Code Updates

code developments and announcements

Special Reinforced Concrete Shear Walls

Design and Detailing Requirements of ACI 318-14

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The American Concrete Institute (ACI) published the *Building Code Requirements for Structural Concrete* (ACI 318-14) *and Commentary* (ACI 318R-14) in the Fall of 2014. ACI 318-14 has been adopted by reference into the 2015 *International Building Code* (IBC). There are very significant organizational as well as technical changes between ACI 318-11 and ACI 318-14. A two-part article on the changes was published in the April and May 2016 issues of STRUCTURE magazine.

This current article discusses one of the most significant technical changes – located in the seismic design provisions for special or specially detailed shear walls, which are the only shear walls that can be used as part of the seismic force-resisting system of a building assigned to Seismic Design Categories (SDC) D, E, or F.

Introduction to the Changes

ACI 318-14 Section 18.10, previously ACI 318-11 Section 21.9, has been extensively revised in light of the performance of buildings in the Chile earthquake of 2010 and the Christchurch, New Zealand earthquakes of 2011, as well as performance observed in the 2010 E-Defense full-scale reinforced concrete building tests [Gavridou, et al., 2012]. In these earthquakes and laboratory tests, concrete spalling and vertical reinforcement buckling were at times observed at wall boundaries. Wall damage was often concentrated over a wall height of two or three 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; this failure mode had previously been observed only in a few, moderate-scale laboratory tests.

The following are the significant changes.

Applicability of Displacement-Based Design

The displacement-based design procedure in Section 18.10.6.2 has all along been applicable only to a cantilever wall with a critical section at the base. Another requirement is now added for the displacement-based design procedure to be applicable – the total height to total length ratio (h_w/ℓ_w) of the wall must be no less than two; in other words, the wall must be reasonably slender.

Trigger for Requiring Specially Confined Boundary Zone

In the displacement-based approach, special confinement is required over a part of the compression zone, if:

$$c \geq \frac{\ell_w}{600(1.5\delta_u/h_w)} \qquad \textit{ACI 318-14 Equation (18.10.6.2)}$$

Where c is the largest neutral axis depth calculated for the factored axial force and nominal moment

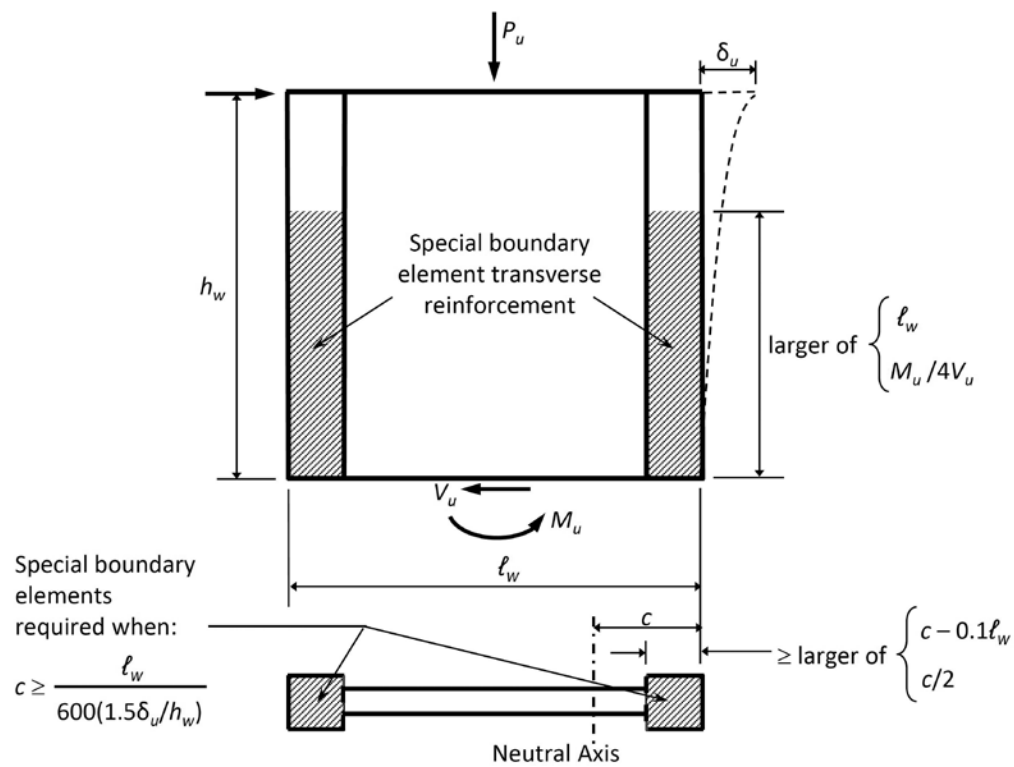

Figure 1. Specially confined boundary zone of special shear wall.

