

An ACI Standard
An ANSI Standard

Building Code Requirements for Structural Concrete Reinforced with Glass Fiber- Reinforced Polymer (GFRP) Bars—Code and Commentary

Reported by ACI Committee 440

ACI CODE-440.11-22



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Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars—Code and Commentary

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Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars—Code and Commentary

An ACI Standard

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This Code was developed by an ANSI-approved consensus process and addresses structural systems, members, and connections, including cast-in-place, precast, nonprestressed, and composite construction. The “Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars” (“Code”) provides minimum requirements for the materials, design, and detailing of structural concrete buildings and, where applicable, nonbuilding structures reinforced with GFRP bars that conform to the requirements of ASTM D7957-22. Among the subjects covered are: design and construction for strength, serviceability, and durability; load combinations, load factors, and strength reduction factors; structural analysis methods; deflection limits; development and splicing of reinforcement; construction document information; field inspection and testing; and methods to evaluate the strength of existing structures.

Keywords: admixtures; aggregates; beam-column frame; beams (supports); cements; columns (supports); combined stress; composite construction (concrete to concrete); compressive strength; concrete; construction documents; continuity (structural); cover; curing; deflections; durability; flexural strength; floors; footings; formwork (construction); GFRP reinforcement; inspection; joints (junctions); joists; load tests (structural); loads (forces); mixture proportioning; modulus of elasticity; moments; piles; placing; precast concrete; quality control; reinforced concrete; roofs; serviceability; shear strength; spans; splicing; strength analysis; stresses; structural analysis; structural design; structural integrity; structural walls; T-beams; torsion; walls; water.

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PREFACE

This Code was developed by an ANSI-approved consensus process and addresses structural systems, members, and connections, including cast-in-place, precast, nonprestressed, and composite construction. The “Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars” (“Code”) provides minimum requirements for the materials, design, and detailing of structural concrete buildings and, where applicable, nonbuilding structures reinforced with GFRP bars that conform to the requirements of ASTM D7957-22, “Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement.” Among the subjects covered are: design and construction for strength, serviceability, and durability; load combinations, load factors, and strength reduction factors; structural analysis methods; deflection limits; development and splicing of reinforcement; construction document information; field inspection and testing; and methods to evaluate the strength of existing structures.

This Code covers the design of reinforced concrete members that are reinforced entirely with GFRP; the design of “hybrid” members with mixed types of reinforcement is outside the scope of this Code. However, this Code can be used for the design of GFRP-reinforced concrete members that are part of a structure that also includes members that are not reinforced with GFRP. In such a situation, this Code would cover the design of the GFRP-reinforced concrete members, and other suitable standards (such as ACI 318) would cover the design of other types of members in the structure. This Code covers the design of GFRP-reinforced concrete members in a structure assigned to Seismic Design Category (SDC) A. This Code also covers the design of GFRP-reinforced concrete members not designated as part of the seismic-force-resisting system in Seismic Design Categories B and C. This initial version of the Code, which has been developed from the body of GFRP-reinforced concrete research that has been published over the past 30 years, does not cover GFRP-reinforced concrete members in any structure assigned to Seismic Design Categories D, E, and F although subsequent editions of this Code are expected to incorporate additional SDCs as further research becomes available. Other topics that are not addressed in this version of the Code but are expected to be covered in subsequent editions include prestressed construction, lightweight concrete, shotcrete, connections of precast members, diaphragms, deep beams, drilled piers and caissons, brackets and corbels, methods for designing discontinuity regions using strut-and-tie theory where section-based methods do not apply, shear friction, and anchoring to concrete.

This Code is dependent on ACI 318-19 and adheres to the chapter and section numbering of ACI 318-19, with the exception of Chapter 15 in which language and numbering is dependent on ACI 318-14. This Code does not include several chapters that are addressed in ACI 318-19, specifically Chapter 12: Diaphragms, Chapter 17: Anchoring to Concrete, Chapter 18: Earthquake-Resistant Structures, and Chapter 23: Strut-and-Tie Method. These chapters have been identified as “Not Addressed” in this version of the Code, but are expected to be included in future versions of this Code as additional research becomes available. This Code also does not include Chapter 14: Plain Concrete from ACI 318-19 which has been identified as “Not Applicable” because it is not related to design with GFRP reinforcement and is not expected to be included in future versions of this Code, as ACI 318 is the applicable standard. Within chapters, the terms “out of scope” and “not applicable” are used for numbered section headings from ACI 318-19 that are not covered by this Code, while the term “intentionally left blank” is used as a place holder to maintain consistency with section numbering in situations where ACI 318-19 includes a numbered provision that is not also in this Code.

For ease of use, language in common with ACI 318 has been reproduced in this document. Provisions that are identical to ACI 318-19 are denoted with an equal sign (“=”). Accordingly, this Code follows the organizational philosophy of ACI 318, which is to present all design and detailing requirements for structural systems or for individual members in chapters devoted to those individual subjects, and to arrange the chapters in a manner that generally follows the process and chronology of design and construction. Information and procedures that are common to the design of multiple members are located in utility chapters.

Uses of the Code include adoption by reference in a general building code. The Code is written in a format that allows such reference without change to its language. Therefore, background details or suggestions for carrying out the requirements or intent of the Code provisions cannot be included within the Code itself. The Commentary is provided for this purpose. This Code can supplement a current International Code Council (ICC) building code, supplement the codes governing new and existing structures of a local jurisdiction authority, or act as a stand-alone code in a locality that has not adopted an existing building code.

Some considerations of the committee in developing the Code are discussed in the Commentary, with emphasis given to the explanation of differences in design between GFRP-reinforced concrete and steel-reinforced concrete. For example, GFRP bars do not yield; rather, they are linear elastic until failure. Design procedures in this Code account for this difference from the traditional steel-reinforced concrete design procedures adopted in ACI 318, and approach design from the perspective of deformability (the ability of a member to undergo large displacements prior to failure) rather than from the steel-reinforced concrete design focus on ductility. Consequently, this Code permits GFRP-reinforced concrete flexural members to have either tension-controlled or compression-controlled failure modes.

Furthermore, GFRP bars possess high tensile strength only in the direction of the reinforcing fibers, which affects shear strength, dowel action, and bond performance; thus, design equations for shear strength and development length are necessarily different from the equations used for steel reinforcement in ACI 318, although the design procedures themselves are similar. Other significant differences from ACI 318 occur in serviceability design for deflection and crack control. GFRP reinforcement can be as small as one-fourth that of steel reinforcement. Because the mechanical and bond properties of

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GFRP bars are more negatively impacted at elevated temperatures than are steel bars, and reports from ASTM E119 fire tests on GFRP-reinforced concrete members are not yet available, this Code is only applicable where fire-resistance ratings are not required or where approved by the building official under the alternative means and methods provisions of 1.10.1. Recommendations for increasing the fire resistance of GFRP-reinforced concrete members have been included in the Commentary. Much of the research data referenced in the Commentary is cited for the user desiring greater detail on this subject. Other documents that provide suggestions for carrying out the requirements of the Code are also cited in the Commentary.

CODE

CHAPTER 1—GENERAL

1.1—Scope of ACI CODE-440.11-22

¶1.1.1 This chapter addresses (a) through (h):

- (a) General requirements of this Code
- (b) Purpose of this Code
- (c) Applicability of this Code
- (d) Interpretation of this Code
- (e) Definition and role of the building official and the licensed design professional
- (f) Construction documents
- (g) Testing and inspection
- (h) Approval of special systems of design, construction, or alternative construction materials

1.2—General

1.2.1 ACI CODE-440.11, “Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars,” is hereafter referred to as “this Code.”

¶1.2.2 In this Code, the general building code refers to the building code adopted in a jurisdiction. When adopted, this Code forms part of the general building code.

¶1.2.3 The official version of this Code is the English language version, using inch-pound units, published by the American Concrete Institute.

¶1.2.4 In case of conflict between the official version of this Code and other versions of this Code, the official version governs.

1.2.5 This Code provides minimum requirements for the materials, design, construction, and strength evaluation of GFRP-reinforced concrete members and systems in any structure designed and constructed under the requirements of the general building code.

¶1.2.6 Modifications to this Code that are adopted by a particular jurisdiction are part of the laws of that jurisdiction, but are not a part of this Code.

¶1.2.7 If no general building code is adopted, this Code provides minimum requirements for the materials, design,

COMMENTARY

CHAPTER R1—GENERAL

R1.1—Scope of ACI CODE-440.11-22

¶R1.1.1 This Code includes provisions for the design of nonprestressed glass fiber-reinforced polymer (GFRP)-reinforced concrete used for structural purposes. This Code does not address concrete prestressed with GFRP. This Code does not cover any applications of steel reinforcement of concrete. The design of structural concrete reinforced with steel is governed by ACI 318. This Code covers the design of reinforced concrete members that are reinforced entirely with GFRP; the design of “hybrid” members with mixed types of reinforcement is outside the scope of this Code. However, this Code can be used for the design of GFRP-reinforced concrete members that are part of a structure that also includes members that are not reinforced with GFRP. Steel reinforcement may be present in GFRP-reinforced concrete members designed using this Code, but the steel reinforcement should not be considered as part of the reinforcement for that member for the purposes of strength or serviceability calculations.

This Code is a dependent code on ACI 318-19. This chapter includes a number of provisions that explain where this Code applies and how it is to be interpreted.

R1.2—General

¶R1.2.2 The American Concrete Institute recommends that this Code be adopted in its entirety.

R1.2.3 Committee 440 develops the Code in English, using inch-pound units. Based on that version, Committee 440 approved a version in English using SI units.

¶R1.2.5 This Code provides minimum requirements and exceeding these minimum requirements is not a violation of the Code.

The licensed design professional may specify project requirements that exceed the minimum requirements of this Code.

CODE

construction, and strength evaluation of members and systems in any structure within the scope of this Code.

1.3—Purpose

1.3.1 The purpose of this Code is to provide for public health and safety by establishing minimum requirements for strength, stability, serviceability, durability, and integrity of GFRP-reinforced concrete structures.

1.3.2 This Code does not address all design considerations.

1.3.3 Construction means and methods are not addressed in this Code.

1.4—Applicability

1.4.1 This Code shall apply to GFRP-reinforced concrete structures designed and constructed under the requirements of the general building code.

1.4.2 Provisions of this Code shall be permitted to be used for the assessment, repair, and rehabilitation of existing structures.

1.4.3 Applicable provisions of this Code shall be permitted to be used for structures not governed by the general building code.

1.4.4 Intentionally left blank.

1.4.5 This Code shall apply to the design of slabs cast on stay-in-place, noncomposite steel decks.

1.4.6 Intentionally left blank.

1.4.7 This Code does not apply to the design and installation of concrete piles, drilled piers, and caissons embedded in ground, except as provided in (a) and (b):

- (a) For portions of deep foundation members in air or water, or in soil incapable of providing adequate lateral restraint to prevent buckling throughout their length
- (b) For precast concrete piles supporting structures assigned to Seismic Design Categories A and B

COMMENTARY

R1.3—Purpose

R1.3.1 This Code provides a means of establishing minimum requirements for the design and construction of GFRP-reinforced concrete, as well as for acceptance of design and construction of GFRP-reinforced concrete structures by the building officials or their designated representatives.

This Code does not provide a comprehensive statement of all duties of all parties to a contract or all requirements of a contract for a project constructed under this Code.

R1.3.2 The minimum requirements in this Code do not replace sound professional judgment or the licensed design professional's knowledge of the specific factors surrounding a project, its design, the project site, and other specific or unusual circumstances to the project.

R1.4—Applicability

R1.4.2 Specific provisions for assessment, repair, and rehabilitation of existing concrete structures are provided in **ACI 562-19**. Existing structures in ACI 562 are defined as structures that are complete and permitted for use.

R1.4.3 Structures such as underground utility structures and sea walls involve design and construction requirements that are not specifically addressed by this Code. Many Code provisions, however, may be applicable for these structures if approved by the authority having jurisdiction.

R1.4.5 In its most basic application, the noncomposite steel deck serves as a form, and the concrete slab is designed to resist all loads, while in other applications the concrete slab may be designed to resist only the superimposed loads.

