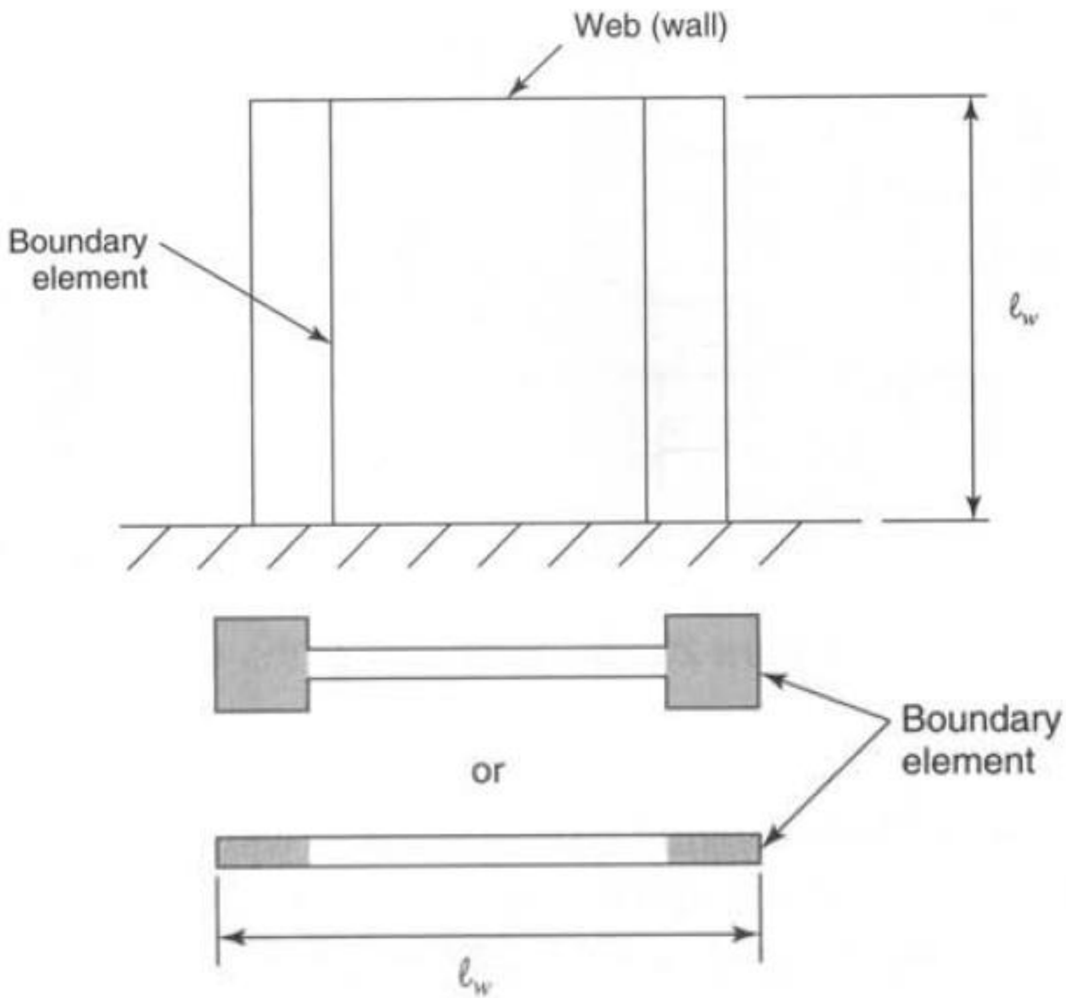
SHEAR WALLS

1. Wall system is a structural system that provides support for all gravity loads and all lateral loads applied to the structure.
2. A structural wall system is much stiffer than a frame system and a performance during an earthquake is much better than the performance of the frame system.
3. A structural wall should be properly designed to sustain all loads acting on it.
4. Boundary elements of the structural walls are the areas around the structural wall edges that are strengthened by longitudinal and transverse reinforcement.

SHEAR WALLS



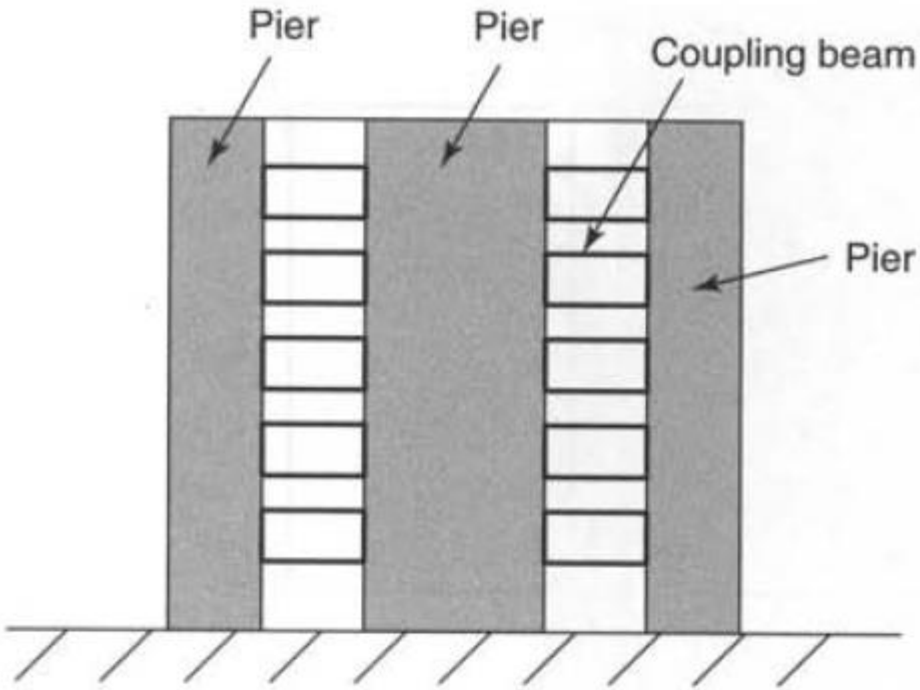
SHEAR WALLS

Shear wall after an earthquake.

