CHAPTER 4—STRUCTURAL SYSTEM REQUIREMENTS

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4.1—Scope

4.1.1 This chapter shall apply to design of structural concrete in structures or portions of structures defined in Chapter 1.

4.2—Materials

4.2.1 Design properties of concrete shall be selected to be in accordance with Chapter 19.

4.2.1.1 Design properties of shotcrete shall conform to the requirements for concrete except as modified by provisions of the Code.

4.2.2 Design properties of reinforcement shall be selected to be in accordance with Chapter 20.

4.3—Design loads

4.3.1 Loads and load combinations considered in design shall be in accordance with Chapter 5.

4.4—Structural system and load paths

4.4.1 The structural system shall include (a) through (g), as applicable:

(a) Floor construction and roof construction, including one-way and two-way slabs
(b) Beams and joists
(c) Columns
(d) Walls
(e) Diaphragms
(f) Foundations

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R4.1—Scope

R4.1.1 This chapter was added to the 2014 Code to introduce structural system requirements. Requirements more stringent than the Code provisions may be desirable for unusual construction or construction where enhanced performance is appropriate. The Code and Commentary must be supplemented with sound engineering knowledge, experience, and judgment.

R4.2—Materials

R4.2.1.1 Shotcrete is considered to behave and have properties similar to concrete unless otherwise noted. Sections where use of shotcrete is specifically addressed in the Code are shown in Table R4.2.1.1. Additional information on shotcrete can be found in ACI PRC-506 and ACI SPEC-506.2.

Table R4.2.1.1—Sections in Code with shotcrete provisions

Topic covered	Section
Freezing and thawing	19.3.3.3 through 19.3.3.6
Reinforcement	25.2.7 through 25.2.10, 25.5.1.6, and 25.5.1.7
Where shotcrete is required or permitted	26.3.1, 26.3.2
Materials	26.4.1.2, 26.4.1.4, and 26.4.1.6
Proportioning mixtures	26.4.3
Documentation of mixtures	26.4.4.1
Placement and consolidation	26.5.2.1
Curing	26.5.3
Joints	26.5.6
Evaluation and acceptance	26.12

R4.4—Structural system and load paths

R4.4.1 Structural concrete design has evolved from emphasizing the design of individual members to designing the structure as an entire system. A structural system consists of structural members, joints, and connections, each performing a specific role or function. A structural member may belong to one or more structural systems, serving different roles in each system and having to meet all the detailing requirements of the structural systems of which they are a part. Joints and connections are locations common to intersecting members or are items used to connect one

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(g) Joints, connections, and anchors as required to transmit forces from one component to another

4.4.2 Design of structural members including joints and connections given in 4.4.1 shall be in accordance with Chapters 7 through 18.

4.4.3 It shall be permitted to design a structural system comprising structural members not in accordance with 4.4.1 and 4.4.2, provided the structural system is approved in accordance with 1.10.1.

4.4.4 The structural system shall be designed to resist the factored loads in load combinations given in 4.3 without exceeding the appropriate member design strengths, considering one or more continuous load paths from the point of load application or origination to the final point of resistance.

4.4.5 Structural systems shall be designed to accommodate anticipated volume change and differential settlement.

4.4.6 *Seismic-force-resisting system*

4.4.6.1 Every structure shall be assigned to a Seismic Design Category in accordance with the general building code or as determined by the building official in areas without a legally adopted building code.

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member to another, but the distinction between members, joints, and connections can depend on how the structure is idealized. Throughout this chapter, the term "members" often refers to "structural members, joints, and connections."

Although the Code is written considering that a structural system comprises these members, many alternative arrangements are possible because not all structural member types are used in all building structural systems. The selection types of the members to use in a specific project and the role or roles these member types play is made by the licensed design professional complying with requirements of the Code.

