CFA Technical Note: XX-2010

A Guide for the Interpretation of Structural Design Options for Residential Concrete Structures

This CFA Technical Note is intended to serve as a guide to assist in the interpretation of applicable design requirements for the design of the traditional one and two family dwelling units. Currently, the structural design provisions for residential concrete construction are presented in ACI 332. However, the ACI 332 provisions largely refer back to ACI 318 provisions. There are numerous difficulties with this approach. One is that this leaves the designer in the position of interpreting, which ACI 318 provisions are applicable and which ones are not. Another is that ACI 318 provisions are intended for use in traditional reinforced concrete construction in buildings and structures and therefore have many more materials and structural considerations. It is widely held that because of these complications that this hinders the design of concrete in one and two family dwellings. It is also widely believed that the lack of an appropriate design provisions hinders the use of concrete in non-traditional applications such as above grade walls and floor slabs.

There are actually three distinct approaches that a designer may choose for residential concrete construction. These are plain concrete, moderately reinforced concrete and reinforced concrete. Moderately reinforced concrete refers to the use of reinforcing steel as flexural steel - not temperature or shrinkage- at bar spacing greater than allowed by ACI 318. Plain and reinforced concrete is traditionally recognized by ACI however moderately reinforced is not, even though it has been used in masonry construction for years and has been allowed through the use of prescriptive foundation tables in the building code as well. ACI 332 currently allows for the use of bar spacing up to 48-inches for foundation walls with a minimum thickness of 71/2 inches.

Notation

a = depth of equivalent rectangular stress block as defined in Section 2.6 and 3.6.

A_c = area of concrete section resisting shear transfer, in^2.

A_g = gross area of concrete, in^2.

A_s = area of tension reinforcement, in^2.

A_{se} = area of effective longitudinal tension reinforcement, in wall segment, in^2, as calculated in Section 1.12.

$A_{s,\,min}$ = minimum amount of flexural reinforcement, in^2.

A_{st} = total area of longitudinal reinforcement, in^2.

A_v = area of shear reinforcement within a distance **s**, in^2.

A_1 = loaded area, in^2.

A_2 = the area of the lower base of the largest frustum of a pyramid, cone or tapered wedge contained wholly within the support and having for its upper base the loaded area, and having side slopes of 1 vertical to 2 horizontal, in^2.

b_o = perimeter of critical section for shear in footings, in.

b_w = web width, in.

B_n = nominal bearing strength, lb.

c = distance from extreme compression fiber to neutral axis, in.

c_c = spacing or cover dimension, in.

C_m = factor relating actual moment diagram to a equivalent uniform diagram.

d = distance from compression fiber to centroid of longitudinal tension reinforcement, in.

d_b = nominal diameter of steel reinforcing bar or wire.

D = dead loads, or related internal moments and forces.

E = load effects of earthquake, or related internal moments and forces.

E_c = modulus of elasticity of concrete, psi.

E_s = modulus of elasticity of reinforcement, psi.

EI = flexural stiffness of compression member, in^2-lb.

f_c' = specified compressive strength of concrete, psi

$\sqrt{f_c'}$ = square root of specified compressive strength of concrete, psi .

f_r = modulus of rupture of concrete, psi.

f_y = design yield strength of reinforcement, psi.

F = loads due to weight and pressure of fluids with well-defined densities and controllable maximum heights, or related internal moments and forces.

h = overall thickness or height of member, in.

H = loads due to weight and pressure of soil, water in soil or other materials, or related internal moments and forces.

I_e = effective moment of inertia for computation of deflection, in ^{4}.

I_{cr} = moment of inertia of cracked section transferred to concrete, in^4.

I_g = moment of inertia of gross concrete section about centroidal axis, neglecting reinforcement, in^4.

I_{se} = moment of inertia of reinforcement about centroid axis of member cross section, in^4.

k = effective length factor.

ℓ = span length of beam or one way slab; clear projection of cantilever, in.

ℓ_a = additional embedment length beyond centerline of support or point of inflection, in.

ℓ_c = length of compression member in a frame measured from center-to-center of the joints in the frame, in.

ℓ_d = development length in tension of deformed bar, in.

ℓ_{db} = basic development length, in.

ℓ_u = unsupported length of compression member, in.

ℓ_w = length of entire wall or length of segment of wall considered in direction of shear force, in.

L = live loads, or related internal moments and forces.

L_r = roof live loads, or related internal moments and forces.

M_a = maximum moment in member due to service loads at stage deflection is computed, in.-lb.

M_c = factored moment amplified for the effects of member curvature used for design of compression member, in.-lb.

M_{cr} = cracking moment, in.-lb.

M_n = nominal flexural strength at section in.-lb.

M_{sa} = maximum unfactored applied moment due to service loads, not including ***P)*** effects, in.-lb.

M_u = factored moment at section including ***P)*** effects, in.-lb.

M_{ua} = moment at midheight of the wall due to factored lateral and eccentric vertical loads, in.-lb.

M_1 = smaller factored end moment on a compression member, to be taken as positive if member is bent in single curvature, and negative if bent in double curvature, in.-lb.

M_2 = larger factored end moment on compression member. If transverse loading occurs between supports, M_2 is taken as the largest moment occurring in member. Value of M_2 always positive, in.-lb.

$M_{2,min}$ = minimum value of M_2 , in.-lb.

n = modular ratio of elasticity E_s / E_c, but not less than 6

P_b = nominal axial load strength at balanced strain conditions, lb.

P_c = critical buckling load, lb.

P_n = nominal axial load strength at given eccentricity, lb.

P_s = unfactored axial load at the design (midheight) section including effects of self-weight, lb.

P_u = factored axial force; to be positive for compression and negative for tension, lb.

r = radius of gyration of cross section of compression member, in.

R = rain load or related internal moments and forces.

s = center to center spacing of reinforcement or anchorage, in.

$\boldsymbol{S}$ = snow load, or related internal moments and forces.

$\boldsymbol{s_m}$ = elastic section modulus of the cross section**,** in^3

$\boldsymbol{T}$ = cumulative effect of temperature, creep, shrinkage, differential settlement, and shrinkage-compensating concrete.

$\boldsymbol{U}$ = required strength to resist factored loads or related internal moments and forces.

$\boldsymbol{V_n}$ = nominal shear stress, psi.

$\boldsymbol{V_c}$ = nominal shear strength provided by concrete, lb.

$\boldsymbol{V_u}$ = factored shear force at the section, lb.

$\boldsymbol{W}$ = wind load, or related internal moments and forces.

$\boldsymbol{y_t}$ = distance from centroid axis of gross section, neglecting reinforcing, to extreme fiber in tension, in.

