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To cite this article: T Z H Ting *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **943** 012033

IOP Conf. Series: Materials Science and Engineering **943** (2020) 012033 doi:10.1088/1757-899X/943/1/012033

A Review on One-Way Concrete Wall Under Axial Loading

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Abstract. As concrete wall panel is gaining popularity in precast construction industry, better insight into its behaviour is of paramount importance. Considerable research has been carried out on concrete wall under axial loading. Most of the published literatures have proposed design equations for wall design purpose. In this aspect, the paper is aimed to review the design equations of one-way concrete wall. The limitations of existing design equations are subsequently identified.

1. Introduction

Concrete wall panel is becoming increasingly popular as a load bearing structural member to transfer load from roof to foundation. Previously, concrete wall panel was mostly viewed as a partition member to isolate the internal building interspace as well as to provide protection against external environment [1]. Due to the extremely conservative design approach provided in the early version of concrete design standards, concrete wall panel was mostly designed with little consideration of structural capacity to sustain load.

With better understanding of the behavior of concrete wall panel as load carrying structural member due to substantial research, design guidelines have been gradually developed and improved. More reliable data has proven that the early version of concrete design standard underestimated the capability of concrete wall panel to be used as structural member [2-4]. Nevertheless, all the current standards allow concrete wall panel to be designed as structural member.

Reinforced concrete wall panels are now considered as important load transferring structural members in building structures. The function of concrete wall panel is determined by the chosen structural system as well as the corresponding type of loading. For wall subjected to wind and seismic loadings, it behaves as a shear wall to resist lateral loading. Concrete wall panel can be designed as load bearing wall if it resists vertical loading only, without being subjected to bending.Thus, the main objective of this paper is to review the current equations from published literature. The features, as well as the associated limitations, of the equations are discussed.

2. Research on Load Bearing Wall and Design Equation

In this section, design equations for concrete load bearing walls from the published literatures are reviewed. The experimental features from previous researchers, derived design equations as well as the associated limitations are also discussed. These semi-empirical equations are generally derived by correlating the experimental data with the equations based on scientific theory.

2.1. Leabu (1959)

Meanwhile, Leabu [5] conducted theoretical study based on allowable compressive stress concept to derive an equation for concrete wall panel under concentric loading. The equation is presented as (1).

$$P_u = 0.2\mathrm{f'}_\mathrm{c}\left[1-\left(\frac{\mathrm{H}}{40\mathrm{t}}\right)^3\right] \quad (1)$$

This equation only takes the effect of slenderness ratio into account without considering other factors. It is noticed that the factor of this equation is extremely low which will yield very conservative result. This equation is quite similar to the early version of ACI 318 (1963) empirical equation with the exception that a higher factor of 0.225 is being used in ACI 318 (1963) equation.

2.2. Oberlender (1975)

Oberlender [6] conducted a comprehensive study on 54 wall panels with slenderness ratio varied from 8 to 28 and aspect ratio from 1 to 3.5. The compressive cylinder strength of wall panels also varied from 28 to 42MPa. Minimum reinforcement ratios of 0.0033 and 0.0047 were provided for vertical and horizontal direction respectively. The wall panels were tested while hinged at both the top and bottom. They were subjected to uniformly distributed concentric loading and eccentric loading at $1/6^{th}$ of wall thickness. For the wall loaded under concentric loading, the authors noticed crushing failure for wall panel with slenderness ratio less than 20 while buckling failure was observed for slenderness ratio at 28. Combinations of crushing and slight buckling were observed for slenderness ratios of 20 and 24. It was noticed that buckling failure was observed for slenderness ratio of greater than 20 when the wall panel loaded eccentrically. The authors proposed an empirical equation based on their research findings as (2).

$$P_u = \varphi 0.6 f'_u A_c\left[1-\left(\frac{H}{30t}\right)^2\right] \quad (2)$$

