Behaviour of shear wall with openings - A review

Discussion by N. Subramanian and N. Prabhakar

Replies by Muthukumar G. and Manoj Kumar

Dear Sir,

This has reference to the paper titled 'Behaviour of shear wall with openings – A review' authored by Muthukumar, G. and Manoj Kumar, published in The Indian Concrete Journal, February 2017, (Vol. 91, No. 2, pp 38 - 46).

Though the authors have provided a review on this important topic, including experimental investigations carried out since 1940s to the present day, and the provisions in the older versions of the Indian and American codes of practices on shear wall with openings. However, the paper looks like a chapter on literature review written for a Masters thesis of some universities and does not even present the latest information, especially with regards to code provisions. It does not include the behaviour of shear walls in some recent earthquakes, based on which the clauses in ACI 318 have been revised. It also does not include some latest work done in India, especially in IITK and IITM, based on which the clauses in IS 13920 have been revised. The discussers would like to make the following observations and comments:

COMMENT 1

The paper makes a reference to ACI 318 Building code [ACI 318-2011]. This reference is to an earlier version of the ACI code, the latest version being ACI 318-14. Special shear walls section 18.10 (Section 21.9 in older versions), has been extensively revised in ACI 318-14 in view of the performance of buildings in the Chile earthquake of 2010 [EERI, 2012] and the Christchurch, New Zealand, earthquakes of 2011[57], as well as performance observed in the 2010 E-Defense full-scale reinforced concrete building tests [Wallace, 2012]. In these earthquakes and laboratory tests, sometimes spalling of concrete and buckling of vertical reinforcement were observed at wall boundaries. Wall damage was often concentrated over a wall height of 2 to 3 times the wall thicknesses, much less than the commonly assumed plastic-hinge height of one-half the wall length. Out-of-plane buckling failures over partial story heights were also observed (see Wallace, 2012). This failure mode had been observed only in a few earlier moderate scale laboratory tests. Based on these observations, several changes were made in the 2014 version of the ACI code. Only a few are pointed out here. ACI 318 provides two methods for determining whether special boundary elements are required. The preferred method is the displacement-based design procedure described in clause 18.10.6.2,which is applicable only to a cantilever wall with a critical section at the base. To use the method, the seismic force resisting system has to be first sized and then analysed to determine the top-level design displacement δ_u and corresponding maximum value of axial force P_u in the structural wall. The flexural compression depth c corresponding to nominal moment strength $M_{n,CS}$ under axial force P_u is then calculated. If

$$c \geq \frac{\ell_w}{600(\frac{1.5\delta_u}{H_w})} \quad ...(1)$$

where h_w, and ℓ_w refer to total wall height from critical section to top of wall and length of wall, then special boundary elements are required (see also Figure 6). In the ACI 318-14 version of the code a factor of 1.5 has been inserted in the denominator.

Thus, more structural walls will require confined boundary zones under ACI 318-14 than under ACI 318-11. The following four considerations were responsible for the inclusion of the factor 1.5 [Ghosh, S.K., 2016]:

1. The deflection amplification factor C_d of ASCE 7 may underestimate displacement response.
2. Because collapse prevention under the maximum considered earthquake is the prime objective of ASCE 7 seismic design, the displacements caused by the maximum considered earthquake, rather than the design earthquake, should be considered. The maximum considered earthquake is 150% as strong as the design earthquake.
3. There is dispersion in seismic response, making it desirable to aim at an estimate that is not far from the expected upper-bound response.
4. Damping may be lower than the 5% value assumed in the ASCE 7 design spectrum. Instead of changing the constant in the denominator to 900, the 1.5 factor is applied to the design displacement to emphasize that it is the design displacement that is modified.

It is found that the use of a single curtain of web reinforcement makes structural walls more susceptible to instability failure. This is because following yielding of the longitudinal reinforcement in tension, a single layer of vertical web reinforcement lacks a mechanism to restore stability. Hence ACI 318-14 requires two curtains of web reinforcement in all walls having $h_w/\ell_w \geq 2.0$ (section 18.10.2.2). In addition, the slenderness ratio at all specially confined boundary zones is limited to $\ell_u/16$ (section 18.10.6.4b).

