Review on Structural Behavior of RC Wall with and without Openings

Sanjivan Mahadik
Department of civil, Ph.D. Scholar, DBATU lonere, India

S. R . Bhagat
Department of civil, Asso. Prof., DBATU lonere, India

Abstract- RC walls are often used on building industries due to their added advantages like high strength, stiffness easiness in construction, more speed in construction and requiring less space. Initially walls were designed as non-loadbearing but due to tilt up constructions and/or due to seismic forces or deflection in beams some stresses are set up in wall panels which made essential to design wall load bearing. Many times the wall panels are placed eccentric when they are placed as outer wall and also due to imperfection in construction. Reinforced concrete wall panels are widely used as load-bearing components within the core of high-rise buildings and in tilt-up construction. Openings are required to be provided in the wall panel for functional requirements like doors windows or for providing some building services like ac. ducts or ducts provided for electrification or other like services. Most of the code had not provided design of wall with openings however given provision of additional reinforcement around walls. Many researchers have worked on behavior of RC wall panel with openings with different aspect ratio, area ratio, position, size and loading conditions. This paper consists of a brief review of code provisions and investigation of previous researchers related to RC wall with openings.

Keywords – RC wall, opening, one-way support, two-way support, FEM, code of standards, strength, stiffness, ultimate load, eccentricity.

I. INTRODUCTION

There are very limited provisions in Codes for design of RC wall with openings. Provision given in most of the codes seems to be inadequate or not as per analysis and design based, however Australian Standard AS3600-2009 has added effect of support conditions on strength of RC wall which accounts the effect of openings indirectly. AIJ standards give provision of reinforcement along edges of openings. Australian Concrete Standard, AS3600- 2009, has provided extended rules for the use of the simplified wall design equation for walls supported on either two, three or four sides, and for walls with higher concrete strengths. Researchers had tried to develop formulae which account effect of location and sizes of openings some of which are reviewed in this paper. This paper also covers review research work done on RC wall panel with openings related to its strength, stiffness, cracking behavior and effect of support conditions.

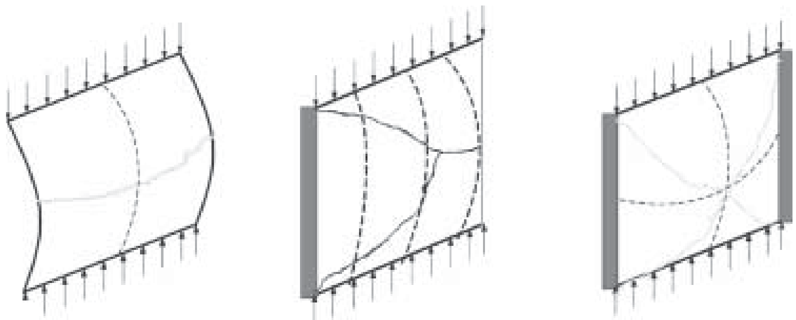
II. CODE PROVISION

2.1 ACI 318

As per ACI 318 structural walls shall have special boundary elements at boundaries and edges around openings of structural walls where the maximum extreme fiber compressive stress, corresponding to factored forces including earthquake effect, exceeds 0.2 f_c'. The special boundary element shall be permitted to be discontinued where the calculated compressive stress is less than 0.15f_c'. Stresses shall be calculated for the factored forces using a linearly elastic model and gross section properties. Where f_c' is a specified compressive strength of concrete [15].

2.2 Australian Code (AS 3600:2009)

The Standard provides two methods for the axial strength design of concrete walls. Out of one is by using a simplified design formula that can be used when certain loading and bracing restrictions are met. Otherwise, the Standard allows any wall to be designed as a column. The Standard presents and recognizes wall panels in two-way action that are supported laterally on three and four sides. Figure1(a), (b) and (c), respectively, shows failure modes of wall panels in one-way action, and in two-way action with either three or four sides supported[16,17].



(a) One-way action (b) Two-way action with three sides supported laterally(c) Two-way action with all four sides supported laterally

Fig.1 Behavior of vertically loaded wall panels [17]

As per simplified method AS 3600:2009 design axial strength per unit length of a braced wall in compression is given as

$$\phi N_u = \phi(t_w - 1.2e - 2e_a)0.6f'_c$$

where

$\phi = 0.6$ is the capacity reduction factor

e = eccentricity of the load applied to the top of the wall and measured at right angle to the plane of wall not less than $0.05tw$.