2.3. Pillai and Parthasarathy (1977)

Pillai and Parthasarathy [7] focused on testing of reinforced concrete wall panel with one layer of mesh embedded in its mid thickness. A total of 18 panels with slenderness ratios which ranged from 5 to 30, aspect ratios from 0.57 to 3.0 and wall thickness values of 40 to 80mm had been tested. The tests were carried out while hinged at both the top and bottom and under eccentric loading at t/6. The proposed studies were to verify the accuracy of theoretical calculation of extended column concept and empirical equation from ACI 318 (1971). The author noticed that the ultimate strength of wall panels estimated from column theory method with moment magnification as well as empirical equation were very conservative. The authors further recommended an empirical equation derived from their research results, shown as (3). The only difference of this proposed equation from that of ACI 318 (1971) was that the slenderness ratio term was modified to 50 instead of 40. It still has all the limitations of the later.

$$P_u = \varphi 0.57 f'_c A_c\left[1-\left(\frac{H}{50t}\right)^2\right] \quad (3)$$

2.4. Kripanarayanan (1977)

Meanwhile, Kripanarayanan [8] conducted a theoretical analysis of reinforced concrete walls which were 200, 250 and 300mm in thickness while the reinforcement ratio was varied from 0.0015 to 0.01. The panels were load at the eccentricity of t/6. The authors proposed an empirical equation, (4), which consists of two functions, F_1 and F_2.

$$P_u = F_1 f'_c A_g F_2 \quad (4)$$

where F_1=0.55 and $F_2 = \left[1-\left(\frac{H}{32t}\right)^2\right]$.

The authors stated that substantial increase of wall capacity was observed when reinforcement ratio was increased from 0.0075 to 0.01. However, the wall axial capacity did not increase significantly with minimum reinforcement (0.0025) and therefore the contribution by reinforcement was neglected in the equation. Since the proposed F_2 did not yield realistic capacity estimation for wall with pin-ended supports, the authors recommended to include k factor in F_2 and it was modified to $F_2 = \left[1-\left(\frac{kH}{40t}\right)^2\right]$.

2.5. Zielinski et al. (1983)

Zielinski, Troitski [9] carried out an experimental study on five full scale ribbed walls under both concentric loading and eccentric loading of t/6. These wall panels were reinforced with two layers of mesh and had the geometry of 13.5 as slenderness ratio and 2.25 as aspect ratio. The authors compared the results of un-ribbed and ribbed wall and concluded that the inclusion of ribs can improve the stiffness and rigidity of wall panels. The authors proposed a design equation based on their research findings as (5).

$$P_u = \varphi 0.55 f'_c A_c \left[1 - \left(\frac{H}{40t}\right)^2\right] [1 + \rho_m (m-1)] \quad (5)$$

The proposed equation is only applicable to the wall with slenderness ratio up to 40 and the applied load must be at eccentricity less than t/6. One of the features of the proposed equation is that the effect of reinforcement ratio is included.

2.6. Saheb and Desayi [2]

Saheb and Desayi [2] conducted a number of investigations into the effects of aspect ratio, slenderness ratio, vertical and horizontal reinforcement ratio on load bearing capacity of reinforced concrete wall under one-way action. A total of 24 samples of concrete grade 20 were studied. The slenderness ratio was varied from 9 to 27 while aspect ratio varied from 0.67 to 2. The vertical reinforcement ratio was varied from 0.0017 to 0.0085 while horizontal reinforcement varied from 0.002 to 0.005. Similar to other researchers, the wall panels were loaded at $1/6^{th}$ of wall thickness with hinges at both the top and bottom. From their research outcome, the authors concluded that the ultimate strength of wall panel decreased with increasing of aspect ratio from 0.67 to 2.0. Also, the ultimate strength of wall panel decreased non-linearly with increasing of slenderness ration from 9 to 27. The authors also found that the ultimate strength of wall panel increased linearly with vertical reinforcement ratio but the increase of horizontal reinforcement ratio had negligible effect. The authors introduced aspect ratio effect and modified the design equations from ACI equation and Zielinski, Troitski [9]. The new equations are divided into two parts and are shown as (6) and (7) respectively.

