW) where the wall is supported top, bottom, one side or both sides. From the study by Saheb [10], it is demonstrated that TW walls are more rigid and stronger compare to OW in deflection and ultimate load. A more recent study has also verified the relationship, axial strength ratio increase as the number of support sides increases [11] – [14]. Depending on the boundary condition, the failure pattern and type also differs, as shown in Fig. 1.

OW wall shows single out of plane curvature while TW wall show bi-axial curvature in both vertical and horizontal direction. Generally, there are two types of failure the wall exhibit when loading axially under eccentricity, buckling type and bending type. Under the bending type of failure for crack pattern, OW wall exhibit pronounced horizontal cracks at the middle of the wall with deflection. While TW wall exhibit cracks pattern similar to yield line theory in the slab where cracks develop from wall corner to the opening corner. Under buckling type, the column section of the wall unable to withstand the load, crack and crush prematurely before exhibiting out of plane curvature. The critical condition causes buckling is usually high slenderness ratio, low aspect ratio and high opening ratio.

1.2 Slenderness Ratio

From research works as in [13], [15], [16], slenderness ratio showing clear sign inversely proportional to ultimate load capacity and highlighted slenderness ratio is sensitive to failure type. The effect is more significant under high slenderness ratio where axial strength ratio gradually decreases.

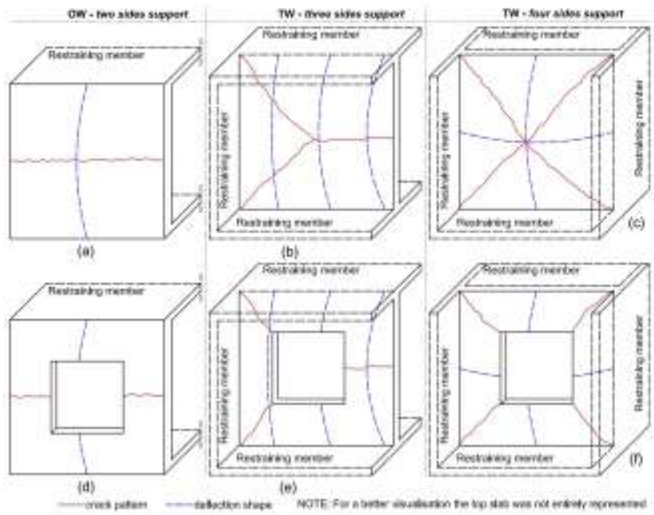

Figure 1 Typical deformation pattern and cracking pattern of axially loaded RC wall from [6].

1.3 Aspect Ratio

The relationship between aspect ratio and ultimate load capacity found depends on the boundary condition according to [10], [15], [17], [18]. In OW wall, the aspect ratio is inversely proportional to ultimate load capacity while TW wall shows the opposite relation, whereas the aspect ratio increase, the load-carrying capacity also increases.

1.4 Opening Ratio

By increasing the opening area on the wall, the ultimate load capacity is found to reduce greatly from the study in [19]. The position also found to have a notable effect on the internal stress distribution causing different failure mode in deformation, cracking and ultimate failure. In [20], it is also found that the opening height ratio, length ratio and area ratio all have an effect on ultimate load capacity.

1.5 Code Design Equation

The recommendation provided by the current version of code develop around the concept of column theory condition and empirical method. Slight differences can be found among different codes, for example, in stress block where Eurocode adopt a rectangular method while American code considers as triangular. Study starting from previous decades have been reported that code design equation has the tendency of being conservative and inapplicable on wall with opening [11], [12], [20], [21]. According to Cosminet. al, equation of different codes is expressed in similar terms and shown in Eq. 1 – Eq.5. Where k is constant for restriction of rotation is strength reduction factors and is the axial strength ratio, which is the factor accounting for the influence of the eccentricity, aspect ratio, and boundary conditions [10], [22], [23].

