Part 1: Foundational Concepts (Chapters 1-3)

Chapter 1: General

Overview

This chapter establishes the legal and procedural framework for the ACI 318-19 Code. It defines the Code's scope, purpose, and applicability. It outlines the principles of interpretation, the roles and responsibilities of the building official and licensed design professional, and the requirements for construction documents, testing, inspection, and the approval of special or alternative systems. The Code is written to be adopted by reference into a general building code.

Key Standards and Codes Referenced

- ACI 318M, ACI 318S, ACI 318SUS (Alternative unit versions of the Code)
- ACI 562-19: Code Requirements for Assessment, Repair, and Rehabilitation of Existing Concrete Structures
- ACI 318.2: Building Code Requirements for Concrete Thin Shells
- ACI 307-08: Code Requirements for Reinforced Concrete Chimneys
- ACI 313-97: Standard Practice for Design and Construction of Concrete Silos and Stacking Tubes for Storing Granular Materials
- ACI 349: Code Requirements for Nuclear Safety-Related Concrete Structures
- ACI 359: Code for Concrete Containments
- ACI 332: Residential Code Requirements for Structural Concrete
- ACI 350: Code Requirements for Environmental Engineering Concrete Structures
- ACI 334.1R: Concrete Shell Structures Practice and Commentary
- ACI 372R: Guide to Design and Construction of Circular Wire- and Strand-Wrapped Prestressed-Concrete Structures
- ACI 360R: Guide to Design of Slabs-on-Ground
- ACI 543R: Guide to Design, Manufacture, and Installation of Concrete Piles
- ACI 336.3R: Design and Construction of Drilled Piers
- ACI Concrete Terminology
- 2015 International Building Code (IBC)
- PTI DC10.5-12: Standard Requirements for Design and Analysis of Post-Tensioned Slabs-on-Ground
- SDI NC: Standard for Non-Composite Steel Floor Deck
- SDI C: Standard for Composite Steel Floor Deck-Slabs
- PCI (1993): Recommended Practice for Design, Manufacture, and Installation of Prestressed Concrete Piling

Technical Specifications

- 1.2 General:
  - Official Version: The official version of the Code is in the English language using inch-pound units (1.2.3). Jurisdictions may adopt other versions (SI or Spanish). In case of conflict, the official English, inch-pound version governs (1.2.4).
  - Scope: The Code provides minimum requirements for materials, design, construction, and strength evaluation of structural concrete members and systems (1.2.5). It is intended to be used as part of a legally adopted general building code (1.2.2).
- 1.3 Purpose:
  - Primary Goal: To provide for public health and safety by establishing minimum requirements for strength, stability, serviceability, durability, and integrity of concrete structures (1.3.1).
  - Limitations: The Code does not address all design considerations (1.3.2) or construction means and methods (1.3.3). Professional judgment is required.
- 1.4 Applicability:
  - Primary Application: Applies to concrete structures designed under a general building code (1.4.1).
  - Special Structures: It is permitted for assessment of existing structures (1.4.2) and for structures not governed by a general building code (1.4.3), such as arches, bins, silos, and blast-resistant structures. The commentary lists specific codes (ACI 307, 313, 349, 359) for these cases.
  - Exclusions: The code explicitly does not apply to:
    - Design and installation of most concrete piles, drilled piers, and caissons (1.4.7), which are covered by the general building code. Exceptions are made for portions of deep foundations in air/water or unsupported soil, and for specific seismic design categories.
    - Most slabs-on-ground, unless they transmit vertical or lateral loads from the structure (1.4.8).
    - Tanks and reservoirs (1.4.9), which are covered by ACI 350, ACI 334.1R, and ACI 372R.
    - Composite design slabs on composite steel deck (1.4.10).
- 1.5 Interpretation:
  - Mandatory Language: The word "shall" is always mandatory. Provisions are mandatory even if "shall" is not used (1.5.6).
  - Hierarchy: Specific provisions govern over general provisions (1.5.4). If there is a conflict between this code and referenced standards, this Code (ACI 318-19) shall apply (1.5.8).

- Severability: If a provision is declared invalid by a court, the rest of the Code remains in effect (1.5.7).
- 1.8 Construction Documents and Design Records:
  - Requirement: The licensed design professional shall provide the information required in Chapter 26 in the construction documents (1.8.1).
  - Calculations: Computer-generated output is acceptable, provided design assumptions and user input are submitted. Model analysis can supplement calculations (1.8.2).
- 1.10 Approval of Special Systems:
  - Procedure: Establishes a process for approving alternative design systems, materials, or construction methods not covered by the Code. Sponsors must present evidence (successful use, analysis, or tests) to a board of examiners appointed by the building official (1.10.1).

BOQ Implications

- The requirement for specific referenced standards (Chapter 3) dictates the quality and cost of materials (e.g., ASTM A706 vs. A615 steel), which must be clearly specified in the BOQ.
- The use of alternative systems (1.10) may require additional line items for testing, specialized materials, and unique construction procedures, impacting the overall project budget.
- The requirement for the licensed design professional to provide comprehensive construction documents (1.8) is the direct prerequisite for generating an accurate BOQ. These documents must contain all necessary material specifications, dimensions, and tolerances.

Critical Notes and Warnings

- Disclaimer: ACI and its members disclaim all liability for damages arising from the use of this publication. The information is provided "as is" without warranty (Page 4).
- User Responsibility: The user of the document is responsible for evaluating its limitations and for establishing appropriate health and safety practices, including compliance with OSHA standards (Page 4).
- Commentary is Not Code: The Commentary provides background and intent but is not legally part of the Code's mandatory provisions. Commentary section numbers are prefixed with "R" (Page 6). To make a commentary suggestion mandatory, it must be restated in mandatory language in the contract documents.

Chapter 2: Notation and Terminology

Overview

This chapter serves as the authoritative dictionary for the entire ACI 318-19 standard. It is divided into two main sections: Notation (2.2), which lists and defines all the symbols and variables used in formulas, and Terminology (2.3), which provides precise definitions for key terms used throughout the code. This chapter is fundamental to correctly interpreting and applying the Code's requirements.

Key Standards and Codes Referenced

- ASTM C330: Standard Specification for Lightweight Aggregates
- ASTM C29: Standard Test Method for Bulk Density, "Unit Weight," and Voids in Aggregate
- ASTM C567: Standard Test Method for Determining Density of Structural Lightweight Concrete
- AWS D1.1: Structural Welding Code—Steel
- ASCE/SEI 7: Minimum Design Loads and Associated Criteria for Buildings and Other Structures

Technical Specifications (Terminology Highlights)

- Admixture: A material other than water, aggregate, or hydraulic cement, used to modify the properties of the mixture.
- Aggregate, lightweight: Aggregate meeting ASTM C330 requirements with a loose bulk density of 70 lb/ft^3 or less.
- Anchor: A steel element, either cast-in or post-installed, used to transmit loads to the concrete. The Code defines multiple specific types:
  - anchor, adhesive: Bonds to concrete via an adhesive.
  - anchor, cast-in: Installed before concrete is placed (e.g., headed bolt, J-bolt, L-bolt).
  - anchor, expansion: Transfers load via friction/bearing from expansion.
  - anchor, screw: Transfers load by threads cutting into a predrilled hole.
  - anchor, undercut: Develops strength from mechanical interlock at the embedded end.
- B-region vs. D-region:
  - B-region: A portion of a member where the assumption of linear strain (plane sections remain plane) is valid.
  - D-region: A portion of a member within a distance *h* (member depth) of a force or geometric discontinuity, where the strain distribution is nonlinear.
- Concrete, lightweight vs. sand-lightweight: Distinguished by the type of fine aggregate used (lightweight vs. normalweight).
- Reinforcement, plain vs. deformed: Deformed reinforcement has ribs, lugs, or other protrusions to improve bond with concrete; plain reinforcement does not.

Visual Elements Analysis

Figure R2.1: Types of anchors (Page 34)

- Description: This figure provides visual examples of the two main anchor categories: Cast-in anchors and Post-installed anchors. It shows cross-sections of each anchor type embedded in concrete.
- Technical Details:
    - (A) Cast-in anchors: Illustrates (a) a hex head bolt with washer, (b) an L-bolt, (c) a J-bolt, and (d) a welded headed stud. The effective embedment depth, `hef`, is dimensionally labeled from the bearing surface of the head/nut to the concrete surface.
    - (B) Post-installed anchors: Illustrates (a) an adhesive anchor, (b) an undercut anchor, (c1) a sleeve-type expansion anchor, (c2) a stud-type expansion anchor, (d) a drop-in displacement-controlled anchor, and (e) a screw anchor. `hef` is also shown for each of these types.
- Construction Notes: This visual aid is critical for identifying the specific anchor type being specified or installed. The commentary explains the different mechanisms (torque-controlled vs. displacement-controlled), which have different installation and inspection requirements.
- Relationship to Text: The figure directly supports the definitions provided in the Terminology section (2.3) for each type of anchor, making the text definitions much clearer.

Figure R2.2: Possible orientations of overhead, upwardly inclined, or horizontal anchors (Page 35)

- Description: Three simple diagrams show anchors installed in a concrete member at various angles relative to the horizontal plane.
- Technical Details: The diagrams show an anchor installed horizontally, one at approximately a 45-degree upward angle, and one installed vertically into an overhead surface.
- Construction Notes: This clarifies what is meant by "upwardly inclined," which is a critical parameter for certain anchor types (especially adhesive anchors) that can be sensitive to installation orientation.
- Relationship to Text: This figure visually defines the term "anchor, horizontal or upwardly inclined," removing ambiguity from the text-only definition.

Calculations and Formulas (Notation)

This chapter does not contain procedural formulas but instead provides the comprehensive list of variables used in all formulas throughout the Code. Below is a representative sample of key variables.

- `a` = depth of equivalent rectangular stress block, in.

- 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 void.
- A_s = area of nonprestressed longitudinal tension reinforcement, in.^{2}
- A_{tr} = total cross-sectional area of all transverse reinforcement within spacing s that crosses the potential plane of splitting through the reinforcement being developed, in.^{2}
- b = width of compression face of member, in.
- b_w = web width or diameter of circular section, in.
- d = distance from extreme compression fiber to centroid of longitudinal tension reinforcement, in.
- E_c = modulus of elasticity of concrete, psi
- f_c' = specified compressive strength of concrete, psi
- f_y = specified yield strength of nonprestressed reinforcement, psi
- h_{ef} = effective embedment depth of anchor, in.
- λ = modification factor to reflect the reduced mechanical properties of lightweight concrete
- ρ = ratio of A_s to bd
- ϕ = strength reduction factor

BOQ Implications

- The precise definitions in this chapter are critical for creating an unambiguous BOQ. For example, the BOQ should specify "ASTM A706 deformed reinforcement" rather than just "rebar" if required by design.
- Notations for areas (A_g, A_s, etc.) are the basis for all quantity takeoffs for concrete and steel reinforcement.
- The definitions for different anchor types (`anchor, adhesive` vs. `anchor, expansion`) will correspond to different line items with significantly different material and installation costs.

Critical Notes and Warnings

- The chapter emphasizes that these definitions and notations are specific to this Code and must be used as intended to avoid misinterpretation of subsequent requirements.
- The commentary for "aggregate" provides a critical warning: the standard ASTM definition is very broad, and not all materials meeting it are suitable for structural concrete. Additional precautions are required for recycled aggregates.
- The commentary for "anchor, screw" notes that the required predrilled hole size is provided by the manufacturer, highlighting the need to follow manufacturer-specific instructions, which is a recurring theme for post-installed systems.

Chapter 3: Referenced Standards

Overview

This chapter is a complete, itemized list of all external standards that are incorporated by reference into the ACI 318-19 Code, thereby making them legally enforceable parts of the Code. It provides the full designation, including the year of adoption, for standards from organizations such as AASHTO, ACI, ASCE, ASTM, and AWS. The purpose is to provide a single, centralized location for all external standard citations.

Key Standards and Codes Referenced

This chapter is entirely a list of referenced standards. Below is a summary of the organizations and a few key standards mentioned to illustrate the scope.

- American Association of State Highway and Transportation Officials (AASHTO)
  - LRFDUS-8: LRFD Bridge Design Specifications
  - LRFDCONS-4: LRFD Bridge Construction Specifications
- American Concrete Institute (ACI)
  - ACI 301-16: Specifications for Structural Concrete
  - ACI 318.2-19: Building Code Requirements for Concrete Thin Shells and Commentary
  - ACI 355.2-19: Qualification of Post-Installed Mechanical Anchors in Concrete and Commentary
  - ACI 355.4-11: Qualification of Post-Installed Adhesive Anchors in Concrete
- American Society of Civil Engineers (ASCE)
  - ASCE/SEI 7-16: Minimum Design Loads for Buildings and Other Structures
- ASTM International (ASTM)
  - Concrete & Aggregates: C33 (Aggregates), C94 (Ready-Mixed Concrete), C150 (Portland Cement), C595 (Blended Hydraulic Cements), C1140 (Shotcrete Test Panels)
  - Reinforcement: A615 (Deformed Carbon-Steel Bars), A706 (Deformed Low-Alloy Steel Bars), A416 (Steel Strand, Uncoated Seven-Wire for Prestressed Concrete)
  - Testing: C31 (Making and Curing Test Specimens), C39 (Compressive Strength), C42 (Drilled Cores and Sawed Beams)
- American Welding Society (AWS)

    - D1.1/D1.1M: 2015 – Structural Welding Code – Steel
    - D1.4/D1.4M: 2018 – Structural Welding Code – Reinforcing Steel

Technical Specifications

- Mandatory Reference: All listed standards are referenced without exception in the Code (3.1.1). They are to be considered part of the requirements of this Code.
- Edition: The specific edition (including year) listed is the one that applies.
- Commentary Context: The commentary (R3.2.2) clarifies the purpose of some key references. For example:
    - ACI 301 is referenced for mixture proportioning methods.
    - ACI 355.2 is referenced for qualifying post-installed mechanical anchors (expansion, screw, undercut) for use in cracked and uncracked concrete.
    - ACI 355.4 is referenced for qualifying adhesive anchors.
    - ACI 423.7 is referenced for the use of encapsulated tendon systems.