$$P_u = 0.55\left[f'_c A_c + \left(f_y - f'_c\right) A_s\right] \left[1 - \left(\frac{kH}{32t}\right)^2\right] \left[1.2 - \frac{h}{10L}\right] \text{ for } \frac{H}{L} < 2 \quad (6)$$

$$P_u = 0.55\left[f'_c A_c + \left(f_y - f'_c\right) A_s\right] \left[1 - \left(\frac{kH}{32t}\right)^2\right] \text{ for } \frac{H}{L} \geq 2 \quad (7)$$

It can be seen that reinforcement has been considered in the proposed equation and the term representing slenderness ratio effect is similar to that in ACI equation. The authors demonstrated that the proposed equations could estimate the ultimate strength of reinforced concrete wall panel conservatively by using the test data available in the published literature. However, the proposed equations can only be used for wall with the slenderness ratio up to 32 and are limited to eccentricity of t/6.

2.7. Fragomeni and Mendis (1996)

Fragomeni and Mendis [10] performed a series of research to study normal and high strength concrete wall panels. 16 samples were tested as one-way wall while 4 samples were tested as two-way wall at the eccentricity of t/6. The slenderness ratio was varied from 12 to 25 while aspect ratio was varied from 2 to 5. The compressive strength of concrete was in the range of 32.9 to 67.4 MPa. Minimum reinforcement was provided in both vertical and horizontal directions. From the research outcome, the author observed that wall panel of H/t less than 20 failed by crushing while wall panel with H/t equal or greater than 20 failed by buckling. Comparing the normal strength and high strength wall panels of the same dimensions, high strength concrete wall panel exhibited more brittle failure under one-way action. The authors concluded that the failure mode of reinforced concrete wall panel under axial loading is governed by the concrete strength, slenderness ratio, and the amount of reinforcement provided. By comparing the experimental results with those calculated using AS equation, the authors concluded that the implementation of AS 3600 equation was unsafe for high strength concrete wall panel, especially when only minimum amount of reinforcement was provided. Thus, the equation underestimates the wall capacity.

The authors modified the design equation of AS 3600 by including high strength concrete parameters. The equations are shown in (8) and (9) respectively. They also incorporated an effective height factor from German Code DIN 1045 (1988) into the proposed equations in order to account for the effect of side support.

$$\varphi N_u = \varphi(t_w - 1.2e - 2e_a)0.6f_c' \text{ for} 20 \leq f_c' \leq 50 \quad (8)$$

$$\varphi N_u = \varphi(t_w - 1.2e - 2e_a)35(1 + (f_c' - 50)/80) \text{ for } 50 \leq f_c' \leq 80 \quad (9)$$

Although the investigation was only limited to compressive strength up to 70MPa, the author stated that the proposed equation was valid for wall panel with compressive strength up to 80MPa due to the conservative approach taken and the use of proper reduction factor.

2.8. Doh and Fragomeni (2005)

Doh and Fragomeni [4] conducted a series of comprehensive research on normal and high strength concrete walls through both experimental and numerical modelling studies. A total of 18 wall panels were tested experimentally with 6 of them tested as one-way wall while 12 of them tested as two-way wall. All the samples were tested at the eccentricity of t/6. The slenderness ratio was varied from 25 to 40 while aspect ratio varied from 1 to 1.6. Minimum reinforcement ratio of 0.0031 was provided in both vertical and horizontal directions. The authors proposed an empirical design equation by modifying the design equation of AS 3600 and the one proposed by Fragomeni and Mendis [10]. The proposed equation (10) shows that wall strength does not increase proportionally with concrete strength but is represented by $f_c'^{0.7}$.

$$\varphi N_u = \varphi 2 f_c'^{0.7}(t_w - 1.2e - 2e_a) \quad (10)$$

The equation is applicable for wall with slenderness ratio greater than 30 and it accounts for the effect of side support. It also accounts for the effect of non-linear increase of wall strength with increase of concrete strength. However, the proposed equation still does not consider the effect of lightweight aggregates.