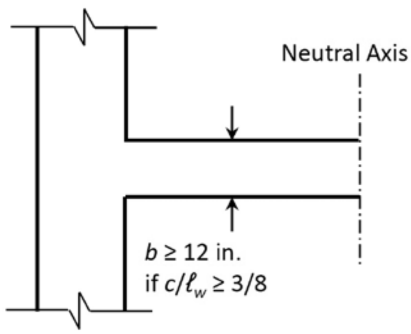

Figure 2. Minimum thickness of compression zone of special shear wall that is not tension-controlled.

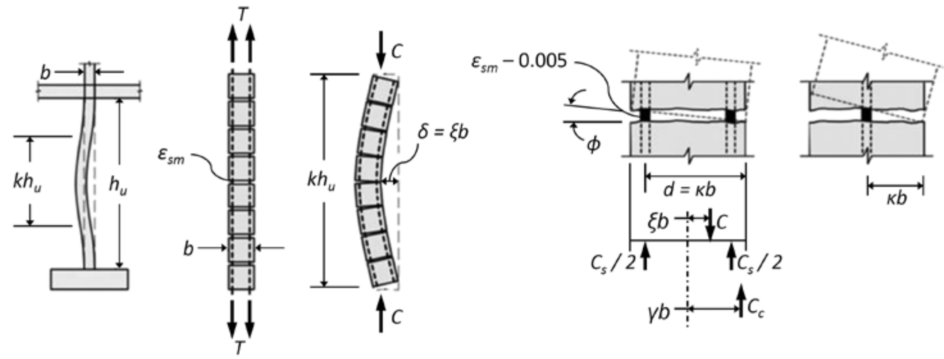

Figure 3. Lateral instability of wall boundary previously yielded in tension [NIST, 2014].

strength consistent with the direction of the design displacement δ_u (*Figure 1*). Note that the 1.5 factor is inserted in the denominator in ACI 318-14. Thus, more shear walls will require confined boundary zones under ACI 318-14 than under ACI 318-11. There were four considerations behind the insertion: (1) The deflection amplification factor, C_d, of ASCE 7 may underestimate displacement response. (2) Since collapse prevention under the Maximum Considered Earthquake (MCE) is the prime objective of IBC/ASCE 7 seismic design, maybe displacements caused by the MCE, rather than the Design Earthquake (DE), should be considered; the MCE is 150% as strong as the DE. (3) There is a 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. The 1.5 factor is applied to the design displacement to emphasize that it is the design displacement that is modified (versus changing the constant in the denominator to 900).

The lower limit of $\delta_u/h_w = 0.007$ in Equation 21-8 of ACI 318-11 is changed to 0.007/1.5 = 0.0047 (0.005) to be consistent with the above change. The Commentary already stated: "The lower limit of 0.005 on the quantity δ_u/h_w requires moderate wall deformation capacity for stiff buildings." The following new sentence has been added: "The lower limit of 0.005 on the quantity δ_u/h_w requires special boundary elements if wall boundary longitudinal reinforcement tensile strain does not reach approximately twice the limit used to define tension-controlled beam sections according to 21.2.2."

Minimum Wall Thickness

ACI 318-14 Equation 18.10.6.2 shown above is based on the assumption that yielding at the assumed critical section occurs over a plastic hinge height of one-half of the wall length. To achieve this spread of plasticity, the wall section should be either tension-controlled, or the compression zone must remain stable when subjected to large compressive strains (transition or compression-controlled section). Observations from the 2010 Chile earthquake, supported by the 2010 E-Defense tests, indicated that brittle failures are possible for thin walls. Two changes have been made in light of this observation. First, the sentence noted at the end of the preceding section has been added to Commentary Section R18.10.6.2. Second, a minimum wall thickness of 12 inches is imposed throughout the specially confined boundary zone where the wall section is not tension-controlled (see 18.10.6.4(c), *Figure 2*).