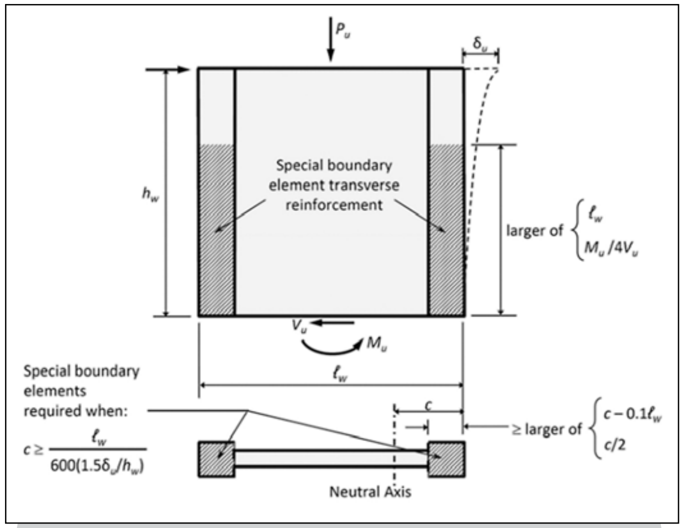

Figure 6. Specially confined boundary zone of special structural wall

Walls with openings are considered to be composed of vertical and horizontal wall segments (Fig. 7). A vertical wall segment is bounded horizontally by two openings or by an opening and an edge. Similarly, a horizontal wall segment is bounded vertically by two openings or by an opening and an edge. Some walls, including some tilt-up walls, have narrow vertical wall segments that are essentially columns, but whose dimensions do not satisfy requirements of special moment frame columns. In consideration of these, ACI 318 defines a wall pier as a vertical wall segment having $\ell_w/b_w \leq 6.0$ and $h_w/\ell_w \geq 2.0$. The lower left vertical wall segment in Fig.7(b) might qualify as a wall pier. Special provisions apply to wall pier (see Clause 18.10.8 of ACI 318-14). For walls with openings, the influence of the opening(s) on

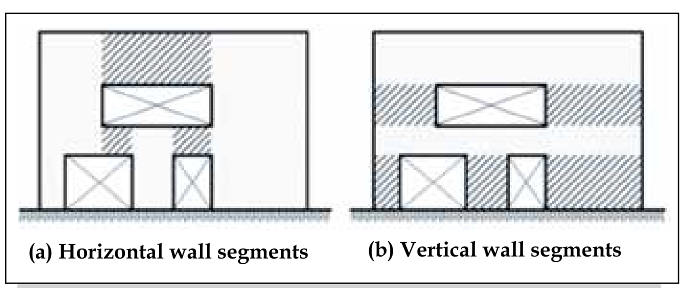

Figure 7. Wall with openings-vertical and horizontal wall segments (hatched)

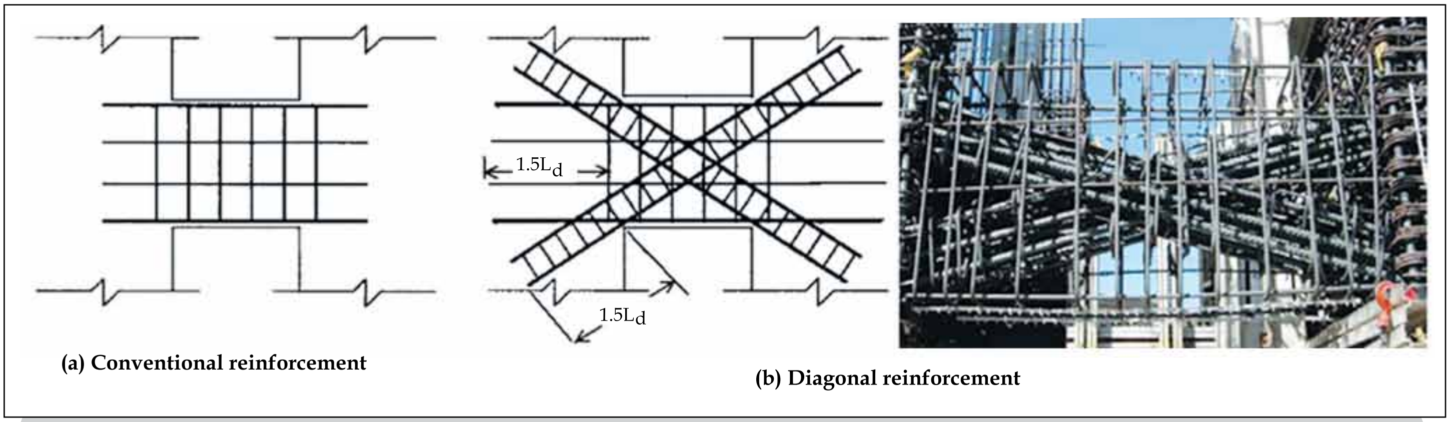

Figure 8. Diagonal reinforcement in a story-high coupling beam, an innovation introduced by Prof. Paulay and followed internationally