ACI 318-11

$$N_u = 0.55\phi[1 - \left(\frac{k\lambda}{32}\right)^2]f_c L t \quad (1)$$

OW, k = 0.65 when restricted rotation, k = 1 when rotation is not restricted

AS3600-2009

$$N_u = 0.48\phi\left[1 - \left(\frac{k\lambda}{31.6}\right)^2\right]f_c L t \quad (2)$$

OW, k = 0.755 when restricted rotation, k = 1 when rotation is not restricted

TW, $\text{TW4S}, k = \frac{1}{(1+\left(\frac{H_w}{L_w}\right)^2)}$ (3)

EN1992-1-1

$$N_u = \Phi \frac{1}{\gamma_c} f_c L t \quad (4)$$

$$\Phi = 0.76 - 0.0257k\lambda \ \leq \ 0.67 - \frac{k\lambda}{200} \quad (5)$$

1.6 Proposed Design Equation

Multiple design equation has been proposed. With the knowledge gap in the current understanding of this subject, actual limitation and application of these equations are not yet determined. To determine the ultimate load capacity of TW supported wall with opening, the equation by Doh and Saheb as in [16] and [17] are investigated. A similar approach can be found in both equations where the equation is first developed from solid wall empirically, then a modification considering the opening factor is applied. In Fig. 2, the geometrical designations for Eq. (6) to Eq. (8) are presented.

$$N_{uo} = (k_1 - k_2\alpha_x)N_u \quad (6)$$

Where the coefficient k and N are used to take account the geometry of wall and opening,

$$\alpha_x = \frac{A_{0x}}{A_x} + \frac{a}{L}, A_{0x} = L_0 t\, A_x = L\, t \quad (7)$$

$$\bar{a} = \frac{\left(\frac{L^2 t}{2}\right) - L_0 t a_0}{L_t - L_0 t} \quad (8)$$

Saheb and Desayi as in [10]

For Eq. 6 TW, use $k_1 = 1.02 k_2 = 1.00$

TW, $N_u = 0.67\emptyset[1 - \left(\frac{\eta}{120}\right)^2](1 + 0.12\delta)f_c L t$ (9)

Doh and Fragomeni as in [16]

For Eq. 6 TW, use $k_1 = 1.004 k_2 = 0.933$

$$N_u = \emptyset \left[t - 12e - 2\left(\frac{k^2 \lambda H}{2500}\right) \right] 2.0 f_c^{\,0.7} L \qquad (10)$$

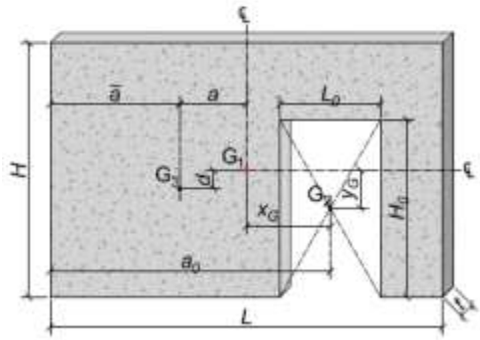

Figure 2 Symbols For Eq. 6 [6] As In [17]

Understanding and knowledge on how to predict ultimate load capacity of the wall with opening will able to address the mentioned issues, do improvement on proposed design equation and more economical design in practice. In this study, the Finite Element Method (FEM) models are setup to investigate the effect of different geometrical properties, slenderness ratio, aspect ratio and opening ratio to ultimate load capacity. Axial strength ratio is a dimensionless parameter used to represent the ultimate load capacity of the wall. In this paper, two of the proposed equation (i.e. Eq. (9) and Eq. (10)) are explored and compared to the result of the model in ANSYS.

2 Method And Materials

A modified and simplified method adopted from LFEM (Layered Finite Element Method) as in [20] is used to analyse the effect of geometry parameters. The result produced by LFEM are found at high satisfactory across different experiment results [7], [11], [17], [20]. In the analysis, solid elements are used instead of layer element capable of simulating non-linear properties of both concrete and reinforcement, boundary condition and loading action up to cracking of the model in ANSYS. Then a correction number of 40% increase is applied on the crack load to determine the ultimate load according to the relationship obtained by [17]. The set of experiment result from [16] are used as a benchmark to validate the model with the opening. The validation process consists of 3 stages, deformation pattern, cracking pattern and ultimate load capacity to simulate the actual behaviour. A 3% to 5% difference in ultimate load is found between the result of the model and the actual experiment. Table 1 and Fig. 3

present the result from the validation work of the numerical model developed in this study.