An additional eccentricity due to the deformation of the wall is

$$e_a = H_{we}^2/2500t_w$$

t_w= the thickness of the wall

H_{we}= the effective wall height is taken to be

kH_w, in which H_w is the unsupported height of the wall and k is determined for various support conditions as follows:

(a) For one-way action with top and bottom floors providing the lateral support at both ends:

(i) k = 0.75 where restraint against rotation is provided at both ends.

(ii) k = 1.0 where no restraint against rotation is provided at one or both ends.

(b) For two-way action with three sides supported laterally by floors and intersecting

Walls

$$k = \frac{1}{1+\left(\frac{H_w}{3L_1}\right)^2}$$

but not less than 0.3 or greater than what is obtained in condition (a).

(c) For two-way action with four sides supported laterally by floors and intersecting

Walls

$$k = \frac{1}{1 + \left(\frac{H_w}{3L_1}\right)^2} \; where\; H_w \leq L_1$$

$$k = \frac{L_1}{2H_w} \; where\; H_w > L_1$$

in which Hw is the unsupported height of the wall and L_1, the horizontal length of the wall between the centers of lateral restraints. Above clause of Standard also covers walls with openings.

Standard also limits the application of above equation to walls with a slenderness ratio $H_{we}/t_w \leq 30$. A minimum eccentricity of $0.05t_w$ must be designed for. The required minimum wall reinforcement ratios are: $p_w = 0.0015$ in the vertical direction and $p_w = 0.0025$ in the horizontal direction. In computing p_w, the overall thickness t_w is used.

III. DESIGN FORMULAS BY RESEARCHERS

3.1. Saheb and Desayi (1990) Formula for Walls with Openings

For wall panels with openings, Saheb and Desayi (1990) proposed that the ultimate load is [12,13]

$$Puo = (k_1 - k_2)P_u$$

Where Pu is the ultimate load of an identical one-way and two-way solid wall panel defined as

$$0.55\,[Agf'_c + (fy - f'_c)Asv\,]\{1 - [H/(32tw)^2]\}\; and\; 0.67\, f'_c Ag\{1 - [L/(120tw)]^2\}\{1 + 0.12(H/L)\}$$

respectively. k_1 and k_2 were respectively, obtained from the test results, 1.25 and 1.22 for one-way action and 1.02 and 1.00 for two way action. Above equation is only applicable to concrete walls with slenderness ratio $H/tw < 12$ and normal strength concrete, relating to the test data from which they were derived.

3.2 Doh and Fragomeni (2006)

Doh and Fragomeni (2006) proposed the equation [8],

$$Nuo = (k_1 - k_2\chi)\, Nu$$

Where *Nu* is the ultimate load of an identical one-way and two-way solid wall panel defined as

$Nu = 2.0\, f_c'^{\,0.7}(t_w - 1.2e - 2e_a)$, which is a modified version of the AS3600 equation and intended for panels with high slenderness ratios. $e_a = H_{we}^2/(2500t_w)$, as before with $H_{we} = \beta H$

$\beta = 1\; for\; H/t_w < 27, and\; \beta = 18/(H/t_w)^{0.88}$ for $H/t_w \geq 27$ when panel is in one way action. $\beta = \alpha \frac{1}{1+\left(\frac{H}{L}\right)^2}$ for $H \leq L_r$ and $\beta = \alpha \frac{L}{2H}$ for $H > L$ when two way action, in these equation, eccentricity parameter $\alpha = \frac{1}{1-e/t}$ for $H/t_w < 27$ and $\alpha = \frac{1}{1-e/t} \times \frac{18}{\left(\frac{Hw}{tw}\right)^{0.88}}$ for $H/t_w \geq 27$

k_1 and k_2 were respectively, obtained from the test results 1.175 and 1.118 for one way and 1.004 and 0.993 for two way action.

Figure 2 identifies the important symbols used where

G1 & G2 = centers of gravity of wall cross section with and without opening, respectively;

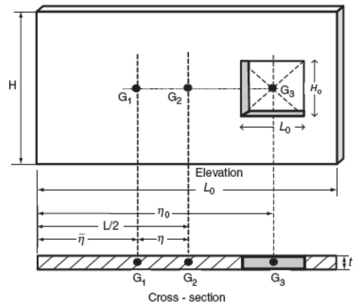


Fig. 2 Geometry of wall openings in elevation and cross-section plan [8].