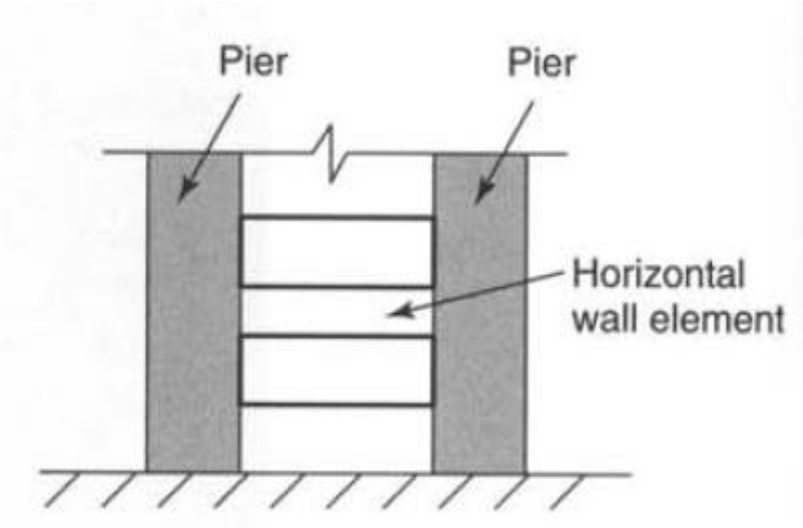
SHEAR WALLS

1. Boundary element increases the rigidity and strength of the wall panels
2. The web reinforcement is anchorage into the boundary elements.
3. The vertical wall segment bounded by two openings is called pier.
4. A horizontal wall section between the openings is called a horizontal wall segment.
5. When the opening are aligned vertical over the building height, the horizontal wall segments between the openings are called coupling beam.

SHEAR WALLS



SHEAR WALLS



SHEAR WALLS

R21.9.3 — Design forces

Design shears for structural walls are obtained from lateral load analysis with the appropriate load factors. However, the possibility of yielding in components of such structures should be considered, as in the portion of a wall between two window openings, in which case the actual shear may be in excess of the shear indicated by lateral load analysis based on factored design forces.

SHEAR WALLS (Section 21.9 ACI-2008)

Reinforcement Requirements (Section 20.5.2.1). Shear reinforcement should be provided in two orthogonal directions in the plane of the wall. (ACI 2008, Section 21.9.2.1) The minimum reinforcement ratio for both longitudinal and transverse directions can be determined as follows:

1. If the design shear $V_u > A_{cv}\lambda\sqrt{f'_c}$, the distributed web reinforcement ratios, ρ_v and ρ_n, should not be less than 0.0025.

$$\rho_l = \frac{A_{sv}}{A_{cv}} = \rho_n \geq 0.0025 \qquad (20.51)$$

where

ρ_t = ratio of area of distributed reinforcement parallel to the plane of A_{cv} to gross concrete area perpendicular to that reinforcement (Fig. 20.26)

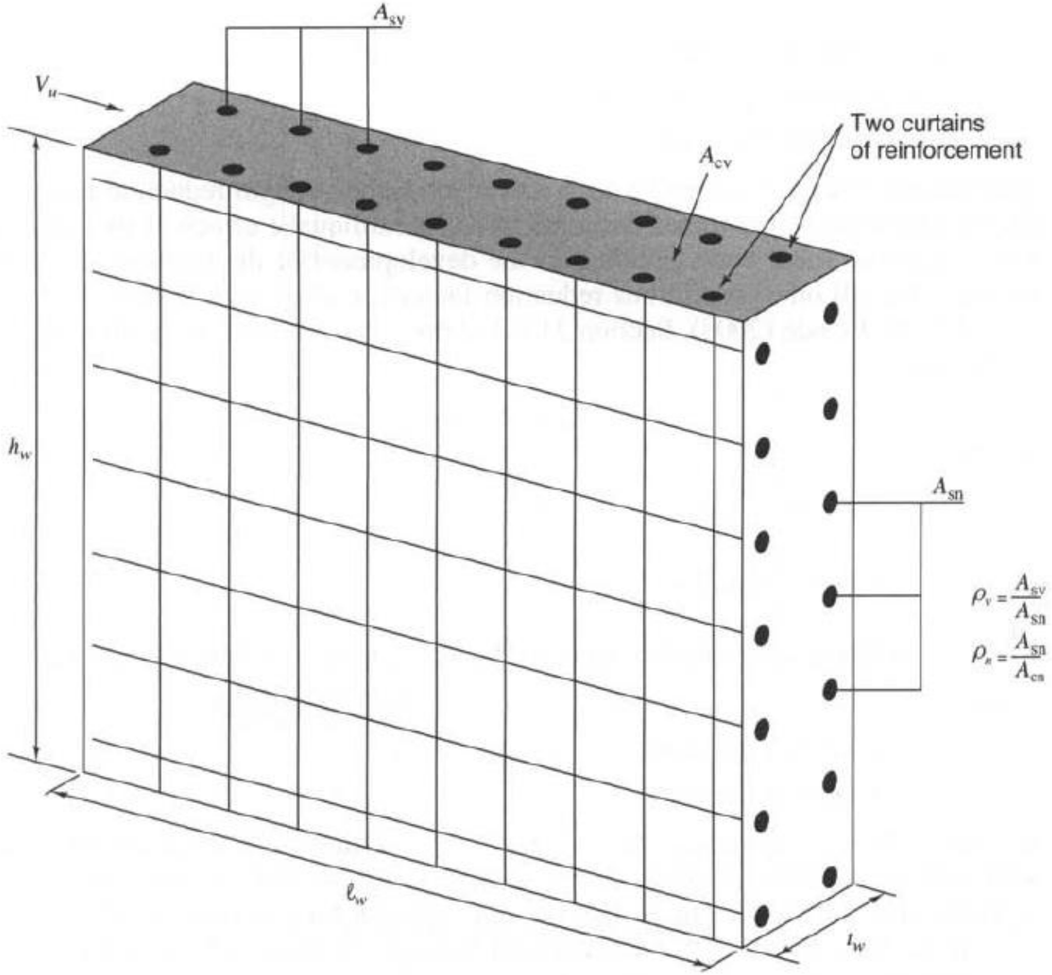
ρ_l = ratio of area of distributed reinforcement perpendicular to the plane of A_{cv} to gross concrete area A_{cv}. (Fig. 20.26)

A_{cv} = gross area of concrete section (product of thickness and length of the section in the direction of shear force)

A_{sv} = Projection on A_{cv} of area of shear reinforcement crossing the plane of A_{cv}

λ = factor for lightweight aggregate concrete

SHEAR WALLS



A_{sv}
V_u
Two curtains
of reinforcement
A_{cv}
h_w
A_{sn}
$\rho_v = \frac{A_{sv}}{A_{sn}}$
$\rho_n = \frac{A_{sn}}{A_{cn}}$
ℓ_w
t_w

SHEAR WALLS

2. If the design shear $(V_u) < A_{cv}\lambda\sqrt{f_c'}$, the minimum reinforcement for ordinary structural walls can be utilized:

$$\text{Minimum vertical reinforcement ratio, } \rho_l = 0.0012 \text{ for no. 5 bars and smaller}$$

$$= 0.0015 \text{ for no. 6 bars and larger}$$

$$\text{Minimum horizontal reinforcement ratio, } \rho_t = 0.0020 \text{ for no. 5 bars and smaller}$$

$$= 0.0025 \text{ for no. 6 bars and larger}$$

SHEAR WALLS

The spacing of the reinforcement can be calculated as follows:

$$s = 2A_s^1/A_s \text{required (per foot of wall)}$$

where

A_s^1 = area of one bar (Fig. 20.26)

Maximum spacing of reinforcement is 18 in. each way according to ACI Section 21.9.2.1.