R1.4.7 The design and installation of concrete piles fully embedded in the ground is regulated by the general building code.

CODE

1.4.8 This Code does not apply to design and construction of slabs-on-ground unless the slab transmits vertical loads from other portions of the structure to the soil.

1.4.9 This Code does not apply to the design and construction of tanks and reservoirs.

1.4.10 This Code does not apply to composite design slabs cast on stay-in-place composite steel deck.

1.4.11 This Code does not apply to the design and construction of GFRP-reinforced lightweight concrete members and systems.

1.4.12 This Code does not apply to the design and construction of concrete prestressed with GFRP.

1.4.13 This Code does not apply to the design and construction of members for structures classified as Seismic Design Categories D through F, or to the design and construction of members that are part of the lateral-load-resisting system for structures classified as Seismic Design Categories B or C.

1.5—Interpretation

1.5.1 The principles of interpretation in this section shall apply to this Code as a whole unless otherwise stated.

1.5.2 This Code consists of chapters including text, headings, tables, figures, footnotes to tables and figures, and referenced standards.

1.5.3 The Commentary consists of a preface, introduction, commentary text, tables, figures, and cited publications. The Commentary is intended to provide contextual information, but is not part of this Code, does not provide binding requirements, and shall not be used to create a conflict with or ambiguity in this Code.

1.5.4 This Code shall be interpreted in a manner that avoids conflict between or among its provisions. Specific provisions shall govern over general provisions.

1.5.5 This Code shall be interpreted and applied in accordance with the plain meaning of the words and terms used. Specific definitions of words and terms in this Code shall be used where provided and applicable, regardless of whether other materials, standards, or resources outside of this Code provide a different definition.

1.5.6 The following words and terms in this Code shall be interpreted in accordance with (a) through (i):

COMMENTARY

R1.4.8 **ACI 360R** presents information on the design of steel-reinforced concrete slabs-on-ground, primarily industrial floors and the slabs adjacent to them. Information from ACI 360R can be used in conjunction with the guidelines found in **ACI 440.1R** for the design of slabs-on-ground that do not transmit vertical loads or from other portions of the structure to the soil.

R1.4.11 Lightweight concrete has been excluded due to a lack of experimental data on the behavior of GFRP-reinforced concrete members made with lightweight concrete.

R1.5—Interpretation

R1.5.4 General provisions are broad statements, such as a building needs to be serviceable. Specific provisions, such as explicit reinforcement distribution requirements for crack control, govern over the general provisions.

R1.5.5 ACI Concrete Terminology (**CT-21**) is the primary resource to help determine the meaning of words or terms that are not defined in the Code. Dictionaries and other reference materials commonly used by licensed design professionals may be used as secondary resources.

CODE

COMMENTARY

- (a) The word “shall” is always mandatory.
- (b) Provisions of this Code are mandatory even if the word “shall” is not used.
- (c) Words used in the present tense shall include the future.
- (d) The word “and” indicates that all of the connected items, conditions, requirements, or events shall apply.
- (e) The word “or” indicates that the connected items, conditions, requirements, or events are alternatives, at least one of which shall be satisfied.
- (f) The term “Not addressed” refers to chapters that are not included in this version of the Code but are expected to be included in future versions of this Code.
- (g) The term “Not applicable” refers to chapters and section headings in **ACI 318** that are not related to design with GFRP reinforcement.
- (h) The term “Out of scope” refers to numbered section headings from ACI 318 that are not covered by this Code.
- (i) The term “Intentionally left blank” is used as a place holder to maintain consistency with section numbering in ACI 318.

1.5.7 In any case in which one or more provisions of this Code are declared by a court or tribunal to be invalid, that ruling shall not affect the validity of the remaining provisions of this Code, which are severable. The ruling of a court or tribunal shall be effective only in that court’s jurisdiction, and shall not affect the content or interpretation of this Code in other jurisdictions.

1.5.8 If conflicts occur between provisions of this Code and those of standards and documents referenced in **Chapter 3**, this Code shall apply.

1.6—Building official

1.6.1 All references in this Code to the building official shall be understood to mean persons who administer and enforce this Code.

1.6.2 Actions and decisions by the building official affect only the specific jurisdiction and do not change this Code.

1.6.3 The building official shall have the right to order testing of any materials used in concrete construction to determine if materials are of the quality specified.

1.7—Licensed design professional

1.7.1 All references in this Code to the licensed design professional shall be understood to mean the engineer in either 1.7.1.1 or 1.7.1.2.

1.7.1.1 The licensed design professional responsible for, and in charge of, the structural design work.

1.7.1.2 A specialty engineer to whom a specific portion of the structural design work has been delegated subject to the conditions of (a) and (b).

R1.5.7 This Code addresses numerous requirements that can be implemented fully without modification if other requirements in this Code are determined to be invalid. This severability requirement is intended to preserve this Code and allow it to be implemented to the extent possible following legal decisions affecting one or more of its provisions.

R1.6—Building official

R1.6.1 Building official is defined in **2.3**.

R1.6.2 Only the American Concrete Institute has the authority to alter or amend this Code.

R1.7—Licensed design professional

R1.7.1 Licensed design professional is defined in **2.3**.

CODE

(a) The authority of the specialty engineer shall be explicitly limited to the delegated design work.

(b) The portion of design work delegated shall be well defined such that responsibilities and obligations of the parties are apparent.

1.8—Construction documents and design records

1.8.1 The licensed design professional shall provide in the construction documents the information required in **Chapter 26** and that required by the jurisdiction.

1.8.2 Calculations pertinent to design shall be filed with the construction documents if required by the building official. Analyses and designs using computer programs shall be permitted provided design assumptions, user input, and computer-generated output are submitted. Model analysis shall be permitted to supplement calculations.

1.9—Testing and inspection

1.9.1 Concrete materials shall be tested in accordance with the requirements of Chapter 26.

1.9.2 Concrete construction shall be inspected in accordance with the general building code and in accordance with Chapter 26.

1.9.3 Inspection records shall include information required in Chapter 26.

1.10—Approval of special systems of design, construction, or alternative construction materials

1.10.1 Sponsors of any system of design, construction, or alternative construction materials within the scope of this Code, the adequacy of which has been shown by successful use or by analysis or test, but which does not conform to or is not covered by this Code, shall have the right to present the data on which their design is based to the building official or to a board of examiners appointed by the building official.

COMMENTARY

R1.7.1.2(b) A portion of the design work may be delegated to a specialty engineer during the design phase or to the contractor in the construction documents. An example of design work delegated to a specialty engineer or contractor is precast concrete.

R1.8—Construction documents and design records

R1.8.1 The provisions of Chapter 26 for preparing project drawings and specifications are, in general, consistent with those of most general building codes. Additional information may be required by the building official.

R1.8.2 Documented computer output is acceptable instead of manual calculations. The extent of input and output information required will vary according to the specific requirements of individual building officials. However, if a computer program has been used, only skeleton data should normally be required. This should consist of sufficient input and output data and other information to allow the building official to perform a detailed review and make comparisons using another program or manual calculations. Input data should be identified as to member designation, applied loads, and span lengths. The related output data should include member designation and the shears, moments, and reactions at key points in the span. For column design, it is desirable to include moment magnification factors in the output where applicable.

The Code permits model analysis to be used to supplement structural analysis and design calculations. Documentation of the model analysis should be provided with the related calculations. Model analysis should be performed by an individual having experience in this technique.

R1.10—Approval of special systems of design, construction, or alternative construction materials

R1.10.1 New methods of design, new materials, and new uses of materials should undergo a period of development before being covered in a code. Hence, good systems or components might be excluded from use by implication if means were not available to obtain acceptance.

For special systems considered under this Code, specific tests, load factors, deflection limits, and other pertinent

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cial. This board shall be composed of competent engineers and shall have authority to investigate the data so submitted, require tests, and formulate rules governing design and construction of such systems to meet the intent of this Code. These rules, when approved by the building official and promulgated, shall be of the same force and effect as the provisions of this Code.

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requirements should be set by the board of examiners and should be consistent with the intent of the Code.

The provisions of this section do not apply to model tests used to supplement calculations under 1.8.2 or to strength evaluation of existing structures under **Chapter 27**.

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CHAPTER 2—NOTATION AND TERMINOLOGY

2.1—Scope

2.1.1 This chapter defines notation and terminology used in this Code.

2.2—Notation

- A_1 = loaded area for consideration of bearing strength, in.²
- A_2 = area of the lower base of the largest frustum of a pyramid, cone, or tapered wedge contained wholly within the support and having its upper base equal to the loaded area. The sides of the pyramid, cone, or tapered wedge shall be sloped one vertical to two horizontal, in.²
- A_{ch} = cross-sectional area of a member measured to the outside edges of transverse reinforcement, in.²
- A_{cp} = area enclosed by outside perimeter of concrete cross section, in.²
- A_f = area of GFRP longitudinal tension reinforcement, in.²
- $A_{f,min}$ = minimum area of GFRP flexural reinforcement, in.²
- $A_{f,provided}$ = provided area of GFRP reinforcement to resist flexure, in.²
- $A_{f,required}$ = required area of GFRP reinforcement to resist flexure, in.²
- A_{ft} = total area of GFRP longitudinal reinforcement to resist torsion, in.²
- $A_{ft,min}$ = minimum area of GFRP longitudinal reinforcement to resist torsion, in.²
- A_{ft} = area of one leg of a closed GFRP stirrup, or tie resisting torsion within spacing s , in.²
- A_{fv} = area of GFRP shear reinforcement within spacing s , in.²
- $A_{fv,min}$ = minimum area of GFRP shear reinforcement within spacing s , in.²
- A_{fw} = total area of GFRP longitudinal reinforcement, in.²
- A_g = gross area of concrete section, in.² For a hollow section, A_g is the area of the concrete only and does not include the area of the void(s)
- A_o = gross area enclosed by torsional shear flow path, in.²
- A_{oh} = area enclosed by centerline of the outermost closed transverse torsional reinforcement, in.²
- a = depth of equivalent rectangular stress block, in.
- B_n = nominal bearing strength, lb

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CHAPTER R2—NOTATION AND TERMINOLOGY

R2.2—Notation

- A_b = nominal area of an individual bar, in.²
- A_{fb} = total area of GFRP longitudinal tension reinforcement for which the design rupture strain in the extreme tension layer of the GFRP longitudinal reinforcement occurs simultaneously with crushing of the concrete in the extreme compression fiber of the cross section, in.²

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COMMENTARY

B_u	= factored bearing load, lb
b	= dimension of the column section perpendicular to the direction under consideration, in.
b_1	= dimension of the critical section b_o measured in the direction of the span for which moments are determined, in.
b_2	= dimension of the critical section b_o measured in the direction perpendicular to b_1 , in.
b_f	= effective flange width, in.
b_o	= perimeter of critical section for two-way shear in slabs and footings, in.
b_{slab}	= effective slab width, in.
b_t	= width of that part of cross section containing the closed stirrups resisting torsion, in.
b_v	= width of cross section at contact surface being investigated for horizontal shear, in.
b_w	= web width or diameter of circular section, in.
C_E	= environmental reduction factor
C_m	= factor relating actual moment diagram to an equivalent uniform moment diagram
c	= distance from extreme compression fiber to neutral axis, in.
c_1	= dimension of rectangular or equivalent rectangular column, capital, or bracket measured in the direction of the span for which moments are being determined, in.
c_2	= dimension of rectangular or equivalent rectangular column, capital, or bracket measured in the direction perpendicular to c_1 , in.
c_b	= lesser of: (a) the distance from center of a bar to nearest concrete surface, and (b) one-half the center-to-center spacing of bars being developed, in.
c_c	= clear cover of reinforcement, in.
D	= effect of service dead load
D_s	= effect of superimposed dead load
D_w	= effect of self-weight dead load of the concrete structural system
d	= distance from extreme compression fiber to centroid of longitudinal tension reinforcement, in.
d_{agg}	= nominal maximum size of coarse aggregate, in.
d_b	= nominal diameter of bar, in.
d_c	= thickness of concrete cover measured from extreme tension fiber to center of bar location closest thereto, in.
d_{pile}	= diameter of pile at footing base, in.
E	= effect of horizontal and vertical earthquake-induced forces
E_c	= modulus of elasticity of concrete, psi
E_{cb}	= modulus of elasticity of beam concrete, psi
E_{cs}	= modulus of elasticity of slab concrete, psi

b = width of compression face of member, in.

c_{bal} = distance from extreme compression fiber to neutral axis at the balanced condition, in.

d_{pa} = depth of drop panel or insulation protecting GFRP reinforcement from fire, in.