Table 1 The Comparison Validation Model And Experimental Model

Wall	H_w	L_w	t_w	λ	δ	Opening Size		N_{uo}	Axial Strength Ratio
						H_o	L_o		
Val.	1600	1600	40	40	1	400	400	1030.1	0.4266
Ex.	1600	1600	40	40	1	400	400	1010.6	0.4075

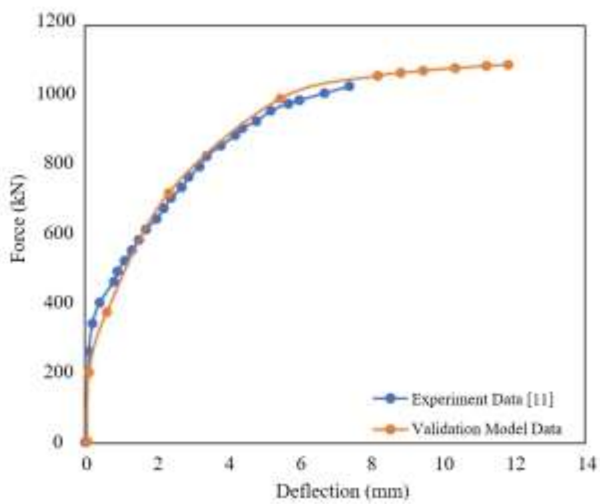

Figure 3 Force Versus Deflection Curve From Numerical Model And Validation Model

There were three group of parametric numerical study conducted. The first aim to determine the slenderness ratio of wall with opening to ultimate load carrying capacity by fixing the aspect ratio and opening size. The model was with TW support condition, load eccentricity, e of t/6 and a normal strength concrete fc = 50 kN/m2 under slenderness ratio of 10. The slenderness is then increased to 20, 30, 40 and 50 to investigate the effect of low slenderness ratio and high slenderness ratio to the ultimate load carrying capacity. Since the behaviour of high slenderness ratio wall is not linear, more attention has directed to determine the behaviour of high slenderness ratio wall. The second parametric study revolve around the aspect ratio of wall with openings. Similar to slenderness ratio, the study investigate the effect of aspect ratio to ultimate load carrying capacity with aspect ratio of 1/3, 1, 4/3 and 2 with the constant on eccentricity, e = t/6 and concrete strength, fc = 50 kN/m2. To study the effect of opening size, a dimensionless quantity is compare to the ultimate load carrying capacity of the wall. First the length of the opening is kept constant, the height of the opening increases in three stages to ultimate load carrying capacity is determined. Next, the height of the opening is kept constant while the length of the opening increases also in three stages to ultimate load carrying capacity. Finally, the combination of both length and height increases to ultimate load carrying capacity.

The geometry properties in the numerical model disiguished into three group namely S group for slenderness ratio, A group for aspect ratio and O group for opening ratio shown in Table 2. The S group range from 20 to 50 in slenderness ratio, the A group range from 0.5 to 1.5 aspect ratio and the O group range from 0.5 to 0.125 in opening height ratio and opening length ratio. For opening area ratio, the range is from 1.56 to 25.