*G*3 =center of gravity of the opening. The non-dimensional quantity $\chi = (\frac{A_o}{A} + \frac{\eta}{L})$ in which $\eta = (\frac{L}{2} - \bar{\eta})$ in which $\bar{\eta}$ being the distance from the left vertical edge to the center of gravity of the cross-section of the panel with openings. The prediction equation was found to give very good prediction of failure loads for the walls tested and can be extended for use for normal and high strength concrete walls with one or two openings and high slenderness(8).

3.3 Jeung -Hwan DOH, Sam FRAGOMENI, et al.

Design Formula for walls with openings proposed by[9]The main focus of this paper is to investigate the behavior of axially loaded concrete wall panels with various opening size and locations.

The proposed new design equation is as follows:

$$N_{uo} = \{k_1 \quad k_2(\chi_x \mid \lambda\chi_y)\}N_u$$

where N_u may be calculated using Equation $(N_u = 2.0 f'_c{}^{0.7}(t - 1.2e - 2e_a))$ given by AS 3600 01and χ_x and χ_y are the parameters introduced to account opening variation in vertical direction. N_{uo} is design axial strength of wall with openings (N/mm). k_1 and k_2 respectively, are obtained from experimental results, and they are 1.12 and 1.24 for one-way action, and 0.8 and 0.27 for two-way action. λ is 0.16 for one-way action and 0.53 for two-way action.

3.4 Hong Guan, Carlia Cooper and Dong-Jun Lee

Based on the findings of parametric study and the test results of Lee, the following ultimate load formula is proposed [4]

$$Nuo = (k_1 - k_2\alpha_{xy})Nu \quad (a)$$

where $$\alpha_{xy} = (\alpha_x + \lambda\alpha_y)/(1 + \lambda) \quad (b)$$

and $$\alpha_y = A_{oy}/A_y + d_y/H \quad (c)$$

in which A_{oy}/A_y accounts for the opening size in the vertical plane, d_y/H corresponds to the opening location in the vertical direction, and d_y is the distance between centers of gravity (C_y and C) of the panel with and without an opening, respectively, in the vertical plane. Fig. 3

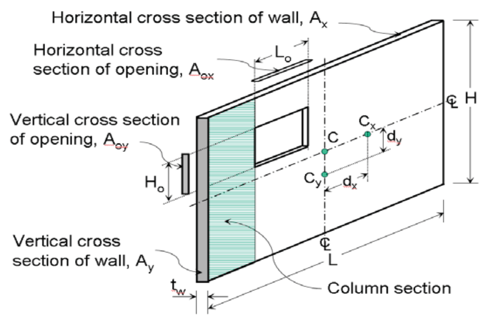


Fig. 3 Geometry of wall panel with opening[4]

As a function of α*x* and α_y, the proposed opening parameter α_{xy} is now able to cover the effect of both the opening length and height. In Eq. (b), $\lambda\ (0 \leq \lambda \leq 1)$ is the weighting ratio indicating the percentage of α_y in relation to α_x. λ together with the constants k_1 and k_2 can be determined by a standard regression analysis.

IV. STRENGTH

Experimental study of Concrete walls with and without openings supported on three sides presented by [5] on six half-scale reinforced concrete walls supported on three sides with various opening configurations. All panels, with a slenderness ratio of 30, were subjected to a uniformly distributed axial load at an eccentricity of $t_w/6$. Crack pattern behavior and effects on ultimate strengths are discussed. Comparisons are made with identically sized wall panels supported on two, three or four sides (with and without openings) in other studies. It is concluded that axial strength varies with location of openings. If opening is near to unsupported edge it behave like two way supported wall panel. Adding side support increases strength of wall. Similar investigation is made by [6] and investigated percentage increase in axial strength for one way and two way supported panels. Seven half-scale reinforced concrete wall panels supported by three sides with and without openings were tested to failure. The panels with a slenderness ratio of 30 were subjected to a uniformly distributed axial load with an eccentricity of $t_w/6$. Panels were casted with normal and high strength concrete. Comparison of strength ratio of solid panel and panel with central opening was made and it is observed that there is increase of axial strength by average 40% to 77 % by providing two way and three way support. Incorporating current test results with other published test results, the comparative study has been extended for predicting the ultimate load of walls supported by three sides. The study found that side lateral supports greatly change the ultimate strength of wall panels with various opening location. wall panel having three side support takes more load than one way support and less than two way support. Axial strength ratio for wall with openings near free support is more than that of opening near supported ends.