BOQ Implications

- This chapter is the foundation for the material specification section of any BOQ for a concrete structure.
- The BOQ must reference the exact ASTM standard for every material, from cement (ASTM C150) and rebar (e.g., ASTM A615 or A706) to testing procedures (e.g., ASTM C39 for strength tests).
- Costs for materials vary significantly based on the specified standard (e.g., A706 low-alloy steel is typically more expensive than A615 carbon-steel).
- The cost of quality control is directly tied to the testing standards listed here (e.g., ASTM C172 for sampling, C31 for curing specimens). The frequency and type of testing must be accounted for in the project budget.

Critical Notes and Warnings

- Use Correct Edition: The commentary (R3.2.4) emphasizes that the listed ASTM standards are the specific editions adopted by the Code. While standards are frequently revised, using a different edition than what is referenced is not permitted without careful consideration and approval.
- Metric Designations: For simplicity, combined standards (e.g., ASTM A36/A36M) are referenced without the metric (M) designation in the text, but the full designation is given in this chapter. This is important for international projects or those specifying metric units.

Part 2: System Requirements & Analysis (Chapters 4-6)

Chapter 4: Structural System Requirements

Overview

This chapter establishes the fundamental principles for designing a complete structural system. It moves beyond the design of individual components to address the interaction of members and the overall behavior of the structure. Key topics include material properties, design loads, the definition of load paths, and overarching requirements for strength, serviceability, durability, sustainability, structural integrity, and fire resistance. It also introduces specific requirements for different construction types like shotcrete and precast concrete.

Key Standards and Codes Referenced

- ASCE/SEI 7: Used as the basis for design loads and load combinations referenced in Chapter 5.
- ACI 506R: Provides guidance on shotcrete.
- ACI 506.2: Provides specifications for shotcrete.
- ACI 216.1: Provides guidance on determining the fire resistance of concrete.
- PCI Design Handbook (PCI MNL 120): Referenced for guidance on precast concrete design and tolerances.

Technical Specifications

- 4.2 Materials:
  - Concrete: Design properties must be selected according to Chapter 19.
  - Reinforcement: Design properties must be selected according to Chapter 20.
  - Shotcrete: Is considered to have properties similar to conventional concrete unless otherwise noted. Specific provisions for shotcrete are distributed throughout the code as detailed in Table R4.2.1.1.
- 4.3 Design Loads:
  - Loads and load combinations must be in accordance with Chapter 5.
- 4.4 Structural System and Load Paths:
  - Requirement: The structural system shall be designed to provide a continuous load path that transfers all factored loads from the point of application to the foundation (4.4.4).
  - Components: The system includes floors, roofs, beams, columns, walls, diaphragms, foundations, and their connections and anchors (4.4.1).
  - Design: Members, joints, and connections shall be designed according to Chapters 7 through 18 (4.4.2).
  - Alternative Systems: Systems not explicitly covered by the code can be used if approved in accordance with 1.10.1 (4.4.3).

- 4.6 Strength:
    - Fundamental Requirement: The design strength of any member or section (ϕSn) must be greater than or equal to the required strength (U) calculated from factored loads. $\phi Sn \geq U$ (4.6.2).
    - Design Strength: Calculated as the nominal strength (Sn) multiplied by the applicable strength reduction factor (ϕ) (4.6.1).
- 4.11 Fire Resistance:
    - Structural concrete members must satisfy the fire protection requirements of the general building code (4.11.1).
- 4.12 Requirements for Specific Types of Construction:
    - Precast Concrete (4.12.1): Design must account for all loading and restraint conditions from fabrication to final use, including form removal, storage, transport, and erection.
    - Composite Concrete (4.12.3): Members must be designed for all critical loading stages. Reinforcement must be detailed to minimize cracking and prevent separation of components.

Visual Elements Analysis

Table R4.2.1.1: Sections in Code with shotcrete provisions (Page 53)

- Description: This table serves as a quick-reference guide, directing users to the specific sections of the ACI code that contain provisions applicable to shotcrete construction.
- Technical Details: The table is organized by topic and lists the corresponding code section number(s).
    - Freezing and thawing: 19.3.3.3 through 19.3.3.6
    - Reinforcement: 25.2.7 through 25.2.10, 25.5.1.6, and 25.5.1.7
    - Where required or permitted: 26.3.1, 26.3.2
    - Materials: 26.4.1.2, 26.4.1.4, and 26.4.1.6
    - Proportioning mixtures: 26.4.3
    - Documentation: 26.4.4.1
    - Placement and consolidation: 26.5.2.1
    - Curing: 26.5.3
    - Joints: 26.5.6
    - Evaluation and acceptance: 26.12
- Relationship to Text: This table supports section R4.2.1.1 by providing a consolidated list of shotcrete-related requirements that are otherwise distributed throughout the document.

Calculations and Formulas

- Fundamental Strength Design Equation:

- Formula: $\phi S_n \geq U$
- Variables:
  - ϕ: Strength reduction factor (from Chapter 21).
  - S_n: Nominal strength of a member or cross section.
  - U: Required strength to resist factored loads.
- Procedure: This is the core principle of strength design. The calculated "usable" strength of a member (ϕS_n) must exceed the strength required by the calculated factored loads (U).

BOQ Implications

- System-Level Requirements: The emphasis on a complete structural system means that the BOQ must account for not just the primary members, but all connection and interface materials (e.g., dowels, shear keys, collector reinforcement) necessary to ensure a continuous load path.
- Specialized Construction: If shotcrete is used, the BOQ must include costs for specialized labor (certified nozzlemen), equipment, and the creation and testing of mockup panels (as per Table R4.2.1.1), which are not typically required for cast-in-place concrete.
- Seismic Considerations: The assignment of a structure to a Seismic Design Category (SDC) (4.4.6) is a primary cost driver. Higher SDCs will trigger more stringent and material-intensive detailing requirements from Chapter 18, significantly impacting the quantity of reinforcement and concrete member sizes in the BOQ.

Critical Notes and Warnings

- Minimum Requirements: The commentary repeatedly emphasizes that the Code provides *minimum* requirements. For unusual construction or where enhanced performance is desired, the licensed design professional must supplement the Code with sound engineering judgment (R4.1).
- Load Path Integrity: Commentary R4.4.4 warns that the design professional may need to study multiple alternative load paths to identify potential weak links in the structure. This is a critical design responsibility.

Chapter 5: Loads

Overview

This chapter specifies the loads and, critically, the load combinations and load factors that must be used to determine the required strength (U) for structural design. It establishes the basis for all force calculations, ensuring that structures are designed with a consistent level of safety against a variety of loading scenarios. The provisions are closely aligned with ASCE/SEI 7.

Key Standards and Codes Referenced

- ASCE/SEI 7: The primary source for load combinations and definitions. Specific versions are cited in the commentary (e.g., ASCE/SEI 7-16).
- International Building Code (IBC), NFPA 5000, BOCA National Building Code, Standard Building Code (SBC), Uniform Building Code (UBC): Referenced in the commentary to correlate seismic design terminology (SDC vs. seismic zones).

Technical Specifications

- Load Factors and Combinations (5.3): The required strength `U` shall be at least equal to the effects of the factored loads in the combinations given in Table 5.3.1.
- Live Load Reductions (5.2.3): Permitted in accordance with the general building code or, in its absence, with ASCE/SEI 7.
- Special Loads: The chapter includes specific provisions for including loads from fluids (`F`), lateral earth pressure (`H`), ponding rain (`R`), and temperature, creep, shrinkage, and differential settlement (`T`).
- Earthquake Loads: The earthquake load `E` includes effects of horizontal and vertical ground motions. The vertical component is applied as an addition to the dead load (`D`).

Visual Elements Analysis

Table R5.2.2: Correlation between seismic-related terminology in model codes (Page 64)

- Description: This table provides a historical and cross-code correlation for seismic design classifications.
- Technical Details: It maps the Seismic Design Categories (SDC A, B, C, D, E, F) used in recent ACI 318 and IBC editions to the older "Seismic Risk" levels (Low, Moderate/Intermediate, High) from previous ACI editions and the "Seismic Zones" (0, 1, 2, 3, 4) from the Uniform Building Code.
- Relationship to Text: This table gives context to the seismic provisions and helps users interpret older documents or work across different code jurisdictions.

Calculations and Formulas

Table 5.3.1: Load Combinations

- Formula 1: `U = 1.4D`
- Formula 2: `U = 1.2D + 1.6L + 0.5(Lr or S or R)`
- Formula 3: `U = 1.2D + 1.6(Lr or S or R) + (1.0L or 0.5W)`

- Formula 4: `U = 1.2D + 1.0W + 1.0L + 0.5(Lr or S or R)`
- Formula 5: `U = 1.2D + 1.0E + 1.0L + 0.2S`
- Formula 6: `U = 0.9D + 1.0W`
- Formula 7: `U = 0.9D + 1.0E`
- Variables:
  - `U`: Required strength
  - `D`: Dead load
  - `L`: Live load
  - `Lr`: Roof live load
  - `S`: Snow load
  - `R`: Rain load
  - `W`: Wind load
  - `E`: Earthquake load
- Procedure: The design of any member must be based on the load combination that produces the most critical effect (e.g., maximum moment, shear, or axial load).
- Special Load Factors:
  - Fluid (`F`): Added with a factor of 1.4 (if acting alone) or 1.2 (if adding to a primary load).
  - Lateral Earth Pressure (`H`): Added with a factor of 1.6.
  - Internal Loads from Prestressing (`T`): Added with a load factor of 1.0.

BOQ Implications

- Material Quantities: The load factors are safety multipliers that directly increase the design forces. Larger design forces necessitate larger member dimensions and greater quantities of concrete and steel reinforcement, which are the primary cost drivers captured in the BOQ.
- Design Conservatism: The combinations with `0.9D` (Formulas 6 & 7) are for cases where dead load counteracts uplift or overturning from wind or seismic forces. Using a reduced dead load factor ensures a conservative design against instability, which may require larger or heavier foundations, impacting excavation and material quantities.

Critical Notes and Warnings

- Self-Limiting Process: The commentary for rain load (`R`) notes that roofs should be designed with sufficient slope or camber to prevent ponding. If ponding is possible, the design must ensure the process is self-limiting and does not lead to progressive collapse (R5.3.3).
- Strength vs. Service Loads: The commentary (R5.2.1) clarifies that service-level wind loads (`Wa`) from ASCE/SEI 7 are for serviceability checks (like deflections)

and are not appropriate for strength design; the factored wind loads must be used.

Chapter 6: Structural Analysis

Overview

This chapter details the methods and assumptions permitted for analyzing a structure to determine the internal forces (moments, shears, axial forces) that result from the factored loads defined in Chapter 5. It covers modeling of members, arrangement of live loads, simplified analysis methods, and three tiers of increasingly complex analysis: linear elastic first-order, linear elastic second-order (P-delta effects), and inelastic analysis.

Key Standards and Codes Referenced

- Portland Cement Association (PCA): Referenced for analysis of haunched members.
- ACI SP-17(09): Source for the Jackson and Moreland Alignment Charts.

Technical Specifications

- Modeling Assumptions (6.3):
  - General: Assumptions must be reasonable and consistent throughout the analysis (6.3.1.1).
  - Stiffness: Analysis must account for the effects of cracking and member reinforcement by using a reduced effective moment of inertia (I_e) as specified in Table 6.6.3.1.1(a).
- Live Load Arrangement (6.4): Factored live load must be placed in patterns that produce the maximum load effects. For example, to find maximum positive moment in a beam, L is placed on the span and alternate spans; for maximum negative moment, L is placed on adjacent spans (6.4.2).
- Slenderness Effects (6.2.5): Slenderness effects (the influence of axial load on lateral deflections) must be considered unless they can be neglected based on the slenderness ratio $k\ell u/r$.
  - Nonsway columns: Neglect if $k\ell u/r \leq 22$.
  - Sway columns: Neglect if the stability index $Q \leq 0.05$.

Visual Elements Analysis

Figure R6.2.5.1: Alignment charts for effective length factor, k (Page 71)

- Description: Two nomographs are provided, one for nonsway (braced) frames and one for sway (unbraced) frames, to determine the effective length factor k for columns.
- Technical Details: The charts relate the relative stiffness of columns to beams at the top and bottom of a column (Ψ_A and Ψ_B) to the k factor. Ψ is the ratio of Σ(EI/ℓ) of columns to Σ(EI/ℓ) of beams in a plane at one end of a column.
- Construction Notes: This is a classic design aid for calculating the effective length of a column, which is a critical parameter in determining if slenderness effects need to be considered. It requires calculating the stiffness of all connecting members.