flexural and shear strength is to be considered and a load-path around the opening(s) should be verified. Capacity design concepts and strut-and-tie models, as envisaged by Taylor et al., 1998, are suggested by the ACI Code.

A horizontal wall segment is also referred to as a *coupling beam*, when the openings are aligned vertically over the building height. *Coupling beams are not considered in the paper at all.* In 1969, Prof. Paulay, as part of his doctoral studies under the supervision of Professor Hopkins, recognized the deficiencies in deformation capacity of the coupling beams of coupled wall buildings, and developed the innovative concept of diagonal reinforcement—a simple yet elegant solution that greatly reduced potential for damage and increased safety by increasing the controlled deformation capacity (Subramanian, 2013 and Subramanian and Vivek, 2016).

Clause 18.10.7 of ACI 318-14 (Clause 21.9.7 in previous editions) classifies coupling beams into the following three categories based on aspect ratio ℓ_n/h and shear demand.

(1) Coupling beams with $\ell_n/h \geq 4$ must satisfy proportioning and detailing requirements specified for beams of special moment frames, except certain dimensional limits are exempted. Such beams are

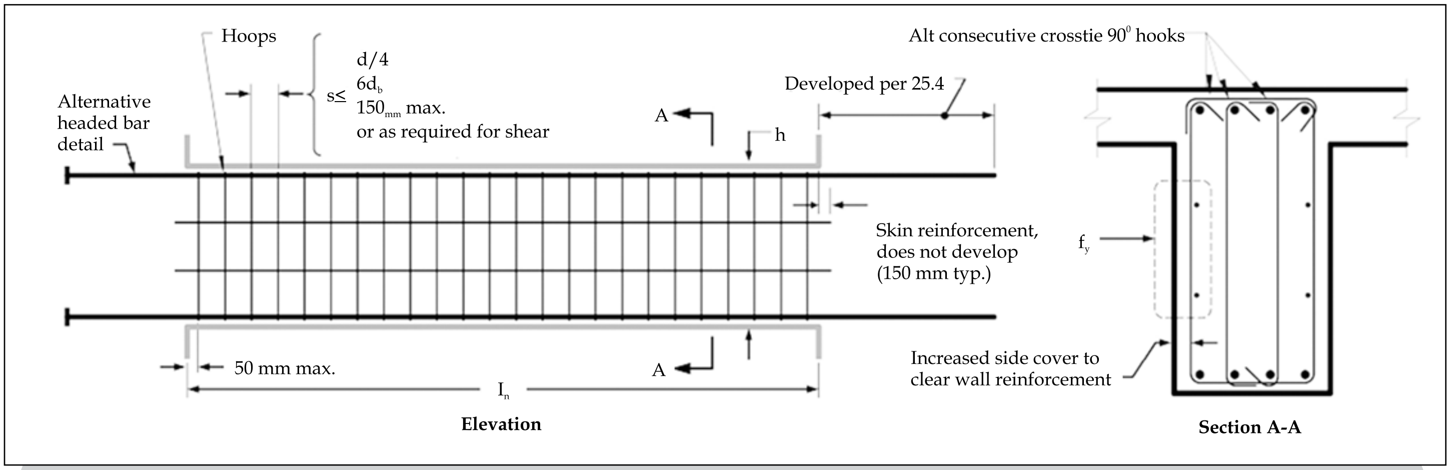

Figure 9. Details for conventionally reinforced coupling beams as per ACI 318-14 (Source:Moehle, et al. 2011)

considered too shallow for efficient use of diagonally placed reinforcement as allowed for deeper beams. Instead, flexural reinforcement is placed horizontally at top and bottom of the beam (see Fig. 9).