α = angle defining the orientation of reinforcement.

β_b = ratio of area of reinforcement cut off to total area of tension reinforcement at the section.

β_c = ratio of long side to short side of concentrated load or reaction area.

β_d = the ratio of the maximum factored axial sustained load to the maximum factored axial load associated with the same load combination.

β_1 = factor relating depth of equivalent rectangular compressive stress block to neutral axis depth.

Δ_o = relative lateral deflection between the top and bottom of a story due to lateral forces computed using first order elastic frame analysis and stiffness values.

Δ_s = computed out of plane deflection at mid-height of wall due to service loads, in.

Δ_u = computed deflection at midheight of wall due to factored loads, in.

ρ = ratio of $\boldsymbol{A_s}$ to ***bd***.

ρ_b = ratio of $\boldsymbol{A_s}$ to ***bd*** producing balanced strain conditions.

μ = coefficient of friction.

δ_{ns} = moment magnification factor for frames braced against sidesway, to reflect effects of concrete member curvature between ends of compression concrete member.

π = a mathematical constant equal to 3.14 .

ϕ = strength reduction factor .

ψ = ratio of sum of stiffness of compression members to sum of stiffness of flexural members at one end of a compression member.

1 — General Requirements

1.1 — Concrete members shall be designed and constructed in accordance with the applicable reinforced concrete, moderately reinforced concrete and unreinforced concrete provisions of this standard.

1.2 — Loads shall be determined in accordance with the general residential code.

1.3 — Properties

1.3.1 — Modulus of elasticity $\boldsymbol{E_c}$, for concrete with a density of 90 to 155 lb/ft^3 shall be $\boldsymbol{57{,}000\sqrt{f_c'}}$.

1.3.2 — Specified compressive strength, $\boldsymbol{f_c'}$ shall not exceed 10,000 psi.

1.3.3 — Modulus of elasticity $\boldsymbol{E_s}$, for steel reinforcement shall be 29,000,000 psi.

1.3.4 — Design yield strength of reinforcement, $\boldsymbol{f_y}$, shall not exceed 80,000 psi.

1.4 — Span length of concrete members not built integrally with supports shall be the smaller of the clear span plus the depth of the member or the distance between the center to center of supports.

1.5 — Concrete members shall be designed and constructed such that the design strength of the concrete member is greater than or equal to the required strength.

1.6 — Required strength, ***U,*** shall be the largest of the following load combinations:

$$U = 1.4(D+F)$$

$$U = 1.2(D + F + T) + 1.6(L+H)+0.5(L_r \text{ or } S \text{ or } R)$$

$$U = 1.2D + 1.6(L_r \text{ or } S \text{ or } R)+(1.0L \text{ or } 0.8W)$$

$$U = 1.2D + 1.6W + 1.0L + 0.5(L_r \text{ or } S \text{ or } R)$$

$$U = 1.2D + 1.0E + 1.0L + 0.2S$$

$$U = 0.9D + 1.6W + 1.6H$$

$$U = 0.9D + 1.0E + 1.6H$$

Where necessary, the effects of one or more loads, or portions thereof, not acting shall be investigated.

1.7 — Design strength shall be taken as the nominal strength calculated multiplied by the applicable strength reduction factor, ϕ **:**

Reinforced and Moderately Reinforced concrete members:

Flexure, without axial load: 0.90

Axial load, and axial load with flexure.(For axial load with flexure, both axial load and moment nominal strength shall be multiplied by appropriate value of ϕ)

Tension, and tension with flexure: 0.90

Compression, and compression with flexure: 0.65

Strength reduction factor, ϕ, shall vary linearly to 0.90 as the factored nominal axial load strength, ϕP_n, decreases from the smaller of product of, **0.10** $f_c' A_g$ or ϕP_n, to zero.

Shear and torsion: 0.75

Bearing on concrete: 0.65

Unreinforced concrete members:

Flexure; Compression; Shear; and Bearing: 0.60.

1.8 — Deflection shall be computed using effective moment of inertia, I_e ,with the modulus of elasticity E_c, but not greater than the gross moment of inertia, I_g.

$$I_e = (M_{cr} / M_a)^3 I_g + [1-(M_{cr}/M_a)^3] I_{cr}$$

where

$$M_{cr} = f_r I_g / y_t$$

$$f_r = 7.5\sqrt{f_c'}$$

1.9 — For continuous concrete members, the effective moment of inertia, I_e , shall be the average of the values obtained from effective moment of inertia, I_e , determined at the critical positive and negative moment sections. For prismatic concrete members, effective moment of inertia shall be the value obtained from effective moment of inertia, I_e, determined at midspan for simple and continuous spans, and at support for cantilevers.

1.10 — Calculated longterm deflection shall be less than 0.3 inches or $\ell / 480$. Calculated out of plane deflection of walls shall not exceed $\ell / 240$.

1.11 Slenderness

1.11.1 — Lateral loads shall be resisted by a structural system composed of shear walls and horizontal diaphragms.

1.11.2 — The factored axial forces P_u , the factored moments M_1 and M_2 at the points of lateral support of the walls, the relative lateral story deflections, Δ_o, shall be computed using an elastic first-order frame analysis with the section properties determined by use of the following properties:

Modulus of elasticity...E_c
Moments of inertia
Walls — Uncracked...**0.70** I_g
Cracked..**0.35** I_g
Area.. **1.0** A_g
The moments of inertia shall be divided by $(1 + \beta_d)$ when sustained lateral loads act.

1.11.3 — For rectangular concrete members, the radius of gyration r shall be equal to 0.30 times the overall dimension in the direction stability is being considered for rectangular compression concrete members and 0.25 times the diameter for circular compression concrete members. For other shapes, the radius of gyration r shall be based on the radius of gyration for the gross concrete section.

1.11.4 — The unsupported length, ℓ_u, of a compression concrete member shall be taken as the clear distance between concrete member capable of providing lateral support in the direction being considered.

1.11.5 — The slenderness ratio of a wall, $k \ell_u / r$, shall not exceed 100.