Figure R6.2.5.3: Flowchart for determining column slenderness effects (Page 73)

- Description: This is a procedural decision flowchart that guides the designer through the slenderness analysis process.
- Construction Notes: The flowchart starts with the question "Neglect slenderness?" (6.2.5.1). If yes, only a first-order analysis is needed. If no, the designer must determine if the frame is nonsway or sway. Based on this, different paths are taken, involving either moment magnification methods or a full second-order analysis, until a final design moment is achieved. This visual is a roadmap for the entire slenderness design process.

Table 6.5.2 & 6.5.4: Approximate moments and shears (Page 76-77)

- Description: These tables provide simplified coefficients for calculating design moments and shears in continuous beams and one-way slabs under specific, limited conditions.
- Technical Details: They list coefficients (e.g., 1/11, 1/14, 1/16) to be used in formulas like $M_u = w_u \ell_n^2/\text{coefficient}$. The conditions for use are strict: members must be prismatic, loads uniform, at least two spans, similar span lengths, and live load not exceeding 3 times the dead load.
- Relationship to Text: These tables are the core of the "Simplified method of analysis" described in section 6.5.

Table 6.6.3.1.1(a): Moments of inertia and cross-sectional areas for elastic analysis (Page 78)

- Description: This table specifies the reduced stiffness values (moment of inertia I and area A) that must be used in a linear elastic analysis to account for cracking.
- Technical Details: It provides stiffness modifiers as a fraction of the gross-section properties (I_g and A_g).
    - Columns: $I = 0.70I_g$
    - Walls (Uncracked): $I = 0.70I_g$
    - Walls (Cracked): $I = 0.35I_g$
    - Beams: $I = 0.35I_g$

- Flat plates and flat slabs: $I = 0.25I_g$
- Relationship to Text: This table is mandatory for any first- or second-order elastic analysis (6.6.3.1.1) and is fundamental to achieving a realistic model of structural behavior.

Calculations and Formulas

- Approximate Moments:
  - Formula: $M_u = (w_u * \ell_n^2) / C$
  - Variables: w_u = factored load per unit length, ℓ_n = clear span, C = coefficient from Table 6.5.2.
- Slenderness Ratio:
  - Formula: $k * \ell_u / r$
  - Variables: k = effective length factor, ℓ_u = unsupported length, r = radius of gyration ($\sqrt{I_g/A_g}$).
- Stability Index (Q):
  - Formula: $Q = (\Sigma P_u * \Delta_o) / (V_{us} * \ell_c)$
  - Variables: ΣP_u = total factored vertical load in a story, Δ_o = first-order relative lateral deflection, V_{us} = factored horizontal story shear, ℓ_c = length of compression member.
- Critical Buckling Load (Pc):
  - Formula: $P_c = (\pi^2 * (EI)_{eff}) / (k * \ell_u)^2$
- Moment Magnifier (δ) for nonsway columns:
  - Formula: $\delta = C_m / (1 - (P_u / (0.75 * P_c))) \geq 1.0$
  - Variables: C_m = factor relating actual moment diagram to equivalent uniform moment diagram.

BOQ Implications

- Analysis Method: The choice of analysis method directly impacts engineering costs and can affect material quantities. The Simplified Method (6.5) is quick but conservative, potentially leading to higher material quantities in the BOQ. A full second-order analysis (6.7) is more complex but can result in a more optimized (and potentially less expensive) structure.
- Stiffness Modifiers: Using reduced stiffness values (Table 6.6.3.1.1a) will result in larger calculated deflections and potentially larger moments from second-order effects. This may require larger member sizes or more reinforcement to meet strength and serviceability limits, thus increasing BOQ quantities.

Critical Notes and Warnings

- Simplified Method Limitations: The commentary warns that the simplified moment coefficients in 6.5 are only valid for the specific conditions listed. Their use is inappropriate for beams with unusual loading or geometry.
- Cracked vs. Uncracked Sections: Using gross moment of inertia (I_g) instead of the required effective moment of inertia (I_e) for analysis is a common error that can lead to an unsafe underestimation of deflections and second-order effects. The Code mandates using reduced stiffness to account for cracking.

Part 3: Slab Systems (Chapters 7-8)

Chapter 7: One-Way Slabs

Overview

This chapter provides the requirements for the design of slabs that are reinforced to resist flexural stresses primarily in one direction. It covers a range of one-way slab systems, including solid slabs, slabs cast on stay-in-place steel deck, composite slabs, and precast, prestressed hollow-core slabs. The chapter outlines the minimum requirements for slab thickness to control deflections, the calculation of required strength, the determination of design strength, and specific rules for reinforcement limits and detailing.

Key Standards and Codes Referenced

- SDI C: Standard for Composite Steel Floor Deck-Slabs (referenced in commentary R7.1.1).

Technical Specifications

- 7.3 Design Limits:
  - Minimum Thickness (7.3.1.1): For solid nonprestressed slabs not supporting or attached to partitions or other construction likely to be damaged by large deflections, the overall slab thickness, h, shall not be less than the limits in Table 7.3.1.1. These limits are for normalweight concrete and f_y = 60,000 psi.
    - For f_y other than 60,000 psi, the values in the table shall be multiplied by (0.4 + fy/100,000) (7.3.1.1.1).
    - For lightweight concrete with equilibrium density w_c between 90 and 115 lb/ft³, the values shall be multiplied by the greater of (1.65 – 0.005wc) and 1.09 (7.3.1.1.2).
  - Deflection Calculations (7.3.2): For slabs not satisfying the minimum thickness requirements of 7.3.1, immediate and time-dependent

deflections must be calculated in accordance with 24.2 and not exceed the limits in 24.2.2.

- 7.4 Required Strength:
  - Factored moments (M_u) and shears (V_u) are to be calculated at the face of supports for slabs built integrally with them (7.4.2.1, 7.4.3.1).
  - For nonprestressed slabs, shear sections located less than a distance d from the face of the support can be designed for the shear V_u at d (7.4.3.2).
- 7.6 Reinforcement Limits:
  - Minimum Flexural Reinforcement (Nonprestressed) (7.6.1.1): The minimum area of flexural reinforcement, $A_{s,min}$, shall be $0.0018A_g$, where A_g is the gross area of the concrete section. This reinforcement is to be provided at the tension face.
  - Minimum Flexural Reinforcement (Prestressed) (7.6.2.1): For slabs with bonded tendons, the total reinforcement (A_s and A_{ps}) must be adequate to develop a factored load at least 1.2 times the cracking load based on the modulus of rupture f_r from 19.2.3.
  - Minimum Bonded Reinforcement (Unbonded Tendons) (7.6.2.3): For slabs with unbonded tendons, a minimum area of bonded deformed longitudinal reinforcement, $A_{s,min}$, shall be provided based on the formula: $A_{s,min} \geq 0.004A_{ct}$, where A_{ct} is the area of that part of the cross section between the flexural tension face and the centroid of the gross section.
  - Shrinkage and Temperature Reinforcement (7.6.4): Reinforcement for shrinkage and temperature stresses shall be provided in accordance with 24.4.
- 7.7 Reinforcement Detailing:
  - Spacing (7.7.2.2): For nonprestressed and Class C prestressed slabs, the spacing of bonded longitudinal reinforcement closest to the tension face shall not exceed the limits given in 24.3.
  - Termination of Reinforcement (7.7.3.8):
    - At simple supports, at least one-third of the maximum positive moment reinforcement shall extend along the slab bottom into the support.
    - At other supports, at least one-fourth of the maximum positive moment reinforcement shall extend along the slab bottom into the support at least 6 in.
  - Structural Integrity (7.7.7): At least one-quarter of the maximum positive moment reinforcement shall be continuous. At noncontinuous supports, this reinforcement must be anchored to develop f_y.

Visual Elements Analysis

Table 7.3.1.1: Minimum thickness of solid nonprestressed one-way slabs (Page 92)

- Description: This table provides simplified minimum slab thickness (h) requirements to control deflections without performing explicit calculations. It is based on the support condition of the slab.
- Technical Details:
  - Simply supported: $h = \ell/20$
  - One end continuous: $h = \ell/24$
  - Both ends continuous: $h = \ell/28$
  - Cantilever: $h = \ell/10$
  - Footnote: Specifies that these expressions are for normalweight concrete and f_y = 60,000 psi. For other cases, h must be modified.
- Relationship to Text: This table is the primary provision of section 7.3.1 and provides the prescriptive path for satisfying deflection serviceability for many common one-way slab designs.

Figure R7.6.4.2: Section through beams cast monolithically with slab (Page 96)

- Description: The figure shows a plan and a cross-section of a slab-and-beam system, illustrating the placement of shrinkage and temperature reinforcement in the slab.
- Technical Details:
  - Plan View: Shows slab panels with spans $L1$ and $L2$. Beam tendons are shown running longitudinally in the beams. Slab shrinkage and temperature tendons are shown running perpendicular to the beam tendons. Additional reinforcement is shown required within a certain distance of the beams.
  - Section A-A: A cross-section that highlights a portion of the slab tributary to each beam (shown as an "orange area").
  - Callout: "Beam and slab tendons within the orange area must provide 100 psi minimum average compressive stress in the orange area (gross area tributary to each beam)."
- Construction Notes: This visual clarifies the requirement in 24.4.4.1 (referenced by 7.6.4) for providing a minimum level of prestressing for shrinkage and temperature control. It defines the specific cross-sectional area over which the average stress must be calculated.
- Relationship to Text: The figure visually explains the application of prestressing as a method for shrinkage and temperature reinforcement, which is an alternative to conventional deformed bars.

Calculations and Formulas

- Minimum Flexural Reinforcement:
  - Formula: $A_{s,min} = 0.0018 * A_g$
  - Variables: $A_{s,min}$ = minimum area of flexural reinforcement (in.²), A_g = gross area of the concrete section (in.²).
- Minimum Bonded Reinforcement for Unbonded Tendons:
  - Formula: $A_{s,min} = 0.004 * A_{ct}$
  - Variables: $A_{s,min}$ = minimum area of bonded reinforcement (in.²), A_{ct} = area of concrete in tension (in.²).

BOQ Implications

- Concrete Volume: The minimum thickness requirements from Table 7.3.1.1 are a primary driver of the concrete quantity in the BOQ for one-way slabs.
- Steel Quantity: The minimum reinforcement requirement of $0.0018A_g$ establishes a baseline quantity of steel that must be included in the BOQ, regardless of strength requirements. This is often the controlling factor for temperature and shrinkage reinforcement.
- Material Specifications: The code distinguishes between nonprestressed and prestressed systems. The BOQ must clearly define the material type (e.g., deformed bars vs. prestressing strand), which have different material costs and labor requirements for installation.

Critical Notes and Warnings

- Applicability of Minimum Thickness: The commentary (R7.3.2) warns that the simplified minimum thickness table is not sufficient for slabs supporting nonstructural elements sensitive to deflection. In such cases, detailed deflection calculations are mandatory.
- T-Beam Action: The commentary (R7.5.2.3) notes a specific provision where a slab may act as the flange of a supporting beam. This requires additional top reinforcement perpendicular to the beam to handle negative moments that may develop, which is a detail that could be missed if only designing the slab for one-way action.

Chapter 8: Two-Way Slabs

Overview

This chapter covers the design of slabs supported on all four sides, which resist loads through flexure in two directions. It includes provisions for various systems such as solid flat plates, flat slabs (with drop panels or shear caps), and slabs supported by beams. The chapter provides methods for determining minimum thickness, calculating and distributing moments to column and middle strips, and detailing reinforcement for flexure, shear, and structural integrity.

Key Standards and Codes Referenced

- The commentary (R8.1) lists an extensive series of research papers and tests that form the empirical basis for the two-way slab design provisions.

Technical Specifications

- 8.2 General:
  - Drop Panel: Defined as a projection below the slab used to reduce negative reinforcement or minimum thickness. Must project at least $h/4$ below the slab and extend at least $\ell/6$ in each direction from the column centerline (8.2.4).
- 8.3 Design Limits - Minimum Thickness:
  - Slabs without Interior Beams (Table 8.3.1.1): For slabs with a max long-to-short span ratio of 2, minimum thickness h is specified (e.g., $\ell n/33$, $\ell n/30$) based on the presence of drop panels and edge beams. Minimum thickness is 5 in. without drop panels and 4 in. with drop panels.
  - Slabs with Beams on All Sides (Table 8.3.1.2): Minimum thickness is governed by more complex formulas involving αfm (the average value of stiffness ratio αf for all beams on the edges of a panel).
- 8.4 Required Strength:
  - Moment Transfer (8.4.2.2): A portion of the slab moment at a support (Msc) is transferred to the column by flexure, governed by γf. The remainder is transferred by eccentricity of shear.
  - Flexural Transfer Fraction γf: $\gamma f = 1 / (1 + (2/3) * \sqrt{(b1/b2)})$ where $b1$ and $b2$ are dimensions of the critical section for shear.
- 8.6 Reinforcement Limits:
  - Minimum Flexural Reinforcement (8.6.1.1): The ratio of reinforcement area to gross concrete area shall be at least 0.0018.
  - Prestressed Slabs (Table 8.6.2.3): Specifies minimum bonded reinforcement required in the precompressed tension zone based on the calculated tensile stress ft.
- 8.7 Reinforcement Detailing:
  - Reinforcement Distribution: Slab reinforcement is apportioned between column strips and middle strips according to specified percentages (e.g., 75% of negative moment reinforcement in the column strip).
  - Corner Reinforcement (8.7.3): Special reinforcement is required at exterior corners to control lifting and cracking.