(2) Coupling beams with $\ell_n /h< 2$ and $V_u>0.33\lambda\sqrt{f_c}\ A_{cw}$ are required to be reinforced with two intersecting groups of diagonally placed bars symmetrical about the mid-span (as shown in Figures 8 and 10), unless it can be shown that loss of stiffness and strength of the coupling beams will not impair the vertical load carrying ability of the structure, post-earthquake egress from the structure, or the integrity of non-structural components and their connections to the structure.

(3) Other coupling beams not falling within the limits of the preceding two categories are permitted to be reinforced as either conventionally reinforced special moment frame beams or diagonally reinforced beams.

Clause 18.10.7.4 of ACI 318 prescribes two confinement reinforcement options for coupling beams with diagonal reinforcement. The first option of confining individual diagonals using hoops and crossties such that corner and alternate diagonal bars are restrained in a hoop or crosstie corner is shown in Figure 9. For the second option, which will ease construction difficulties and confines the entire beam cross section with hoops and crossties, readers may refer Fig.R18.10.7 of the ACI code.

Unfortunately these two detailing of reinforcements (Figures 9 and 10) are not at all mentioned in the paper; interestingly, the detailing shown in Figure 3 and Figure 5 are not recommended either in ACI 318 or IS 13920.

ACI 318-14 has also made some changes in the non-special confinement requirements of section 18.10.6.5(a)and the commentary to ACI 318-14 has added two useful figures summarizing the boundary confinement requirements for walls with $h_w/\ell_w \geq 2$ and a single critical section controlled by flexure and axial load (See Fig. R18.10.6.4.2 of ACI 318-14).

Replies from the authors

At the outset, the authors would like to thank the reader for initiating the discussion and providing insightful comments related to this important topic of shear wall with openings, especially with respect to code provisions