Confinement Requirements for Specially Confined Boundary Zones

Required transverse reinforcement for specially confined boundary zones of special shear walls has traditionally been determined using provisions for potential hinging regions of special moment frame (SMF) columns. In the plastic hinge region of an SMF column, ACI 318-11 required the minimum cross-sectional area of transverse reinforcement to be the larger of amounts given by Equations (21-4) and (21-5). In the case of specially confined boundary zones of special shear walls, however, two exceptions were made. Equation (21-4) was declared inapplicable. Moreover, the maximum spacing limitation of one-quarter the minimum plan dimension was relaxed to one-third. In ACI 318-14, instead of referencing the SMF section of the code, ACI 318-11 Equations (21-4) and (21-5) are now reproduced in Table 18.10.6.4(f), and both of them are now applicable for the special boundary zone confinement of special shear walls. However, the second relaxation (on the maximum spacing of transverse reinforcement) remains intact. As to the minimum cross-sectional area of transverse reinforcement, there is no difference now between an SMF column hinging region and the specially confined boundary zone of a special shear wall. Also, the maximum center-to-center horizontal spacing of crossties and hoop legs, h_x, of 14 inches has been found not to provide sufficient confinement to thin walls. Based on laboratory tests by Thomasen and Wallace, the maximum center-to-center horizontal spacing of crossties and hoop legs is now restricted to the lesser of two-thirds the wall thickness and 14 inches (Section 18.10.6.4(e)).

Slenderness Considerations

No slenderness limits existed in 318-11 Section 21.9 for specially confined boundary zones, primarily because this failure mode had only been observed in moderate-scale laboratory tests. Observations of wall instabilities following the recent earthquakes in Chile and New Zealand prompted a reexamination of this issue.

The 1997 *Uniform Building Code* (UBC) included a limit of $\ell_u/16$ for Special Boundary Elements. Both the Canadian and New Zealand codes include more restrictive limits.

Observations of wall performance in recent earthquakes and laboratory tests indicate that slender walls, which typically have low shear stress, are susceptible to lateral instability failures. In ACI 318-11 Section 21.9.2, a single curtain of web reinforcement was allowed as long as V_u did not exceed $2A_{cv}\lambda\sqrt{f_c'}$. Use of a single curtain of web reinforcement makes these walls more susceptible to instability failure because, following yielding of the longitudinal reinforcement in tension, a single layer of vertical web reinforcement lacks a mechanism to restore stability (*Figure 3*).

Two changes have been made to address the issues identified above,

(a) Limit the slenderness ratio at all specially confined boundary zones

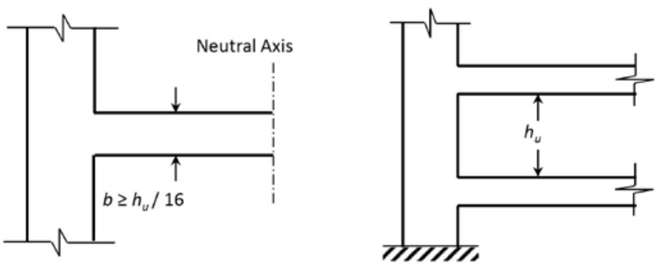

Figure 4. Minimum thickness of compression zone of special shear wall.

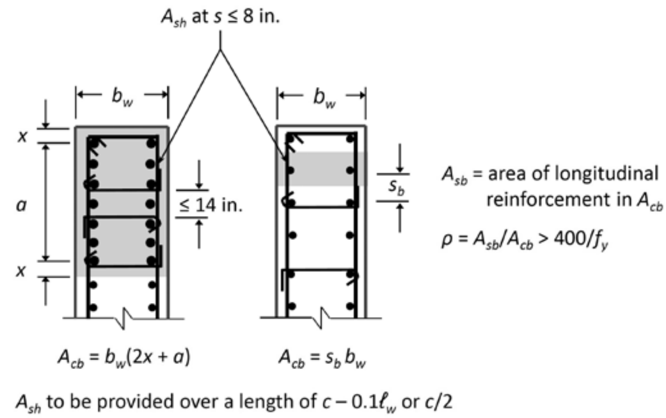

Figure 5. "Local" reinforcement ratio at shear wall boundary.

to $\ell_u/16$ (Section 18.10.6.4b, *Figure 4*), and

(b) Require two curtains of web reinforcement in all walls having $h_w/\ell_w \geq 2.0$ (Section 18.10.2.2).