- Structural Integrity (8.7.4.2): For two-way slabs without beams, all bottom bars within the column strip in each direction must be continuous or spliced with Class B tension lap splices. At least two of these bars in each direction must pass through the column core.

Visual Elements Analysis

Figure 8.7.4.1.3: Minimum extensions for deformed reinforcement in two-way slabs without beams (Page 119)

- Description: This is a critical and highly detailed diagram showing the required placement, termination points, and splices for top and bottom reinforcement in both column and middle strips of a two-way slab system.
- Technical Details:
  - Bar lengths are specified as fractions of the clear span, ℓ_n. For example, at an interior support, 50% of the top column strip bars extend $0.30\ell_n$ into the span, while the other 50% extend $0.20\ell_n$.
  - It shows that 100% of bottom reinforcement in the column strip must be continuous or spliced near the support ("Continuous bars").
  - The location of splices is mandated: top bar splices must be at or near midspan; bottom bar splices must be at or near the support.
- Relationship to Text: This figure is the primary guide for detailing reinforcement in two-way slabs without beams, visually codifying the rules in section 8.7.4.

Figure R8.7.4.1.3: Punching shear cracks in ordinary and thick slabs (Page 120)

- Description: This figure illustrates the benefit of extending top reinforcement beyond the code minimums to intercept a potential punching shear failure plane.
- Technical Details:
  - (a) Ordinary Slab: Shows a potential punching shear crack originating from the column and extending upwards through the slab. The standard termination of top reinforcement at $0.3\ell_n$ may not intercept this crack.
  - (b) Thick Slab: Shows the same potential crack but illustrates that extending the top reinforcement to a distance of $5d$ from the column face is required to intercept the crack.
- Relationship to Text: This visual explains the rationale behind advanced detailing for thick slabs where punching shear is a critical concern, going beyond the basic rules of Figure 8.7.4.1.3.

Calculations and Formulas

- Moment Transfer Fraction:
  - Formula: $\gamma_f = 1 / (1 + (2/3)\sqrt{(b_1/b_2)})$
  - Variables: b_1 = width of the critical section for shear in the direction of the span, b_2 = width of the critical section for shear transverse to the span.

- Minimum Reinforcement:
  - Formula: `As,min = 0.0018 * b * h`
  - Variables: `b` = width of strip, `h` = slab thickness.

BOQ Implications

- Reinforcement Complexity: The BOQ for two-way slabs is much more complex than for one-way. Steel takeoff must be done strip by strip (column vs. middle) and layer by layer (top vs. bottom). The varying bar lengths from Figure 8.7.4.1.3 must be meticulously calculated.
- Formwork Costs: The use of drop panels (8.2.4) or shear caps significantly increases the complexity and cost of formwork compared to a simple flat plate. These must be separate line items in the BOQ.
- Structural Integrity Steel: The requirement for continuous bottom bars through the column core is a specific quantity of steel that must be added to the BOQ, with lengths sufficient to develop Class B splices if needed.

Critical Notes and Warnings

- Moment Transfer is Critical: The transfer of moment between the slab and column is a fundamental aspect of two-way slab behavior. The commentary (R8.4.2.2) emphasizes that reinforcement must be properly placed within the effective width to resist these moments.
- Punching Shear: The commentary (R8.6.1.1 and R8.7.4.1.3) repeatedly warns about the danger of punching shear failure. Proper detailing, especially of top reinforcement and at corners, is critical to prevent this brittle failure mode.
- Integrity Reinforcement: The commentary (R8.7.4.2) explains that the continuous bottom bars are essential to provide residual capacity and prevent progressive collapse if a single column support fails due to punching shear.

Part 4: Beams and Columns (Chapters 9-10)

Chapter 9: Beams

Overview

This chapter provides the comprehensive requirements for the design of beams, which are defined as members subjected primarily to flexure and shear. It covers composite beams, one-way joist systems, and deep beams. The chapter details requirements for stability (lateral bracing), minimum depth to control deflection, calculation of required strength, determination of design strength, and extensive rules for reinforcement limits and detailing.

Key Standards and Codes Referenced

- AISC 360: Standard for structural steel buildings, referenced in the commentary (R9.1.1) for the design of composite structural steel-concrete beams, which are not covered by this chapter.

Technical Specifications

- 9.2 Stability:
  - Lateral Bracing (9.2.3.1): For a beam not continuously braced, the spacing of lateral bracing for the compression flange shall not exceed 50 times the least width `b` of the compression flange or face.
- 9.3 Design Limits:
  - Minimum Depth (9.3.1.1): For nonprestressed beams not supporting or attached to partitions or other construction likely to be damaged by large deflections, the overall depth `h` shall not be less than the limits in Table 9.3.1.1. These values are for normalweight concrete and `fy` = 60,000 psi.
    - `fy` other than 60,000 psi: Multiply values by (0.4 + fy/100,000).
    - Lightweight concrete: Multiply values by the greater of (1.65 – 0.005wc) and 1.09.
- 9.4 Required Strength:
  - Critical Section for Shear (9.4.3.2): For members supported on top, sections located less than a distance `d` from the face of the support are permitted to be designed for the shear `Vu` at `d`. The commentary (R9.4.3.2) clarifies that this does not apply if loads are applied near the bottom of the beam, which would require the critical section to be taken at the face of the support.
- 9.6 Reinforcement Limits:
  - Minimum Flexural Reinforcement (`As,min`) (9.6.1.2): `As,min` shall be the larger of (a) and (b):
    - (a) `(3√fc' / fy) * bw * d`
    - (b) `(200 / fy) * bw * d`
    - For T-beams with the flange in tension, `bw` is replaced by the lesser of the effective flange width `bf` or `2bw`.
  - Maximum Flexural Reinforcement (9.6.1.1): The reinforcement ratio `ρ` shall not exceed 0.025 for Grade 60 reinforcement and 0.02 for Grade 80 reinforcement.
- 9.7 Reinforcement Details:
  - Skin Reinforcement (9.7.2.3): For beams with `h > 36 in.`, longitudinal skin reinforcement shall be uniformly distributed on both side faces of the beam for a distance `h/2` from the tension face. Spacing shall not exceed the limits in 24.3.2.

    - Termination of Reinforcement (9.7.3.3): Reinforcement shall extend a distance of d or $12d_b$ (whichever is greater) beyond the point where it is no longer required to resist flexure.
    - Structural Integrity (9.7.7.1): At least one-third of the positive moment reinforcement at simple supports and one-fourth at continuous supports shall extend along the same face of the member into the support. For frames, this reinforcement shall be anchored to develop f_y at the face of the support.
- 9.9 Deep Beams:
    - Definition (9.9.1.1): Members with a clear span $\ell_n \le 4h$ or with concentrated loads placed within a distance $2h$ from the face of the support.
    - Design Method (9.9.1.3): The strut-and-tie method of Chapter 23 is deemed to satisfy the requirement for considering the nonlinear strain distribution.

Visual Elements Analysis

Figure R9.2.4.4: Examples of the portion of slab to be included with the beam for torsional design (Page 130)

- Description: Two diagrams show the cross-section of a T-beam and an L-beam, illustrating the effective overhanging flange width that must be included for torsional calculations.
- Technical Details: The effective overhanging flange on each side shall not exceed the lesser of the beam projection h_b and $4h_f$. This defines the section properties A_{cp} and p_{cp} used in torsion design.
- Relationship to Text: This figure visually defines the geometry specified in section 9.2.4.4 for calculating torsional properties.

Figure R9.4.3.2a: Free body diagrams of the end of a beam (Page 133)

- Description: A critical diagram showing the forces acting on the end of a beam, illustrating why the critical section for shear is located at a distance d from the support face.
- Technical Details: The diagram shows that loads applied to the beam between the support and distance d are transferred directly to the support by compression in the web. The shear force V_u at the critical section is resisted by the concrete (V_c) and the stirrups that cross the inclined crack ($\Sigma A_v f_{yt}$).
- Relationship to Text: This figure provides the theoretical basis for the rule in 9.4.3.2, justifying the location of the critical section for shear calculations.

Calculations and Formulas

- Minimum Flexural Reinforcement ($A_{s,min}$):

- Formulas: $A_{s,min} = (3\sqrt{f_c'} / f_y) * b_w * d$ OR $A_{s,min} = (200 / f_y) * b_w * d$ (use the larger value).
- Variables: f_c' = specified compressive strength of concrete (psi), f_y = specified yield strength of reinforcement (psi), b_w = web width (in.), d = effective depth (in.).

BOQ Implications

- Minimum Steel: The $A_{s,min}$ requirement sets a baseline quantity of longitudinal steel for all beams, which must be included in the BOQ even if strength calculations require less.
- Skin Reinforcement: For deep beams ($h > 36$ in.), the requirement for skin reinforcement adds a specific quantity of smaller-diameter bars to the BOQ that would not be present in shallower beams.
- Lateral Bracing: The stability requirement of bracing at $50b$ intervals may require additional steel members or concrete elements (like cross-beams) to be added to the project scope and BOQ.
- T-Beam Formwork: Designing a section as a T-beam implies monolithic placement of the slab and beam stem, which is a common formwork configuration. The effective flange width calculations in 9.2.4 do not change the physical formwork but are critical for design accuracy.

Critical Notes and Warnings

- Deep Beams: The commentary (R9.9.1.1) strongly emphasizes that deep beams behave differently from slender beams. The linear strain assumption is invalid, and the strut-and-tie model (Chapter 23) should be used. This is a fundamental shift in design methodology.
- Torsion in Combination with Shear: The commentary (R9.5.4.3) explains that transverse reinforcement must be designed for the sum of shear and torsion requirements. It is a common error to handle them separately; the stirrups must resist the combined effect.

Chapter 10: Columns

Overview

This chapter covers the design of members that resist primarily axial compression, or combined axial compression and flexure. It includes provisions for both nonprestressed and prestressed columns, as well as reinforced concrete pedestals. Key topics include dimensional limits, minimum and maximum reinforcement limits, and extensive requirements for detailing of longitudinal and transverse reinforcement (ties and spirals) to ensure strength and ductility.

Key Standards and Codes Referenced

- This chapter is largely self-contained but relies on principles and formulas from other chapters (e.g., Chapter 6 for slenderness, Chapter 22 for strength calculation, Chapter 25 for detailing).

Technical Specifications

- 10.3 Design Limits:
  - Oversized Columns (10.3.1.2): For columns with a cross-section larger than required by loading, it is permitted to base the minimum reinforcement and design strength on a reduced effective area, but not less than one-half the total area. This provision does not apply to columns in special moment frames.
- 10.6 Reinforcement Limits:
  - Longitudinal Reinforcement (A_{st}) (10.6.1.1): The area of longitudinal reinforcement shall be at least $0.01A_g$ and shall not exceed $0.08A_g$.
  - Minimum Number of Bars (10.7.3.1):
    - At least 3 bars within triangular ties.
    - At least 4 bars within rectangular or circular ties.
    - At least 6 bars enclosed by spirals or for columns in special moment frames.
- 10.7 Detailing:
  - Transverse Reinforcement - Ties (10.7.6.1): Spacing of ties shall not exceed the least of:
    - 16 longitudinal bar diameters ($16d_b$).
    - 48 tie bar diameters ($48d_b$).
    - The smallest cross-sectional dimension of the member.
  - Transverse Reinforcement - Spirals (10.7.6.3): The ratio of spiral reinforcement ρ_s shall satisfy the formula in 25.7.3.3 to provide adequate confinement.
  - Lap Splices (10.7.5): Must be located, if possible, within the center half of the member length. Tension lap splices must be used if the bar stress can exceed $0.5f_y$ in tension.

Visual Elements Analysis

Figure R10.4.2.1: Critical column load combination (Page 159)

- Description: This is a P-M (Axial Load vs. Moment) interaction diagram, a fundamental tool for column design. It shows the capacity of a column section under varying combinations of axial load and moment.
- Technical Details:
  - The outer curve (M_n, P_n) represents the nominal strength of the section.
  - The inner curve (ϕM_n, ϕP_n) represents the design strength.
  - An "Acceptable region" is shown inside the design strength curve.
  - Points LC1, LC2, and LC3 represent the required strength (P_u, M_u) from different factored load combinations.
- Construction Notes: The diagram visually demonstrates that *all* load combinations must fall within the "Acceptable region." It is not sufficient to only check the points of maximum axial load and maximum moment independently.
- Relationship to Text: This figure is a graphical representation of the core design requirement for columns: ensuring that the required strength for all load cases is less than or equal to the design strength of the member.