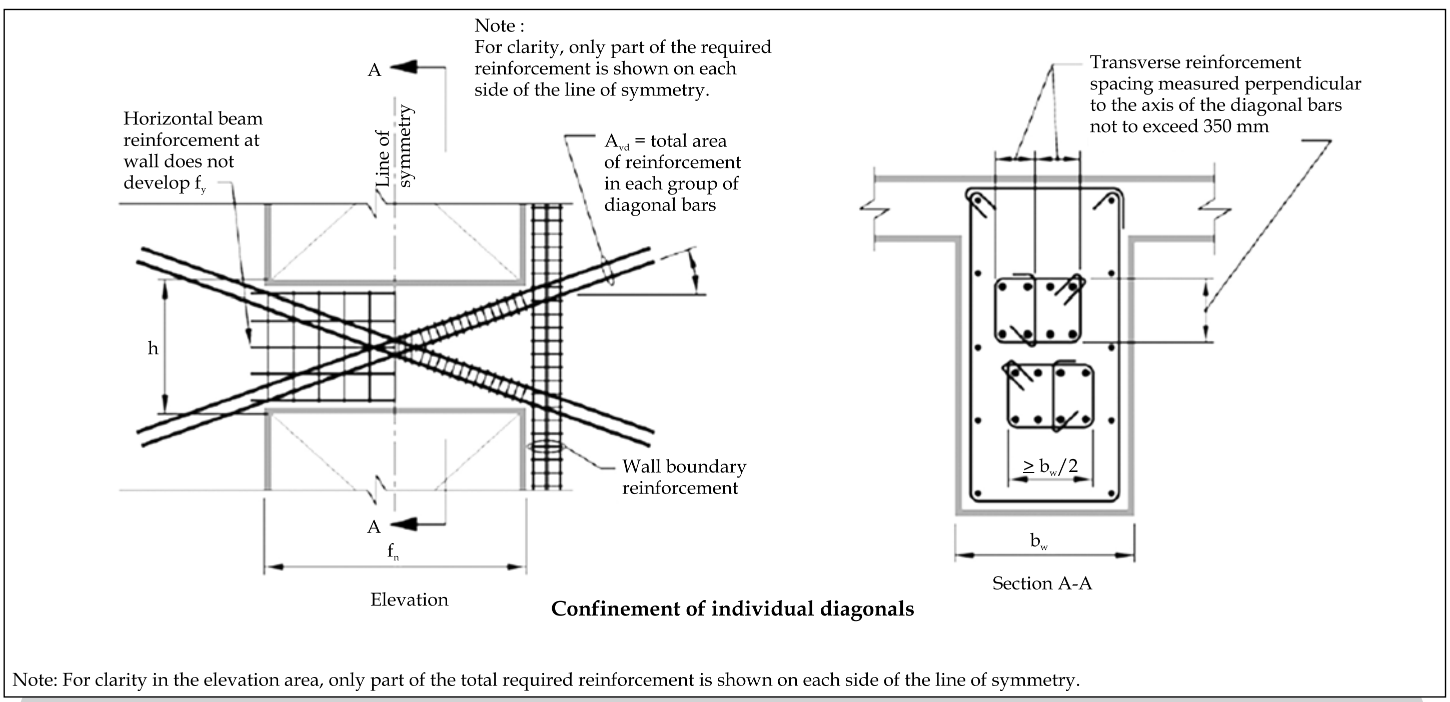

Figure 10. Coupling beams with diagonally oriented reinforcement. Wall boundary reinforcement shown on one side only for clarity (Source: ACI 318:2014)

of ACI 318 and IS 13920. The authors acknowledge the fact that ACI 318-2014 and IS 13920:2016 are the recent code provisions available in practice.

Response to comment 1: The authors also acknowledge the significant changes brought in the ACI 318-2014, especially with respect to "Earthquake Resistant Structures" in general and shear wall in particular. The authors would like to compliment the paper titled "Significant changes from the 2011 to the 2014 edition of ACI 318" authored by Prof. S.K. Ghosh which explains the provisions related to special shear walls with more stringent requirements proposed in the recent code (ACI 318-14) with respect to special confining reinforcement following the performance of buildings in few of the recent earthquakes such Chile earthquake in 2010, Christchurch earthquake in 2011. The authors would also like to acknowledge the contribution made through the experimental full scale testing of RC building as a part of E-Defense project. The scope of this paper is limited to the shear wall with openings and hence the coupled shear walls were not highlighted in the paper.

Though it is acknowledged that the reinforcement detailing advocated in the code provisions (ACI 318-2014), the importance of reinforcement shown in the published paper was presented and discussed in the following paper (referred in reference 44).

44. Sittipunt, C., and Wood, S.L. (1995). "Influence of web reinforcement on the cyclic response of structural walls." ACI Structural Journal, 92(6), 745-767.

COMMENT 2

Again, the paper makes a reference to the old Indian Standards IS 13920:1993. After circulating two drafts in 2006 and 2014, the Bureau of Indian Standards released the new version of IS 13920 in 2016, and changed the tile itself to include the word "Design". The new code has several significant additions and changes from the previous code, especially on structural (shear) walls. These are (see Clause 10.1 of IS 13920:2016):

a) Improved provisions for design of slender RC structural walls.

b) New procedure for estimating design moment of resistance of structural walls with boundary elements.

c) Expression for calculating special confining reinforcement in boundary element in structural wall (See Clause 10.4 of the code).

$$A_{sh} = 0.05 s_v h \frac{f_{ck}}{f_v} \quad \text{...(2)}$$

d) Addition of a figure showing reinforcement detail for coupled structural wall with diagonal reinforcement (which is same as Fig 10).

It has to be noted that the minimum thickness of wall for coupled structural walls in seismic zones is 300 mm and not 150 mm, as mentioned in the paper. The minimum ratio of length of wall to its thickness should be 4. Moreover, the structural wall is classified as squat, intermediate and slender depending on whether the h_w/ℓ_w ratio is less than 1, in between 1 and 2, and greater than 2 ,respectively. Accordingly the minimum reinforcement is prescribed, based on the research at IITM (Rohit et al., 2011), as shown in Table 1, and not as presented in the paper (note some errors in the table of IS 13920 are corrected in the Table 1).

Reply: The authors acknowledge the comment with respect to the new code IS 13920:2016 titled "Ductile Design and Detailing of Reinforced Concrete Structures subjected to Seismic Forces - Code of Practice". It is also to be acknowledged that the key provisions have been incorporated with respect to the minimum reinforcement ratios and minimum thickness specified for different types of special shear walls (Squat, intermediate and slender). Also, the definition of squat, intermediate and slender was incorporated for the first time in the code based on the aspect ratio of the shear wall.

In fact, at the time of submission of manuscript, the copy of the first revision of the code (IS 13920:2016) was not available for purchase to the knowledge of the authors and hence only the provisions of IS 13920:1993 were incorporated.