R4.4.2 In the chapter for each type of structural member, requirements follow the same general sequence and scope, including general requirements, design limits, required strength, design strength, reinforcement limits, reinforcement detailing, and other requirements unique to the type of member.

R4.4.3 Some materials, structural members, or systems that may not be recognized in the prescriptive provisions of the Code may still be acceptable if they meet the intent of the Code. Section 1.10.1 outlines the procedures for obtaining approval of alternative materials and systems.

R4.4.4 The design should be based on members and connections that provide design strengths not less than the strengths required to transfer the loads along the load path. The licensed design professional may need to study one or more alternative paths to identify weak links along the sequence of elements that constitute each load path.

R4.4.5 The effects of column and wall creep and shrinkage, restraint of creep and shrinkage in long roof and floor systems, creep caused by prestress forces, volume changes caused by temperature variation, as well as potential damage to supporting members caused by these volume changes should be considered in design. Reinforcement, closure strips, or expansion joints are common ways of accommodating these effects. Minimum shrinkage and temperature reinforcement controls cracking to an acceptable level in many concrete structures of ordinary proportions and exposures.

Differential settlement or heave may be an important consideration in design. Geotechnical recommendations to allow for nominal values of differential settlement and heave are not normally included in design load combinations for ordinary building structures

R4.4.6 *Seismic-force-resisting system*

R4.4.6.1 Design requirements in the Code are based on the seismic design category to which the structure is assigned. In general, the seismic design category relates to seismic risk level, soil type, occupancy, and building use. Assignment of

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a building to a seismic design category is under the jurisdiction of a general building code rather than ACI CODE-318. In the absence of a general building code, ASCE/SEI 7 provides the assignment of a building to a seismic design category.

4.4.6.2 Structural systems designated as part of the seismic-force-resisting system shall be restricted to those systems designated by the general building code or as determined by the building official in areas without a legally adopted building code.

R4.4.6.2 The general building code prescribes, through ASCE/SEI 7, the types of structural systems permitted as part of the seismic-force-resisting system based on considerations such as seismic design category and building height. The seismic design requirements for systems assigned to Seismic Design Categories B through F are prescribed in Chapter 18. Other systems can be used if approved by the building official.

4.4.6.3 Structural systems assigned to Seismic Design Category A shall satisfy the applicable requirements of this Code. Structures assigned to Seismic Design Category A are not required to be designed in accordance with Chapter 18.

R4.4.6.3 Structures assigned to Seismic Design Category A are subject to the lowest seismic hazard. Chapter 18 does not apply.

4.4.6.4 Structural systems assigned to Seismic Design Category B, C, D, E, or F shall satisfy the requirements of Chapter 18 in addition to applicable requirements of other chapters of this Code.

R4.4.6.4 Chapter 18 contains provisions that are applicable depending on the seismic design category and on the seismic-force-resisting system used. Not all structural member types have specific requirements in all seismic design categories. For example, Chapter 18 does not include requirements for structural walls in Seismic Design Categories B and C, but does include special provisions for Seismic Design Categories D, E, and F.

4.4.6.5 Structural members assumed not to be part of the seismic-force-resisting system shall be permitted, subject to the requirements of 4.4.6.5.1 and 4.4.6.5.2.

R4.4.6.5 In Seismic Design Categories D, E, and F, structural members not considered part of the seismic-force-resisting system are required to be designed to accommodate drifts and forces that occur as the building responds to an earthquake.

4.4.6.5.1 In structures assigned to Seismic Design Category B, C, D, E, or F, the effects of those structural members on the response of the system shall be considered and accommodated in the structural design.

4.4.6.5.2 In structures assigned to Seismic Design Category B, C, D, E, or F, the consequences of damage to those structural members shall be considered.

4.4.6.5.3 In structures assigned to Seismic Design Category D, E, or F, structural members not considered part of the seismic-force-resisting system shall meet the applicable requirements in Chapter 18.

