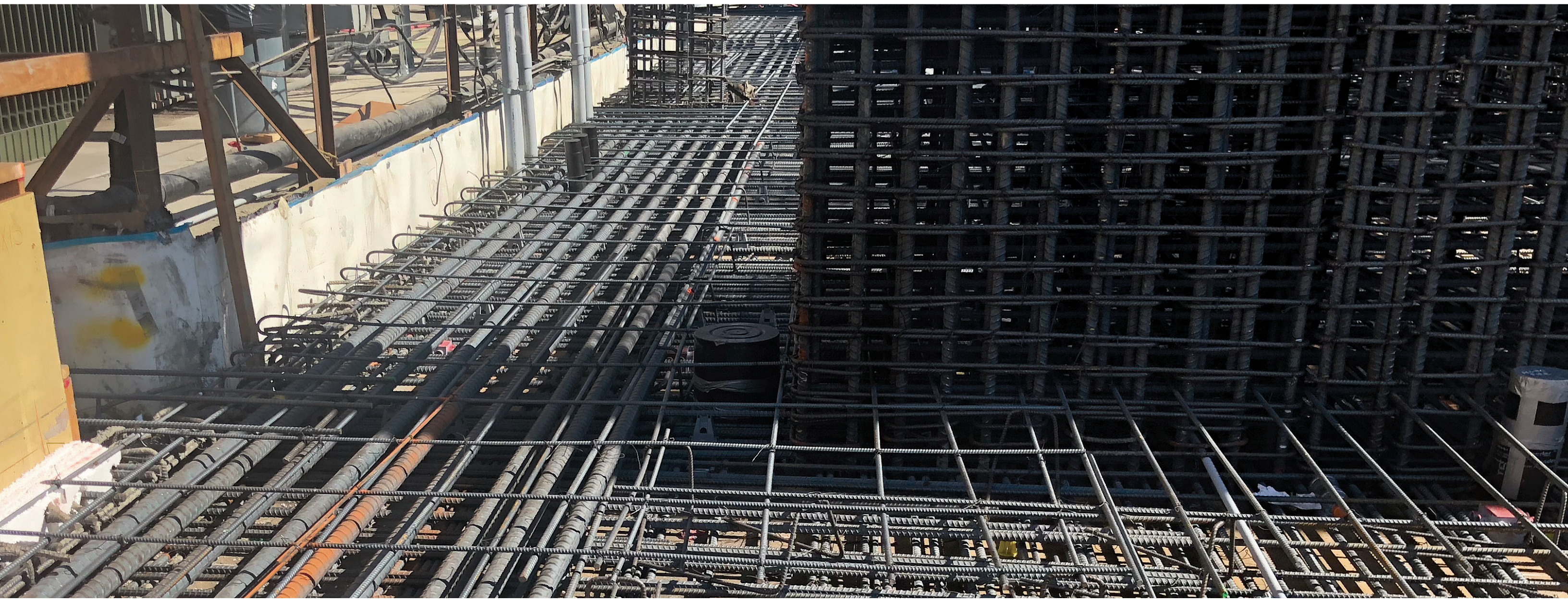
Design Guide for Reinforced Concrete Diaphragms



A guide to assist design professionals in efficiently designing and detailing reinforced concrete diaphragms.

First Edition

CRSI Concrete Reinforcing Steel Institute

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Founded in 1924, the Concrete Reinforcing Steel Institute (CRSI) is a technical institute and an ANSI-accredited Standards Developing Organization (SDO) that stands as the authoritative resource for information related to steel reinforced concrete construction. Serving the needs of engineers, architects and construction professionals, CRSI offers many industry-trusted technical publications, standards documents, design aids, reference materials and educational opportunities. CRSI Industry members include manufacturers, fabricators, material suppliers and placers of steel reinforcing bars and related products. Our Professional members are involved in the research, design, and construction of steel reinforced concrete. CRSI also has a broad Region Manager network that supports both members and industry professionals and creates awareness among the design/construction community through outreach activities. Together, they form a complete network of industry information and support.

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Foreword

In the 2014 edition of ACI 318, a new chapter devoted to the design and detailing of reinforced concrete diaphragms was included for the first time. The purpose of this Design Guide is to provide explanatory material based on the provisions of that chapter for diaphragms in buildings assigned to any Seismic Design Category. Included are many design aids and worked-out example problems that illustrate the proper application of the code requirements.