Figure R10.7.5.2.1: Application of an example of application of 10.7.5.2.1(a) (Page 163)

- Description: A cross-section of a rectangular tied column illustrating how to calculate the effective area of transverse reinforcement required for compression lap splices.
- Technical Details: The diagram shows a column with dimensions h_1 and h_2. It provides the formulas for the required area of ties in each direction: Direction 1: $4A_b \geq 0.0015 h_1 S$ and Direction 2: $2A_b \geq 0.0015 h_2 S$.
- Relationship to Text: This figure clarifies the application of the formula in 10.7.5.2.1(a) for providing confinement over lap splices, which allows for a reduction in the splice length. It shows how to count the number of effective tie legs in each direction.

Calculations and Formulas

- Minimum Spiral Reinforcement Ratio:
  - Formula: $\rho_s \geq 0.45 * (A_g/A_{ch} - 1) * (f_c'/f_{yt})$ (from 25.7.3.3)
  - Variables: ρ_s = ratio of volume of spiral reinforcement to total volume of core, A_g = gross area of section, A_{ch} = area of core, f_c' = concrete strength, f_{yt} = yield strength of spiral reinforcement.
- Nominal Axial Strength at Zero Eccentricity (P_o):
  - Formula: $P_o = 0.85 * f_c' * (A_g - A_{st}) + f_y * A_{st}$ (from 22.4.2.2)
  - Variables: A_g = gross area, A_{st} = total area of longitudinal reinforcement.

BOQ Implications

- Steel Quantity: The minimum longitudinal steel ratio of 1% (`0.01Ag`) is a significant cost driver and often governs the design of lightly loaded columns. This establishes a baseline steel quantity for all columns in the BOQ.
- Labor for Ties/Spirals: The fabrication and installation of transverse reinforcement, especially closely spaced spirals or multi-leg tie sets, is labor-intensive. The BOQ must account for this higher labor cost compared to simple beam stirrups.
- Splice Locations and Types: The requirement for tension lap splices (which are longer and more expensive than compression splices) in certain zones, and the potential need to stagger splices, affects both material quantity and labor complexity.

Critical Notes and Warnings

- Maximum Reinforcement Ratio: The commentary (R10.6.1.1) provides a critical practical warning: while the code permits a maximum longitudinal steel ratio of 8%, it is very difficult to place concrete properly in columns with that much reinforcement, especially at lap splice locations where the steel area doubles. A more practical upper limit is often around 4%. Exceeding this can lead to honeycombing and may necessitate special concrete mixtures (e.g., self-consolidating concrete), which have cost implications.
- Confinement is Key: The extensive and detailed rules for transverse reinforcement (ties and spirals) are not arbitrary. They are essential for providing confinement to the concrete core, which prevents the longitudinal bars from buckling and dramatically increases the column's ductility and strength, especially under seismic loading.

Part 5: Walls and Diaphragms (Chapters 11-12)

Chapter 11: Walls

Overview

This chapter provides the design and detailing requirements for structural walls, which are vertical elements designed to resist axial load, lateral load, or both. It covers general walls, plain concrete walls, and walls designed by an alternative method for out-of-plane slender walls. The chapter outlines requirements for minimum thickness, load distribution, required strength based on in-plane and out-of-plane forces, design strength calculations for shear and flexure, and minimum reinforcement limits and detailing.

Key Standards and Codes Referenced

This chapter is primarily self-referential, directing users to other chapters within ACI 318-19 for fundamental calculations (e.g., Chapter 5 for loads, Chapter 22 for sectional strength).

Technical Specifications

- 11.2 Load Distribution:
    - Concentrated Loads (11.2.3.1): The effective horizontal length of a wall resisting a concentrated load shall not exceed the lesser of the center-to-center distance between loads or the bearing width plus four times the wall thickness.
- 11.3 Design Limits:
    - Minimum Thickness (11.3.1.1): Prescriptive minimum wall thicknesses are provided in Table 11.3.1.1.
        - Bearing Walls: The greater of 4 in. and 1/25 of the unsupported length.
        - Nonbearing Walls: The greater of 4 in. and 1/30 of the unsupported length.
        - Exterior Basement and Foundation Walls: 7.5 in.
- 11.5 Design Strength:
    - In-Plane Shear Strength (V_n) (11.5.4): The nominal in-plane shear strength is calculated by:
        - $V_n = (\alpha_c * \lambda * \sqrt{f_c'} + \rho_t * f_y) * A_{cv}$
        - The coefficient α_c varies linearly from 3.0 for walls with $h_w/\ell_w \leq 1.5$ down to 2.0 for walls with $h_w/\ell_w \geq 2.0$.
        - The maximum in-plane shear strength is limited to $V_n \leq 8\sqrt{f_c'} * A_{cv}$ to prevent diagonal compression failure.
- 11.6 Reinforcement Limits:
    - Minimum Reinforcement Ratios (11.6.1): Minimum ratios for distributed web reinforcement are specified in Table 11.6.1.
        - Minimum Longitudinal Reinforcement Ratio ($\rho_{\ell,min}$): Varies from 0.0012 to 0.0025 based on bar size and yield strength.
        - Minimum Transverse Reinforcement Ratio ($\rho_{t,min}$): Varies from 0.0020 to 0.0025 based on bar size and yield strength.
- 11.7 Reinforcement Detailing:
    - Layers of Reinforcement (11.7.2.3): For walls thicker than 10 in., reinforcement shall be placed in at least two layers, one near each face.
    - Spacing (11.7.2.1): Spacing of longitudinal bars in cast-in-place walls shall not exceed the lesser of 3h and 18 in.

- Reinforcement around Openings (11.7.5): At least two No. 5 bars shall be provided around window, door, and similarly sized openings, anchored to develop f_y at the corners.

Visual Elements Analysis

Figure R11.4.1.3: In-plane and out-of-plane forces (Page 169)

- Description: This is an isometric 3D diagram of a single wall panel illustrating the different types of forces that can act upon it.
- Technical Details: The diagram uses vectors to show the direction of each force type:
    - Axial force: A vertical force acting downwards along the wall's centroidal axis.
    - Self-weight: A downward force representing the mass of the wall itself.
    - In-plane shear: A horizontal force acting parallel to the length of the wall.
    - Out-of-plane shear: A horizontal force acting perpendicular to the face of the wall.
    - In-plane moment: A moment that causes bending within the primary plane of the wall (like a deep, vertical beam).
    - Out-of-plane moment: A moment that causes the wall to bend out of its primary plane (like a slender slab).
- Relationship to Text: This figure provides essential visual context for the entire chapter, clarifying the distinction between in-plane and out-of-plane actions, which are governed by different design provisions and strength calculations.

Calculations and Formulas

- In-Plane Shear Strength (V_n):
    - Formula: $V_n = (\alpha_c * \lambda * \sqrt{f_c'} + \rho_t * f_y) * A_{cv}$
    - Variables:
        - α_c: Coefficient based on wall aspect ratio (h_w/ℓ_w).
        - λ: Lightweight concrete modification factor.
        - f_c': Specified compressive strength of concrete (psi).
        - ρ_t: Ratio of distributed transverse reinforcement area to gross concrete area.
        - f_y: Specified yield strength of transverse reinforcement (psi).
        - A_{cv}: Gross area of concrete section bounded by web thickness and length of section in the direction of shear force (in.^{2}).

BOQ Implications

- Minimum Thickness: The prescriptive minimums in Table 11.3.1.1 (e.g., 7.5 in. for basement walls) provide a baseline for concrete quantity takeoffs in the BOQ.

- Minimum Reinforcement: The minimum reinforcement ratios ($\rho_{\ell,min}$ and $\rho_{t,min}$) from Table 11.6.1 establish the minimum weight of steel per unit area of wall, which is a significant cost component. This reinforcement is required even if not needed for strength.
- Two Layers of Steel: The requirement for two layers of reinforcement in walls thicker than 10 inches doubles the labor complexity for placing and tying steel compared to a single mat, which must be factored into labor costs in the BOQ.

Critical Notes and Warnings

- Shear Strength Limit: The commentary (R11.5.4.2) warns that the upper limit on shear strength ($V_n \leq 8\sqrt{f_c'} * A_{cv}$) is imposed to guard against a brittle diagonal compression failure of the concrete itself, which must be avoided.
- Confinement at Floor Joints: The commentary (R11.2.4.2) notes that when floor-system concrete has a lower strength than the wall concrete, the capacity of the wall can be reduced at that location due to less confinement. This is a critical detail for multi-story construction.

Chapter 12: Diaphragms

Overview

This chapter covers the design of diaphragms, which are typically horizontal or nearly horizontal systems (such as floor and roof slabs) that transmit lateral forces to the vertical elements of the lateral-force-resisting system (e.g., shear walls or frames). It addresses various diaphragm types, including cast-in-place, composite, and untopped precast systems. The chapter provides requirements for analysis and modeling, design strength, and detailing of reinforcement for chords, collectors, and the diaphragm body.

Key Standards and Codes Referenced

This chapter is primarily self-referential.

Technical Specifications

- 12.3 Minimum Thickness:
    - For diaphragms transmitting earthquake forces, concrete slabs and composite topping slabs must be at least 2 in. thick (12.6.1). Topping slabs on precast elements that do not rely on composite action must be at least 2-1/2 in. thick.
- 12.4 Analysis and Modeling:

- Permitted Models (12.4.2.4): Diaphragms can be analyzed using several models:
    - Rigid Diaphragm Model: Assumes the diaphragm has infinite in-plane stiffness and distributes lateral forces to vertical elements based on their relative stiffness.
    - Flexible Diaphragm Model: Assumes the diaphragm has no in-plane stiffness and distributes forces based on tributary area.
    - Bounding Analysis: Uses the envelope of results from both rigid and flexible analyses.
    - Finite Element Analysis.
    - Strut-and-Tie Model.
- 12.5 Design Strength:
  - Collectors (12.5.4): Collectors must be designed as tension members, compression members, or both, in accordance with 22.4.
  - Shear Strength (Topping Slabs) (12.9.3): For topping slabs over precast elements, the shear strength above the joints is limited to the shear-friction capacity, calculated as `Vn = Avf * fy * μ`.
- 12.7 Reinforcement and Connections:
  - Collectors (12.5.4.1): Collector reinforcement must extend from the vertical elements across all or part of the diaphragm as required to transfer the calculated shear forces.
  - Diaphragm Reinforcement (12.6.3): Reinforcement provided for in-plane diaphragm forces is in addition to reinforcement required for other effects (e.g., gravity loads, shrinkage).

Visual Elements Analysis

Figure R12.1.1: Typical diaphragm actions (Page 178)

- Description: This is an essential isometric diagram of a multi-story building that visually defines the role of a diaphragm and its components in a lateral-force-resisting system.
- Technical Details: The figure shows a roof slab acting as a diaphragm. Key labeled elements and actions include:
  - In-plane inertial loads: Forces generated within the diaphragm's mass.
  - Out-of-plane wind pressure: Force applied to the building facade, which is transferred to the diaphragm.
  - Diaphragm: The horizontal floor/roof element.
  - Collector: A structural element (often a beam or a reinforced band in the slab) that collects shear from the diaphragm and transfers it to a shear wall.

    - Structural (shear) wall: The vertical element that receives the lateral load from the collector.
    - Thrust: Shows how an inclined column creates horizontal forces that must be resisted by the diaphragm.
- Relationship to Text: This figure perfectly illustrates the concepts defined in the text. It makes clear that a diaphragm is not just a slab but a complete system for transferring lateral loads, involving distinct components like collectors and chords that require specific design attention.

Calculations and Formulas

- Diaphragm Shear Strength:
    - Formula: `Vn = Acv * (2λ√fc' + ρt*fy)`
    - Variables: Same as the wall shear equation, but applied to the diaphragm cross-section.
- Shear-Friction Strength (at joints):
    - Formula: `Vn = Avf * fy * μ`
    - Variables: `Avf` = area of shear-friction reinforcement (in.^{2}), `fy` = yield strength (psi), `μ` = coefficient of friction (from 22.9).

BOQ Implications

- Collector Reinforcement: Collectors often require significant amounts of longitudinal reinforcement that must be quantified in the BOQ. This steel is in addition to the standard slab reinforcement.
- Chord Reinforcement: While not explicitly detailed in this figure, the edges of the diaphragm act as the flange of a deep beam and often require concentrated longitudinal reinforcement (chords) to resist in-plane bending moments. This is another specific steel quantity for the BOQ.
- Topping Slabs: If a composite topping slab is used, the BOQ must include costs for surface preparation of the precast elements (roughening) to ensure proper bond for shear transfer.
- Minimum Thickness: The 2-inch minimum thickness for diaphragms sets a baseline concrete volume.

Critical Notes and Warnings

- Complete Load Path: The commentary (R12.5.1.1) emphasizes that a complete load path is required for all forces. A failure in a collector or its connection to a shear wall is a failure of the entire lateral system.
- Slabs-on-Ground: The commentary (R13.2.4, referenced from this chapter) warns that slabs-on-ground are often designed to act as diaphragms to tie the foundation together. When this is the case, the construction documents must

clearly state this, and prohibit random saw-cutting of the slab, which would destroy its integrity.

Part 6: Foundations and Plain Concrete (Chapters 13-15)

Chapter 13: Foundations

Overview

This chapter provides the specific requirements for the design of structural concrete foundations. It covers a wide range of foundation types, including shallow systems like strip, isolated, combined, and mat foundations, as well as deep systems like piles, piers, and caissons. The chapter focuses on establishing the critical sections for analysis, determining required strength, and detailing reinforcement. Most of the fundamental principles for shear and flexure are cross-referenced from other chapters (e.g., Chapters 7, 8, 22), while this chapter provides the application rules specific to foundations.