4.4.6.6 Effects of nonstructural members shall be accounted for as described in 18.2.2.1 and consequences of damage to nonstructural members shall be considered.

R4.4.6.6 Although the design of nonstructural elements for earthquake effects is not included in the scope of ACI CODE-318, the potential negative effects of nonstructural elements on the structural behavior need to be considered in Seismic Design Categories B, C, D, E, and F. Interaction of nonstructural elements with the structural system—

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4.4.6.7 Design verification of earthquake-resistant concrete structures using nonlinear response history analysis shall be in accordance with Appendix A.

4.4.7 *Diaphragms*

4.4.7.1 Diaphragms, such as floor or roof slabs, shall be designed to resist simultaneously both out-of-plane gravity loads and in-plane lateral forces in load combinations given in 4.3.

4.4.7.2 Diaphragms and their connections to framing members shall be designed to transfer forces between the diaphragm and framing members.

4.4.7.3 Diaphragms and their connections shall be designed to provide lateral support to vertical, horizontal, and inclined elements.

4.4.7.4 Diaphragms shall be designed to resist applicable lateral loads from soil and hydrostatic pressure and other loads assigned to the diaphragm by structural analysis.

4.4.7.5 Collectors shall be provided where required to transmit forces between diaphragms and vertical elements.

4.4.7.6 Diaphragms that are part of the seismic-force-resisting system shall be designed for the applied forces in accordance with Chapter 12 and Chapter 18 where applicable.

4.5—Structural analysis

4.5.1 Analytical procedures shall satisfy compatibility of deformations and equilibrium of forces.

4.5.2 The methods of analysis given in Chapter 6 shall be permitted.

4.6—Strength

4.6.1 Design strength of a member and its joints and connections, in terms of moment, shear, torsional, axial, and bearing strength, shall be taken as the nominal strength S_n multiplied by the applicable strength reduction factor ϕ.

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for example, the short-column effect—had led to failure of structural members and collapse of some structures during earthquakes in the past.

R4.4.7 *Diaphragms*

R4.4.7.1 Floor and roof slabs play a dual role by simultaneously supporting gravity loads and transmitting lateral forces in their own plane as a diaphragm. General requirements for diaphragms are provided in Chapter 12, and roles of the diaphragm are described in the Commentary to that chapter. Additional requirements for design of diaphragms in structures assigned to Seismic Design Categories D, E, and F, and in some cases Seismic Design Category C, are prescribed in Chapter 18.

R4.4.7.5 All structural systems must have a complete load path in accordance with 4.4.4. The load path includes collectors where required.

R4.6—Strength

R4.6.1 The basic requirement for strength design may be expressed as follows:

$$\text{design strength} \geq \text{required strength}$$
$$\phi S_n \geq U$$

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In the strength design procedure, the level of safety is provided by a combination of factors applied to the loads and strength reduction factors ϕ applied to the nominal strengths.

The strength of a member or cross section, calculated using standard assumptions and strength equations, along with nominal values of material strengths and dimensions, is referred to as nominal strength and is generally designated S_n. Design strength or usable strength of a member or cross section is the nominal strength reduced by the applicable strength reduction factor ϕ. The purpose of the strength reduction factor is to account for the probability of under-strength due to variations of in-place material strengths and dimensions, the effect of simplifying assumptions in the design equations, the degree of ductility, potential failure mode of the member, the required reliability, and significance of failure and existence of alternative load paths for the member in the structure.

The Code, or the general building code, prescribes design load combinations, also known as factored load combinations, which define the way different types of loads are multiplied (factored) by individual load factors and then combined to obtain a factored load U. The individual load factors and additive combination reflect the variability in magnitude of the individual loads, the probability of simultaneous occurrence of various loads, and the assumptions and approximations made in the structural analysis when determining required design strengths.