Behaviour of axially loaded concrete wall panel with one and two openings is studied by [11]. Walls with two openings compared to identical walls with one opening and observed reduction in strength. For panels in one-way action this axial strength ratio tends to decrease with an increased slenderness ratio. Results of two way panels were inconclusive. Results of tests conducted were compared with results obtained from AS code equation correction factor for the AS code equation is suggested due to deviation in result. Effect of the openings in the strength and stiffness of reinforced concrete structural wall[3] is studied with DIANA software. Fifteen walls with different shape and locations were analyzed with DIANA Software. The strength and stiffness are overestimated by the code equations. Code equations gives same strength and stiffness for wall having same opening area with different locations however DIANA software gives different strength for walls having same area but different locations. It is found that, strength and stiffness of wall is minimum when openings position is at upper edge.

The experimental and LFEM estimate of ultimate loads and maximum deflections are presented by [2]. The ratio between the experimental and the LFEM predictions comes near about 0.90. The comparison shows that the LFEM gives reasonable and satisfactory prediction, where the average of the loads and deflection ratios are close to unity. A numerical method analyzing wall behavior in two-way action, incorporated into a computer program LFEM is presented [7]. The experimental results are then compared to predicted results from the LFEM output. The verified LFEM method is then used to conduct a parametric study to analyze axially loaded reinforced concrete panels supported on all sides. This parametric study focuses on the effect of varying panel properties such as wall slenderness ratios $(20 \leq H/tw \leq 60)$, reinforcement ratios $(0.0015 \leq \rho \leq 0.01)$, eccentricities $(tw/20 \leq e \leq tw/3)$, and concrete strengths (30 MPa ≤ f'c ≤ 80 MPa). Parametric study showed that, axial strength ratio obtained using program WASTABT, decrease with an increase in the H/t_w ratio of wall. The decrease in strength is more pronounced after $H/t_w > 30$ however increase in strength does not appear for panel with high strength ratio. Investigation on concrete walls in compression under short term axial and eccentric loads made by[1]shows that, strength of thin wall is considerable when load is axial, also strength of wall panel increases when reinforcement provided is in two layers. Ultimate load formula for reinforced concrete wall with openings made by [8] concludes that, strength ratio of two way panel is 2.4 to 3.5 more than one way panel axial strength ratio decreases with number of openings. Investigation made be (13) on wall panel with opening shows that, cracking load is slightly more in two way panel whereas ultimate load is nearly same for both type of wall. The axial strength ratio of two-way action panels is generally larger than that of one-way panels by at least 2.4 to 3.5 times. Axial strength ratios are noticed to decrease with the number of opening in walls [8].

V. CRACK PATTERNS

In experimental study general crack patterns for the panels tested are presented [5]. It observed that, the majority of cracking propagated diagonally from the restrained corners to the opening and then horizontally from the opening to unrestrained edges indicating typical two-way behavior close to the restrained ends and one-way behavior between unsupported edges. The high strength concrete panels developed a single large crack, commencing at restrained corners at the tension face then horizontally towards the unrestrained edge. This indicates a brittle failure mode, with possibly some yielding of reinforcement taking place. In contrast, the normal strength panels exhibited more ductile behavior with a number of parallel cracks. Biaxial curvature was evident as a result of the wall panels being supported on three sides. In similar experiment made by [6] in which it is observed that, wall panels tested exhibited crack patterns and failure modes that are consistent with the expected behavior of wall panels with three side lateral supports. It observed that the majority of cracking propagates diagonally from the restrained corners to the opening and then horizontally from the opening to the unrestrained edge. A comparison of normal strength and high strength concrete wall crack patterns illustrates differences in failure modes of two-way action with three side lateral support. The high strength concrete panel developed a single large crack, commencing at restrained corners at the tension face then splitting in two separate parts near unrestrained region. This indicates that the high strength concrete panels possessed a more brittle failure mode, with some yielding of reinforcement taking place before concrete failure. In contrast, several minor cracks propagate in normal strength concrete panel.