If the in-plane factored shear force assigned to the wall exceeds $2A_{cv}\lambda\sqrt{f_c'}$, at least two curtains of reinforcement should be provided, as shown in Figure 20.26.

All continuous reinforcement in structural walls should be anchored and spliced as reinforcement in tension for special moment frame (Section 21.9.2.3).

SHEAR WALLS

Shear Strength Requirements (Section 21.9.2.2). The shear strength of structural wall is adequate if the following condition is satisfied:

$$V_u \leq \phi V_n \qquad (20.52)$$

where

V_u = factored axial force
V_n = nominal shear strength
ϕ = strength reduction factor

According to the ACI Code (2008), Section 9.3.4, the strength reduction factor for shear will be 0.6 for any structural member designed to resist earthquake effects if its nominal shear strength is less than the shear corresponding to the development of the nominal flexural strength of the member. For all other conditions reduction factor for shear will be 0.75.

The ACI Code (2008), Section 21.9.4, defines the nominal shear strength of structural walls as follows:

$$V_n = A_{cv}(\alpha_c \lambda \sqrt{f'_c} + \rho_t f_y) \qquad (20.53)$$

SHEAR WALLS

where

$$\alpha_c = 3.0 \text{ for } \frac{h_w}{l_w} \leq 1.5$$
$$= 2.0 \text{ for } \frac{h_w}{l_w} \geq 2.0$$
$$= \text{linear interpolation between 3.0 and 2.0 for } \frac{h_w}{l_w} \text{ between 1.5 and 2.0}$$

where

h_w = height of the wall
l_w = length of the wall

For the walls with openings, the value of h_w/l_w shall be the larger of the ratios for the entire wall and the segment of wall considered. This ensures that the assigned unit strength of any segment of a wall is not larger than the unit strength for the whole wall.

If the ratio $h_w/l_w \leq 2$, reinforcement ratio ρ_v should not be less than ρ_n.

For the walls with openings, the nominal shear strength, V_n, for vertical and horizontal walls segments should satisfy the following:

SHEAR WALLS

For the walls with openings, the nominal shear strength, V_n, for vertical and horizontal walls segments should satisfy the following:

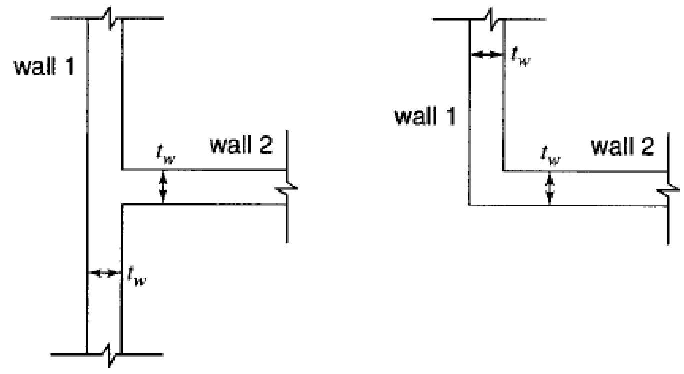
1. If the factored shear force is resisted several pier, the nominal shear strength, V_n, for all wall segments should be $\leq 8A_{\mathrm{cv}}\sqrt{f'_c}$, where A_{cv} is the total cross-section area of the walls (piers) and $V_n \leq 10A_{\mathrm{cp}}\sqrt{f'_c}$, where A_{cp} is the cross-section area of the pier considered.
2. Nominal shear strength of horizontal wall segment and coupling beams should be $\leq 10A_{\mathrm{cp}}\sqrt{f'_c}$, where A_{cp} is the cross-section area of the horizontal wall segment or coupling beam.

SHEAR WALLS

Design for flexure and axial loads (Section 20.5.2.3). Flexural strength of walls should be determined according to the procedure used for columns subjected to flexure and axial loads (ACI 2008, Section 21.9.5). The reinforcement in the whole cross-section of the wall, including boundary elements and web, should be included in calculations of the capacity of the wall. Openings in walls should also be considered.

Where the wall sections intersect, they from L-sections, T-sections, or other cross-section shapes of the flanges (as shown in Fig. 20.27), which need to be considered in design. Flange width should be determined as follows:

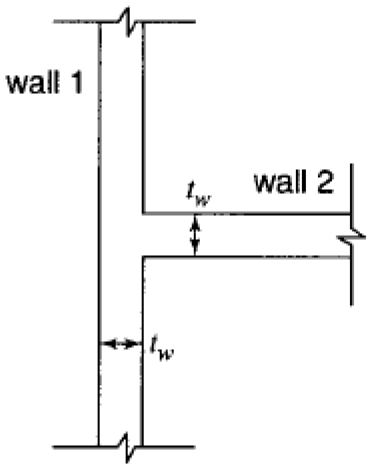
Effective flange width from the face of the web should extend a distance equal to or smaller than $\frac{1}{2}$ the distance to an adjacent wall web or 25% of the total wall height (Fig. 20.28), (ACI Section 21.9.5.2).



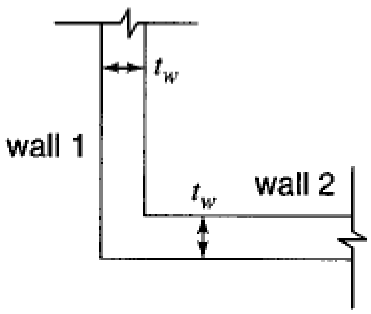
T-section

L-section

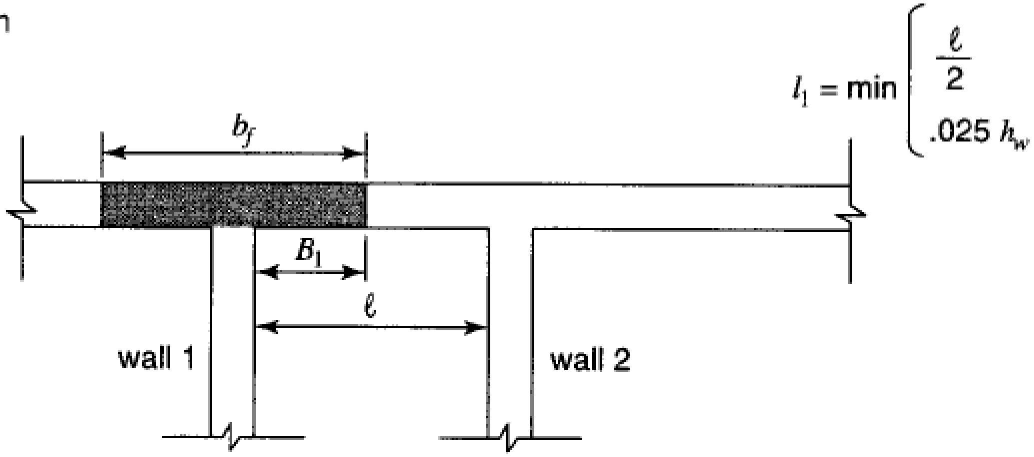
SHEAR WALLS



T-section



L-section



SHEAR WALLS

Special Boundary Elements of Special Reinforced Structural Walls (Section 20.5.2.4). During an earthquake, a structural wall behaves as cantilever beam (Fig. 20.29). Boundary elements can be very heavily loaded due to earthquake loads. A plastic hinge can form at the base of the wall, which requires special reinforcement detailing to provide necessary strength and ductility of the structural wall. According to the ACI Code (2008), Section 21.9.6.1, there are two design approaches for evaluating the detailing requirements of wall boundary element. These are defined as follows:

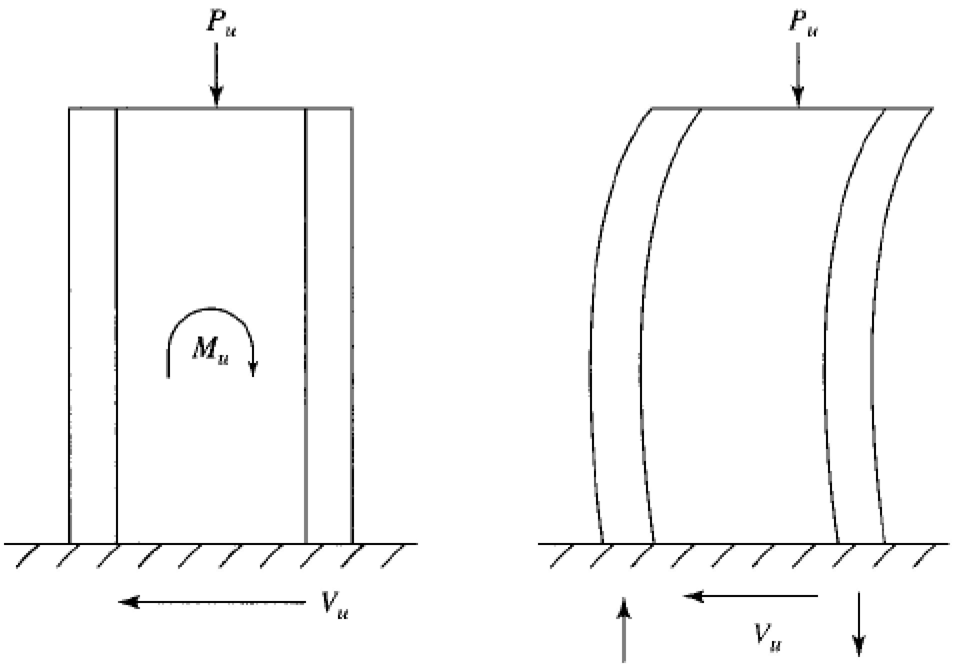
1. Displacement based design (ACI Section 21.9.6.2). For the walls or walls pier that are effectively continuous from the base of the structure to the top of the wall, design to have a single critical section for flexure and axial load compression zones should be reinforced with special boundary elements if

$$c \geq \frac{l_w}{600\left(\dfrac{\delta_u}{h_w}\right)} \tag{20.54}$$

where

$$\frac{\delta_u}{h_w} \geq 0.007$$

SHEAR WALLS



SHEAR WALLS

c = the distance from the extreme compression fiber to the neutral axis, calculated for the factored axial force and nominal moment strength

l_w = the length of the wall in the direction of shear force

δ_u = design displacement

The special boundary reinforcement should extend vertically from a critical section a distance (Fig. 20.30).

$$\geq \begin{cases} l_w \\ \dfrac{M_u}{4V_u} \end{cases} \tag{20.55}$$

SHEAR WALLS

2. Shear based design (ACI Section 21.9.6.3). Structural walls not designed to the displacement based approach shall have special boundary elements at boundaries and edges around openings of the structural wall. A special boundary element should be provided where the maximum extreme fiber compressive stress due to factored forces including earthquake effects exceeds $0.2f'_c$. The boundary elements may be discontinued when the compressive stress becomes less than $0.15f'_c$.

Detailing of the special boundary elements should satisfy the following:

1. Extend horizontally from the extreme compression fiber a distance (Fig. 20.30).

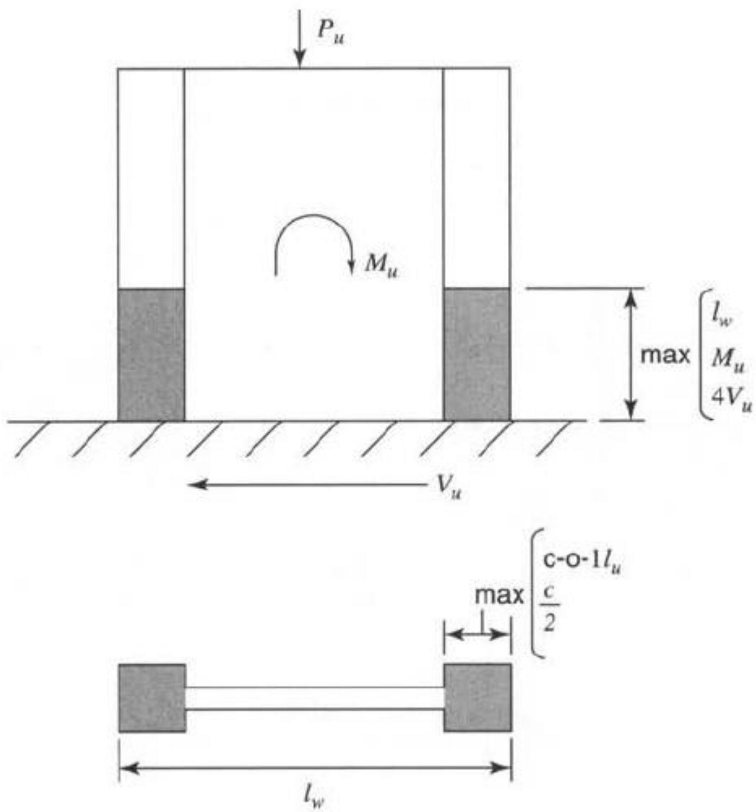
$$\geq \begin{cases} c - 0.1l_w \\ \dfrac{c}{2} \end{cases}$$