A typical design approach, where linear analysis is applicable, is to analyze the structure for individual unfactored load cases, and then combine the individual unfactored load cases in a factored load combination to determine the design load effects. Where effects of loads are nonlinear—for example, in foundation uplift—the factored loads are applied simultaneously to determine the nonlinear, factored load effect. The load effects relevant for strength design include moments, shears, torsions, axial forces, bearing forces, and punching shear stresses. Sometimes, design displacements are determined for factored loads. The load effects relevant for service design include stresses and deflections.

In the course of applying these principles, the licensed design professional should be aware that providing more strength than required does not necessarily lead to a safer structure because doing so may change the potential failure mode. For example, increasing longitudinal reinforcement area beyond that required for moment strength as derived from analysis without increasing transverse reinforcement could increase the probability of a shear failure occurring prior to a flexural failure. Excess strength may be undesirable for structures expected to behave inelastically during earthquakes.

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4.6.2 Structures and structural members shall have design strength at all sections, ϕS_n, greater than or equal to the required strength U calculated for the factored loads and forces in such combinations as required by this Code or the general building code.

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4.7—Serviceability

4.7.1 Evaluation of performance at service load conditions shall consider reactions, moments, shears, torsions, and axial forces induced by prestressing, creep, shrinkage, temperature change, axial deformation, restraint of attached structural members, and foundation settlement.

4.7.2 For structures, structural members, and their connections, the requirements of 4.7.1 shall be deemed to be satisfied if designed in accordance with the provisions of the applicable member chapters.

4.8—Durability

4.8.1 Concrete mixtures shall be designed in accordance with the requirements of 19.3.2 and 26.4, considering applicable environmental exposure to provide required durability.

4.8.2 Reinforcement shall be protected from corrosion in accordance with 20.5.

4.9—Sustainability and resilience

4.9.1 The licensed design professional shall be permitted to incorporate the applicable sustainability and resilience provisions of Appendix C in the design.

4.10—Structural integrity

4.10.1 *General*

4.10.1.1 Reinforcement and connections shall be detailed to tie the structure together effectively and to improve overall structural integrity.

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R4.7—Serviceability

R4.7.1 Serviceability refers to the ability of the structural system or structural member to provide appropriate behavior and functionality under the actions affecting the system. Serviceability requirements address issues such as deflections and cracking, among others. Serviceability considerations for vibrations are discussed in R6.6.3.2.2 and R24.1.

Except as stated in Chapter 24, service-level load combinations are not defined in the Code, but are discussed in Appendix C of ASCE/SEI 7. Appendixes to ASCE/SEI 7 are not considered mandatory parts of the standard.

R4.8—Durability

R4.8.1 The environment where the structure will be located will dictate the exposure category for materials selection, design details, and construction requirements to minimize potential for premature deterioration of the structure caused by environmental effects. Durability of a structure is also impacted by the level of preventative maintenance, which is not addressed in the Code.

Chapter 19 provides requirements for protecting concrete against major environmental causes of deterioration.

R4.9—Sustainability and resilience

R4.9.1 Appendix C describes approaches for increasing the sustainability and resilience of concrete structures and includes requirements for concrete mixtures and construction.The licensed design professional and stakeholders should establish the hazard events the design process must consider.

R4.10—Structural integrity

R4.10.1 *General*

R4.10.1.1 It is the intent of the structural integrity requirements to improve redundancy and ductility through detailing of reinforcement and connections so that, in the event of damage to a major supporting element or an abnormal loading, the resulting damage will be localized and the structure will have a higher probability of maintaining overall stability.

Integrity requirements for selected structural member types are included in the corresponding member chapter in the sections noted.

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4.10.2 *Minimum requirements for structural integrity*

4.10.2.1 Structural members and their connections shall be in accordance with structural integrity requirements in Table 4.10.2.1.