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E_f	= modulus of elasticity of GFRP reinforcement, psi
EI	= flexural stiffness of member, in. ² -lb
$(EI)_{eff}$	= effective flexural stiffness of member, in. ² -lb
F	= effect of service load due to fluids with well-defined pressures and maximum heights
f'_c	= specified compressive strength of concrete, psi
$\sqrt{f'_c}$	= square root of specified compressive strength of concrete, psi
f_f	= tensile stress in the GFRP reinforcement at factored moment M_u , psi
f_{fb}	= design tensile strength of bent portion of GFRP reinforcement, psi; see 20.2.2.4
f_{fb}^*	= guaranteed tensile strength of bent portion of GFRP reinforcement, psi
f_{fd}	= tensile design strength in the GFRP longitudinal reinforcement for columns corresponding to a strain of 0.01, psi
f_{fr}	= tensile stress in the GFRP reinforcement required to develop the full nominal sectional capacity, psi
f_{fs}	= tensile stress in GFRP reinforcement at service loads, psi
$f_{fs,sus}$	= tensile stress in GFRP longitudinal reinforcement due to sustained service loads, psi
f_{ft}	= design tensile strength of GFRP transverse reinforcement, psi; see 20.2.2.6
f_{fu}	= design tensile strength of GFRP longitudinal reinforcement, psi; see 20.2.2.3
f_{fu}^*	= guaranteed tensile strength of GFRP longitudinal reinforcement, psi
f_r	= modulus of rupture of concrete, psi
H	= effect of service load due to lateral earth pressure, ground water pressure, or pressure of bulk materials, lb
h	= overall thickness, height, or depth of member, in.
I	= moment of inertia of section about centroidal axis, in. ⁴
I_b	= moment of inertia of gross section of beam about centroidal axis, in. ⁴
I_{cr}	= moment of inertia of cracked section transformed to concrete, in. ⁴
I_e	= effective moment of inertia for calculation of deflection, in. ⁴
I_{e+}	= effective moment of inertia at location of maximum positive moment for calculation of deflection, in. ⁴
I_{e1-}	= effective moment of inertia at location of maximum negative moment at the near end of the span for calculation of deflection, in. ⁴
I_{e2-}	= effective moment of inertia at location of maximum negative moment at the far end of the span for calculation of deflection, in. ⁴
I_f	= moment of inertia of GFRP reinforcement about centroidal axis of member cross section, in. ⁴



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

k = effective length factor for compression members
 k_b = bond-dependent coefficient
 k_{cr} = ratio of the depth of the elastic cracked section neutral axis to the effective depth

L = effect of service live load
 L_r = effect of service roof live load
 ℓ = span length of beam or one-way slab; clear projection of cantilever, in.
 ℓ_1 = length of span in direction that moments are being determined, measured center-to-center of supports, in.
 ℓ_2 = length of span in direction perpendicular to ℓ_1 , measured center-to-center of supports, in.
 ℓ_a = additional embedment length beyond centerline of support or point of inflection, in.
 ℓ_c = length of compression member, measured center-to-center of the joints, in.
 ℓ_d = development length in tension of bar, in.
 ℓ_{dc} = development length in compression of bars, in.
 ℓ_{dh} = development length in tension of bar with a standard hook, measured from outside end of hook, point of tangency, toward critical section, in.
 ℓ_{ext} = straight extension at the end of a standard hook, in.

ℓ_n = length of clear span measured face-to-face of supports, in.

ℓ_{st} = tension lap splice length, in.
 ℓ_u = unsupported length of column or wall, in.

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

M_1 = lesser factored end moment on a compression member, in.-lb

M_{1ns} = factored end moment on a compression member at the end at which M_1 acts, due to loads that cause no appreciable sidesway, calculated using a first-order elastic frame analysis, in.-lb

M_{1s} = factored end moment on compression member at the end at which M_1 acts, due to loads that cause appreciable sidesway, calculated using a first-order elastic frame analysis, in.-lb

M_2 = greater factored end moment on a compression member. If transverse loading occurs between

K_t = torsional stiffness of member; moment per unit rotation

$k_{cr,rect}$ = ratio of depth of elastic cracked section neutral axis to the effective depth for a rectangular cross section

ℓ_{in} = length of insulated area, in.

ℓ_{pa} = length of GFRP reinforcement protected from fire, in.

ℓ_{un} = length of GFRP reinforcement at anchorage not exposed to fire, in.

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COMMENTARY

	supports, M_2 is taken as the largest moment occurring in member. Value of M_2 is always positive, in.-lb
$M_{2,min}$	= minimum value of M_2 , in.-lb
M_{2ns}	= factored end moment on compression member at the end at which M_2 acts, due to loads that cause no appreciable sidesway, calculated using a first-order elastic frame analysis, in.-lb
M_{2s}	= factored end moment on compression member at the end at which M_2 acts, due to loads that cause appreciable sidesway, calculated using a first-order elastic frame analysis, in.-lb
M_a	= maximum moment in member due to service loads at stage deflection is calculated, 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_s	= moment due to total service loads, in.-lb
M_{sc}	= factored slab moment that is resisted by the column at a joint, in.-lb
$M_{s,sus}$	= moment due to sustained service loads, in.-lb
M_u	= factored moment at section, in.-lb
N_u	= factored axial force normal to cross section occurring simultaneously with V_u or T_u ; to be taken as positive for compression and negative for tension, lb
P_c	= critical buckling load, lb
P_n	= nominal axial compressive strength of member, lb
$P_{n,max}$	= maximum nominal axial compressive strength of a member, lb
P_{nt}	= nominal axial tensile strength of member, lb
$P_{nt,max}$	= maximum nominal axial tensile strength of member, lb
P_o	= nominal axial strength at zero eccentricity, lb
P_u	= factored axial force; to be taken as positive for compression and negative for tension, lb
p_{cp}	= outside perimeter of concrete cross section, in.
p_h	= perimeter of centerline of outermost closed transverse torsional reinforcement, in.
Q	= stability index for a story
q_u	= factored load per unit area, lb/ft ²
R	= cumulative load effect of service rain load
r	= radius of gyration of cross section, in.
S	= effect of service snow load
S_n	= nominal moment, shear, axial, torsional, or bearing strength

n_f = ratio of modulus of elasticity of GFRP bars to modulus of elasticity of concrete

$P\delta$ = secondary moment due to individual member slenderness, in.-lb

$P\Delta$ = secondary moment due to lateral deflection, in.-lb

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COMMENTARY

s	= center-to-center spacing of items, such as longitudinal reinforcement or transverse reinforcement, in.	
s_w	= clear distance between adjacent webs, in.	
T	= cumulative effects of service temperature, creep, shrinkage, differential settlement, and shrinkage-compensating concrete	
T_{cr}	= cracking torsional moment, in.-lb	
T_n	= nominal torsional moment strength, in.-lb	
T_t	= total test load, lb	
T_{th}	= threshold torsional moment, in.-lb	
T_u	= factored torsional moment at section, in.-lb	
		t = wall thickness of hollow section, in.
t_f	= thickness of flange, in.	
U	= strength of a member or cross section required to resist factored loads or related internal moments and forces in such combinations as stipulated in this Code	
V_c	= nominal shear strength provided by concrete, lb	
V_f	= nominal shear strength provided by GFRP shear reinforcement, lb	
V_n	= nominal shear strength, lb	
V_{nh}	= nominal horizontal shear strength, lb	
V_u	= factored shear force at section, lb	
V_{us}	= factored horizontal shear in a story, lb	
v_c	= stress corresponding to nominal two-way shear strength provided by concrete, psi	
v_n	= equivalent concrete stress corresponding to nominal two-way shear strength of slab or footing, psi	
v_u	= maximum factored two-way shear stress calculated around the perimeter of a given critical section, psi	
v_{uv}	= factored shear stress on the slab critical section for two-way action due to gravity loads without moment transfer, psi	
W	= effect of wind load	
w_c	= density, unit weight, of normalweight concrete, lb/ft ³	
w_u	= factored load per unit length of beam or one-way slab, lb/in.	
y_t	= distance from centroidal axis of gross section, neglecting reinforcement, to tension face, in.	
α_f	= ratio of flexural stiffness of beam section to flexural stiffness of a width of slab bounded laterally by centerlines of adjacent panels, if any, on each side of the beam	
β	= ratio of long to short dimensions: clear spans for two-way slabs, sides of column, concentrated load or reaction area; or sides of a footing	
β_1	= factor relating depth of equivalent rectangular compressive stress block to depth of neutral axis	
β_b	= ratio of area of reinforcement cut off to total area of tension reinforcement at section	
β_{cr}	= ratio of distance from elastic cracked section neutral axis to extreme tension fiber to distance	

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	from elastic cracked section neutral axis to centroid of tensile reinforcement
β_{dns}	= ratio used to account for reduction of stiffness of columns due to sustained axial loads
β_{ds}	= ratio of maximum factored sustained shear within a story to the maximum factored shear in that story associated with the same load combination
γ	= parameter to account for the variation in stiffness along the length of the flexural member
γ_f	= factor used to determine the fraction of M_{sc} transferred by slab flexure at slab-column connections
γ_s	= factor used to determine the portion of reinforcement located in center band of footing
γ_v	= factor used to determine the fraction of M_{sc} transferred by eccentricity of shear at slab-column connections
Δ_1	= maximum deflection, during first load test, measured 24 hours after application of the full test load, in.
Δ_2	= maximum deflection, during second load test, measured 24 hours after application of the full test load. Deflection is measured relative to the position of the structure at the beginning of the second load test, in.
Δ_o	= relative lateral deflection between the top and bottom of a story due to V_{us} , in.
δ	= moment magnification factor used to reflect effects of member curvature between ends of a compression member
δ_s	= moment magnification factor used for frames not braced against sidesway, to reflect lateral drift resulting from lateral and gravity loads
ϵ_{ft}	= net tensile strain in extreme layer of GFRP longitudinal tension reinforcement at nominal strength, excluding strains due to creep, shrinkage, and temperature
ϵ_{fu}	= design rupture strain of GFRP reinforcement; see 20.2.2.5
ϵ_{fu}^*	= guaranteed rupture strain of GFRP longitudinal reinforcement
ϕ	= strength reduction factor
λ_s	= factor used to modify shear strength based on the effects of member depth, commonly referred to as the size effect factor
λ_{Δ}	= multiplier used for additional deflection due to long-term effects
ξ	= time-dependent factor for sustained load
ρ_f	= ratio of A_f to bd
ρ_{fb}	= GFRP reinforcement ratio producing balanced strain conditions

ϵ_c	= strain in concrete at extreme compression fiber
ϵ_{cu}	= maximum usable strain at extreme concrete compression fiber

ϕ_K	= stiffness reduction factor
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COMMENTARY

ρ_{fl} = ratio of area of distributed GFRP longitudinal reinforcement to gross concrete area perpendicular to that reinforcement

ρ_{ft} = ratio of area of distributed GFRP transverse reinforcement to gross concrete area perpendicular to that reinforcement

ρ_s = ratio of volume of spiral reinforcement to total volume of core confined by the spiral, measured out-to-out of spirals

ψ_t = factor used to modify development length for casting location in tension

ρ_{fv} = ratio of the area of GFRP shear reinforcement to the product of web width and GFRP shear reinforcement spacing

θ = angle between compression diagonal and the tension chord of the members

2.3—Terminology

admixture—material other than water, aggregate, cementitious materials, and fiber reinforcement used as an ingredient, which is added to grout, mortar, or concrete, either before or during its mixing to modify the freshly mixed, setting, or hardened properties of the mixture.

aggregate—granular material, such as sand, gravel, crushed stone, and iron blast-furnace slag, or recycled aggregates including crushed hydraulic cement concrete, used with a cementing medium to form concrete or mortar.

alternative cement—an inorganic cement that can be used as a complete replacement for portland cement or blended hydraulic cement, and that is not covered by applicable specifications for portland or blended hydraulic cements.

anchor—an element either cast into concrete or post-installed into a hardened concrete member and used to transmit applied loads to the concrete.

anchor bolt—a bolt or stud, headed or threaded, cast in place, grouted in place, or drilled and fastened into existing concrete either by expansion or by chemical adhesives.

anchorage length—length over which force is transferred by bond stress between the GFRP reinforcement and the concrete.

area of GFRP—the nominal cross-sectional area of the GFRP reinforcement calculated using the nominal bar diameter.

balanced moment—moment capacity at simultaneous crushing of concrete and rupture of the extreme layer of GFRP tension reinforcement.

balanced reinforcement—an amount and distribution of GFRP reinforcement in a flexural member such that in strength design, the extreme layer of GFRP tensile reinforcement reaches its design rupture strain simultaneously with

R2.3—Terminology

ACI Concrete Terminology (CT-21) is the primary resource for the meaning of terms that are not defined for general use in this Code.

aggregate—The definition of recycled materials in ASTM C33 is very broad and is likely to include materials that would not be expected to meet the intent of the provisions of this Code for use in structural concrete. Use of recycled aggregates, including crushed hydraulic-cement concrete in structural concrete, requires additional precautions. Refer to 26.4.1.2.1(c).

alternative cements—alternative cements are described in the references listed in R26.4.1.1.1(b). Refer to 26.4.1.1.1(b) for precautions when using these materials in concrete covered by this Code.