Key Standards and Codes Referenced

- ASCE/SEI 7: Referenced for allowable stress design load combinations.
- IBC (International Building Code): Referenced in commentary for provisions related to deep foundations.
- ACI 336.2R: Guide to Design of Combined Footings and Mat Foundations.
- CRSI Handbook: Referenced in commentary for design guidance.

Technical Specifications

- 13.2 General:
    - Critical Sections (13.2.7): The location for calculating factored moment (`Mu`) and shear (`Vu`) at the interface of a foundation and the supported member is precisely defined in Table 13.2.7.1.
        - Moment: At the face of the column, pedestal, or concrete wall. For members on steel base plates, it is halfway between the face of the column and the edge of the plate.
        - Shear: Measured from the critical section for moment.
    - Development of Reinforcement (13.2.8): Reinforcement must be developed on each side of the critical section for moment.
- 13.3 Shallow Foundations:
    - Rectangular Footing Reinforcement (13.3.3.3): For two-way rectangular footings, reinforcement in the short direction must be concentrated in a central band. The ratio of reinforcement in the band width to the total

reinforcement in the short direction (γ_s) is calculated by the formula: $\gamma_s = 2 / (\beta + 1)$, where β is the ratio of the long side to the short side of the footing.

- 13.4 Deep Foundations:
  - Allowable Strength (13.4.2): Provides maximum allowable compressive strengths for various deep foundation types (piles, piers) based on formulas in Table 13.4.2.1. This is an allowable stress design approach.
  - Strength Design (13.4.3): Provides strength reduction factors (ϕ) in Table 13.4.3.2 for a strength design approach. ϕ varies from 0.55 for uncased augered piles to 0.70 for metal-cased concrete piles.

Visual Elements Analysis

Figure R13.1.1: Types of foundations (Page 194)

- Description: This figure provides clear isometric diagrams of the various foundation types covered by the chapter.
- Technical Details: The figure visually defines:
  - Shallow Foundations: Strip footing (continuous wall support), Isolated footing (single column), Stepped footing (variable elevation), Combined footing (multiple columns), Mat foundation (large slab supporting multiple columns).
  - Deep Foundations: A system showing multiple piles connected by a pile cap.
  - Retaining Walls: A cantilever wall (showing toe, heel, stem) and a counterfort/buttressed wall.
- Relationship to Text: This figure is the visual key for the entire chapter, illustrating the terminology used in the scope (13.1.1).

Figure R13.2.6.5: One-way shear design of a spread footing using the strut-and-tie method (Page 197)

- Description: A diagram showing a column on a spread footing, illustrating how internal forces are resolved using a strut-and-tie model.
- Technical Details: It shows an inclined compression strut (θ) forming from the column to the soil reaction. The diagram clarifies that soil pressure within a distance d from the column face does not contribute to the shear force V_u at the critical section but does contribute to the bending moment at the column face.
- Relationship to Text: This figure provides the theoretical basis for the rules in 13.2.7.2, explaining why the critical section for shear is located away from the support face.

Figure R13.2.7.2: Modified critical perimeter for shear with overlapping critical perimeters (Page 198)

- Description: A plan view of a pile cap with two closely spaced piles, showing how the critical perimeter for two-way (punching) shear must be modified when the individual shear zones overlap.
- Technical Details: Two circular piles are shown with their individual circular shear perimeters ($d/2$ from the pile face). Where they overlap, the critical perimeter becomes the smallest envelope that encloses both individual perimeters, resulting in a flattened or "racetrack" shape.
- Relationship to Text: This visual explains a critical concept for the design of pile caps with closely spaced piles, where simply summing the capacity of individual piles would be unconservative.

Calculations and Formulas

- Rectangular Footing Reinforcement Ratio:
    - Formula: $\gamma s = 2 / (\beta + 1)$
    - Variables:
        - γs: Ratio of reinforcement in central band to total reinforcement in short direction.
        - β: Ratio of long side to short side of footing.
- Allowable Compressive Strength of Uncased Pile:
    - Formula: $Pa = 0.3fc'Ag + 0.4fyAs$ (from Table 13.4.2.1)
    - Variables: Pa = allowable axial strength, fc' = concrete strength, Ag = gross area, fy = steel yield strength, As = steel area.

BOQ Implications

- Excavation and Concrete Volume: The primary cost driver for foundations is the volume of excavation and concrete, which is determined by the required bearing area calculated from geotechnical data and factored loads.
- Reinforcement Distribution: The requirement to concentrate reinforcement in a central band for rectangular footings (γs formula) directly affects the steel detailing and takeoff. This can lead to different bar spacings in the center versus the outer portions of the footing.
- Deep Foundations: The choice between deep foundation types (e.g., precast piles vs. cast-in-place drilled piers) has massive cost implications for labor, equipment, and materials, which must be clearly specified in the BOQ.

Critical Notes and Warnings

- Geotechnical Interface: The commentary repeatedly emphasizes that foundation design is a collaborative effort between the structural engineer and the geotechnical engineer. The ACI code governs the concrete design, but the

permissible soil pressures and foundation member capacities are determined by principles of soil mechanics (R13.2.6.1).
- Critical Sections: The precise locations of critical sections for moment and shear are fundamental to a safe design. Using the wrong location (e.g., calculating moment at the column centerline instead of the face) is a common error that can lead to an under-designed foundation.

Chapter 14: Plain Concrete

Overview

This chapter provides requirements for structural members constructed with plain concrete, meaning concrete with no reinforcement or with less reinforcement than the minimum specified for reinforced concrete. The use of plain concrete is severely restricted to situations where ductility is not required and where tensile stresses are minimal. Design is fundamentally based on the concrete's own modest tensile strength (modulus of rupture).

Key Standards and Codes Referenced

- This chapter is self-contained.

Technical Specifications

- Limitations on Use (14.1.3): Plain concrete is permitted only in:
    - Members continuously supported by soil or other structural members (e.g., some footings).
    - Members where arch action provides compression under all loading conditions.
    - Walls and pedestals.
- Prohibited Uses (14.1.5): Plain concrete shall not be permitted for columns or pile caps.
- Minimum Thickness:
    - Footings (14.3.2.1): Shall be at least 8 in. thick.
    - Bearing Walls (Table 14.3.1.1): Minimum thickness is 5.5 in. or 1/24 of the unsupported length, whichever is greater.
- Design Strength (14.5):
    - Strength reduction factor ϕ is 0.60 for all actions (flexure, compression, shear, and bearing).
    - Design is based on a linear stress-strain relationship (14.5.1.4).

Calculations and Formulas

- Nominal One-Way Shear Strength (V_n):
  - Formula: $V_n = (4/3) * \lambda * \sqrt{f_c'} * b * h$
- Nominal Two-Way Shear Strength (v_c):
  - Formula: v_c is the lesser of $(2 + 4/\beta)\lambda\sqrt{f_c'}$ and $4\lambda\sqrt{f_c'}$.
- Combined Flexure and Axial Load (Interaction Equation):
  - Formula: $(M_u/S_m) + (P_u/A_g) \le \phi * 5\lambda\sqrt{f_c'}$ (for tension face)
  - Variables: M_u = factored moment, S_m = elastic section modulus, P_u = factored axial load, A_g = gross area.

BOQ Implications

- Material Costs: The primary advantage of plain concrete is the elimination of the cost of reinforcing steel and the associated labor for placing it.
- Volume and Formwork: To compensate for the lack of reinforcement, plain concrete members are typically much larger in cross-section than their reinforced counterparts. This increases the BOQ quantities for excavation, concrete, and formwork.

Critical Notes and Warnings

- Brittle Failure: Plain concrete lacks ductility. The commentary (R14.1.5) warns that failure is sudden and without warning, which is why its use is so restricted. It is completely unsuitable for seismic applications.
- Importance of Joints (14.3.4): The commentary (R14.3.4.1) emphasizes that for plain concrete, contraction and isolation joints are the *only* means of controlling and relieving tensile stresses from shrinkage and temperature changes. Proper jointing is critical to prevent uncontrolled cracking and potential failure.

Chapter 15: Beam-Column and Slab-Column Joints

Overview

This chapter focuses on the design of the critical connection regions where beams and columns, or slabs and columns, intersect. A joint must be able to transfer all forces (shear, moment, axial load) from the members framing into it without failing. The chapter provides specific methods for calculating the design shear strength of the joint itself, which is treated as a distinct structural element, and details the reinforcement required for confinement.

Key Standards and Codes Referenced

- ACI 352R: Recommendations for Design of Beam-Column Connections in Monolithic Reinforced Concrete Structures (referenced in commentary for guidance).

Technical Specifications

- Joint Shear (15.2.3): Shear resulting from the transfer of moment at beam-column joints shall be considered in the design of the joint.
- Detailing (15.3):
  - Column Reinforcement: Column transverse reinforcement (ties or spirals) must be continued through the joint unless the joint is confined on all four sides by beams of approximately equal depth (15.3.1.1).
  - Slab-Column Joints: Column transverse reinforcement must be continued through the joint, including through any drop panels or shear caps (15.3.2.1).
- Design Shear Strength (`Vn`) (15.4.2): The nominal shear strength of a joint is calculated as `Vn = γ * √fc' * Aj`. The coefficient `γ` depends on the joint's confinement condition, as specified in Table 15.4.2.3.
  - `γ = 24` for confined interior joints.
  - `γ = 20` for joints confined on three faces or two opposite faces.
  - `γ = 15` for joints confined on one face (exterior joints).
  - `γ = 12` for all other cases (corner joints).
- Transfer of Column Axial Force (15.5): When the concrete strength of the floor system is less than 75% of the column strength (`0.75fc'`), special measures are required to transfer the column load, such as using vertical dowels or extending the stronger column concrete into the joint.

Visual Elements Analysis

Table 15.4.2.3: Nominal joint shear strength Vn (Page 216)

- Description: This is the central table of the chapter, providing the strength coefficient `γ` for calculating the nominal shear strength of a beam-column joint.
- Technical Details: The table classifies joints based on two factors:
  i. Beam Continuity: Whether the beam is continuous through the joint or terminates at the joint.
  ii. Confinement: Whether the joint is "Confined" by transverse beams according to 15.2.8, or "Not confined".
- Relationship to Text: This table is the direct source for the `γ` factor used in the primary strength calculation of section 15.4.2. The commentary (R15.3.1) confirms that a joint confined on all four sides by beams is the strongest case and may not require shear reinforcement.

Figure R15.4.2: Effective joint area, Aj (Page 216)

- Description: A plan view and a cross-section of a beam-column joint that visually defines the dimensions used to calculate the effective joint area `Aj`.
- Technical Details:
  - Joint Depth (`h`): Equal to the overall depth of the column.
  - Effective Joint Width (`b`): The lesser of `(b + h)` and `(b + 2x)`, where `b` is the beam width and `x` is the smaller perpendicular distance from the longitudinal axis of the beam to the side face of the column.
- Relationship to Text: This figure provides the geometric definitions necessary to calculate `Aj` for use in the shear strength formula from 15.4.2.

BOQ Implications

- Joint Reinforcement: The requirement to continue column ties through the joint (15.3.1) means that the BOQ must include this quantity of transverse steel. In seismic design, this reinforcement can be very dense, significantly increasing labor and material costs.
- High-Strength Concrete: The provision for handling mismatched concrete strengths (15.5) may require a separate BOQ line item for placing a small volume of high-strength concrete in the joint area (a "puddle pour"), which has higher material and labor costs than the general floor concrete.

Critical Notes and Warnings

- Joints are Critical: The commentary emphasizes that joints are a critical part of the structural frame. A failure in the joint can lead to a catastrophic failure of the entire system.
- Confinement is Key: The shear strength of a joint is highly dependent on the confinement provided by surrounding members. A corner joint ($\gamma = 12$) has only half the shear strength of a fully confined interior joint ($\gamma = 24$). This highlights the importance of the framing layout in the overall structural capacity.
-

Part 7: Connections and Anchoring (Chapters 16-17)

Chapter 16: Connections Between Members

Overview

This chapter provides the requirements for the design of connections between concrete members, with a focus on precast concrete construction. It covers the transfer of forces through various means such as grouted joints, shear keys, anchors, and mechanical connectors. The chapter also provides detailed provisions for the design of brackets and corbels, which are short cantilever members supporting concentrated loads.

Key Standards and Codes Referenced

- PCI Design Handbook (MNL 120): Referenced in commentary for guidance on precast concrete connection details.