Table 4.10.2.1—Minimum requirements for structural integrity

Member type	Section
Nonprestressed one-way cast-in-place slabs	7.7.7
Nonprestressed two-way slabs	8.7.4.2
Prestressed two-way slabs	8.7.5.6
Nonprestressed two-way joist systems	8.8.1.6
Cast-in-place beam	9.7.7
Nonprestressed one-way joist system	9.8.1.6
Precast joints and connections	16.2.1.8

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R4.10.2 *Minimum requirements for structural integrity*

R4.10.2.1 Structural members and their connections referred to in this section include only member types that have specific requirements for structural integrity. Notwithstanding, detailing requirements for other member types address structural integrity indirectly.

4.11—Fire resistance

4.11.1 Structural concrete members shall satisfy the fire protection requirements of the general building code.

4.11.2 Where the general building code requires a thickness of concrete cover for fire protection greater than the concrete cover specified in 20.5.1, such greater thickness shall govern.

R4.11—Fire resistance

R4.11.1 Additional guidance on fire resistance of structural concrete is provided by ACI/TMS CODE-216.1.

4.12—Requirements for specific types of construction

4.12.1 *Precast concrete systems*

4.12.1.1 It shall be permitted to design precast concrete members and connections in accordance with ACI/PCI CODE-319, "Building Code Requirements for Structural Precast Concrete—Code and Commentary."

4.12.1.2 Design of precast concrete members and connections shall include loading and restraint conditions from initial fabrication to end use in the structure, including form removal, storage, transportation, and erection.

R4.12—Requirements for specific types of construction

R4.12.1 *Precast concrete systems*

This section contains requirements that are related to specific types of construction. Additional requirements that are specific to member types appear in the corresponding member chapters.

R4.12.1.1 ACI/PCI CODE-319 provides structural concrete code requirements unique to design of precast concrete including pretensioned concrete.

R4.12.1.2 All requirements in the Code apply to precast systems and members unless specifically excluded. In addition, some requirements apply specifically to precast concrete. This section contains specific requirements for precast systems. Other sections of the Code also provide specific requirements, such as required concrete cover, for precast systems.

Precast systems differ from monolithic systems in that the type of restraint at supports, the location of supports, and the induced stresses in the body of the member vary during fabrication, storage, transportation, erection, and the final

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interconnected configuration. Consequently, the member design forces to be considered may differ in magnitude and direction with varying critical sections at various stages of construction. For example, a precast flexural member may be simply supported for dead load effects before continuity at the supporting connections is established and may be a continuous member for live or environmental load effects due to the moment continuity created by the connections after erection.

4.12.1.3 Design, fabrication, and construction of precast members and their connections shall include the effects of tolerances.

R4.12.1.3 For guidance on including the effects of tolerances, refer to the *PCI Design Handbook* (PCI MNL 120).

4.12.1.4 When precast members are incorporated into a structural system, the forces and deformations occurring in and adjacent to connections shall be included in the design.

4.12.1.5 Where system behavior requires in-plane loads to be transferred between the members of a precast floor or wall system, (a) and (b) shall be satisfied:

(a) In-plane load paths shall be continuous through both connections and members.
(b) Where tension loads occur, a load path of steel or steel reinforcement, with or without splices, shall be provided.

4.12.1.6 Distribution of forces that act perpendicular to the plane of precast members shall be established by analysis or test.

R4.12.1.6 Concentrated and line loads can be distributed among members provided the members have sufficient torsional stiffness and shear can be transferred across joints. Torsionally stiff members such as hollow-core or solid slabs will provide better load distribution than torsionally flexible members such as double tees with thin flanges. The actual distribution of the load depends on many factors discussed in detail in LaGue (1971), Johnson and Ghadiali (1972), Pfeifer and Nelson (1983), Stanton (1987, 1992), *PCI Manual for the Design of Hollow Core Slabs and Walls* (PCI MNL 126), Aswad and Jacques (1992), and the *PCI Design Handbook* (PCI MNL 120). Large openings can cause significant changes in distribution of forces.