Table 1. Minimum reinforcement ratios in vertical and horizontal directions of structural walls as per IS 13920:2016

Type of wall $\ell_w/t_w > 25$	Minimum reinforcement ratios
Squat wall $h_w/\ell_w < 1$	$(\rho_h)_{min} = 0.0025$ $(\rho_{v,web})_{min} = 0.0025 + 0.5\left(1 - \frac{h_w}{\ell_w}\right)(\rho_h - 0.0025)$ $(\rho_{v,net})_{min} = (\rho_{v,web})_{min} + \left(\frac{t_w}{\ell_w}\right)\left[0.02 - 2.5(\rho_{v,web})_{min}\right]$ $(\rho_v)_{provided} < (\rho_h)_{provided}$
Intermediate wall $1 \le h_w/\ell_w \le 2$	$(\rho_h)_{min} = 0.0025$ $(\rho_{v,be})_{min} = 0.0080$ $(\rho_{v,web})_{min} = 0.0025$ $(\rho_{v,net})_{min} = 0.0025 + \left(\frac{t_w}{\ell_w}\right) 0.01375$
Slender walls $h_w/\ell_w > 2$	$(\rho_h)_{min} = 0.0025 + 0.5\left(\frac{h_w}{\ell_w} - 2\right)(\rho_h - 0.0025)$ $(\rho_{v,be})_{min} = 0.0080$ $(\rho_{v,web})_{min} = 0.0025$ $(\rho_{v,net})_{min} = 0.0025 + \left(\frac{t_w}{\ell_w}\right) 0.01375$

ρ_h= Ratio of horizontal reinforcement area to gross concrete area of section
ρ_v= Ratio of vertical reinforcement area to gross concrete area of section
$\rho_{v,web}$= Ratio of web vertical reinforcement area to gross concrete area of section
$\rho_{v,net}$= Ratio of net vertical reinforcement area to gross concrete area of section

COMMENT 3

The paper is devoid of any formula or suggestions for the design of shear walls with openings, which would have made the paper useful to the practicing engineers.

Reply: Though the design formulas of shear wall were not presented in the paper, the authors have mentioned the importance of size and position of openings on the structural response of shear wall. Most of the times, the size and position are decided on the basis of the functional requirements and hence the ductile design and detailing becomes important in order to avoid shear failure. The authors acknowledge the code provisions with respect to design & detailing of shear wall around the openings. It is also to be noted that the dual structural configuration of shear wall frame may also to be incorporated in the future revisions. The wall frame buildings are quite popular in residential and commercial buildings. Though the shear wall is generally extended till the full height of the building, it is generally curtailed at some height depending upon the level of interaction between the frame and shear wall.

COMMENT 4

The paper has not included several important papers and reports, such as those of Medhekar and Jain (1993), Ingle and Jain (IITK-GSDMA/EQ22), Rohit, et al. (2013), Moehle, et al.(2011), and Wallace (2012),among the list of references:

In our opinion, the paper would have been more comprehensive if the above comments had been included in it.

References

56.Canterbury Earthquakes Royal Commission (2012). *Final Report-3 Parts*, Ministry of Business, Innovation, and

Employment, Wellington, New Zealand[http://canterbury.royalcommission.govt.nz/CommissionReports/]

57.EERI (Earthquake Engineering Research Institute)(2012) "2010 Maule, Chile, Earthquake Special Issue", *Earthquake Spectra*, Vol. 28, No.S1, EERI, Oakland, CA.

58.Ghosh, S.K. (2016) "Significant changes from the 2011 to the 2014 edition of ACI 318", *PCI Journal*, Vol. 61, No.2, Mar.-Apr., pp.56-80.

59.Ingle, R.K., and Jain, S.K., *Explanatory Examples for Ductile Detailing of RC Buildings*, NICEE, IIT Kanpur [http://www.iitk.ac.in/nicee/IITK-GSDMA/EQ22.pdf].

60.IS 13920:2016, *Code of Practice for Ductile Design and Detailing of Reinforced Concrete Structures Subjected to Seismic Forces*, (First Revision), Bureau of Indian Standards, New Delhi, 24 pp.

61.Medhekar, M.S., and Jain, S.K. (1993), "Seismic behaviour, design and detailing of RC shear walls, Part 1 and 2", *The Indian Concrete Journal*, Vol. 67, July 1993, pp. 311-18 and Sept. 1993, pp. 451-57.