Technical Specifications

- 16.2 Connections of Precast Members:
  - Prohibited Connections (16.2.1.3): Connection details that rely solely on friction caused by gravity loads shall not be permitted.
  - Integrity Ties (16.2.4): Longitudinal and transverse integrity ties are required to connect precast members to the lateral-force-resisting system. For diaphragms, these ties must have a nominal tensile strength of at least 300 lb per linear ft (16.2.4.2).
- 16.5 Brackets and Corbels:
  - Scope (16.5.1.1): These provisions apply to brackets and corbels with a shear span-to-depth ratio (a_v/d) of 1.0 or less.
  - Required Strength (16.5.3): The section at the face of the support must be designed to simultaneously resist the factored shear V_u, factored restraint force N_{uc}, and factored moment M_u.
  - Reinforcement Limits (16.5.5): The area of primary tension reinforcement, A_{sc}, shall be at least the greatest of three calculated values, including a minimum of $0.04(f_c'/f_y)(b_w d)$.
  - Closed Stirrups/Ties (A_h) (16.5.5.2): Horizontal ties must be provided with a total area A_h of at least $0.5(A_{sc} - A_n)$, where A_n is the area of reinforcement resisting the restraint force N_{uc}.
- 16.4 Horizontal Shear Transfer:
  - Shear-Friction (16.4.4.1): For high shear ($V_u > \phi(500 b_v d)$), horizontal shear strength V_{nh} must be calculated using the shear-friction provisions of 22.9.
  - Simplified Method (Table 16.4.4.2): For lower shear, V_{nh} can be calculated based on whether the contact surface is intentionally roughened. For a roughened surface with minimum ties, V_{nh} is the lesser of $(260 + 0.6\rho_v f_y)\lambda b_v d$ and $500 b_v d$. For an unroughened surface, $V_{nh} = 80 b_v d$.

Visual Elements Analysis

Figure R16.5.1a & R16.5.1b: Structural action of a corbel and notation (Page 230)

- Description: These two figures are critical for understanding the behavior and design of corbels. Figure R16.5.1a shows the internal force flow, while R16.5.1b defines the notation.
- Technical Details:
  - Figure R16.5.1a: Illustrates the corbel acting as a simple truss. A diagonal compression strut forms in the concrete, and a primary tension tie is formed by the top longitudinal reinforcement (A_{sc}). A potential shear failure plane is shown at the interface with the column.
  - Figure R16.5.1b: Defines the key variables: a_v (shear span), d (effective depth), h (overall depth), N_{uc} (factored restraint force, often from shrinkage/creep), V_u (factored vertical force), A_{sc} (primary tension reinforcement), and A_h (horizontal stirrups).
- Relationship to Text: These figures visually represent the strut-and-tie model that is the basis for the corbel design equations in section 16.5. They clarify the meaning of the variables used in the strength and reinforcement calculations.

Calculations and Formulas

- Corbel Primary Tension Reinforcement (A_{sc}):
  - Formula: A_{sc} shall be the greater of:
    - $A_f + A_n$ (Flexural reinforcement + Tension reinforcement)
    - $(2/3)A_{vf} + A_n$ (Shear-friction reinforcement + Tension reinforcement)
    - $0.04(f_c'/f_y)(b_w d)$ (Minimum reinforcement)
  - Variables: A_f = area of reinforcement to resist M_u, A_n = area of reinforcement to resist N_{uc}, A_{vf} = area of shear-friction reinforcement.
- Corbel Horizontal Stirrups (A_h):
  - Formula: $A_h \geq 0.5 * (A_{sc} - A_n)$
  - Variables: A_h = total area of closed stirrups, A_{sc} = primary tension reinforcement, A_n = tension reinforcement.

BOQ Implications

- Connection Hardware: The design of precast systems requires a detailed takeoff of connection hardware in the BOQ, including grouted sleeves, bearing pads, mechanical connectors, and steel embed plates.
- Corbel Reinforcement: The BOQ for a corbel will include a significant amount of steel in a small volume of concrete. This includes large primary tension bars (A_{sc}) that must be properly welded or anchored, and multiple layers of horizontal stirrups (A_h). The labor for fabricating and placing this dense reinforcement cage is high.

- Surface Preparation: If horizontal shear transfer relies on shear-friction, the BOQ must include the cost of intentionally roughening the concrete surface to the required 1/4 in. amplitude, which is a specific construction task.

Critical Notes and Warnings

- No Friction-Only Connections: Section 16.2.1.3 is a critical safety provision. Connections cannot rely only on gravity-induced friction for stability; a positive mechanical connection must be provided.
- Corbel Failure Modes: The commentary (R16.5.1) warns of the multiple potential failure modes for a corbel, including yielding of the tension tie, crushing of the compression strut, or shearing along the interface. The design provisions are intended to ensure a ductile failure by yielding of the tension tie.
- Restraint Forces (`Nuc`): The commentary (R16.2.2.3) emphasizes the importance of accounting for horizontal forces on bearing connections caused by volume changes (creep, shrinkage, temperature). These forces are treated as live loads and can be significant, requiring additional tension reinforcement (`An`).

Chapter 17: Anchoring to Concrete

Overview

This chapter provides the comprehensive requirements for designing anchors used to transmit loads to concrete. It covers cast-in anchors (headed studs, headed bolts, hooked bolts) and post-installed anchors (expansion, undercut, screw, adhesive). The design methodology is based on the Concrete Capacity Design (CCD) approach, which requires checking a series of potential steel and concrete failure modes for both tension and shear loads. The lowest calculated capacity governs the design.

Key Standards and Codes Referenced

- ACI 355.2: Standard for qualifying post-installed mechanical anchors.
- ACI 355.4: Standard for qualifying post-installed adhesive anchors.
- ASME B1.1, B18.2.1, B18.2.6: Standards for thread and head geometries of bolts.
- ICC-ES AC193: Acceptance criteria for mechanical anchors.

Technical Specifications

- Failure Modes to be Checked: The design must consider all applicable failure modes (17.5.1.2):

    - Tension: Steel strength (N_{sa}), Concrete breakout (N_{cb}), Pullout (N_p), Side-face blowout (N_{sb}), Bond strength (adhesive anchors, N_a).
    - Shear: Steel strength (V_{sa}), Concrete breakout (V_{cb}), Concrete pryout (V_{cp}).
- Design Principle: The design strength ϕN_n or ϕV_n must be greater than or equal to the required strength N_{ua} or V_{ua} for each potential failure mode (Table 17.5.2).
- Strength Reduction Factors (ϕ): ϕ factors are specified in Table 17.5.3 and vary based on the failure mode and the ductility of the anchor.
    - Ductile Steel Failure: $\phi = 0.75$ (Tension), $\phi = 0.65$ (Shear).
    - Brittle Concrete Failure: ϕ can be as low as 0.45, depending on anchor category and whether supplementary reinforcement is present.
- Concrete Breakout Strength (N_{cb}) (17.6.2):
    - $N_{cb} = (A_{Nc} / A_{Nco}) * \psi_{ed,N} * \psi_{c,N} * \psi_{cp,N} * N_b$
    - This is the fundamental CCD equation, where a basic strength (N_b) is modified by factors accounting for anchor group effects (A_{Nc}/A_{Nco}), edge effects ($\psi_{ed,N}$), cracking ($\psi_{c,N}$), and splitting ($\psi_{cp,N}$).
- Anchor Reinforcement (17.5.2.1): If the factored load exceeds the concrete breakout strength, it is permitted to provide anchor reinforcement to transfer the full load, bypassing the concrete breakout check.

Visual Elements Analysis

Figure R17.5.1.2: Failure modes for anchors (Page 240)

- Description: This is the most important figure in the chapter, providing clear diagrams of the various potential failure modes for anchors in tension and shear.
- Technical Details:
    - (a) Tensile loading: Illustrates steel failure, pullout, concrete breakout (showing the characteristic 35° cone), concrete splitting, side-face blowout, and bond failure. It also distinguishes between single anchor and group behavior.
    - (b) Shear loading: Illustrates steel failure preceded by concrete spall, concrete pryout, and concrete breakout.
- Relationship to Text: This figure is the visual encyclopedia for the entire CCD method. Each failure mode diagrammed corresponds to a specific calculation section within Chapter 17.

Figure R17.6.2.1: Calculation of ANc and ANco for single anchors and anchor groups (Page 250)

- Description: This figure shows how to calculate the projected concrete failure area for a single anchor (A_{Nco}) and an anchor group (A_{Nc}).
- Technical Details: The failure area is projected from the anchor head(s) outward at an angle of approximately 35°, which simplifies to a plan-view projection

extending 1.5hef from the anchor centerline(s). The figure shows how these areas are truncated by edges or overlap for groups.

- Relationship to Text: This figure provides the geometric basis for the `ANc/ANco` ratio, which is the primary factor used to account for group effects in the concrete breakout strength calculation (17.6.2.1).

Calculations and Formulas

- Basic Concrete Breakout Strength in Tension (`Nb`):
  - Formula: `Nb = kc * λa * √fc' * hef^1.5`
  - Variables: `kc` = factor (24 for cast-in, 17 for post-installed), `λa` = lightweight concrete factor, `hef` = effective embedment depth.
- Modification Factor for Edge Effects (`ψed,N`):
  - Formula: `ψed,N = 0.7 + 0.3 * (ca,min / (1.5hef))` (for `ca,min < 1.5hef`)
  - Variables: `ca,min` = minimum edge distance.

BOQ Implications

- Anchor Specification: The BOQ must be extremely precise, specifying the exact anchor type (e.g., "M16 torque-controlled expansion anchor qualified per ACI 355.2 for cracked concrete"), as different anchors have vastly different costs and performance characteristics.
- Special Inspection: The use of post-installed anchors, especially adhesive anchors in sustained tension or seismic applications, requires continuous special inspection by certified personnel (26.13.1). This is a significant cost item for quality control that must be included in the BOQ.
- Supplementary Reinforcement: If anchor reinforcement is used to bypass concrete breakout calculations, the BOQ must include the material and labor for this additional rebar (often hairpins or stirrups), which is separate from the primary member reinforcement.

Critical Notes and Warnings

- Cracked vs. Uncracked Concrete: The capacity of most anchors is significantly lower in cracked concrete than in uncracked concrete. The commentary (R17.6.2.5) warns that unless an analysis proves otherwise, the concrete should be assumed to be cracked for design purposes. Using uncracked concrete values where cracking is likely is a dangerous and non-conservative error.
- Installation is Critical: The commentary (R17.1.2, R26.7.1) repeatedly warns that the performance of post-installed anchors is highly sensitive to proper installation, including hole drilling, cleaning, and torque. Failure to follow the Manufacturer's Printed Installation Instructions (MPII) can lead to a catastrophic failure at a load far below the design value.

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Part 8: Seismic Design (Chapter 18)

Chapter 18: Earthquake-Resistant Structures

Overview

This chapter provides mandatory requirements for the design and detailing of concrete structures assigned to Seismic Design Categories (SDC) B through F. Its fundamental purpose is to ensure that structures can resist earthquake motions through a combination of strength and, critically, ductile inelastic response. The provisions are tiered based on the structure's SDC, with increasingly stringent requirements for higher seismic risk. The chapter introduces three classes of seismic systems—Ordinary, Intermediate, and Special—each with specific detailing rules designed to achieve a target level of deformation capacity. The core philosophy is capacity design, where members are detailed to ensure ductile flexural yielding occurs in predictable locations (plastic hinges) while preventing brittle failures like shear, bond, or anchorage failure.

Key Standards and Codes Referenced

- ACI 374.1: Acceptance Criteria for Moment Frames Based on Structural Testing.
- ACI 550.3: Acceptance Criteria for Special Unbonded Post-Tensioned Precast Structural Walls.
- ACI 550.5: Code Requirements for the Design of Precast Concrete Diaphragms.
- AWS D1.4: Structural Welding Code—Reinforcing Steel.
- ASTM A706: Standard Specification for Deformed and Plain Low-Alloy Steel Bars for Concrete Reinforcement (required for most seismic applications).
- NIST GCR 14-917-30: Use of High-Strength Reinforcement in Earthquake-Resistant Concrete Structures.

Technical Specifications

- System Hierarchy: The chapter defines requirements for three levels of seismic moment frames and two levels of structural walls, with applicability tied to the SDC.
  - Ordinary Moment Frames (18.3): Permitted in SDC B. Have minimal additional detailing beyond standard construction.
  - Intermediate Moment Frames (18.4): Permitted in SDC C. Require moderate detailing for ductility, including hoops at the ends of beams and columns.

    - Special Moment Frames (18.6, 18.7, 18.8): Required for SDC D, E, and F. Have extensive and stringent detailing requirements to ensure high ductility.
    - Ordinary Structural Walls: Permitted in SDC B and C. No special seismic detailing required.
    - Special Structural Walls (18.10): Required for SDC D, E, and F. Require special detailing of boundary elements and coupling beams.
- Material Requirements (18.2.6):
    - Reinforcement in seismic systems is generally required to be ASTM A706 to ensure controlled yield strength and adequate tensile strength-to-yield strength ratio.
    - ASTM A615 Grade 60 is permitted only if it meets the stringent requirements of 20.2.2.5 (actual yield strength not more than 18,000 psi above specified, and ratio of actual tensile to actual yield strength ≥ 1.25).
- Special Moment Frames:
    - Beams (18.6):
        - Clear Span: $\ell_n \geq 4d$.
        - Reinforcement: Lap splices are prohibited within the joint or within a distance of $2h$ from the joint face. At least two bars must be continuous top and bottom.
        - Hoops: Required at both ends of the beam over a length of $2h$, with spacing not exceeding the lesser of $d/4$, $6d_b$ (Grade 60) or $5d_b$ (Grade 80) of the smallest longitudinal bar, or 6 in.
    - Columns (18.7):
        - Strong-Column/Weak-Beam (18.7.3.2): The sum of the nominal flexural strengths of the columns framing into a joint shall be at least 1.2 times the sum of the nominal flexural strengths of the beams framing into the joint ($\Sigma M_{nc} \geq (6/5)\Sigma M_{nb}$). This forces plastic hinging to occur in the beams rather than the columns.
        - Transverse Reinforcement: Extensive hoop or spiral reinforcement is required over a length ℓ_o at the top and bottom of the column to provide confinement. Spacing is very tight, not to exceed the lesser of $1/4$ of the minimum member dimension, $6d_b$ (or $5d_b$), or s_o calculated by formula.
    - Joints (18.8):
        - Shear Strength: Calculated based on the joint confinement condition, with strength coefficients γ ranging from 8 to 20 (Table 18.8.4.3).