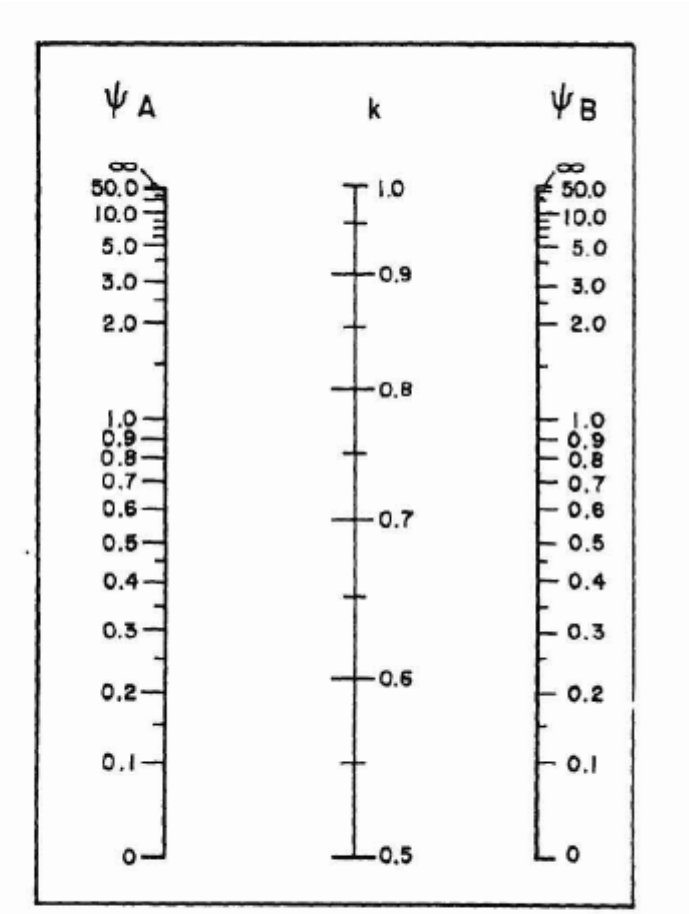
1.11.6 — Walls subject to bending about both principal axes, the moment about each axis shall be magnified separately based on the conditions of restraint corresponding to that axis.

1.11.7 — The effective length factor k shall be taken as 1.0, unless analysis shows that a lower value is justified. The calculation of k shall be based on the E and I values used in Section 1.11.2.

1.11.8 — Slenderness effects shall be permitted to be ignored where:

$$k \ell_u / r \le 34 - 12(M_1 / M_2)$$

where the term **[34 - 12M_1/M_2]** shall not be taken greater than 40. The term M_1/M_2 is positive if the wall is bent in single curvature, and negative if the wall is bent in double curvature.



Nonsway

ψ **= ratio of** Σ(EI / ℓ_c) **of compression concrete members to** Σ (EI / ℓ_c) **of flexural concrete members in a plane at one end of a compression concrete member**

ℓ **= span length of flexural concrete member measured center to center of joints**

Fig. R 1.11.10-Effective length factors, k

1.11.10 — Walls shall be designed for the factored axial load P_u and the moment amplified for the effects of concrete members curvature M_c as follows:

where

$$M_c = \delta_{ns} M_2$$

$$\delta_{ns} = C_m / (1 - P_u / 0.75 P_c) \exists 1.0$$

$$P_c = \pi^2 EI / (k \ell_u)^2$$

EI shall be taken as

$$EI = (0.2 E_c I_g + E_s I_{se}) /(1 + \beta_d)$$

$$EI = 0.4 E_c I_g / (1 + \beta_d)$$

1.11.11 — For walls without transverse loads between supports, C_m shall be taken as

$$C_m = 0.6 + 0.4 M_1 / M_2 \geq 0.4$$

where M_1 / M_2 is positive if the wall is bent in single curvature. For walls with transverse loads between supports, C_m shall be taken as 1.0.

1.11.12 — The factored moment M_2 shall not be taken less than

$$M_{2,min} = P_u (0.6 + 0.03h)$$

about each axis separately, where 0.6 and h are in inches. For concrete members for which $M_{2,min}$ exceeds M_2, the value of C_m shall either be taken equal to 1.0, or shall be based on the ratio of the computed end moments M_1 and M_2.

1.12 — Alternative to the slender wall provisions in Section 1.11, walls determined to be slender by

$$k l_u / r > 34 - 12(M_1 / M_2)$$

shall be designed in accordance with the provisions of this section. The term **[34 - 12M_1/M_2]** shall not be taken greater than 40. The term M_1/M_2 is positive if the wall is bent in single curvature, and negative if the wall is bent in double curvature.

1.12.2 — Walls designed by these provisions shall satisfy 1.12.2.1 through 1.12.2.

1.12.2.1 — The wall panel shall be designed as a simply supported, axially loaded member subjected to an out-of-plane uniform lateral load, with maximum moments and deflections occurring at midspan.

1.12.2.2 — The cross section is constant over the height of the panel.

1.12.2.3 — The reinforcement ratio Δ shall not exceed 0.6 ρ_b

1.12.2.4 — Reinforcement shall be provided such that the design strength

$$\phi M_n \geq M_{cr}$$

where M_{cr} shall be obtained using the modulus of rupture given by:

$M_{cr} = f_r I_g / y_t$

$f_r = 7.5 \sqrt{f_c'}$

1.12.2.5 — Concentrated gravity loads applied to the wall above the design flexural section shall be assumed to be distributed over a width:

(a) Equal to the bearing width, plus a width on each side that increases at a slope of 2 vertical to 1 horizontal down to the design section; but

(b) Not greater than the spacing of the concentrated loads; and

(c) Does not extend beyond the edges of the wall panel.

1.12.2.6 — Vertical stress P_u / A_g at the midheight section shall not exceed $0.06 f_c'$.

1.12.3 — The design moment strength $N M_n$ for combined flexure and axial loads at the midheight cross section shall be:

$$\phi M_n \geq M_u$$

where:

$$M_u = M_{ua} + P_u \Delta_u$$

M_{ua} is the moment at the midheight section of the wall due to factored loads, and $)_u$ is:

$$\Delta_u = 5 M_u \ell_c^2 / (.75 \; 48 E_c I_{cr})$$

M_L shall be obtained by iteration of deflections, or by direct calculation using

$$M_u = M_{ua} / (1 - 5 P_u \ell_c^2 / (.75 \; 48 E_c I_{cr}))$$

where:

$$I_{cr} = n A_{se} (d - c)^2 + \ell_w c^3 / 3$$

and

$$A_{se} = (P_u + A_s f_y) / f_y$$

1.12.4 — The maximum deflection Δ_s due to service loads, including $P\Delta$ effects, shall not exceed

$\ell_c / 150$ The midheight deflection Δ_s shall be determined by:

$$\Delta_s = (5 M l_c^2) / (48 E_c I_e)$$

$$M = M_{sa} / (1 - 5 P_s \ell_c^2 / 48 E_c I_e)$$

I_e shall be calculated using,

$$I_e = (M_{cr} / M_a)^3 I_g + [1-(M_{cr}/M_a)^3] I_{cr}$$

substituting M for M_a where:

$$I_{cr} = n A_{se} (d - c)^2 + \ell_w c^3 / 3$$

$$M_{cr} = f_r I_g / y_t$$

$$f_r = 7.5 \sqrt{f_c'}$$

1.13 — Contraction or isolation joints shall be provided to divide moderately reinforced and unreinforced concrete members into flexurally discontinuous members. The number and location of contraction or isolation joints, shall be based on: climatic conditions; selection and proportioning of materials; mixing, placing, and curing of concrete; degree of restraint to movement; stresses due to loads to which an member is subject; and construction techniques.