Table 2 The Geometry of The Numerical Model

Wall	H_w	L_w	t_w	**λ**	**δ**	**Opening Size**		**Opening Ratio**		
						H_o	L_o	O_h	O_l	O_a
S1	2	2	40	50	1	0.5	0.5	0.25	0.25	6.25
S2	1.6	1.6	40	40	1	0.4	0.4	0.25	0.25	6.25
S3	1.2	1.2	40	30	1	0.3	0.3	0.25	0.25	6.25
S4	0.8	0.8	40	20	1	0.2	0.2	0.25	0.25	6.25
A1	2.4	1.6	60	40	1.5	0.6	0.4	0.25	0.25	6.25
A2	2	1.6	50	40	1.3	0.5	0.4	0.25	0.25	6.25
A3	1.6	1.6	40	40	1	0.4	0.4	0.25	0.25	6.25
A4	0.8	1.6	20	40	0.5	0.2	0.4	0.25	0.25	6.25
O1	1.6	1.6	40	40	1	0.8	0.8	0.5	0.5	25
O2	1.6	1.6	40	40	1	0.4	0.8	0.25	0.5	12.5
O3	1.6	1.6	40	40	1	0.2	0.8	0.13	0.5	6.25
O4	1.6	1.6	40	40	1	0.8	0.4	0.5	0.25	12.5
O5	1.6	1.6	40	40	1	0.8	0.2	0.5	0.13	6.25
O6	1.6	1.6	40	40	1	0.4	0.4	0.25	0.25	6.25
O7	1.6	1.6	40	40	1	0.2	0.2	0.13	0.13	1.56

3 Results and Discussion

A modified and simplified method adopted from LFEM is used to analyse the effect of geometry. The parameter of each geometry properties is plotted against axial strength ratio as shown in Fig. 3 to Fig. 6.

3.1 Slenderness Ratio

From Fig. 4, it can be observed that as slenderness ratio decreases, the axial strength ratio increases with R2 value of 0.96 on a non-linear relationship, showing a strong correlation. Comparing the slenderness ratio of 50 to slenderness ratio of 20, a reduction of 37.27% is observed. Notice that under high slenderness ratio of 40 and 50, only a difference 0.26% can be observed. Since high slenderness is more likely to fail under buckling type, it is suspect that the failure type is starting to transition from bending to buckling, causing the non-linear relationship. On the other hand, under lower range slenderness ratio of 20, a high agreement linear relationship forecast backwards which do not contrary on previous findings. Generally, as slenderness ratio increases, ultimate load capacity decreases.

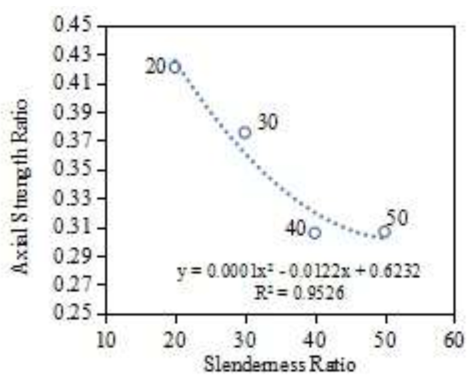

Figure 4 Axial Strength Ratio Versus Slenderness Ratio

3.2 Aspect Ratio

A non-linear relationship can also be observed as in Fig. 5 with a strong correlation of R2 value of 0.96. Comparing aspect ratio 1.5 to aspect ratio 0.5, a 60.05% difference can be seen. Considering only the lower range aspect ratio below 1.25, similarly, a linear relationship is a better fit for the graph. The initial non-linear relationship started more significant than 1 and above. Note that under high aspect ratio 1.5, the failure type is more likely to be buckling instead of bending. To further support the effect of buckling type failure, under high aspect ratio, non-linear relationship signs are present. With only consider the linear section of the curve, the relationship found do not contrary from previous studies where, as aspect ratio increases, ultimate load capacity decreases.

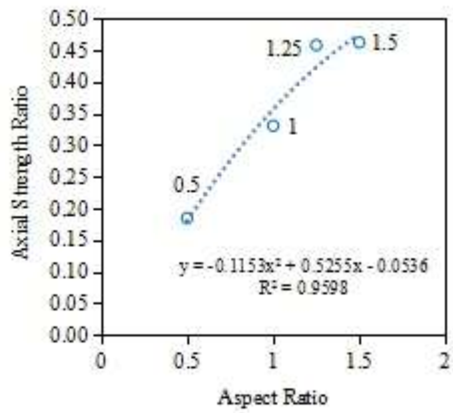

Figure 5 Axial Strength Ratio Versus Aspect Ratio

3.3 Opening Ratio

From Fig. 6 and Fig. 7, various opening ratio commonly exhibit a linear relationship to axial strength ratio with high correlations. Comparing opening height ratios of 0.25 to 0.125, an increase of 31.99% can be found, in opening length ratio, 0.25 to 0.125, an increase of 34.76% can be found while in opening area ratio 25% to 1.563%, an increase of 47.62% can be found.