where

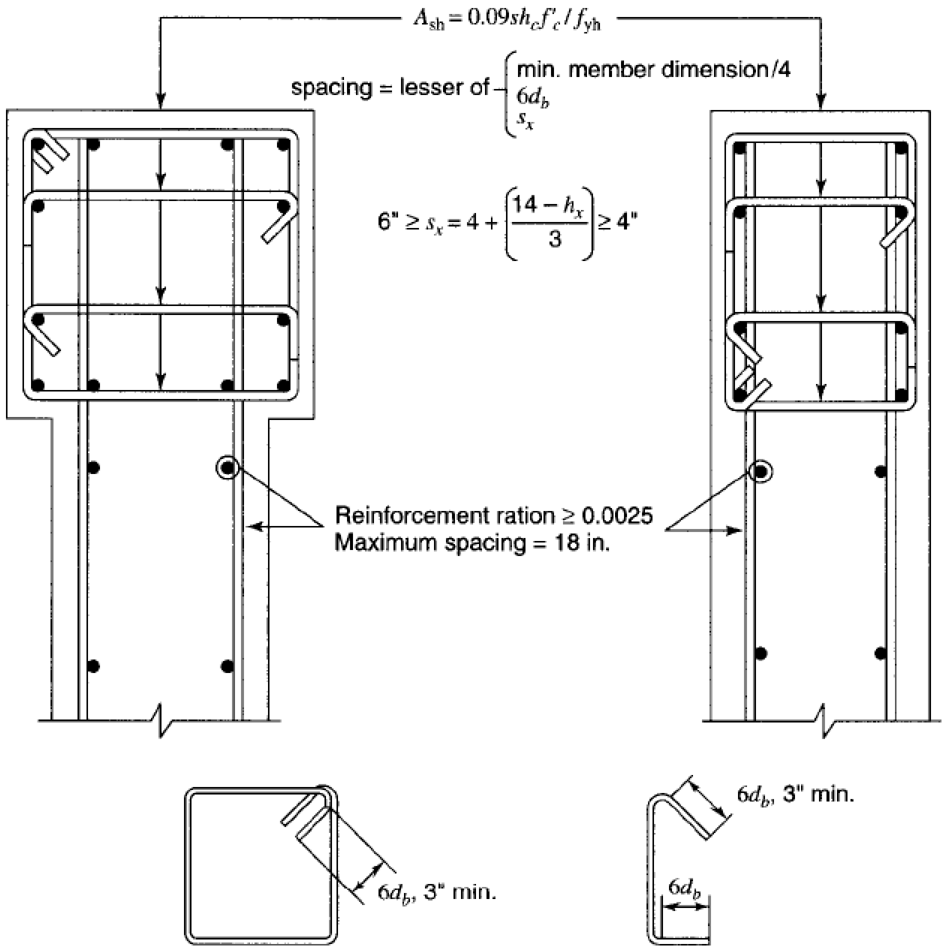
c = the largest neutral axis depth calculated for the factored axial force and nominal moment strength consistent with δ_u.

SHEAR WALLS

2. Transverse reinforcement should be designed by the provisions given for the special moment frame members subjected to bending and axial forces (Fig. 20.31).



SHEAR WALLS



$A_{sh} = 0.09 s h_c f'_c / f_{yh}$
spacing = lesser of
min. member dimension/4
$6d_b$
s_x
$6" \geq s_x = 4 + \left(\frac{14 - h_x}{3}\right) \geq 4"$
Reinforcement ration ≥ 0.0025
Maximum spacing = 18 in.
$6d_b$, 3" min.
$6d_b$, 3" min.
$6d_b$

SHEAR WALLS

Coupling Beams (Section 20.5.2.5). The coupling beam is the structural element that rigidly connects two walls. In a properly designed earthquake-resistant coupled wall system, the coupled beams should yield first, before the base of the wall where the bending moment has the highest value. Also, the beam should have significant ductility and dissipate the energy through the inelastic deformation.

According to the ACI Code, Section 21.9.7, the coupled beams should be designed as follows:

1. If $l_n/h \geq 4$, where l_n is the length and h is the height of the coupled beam, design the coupled beam to satisfy requirements given for flexural members of special moment frame.
2. If $l_n/h < 4$, the beam should be reinforced with two intersecting groups of diagonally placed bars symmetrical about the midspan. The diagonal bars are also required for coupling beam with aspect ratio $l_n/h < 2$ and $V_u > 4\lambda\sqrt{f_c'}A_{cw}$, where A_{cw} is the area of concrete section, resisting shear, of individual pier or horizontal wall segment.

SHEAR WALLS

Two confinement options are described in ACI 318-08 as shown in Figure 20.32. According to ACI Section 21.9.7.4(c) each diagonal element consists of a cage of longitudinal and transverse reinforcement as shown in Figure 20.32(a). Each cage contains at least four diagonal bars and confines a concrete core. The requirement on side dimensions of the cage and its core is to provide adequate toughness and stability to the core section when the bars are loaded beyond yielding.

ACI Section 21.9.7.4(d) describes a second option for confinement of the diagonals as shown in Figure 20.32(b). This second option is to confine the entire beam cross section instead of confining the individual diagonals. This option can considerably simplify field

placement for hoops, which can be challenging where diagonal bars intersect each other or entire wall boundary.

Nominal shear strength can be determined using the following equation:

$$V_u = 2A_{\mathrm{vd}} f_y \sin\alpha \le 10\sqrt{f_c'}A_{\mathrm{cw}} \qquad (20.56)$$

SHEAR WALLS

where

A_{vd} = total area of reinforcement in each group of diagonal bars in a diagonally reinforced coupling beam

α = angle between the diagonal reinforcement and the longitudinal axis of a diagonally reinforced coupling beam

Transverse reinforcement for each group of diagonally placed bars should be designed as transverse reinforcement for the members of a special moment frame subjected to bending and axial force.

Detailing of coupling beam reinforcement should be in accordance with Fig. 20.32.

SHEAR WALLS

21.9.7 — Coupling beams

21.9.7.1 — Coupling beams with $(\ell_n/h) \geq 4$ shall satisfy the requirements of 21.5. The provisions of 21.5.1.3 and 21.5.1.4 need not be satisfied if it can be shown by analysis that the beam has adequate lateral stability.

21.9.7.2 — Coupling beams with $(\ell_n/h) < 2$ and with V_u exceeding $4\lambda\sqrt{f_c'}\,A_{cw}$ shall be reinforced with two intersecting groups of diagonally placed bars symmetrical about the midspan, 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, the egress from the structure, or the integrity of nonstructural components and their connections to the structure.

SHEAR WALLS

21.9.7.3 — Coupling beams not governed by 21.9.7.1 or 21.9.7.2 shall be permitted to be reinforced either with two intersecting groups of diagonally placed bars symmetrical about the midspan or according to 21.5.2 through 21.5.4.

21.9.7.4 — Coupling beams reinforced with two intersecting groups of diagonally placed bars symmetrical about the midspan shall satisfy (a), (b), and either (c) or (d). Requirements of 11.7 shall not apply.

(a) V_n shall be determined by

$$V_n = 2A_{vd}f_y\sin\alpha \leq 10\sqrt{f_c'}\,A_{cw} \qquad (21\text{-}9)$$

SHEAR WALLS

where α is the angle between the diagonal bars and the longitudinal axis of the coupling beam.

(b) Each group of diagonal bars shall consist of a minimum of four bars provided in two or more layers. The diagonal bars shall be embedded into the wall not less than 1.25 times the development length for f_y in tension.