R1.13 — *The rationale for providing contraction joints or isolation joints for moderately reinforced and unreinforced concrete is that the joint provides a location for movement to occur as a result of creep, shrinkage, and temperature.*

For reinforced concrete, the reinforcement provides the necessary restraint against shrinkage and temperature fluctuations.

1.14 — Development of reinforcement

1.14.1 — Calculated tension in reinforcement shall be provided by embedment length, ℓ_d

1.14.2 — Development length, ℓ_d for No. 6 and smaller deformed steel bars and deformed wires in tension shall be the smaller value from the following two equations but not less than 12-inches.

$$\ell_d = 3.0 f_y d_b \alpha / [50 \sqrt{f_c'}]$$

$$\ell_d = 2.4 f_y d_b \alpha / [40 \sqrt{f_c'} (c / d_b)]$$

where c

ℓ_d / d_b shall not be taken greater than 2.5

c = smaller of the distance from the center of the bar to the nearest concrete surface or one-half the center-to-center spacing of the bars being developed, inches.

α shall be equal to 1.0 except where 12 inches or more of concrete is placed below horizontal reinforcement for which case shall be equal 1.3.

1.14.3 — Where the area of tension reinforcement is larger than required, the development length ℓ_d or, shall be multiplied by the ratio of required steel area to steel area provided, (A_s required) / (A_s provided).

1.14.4 — The development length, ℓ_d or ℓ_{db}, shall be provided prior to points of maximum stress and at points where adjacent reinforcement terminates, or is bent.

1.14.5 — Reinforcement shall extend beyond the point at which it is no longer required to resist flexure for a distance equal to the greater of the effective depth of concrete member or **12** d_b , except at supports of simple spans and at the free end of cantilevers.

1.14.6 — Continuing reinforcement shall be embedded a length not less than the development length, ℓ_d beyond the point where bent or terminated tension reinforcement is no longer required to resist flexure.

1.14.7 — Flexure reinforcement shall not be terminated in tension zone, unless the factored shear, V_u, at the cutoff point does not exceed two-thirds of the design shear strength, $\frac{2}{3} \phi V_n$.

1.14.8 — For development of positive moment reinforcement, a minimum of one-third of the required tension reinforcement in simple members and one-fourth the reinforcement in continuous concrete members shall extend along the same face of concrete member and extend into the support a minimum of 6 inches.

1.14.9 — When a flexural member is part of a primary load resisting system, positive moment reinforcement required to be extended into the support by 1.14.10 shall be fully developed at the face of the support.

1.14.10 — Except where reinforcement is terminated beyond the centerline of simple supports by a standard hook, or a mechanical anchorage, the development length, l_d at simple supports and at points of inflection for the reinforcement that resists moment shall satisfy:

$$\ell_d \leq M_n / V_u + \ell_a$$

M_n is nominal moment strength

V_u is factored shear force at the section;

ℓ_a at a support shall be the embedment length beyond center of support;

ℓ_a at a point of inflection shall be limited to the greater of the distance from the extreme compression fiber to the centroid of tension reinforcement, d or twelve times the bar diameter, **12** d_b.

1.14.11 — The location and length of splices of tension and compression reinforcement shall be provided in the construction documents.

1.14.12 — The maximum space between laps of a bar shall be the smaller of 1/5 the lap splice length or 6 - inches.

1.15 — Openings
In accordance with the provisions of Section 1.5, the wall and lintel adjacent to an opening shall be designed for the load and eccentricities to which they are subjected. A minimum of one No. 4 bar shall be provided around openings greater than 2 feet in height or width, and extended beyond the edge of the opening a minimum of 24 inches.

R1.16 — Dowels
R1.1 1 — *A typical application of dowel bars is at the connection of the foundation wall to footing or at the base of a column to a footing.*

1.16 — Dowels
1.16.1 — Where shear transfer is across a shear plane and is provided by deformed steel reinforcing located between two concrete members cast at different times, the factored nominal shear strength shall be equal to or larger than the factored force,

$$\phi V_n \geq V_u.$$

1.16.1.2 — V_n shall be:

$$V_n = A_v f_y \mu$$

Reinforcement shall be perpendicular to shear plane,μ shall be equal to **0.6** and A_v the area of the reinforcement perpendicular to the shear plane.

1.16.1.3 — V_n shall not exceed **0.2** $f_c' A_c$ nor 800 A_c where A_c is the area of concrete resisting shear and f_y shall be less than or equal to 60,000 psi.

1.16.1.4 — Reinforcement shall be appropriately placed along the shear plane and shall be developed on both sides of the shear plane by embedment or hooks.

1.17 — Anchors
The capacity of an anchor shall be substantiated through the use of applicable recognized design standards or tests.

R1.17 — Anchors
Examples of anchors are the typical cast-in-place anchor bolts and headed bolts, as well as light gauge metal straps, and post installed anchors.

1.18 — Seismic provision for unreinforced and moderately reinforced concrete
Structures located in areas designated as Seismic Design Category D, E, and F shall not have members of unreinforced and moderately reinforced concrete, except as:

(a) Detached one- and two-family dwellings three stories or less in height and constructed with stud bearing walls, unreinforced concrete footings without longitudinal reinforcement supporting walls and isolated unreinforced concrete footings supporting columns or pedestals are permitted.

(b) Detached one- and two-family dwellings three stories or less in height and constructed with stud bearing walls, unreinforced concrete foundations or basement walls are permitted provided the wall is not less than 7½ inches and retains no more than 4 feet of unbalanced fill.

2 — Reinforced concrete
2.1 — In addition to the applicable requirements of Section 1, design of reinforced concrete shall be in accordance with this section.

2.2 — Strain in reinforcement and concrete shall be assumed to be directly proportional to the distance from the neutral axis of the concrete member.

2.3 — Maximum strain at extreme concrete compression fiber shall be 0.003.