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the concrete in compression reaching its assumed crushing strain of 0.003.

bar—a long, slender structural element used to reinforce concrete. In this Code, bars are normally composed of GFRP.

beam—member subjected primarily to flexure and shear, with or without axial force or torsion; beams in a moment frame that forms part of the lateral-force-resisting system are predominantly horizontal members; a girder is a beam.

bent bar—a GFRP reinforcing bar factory formed to a prescribed bent shape. (See also **hook**, **hooked bar**, **stirrup**, and **tie**.)

boundary element—portion along wall and diaphragm edge, including edges of openings, strengthened by longitudinal and transverse reinforcement.

building official—term used to identify the authority having jurisdiction or individual charged with administration and enforcement of provisions of the building code. Such terms as building commissioner or building inspector are variations of the title, and the term “building official” as used in this Code, is intended to include those variations, as well as others that are used in the same sense.

cementitious materials—materials that have cementing value if used in grout, mortar, or concrete, including portland cement, blended hydraulic cements, expansive cement, fly ash, raw or calcined natural pozzolans, slag cement, and silica fume, but excluding alternative cements.

collector—element that acts in axial tension or compression to transmit forces between a diaphragm and a vertical element of the lateral-force-resisting system.

column—member, usually vertical or predominantly vertical, used primarily to support axial compressive load, but that can also resist moment, shear, or torsion. Columns used as part of a lateral-force-resisting system resist combined axial load, moment, and shear. See also **moment frame**.

column capital—enlargement of the top of a concrete column located directly below the slab or drop panel that is cast monolithically with the column.

compliance requirements—construction-related code requirements directed to the contractor to be incorporated into construction documents by the licensed design professional, as applicable.

composite concrete flexural members—concrete flexural members of precast or cast-in-place concrete elements, constructed in separate placements but connected so that all elements respond to loads as a unit.

compression-controlled section—cross section in which the net tensile strain in the extreme tension reinforcement at nominal strength is less than or equal to the compression-controlled strain limit.

compression-controlled strain limit—net tensile strain of $0.8\epsilon_{fu}$ which corresponds to a GFRP reinforcement ratio of $1.4\rho_{fb}$.

concrete—mixture of portland cement or any other cementitious material, fine aggregate, coarse aggregate, and water, with or without admixtures.

COMMENTARY

bent bar—GFRP bars are not field bent.

cementitious materials—Cementitious materials permitted for use in this Code are addressed in 26.4.1.1. Fly ash, raw or calcined natural pozzolan, slag cement, and silica fume are considered supplementary cementitious materials.

compliance requirements—Although primarily directed to the contractor, the compliance requirements are also commonly used by others involved with the project.

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COMMENTARY

concrete, lightweight—concrete containing lightweight aggregate and having an equilibrium density, as determined by [ASTM C567](#), between 90 and 115 lb/ft³.

concrete, nonprestressed—reinforced concrete with at least the minimum amount of nonprestressed GFRP reinforcement and no prestressed reinforcement.

concrete, normalweight—concrete containing only coarse and fine aggregates that conform to [ASTM C33](#) and having a density greater than 135 lb/ft³.

concrete, precast—structural concrete element cast elsewhere than its final position in the structure.

concrete, prestressed—reinforced concrete in which internal stresses have been introduced by prestressed reinforcement to reduce potential tensile stresses in concrete resulting from loads, and for two-way slabs, with at least the minimum amount of prestressed reinforcement.

concrete, reinforced—structural concrete reinforced with at least the minimum amount of nonprestressed reinforcement, prestressed reinforcement, or both, as specified in this Code.

concrete, steel-reinforced—structural concrete reinforced entirely with steel reinforcement conforming to requirements of Chapter 20 in [ACI 318-19](#).

concrete strength, specified compressive (f'_c)—compressive strength of concrete used in design and evaluated in accordance with provisions of this Code, psi; wherever the quantity f'_c is under a radical sign, the square root of numerical value only is intended, and the result has units of psi.

connection—region of a structure that joins two or more members; a connection also refers to a region that joins members of which one or more is precast.

construction documents—written and graphic documents and specifications prepared or assembled for describing the location, design, materials, and physical characteristics of the elements of a project necessary for obtaining a building permit and construction of the project.

continuous closed stirrup—stirrup manufactured by wrapping continuous, wet fibers around a jig or mandrel to form the desired closed shape and eliminate the need for lapped open stirrups or hooks.

continuous closed tie—tie manufactured by wrapping continuous, wet fibers around a jig or mandrel to form the desired closed shape and eliminate the need for lapped open ties.

contraction joint—formed, sawed, or tooled groove in a concrete structure to create a weakened plane and regulate the location of cracking resulting from the dimensional change of different parts of the structure.

cover, specified concrete—distance between the outermost surface of embedded reinforcement and the closest outer surface of the concrete.

creep rupture—breakage of a material under sustained loading at stresses less than the tensile strength.

crosstie—a continuous GFRP reinforcing bar having standard hooks with a bend not less than 90 degrees with at

concrete, normalweight—normalweight concrete typically has a density (unit weight) between 135 and 160 lb/ft³ and is normally taken as 145 to 150 lb/ft³.

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least a $12d_b$ extension at both ends. The hooks shall engage peripheral longitudinal bars.

cutoff point—point where reinforcement is terminated.

deformability—the ability of a member to undergo large displacements prior to failure.

design information—project-specific information to be incorporated into construction documents by the licensed design professional, as applicable.

design load combination—combination of factored loads and forces.

development length—length of embedded reinforcement required to develop the design strength of reinforcement at a critical section.

discontinuity—abrupt change in geometry or loading.

dowel—(1) a reinforcing bar intended to transmit tension, compression, or shear through a construction joint; (2) smooth bar acting as a load transfer device between concrete slabs where expansion and contraction movement along the main dowel axis is not inhibited.

drop panel—projection below the slab used to reduce the amount of negative reinforcement over a column or the minimum required slab thickness, and to increase the slab shear strength.

durability—ability of a structure or member to resist deterioration that impairs performance or limits service life of the structure in the relevant environment considered in design.

effective depth of section—distance measured from extreme compression fiber to centroid of longitudinal tension reinforcement.

effective stiffness—stiffness of a structural member accounting for cracking, creep, and other nonlinear effects.

embedment length—length of embedded reinforcement provided beyond a critical section.

embedments—items embedded in concrete, excluding reinforcement as defined in Chapter 20. Reinforcement or anchors connected to the embedded item to develop the strength of the assembly, are considered part of the embedment.

embedments, pipe—embedded pipes, conduits, and sleeves.

environmental reduction factor—a factor applied to guaranteed GFRP reinforcing bar material properties in design equations to account for potential change in material properties resulting from exposure to the concrete environment.

extreme tension reinforcement—layer of reinforcement that is the farthest from the extreme compression fiber.

fiber content—the amount of fiber present in a composite.

fiber roving—parallel bundle of continuous fibers with little or no twist.

fiber-reinforced polymer (FRP) bar—composite material formed into a long, slender structural shape suitable

fiber content is typically measured by the fiber volume fraction, which is the ratio of the volume of the fibers to the volume of the composite; alternatively, fiber content can also be measured by the fiber weight fraction, which is the ratio of the weight of the fibers to the weight of the composite.

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for the internal reinforcement of concrete and consisting primarily of longitudinal unidirectional fibers bound and shaped by a rigid polymer resin material.

finite element analysis—a numerical modeling technique in which a structure is divided into a number of discrete elements for analysis.

fire-protected embedment zone—in fire protection, the region at the end of the member that is not directly exposed to fire or is protected from exposure to fire by additional cover concrete or externally applied insulation.

GFRP-reinforced concrete—concrete in which GFRP reinforcement is used as internal reinforcement.

GFRP reinforcement—glass fiber reinforced polymer reinforcement meeting the requirements of **ASTM D7957**.

GFRP structural profile—structural GFRP shape of constant cross section, manufactured by the pultrusion process.

head—a separate piece of any shape firmly attached to the end of a bar, or a protuberance of the bar itself at the end, used to anchor the reinforcing bar in concrete.

headed GFRP bars—GFRP reinforcing bars with heads attached at one or both ends.

helical wrapping—a surface treatment for GFRP reinforcing bars consisting of a glass roving or other fiber, which is applied by a stationary winding operation as the GFRP reinforcing bar is simultaneously pulled in the longitudinal direction during manufacture. (See also **surface enhancement**).

insert—anything other than reinforcement that is rigidly positioned within a concrete form for permanent embedment in the hardened concrete.

inspection—observation, verification, and required documentation of the materials, installation, fabrication, erection, or placement of components and connections to determine compliance with construction documents and referenced standards.

inspection, continuous—the full-time observation, verification, and required documentation of work in the area where the work is being performed.

inspection, periodic—part-time or intermittent observation, verification, and required documentation of work in the area where the work is being performed.

isolation joint—separation between adjoining parts of a concrete structure, usually a vertical plane at a designed location such as to interfere least with performance of the structure, yet such as to allow relative movement in three directions and avoid formation of cracks elsewhere in the concrete, and through which all or part of the bonded reinforcement is interrupted.

joint—portion of structure common to intersecting members.

lap splice—a connection of reinforcing bars made by lapping the ends of bars.

licensed design professional—an individual who is licensed to practice structural design as defined by the statutory requirements of the professional licensing laws of the

licensed design professional—May also be referred to as “registered design professional” in other documents. A licensed design professional in responsible charge of the

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state or jurisdiction in which the project is to be constructed, and who is in responsible charge of the structural design.

load—forces or other actions that result from the weight of all building materials, occupants, and their possessions, environmental effects, differential movement, and restrained dimensional changes; permanent loads are those loads in which variations over time are rare or of small magnitude; all other loads are variable loads.

load, dead—(a) the weights of the members, supported structure, and permanent attachments or accessories that are likely to be present on a structure in service; or (b) loads meeting specific criteria found in the general building code; without load factors.

load, factored—load, multiplied by appropriate load factors.

load, live—(a) load that is not permanently applied to a structure but is likely to occur during the service life of the structure (excluding environmental loads); or (b) loads meeting specific criteria found in the general building code; without load factors.

load, self-weight dead—weight of the structural system, including the weight of any bonded concrete topping.

load, service—all loads, static or transitory, imposed on a structure or element thereof, during the operation of a facility, without load factors.

load, superimposed dead—dead loads other than the self-weight that are present or considered in the design.

load effects—forces and deformations produced in structural members by applied loads or restrained volume changes.

load path—sequence of members and connections designed to transfer the factored loads and forces in such combinations as are stipulated in this Code, from the point of application or origination through the structure to the final support location or the foundation.

mat—an assembly of reinforcement composed of two or more layers of bars placed at angles to each other and secured together.

mechanical anchorage—any mechanical device capable of developing the specified strength of the reinforcement without damage to the concrete.

modular ratio—the ratio of modulus of elasticity of reinforcement to that of concrete.

modulus of elasticity—ratio of normal stress to corresponding strain for tensile or compressive stresses below proportional limit of material.

moment frame—frame in which beams, slabs, columns, and joints resist forces predominantly through flexure, shear, and axial force; beams or slabs are predominantly horizontal or nearly horizontal; columns are predominantly vertical or nearly vertical.

negative reinforcement—reinforcement for negative moment.

net tensile strain—the tensile strain at nominal strength exclusive of strains due to creep, shrinkage, and temperature.