SHEAR WALLS

(c) Each group of diagonal bars shall be enclosed by transverse reinforcement having out-to-out dimensions not smaller than $b_w/2$ in the direction parallel to b_w and $b_w/5$ along the other sides, where b_w is the web width of the coupling beam. The transverse reinforcement shall satisfy 21.6.4.2 and 21.6.4.4, shall have spacing measured parallel to the diagonal bars satisfying 21.6.4.3(c) and not exceeding six times the diameter of the diagonal bars, and shall have spacing of crossties or legs of hoops measured perpendicular to the diagonal bars not exceeding 14 in.

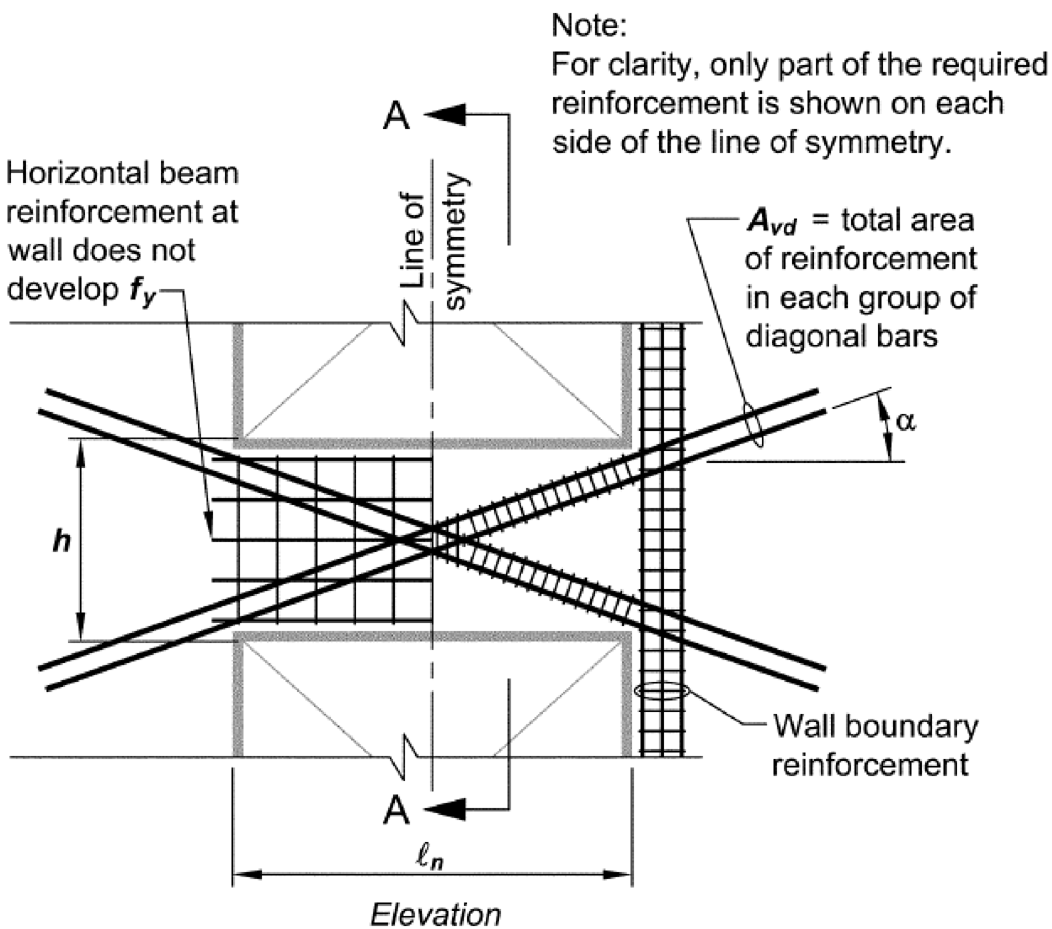
SHEAR WALLS

For the purpose of computing A_g for use in Eq. (10-5) and (21-4), the concrete cover as required in 7.7 shall be assumed on all four sides of each group of diagonal bars. The transverse reinforcement, or its alternatively configured transverse reinforcement satisfying the spacing and volume ratio requirements of the transverse reinforcement along the diagonals, shall continue through the intersection of the diagonal bars. Additional longitudinal and transverse reinforcement shall be distributed around the beam perimeter with total area in each direction not less than $0.002 b_w s$ and spacing not exceeding 12 in.

SHEAR WALLS

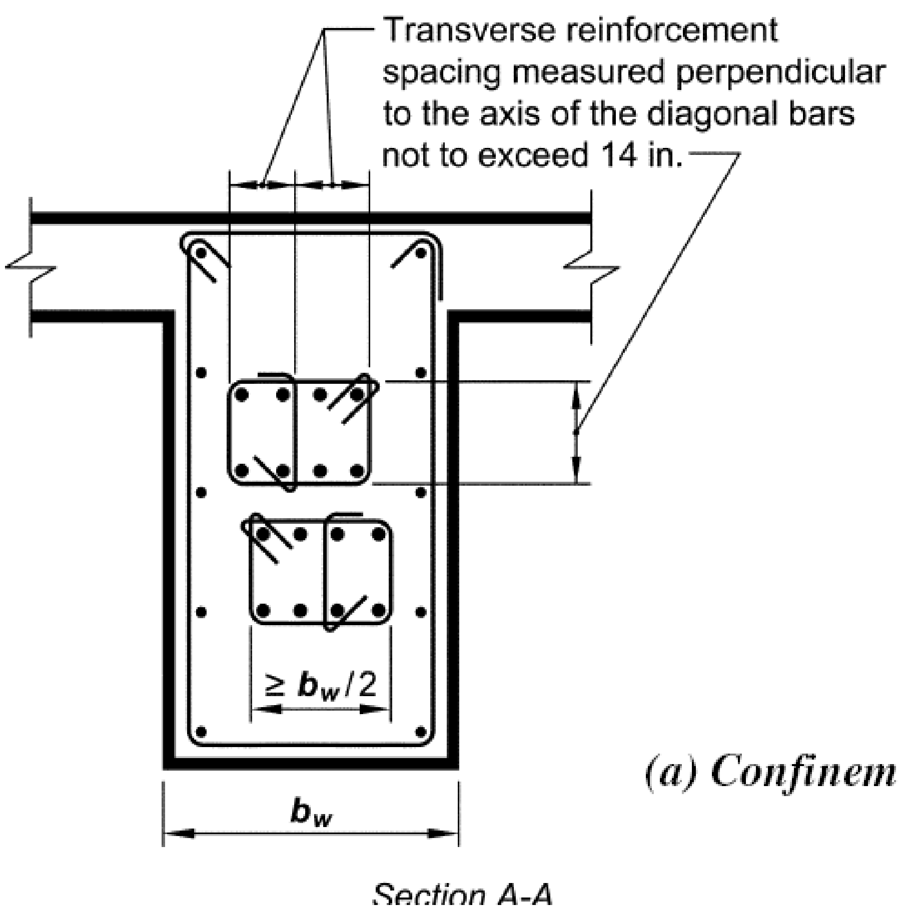
(d) Transverse reinforcement shall be provided for the entire beam cross section satisfying 21.6.4.2, 21.6.4.4, and 21.6.4.7, with longitudinal spacing not exceeding the smaller of 6 in. and six times the diameter of the diagonal bars, and with spacing of crossties or legs of hoops both vertically and horizontally in the plane of the beam cross section not exceeding 8 in. Each crosstie and each hoop leg shall engage a longitudinal bar of equal or larger diameter. It shall be permitted to configure hoops as specified in 21.5.3.6.