2.4 — Stress of reinforcement below specified yield strength f_y shall be modulus of elasticity of reinforcement, E_s , multiplied by the steel strain. Where calculated strain in steel is greater than the strain at yield, f_y / E_s, the reinforcement stress shall be considered equal to f_y.

2.5 — Tensile strength of concrete shall be assumed to be zero.

2.6 — The relationship between concrete compressive stress distribution and concrete strain shall be rectangular. Concrete stress of $0.85\, f_c'$, shall be distributed over the compression zone bounded by edges of the cross section and a line parallel to the neutral axis at a distance

$a = \beta_1 c$ from the extreme concrete compression fiber.

c = the distance from the fiber of maximum strain to the neutral axis measured perpendicular to that axis.

β_1 = 0.85 for f_c' up to and including 4,000 psi. For f_c' above 4,000 psi, β_1 shall be reduced continuously at a rate of 0.05 for each 1,000 psi of strength in excess of 4,000 psi, but β_1 shall not be less than **0.65**.

R2.6 — The flexural design strength of a singly-reinforced cross section (without compression reinforcement) is commonly expressed as:

$$\phi M_n = \phi\, [\, A_s f_y\, (\, d - a/2\,)]$$

2.7 — Design of reinforced concrete subject to flexure or axial loads or to combined flexure and axial loads shall be based on stress and strain compatibility using the provisions of this section.

2.8 — Balanced strain condition is the condition that exists at a cross section when tension reinforcement attains the strain corresponding to its specified yield strength, f_y , simultaneously concrete is at the compression strain of 0.003.

2.9 — For concrete members subject to flexure, as well as concrete members subject to combined flexure and compressive axial loads, when the design axial load strength, ϕP_n , is less than the smaller of $0.10\, f_c' A_g$ or ϕP_b, the ratio of reinforcement, Δ , shall not exceed 0.75 of the ratio Δ_b , that would produced balanced strain condition, as defined in Section 2.8.

2.10 — The axial load strength of compression concrete members shall not be taken greater than the following:

$$\phi P_n = 0.80\, \phi\, [\, 0.85\, f_c'(A_g - A_{st}) + f_y A_{st}\,]$$

2.11 — Concrete members subject to compressive axial load shall be designed for the maximum moment that can accompany the axial load. The factored axial load, P_u , at given eccentricity shall not exceed the value obtained from Section 2.10.

2.12 — Unless the area of reinforcement provided is one-third greater than that required by analysis or by the provisions of Section 2.17.10, every portion of a concrete member resisting flexural stresses shall be provided at a minimum, the larger minimum steel area, $A_{s,\,min}$ of $3 / f_c' b_w d / f_y$ or $200 b_w d / f_y$.

2.13 — The bearing strength of reinforced concrete shall be $\phi\, (0.85\, f_c' A_1)$, except when the supporting surface is wider on all sides than the loaded area, then the design bearing strength on the loaded area shall be multiplied by $\sqrt{(A_2 / A_1)} \leq 2$.

2.14 — Shear Strength
Reinforced concrete members subject to shear shall comply with $\phi V_n \geq V_u$ where V_u is the factored shear force at the section considered and V_n is nominal shear strength computed by: $V_n = V_c + V_s$ where V_c

, is nominal concrete shear strength, and V_s is nominal shear strength provided by shear reinforcement when provided.

2.14.1 — The factored shear force, V_u , shall be determined at a distance equal to the extreme compression fiber to the centroid of longitudinal tension reinforcement, ***d***, from the face of support.

2.14.2 — Nominal concrete shear strength, V_c, of members subject to shear, flexure, and compression, or combination shall be $2 / f_c' b_w d$.

2.14.3 — Shear reinforcement shall be No. 5 and smaller, deformed reinforcement stirrups located perpendicular to axis of member or D31 and smaller welded wire fabric with wires located perpendicular to axis of member.

2.14.4 — Design yield strength, f_y, for welded deformed wire fabric shall not to exceed 80,000 psi. The design yield strength, f_y , of deformed shear reinforcement shall not exceed 60,000 psi.

2.14.5 — Shear reinforcement shall be as close to the compression and tension surface as cover requirements and proximity of other reinforcement permits. Both ends of No. 5 and smaller shear reinforcement bars shall be anchored with 90-degree bend plus a 6 d_b extension around longitudinal reinforcement.

2.14.6 — When nominal shear strength provided by shear reinforcement, V_s, is less than or equal to $4/ f_c' b_w d$, the spacing of shear reinforcement placed perpendicular to axis of concrete member shall not exceed $d/2$ or 24 inches.

2.14.7 — When nominal shear strength provided by shear reinforcement, V_s exceeds $4/ f_c' b_w d$, the maximum spacing shall not exceed $d/4$ or 12 inches.

2.14.8 — V_s shall not exceed $8\sqrt{f_c'} b_w d$.

2.14.9 — Except in footings, for reinforced concrete where factored shear force, V_u, exceeds one-half the shear strength provided by concrete, $\phi V_n / 2$, a minimum area of shear reinforcement shall be provided.

2.14.10 — Where shear reinforcement is required the minimum area of shear reinforcement shall be

$A_v = 50\, b_w s / f_y$ where b_w and s are in inches.

2.14.11— Where the factored shear force, V_u, exceeds design concrete shear strength, ϕV_c, shear reinforcement shall be provided such that the reduced nominal shear strength of the concrete and shear strength provided by the shear reinforcement is greater than or equal to the factored shear force, $\phi (V_c + V_s) \geq V_u$. When shear reinforcement is perpendicular to axis of concrete member nominal shear strength, V_s, shall be based on $V_s = A_v f_y d / s$ where A_v is the total cross sectional area of shear reinforcement within a distance s.

2.15 — Reinforced concrete walls

2.15.1 — Reinforced concrete walls shall be designed for the loads and eccentricities to which they are subjected.

2.15.2 — The effective length of a wall supporting a concentrated load shall be the smaller of the center - to - center spacing of load or the width of bearing plus four times the wall thickness.

2.15.3 — Walls shall be anchored to intersecting members, such as floors and roofs; or to columns, pilasters, buttresses, and intersecting concrete walls; and to footings.

2.15.4 — Unless greater amount of shear or flexural steel is required, the minimum amount of steel shall be:

2.15.4.1 Minimum ratio of vertical reinforcement area to gross concrete area shall be:

(a) 0.0012 for deformed bars not larger than No. 5 with a specified yield strength not less than 60,000 psi; or

(b) 0.0015 for other deformed bars; or

(c) 0.0012 for welded wire fabric (plain or deformed) not larger than W31 or D31.

R2.15.4 — *This section specifies that the effective depth of shear wall is to be* $0.8\,\ell_w$.