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design work is often referred to as “the engineer of record” (EOR).

loads—Numerous definitions for loads are given as the Code contains requirements that are to be met at various load levels. The terms “dead load” and “live load” refer to the unfactored, sometimes called “service” loads specified or defined by the general building code. Service loads (loads without load factors) are to be used where specified in the Code to proportion or investigate members for adequate serviceability. Loads used to proportion a member for adequate strength are defined as factored loads. Factored loads are service loads multiplied by the appropriate load factors for required strength except Wind and Earthquake which are already specified as strength loads in [ASCE/SEI 7](#). The factored load terminology clarifies where the load factors are applied to a particular load, moment, or shear value as used in the Code provisions.

load effects—Stresses and strains are directly related to forces and deformations and are considered load effects.

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one-way construction—members designed to be capable of supporting all loads through bending in a single direction; see also **two-way construction**.

pedestal—member with a ratio of height-to-least lateral dimension less than or equal to 3 used primarily to support axial compressive load; for a tapered member, the least lateral dimension is the average of the top and bottom dimensions of the smaller side.

percentage of reinforcement—ratio of nominal cross-sectional area of reinforcement to the effective cross-sectional area of a member, expressed as a percentage.

pullout failure—failure mode in which the reinforcement pulls out of the concrete without development of the required design strength.

pultrusion—continuous process for manufacturing composites that have a constant cross-sectional shape. The process consists of pulling a fiber-reinforcing material through a resin impregnation bath and through a shaping die, where the resin is subsequently cured.

reinforcement, bond-critical—in fire performance, GFRP reinforcement which relies upon the bond of the GFRP bars to concrete for strength in zones directly exposed to fire.

reinforcement, non-bond-critical—in fire performance, GFRP reinforcement that does not rely upon the bond of the GFRP bars to concrete in zones directly exposed to fire for strength of the member in fire.

reinforcement, nonprestressed—bonded reinforcement that is not prestressed.

reliability index—measure of the probability of failure.

roof live load—a load on a roof produced: (a) during maintenance by workers, equipment, and materials, and (b) during the life of the structure by movable objects, such as planters or other similar small decorative appurtenances that are not occupancy related; or loads meeting specific criteria found in the general building code; without load factors.

sand-coated bar—GFRP bar to which a sand coating has been applied to increase bond strength.

Seismic Design Category—classification assigned to a structure based on its occupancy category and the severity of the design earthquake ground motion at the site, as defined by the general building code. Also denoted by the abbreviation SDC.

seismic-force-resisting system—portion of the structure designed to resist earthquake effects required by the general building code using the applicable provisions and load combinations.

service temperature—highest ambient temperature expected to be experienced by a structure or structural member under intended occupancy and use.

shear cap—projection below the slab used to increase the slab shear strength.

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one-way construction—Joists, beams, girders, and some slabs and foundations are considered one-way construction.

reinforcement, non-bond-critical—In most cases, non-bond-critical reinforcement is the reinforcement that is anchored in a fire-protected embedment zone. Spiral reinforcement is an example of non-bond-critical reinforcement that does not rely on anchorage in a fire-protected embedment zone, as the continuity of the spiral eliminates reliance on bond with the concrete to develop strength.

reliability index—larger reliability index values indicate lower probability of failure.

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shotcrete—mortar or concrete placed pneumatically by high velocity projection from a nozzle onto a surface.

slip—movement occurring between reinforcement and concrete, indicating loss of bond.

spacing—center-to-center distance between adjacent items, such as longitudinal reinforcement or transverse reinforcement.

spacing, clear—least dimension between the outermost surfaces of adjacent items.

span length—distance between supports.

specialty engineer—a licensed design professional to whom a specific portion of the design work has been delegated.

spiral reinforcement—continuously wound reinforcement in the form of a cylindrical helix.

squat wall—reinforced concrete wall with clear height to horizontal length ratio less than 2.

standard hooked bar—a GFRP reinforcing bar with the end factory formed into a hook of prescribed geometry to provide anchorage.

stirrup—GFRP reinforcement used to resist shear and torsion forces in a member; typically bars, either single leg or factory formed into L, U, C or rectangular shapes and located perpendicular to longitudinal reinforcement. See also **tie**.

strength, design—nominal strength multiplied by a strength reduction factor ϕ .

strength, nominal—strength of a member or cross section calculated in accordance with provisions and assumptions of

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shotcrete—Terms such as “gunite” and “sprayed concrete” are sometimes used to refer to shotcrete.

stirrup—The term “stirrup” is usually applied to transverse reinforcement in beams or slabs and the term “ties” to transverse reinforcement in compression members. Figures R2.3a and R2.3b illustrate C-shaped and U-shaped transverse reinforcement.

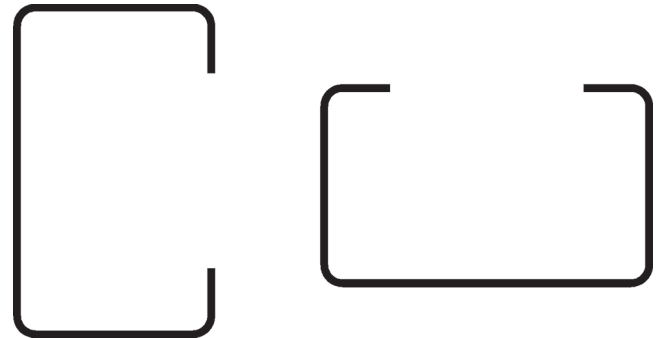


Fig. R2.3a—C-shaped transverse reinforcement.



Fig. R2.3b—U-shaped transverse reinforcement.

strength, nominal—Nominal or specified values of material strengths and dimensions are used in the calculation

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the strength design method of this Code before application of any strength reduction factors.

strength, required—strength of a member or cross section required to resist factored loads or related internal moments and forces in such combinations as stipulated in this Code.

structural diaphragm—member, such as a floor or roof slab, that transmits forces acting in the plane of the member to vertical elements of the lateral-force-resisting system. A structural diaphragm may include chords and collectors as part of the diaphragm.

structural integrity—ability of a structure through strength, redundancy, deformability, and detailing of reinforcement to redistribute stresses and maintain overall stability if localized damage or significant overstress occurs.

structural system—interconnected members designed to meet performance requirements.

structural truss—assemblage of reinforced concrete members subjected primarily to axial forces.

structural wall—wall proportioned to resist combinations of shears, moments, and axial forces in the plane of the wall; a shear wall is a structural wall.

structural wall, ordinary reinforced concrete—a wall complying with [Chapter 11](#).

strut—intact concrete that carries the compressive forces between diagonal tension cracks.

surface enhancement—treatment applied or created during manufacture of GFRP reinforcing bars, in the form of sand coating, spiral winding, machined grooves, or other methods, or combinations thereof to enhance bond strength of GFRP reinforcement.

tension-controlled section—a cross section in which the extreme layer of the GFRP tensile reinforcement ruptures before the concrete crushes.

tie—reinforcing bar enclosing longitudinal reinforcement; a continuously wound transverse bar in the form of a circle, rectangle, or other polygonal shape without reentrant corners enclosing longitudinal reinforcement. See also **stirrup**.

transition section—a cross section in which the net tensile strain in the extreme GFRP tension reinforcement at nominal strength is between $0.8\epsilon_{fu}$ and ϵ_{fu} .

two-way construction—members designed to be capable of supporting loads through bending in two directions; some slabs and foundations are considered two-way construction. See also **one-way construction**.

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of nominal strength. The subscript n is used to denote the nominal strengths; for example, nominal axial load strength P_n , nominal moment strength M_n , and nominal shear strength V_n . For additional discussion on the concepts and nomenclature for strength design, refer to the Commentary of Chapter 22.

strength, required—The subscript u is used only to denote the required strengths; for example, required axial load strength P_u , required moment strength M_u , and required shear strength V_u , calculated from the applied factored loads and forces. The basic requirement for strength design may be expressed as follows: design strength $\geq$ required strength; for example, $\phi P_n \geq P_u$; $\phi M_n \geq M_u$; $\phi V_n \geq V_u$. For additional discussion on the concepts and nomenclature for strength design, refer to the Commentary of [Chapter 22](#).

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wall—a vertical element designed to resist axial load, lateral load, or both, with a horizontal length-to-thickness ratio greater than 3, used to enclose or separate spaces.

wall segment—portion of wall bounded by vertical or horizontal openings or edges.

wall segment, horizontal—segment of a structural wall, bounded vertically by two openings or by an opening and an edge.

wall segment, vertical—segment of a structural wall, bounded horizontally by two openings or by an opening and an edge; wall piers are vertical wall segments.

water-cementitious materials ratio—ratio of mass of water, excluding that absorbed by the aggregate, to the mass of cementitious materials in a mixture, stated as a decimal.

work—the entire construction or separately identifiable parts thereof that are required to be furnished under the construction documents.



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CHAPTER 3—REFERENCED STANDARDS

3.1—Referenced standards

Standards, or specific sections thereof, cited in this Code, including Annex, Appendixes, or Supplements where prescribed, are referenced without exception in this Code, unless specifically noted. Cited standards are listed in the following with their serial designations, including year of adoption or revision.

3.1.1

ACI 301-16—Specifications for Structural Concrete
 ACI 318-19—Building Code Requirements for Reinforced Concrete and Commentary
 ACI SPEC-440.5-22—Construction with Glass Fiber-Reinforced Polymer Reinforcing Bars—Specification

3.1.2 *American Society of Civil Engineers*

ASCE/SEI 7-16—Minimum Design Loads for Buildings and Other Structures, Sections 2.3.2, Load Combinations Including Flood Loads; and 2.3.3, Load Combinations Including Atmospheric Ice Loads

3.1.3 *ASTM International*

ASTM C31/C31M-19—Standard Practice for Making and Curing Concrete Test Specimens in the Field
 ASTM C33/C33M-18—Standard Specification for Concrete Aggregates
 ASTM C39/C39M-18—Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
 ASTM C42/C42M-18a—Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
 ASTM C94/C94M-18—Standard Specification for Ready-Mixed Concrete
 ASTM C150/C150M-19a—Standard Specification for Portland Cement
 ASTM C172/C172M-17—Standard Practice for Sampling Freshly Mixed Concrete
 ASTM C173/C173M-16—Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method
 ASTM C192/C192M-18—Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory
 ASTM C231/C231M-17a—Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method
 ASTM C260/C260M-10a(2016)—Standard Specification for Air-Entraining Admixtures for Concrete
 ASTM C469/C469M-14—Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression

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CHAPTER R3—REFERENCED STANDARDS

R3.1—Referenced standards

In this Code, references to standard specifications or other material are to a specific edition of the cited document. This is done by using the complete serial designation for the referenced standard including the title that indicates the subject and year of adoption. All standards referenced in this Code are listed in this chapter, with the title and complete serial designation. In other sections of the Code, referenced standards are abbreviated to include only the serial designation without a title or date. These abbreviated references correspond to specific standards listed in this chapter.

R3.1.1

Article 4.2.3 of **ACI 301** is referenced for the method of mixture proportioning cited in **26.4.3.1(b)**.

R3.1.2 *American Society of Civil Engineers*

The two specific sections of **ASCE/SEI 7** are referenced for the purposes cited in **5.3.9** and **5.3.10**.