SHEAR WALLS



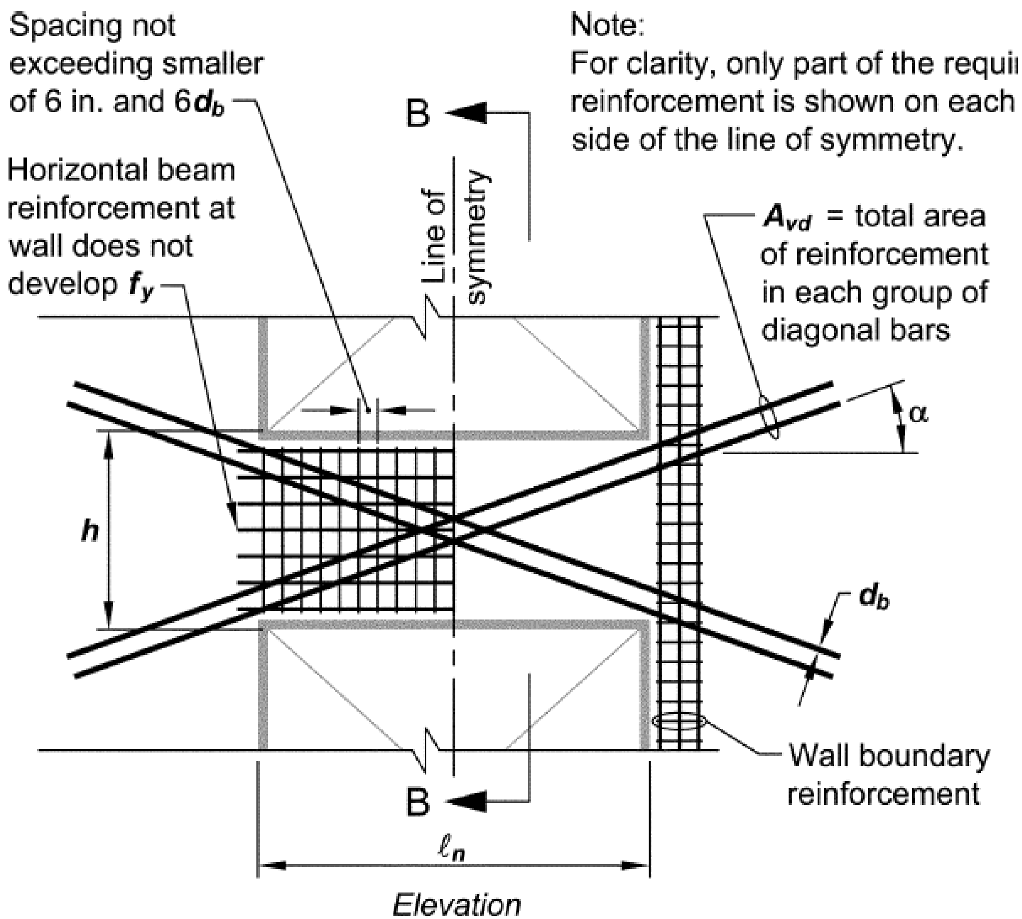
(a) Confinement of individual diagonals.

SHEAR WALLS



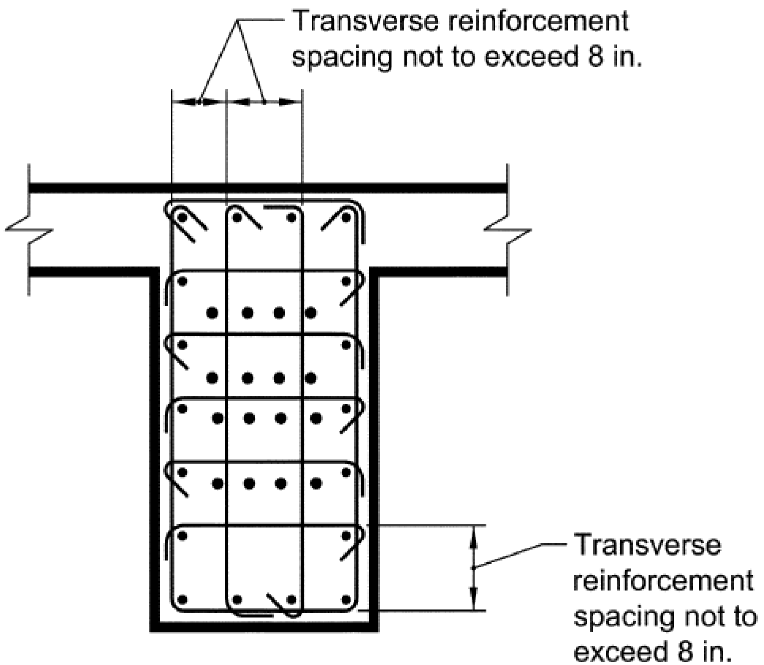
(a) Confinement of individual diagonals.

SHEAR WALLS



(b) Full confinement of diagonally reinforced concrete beam section.

SHEAR WALLS



Section B-B

Note: Consecutive crossties engaging the same longitudinal bar have their 90-degree hooks on opposite sides of beam.

(b) Full confinement of diagonally reinforced concrete beam section.

SHEAR WALLS

R21.9.4 — Shear strength

$$V_n = A_{cv}(\alpha_c \lambda \sqrt{f_c'} + \rho_t f_y) \quad (21\text{-}7)$$

Equation (21-7) recognizes the higher shear strength of walls with high shear-to-moment ratios.[21.14, 21.34, 21.46] The nominal shear strength is given in terms of the net area of the section resisting shear. For a rectangular section without openings, the term A_{cv} refers to the gross area of the cross section rather than to the product of the width and the effective depth. The definition of A_{cv} in Eq. (21-7) facilitates design calculations for walls with uniformly distributed reinforcement and walls with openings.

SHEAR WALLS

A wall segment refers to a part of a wall bounded by openings or by an opening and an edge. Traditionally, a vertical wall segment bounded by two window openings has been referred to as a pier. When designing an isolated wall or a vertical wall segment, ρ_t refers to horizontal reinforcement and ρ_ℓ refers to vertical reinforcement.