2.15.4.2 — Minimum ratio of horizontal reinforcement area to gross concrete area shall be:

(a) 0.0020 for deformed bars not larger than No. 5 with a specified yield strength not less than 60,000 psi; or

(b) 0.0025 for other deformed bars; or

(c) 0.0020 for welded wire fabric (plain or deformed) not larger than W31 or D31.

2.15.5 — Maximum spacing of vertical and horizontal reinforcement shall be the smaller of three times the wall thickness or 18-inches.

2.15.6 — Reinforced concrete walls which resist shear forces perpendicular to the face of the wall shall be designed in accordance with the shear design provisions for reinforced footings.

2.15.7 — Reinforced concrete walls that resist shear forces in plane of wall shall be designed such that the design shear strength of the concrete is greater than or equal to the factored shear force, $\phi V_c / 2 \geq V_u$. Nominal concrete shear strength, V_c, shall be **2** $\sqrt{f_c'} hd$. The distance, ***d***, from the extreme compression fiber to center of force of all reinforcement in tension shall be **0.8** ℓ_w.

2.16 — **Reinforced concrete footings**

2.16.1 — Reinforced concrete footings shall be designed for the loads and eccentricities to which they are subjected.

2.1.6.2 — Footing area shall be determined from unfactored forces and moments transmitted by footing to soil at the soil design pressure.

R2.16 — **Reinforced concrete footings**

R2.1 2 — *See the General Residential Code to determine the applicable requirements for the soil design pressure.*

2.16.3 — The moment acting on a footing shall be determined by passing an imaginary vertical plane through the footing, and computing the moment of the forces acting over entire area of footing on one side of the plane and a maximum factored moment for an isolated footing shall be determined:

2. 16.3.1 At face of column, pedestal, or wall, for footings supporting a concrete column, pedestal, or wall;

2.16.3.2 — At halfway between middle and edge of wall, for footings supporting a masonry wall.

2.16.4 — In one-way reinforced concrete footings and two-way square reinforced concrete footings, reinforcement shall be distributed uniformly across entire width of footing.

2.16.5 — Shear strength of reinforced concrete footings at concentrated loads or reactions shall be governed by the more severe of two conditions:

2.16.5.1 — Beam action for footing, with a critical section extending in an imaginary vertical plane across the entire footing width and located at a distance, ***d***, from face of concentrated load or reaction area. For this condition, the footing shall be designed in accordance with provisions of Section 4.14 for one-way action.

2.16.5.2— Two—way action for footing, with a critical section perpendicular to plane of footing and located so that its perimeter b_o is a minimum, but need not approach closer than ***d / 2*** to perimeter of concentrated load or reaction area. For this condition, the footing shall be designed in accordance with provisions of Section 2.14 for two-way action.

2.16.6 — Calculated tension or compression in reinforcement at each section shall be developed on each side of that section by embedment length, tension hook, mechanical device, or a combination.

2.16.7 — Critical sections for development of reinforcement shall be at the location for maximum factored moment, and at locations where changes of section dimension or reinforcement occur.

2.16.8 — The minimum depth of footing above bottom reinforcement shall be 6 inches.

2.16.9 — The minimum area of tensile reinforcement in each direction shall be as required based on the following reinforcement ratios based on the gross concrete area:

(a) Where Grade 40 or 50 deformed bars are used: 0.0020.

(b) Where Grade 60 deformed bars or welded wire fabric (plain or deformed) are used: 0.0018.

(c) Where reinforcement with yield stress exceeding 60,000 psi measured at a yield strain of 0.35 percent is used, the larger of (0.0018 x 60,000) / f_y or 0.0014.

Maximum spacing of this reinforcement shall be the smaller of three times the thickness or 18 inches.

2.16.10 — Axial forces and moments at the base of the wall shall be transferred to footing by bearing on concrete, keyway, reinforcement, dowels, mechanical connectors or combination.

2.16.11 — Bearing on concrete at the contact surface shall not exceed the bearing strength.

2.16.12 — Reinforcement, dowels, or mechanical connectors between supported and supporting concrete members shall be adequate to transfer:

2.16.12.1 All compressive force that exceeds concrete bearing strength of either concrete members; and

2.16.12.2 Any computed tensile force across interface.

2.16.13 — Where reinforcement or dowel(s) is required by the prior section, reinforcement or dowel(s) shall be provided by extending longitudinal bars into the supporting footing.

2.16.14 — The reinforcement or dowels located across the interface of a wall and footer shall be in accordance with Section 1.16 Dowels shall be extended into supported concrete members, and supporting concrete members, a distance not less than the development length of the bars.

2.16.15 — Where footings slope or step, the footings shall be such that design requirements are satisfied at every section and act as a single structural member.

2.17 — Reinforced concrete lintel
Reinforced concrete lintels shall be designed for the loads and eccentricities to which they are subjected.

3 — Moderately Reinforced Concrete
3.1 — In addition to the applicable requirements of Section 1, design of moderately reinforced concrete shall be in accordance with this section.

3.2 — Strain in reinforcement and concrete shall be assumed to be directly proportional to the distance from the neutral axis of the concrete member.

3.3 — Maximum strain at extreme concrete compression fiber shall be 0.003.

3.4 — Stress of reinforcement below specified yield strength f_y shall be modulus of elasticity of reinforcement, E_s , multiplied by the steel strain. Where calculated strain in steel is greater than the strain at yield, f_y / E_s, the reinforcement stress shall be considered equal to f_y.

3.5 — Tensile strength of concrete shall be assumed to be zero.

3.6 — The relationship between concrete compressive stress distribution and concrete strain shall be rectangular. Concrete stress of $0.85\ f_c'$, shall be distributed over the compression zone bounded by edges of the cross section and a line parallel to the neutral axis at a distance

$a = \beta_1 c$ from the extreme concrete compression fiber.

c = the distance from the fiber of maximum strain to the neutral axis measured perpendicular to that axis.

β_1= 0.85 for f_c' up to and including 4000 psi. For f_c' above 4000 psi, β_1 shall be reduced continuously at a rate of 0.05 for each 1000 psi of strength in excess of 4000 psi, but β_1 shall not be less than **0.65**.

3.7 — Design of moderately reinforced concrete subject to flexure or axial loads or to combined flexure and axial loads shall be based on stress and strain compatibility using the provisions of this section.

3.8 — Balanced strain condition is the condition that exists at a cross section when tension reinforcement attains the strain corresponding to its specified yield strength, f_y , simultaneously concrete is at the compression strain of 0.003.