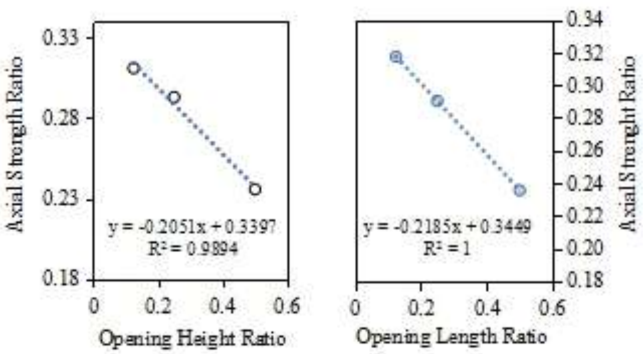

Figure 6 Opening Height Ratio And Opening Length Ratio

The non-linearity occurs only when the transition of failure type to buckling. Due to the low geometry properties under the O group, buckling failure is absent; hence, a linear relationship is observed. However, increasing any opening ratio up to a certain threshold will cause the wall to fail under buckling with high confidence based on the observation from S and A group of the numerical model. Increasing opening height ratio in a sense is similar to increase slenderness ratio, likewise, increasing the opening length ratio have similar behaviour to mention the aspect ratio. High slenderness ratio and high aspect ratio are more susceptible to fail in buckling. Generally, as the opening ratio increases, the ultimate load capacity decreases. The effect of the increase in opening height is slightly less than the increase in opening length. Increasing both length and height simultaneously has the most pronounced reduction on ultimate load capacity.

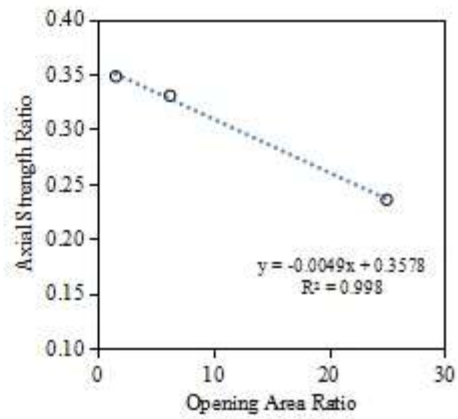

Figure 7 Axial Strength Ratio Versus Opening Aspect Ratio

3.4 Design Equation

Comparison from numerical model and code design equation in Table 3 and Table 4 shown that the code design equations are not applicable in determining the ultimate load of a wall with opening. The mean value of the difference for individual parameter effect to the ultimate load carrying capacity as in Table 3 are 4.88, 3.85 and 1.65 with standard deviations of 9.11, 8.55 and 0.90 respectively observed. The high difference is resulted because the design equation from code does not develop to take consideration of opening.

Table 4 presents the result of comparison between the numerical model with combination parameter to the code that showed high difference in high slenderness ratio and high aspect ratio as in SA5 and SO2. The mean value of the difference for combination parameter effect to the ultimate load carrying capacity are 9.79, 1.39 and 2.12 with standard deviations of 15.06, 0.86 and 1.87 respectively observed.