Since the first CRSI Design Handbook in 1952, users of CRSI publications have been cooperative in suggesting to the Design Aids Committee and CRSI Staff, many improvements, clarifications and additional design short-cuts. This professional assistance is very helpful, and is appreciated. Comments on this design guide are welcome so that future editions can be further improved. Please direct all comments to Mike Mota, Ph.D., P.E., SECB, F.SEI, F.ASCE, F.ACI, CRSI Vice President of Engineering.

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Chapter 1
Introduction

1.1 Overview

The purpose of this publication is to assist in the analysis, design, and detailing of reinforced concrete diaphragms in accordance with the 2014 edition of *Building Code Requirements for Structural Concrete (ACI 318-14)* and *Commentary (ACI 318R-14)* [Reference 1]. One of the main goals is to provide step-by-step design procedures and design aids that make designing and detailing reinforced concrete diaphragms simpler and faster. The procedures and design aids contained in this publication can be used in the design and detailing of reinforced concrete diaphragms in buildings of any size that are assigned to Seismic Design Categories A through F.

The 2018 edition of the *International Building Code* (IBC) [Reference 2] references ACI 318-14, and Section 1901.2 of the IBC requires that structural concrete be designed and constructed in accordance with the provisions of Chapter 19 of the IBC and the 2014 edition of ACI 318 as amended in IBC Section 1905. Thus, ACI 318 is part of the IBC and its applicable provisions must be satisfied when the IBC is adopted in a jurisdiction.

It is important to note that ACI 318 provides *minimum* requirements for the materials, design, construction, and strength evaluation of structural concrete members and systems in any structure designed and constructed under the requirements of the general building code, such as the IBC. The purpose and applicability of the requirements in ACI 318-14 can be found in Sections 1.3 and 1.4 of that document, respectively.

The requirements of the 2016 edition of ASCE/SEI 7 *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (Reference 3) are also used throughout this publication, including several important provisions pertaining to diaphragm loading and Seismic Design Category (SDC).

1.2 Definitions

Diaphragms have an essential role in both the gravity and lateral force-resisting systems in building structures. Reference 2 provides the following definition of a diaphragm:

> *A horizontal or sloped system acting to transmit lateral forces to vertical elements of the lateral force-resisting system. When the term "diaphragm" is used, it shall include horizontal bracing systems.*

A similar definition is given in Reference 3. Basically, diaphragms are roof and floor systems within a structure that must resist and transfer gravity and lateral forces.

Diaphragms must support and transfer gravity loads to columns, walls, and other supporting elements in a building. The weight of the structure, superimposed dead loads, and live loads are common out-of-plane gravity loads that are applied to the surface of a diaphragm. Roof diaphragms must also be able to support effects due to rain, snow, and wind, to name a few. Minimum gravity and vertical environmental loads for floors and roofs are determined accordance with References 2 and 3.

Lateral forces from wind, earthquakes, soil pressure, and other types of forces are transferred from diaphragms to walls, moment-resisting frames, and other types of lateral force-resisting systems in a building. The load path from the application of the force on the diaphragm to the vertical elements of the lateral force-resisting system (LFRS) depends on several factors, including the type of applied force and the rigidity (or, flexibility) of the diaphragm. The in-plane forces, which are determined mainly in accordance with the provisions in References 2 and 3, generate in-plane shear forces, bending moments, and axial forces in a diaphragm. The connections between the diaphragm and the vertical elements of the LFRS are very important; these connections must be properly designed and detailed otherwise there is no mechanism for proper load transfer to the LFRS.

Collectors, which are part of a diaphragm and are sometimes referred to as drag struts, are required where the LFRS does not extend the full depth of a diaphragm or where there is a discontinuity in the LFRS, for example. The following definition of a collector is given in Reference 2:

> *A horizontal diaphragm element parallel and in line with the applied force that collects and transfers diaphragm shear forces to the vertical elements of the lateral force-resisting system or distributes forces within the diaphragm, or both.*

A specific definition related to diaphragms that transfer forces to the vertical elements of a seismic force-resisting system (SFRS) is given in Reference 3. These elements are also an essential part of the overall load path for lateral forces, and References 1 through 3 contain design and detailing requirements based on SDC.

Figure R12.1.1 in Reference 1 depicts typical diaphragm actions in a reinforced concrete building. In general, diaphragms must be designed and detailed for the combined effects due to in-plane and out-of-plane load effects in accordance with the factored load combinations in Chapter 5 of Reference 1.