3.9 — For concrete members subject to flexure, as well as concrete members subject to combined flexure and compressive axial loads, when the design axial load strength, P_n , is less than the smaller of $0.10\ f_c' A_g$ or ϕP_b, the ratio of reinforcement, Δ shall not exceed 0.75 of the ratio, Δ_b , that would produce the balanced strain condition, as defined in Section 2.8.

3.10 — The axial load strength, ϕP_b , of the compression concrete members shall not be taken greater than the following:

$$\phi\ P_n = 0.80\ \phi\ [\ 0.85\ f_c'(A_g - A_{st}) + f_y A_{st}\ ]$$

3.11 — Concrete members subject to compressive axial load shall be designed for the maximum moment that can accompany the axial load. The factored axial load, P_u , at given eccentricity shall not exceed the value obtained from Section 3.10.

R3.8 — *The flexural design strength of a singly-reinforced cross section (without compression reinforcement) is commonly expressed as*

$$\phi M_n = \phi\ [\ A_s\ f_y\ (\ d - a/2\ )]$$

3.12 — The bearing strength of moderately reinforced concrete shall be $\phi(0.85\ f_c' A_1)$, except when the supporting surface is wider on all sides than the loaded area, then the design bearing strength on the loaded area shall be multiplied by $\sqrt{(A_2 / A_1)} \leq 2$.

3.13 — Shear Strength
Moderately reinforced concrete members subject to shear shall comply with: $\phi\ V_n \geq V_u$ where V_u is factored shear force at section considered and V_n is nominal shear strength computed by: $V_n = V_c + V_s$ where V_c , is nominal concrete shear strength. V_s is nominal shear strength provided by shear reinforcement when provided.

3.13.1 — The factored shear force, V_u , shall be determined at a distance equal to the extreme compression fiber to the centroid of longitudinal tension reinforcement, d, from the face of support.

3.13.2 — Nominal concrete shear strength, V_c, of concrete members subject to shear, flexure, and compression, or combination shall be $2\sqrt{f_c'}b_w d$.

3.13.3 — Shear reinforcement shall be No. 5 and smaller, deformed reinforcement stirrups located perpendicular to axis of concrete members or D31 and smaller welded wire fabric with wires located perpendicular to axis of concrete members

3.13.4 — Design yield strength, f_y, for welded deformed wire fabric shall not to exceed 80,000 psi. The design yield strength, f_y , of deformed shear reinforcement shall not exceed 60,000 psi.

3.13.5 — Shear reinforcement shall extend a distance, ***d***, from the extreme compression fiber and shall be anchored at both ends with 90-degree bend plus a 6 d_b extension around longitudinal reinforcement.

3.13.6 — When nominal shear strength provided by shear reinforcement, V_s, is less than or equal to $4/f_c'b_w d$, the spacing of shear reinforcement placed perpendicular to the axis of concrete members shall not exceed ***d/2*** or 24 inches.

3.13.7 — When nominal shear strength provided by shear reinforcement, V_s exceeds $4\sqrt{f_c'}b_w d$, the maximum spacing shall not exceed ***d/4*** or 12 inches.

3.13.8 — Except in footings, for moderately reinforced concrete where factored shear force, V_u, exceeds one-half the shear strength provided by concrete, $\phi V_n / 2$, a minimum area of shear reinforcement shall be provided.

3.13.9 — Where shear reinforcement is required the minimum area of shear reinforcement shall be

$A_v = 50\ b_w s / f_y$ where b_w and ***s*** are in inches.

3.13.10 — Where the factored shear force, V_u, exceeds design concrete shear strength, ϕV_c, shear reinforcement shall be provided such that the reduced nominal shear strength of the concrete and shear strength provided by the shear reinforcement is greater than or equal to the factored shear force, $\phi (V_c + V_s) \geq V_u$. When shear reinforcement is perpendicular to axis of concrete members nominal shear strength, V_s, shall be based on $V_s = A_v f_y d / s$ where A_v is the total cross sectional area of shear reinforcement within a distance ***s***.

3.14 — Moderately reinforced concrete walls

3.14.1 — Moderately reinforced concrete walls shall be designed for the loads and eccentricities to which they are subjected.

R3.14 — Moderately reinforced concrete walls

This section specifies that the effective depth of shear wall is to be $0.8\ \ell_w$.

3.14.2 — The effective length of a wall supporting a concentrated load shall be the smaller of the center - to - center spacing of load or the width of bearing plus four times the wall thickness.

3.14.3 — Walls shall be anchored to intersecting members, such as floors and roofs; or to columns, pilasters, buttresses, and intersecting concrete walls; and to footings.

3.14.6 — Moderately reinforced concrete walls that resist shear forces perpendicular to face of wall shall be designed in accordance with the shear design provisions for reinforced footings.

3.14.7 — Moderately reinforced concrete walls which resist shear forces in the plane of the wall shall be designed in accordance with the provisions of Section 2.14.

3.14.8 — The on center spacing of vertical reinforcement shall not exceed 48 inches.

3.14.9 — The on center spacing of horizontal reinforcement shall not exceed 24 inches, except where the basement wall segment is less than 25 feet in length and (3) #4 horizontal deformed steel reinforcing bars are provided.

3.15 — Moderately reinforced concrete footings

3.15.1 — Moderately reinforced concrete footings shall be designed for the loads and eccentricities to which they are subjected.

3.15.2 — Footing area shall be determined from unfactored forces and moments transmitted by footing to soil at the soil design pressure.

3.15.3 — The moment acting on a footing shall be determined by passing an imaginary vertical plane through the footing, and computing the moment of the forces acting over entire area of footing on one side of the plane and a maximum factored moment for an isolated footing shall be determined:

3.15.3.1 — At face of column, pedestal, or wall, for footings supporting a concrete column, pedestal, or wall;

3.15.3.2 — At halfway between middle and edge of wall, for footings supporting a masonry wall.

3.15.4 — In one-way moderately reinforced concrete footings and two-way square reinforced concrete footings, reinforcement shall be distributed uniformly across entire width of footing.

3.15.5 — Shear strength of moderately reinforced concrete footings at concentrated loads or reactions shall be governed by the more severe of two conditions:

3.15.5.1 — Beam action for footing, with a critical section extending in an imaginary vertical plane across the entire footing width and located at a distance, ***d***, from face of concentrated load or reaction area. For this condition, the footing shall be designed in accordance with provisions of Section 4.14 for one-way action.

3.15.5.2 — Two-way action for footing, with a critical section perpendicular to plane of footing and located so that its perimeter b_o is a minimum, but need not approach closer than $d / 2$ to perimeter of concentrated load or reaction area. For this condition, the footing shall be designed in accordance with provisions of Section 2.14 for two-way action.