Another experiment made by [11] on forty seven reinforced concrete walls with various opening configurations with both one-way and two-way action. The test panels, with a slenderness ratio of 30, 35 or 40, were subjected to a uniformly distributed axial load at an eccentricity of one sixth of the wall thickness (tw/6). One way panel with panel with opening showed single curve bending failure characterized by horizontal cracking at the center of the opening. The two-way panels with openings showed typical double curvature bending failure characterized by diagonal cracking from corners that make their way to corner edges of openings. The distinct differences in failure modes for panels of different strengths is noted, with high strength panels producing distinct brittle cracks whereas more smeared diagonal cracks were evident in normal strength panels. Investigation made by [14] on wall panel with openings shows that the cracking pattern of two way supported panel is similar to slab loaded on four edged. Crack pattern is concentrates near corners and edges of the openings and in pier next to openings [3].

VI. EFFECTS OF ASPECT RATIO AND SLENDERNESS RATIO.

Ultimate strength of reinforced concrete wall panels was investigated by testing of eight reinforced concrete wall panels [10]. The dimensions of the panels were selected by incorporating the provision for varying values of slenderness ratio (SR) and of aspect ratio (AR). The panels were loaded at a small eccentricity (t/6). Ultimate strength found to be increased with aspect ratio. Mixed behavior was observed in case of slenderness ratio that might be due to changes both in length and height. As per investigation made by (1) slenderness ratio of wall panel can be increased by increasing length of wall. In experiments made by [11] it is found that, axial strength ratio for one way panels gradually decreases when slenderness ratios are increased from 30 to 40. Investigation made by[8, 12] shows that axial strength decreases with increase in slenderness ratio. As per investigation made by [12] strength of wall decreases linearly with increase in aspect ratio.

VII. LOAD DEFLECTION CHARACTERISTICS

Typical load versus lateral deflection relationships for the wall panels tested in both one and two-way actions were studied [11]. Comparison of deflection profiles of identical normal and high strength concrete panels is studied. The normal strength curves tended to show a more nonlinear load-deflection path early in their load history whereas high strength panels showed a more linear load-deflection path early before becoming nonlinear. Also normal strength panels had deflections at least double those of the high strength for the same load level. Two-way action panels gives less deflections compared to one-way walls for the same load level [11]. Ultimate strength of wall panel with opening tested by [14]concludes that, deflection of one way supported panel is slightly more than two way supported panel.

VIII. SUPPORT CONDITIONS

Comparison of axial strength ratio of wall panel supported at three sides is made and found that axial strength ratio increases with support at two, three or at four sided with or without openings [5]. Lateral supports greatly change the ultimate strength of wall panels with various opening location. Similar conclusion is drawn by [4] that walls analyzed in two-way action have an increased strength due to the provision of side restraints. The improved strength gained due to the two-way action becomes small when Ao/A (area ratio) are large. As per investigation made by [11], two-way action panels compared to one-way walls gives less deflections for the same load level.

IX. LENGTH HEIGHT AND AREA RATIOS AND NUMBER OF OPENINGS

Ultimate strength analysis of normal and high strength concrete wall panels with varying opening configurations was studied [4]. In this study the nonlinear Layered Finite Element Method (LFEM) is used to undertake a comparative study to verify the effectiveness of the method in predicting the failure characteristics of seven two-way normal strength concrete walls with and without window and door openings. The following discussions are derived from the analysis of twenty wall models in three parametric studies using the LFEM .

Increasing the height and length of the opening Ao/A in equal proportion significantly decreases the axial strength ratio. Increasing Ao/A from 0.25 to 0.67 reduces the load carrying capacity by 92% for one-way and 86% for two-way walls. Ao and A are areas of opening and wall. Increasing only the length of the opening Lo/L decreases the axial strength ratio. Lo and L are length of opening and length of wall respectively. Increasing only the height of the opening Ho/H has little effect on the ultimate carrying capacity and the deflection. Ho and H are height of opening and height of wall respectively. The response of the ultimate load capacity to the variation in the opening size, height and length is approximately linear. Compared to the one-way walls, the strength increase in the two-way counterparts due to provision of side restraints remains relatively constant as the length or the height parameter is increased. Load deflection characteristics and strength ratio of panel having one or two openings are studied by [11]. It is investigated that, effect the failure loads of two-way panels with openings are about 2 to 4 times those of similar one-way panels with openings. Overall, the test results indicate that failure loads decreased when the number of openings was increased from one to two.