R3.1.3 *ASTM International*

The ASTM standards listed are the latest editions at the time the code provisions for the corresponding version of **ACI 318** were adopted. ASTM standards are revised frequently relative to the revision cycle for the Code. Current and historical editions of the referenced standards can be obtained from ASTM International. Use of an edition of a standard other than that referenced in the Code obligates the user to evaluate if any differences in the nonconforming edition are significant to use of the standard.

Many of the ASTM standards are combined standards as denoted by the dual designation, such as **ASTM C31/C31M**. For simplicity, these combined standards are referenced without the metric (M) designation within the text of the Code and Commentary. In this provision, however, the complete designation is given because that is the official designation for the standard.

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ASTM C494/C494M-17—Standard Specification for Chemical Admixtures for Concrete

ASTM C595/C595M-19—Standard Specification for Blended Hydraulic Cements

ASTM C618-19—Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete

ASTM C685/C685M-17a—Standard Specification for Concrete Made by Volumetric Batching and Continuous Mixing

ASTM C845/C845M-18—Standard Specification for Expansive Hydraulic Cement

ASTM C989/C989M-18a—Standard Specification for Slag Cement for Use in Concrete and Mortars

ASTM C1012/C1012M-18b—Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution

ASTM C1017/C1017M-13^{e1}—Standard Specification for Chemical Admixtures for Use in Producing Flowing Concrete

ASTM C1077-17—Standard Practice for Laboratories Testing Concrete and Concrete Aggregates for Use in Construction and Criteria for Testing Agency Evaluation

ASTM C1157/C1157M-17—Standard Performance Specification for Hydraulic Cement

ASTM C1240-15—Standard Specification for Silica Fume Used in Cementitious Mixtures

ASTM C1580-15—Standard Test for Water-Soluble Sulfate in Soil

ASTM C1602/C1602M-18—Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete

ASTM C1797-17—Standard Specification for Ground Calcium Carbonate and Aggregate Mineral Fillers for use in Hydraulic Cement Concrete

ASTM D516-16—Standard Test Method for Sulfate Ion in Water

ASTM D4130-15—Standard Test Method for Sulfate Ion in Brackish Water, Seawater, and Brines

ASTM D7957/D7957M-22—Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement



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CHAPTER 4—STRUCTURAL SYSTEM
REQUIREMENTS

4.1—Scope

4.1.1 This chapter shall apply to design of GFRP-reinforced 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.

4.2.2 Design properties of GFRP 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
- (g) Joints, connections, and anchors as required to transmit forces from one component to another

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CHAPTER R4—STRUCTURAL SYSTEM
REQUIREMENTS

R4.1—Scope

This chapter introduces 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

Chapter 3 identifies the referenced standards permitted for design. Chapters 19 and 20 establish properties of concrete and GFRP reinforcement permitted for design. Chapter 26 presents construction requirements for concrete materials, proportioning, and acceptance of concrete.

R4.3—Design loads

R4.3.1 The provisions in Chapter 5 are based on ASCE/SEI 7. The design loads include, but are not limited to, dead loads, live loads, snow loads, wind loads, earthquake effects, prestressing effects, crane loads, vibration, impact, shrinkage, temperature changes, creep, expansion of shrinkage-compensating concrete, and predicted unequal settlement of supports. Other project-specific loads may be specified by the licensed design professional.

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 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 GFRP-reinforced concrete 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 GFRP-reinforced concrete 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.

This Code does not cover the requirements for, or design of, GFRP-reinforced concrete diaphragms due to a lack of published research on this topic. This Code does not contain requirements for GFRP-reinforced concrete one-way and

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4.4.2 Design of GFRP-reinforced concrete members including joints and connections given in 4.4.1 shall be in accordance with Chapters 7 through 11, 13, 15, and 16.

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. GFRP-reinforced concrete members designated as part of the seismic-force-resisting system in structures assigned to Seismic Design Categories B, C, D, E, and F are not covered by this code.

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.

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two-way slabs if the GFRP reinforcement is not relied upon to transfer the lateral forces from diaphragm action. A structural system may have steel-reinforced concrete diaphragms interacting with other GFRP-reinforced concrete members.

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

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 use. These systems can be used if approved by the building official.

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4.4.6.3 GFRP-reinforced concrete members in structural systems assigned to Seismic Design Category A shall satisfy the applicable requirements of this Code.

4.4.6.4 Intentionally left blank.

4.4.6.5 GFRP-reinforced concrete members assumed not to be part of the seismic-force-resisting system shall be permitted in structures assigned to Seismic Design Category B or C, subject to the requirements of 4.4.6.5.1 and 4.4.6.5.2. GFRP-reinforced concrete members are not permitted in structures assigned to Seismic Design Categories D, E, and F.

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

4.4.7 *Diaphragms*—Out of scope.

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, axial force, shear, torsion, and bearing, shall be taken as the nominal strength S_n multiplied by the applicable strength reduction factor ϕ .

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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R4.4.6.3 Structures assigned to Seismic Design Category A are subject to the lowest seismic hazard.

R4.5—Structural analysis

The role of analysis is to estimate the internal forces and deformations of the structural system and to establish compliance with the strength, serviceability, and stability requirements of the Code. The use of computers in structural engineering has made it feasible to perform analysis of complex structures. The Code requires that the analytical procedure used meets the fundamental principles of equilibrium and compatibility of deformations as provided in Chapter 6.

R4.6—Strength

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

design strength $\geq$ required strength

$$\phi S_n \geq U$$

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, dimensions, the effect of simplifying assumptions in the

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4.7—Serviceability

4.7.1 Evaluation of performance at service load conditions shall consider reactions, moments, torsions, shears, and axial forces induced by 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 in accordance with 20.5.

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.

This 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 load effect, the probability of simultaneous occurrence of various load effects, 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 effect relevant for strength design includes moments, shears, axial forces, torsions, bearing forces, and punching shear stresses. Sometimes, design displacements are determined for factored load effects. 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.

R4.7—Serviceability

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. Creep-rupture failure is addressed under sustained service loads. 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 this Code but are discussed in Appendix C of ASCE/SEI 7-16. Appendixes to ASCE/SEI 7 are not considered mandatory parts of the standard.

R4.8—Durability

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 concrete shall be

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4.9—Sustainability

4.9.1 The licensed design professional shall be permitted to specify in the construction documents sustainability requirements in addition to strength, serviceability, and durability requirements of this Code.

4.9.2 The strength, serviceability, and durability requirements of this Code shall take precedence over sustainability considerations.

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.

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
One-way cast-in-place slabs	7.7.7
Two-way slabs	8.7.4.2
Cast-in-place beam	9.7.7
One-way joist system	9.8.1.6

4.11—Fire resistance and elevated service temperature

4.11.1 Structural concrete reinforced with GFRP bars shall not be permitted where fire-resistance ratings are required except where the structural fire resistance has been shown to be adequate by calculations or tests and approved by the building official.

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

The Code provisions for strength, serviceability, and durability are minimum requirements to achieve a safe and durable concrete structure. The Code permits the owner or the licensed design professional to specify requirements higher than the minimums mandated in the Code. Such optional requirements can include higher strengths, more restrictive deflection limits, enhanced durability, and sustainability provisions.

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 deformability through detailing of GFRP 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.

R4.10.2 Minimum requirements for structural integrity

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. Such is the case for detailing of one-way slabs as provided in 7.7.

R4.11—Fire resistance and elevated service temperature

R4.11.1 The performance of GFRP-reinforced concrete elements at high temperatures relies primarily on the GFRP reinforcement-concrete bond strength being maintained (Hajiloo and Green 2018; Hajiloo et al. 2017, 2019; Nigro et al. 2011). Table R20.5.1.3.1 provides the fire-resistance ratings for the concrete cover specified in Table 20.5.1.3.1 for non-bond-critical GFRP reinforcement. Achieving non-bond-critical GFRP reinforcement requires specific detailing for anchorage. This commentary provides guidance on



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detailing to obtain non-bond-critical GFRP reinforcement in members to prevent anchorage failure during a fire event.

In beams and slabs, specific GFRP reinforcement detailing for anchorage will usually consist of providing adequate embedment length into the support to anchor the GFRP reinforcement or using additional concrete cover or insulation near the supports to reduce the temperature of the GFRP reinforcement near the supports during a fire event. During the fire event, the maximum bar stress due to the service load combination of $1.0D + 1.0L$ should be less than $0.3f_{fu}$ and the average bar temperature over the fire-protected embedment length should be less than 210°F for the required fire-resistance duration. Ideally, the bond development length corresponding to 1.3 times the maximum bar stress due to the full service loads ($1.0D + 1.0L$) should be embedded into the support (that is, in an area not directly exposed to fire). The 1.3 factor accounts for increased stress in the bars during the fire event as a result of extensive deformations in the slabs under combined load and fire effects (Hajiloo et al. 2019). Instead of development length calculations, embedment into the support of the larger of 12 in. or $20d_b$ is conservative for No. 10 and smaller bars with $f'_c \geq 4000$ psi and maximum bar stresses due to full service loads ($1.0D + 1.0L$) less than 35 ksi. If this embedment length into the support or unexposed length ℓ_{un} , cannot be achieved, additional protection can be provided at the ends of GFRP reinforcement near supports by increasing the concrete cover using a haunch or drop panel (Fig R4.11.1a and R4.11.1b) or insulating the concrete (Fig R4.11.1c). In these figures, ℓ_{pa} is the fire-protected embedment length of GFRP reinforcement and is measured from the end of the reinforcing bars to the end of the haunch, drop panel or insulation and d_{pa} is the depth of the haunch, drop panel or insulation. Table R4.11.1 provides the suggested fire-protected embedment length and depth of haunch, drop panel or insulation based on unexposed length at the ends of the GFRP reinforcement for the case of $f'_c \geq 4000$ psi, clear cover c_c at least 1.5 in., and a maximum bar stress due to full service loads ($1.0D + 1.0L$) less than 35 ksi. Tests have shown that a 1.5 in. insulation layer can keep the temperature at the GFRP reinforcing bars with 1.5 in. of clear concrete cover below 210°F for 2 hours of fire exposure (Williams et al. 2008; Adelzadeh et al. 2012).

Any tensile GFRP reinforcement splice in a member will necessarily result in a bond-critical area under fire. Figure R4.11.1d shows one option for protecting positive moment splice regions by adding insulation under the splice region. For $f'_c \geq 4000$ psi, clear cover c_c at least 1.5 in., and a maximum bar stress due to full service loads ($1.0D + 1.0L$) less than 35 ksi, the length of the insulated area (ℓ_{in}) should be the larger of 36 in. or $60d_b$, and extend at least 3 in. beyond each end of the spliced GFRP reinforcement.

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Table R4.11.1—Haunch, drop panel, or insulation for protection of GFRP reinforcement near supports

ℓ_{un} , in.	ℓ_{pa} , in.	d_{pa} , in.
4	Max(22 or $30d_b$)	2
6	Max(20 or $28d_b$)	2
8	Max(16 or $25d_b$)	2
10	Max(14 or $22d_b$)	2
Max(12 or $20d_b$)	—	—

*For 2-hour fire exposure. Assumes clear cover ≥ 1.5 in., $f_c' \geq 4000$ psi, and maximum bar stress due to $1.0D + 1.0L < 35$ ksi.