1.3 Scope

The design and detailing of diaphragms that are cast-in-place concrete slabs utilizing nonprestressed, steel reinforcement in building structures are covered in this publication. Slabs-on-ground that are part of the LFRS and transmit lateral forces from other portions of the structure to the soil are also covered (see Sections 1.4.7 and 13.2.4 of Reference 1). Slabs-on-ground that resist earthquake forces from walls or columns that are part of the SFRS must be designed as diaphragms in accordance with Section 18.12 of ACI 318-14 (see Section 18.13.3.4 of that document).

Because in-plane load effects from wind, earthquakes, and other types of forces play an important part in the design and detailing process, in-depth information from References 2 and 3 is presented on how to calculate these lateral forces for buildings assigned to SDC A through F.

ACI 318-14 provisions related to diaphragms are organized in tables, figures, and flowcharts throughout this publication. These provide a roadmap that guides the reader through the requirements, and are especially useful because ACI 318 underwent a major reorganization going from the 2011 to the 2014 edition, the first such reorganization since 1971. Requirements in ACI 318-14 are organized mainly by member type, which is a major change of how the document was organized in earlier editions. New Chapter 12 and Chapter 18 in ACI 318-14 contain the provisions for reinforced concrete diaphragms, and supplementary requirements in other chapters of ACI 318 are covered as needed.

Throughout this publication, section numbers from ACI 318-14 are referenced as illustrated by the following: Section 12.4 of ACI 318-14 is denoted as ACI 12.4. Section numbers from the 2018 IBC and ASCE/SEI 7-16 are referenced as follows: Section 1613 from the 2018 IBC and Section 12.3 of ASCE/SEI 7-16 are denoted as IBC 1613 and ASCE/SEI 12.3, respectively.

1.4 Organization of this Publication

Chapter 2 contains limits on the specified compressive strength of concrete and the types of nonprestressed reinforcement that are permitted to be specified for reinforced concrete diaphragms. Information is provided based on whether the diaphragm is in a building that contains special seismic systems or not.

Methods on how to determine diaphragm thickness based on serviceability, in-plane, and out-of-plane requirements are given in Chapter 3. Included are minimum thickness provisions for diaphragms in buildings assigned to SDC A through C and SDC D through F.

Chapter 4 contains comprehensive information on how to determine the following forces on a diaphragm: (1) in-plane forces (wind, general structural integrity, seismic, soil, flood, tsunami, transfer, connection, and column bracing), (2) out-of-plane forces, and (3) collector forces. Step-by-step procedures are given on how to calculate these diaphragm forces for buildings assigned to SDC A through F.

Strength design load combinations from References 1 through 3 that are to be used to design diaphragms are given in Chapter 5. Specific load combinations are provided for buildings assigned to SDC A, SDC B, SDC C, and SDC D through F. Included is information on in-plane inertial and transfer forces and direction of loading requirements that must be satisfied based on SDC.

Chapter 6 covers the general modeling and analysis requirements for diaphragms that are given in ACI 12.4.2. Included is information on how to determine whether a diaphragm is rigid or not and horizontal distribution of lateral forces based on the in-plane stiffness of a diagram. A method is provided on how to determine the location of the center of rigidity for a rigid diaphragm. Also included are approximate methods to determine in-plane stiffnesses of moment frames and shear walls, which can be used in equivalent beam models of diaphragms. This chapter also contains the ACI 318 analysis methods, which can be used to determine in-plane design moments and shears in diaphragms. Finally, beam models are presented; these models are utilized to determine in-plane internal forces in rigid diaphragms with and without openings in buildings without major irregularities or transfer forces. Equations are provided on how to calculate chord, shear-transfer, and collector forces for the cases where the collector is the same width as or is wider than the vertical element of the LFRS it frames in to.

The general requirements for strength design pertaining to reinforced concrete diaphragms are given in Chapter 7. Included are basic performance requirements, strength reduction factors, and nominal strength of diaphragms and collectors (moment and axial force, shear, and shear transfer).

Chapter 8 contains comprehensive procedures on how to determine the required reinforcement for diaphragms based on two different types of common construction methods. Numerous design aids and figures are provided that summarize the pertinent design and detailing requirements based on SDC.