The ratio h_w/ℓ_w may refer to overall dimensions of a wall, or of a segment of the wall bounded by two openings, or an opening and an edge. The intent of 21.9.4.2 is to make certain that any segment of a wall is not assigned a unit strength larger than that for the entire wall. However, a wall segment with a ratio of h_w/ℓ_w higher than that of the entire wall should be proportioned for the unit strength associated with the ratio h_w/ℓ_w based on the dimensions for that segment.

SHEAR WALLS

To restrain the inclined cracks effectively, reinforcement included in ρ_t and ρ_ℓ should be appropriately distributed along the length and height of the wall (see 21.9.4.3). Chord reinforcement provided near wall edges in concentrated amounts for resisting bending moment is not to be included in determining ρ_t and ρ_ℓ. Within practical limits, shear reinforcement distribution should be uniform and at a small spacing.

If the factored shear force at a given level in a structure is resisted by several walls or several piers of a perforated wall, the average unit shear strength assumed for the total available cross-sectional area is limited to $8\sqrt{f_c'}$ with the

SHEAR WALLS

additional requirement that the unit shear strength assigned to any single pier does not exceed $\mathbf{10}\sqrt{f_c'}$. The upper limit of strength to be assigned to any one member is imposed to limit the degree of redistribution of shear force.

"Horizontal wall segments" in 21.9.4.5 refers to wall sections between two vertically aligned openings (see Fig. R21.9.4.5). It is, in effect, a pier rotated through 90 degrees. A horizontal wall segment is also referred to as a coupling beam when the openings are aligned vertically over the building height. When designing a horizontal wall segment or coupling beam, ρ_t refers to vertical reinforcement and ρ_ℓ refers to horizontal reinforcement.

SHEAR WALLS

R21.9.5 — Design for flexure and axial loads

R21.9.5.1 — Flexural strength of a wall or wall segment is determined according to procedures commonly used for columns. Strength should be determined considering the applied axial and lateral forces. Reinforcement concentrated in boundary elements and distributed in flanges and webs should be included in the strength computations based on a strain compatibility analysis. The foundation supporting the wall should be designed to develop the wall boundary and web forces. For walls with openings, the influence of the opening or openings on flexural and shear strengths is to be considered and a load path around the opening or openings should be verified. Capacity-design concepts and strut-and-tie models may be useful for this purpose.[21.47]

SHEAR WALLS

R21.9.5.2 — Where wall sections intersect to form L-, T-, C-, or other cross-sectional shapes, the influence of the flange on the behavior of the wall should be considered by selecting appropriate flange widths. Tests[21.48] show that effective flange width increases with increasing drift level and the effectiveness of a flange in compression differs from that for a flange in tension. The value used for the effective compression flange width has little impact on the strength and deformation capacity of the wall; therefore, to simplify design, a single value of effective flange width based on an estimate of the effective tension flange width is used in both tension and compression.

SHEAR WALLS

R21.9.6 — Boundary elements of special structural walls

R21.9.6.1 — Two design approaches for evaluating detailing requirements at wall boundaries are included in 21.9.6.1. Section 21.9.6.2 allows the use of displacement-based design of walls, in which the structural details are determined directly on the basis of the expected lateral displacements of the wall. The provisions of 21.9.6.3 are similar to those of the 1995 Code, and have been retained because they are conservative for assessing required transverse reinforcement at wall boundaries for many walls. Requirements of 21.9.6.4 and 21.9.6.5 apply to structural walls designed by either 21.9.6.2 or 21.9.6.3.

SHEAR WALLS

R21.9.6 — Boundary elements of special structural walls

R21.9.6.2 — Section 21.9.6.2 is based on the assumption that inelastic response of the wall is dominated by flexural action at a critical, yielding section. The wall should be proportioned so that the critical section occurs where intended.

$$c \geq \frac{\ell_w}{600(\delta_u / h_w)} \qquad (21\text{-}8)$$

SHEAR WALLS

R21.9.6 — Boundary elements of special structural walls

Equation (21-8) follows from a displacement-based approach.[21.49,21.50] The approach assumes that special boundary elements are required to confine the concrete where the strain at the extreme compression fiber of the wall exceeds a critical value when the wall is displaced to the design displacement. The horizontal dimension of the special boundary element is intended to extend at least over the length where the compression strain exceeds the critical value. The height of the special boundary element is based on upper bound estimates of plastic hinge length and extends beyond the zone over which concrete spalling is likely to occur. The lower limit of 0.007 on the quantity δ_u / h_w requires moderate wall deformation capacity for stiff buildings.

SHEAR WALLS

R21.9.6 — Boundary elements of special structural walls

The neutral axis depth c in Eq. (21-8) is the depth calculated according to 10.2, except the nonlinear strain requirements of 10.2.2 need not apply, corresponding to development of nominal flexural strength of the wall when displaced in the same direction as δ_u. The axial load is the factored axial load that is consistent with the design load combination that produces the design displacement δ_u.

SHEAR WALLS

R21.9.6 — Boundary elements of special structural walls

R21.9.6.3 — By this procedure, the wall is considered to be acted on by gravity loads and the maximum shear and moment induced by earthquake in a given direction. Under this loading, the compressed boundary at the critical section resists the tributary gravity load plus the compressive resultant associated with the bending moment.

SHEAR WALLS

R21.9.6 — Boundary elements of special structural walls

Recognizing that this loading condition may be repeated many times during the strong motion, the concrete is to be confined where the calculated compressive stresses exceed a nominal critical value equal to $\mathbf{0.2}f'_c$. The stress is to be calculated for the factored forces on the section assuming linear response of the gross concrete section. The compressive stress of $\mathbf{0.2}f'_c$ is used as an index value and does not necessarily describe the actual state of stress that may develop at the critical section under the influence of the actual inertia forces for the anticipated earthquake intensity.

SHEAR WALLS

R21.9.6 — Boundary elements of special structural walls

Because horizontal reinforcement is likely to act as web reinforcement in walls requiring boundary elements, it should be fully anchored in boundary elements that act as flanges (21.9.6.4). Achievement of this anchorage is difficult when large transverse cracks occur in the boundary elements. Therefore, standard 90-degree hooks or mechanical anchorage schemes are recommended instead of straight bar development.

Tests[21.51] show that adequate performance can be achieved using spacing larger than permitted by 21.6.4.3(a).

SHEAR WALLS

R21.9.6 — Boundary elements of special structural walls

R21.9.6.5 — 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 moderate amounts of boundary longitudinal reinforcement, ties are required to inhibit buckling. The longitudinal reinforcement ratio is intended to include only the reinforcement at the wall boundary as indicated in Fig. R21.9.6.5. A larger spacing of ties relative to 21.9.6.4(c) is allowed due to the lower deformation demands on the walls.

SHEAR WALLS

R21.9.6 — Boundary elements of special structural walls

The addition of hooks or U-stirrups at the ends of horizontal wall reinforcement provides anchorage so that the reinforcement will be effective in resisting shear forces. It will also tend to inhibit the buckling of the vertical edge reinforcement. In walls with low in-plane shear, the development of horizontal reinforcement is not necessary.