2.9. Ganesan et al. (2012)

Ganesan, Indira [11] investigated the behaviour of steel fiber reinforced self-compacting concrete (SFRSCC) and steel fiber reinforced concrete (SFRC) wall panels in one-way action. A total of 16 wall samples were tested. The slenderness ratios of 12 to 30 and aspect ratios of 0.75 to 1.5 were studied. A single layer of reinforcement was provided with reinforcement ratios of 0.0088 and 0.0074 for vertical horizontal directions respectively. Loads were applied at the eccentricity of t/6. All the wall panels were tested while pinned at both the top and bottom. From their research, the authors concluded that the inclusion of steel fibers were able to improve the cracking behaviour and ductility of concrete wall. The effects of slenderness ratio and aspect ratio were similar to normal type of concrete wall. (11) was proposed by the authors to calculate the ultimate axial strength of SFRSCC wall panels based on their experimental investigation. This equation includes the effect of slenderness ratio, aspect ratio and reinforcement ratio.

$$P_u = 0.56\left[f'_c A_g + \left(f_y - f'_c\right)A_s\right]\left[1 + \left(\frac{h}{29t}\right) - \left(\frac{H}{26t}\right)^2\right]\left[1 - \left(\frac{h}{11L}\right)\right] \quad (11)$$

2.10. Ganesan et al. (2013)

For more recent research, Ganesan, Indira [12] conducted a series of test on 20 samples of reinforced normal concrete and geopolymer concrete wall panels. The slenderness ratio was varied from 12 to 21 while aspect ratio was varied from 1 to 1.875. All the wall panels were tested with pins at both the top and bottom. Loads were applied at the eccentricity of t/6. The author noticed that for the same wall geometry, geopolymer concrete wall panel exhibited more softening behaviour when compared to normal concrete wall panel. Normal concrete wall panel showed steeper slope in load versus lateral deflection when compared to geopolymer concrete wall panel. The authors explained that content of finer particles in the matrix of geopolymer concrete resulted in more ductile behaviour. Attempts were made by the authors to compare the experimental results with those calculated using design equations from the published literature. The authors concluded that these equations are very conservative in predicting the load bearing capacity of geo polymer concrete wall. The authors proposed an equation based on the experimental results to predict the load bearing capacity of both geopolymer and normal concrete wall as (12). Similar assumptions of Saheb and Desayi [2] were adopted in the derivation of the equation. This equation considered the parameters such as slenderness ratio, aspect ratio and reinforcement ratio. However, the accuracy of this equation is debatable since the equation is derived from only 20 samples. Case study was not conducted to compare the proposed equation with other experimental results to prove the reliability of the equation.

$$P_u = 0.59\left[f'_c A_g + \left(f_y - f'_c\right)A_s\right]\left[1 + \left(\frac{h}{40t}\right) - \left(\frac{H}{30t}\right)^2\right]\left[1 - \left(\frac{h}{18L}\right)\right] \quad (12)$$

3. Conclusion

All these studies provide important insights into the development of reinforced concrete load bearing wall and its design equation. It is noticed that most of the research is concentrated on normal and high strength concrete walls. Hence, there is limited research on axial behaviour of lightweight concrete wall. It is also noted that majority of the researchers prefer to modify or derive the design equation based on ACI equation. These researchers concentrated on modifying the factors to account for geometric effects, which are slenderness ratio and aspect ratio. However, it is obvious that these simplified equations have not taken into consideration of all the material non-linearity effects. Further improvement of simplified equation can be made through the consideration of factors such as non-linear compressive strength increment and lightweight aggregates.

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Acknowledgments

The authors acknowledge funding from Curtin Malaysia Research Institute (CMRI).