A step-by-step design procedure that can be used to design and detail reinforced concrete diaphragms in buildings assigned to SDC A through F based on the information in Chapters 2 through 8 is given in Chapter 9. The following design steps are provided that reference the equations, tables, and figures in the chapters (flowcharts are given for steps 2 through 11):

1. Selecting the materials
2. Determining the diaphragm thickness
3. Determining the design forces
4. Determining the diaphragm classification, selecting the diaphragm model, and determining the diaphragm internal forces
5. Determining the combined load effects
6. Determining the chord reinforcement
7. Determining the diaphragm shear reinforcement
8. Determining the shear transfer reinforcement
9. Determining the reinforcement due to eccentricity of collector forces
10. Determining the anchorage reinforcement
11. Determining the collector reinforcement

Completely worked-out examples are given in Chapters 10 that illustrate the proper application of the code requirements for buildings assigned to SDC A through D. These examples follow the design procedures in the chapters and the flowcharts in Chapter 9 and utilize the design aids wherever possible. Examples are included for diaphragms with relatively large openings and for buildings with horizontal irregularities.

Chapter 2
Materials

2.1 Overview

Limits on the specified compressive strength of concrete and the types of nonprestressed reinforcement that are permitted to be specified for reinforced concrete diaphragms and collectors are covered in this chapter. Information is provided for all the Seismic Design Categories.

2.2 Concrete

ACI Table 19.2.1.1 contains limits on the specified compressive strength of concrete, f_c' (see Table 2.1). For structural members in buildings—including diaphragms and collectors—that are not cast monolithically with portions of special moment frames and/or special structural walls, the minimum compressive strength is 2,500 psi for both normalweight and lightweight concrete. There is no upper limit in such cases. The durability requirements in ACI Table 19.3.2.1 must be satisfied as well.

Table 2.1 Limits for Concrete Compressive Strength

Application	Concrete	f_c' (psi)	
		Minimum	Maximum
General	Normalweight and lightweight	2,500	None
Special seismic systems[(1)]	Normalweight	3,000	None
	Lightweight	3,000	5,000[(2)]

(1) Applicable to special moment frames and special structural walls.
(2) Limit is permitted to be exceeded where demonstrated by experimental evidence that members with lightweight concrete provide strength and toughness equal to or exceeding those of comparable members made with normalweight concrete of the same strength.

The minimum value of f_c' for diaphragms and collectors that are cast monolithically with portions of special moment frames or special structural walls is 3,000 psi for both normalweight and lightweight concrete. There is no upper limit on f_c' for normalweight concrete, but for lightweight concrete, the upper limit is 5,000 psi. This limit is imposed because of the very limited amount of experimental and field data that are available on the behavior and performance of members made with lightweight concrete. However, values of f_c' greater than 5,000 psi for lightweight mixes are permitted if it can be shown that members made from the lightweight mix provide strength and toughness levels that equal or exceed those of comparable members made from normalweight concrete of the same compressive strength.

Typical concrete compressive strengths used in reinforced concrete floor and roof systems with nonprestressed reinforcement are 4,000 psi and 5,000 psi. Using a compressive strength greater than 5,000 psi is usually not warranted.

2.3 Nonprestressed Reinforcement

ACI Table 20.2.2.4a contains maximum values of specified yield strength, f_y, and permissible bar types for deformed reinforcing bars based on usage and application. The following types of reinforcement in diaphragms and collectors are limited to $f_y = 60{,}000$ psi for design calculations:

1. Shear reinforcement in diaphragms
2. Shear-friction reinforcement used to transfer forces between the diaphragm and the vertical elements of the lateral force-resisting system
3. Shear-friction reinforcement used to transfer forces between the diaphragm and collectors
4. Collector transverse reinforcement, including that required by ACI 18.12.7.5

The specified yield strength of collector and chord reinforcement used for flexure and axial force in diaphragms and collectors that are not cast monolithically with portions of special moment frames and/or special structural walls is limited to 80,000 psi; otherwise, f_y is limited to 60,000 psi. Using reinforcing bars with different specified yield strengths in different parts of a slab system is not recommended. That is why Grade 60 reinforcement is commonly specified for the entire slab system.