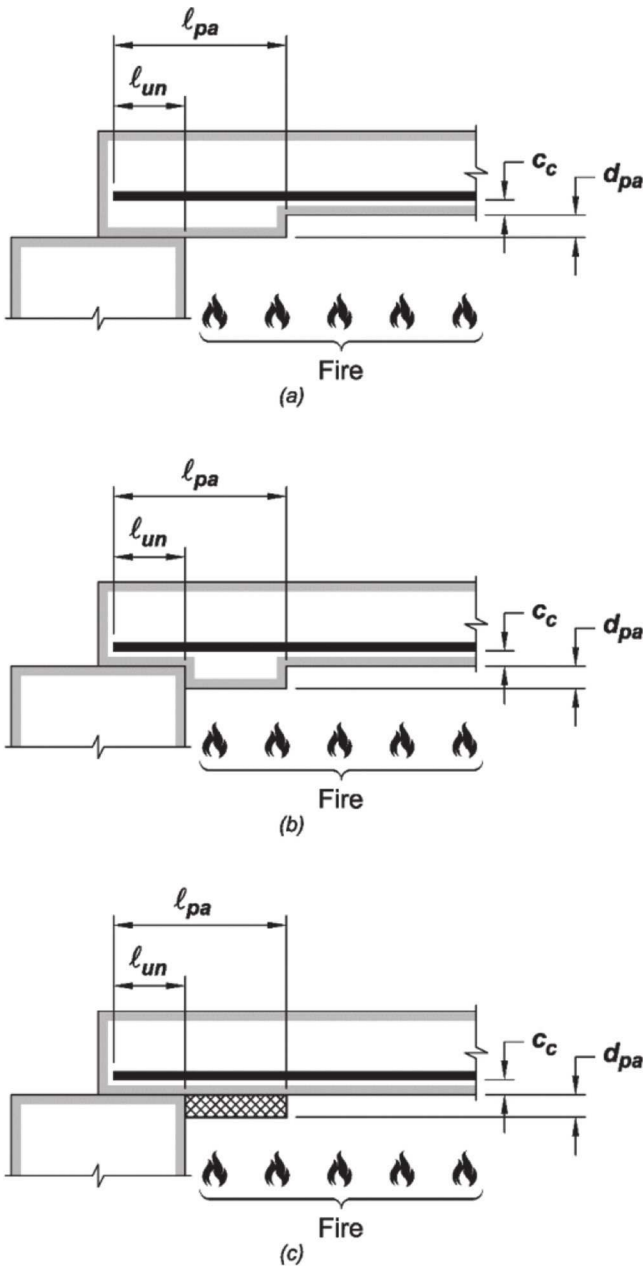


Fig R4.11.1a-c—Protection of GFRP reinforcement near supports.

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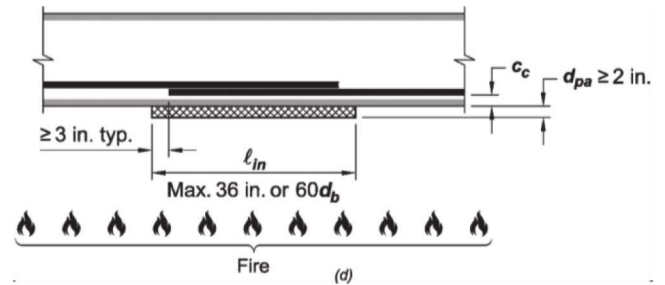


Fig R4.11.1d —Insulation at spliced GFRP reinforcement.

If insulation is used to control GFRP bar temperature, the insulation should be at least 2 in. thick and the insulation material should be tested for application on concrete in accordance with **ASTM E119** to verify that the insulated concrete surface temperature does not exceed 300°F for the duration of the required fire-resistance rating. The increased cover or insulation used to control GFRP bar temperature should extend for the full width of the beam or slab. The length of the fire-protected embedment zone ℓ_{pa} and ℓ_{in} should extend at least ℓ_d as determined from 25.4.2.1 using an f_{fr} of 1.3 times the service bar stress at **1.0D + 1.0L** at the ends of straight bars, ℓ_d as determined from 25.4.3.1 at the ends of longitudinal hooked bars, and the greatest of the splice length plus 6 in., 36 in., and **60d_b** at splices.

Shear reinforcement consisting of lap-spliced GFRP stirrups will necessarily result in a bond-critical area under fire. The maximum stress at ultimate in the transverse reinforcement due to **1.2D + 1.6L** should be less than **0.45f_{fu}**. In general, this stress limit will be satisfied by 20.2.2.6, which limits the strain in the transverse reinforcement to 0.005 at ultimate. For example, using GFRP bars with $f_{fu} = 120$ ksi and $E_f = 9000$ ksi, the 0.005 strain limit at ultimate corresponds to a stress of **0.375f_{fu}** under full factored loads. Assuming a lower bound average load factor of 1.4 (corresponding to a live-to-dead load ratio of 1), the stress under service loads would be no larger than **0.27f_{fu}**. Smaller moduli of elasticity and larger bar strengths would result in stresses attaining an even smaller percentage of f_{fu} . As with longitudinal bars, the average temperature of the GFRP transverse reinforcement in the bond-critical areas should be less than 210°F for the required fire-resistance duration and the insulation should meet the same thickness and test requirements as that for the longitudinal reinforcement protection.

GFRP reinforcement in compression is ineffective at high temperatures due to loss of stiffness of the polymer and buckling of the fibers due to the low polymer modulus; hence, GFRP bars in compression under fire conditions should not be considered in the compressive strength of the member.

The temperatures of the GFRP reinforcement in vertical elements (columns and walls) during fire can be controlled by a combination of concrete cover, insulation, and protective coatings, such as dry wall. Instead of detailed calculations, an insulation system that keeps the concrete surface temperature below 300°F can be considered in determining the required GFRP bar temperature below 210°F. Examples of fire

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4.11.2 Intentionally left blank.

4.11.3 GFRP bars shall not be used in environments with a service temperature higher than 27°F below the glass transition temperature of the bar, as determined in accordance with the requirements of **ASTM D7957**.

4.12—Requirements for specific types of construction**4.12.1** *Precast concrete systems*

4.12.1.1 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.

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

4.12.1.3 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.

4.12.1.4 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.

insulation systems for columns as well as numerical models for concrete columns under fire can be found in **Bisby et al. (2005)** and **Cree et al. (2012)**.

R4.11.3 GFRP bars can lose bond with concrete if used in conditions that have service temperatures approaching the glass transition temperature of the bar, due to softening of the resin (**Xian and Karbhari 2007**). ASTM D7957 requires GFRP bars to have a minimum mean glass transition temperature of 212°F. GFRP bars with glass transition temperatures in excess of 250°F are commercially available.

R4.12—Requirements for specific types of construction

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 *Precast concrete systems*

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 this Code also provide specific requirements 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 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.

R4.12.1.2 For guidance on including the effects of tolerances, refer to the *PCI Design Handbook* (**PCI MNL 120**).

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(b) Where tension loads occur, a load path of reinforcement, with or without splices, shall be provided.

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

4.12.2 Prestressed concrete systems—Out of scope

4.12.3 Composite concrete flexural members

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.

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

4.12.4 Structural plain concrete system—Not applicable

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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R4.12.1.5 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.

R4.12.3 Composite concrete flexural members

This section addresses structural concrete members, either precast or cast-in-place, consisting of concrete cast at different times intended to act as a composite member when loaded after concrete of the last stage of casting. 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.

R4.13—Construction and inspection

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.

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CHAPTER 5—LOADS

5.1—Scope

5.1.1 This chapter shall apply to selection of load factors and combinations used in design, except as permitted in Chapter 27.

5.2—General

5.2.1 Loads shall include self-weight; applied loads; and effects of prestressing, earthquakes, restraint of volume change, and differential settlement.

5.2.2 Loads and Seismic Design Categories (SDCs) shall be in accordance with the general building code, or determined by the building official.

5.2.3 Live load reductions shall be permitted in accordance with the general building code or, in the absence of a general building code, in accordance with ASCE/SEI 7.

5.3—Load factors and combinations

5.3.1 Required strength U for building structures shall be at least equal to the effects of factored loads in Table 5.3.1, with exceptions and additions in 5.3.3 through 5.3.10.

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CHAPTER R5—LOADS

R5.2—General

R5.2.1 Provisions in the Code are associated with dead, live, wind, and earthquake loads such as those recommended in ASCE/SEI 7. The commentary to Appendix C of ASCE/SEI 7 provides service-level wind loads W_a for serviceability checks; however, these loads are not appropriate for strength design. Although this Code does not cover the use of GFRP reinforcement for prestressed concrete members, GFRP-reinforced concrete members may be present in structures that include prestressing effects and are possibly subject to loads from such effects.

If the service loads specified by the general building code differ from those of ASCE/SEI 7, the general building code governs. However, if the nature of the loads contained in a general building code differs considerably from ASCE/SEI 7 loads, some provisions of this Code may need modification to reflect the difference.

R5.2.2 Seismic Design Categories (SDCs) in this Code are adopted directly from ASCE/SEI 7. Similar designations are used by the International Building Code (2012 IBC) and the National Fire Protection Association (NFPA 5000 2012). The BOCA National Building Code (BOCA 1999) and “The Standard Building Code” (SBC 1999) used seismic performance categories. The “Uniform Building Code” (IBCO 1997) relates seismic design requirements to seismic zones.

Design requirements for earthquake-resistant structures in this Code are determined by the SDC to which the structure is assigned. In general, the SDC relates to seismic hazard level, soil type, occupancy, and building use. Assignment of a building to an SDC is under the jurisdiction of the general building code rather than this Code. This code does not cover the design of GFRP-reinforced concrete members designated as part of the seismic-force resisting system in structures assigned to Seismic Design Categories B, C, D, E, or F.

R5.3—Load factors and combinations

R5.3.1 The required strength U is expressed in terms of factored loads, or related internal moments and forces. Factored loads are the loads specified in the general building code multiplied by appropriate load factors. If the load effects such as internal forces and moments are linearly related to the loads, the required strength U may be expressed in terms of load effects multiplied by the appropriate load factors.

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Table 5.3.1—Load combinations

Load combination	Equation	Primary load
$U = 1.4D$	(5.3.1a)	D
$U = 1.2D + 1.6L + 0.5(L_r \text{ or } S \text{ or } R)$	(5.3.1b)	L
$U = 1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (1.0L \text{ or } 0.5W)$	(5.3.1c)	$L_r \text{ or } S \text{ or } R$
$U = 1.2D + 1.0W + 1.0L + 0.5(L_r \text{ or } S \text{ or } R)$	(5.3.1d)	W
$U = 1.2D + 1.0E + 1.0L + 0.2S$	(5.3.1e)	E
$U = 0.9D + 1.0W$	(5.3.1f)	W
$U = 0.9D + 1.0E$	(5.3.1g)	E

with the identical result. If the load effects are nonlinearly related to the loads, such as frame $P\Delta$ effects (Rogowsky and Wight 2010), the loads are factored before determining the load effects. Typical practice for foundation design is discussed in R13.2.6.1. Nonlinear finite element analysis using factored load cases is discussed in R6.9.3.

The factor assigned to each load is influenced by the degree of accuracy to which the load effect usually can be calculated and the variation that might be expected in the load during the lifetime of the structure. Dead loads, because they are more accurately determined and less variable, are assigned a lower load factor than live loads. Load factors also account for variability in the structural analysis used to calculate moments and shears.

The Code gives load factors for specific combinations of loads. In assigning factors to combinations of loading, some consideration is given to the probability of simultaneous occurrence. While most of the usual combinations of loadings are included, it should not be assumed that all cases are covered.

Due regard is to be given to the sign (positive or negative) in determining U for combinations of loadings, as one type of loading may produce effects of opposite sense to that produced by another type. The load combinations with **0.9D** are included for the case where a higher dead load reduces the effects of other loads. The loading case may also be critical for tension-controlled column sections. In such a case, a reduction in compressive axial load or development of tension with or without an increase in moment may result in a critical load combination.

Consideration should be given to various combinations of loading to determine the most critical design condition. This is particularly true when strength is dependent on more than one load effect, such as strength for combined flexure and axial load or shear strength in members with axial load.

If unusual circumstances require greater reliance on the strength of particular members than circumstances encountered in usual practice, some reduction in the stipulated strength reduction factors ϕ or increase in the stipulated load factors may be appropriate for such members.

Rain load R in Eq. (5.3.1b), (5.3.1c), and (5.3.1d) should account for all likely accumulations of water. Roofs should be designed with sufficient slope or camber to ensure adequate drainage accounting for any long-term deflection of the roof due to the dead loads. If deflection of roof members may result in ponding of water accompanied by increased deflection and additional ponding, the design should ensure that this process is self-limiting.