Buckling Restraint

Cyclic load reversals may lead to buckling of boundary longitudinal reinforcement even in cases where the demands on the boundary of the wall do not require special boundary elements. For walls with boundary longitudinal reinforcement ratio exceeding a certain threshold value, ties are required to inhibit buckling (*Figure 5*). The longitudinal reinforcement ratio is intended to include only the reinforcement at the wall boundary, as indicated in *Figure 5*.

The following changes have been made in the non-special confinement requirements of Section 18.10.6.5(a) [*Underlining is used to indicate text that was not in ACI 318-11, but has been added in ACI 318-14; strikeout has been used to indicate text that was included in ACI 318-11 but has been deleted from ACI 318-14.*]:

"The ~~maximum~~ longitudinal spacing of transverse reinforcement ~~in~~ at the wall boundary shall not exceed the lesser of 8 in. and $8d_b$ of the smallest primary flexural reinforcing bars, except the spacing shall not exceed the lesser of 6 in. and $6d_b$ within a distance equal to the greater of ℓ_w and $M_u/4V_u$ above and below critical sections where yielding of longitudinal reinforcement is likely to occur as a result of inelastic lateral displacements."

Summary of Boundary Confinement Requirements

The Commentary to ACI 318-14 has added two very 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. One figure (*Figure 6, which is a reproduction of ACI 318-14 Figure R18.10.6.4.2a*) is for walls designed by the displacement-based approach of Sections 18.10.6.2, 18.10.6.4, and 18.10.6.5. The other figure (*Figure 7, which is a reproduction of ACI 318-14 Figure R18.10.6.4.2b*) is for walls designed by the traditional approach of Sections 18.10.6.3, 18.10.6.4, and 18.10.6.5.

Conclusions

The design and detailing requirements for special reinforced concrete shear walls have undergone significant changes from ACI 318-11 to ACI 318-14. The changes are a result of the unsatisfactory performance of many shear walls in the Chile earthquake of 2010 and the Christchurch, New Zealand earthquake of 2011. Most of the changes make shear wall design and detailing more stringent.▪

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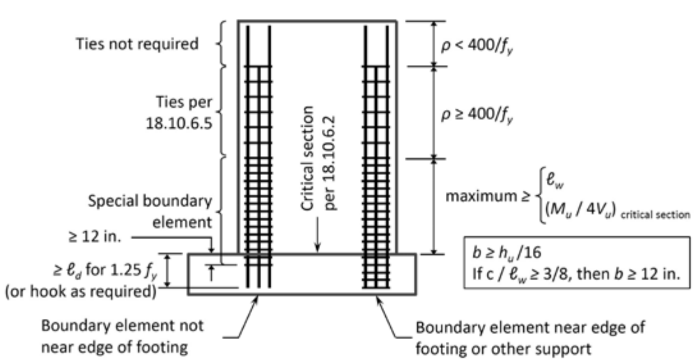

Figure 6. Summary of boundary confinement requirements for walls with $h_w/\ell_w \geq 2$, a single critical section controlled by flexure and axial load, and designed by the displacement-based approach of Sections 18.10.6.2, 18.10.6.4, and 18.10.6.5.

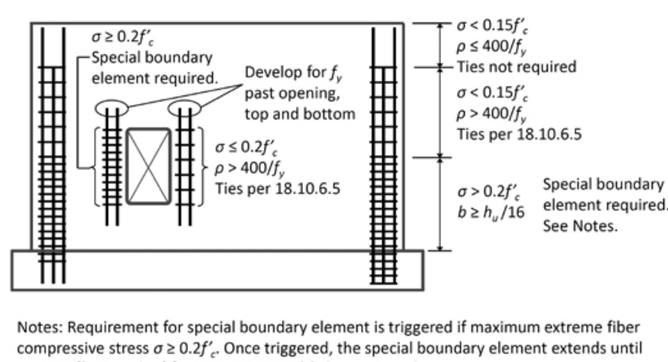

Figure 7. Summary of boundary confinement requirements for walls with $h_w/\ell_w \geq 2$, a single critical section controlled by flexure and axial load, and designed by the traditional approach of Sections 18.10.6.3, 18.10.6.4, and 18.10.6.5.

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