Any of the following types of reinforcement may be used in diaphragms and collectors that are not cast monolithically with portions of special moment frames and/or special structural walls:

1. Carbon-steel (ASTM A615)
2. Low-alloy steel (ASTM A706)
3. Stainless-steel (ASTM A955)
4. Rail-steel and Axle-steel (ASTM A996)

According to ACI 20.2.2.5, ASTM A706 and A615 reinforcement that conforms to ACI 20.2.2.5(b) are required to be used in diaphragms and collectors that are cast monolithically with portions of special moment frames and/or special structural walls. Chord or collector reinforcement that is placed within beams of special moment frames, including the effective slab width of the beam, must be ASTM A706 or equivalent.

Chapter 3
Determining the Diaphragm Thickness

3.1 Overview

According to ACI 12.3.1, diaphragms must have sufficient thickness so that all applicable strength and serviceability requirements are satisfied. The following load effects must be investigated for strength: (1) in-plane moments, in-plane shear forces, and axial forces due to wind, seismic, and other applicable lateral forces and (2) out-of-plane moments and shears due to gravity forces or combinations of gravity and lateral forces.

ACI 318 serviceability requirements are covered in Section 3.2 below, and in-plane and out-of-plane strength requirements are given in Sections 3.3 and 3.4, respectively. Information on how to determine minimum diaphragm thickness for buildings assigned to Seismic Design Category (SDC) A, B, or C is given in Section 3.5. Section 3.6 contains similar information for buildings assigned to SDC D, E, or F.

3.2 Serviceability Requirements

3.2.1 One-way Slabs

Expressions for minimum thickness of solid, nonprestressed one-way slabs that are not supporting or attached to partitions or other construction likely to be damaged by large deflections are given in ACI Table 7.3.1.1 (see Table 3.1).

Table 3.1 Minimum Thickness, h, of Solid, Nonprestressed One-way Slabs

Support Condition	Minimum h[1]
Simply supported	$\ell/20$
One end continuous	$\ell/24$
Both ends continuous	$\ell/28$
Cantilever	$\ell/10$

*(1) Expressions for minimum **h** are applicable to Grade 60 reinforcement and normalweight concrete. These expressions are to be modified in accordance with ACI 7.3.1.1.1 for reinforcement other than Grade 60 and ACI 7.3.1.1.2 for lightweight concrete.*

These expressions are based on span length, ℓ, and are applicable to Grade 60 reinforcement and normalweight concrete. For reinforcement with a specified yield strength other than 60,000 psi, the expressions in the table are to be multiplied by $(0.4 + f_y / 100{,}000)$ where the specified yield strength of the reinforcement, f_y, is in pounds per square inch (ACI 7.3.1.1.1). For lightweight concrete with an equilibrium density, w_c, in the range of 90 to 115 lb/ft^3, the expressions in the table are to be multiplied by the greater of $(1.65 - 0.005w_c)$ and 1.09 (ACI 7.3.1.1.2).

3.2.2 Two-way Slabs

Minimum thickness of nonprestressed two-way slabs without interior beams is determined by the expressions in ACI Table 8.3.1.1 (see Table 3.2), which are based on the clear span length, ℓ_n, in the long direction. For slab systems without drop panels (drop panels are defined in ACI 8.2.4), the minimum thickness is the larger of the value obtained from the expression in Table 3.2 and 5 in. (ACI 8.3.1.1). Similarly, for slab systems with drop panels, the minimum thickness is the larger of the tabulated value and 4 in. According to ACI 8.3.1.1, exterior panels are considered to be without edge beams where $\alpha_f < 0.8$. The term α_f is defined in ACI 8.10.2.7 as the ratio of the flexural stiffness of the beam $(E_{cb}I_b)$ to the flexural stiffness of a slab width bounded laterally by the centerlines of adjacent panels, if any, on each side of the beam $(E_{cs}I_s)$. In typical situations where the concrete mix for the beams and slab are the same, the modulus of elasticity of the beam, E_{cb}, and the modulus of elasticity of the slab, E_{cs}, are equal, so $\alpha_f = I_b / I_s$ where I_b and I_s are the moments of inertia of the beam and slab, respectively.