Model building codes and design load references refer to earthquake forces at the strength level, and the corresponding load factor is 1.0 (ASCE/SEI 7; BOCA [1999]; SBC [1999]; UBC [ICBO 1997]; 2012 IBC). In the absence of a general building code that prescribes strength level earthquake effects, a higher load factor on E would be required. The load effect E in model building codes and design load reference standards includes the effect of both horizontal and

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5.3.2 The effect of one or more loads not acting simultaneously shall be investigated.

5.3.3 The load factor on live load L in Eq. (5.3.1c), (5.3.1d), and (5.3.1e) shall be permitted to be reduced to 0.5 except for (a), (b), or (c):

- (a) Garages
- (b) Areas occupied as places of public assembly
- (c) Areas where L is greater than 100 lb/ft²

5.3.4 If applicable, L shall include (a) through (f):

- (a) Concentrated live loads
- (b) Vehicular loads
- (c) Crane loads
- (d) Loads on handrails, guardrails, and vehicular barrier systems
- (e) Impact effects
- (f) Vibration effects

5.3.5 If wind load W is based on service-level loads, $1.6W$ shall be used in place of $1.0W$ in Eq. (5.3.1d) and (5.3.1f), and $0.8W$ shall be used in place of $0.5W$ in Eq. (5.3.1c).

5.3.6 The structural effects of forces due to restraint of volume change and differential settlement T shall be considered in combination with other loads if the effects of T can adversely affect structural safety or performance. The load factor for T shall be established considering the uncertainty associated with the likely magnitude of T , the probability that the maximum effect of T will occur simultaneously with other applied loads, and the potential adverse consequences if the effect of T is greater than assumed. The load factor on T shall not have a value less than 1.0.

vertical ground motions (as E_h and E_v , respectively). The effect for vertical ground motions is applied as an addition to or subtraction from the dead load effect (D), and it applies to all structural elements, whether part of the seismic force-resisting system or not, unless specifically excluded by the general building code.

Structures other than buildings may require load factors and combinations different from those given in Table 5.3.1. For such structures, the appropriate load factors and combinations may be obtained from relevant codes and standards such as **ASCE/SEI 7** and **AASHTO LRFD** for bridge structures.

R5.3.3 The load modification factor in this provision is different than the live load reductions based on the loaded area that may be allowed in the general building code. The live load reduction, based on loaded area, adjusts the nominal live load (L_0 in ASCE/SEI 7) to L . The live load reduction, as specified in the general building code, can be used in combination with the 0.5 load factor specified in this provision.

R5.3.5 In **ASCE/SEI 7-05**, wind loads are consistent with service-level design; a wind load factor of 1.6 is appropriate for use in Eq. (5.3.1d) and (5.3.1f) and a wind load factor of 0.8 is appropriate for use in Eq. (5.3.1c). ASCE/SEI 7-16 prescribes wind loads for strength-level design and the wind load factor is 1.0. Design wind speeds for strength-level design are based on storms with mean recurrence intervals of 300, 700, and 1700 years, depending on the risk category of the structure. The higher load factors in 5.3.5 apply where service-level wind loads corresponding to a 50-year mean recurrence interval are used for design.

R5.3.6 Several strategies can be used to accommodate movements due to volume change and differential settlement. Restraint of such movements can cause significant member forces and moments, such as tension in slabs and shear forces and moments in vertical members. Forces due to T effects are not commonly calculated and combined with other load effects. Rather, designs rely on successful past practices using compliant structural members and ductile connections to accommodate differential settlement and volume change movement while providing the needed

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5.3.7 If fluid load F is present, it shall be included in the load combination equations of 5.3.1 in accordance with (a), (b), (c) or (d):

(a) If F acts alone or adds to the effects of D , it shall be included with a load factor of 1.4 in Eq. (5.3.1a).

(b) If F adds to the primary load, it shall be included with a load factor of 1.2 in Eq. (5.3.1b) through (5.3.1e).

(c) If the effect of F is permanent and counteracts the primary load, it shall be included with a load factor of 0.9 in Eq. (5.3.1g).

(d) If the effect of F is not permanent but, when present, counteracts the primary load, F shall not be included in Eq. (5.3.1a) through (5.3.1g).

5.3.8 If lateral earth pressure H is present, it shall be included in the load combination equations of 5.3.1 in accordance with (a), (b), or (c):

(a) If H acts alone or adds to the primary load effect, it shall be included with a load factor of 1.6.

(b) If the effect of H is permanent and counteracts the primary load effect, it shall be included with a load factor of 0.9.

(c) If the effect of H is not permanent but, when present, counteracts the primary load effect, H shall not be included.

5.3.9 If a structure is in a flood zone, the flood loads and the appropriate load factors and combinations of ASCE/SEI 7 shall be used.

5.3.10 If a structure is subjected to forces from atmospheric ice loads, the ice loads and the appropriate load factors and combinations of ASCE/SEI 7 shall be used.

resistance to gravity and lateral loads. Expansion joints and construction closure strips are used to limit volume change movements based on the performance of similar structures. Shrinkage and temperature reinforcement, which may exceed the required flexural reinforcement, is commonly proportioned based on gross concrete area rather than calculated force.

Where structural movements can lead to damage of nonductile elements, calculation of the predicted force should consider the inherent variability of the expected movement and structural response.

A long-term study of the volume change behavior of precast concrete buildings (Klein and Lindenberg 2009) recommends procedures to account for connection stiffness, thermal exposure, member softening due to creep, and other factors that influence T forces.

Fintel et al. (1986) provides information on the magnitudes of volume change effects in tall structures and recommends procedures for including the forces resulting from these effects in design.

R5.3.8 The required load factors for lateral pressures from soil, water in soil, and other materials, reflect their variability and the possibility that the materials may be removed. The commentary of ASCE/SEI 7 includes additional useful discussion pertaining to load factors for H .

R5.3.9 Areas subject to flooding are defined by flood hazard maps, usually maintained by local governmental jurisdictions.

R5.3.10 Ice buildup on a structural member increases the applied load and the projected area exposed to wind. ASCE/SEI 7 provides maps of probable ice thicknesses due to freezing rain, with concurrent 3-second gust speeds, for a 50-year return period.

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5.3.11 Intentionally left blank.

5.3.12 Intentionally left blank.

5.3.13 Intentionally left blank.

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CHAPTER 6—STRUCTURAL ANALYSIS

6.1—Scope

6.1.1 This Chapter shall apply to methods of analysis, modeling of members and structural systems, and calculation of load effects.

6.2—General

6.2.1 Members and structural systems shall be permitted to be modeled in accordance with 6.3.

6.2.2 All members and structural systems shall be analyzed for the maximum effects of loads including the arrangements of live load in accordance with 6.4.

6.2.3 Methods of analysis permitted by this chapter shall be (a) through (e). Redistribution of moments calculated in accordance with (a) through (e) is not permitted.

- (a) The simplified method for analysis of continuous beams and one-way slabs for gravity loads in 6.5
- (b) Linear elastic first-order analysis in 6.6
- (c) Linear elastic second-order analysis in 6.7
- (d) Intentionally left blank
- (e) Finite element analysis in 6.9

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CHAPTER R6—STRUCTURAL ANALYSIS

R6.1—Scope

The provisions of this chapter apply to analyses used to determine load effects for design.

Section 6.2 provides general requirements that are applicable for analysis procedures.

Section 6.2.4 directs the licensed design professional to specific analysis provisions that are not contained in this chapter. Section 6.2.4.1 identifies analysis provisions that are specific to two-way slabs.

Section 6.3 addresses modeling assumptions used in establishing the analysis model.

Section 6.4 prescribes the arrangements of live loads that are to be considered in the analysis.

Section 6.5 provides a simplified method of analysis for continuous beams and one-way slabs that can be used in place of a more rigorous analysis when the stipulated conditions are satisfied.

Section 6.6 includes provisions for a comprehensive first-order analysis. The effect of cracked sections and creep are included in the analysis through the use of effective stiffnesses.

Section 6.7 includes provisions for an elastic second-order analysis. Inclusion of the effects of cracking and creep is required. Inelastic analyses are not addressed in this Code.

Section 6.9 includes provisions for the use of the finite element method.

R6.2—General

R6.2.3 GFRP reinforcement is linear elastic until failure; plastic hinge regions associated with moment redistribution do not form.

A first-order analysis satisfies the equations of equilibrium using the original undeformed geometry of the structure. When only first-order results are considered, slenderness effects are not accounted for. Because these effects can be important, 6.6 provides procedures to calculate both individual member slenderness ($P\delta$) effects and sidesway ($P\Delta$) effects for the overall structure using the first-order results.

A second-order analysis satisfies the equations of equilibrium using the deformed geometry of the structure. If the second-order analysis uses nodes along compression members, the analysis accounts for slenderness effects due to lateral deformations along individual members, as well as sidesway of the overall structure. If the second-order analysis uses nodes at the member intersections only, the analysis captures the sidesway effects for the overall structure but neglects individual member slenderness effects. In

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COMMENTARY

6.2.4 Additional analysis methods that are permitted include 6.2.4.1.

6.2.4.1 Two-way slabs shall be permitted to be analyzed for gravity loads in accordance with (a) or (b):

- (a) Direct design method for slabs
- (b) Equivalent frame method for slabs

6.2.4.2 Intentionally left blank.

6.2.4.3 Intentionally left blank.

6.2.4.4. Intentionally left blank.

6.2.5 *Slenderness effects*

6.2.5.1 Slenderness effects shall be permitted to be neglected if (a) or (b) is satisfied:

- (a) For columns not braced against sidesway

$$k\ell_u/r \leq 17 \quad (6.2.5.1a)$$

- (b) For columns braced against sidesway

$$k\ell_u/r \leq 29 + 12(M_1/M_2) \quad (6.2.5.1b)$$

and

$$k\ell_u/r \leq 35 \quad (6.2.5.1c)$$

where M_1/M_2 is negative if the column is bent in single curvature, and positive for double curvature.

If bracing elements resisting lateral movement of a story have a total stiffness of at least 12 times the gross lateral stiffness of the columns in the direction considered, it shall be permitted to consider columns within the story to be braced against sidesway.

this case, the moment magnifier method (6.6.4) is used to determine individual member slenderness effects.

R6.2.4.1 ACI 318 Code editions from 1971 to 2014 contained provisions for use of the direct design method and the equivalent frame method. These methods are well-established and are covered in available texts. These provisions for gravity load analysis of two-way slabs have been removed from ACI 318 because they are considered to be only two of several analysis methods currently used for the design of two-way slabs. The direct design method and the equivalent frame method of **ACI 318-14**, however, may still be used for the analysis of two-way slabs for gravity loads, with the exception that ACI 318-14 Section 8.10.4.3 does not apply to GFRP-reinforced concrete two-way slabs.

R6.2.5 *Slenderness effects*

R6.2.5.1 Second-order effects in many structures are negligible. In these cases, it is unnecessary to consider slenderness effects, and compression members, such as columns, walls, or braces, can be designed based on forces determined from first-order analyses. Slenderness effects can be neglected in both braced and unbraced systems, depending on the slenderness ratio ($k\ell_u/r$) of the member.

M_1/M_2 is negative if bent in single curvature and positive if bent in double curvature.

The primary design aid to estimate the effective length factor k is the Jackson and Moreland Alignment Charts (Fig. R6.2.5.1), which provide a graphical determination of k for a column of constant cross section in a multi-bay frame (**ACI SP-17(09); Column Research Council 1966**).

The slenderness ratio limit given in Eq. (6.2.5.1a) is based on a study conducted by **Mirmiran et al. (2001)** that recognized that the use of low-stiffness GFRP bars makes columns more susceptible to slenderness effects. A parametric study considering more than 11,000 columns was conducted with different reinforcement ratios, modular ratios, strength ratios, compressive/tensile strength ratios, yielding response of reinforcing bars, slenderness ratios, end eccentricities, and eccentricity ratios. Based on the parametric study, the slenderness ratio limit of 22 used for steel-reinforced concrete columns bent in single curvature has been reduced to 17 for GFRP-reinforced concrete columns.

The slenderness ratio limits given in Eq. (6.2.5.1b) and (6.2.5.1c) for columns braced against sidesway are based on Eq. (6.6.4.5.1), allowing for a 5% increase in moments due