4.12.2 *Prestressed concrete systems*

R4.12.2 *Prestressed concrete systems*

Prestressing, as used in the Code, may apply to pretensioning, bonded post-tensioning, or unbonded post-tensioning. All requirements in the Code apply to prestressed systems and members, unless specifically excluded. This section contains specific requirements for prestressed concrete systems. Other sections of the Code also provide specific requirements, such as required concrete cover for prestressed systems.

Creep and shrinkage effects may be greater in prestressed than in nonprestressed concrete structures because of the prestressing forces and because prestressed structures typically have less bonded reinforcement. Effects of movements

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due to creep and shrinkage may require more attention than is normally required for nonprestressed concrete. These movements may increase prestress losses.

Design of externally post-tensioned construction should consider aspects of corrosion protection and fire resistance that are applicable to this structural system.

4.12.2.1 It shall be permitted to design post-tensioned concrete members in accordance with ACI/PTI CODE-320, "Building Code Requirements for Structural Post-Tensioned Concrete—Code and Commentary."

R4.12.2.1 ACI/PTI CODE-320 provides structural concrete code requirements unique to design of post-tensioned concrete.

4.12.2.2 Design of prestressed members and systems shall be based on strength and on behavior at service conditions at all critical stages during the life of the structure from the time prestress is first applied.

4.12.2.3 Provisions shall be made for effects on adjoining construction of elastic and plastic deformations, deflections, changes in length, and rotations due to prestressing. Effects of temperature change, restraint of attached structural members, foundation settlement, creep, and shrinkage shall also be considered.

4.12.2.4 Stress concentrations due to prestressing shall be considered in design.

4.12.2.5 Effect of loss of area due to open ducts shall be considered in computing section properties before grout in post-tensioning ducts has attained design strength.

4.12.2.6 Post-tensioning tendons shall be permitted to be external to any concrete section of a member. Strength and serviceability design requirements of this Code shall be used to evaluate the effects of external tendon forces on the concrete structure.

4.12.3 *Composite concrete flexural members*

R4.12.3 *Composite concrete flexural members*

This section addresses structural concrete members, either precast or cast-in-place, prestressed or nonprestressed, consisting of concrete cast at different times intended to act as a composite member when loaded after concrete of the last stage of casting has set. All requirements in the Code apply to these members unless specifically excluded. In addition, some requirements apply specifically to composite concrete flexural members. This section contains requirements that are specific to these elements and are not covered in the applicable member chapters.

4.12.3.1 This Code shall apply to composite concrete flexural members as defined in Chapter 2.

4.12.3.2 Individual members shall be designed for all critical stages of loading.

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4.12.3.3 Members shall be designed to support all loads introduced prior to full development of design strength of composite members.

4.12.3.4 Reinforcement shall be detailed to minimize cracking and to prevent separation of individual components of composite members.

4.12.4 *Structural plain concrete systems*

4.12.4.1 The design of structural plain concrete members, both cast-in-place and precast, shall be in accordance with Chapter 14.

4.13—Construction and inspection

4.13.1 Specifications for construction execution shall be in accordance with Chapter 26.

4.13.2 Inspection during construction shall be in accordance with Chapter 26 and the general building code.

4.14—Strength evaluation of existing structures

4.14.1 Strength evaluation of existing structures shall be in accordance with Chapter 27.

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R4.13—Construction and inspection

R4.13.1 Chapter 26 has been organized to collect into one location the design information, compliance requirements, and inspection provisions from the Code that should be included in construction documents There may be other information that should be included in construction documents that is not covered in Chapter 26.

R4.14—Strength evaluation of existing structures

R4.14.1 Requirements in Chapter 27 for strength evaluation of existing structures by physical load test address the evaluation of structures subjected to gravity loads only. Chapter 27 also covers strength evaluation of existing structures by analytical evaluation, which may be used for gravity as well as other loadings such as earthquake or wind.