Table 3.2 Minimum Thickness, h, of Nonprestressed Two-way Slabs Without Interior Beams[1]

f_y (psi)[2]	Without Drop Panels[3]			With Drop Panels[3]		
	Exterior Panels		Interior Panels	Exterior Panels		Interior Panels
	Without Edge Beams	With Edge Beams[4]		Without Edge Beams	With Edge Beams[4]	
40,000	$\ell_n/33$	$\ell_n/36$	$\ell_n/36$	$\ell_n/36$	$\ell_n/40$	$\ell_n/40$
60,000	$\ell_n/30$	$\ell_n/33$	$\ell_n/33$	$\ell_n/33$	$\ell_n/36$	$\ell_n/36$
75,000	$\ell_n/28$	$\ell_n/31$	$\ell_n/31$	$\ell_n/31$	$\ell_n/34$	$\ell_n/34$

(1) ℓ_n is the clear span in the long direction, measured face-to-face of supports (in.).
(2) For f_y between the values given in the table, minimum thickness is to be calculated by linear interpolation.
(3) Drop panels are defined in ACI 8.2.4.
(4) Exterior panels with edge beams are defined as slabs with beams between columns along exterior edges. Exterior panels are considered to be without edge beams where $\alpha_f < 0.8$. The value of α_f for an edge beam is calculated in accordance with ACI 8.10.2.7.

Expressions for minimum thickness of nonprestressed two-way slabs with beams spanning between supports on all sides are given in ACI Table 8.3.1.2 (see Table 3.3). For panels without sufficiently stiff beams around the edges (that is, where $\alpha_{fm} \leq 0.2$), the expressions for minimum thickness in Table 3.2 for two-way slabs without interior beams must be used. The term α_{fm} is the average value of α_f for all beams on the edges of a panel.

Table 3.3 Minimum Thickness, *h*, of Nonprestressed Two-way Slabs With Beams Spanning Between Supports on all Sides

α_{fm} (1)	Minimum *h* (in.)	
$\alpha_{fm} \leq 0.2$	ACI 8.3.1.1 applies (see Table 3.2)	
$0.2 < \alpha_{fm} \leq 2.0$	Greater of(2),(3):	$\dfrac{\ell_n\left(0.8 + \dfrac{f_y}{200{,}000}\right)}{36 + 5\beta\left(\alpha_{fm} - 0.2\right)}$
		5.0
$\alpha_{fm} > 2.0$	Greater of(2),(3):	$\dfrac{\ell_n\left(0.8 + \dfrac{f_y}{200{,}000}\right)}{36 + 9\beta}$
		3.5

(1) α_{fm} is the average value of α_f for all beams on the edges of a panel where α_f is determined in accordance with ACI 8.10.2.7.
(2) ℓ_n is the clear span in the long direction, measured face-to-face of supports (in.).
(3) β is the ratio of clear spans in the long to short directions of the slab.

Figure 3.1 can be used to determine minimum slab thickness based on the requirements in ACI 8.3.1.1 and 8.3.1.2 for various types of two-way slab systems assuming Grade 60 reinforcement.

3.3 In-plane Strength Requirements

3.3.1 Overview

Cast-in-place reinforced concrete slabs must have adequate strength to resist in-plane effects, including those due to wind, seismic, fluid, or lateral earth pressure. In general, both flexure and shear must be considered when determining a required slab thickness. A diaphragm thickness based on serviceability requirements is usually adequate to satisfy in-plane strength requirements.

3.3.2 Flexure

In-plane moments, which are determined by one of the models in Chapter 6 of this publication, are typically resisted by chord reinforcement placed perpendicular to the direction of the lateral force. In most cases, this reinforcement is determined using a slab thickness that is sufficient for serviceability or other strength requirements; there is usually no need to increase the thickness of a slab based on in-plane flexural requirements.

Chord reinforcement is normally concentrated near the edges of the slab and around any openings in the slab; however, it is permitted to distribute this reinforcement within 25 percent of the diaphragm depth from the tension edge of the diaphragm (ACI 12.5.2.3; see ACI Figure R12.5.2.3 and Section 8.4 of this publication).

3.3.3 Shear

In-plane shear strength requirements for diaphragms are given in ACI 12.5.3 for buildings assigned to SDC A, B, or C. The nominal shear strength, V_n, of a cast-in-place reinforced concrete diaphragm is determined by ACI Equation (12.5.3.3), which is a function of the area of the diaphragm, A_{cv}, the modification factor, λ, that accounts for the reduced mechanical properties of lightweight concrete relative to normalweight concrete of the same compressive strength, f'_c (which is limited to 10,000 psi), and the amount of distributed shear reinforcement in the slab, ρ_t. The following equation must be satisfied for in-plane shear strength:

$$V_u \leq \phi V_n = \phi A_{cv}(2\lambda\sqrt{f'_c} + \rho_t f_y) \tag{3.1}$$