62.Moehle, J.P., T. Ghodsi, J.D. Hooper, D.C. Fields, and R. Gedhada (2011), *Seismic Design of Cast-in-Place Concrete Special Structural Walls and Coupling Beams: A Gide for Practicing Engineers*, NEHRP Seismic Design Technical Brief No. 6, NIST GCR 11-917-11, National Institute of Standards and Technology, Gaithersburg, MD., 37 pp.

63.Rohit,D.H.H., P. Narahari, R. Sharma, A. Jaiswal and C.V.R. Murty, "When RC Columns Become RC Structural Walls", *The Indian Concrete Journal*, Vol. 85, No. 5, May 2011, pp. 36-45.

64.Rohit, D.H.H., A.K. Jaiswal, and C.V.R. Murty, "Expressions for Moment of Resistance of RC Structural Walls", *The Indian Concrete Journal*, Vol. 87, No. 10, Oct. 2013, pp. 48-62.

65.Subramanian, N., and Vivek, G.A. (2016), "GEM 9: Prof. Tom Paulay- One of the Legends of Earthquake Engineering", *Quarterly Journal of Indian Society of Structural Engineers (ISSE)*, Vol. 18, No. 3, July-Sept. pp 3-8.

66.Subramanian, N.,(2013) *Design of Reinforced Concrete Structures*, Oxford University Press, New Delhi, 880 pp.,

67.Wallace, J.W.(2012) Performance of Structural Walls in Recent Earthquakes and Tests and Implications for US Building Codes, *15th Word Conference on Earthquake Engineering*(WCEE), 24-28 Sept. Lisbon, Portugal.

Reply: The authors acknowledge the contribution made by several eminent people working on the various aspects of shear wall. The references proposed are worth incorporating in the document and provides invaluable information related to ductile design and detailing of RC structures in general, and shear wall in particular.

The following are the few references that may be worth reading related to shear walls and ductile detailing.

68. Ghosh, S.K. (2016) "Significant changes from the 2011 to the 2014 edition of ACI 318", PCI Journal, Vol. 61, No.2, Mar.-Apr., pp.56-80.

69. Rohit, D.H.H., P. Narahari, R. Sharma, A. Jaiswal and C.V.R. Murty, "When RC Columns Become RC Structural Walls", The Indian Concrete Journal, Vol. 85, No. 5, May 2011, pp. 36-45.

70. IS 13920:2016, Code of Practice for Ductile Design and Detailing of Reinforced Concrete Structures Subjected to Seismic Forces, (First Revision), Bureau of Indian Standards, New Delhi, 24 pp.

71. Ingle, R.K., and Jain, S.K., Explanatory Examples for Ductile Detailing of RC Buildings , NICEE, IIT Kanpur [http://www.iitk.ac.in/nicee/IITK-GSDMA/EQ22.pdf].

72 Medhekar, M.S., and Jain, S.K. (1993), "Seismic behaviour, design and detailing of RC shear walls, Part 1 and 2", The Indian Concrete Journal, Vol. 67, July 1993, pp. 311-18 and Sept. 1993, pp. 451-57.

73. Moehle, J.P., T. Ghodsi, J.D. Hooper, D.C. Fields, and R. Gedhada (2011), Seismic Design of Cast-in-Place Concrete Special Structural Walls and Coupling Beams: A Gide for Practicing Engineers, NEHRP Seismic Design Technical Brief No. 6, NIST GCR 11-917-11, National Institute of Standards and Technology, Gaithersburg, MD., 37 pp.

74. Wallace, J. W.(2012) "Performance of Structural Walls in Recent Earthquakes and Tests and Implications for US Building Codes", 15th Word Conference on Earthquake Engineering(WCEE), 24-28 Sept. Lisbon, Portugal.

Discussions by

Dr. N. Subramanian, Structural Engineer, 23, Napa Valley Road, Gaithersburg, MD 20878, USA.

Er. N. Prabhakar, Chartered Structural Engineer, Vasai (E), Pin 401 208, Thane, Maharashtra.

Replies by

Muthukumar G., Assistant Professor, Civil Engineering Department at BITS Pilani, Rajasthan.

Dr. Manoj Kumar, Head of Civil Engineering Department at BITS Pilani, Rajasthan.