Table 3 Comparison of the Ultimate Load Of The Numerical Model With The Code On Individual Parameter

Wall ID	$N_{u,o}$(kN)				Difference		
	Model	**Eq. (1)**	**Eq. (2)**	**Eq. (4)**	**Eq. (1)**	**Eq. (2)**	**Eq. (4)**
S1	1,773.24	-45.94	439.58	321.2	37.6	3.03	4.52
S2	1,414.84	396.56	563.48	537.97	2.57	1.51	1.63
S3	1,302.97	550.18	546.16	614.24	1.37	1.39	1.12
S4	973.63	487.15	422.95	550	1	1.3	0.77
A1	3,209.92	594.84	1,196.15	1,368.99	4.4	1.68	1.34
A2	2,649.78	495.7	888.31	953.48	4.35	1.98	1.78
A3	1,530.34	396.56	563.48	537.97	2.86	1.72	1.84
A4	427.48	198.28	11.97	293.04	1.16	34.7	0.46
O1	1,090.68	396.56	563.48	537.97	1.75	0.94	1.03
O2	1,356.36	396.56	563.48	537.97	2.42	1.41	1.52
O3	1,439.62	396.56	563.48	537.97	2.63	1.55	1.68
O4	1,343.82	396.56	563.48	537.97	2.39	1.38	1.5
O5	1,469.86	396.56	563.48	537.97	2.71	1.61	1.73
O6	1,529.08	396.56	563.48	537.97	2.86	1.71	1.84
O7	1,610.28	396.56	563.48	537.97	3.06	1.86	1.99
Mean					4.88	3.85	1.65
Std.D					9.11	8.55	0.90

Fig. 7 shows the applied load versus displacement on wall with opening where combination parameter of high aspect ratio of 2 and opening ratio derived the behaviour of the wall. The numerical model failed under buckling failure mode.

For proposed design equations as in Eq. (9) and Eq. (10), a safety factor 1.0 is used. The result is shown in Table 5. From an overall perspective, the numerical model, the ultimate load capacity of the wall with opening (Nu,o), show high agreement with both equations with a mean value of the difference of 0.16 and 0.14, and standard deviation of 0.08 and 0.13. Compare to the code design equations, both proposed equations show more reliable solution in all aspect. Both equations seem reflecting well on aspect ratio however high difference due to high slenderness ratio can be observed from S group. One exception in aspect ratio is model A4 where the difference found is 0.67 this is due to the failure type as discussed. For opening ratio, the difference is relatively high ranging from 0.13 to 0.42 especially on model with high height ratio. Note that from the modification equation for opening in Eq. (6) does not consider opening height; hence, the value found in O1, O2 and O3 are the highest. Figure 8 shows Displacement On Wall With Combination Aspect Ratio And Opening Aspect Ratio.

Table 4 Comparison Of The Ultimate Load Of The Numerical Model With The Code On Combination Parameter

Wall ID	$N_{u,o}$(kN)				Difference		
	Model	Eq. (1)	Eq. (2)	Eq. (4)	Eq. (1)	Eq. (2)	Eq. (4)
SA1	693.31	148.71	299.04	342.25	3.66	1.32	1.03
SA2	932.27	297.42	242.31	122.47	2.13	2.85	6.61
SA3	945.57	366.79	429.91	550	1.58	1.2	0.72
SA4	1,436.82	733.57	593	537.97	0.96	1.42	1.67
SA5	1,135.58	-24.81	634.52	-	44.78	0.79	-
SA6	1,489.18	-49.61	1,269.04	-	29.02	0.17	-
AO1	644.42	198.28	439.89	550	2.25	0.46	0.17
AO2	1,055.56	198.28	439.89	550	4.32	1.4	0.92
AO3	1,075.42	495.7	475.02	321.2	1.17	1.26	2.35
AO4	1,222.80	495.7	475.02	321.2	1.47	1.57	2.81
AO5	1,096.17	198.28	470.02	-	4.53	1.33	-
AO6	1,803.06	495.7	1,175.04	-	2.64	0.53	-
SO1	311.91	-11.48	109.9	80.3	26.16	1.84	2.88
SO2	519.54	-11.48	109.9	80.3	44.24	3.73	5.47
SO3	895.03	550.18	546.16	614.24	0.63	0.64	0.46
SO4	1,389.54	550.18	546.16	614.24	1.53	1.54	1.26
SO5	634.48	223.06	316.96	302.61	1.84	1	1.1
SO6	962.6	223.06	316.96	302.61	3.32	2.04	2.18
Mean					9.79	1.39	2.12
Std.D					15.06	0.86	1.87