3.15.6 — Calculated tension or compression in reinforcement at each section shall be developed on each side of that section by embedment length, tension hook, mechanical device, or a combination

3.15.7 — Critical sections for development of reinforcement shall be at the location for maximum factored moment, and at locations where changes of section dimension or reinforcement occur.

3.15.8 — The minimum depth of footing above bottom reinforcement shall be 6 inches.

3.15.9 — Axial forces and moments at the base of the wall shall be transferred to footing by bearing on concrete, keyway, reinforcement, dowels, mechanical connectors or combination.

3.15.10 — Bearing on concrete at the contact surface shall not exceed the bearing strength.

3.15.11 — Reinforcement, dowels, or mechanical connectors between supported and supporting concrete members shall be adequate to transfer:

3.15.11.1 All compressive force that exceeds concrete bearing strength of either concrete member ; and

3.15.11.2 Any computed tensile force across interface.

3.15.12 — Where reinforcement or dowel(s) is required by the prior section, reinforcement or dowel(s) shall be provided by extending longitudinal bars into the supporting footing.

3.15.13 — The reinforcement or dowels located across the interface of a wall and footer shall be in accordance with Section 2.1 4. Dowels shall be extended into supported concrete member, and supporting concrete member , a distance not less than the development length of the bars.

3.15.14 — Where footings slope or step, the footings shall be such that design requirements are satisfied at every section and act as a single structural member.

3.16 — Moderately reinforced concrete lintel
Moderately reinforced concrete lintels shall be designed for the loads and eccentricities to which they are subjected. A minimum of (1) No.4 rebar shall be provided in the longitudinal direction of the lintel.

4 — Unreinforced concrete

4.1 — In addition to the applicable requirements of Section 1, design of unreinforced concrete shall be in accordance with this section.

4.2 — Joints shall be in accordance with the provisions of Section 1.13 of this standard.

4.3 — Unreinforced concrete members subject to flexure and axial loads shall be based on a linear stress-strain relationship in both tension and compression.

4.4 — Where the joint provisions of this standard are followed, tensile strength of concrete shall be permitted to be utilized in the design of unreinforced concrete members.

4.5 — Where steel reinforcement is present in a concrete member designed as an unreinforced concrete member, no strength shall be assign to the steel reinforcement.

4.6 — Tension shall not be transmitted through outside edges, construction joints, contraction joints, or isolation joints of a unreinforced concrete member. No flexural continuity due to tension shall be assumed between adjacent unreinforced concrete members.

4.7 — Where concrete is cast against soil the overall thickness, ***h***, shall be taken as 2 inches less than actual thickness. For design, where concrete is to be cast against formwork the overall thickness, ***h***, shall be taken as the actual thickness.

4.8 — Design of unreinforced concrete subject to flexure shall be based on: $\phi M_n \geq M_u$ where M_u, is factored moment and M_n is nominal moment strength computed by

$$M_n = 5\sqrt{f_c'}S$$

if tension controls, and by

$$M_n = 0.85 f_c' S$$

if compression controls and where S is the elastic section modulus of the cross section.

4.9 — Design of unreinforced concrete subject to compression shall be based on: $\phi P_n \geq P_u$ where P_u is factored load and P_n is nominal compression strength computed by

$$P_n = 0.60 f_c'[1 - (\ell_c / 32 h)^2] A_1$$

where A_1, is the loaded area and l_c is the vertical distance between supports.

4.10 — Unreinforced concrete subject to combined flexure and axial load in compression shall be proportioned such that on the compression face

$$P_u / \phi P_n + M_u / \phi M_n \leq 1$$

and on the tension face

$$M_u / S - P_u / A_g \leq 5 \phi\sqrt{f_c'}$$

4.11 — Design of rectangular unreinforced concrete subject to shear shall be based on $\phi V_n \geq V_u$ where V_u is factored shear and V_n is nominal shear strength computed by:

$$V_n = 4 / 3\sqrt{f_c'}b\, h$$

for beam action and by:

$$V_n = [4 / 3 + 8 / (3 \beta_c)] \sqrt{f_c'} b_o h$$

for two-way action, to a maximum of $2.66 \sqrt{f_c'} b_o h$

4.12 — Unreinforced concrete bearing areas subject to compression shall be based on $\phi B_n \geq P_u$ where P_u is factored bearing load and B_n is nominal bearing strength of loaded area, A_1, computed by $B_n = 0.85 f_c' A_1$ except when the supporting surface is wider on all sides than the loaded area, design bearing strength on the loaded area shall be multiplied by: $\sqrt{(A_2 / A_1)} \leq 2$.

4.13 — Unreinforced concrete walls

4.13.1 — Unreinforced concrete walls shall be continuously supported by soil, footings, foundation walls, grade beams, or other structural concrete members capable of providing continuous vertical support.

4.13.2 — Unreinforced concrete walls shall be designed for an eccentricity corresponding to the maximum moment that can accompany the axial load but not less than $0.10h$. If the resultant of applicable factored loads is located within the middle-third of the overall wall thickness, the design shall be in accordance with Section 4.10.

4.13.3 — Design of unreinforced concrete walls subject to shear loads shall be in accordance with Section 4.11.

4.14 — Unreinforced concrete footings

4.14.1 — Unreinforced concrete footing area shall be determined from unfactored forces and moments transmitted by footing to soil at the soil design pressure.

4.14.2 — The maximum factored shear of unreinforced concrete footings shall be computed in accordance with this section, with location of critical section measured at face of column, pedestal, or wall for footing supporting a column, pedestal, or wall.

4.14.3 — Shear strength of unreinforced concrete footings at concentrated loads or reactions shall be governed by the more severe of two conditions:

4.14.3.1 — Beam action for footing, with a critical section extending in an imaginary vertical plane across the entire footing width and located at a distance, h, from face of concentrated load or reaction area. For this condition, the footing shall be designed in accordance with provisions of Section 4.11 for one-way action.

4.14.3.2 — Two-way action for footing, with a critical section perpendicular to plane of footing and located so that its perimeter b_o is a minimum, but need not approach closer than $h / 2$ to perimeter of concentrated load or reaction area. For this condition, the footing shall be designed in accordance with provisions of Section 4.11 for two-way action.

4.14.4 — Factored bearing load on unreinforced concrete at contact surface between supporting and supported concrete member shall not exceed design bearing strength for either surface specified by Section 4.12.

4.15 — **Unreinforced concrete lintels**

Lintels that occur in walls of unreinforced concrete shall be designed as a reinforced concrete lintel or as a moderately reinforced lintel.