X. CONCLUSIONS

No provision is given in IS 456 2000 to account the effect of openings to obtain strength of RC wall. Limited provisions are given in AS 3600 2009 and AIJ standards for calculation of strength of RC wall with openings. Results of various design formulae developed by various researchers for RC wall with openings well simulates test results. Strength of RC wall changes with support conditions. Strength of RC wall varies with slenderness ratio, aspect ratio, thickness. Strength of RC wall depends on size and location of opening. FEM analysis software gives good results which well simulates the test results. Cracking pattern depends on type of support conditions. High strength RC panel shows comparatively brittle failure than normal strength RC wall panel.

REFERENCES

[1] A. E. Seddon, A.E., "Concrete walls in compression under short term axial and eccentric loads" *IABSE publications, AIPC, IVBH,* Abhandlungen. http://dx.doi.org/10.5169/seals-15077.

[2] D.J. Lee, H. Guan, S. Fragomeni, J.H. Doh, "Preliminary Analysis of Normal Strength Concrete Walls with Openings Using Layered Finite Element Method", *School of Engineering*, Gold Coast campus, Griffith University, PMB 50 Gold Coast Mail Centre, Queensland 9726, Australia.

[3] Emilio Martin Ventura Diaz, "Effect of the openings in the strength and stiffness of reinforced concrete structural wall" MEE06021, kenken.go.jp/synd. Article from internet.

[4] Hong Guan, Carlia Cooperb and Dong-Jun Leea, "ultimate strength analysis of normal and high strength concrete wall panels with varying opening configurations" www98.griffith.edu.au/dspace/bitstream/handle/10072/./63471_1 article from internet.

[5] J.H.Doh, Y.C. Loo, S. Fragomeni, "Concrete walls with and without openings supported on threesides".www98.griffith.edu.au/dspace/bitstream/handle/10072/.../67605_1, paper from internet.

[6] J.H. Doh, D.J. Lee, H. Guan and Y.C. Loo, "Concrete wall with various support conditions" *proceeding of the 4th International Conference on Advances in Structural Engineering and Mechanics (ASEM 08).* Korea Pages 967-975

[7] J.H. Doh1 and S. K. PARK2, "Parametric study on the behavior of reinforced concrete panels by finite element method" *proceedings of the ICCMC/IBST*, 2001 - researchgate.net,
[8] J.H. Doh and S. Fragomeni " Ultimate load formula for reinforced concrete wall panels with openings" *Advances in Structural Engineering* Vol. 9 No. 1 2006, researchgate.net paper from internate**.**
[9] Jeung-Hwan Doh, Sam Fragomeni, Yew-Chaye LOO and Dong-Jun Lee, "Design formula for walls with openings" researchgate.net paper from intern.
[10] N. Ganesan, P. V. Indira And S. Rajendra Prasad, "Ultimate strength of reinforced concrete wall panels" *International Journal of Earth Sciences and Engineering* ISSN 0974-5904, Vol. 02, No. 04, August 2009, pp. 340-350.
[11] S. Fragomeni1,, J.H. Doh and D.J. Lee, "Behavior of axially loaded concrete wall panels with openings: an experimental study" *Advances in Structural Engineering* Vol. 15 No. 8 2012
[12] S. Madina Saheb1 and Prakash Desayi2, "Ultimate strength of RC wall panels in one-way in-plane action" *Journal of Structural Engineering,* Vol. 115, No. 10, October, 1989.
[13] S. Madina Saheb1 and Prakash Desayi2, "Ultimate strength of RC wall panels in two-way in-plane action" *Journal of Structural Engineering,* Vol. 116, No. 5, May, 1990.
[14] S. Madina Saheb and Prakash Desayi, "Ultimate strength of RC wall panels with openings", *Journal of Structural Engineering*, Vol. 116, No. 6, June, 1990.
[15] ACI 318 (2002)."Building Code Requirements for Reinforced Concrete ACI318-02", American Concrete Institute, Detroit.
[16] Australian standard 3600, Concrete Structure, Sydney, 2001.
[17] Reinforced and Prestressed Concrete Analysis and design with emphasis on the application of AS 3600-2009 Yew-Chaye Loo, Sanaul Huq Chowdhury, Cambridge University Press