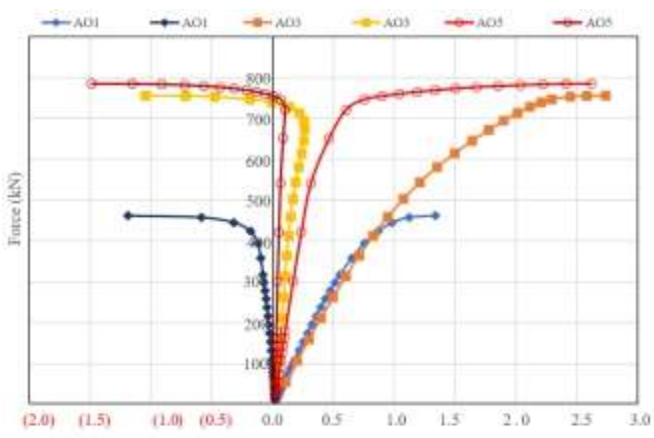

Figure 8 Displacement On Wall With Combination Aspect Ratio And Opening Aspect Ratio

Table 5 Comparison Of The Ultimate Load Of The Numerical Model With The Proposed Equations

Wall ID	$N_{u,o}$(kN)			Difference	
	Model	**Eq. (9)**	**Eq. (10)**	**Eq. (9)**	**Eq. (10)**
S1	1,773.24	2,053.60	2,515.58	0.14	0.30
S2	1,414.84	1,767.13	1,992.25	0.20	0.29
S3	1,302.97	1,397.83	1,475.80	0.07	0.12
S4	973.63	966.40	905.97	0.01	0.07
A1	3,209.92	2,986.63	2,682.14	0.07	0.20
A2	2,649.78	2,370.14	2,324.95	0.12	0.14
A3	1,530.34	1,767.13	1,992.25	0.13	0.23
A4	427.48	522.64	1,282.75	0.18	0.67
O1	1,090.68	1,676.41	1,896.59	0.35	0.42
O2	1,356.36	1,676.41	1,896.59	0.19	0.28
O3	1,439.62	1,676.41	1,896.59	0.14	0.24
O4	1,343.82	1,767.13	1,992.25	0.24	0.33
O5	1,469.86	1,968.00	2,204.07	0.25	0.33
O6	1,529.08	1,767.13	1,992.25	0.13	0.23
O7	1,610.28	1,968.00	2,204.07	0.18	0.27
Mean				0.16	0.14
Std.D				0.08	0.13

Further detail analysis shows that both proposed equation overestimates ultimate load capacity in slenderness ratio and aspect ratio while underestimate in opening ratio compare to the model. The profound difference of ultimate load found are the result of overestimation in slenderness ratio and aspect ratio cancelling underestimation in opening ratio. In short, the main limitation of both equations depends on the failure type of the wall, which is not applicable when the buckling type is imminent. High slenderness ratio, low aspect ratio, high opening ratio causes buckling type failure, which in other words, the limitation of both equations. It is worth to mention that other factors also contribute to the ultimate load capacity such as eccentricity, concrete strength and reinforcement ratio that would affect the performance of the equation and did not cover in this study

4 Conclusion

The general relationship of geometry properties and ultimate load are determined under the specified condition. The main factor in determining ultimate load capacity is the failure type which depends on slenderness ratio, aspect ratio and opening ratio. When buckling type failure is imminent, a non-linear relationship can be observed which significantly reduce ultimate load. On the other hand, under bending type failure, a linear relationship can be observed. The most critical condition in reducing ultimate load is high slenderness ratio, low aspect ratio and high opening ratio which will result in buckling type failure.

Many other equations also proposed throughout the years. The application of theses equations is still limiting by different factors. Regardless of the limitations, the overall performance is still superior to code design equation. There is still room of improvement by modification and improvement. In the future work, study case on the use of proposed equation in practice would provide a hint on improving the equations. Future research should also tackle more on buckling type failure and the non-linear range.

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