        - Development Length: Bar development length for hooks (ℓdh) and straight bars (ℓd) passing through the joint is significantly increased (e.g., $h \geq 20db$ for Grade 60 bars).
- Special Structural Walls (18.10):
    - Reinforcement: Must be placed in at least two curtains if shear $Vu > 2\lambda\sqrt{fc'}Acv$ (18.10.2.2).
    - Boundary Elements (18.10.6): Special boundary elements (zones with column-like confinement reinforcement) are required at wall edges if the expected deformations are large. The need is triggered by either a displacement-based approach ($c/\ell w \geq \ldots$) or a stress-based approach (compressive stress $> 0.2fc'$).
    - Coupling Beams (18.10.7): Beams coupling two structural walls with an aspect ratio $\ell n/h < 2$ must be reinforced with two intersecting groups of diagonally placed bars.

Visual Elements Analysis

Figure R18.4.2: Design shears for intermediate moment frames (Page 295)

- Description: This figure shows free-body diagrams of a beam and column in an intermediate moment frame, illustrating the capacity design principle for shear.
- Technical Details: The design shear force Vu is calculated not from the analysis loads, but from the shear generated when the member develops its nominal moment strength (Mnl and Mnr) at opposite ends, creating a plastic hinge mechanism. The formula shown is $Vu = (Mnl + Mnr)/\ell n + wu\ell n/2$.
- Relationship to Text: This visual explains the core concept of 18.4.2.3 and 18.4.3.1, where shear strength must be greater than the shear corresponding to flexural yielding, preventing a brittle shear failure.

Figure R18.7.5.2: Example of transverse reinforcement in columns of special moment frames (Page 308)

- Description: A cross-section of a special moment frame column showing the required arrangement of hoops and crossties for confinement.
- Technical Details: The diagram shows a perimeter hoop and multiple interior crossties. A key callout notes that the dimension xi between laterally supported longitudinal bars must not exceed 14 inches. It also shows the required 6db extension for the 90-degree hook on the crossties.
- Relationship to Text: This figure visually interprets the dense and complex transverse reinforcement requirements of 18.7.5, which are essential for providing ductility.

Figure R18.10.7a: Confinement of individual diagonals in coupling beams (Page 334)

- Description: A section view of a diagonally reinforced coupling beam, showing the intricate cage of reinforcement required.
- Technical Details: The diagram shows the main diagonal reinforcement (A_{vd}) enclosed by its own transverse reinforcement (ties/hoops). This confinement cage is separate from the overall beam stirrups. The angle of the diagonal bars, α, is also shown.
- Relationship to Text: This figure clarifies the demanding detailing requirements of 18.10.7.4 for ductile coupling beams, which are designed to yield repeatedly and dissipate large amounts of seismic energy.

Calculations and Formulas

- Strong-Column/Weak-Beam Requirement:
    - Formula: $\Sigma M_{nc} \geq (6/5) * \Sigma M_{nb}$
    - Variables: ΣM_{nc} = sum of nominal flexural strengths of columns at a joint, ΣM_{nb} = sum of nominal flexural strengths of beams at a joint.
- Special Wall Boundary Element Trigger (Stress-based):
    - Condition: Special boundary elements are required where $P_u / A_g + M_u / S_g > 0.2f_c'$.
- Coupling Beam Shear Strength (Diagonally Reinforced):
    - Formula: $V_n = 2 * A_{vd} * f_y * \sin(\alpha)$
    - Variables: A_{vd} = area of reinforcement in one group of diagonal bars, α = angle of diagonal bars with the longitudinal axis.

BOQ Implications

- Massive Increase in Steel Quantity: Seismic design under Chapter 18 dramatically increases the amount of reinforcement compared to non-seismic design. This is due to:
    - Dense transverse reinforcement (hoops, spirals, crossties) in columns and at beam ends.
    - Longitudinal reinforcement required for boundary elements in shear walls.
    - Diagonal reinforcement in coupling beams.
- Increased Labor Costs: The complexity of fabricating and placing these dense reinforcement cages is extremely high, leading to a significant increase in labor costs in the BOQ. Congestion is a major issue, requiring careful planning and potentially slower construction cycles.
- Material Specifications: The mandatory use of ASTM A706 steel for most applications increases material cost.
- Increased Concrete Volume: The strong-column/weak-beam requirement often forces column sizes to be larger than they would be for gravity loads alone,

increasing concrete quantities. Joint shear requirements can also lead to larger column dimensions.

Critical Notes and Warnings

- Ductility is the Goal: The primary purpose of this chapter is not just to provide strength, but to ensure the structure can deform in a ductile manner during a severe earthquake without collapsing. Every provision is aimed at achieving this goal.
- Prohibition of Lap Splices: The rule against placing lap splices in potential plastic hinge zones (e.g., near column/beam faces) is absolute. These are locations of intense cyclic yielding where lap splices are unreliable and prone to failure.
- Shear is the Enemy: The entire philosophy of capacity design is to prevent brittle shear failures. The design shear forces are intentionally calculated to be very high (based on the probable flexural strength of the members) to ensure that shear-governed failures are suppressed and ductile flexural yielding occurs instead.

Part 9: Materials, Strength, and Serviceability (Chapters 19-24)

Chapter 19: Concrete: Design and Durability Requirements

Overview

This chapter is the foundation for specifying concrete itself. It establishes the design properties for concrete, including compressive strength (`fc'`), modulus of elasticity (`Ec`), and modulus of rupture (`fr`). Critically, it introduces the concept of durability design through exposure categories and classes, linking environmental conditions to mandatory requirements for concrete mixtures, such as maximum water-cementitious materials ratio (`w/cm`) and minimum compressive strength.

Key Standards and Codes Referenced

- ASTM C330: Standard Specification for Lightweight Aggregates.
- ASTM C567: Standard Test Method for Determining Density of Structural Lightweight Concrete.
- ASTM C1580: Standard Test Method for Water-Soluble Sulfate in Soil.
- ASTM D516 / D4130: Standard Test Methods for Sulfate Ion in Water.
- ASTM C172: Standard Practice for Sampling Freshly Mixed Concrete.
- ASTM C231 / C173: Standard Test Methods for Air Content of Freshly Mixed Concrete.

- ASTM C1240: Standard Specification for Silica Fume Used in Cementitious Mixtures.
- ACI 211.1: Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete.
- ACI 301: Specifications for Structural Concrete.

Technical Specifications

- 19.2 Design Properties:
  - Compressive Strength (`fc'`) (Table 19.2.1.1): Specifies minimum `fc'` for various applications. For example:
    - General Use: 2500 psi.
    - Special Moment Frames: 3000 psi.
    - Special Structural Walls with Grade 100 Reinforcement: 5000 psi.
  - Modulus of Elasticity (`Ec`) (19.2.2):
    - Normalweight Concrete: `Ec = 57,000 * √fc'` (in psi).
    - Lightweight Concrete: `Ec = wc^1.5 * 33 * √fc'` (in psi), where `wc` is the equilibrium density in lb/ft³.
  - Modulus of Rupture (`fr`) (19.2.3): `fr = 7.5 * λ * √fc'`, where `λ` is the lightweight concrete modification factor.
- 19.3 Durability Requirements:
  - Exposure Categories: Members must be assigned to four exposure categories:
    - F (Freezing and Thawing): Classes F0, F1, F2, F3.
    - S (Sulfate): Classes S0, S1, S2, S3.
    - W (Water Contact): Classes W0, W1, W2.
    - C (Corrosion Protection): Classes C0, C1, C2.
  - Table 19.3.2.1: This is the central table linking exposure classes to mandatory concrete mixture requirements. For example:
    - Class F3 (Freezing/Thawing with Deicers): Max `w/cm` = 0.40, Min `fc'` = 5000 psi, plus air entrainment.
    - Class S2 (Severe Sulfate Exposure): Max `w/cm` = 0.45, Min `fc'` = 4500 psi, and must use Type V cement.
    - Class C2 (Chlorides from Deicing Chemicals): Max `w/cm` = 0.40, Min `fc'` = 5000 psi, and max water-soluble chloride ion content of 0.15%.
  - Air Entrainment (Table 19.3.3.1): Specifies required target air content based on exposure class (F1, F2, F3) and nominal maximum aggregate size. For a 3/4-in. aggregate in F2 or F3 exposure, target air content is 6.0%.

Visual Elements Analysis

Table 19.3.1.1: Exposure categories and classes (Page 360)

- Description: This table defines the conditions for each of the four exposure categories (F, S, W, C) and their respective severity classes.
- Technical Details: It provides quantitative thresholds for classification.
    - Sulfate (S): Class S1 is for water with 150-1500 ppm sulfates; Class S2 is 1500-10,000 ppm; Class S3 is >10,000 ppm.
    - Corrosion (C): Class C1 is for concrete exposed to moisture but not an external chloride source. Class C2 is for concrete exposed to chlorides from deicing chemicals, salt, seawater, etc.
- Relationship to Text: This table is the first step in the durability design process outlined in 19.3, requiring the designer to classify the environmental exposure of every concrete member.

Table 19.3.2.1: Requirements for concrete by exposure class (Page 368)

- Description: This is the most critical table in the chapter. It translates the exposure classes from Table 19.3.1.1 into specific, mandatory requirements for the concrete mixture.
- Technical Details: The table is a matrix listing maximum `w/cm`, minimum `fc'`, required cement types (e.g., Type II or V for sulfate resistance), limits on cementitious materials, and maximum chloride ion content for each exposure class.
- Relationship to Text: This table is the prescriptive core of durability design. The licensed design professional uses this table to specify the required concrete properties in the construction documents.

Calculations and Formulas

- Modulus of Elasticity (`Ec`):
    - Formula (Normalweight): `Ec = 57,000 * √fc'`
- Modulus of Rupture (`fr`):
    - Formula: `fr = 7.5 * λ * √fc'`

BOQ Implications

- Concrete Mix Design: This chapter directly dictates the performance requirements for the concrete mixes used in the project. The specified minimum `fc'` and maximum `w/cm` are primary drivers of the cost of the concrete itself. Higher strength and lower `w/cm` mixes are more expensive due to higher cement content and the potential need for admixtures.
- Specialty Cements & SCMs: Requirements for Type V cement (for sulfate resistance) or specific quantities of supplementary cementitious materials

(SCMs) like silica fume or slag must be included as line items in the BOQ, as these materials have different costs and availability than standard Type I/II cement.
- Quality Control Costs: The durability requirements necessitate a higher level of quality control. The BOQ must account for the cost of testing for properties beyond just compressive strength, such as air content (ASTM C173/C231) and chloride ion content (ASTM C1218), which adds to the overall project testing budget.

Critical Notes and Warnings

- Durability is Paramount: The commentary emphasizes that durability is a primary consideration for the service life of a structure. Specifying the correct exposure class and corresponding concrete properties is a critical design responsibility.
- Most Restrictive Requirement Governs: The commentary (R19.3.2) clarifies that if a member is assigned to multiple exposure classes, the concrete mixture must conform to the most restrictive requirements from all applicable classes. For example, a bridge deck in a cold climate (F3) near the ocean (C2, S1) will have its `w/cm` and `fc'` governed by the most stringent of those three classes.
- Lightweight Concrete: A footnote to Table 19.3.2.1 states that the `w/cm` limits do not apply to lightweight concrete because the water absorption of lightweight aggregate makes the `w/cm` calculation uncertain. For lightweight concrete, durability is specified through minimum `fc'` only.

Chapter 20: Steel Reinforcement Properties, Durability, and Embedments

Overview

This chapter focuses on the reinforcement used within concrete. It specifies the required material properties for both nonprestressed and prestressed reinforcement, including yield strength, tensile strength, and modulus of elasticity. It also provides crucial requirements for durability, primarily through specifying concrete cover, and rules for embedments such as pipes and conduits.

Key Standards and Codes Referenced

- ASTM A615: Standard Specification for Deformed and Plain Carbon-Steel Bars.
- ASTM A706: Standard Specification for Deformed and Plain Low-Alloy Steel Bars for Concrete Reinforcement.

- ASTM A416: Standard Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete.
- ASTM A722: Standard Specification for Uncoated High-Strength Steel Bars for Prestressed Concrete.
- ASTM A1044: Standard Specification for Steel Stud Assemblies for Shear Reinforcement of Concrete.

Technical Specifications

- 20.2 Nonprestressed Bars and Wires:
  - Design Properties (20.2.2):
    - Stress below yield: $f_s = E_s * \varepsilon_s$.
    - Stress at or above yield: $f_s = f_y$.
    - Modulus of Elasticity (E_s): Permitted to be taken as 29,000,000 psi.
  - Yield Strength Limits (Table 20.2.2.4(a)): f_y used in design calculations is limited. For shear and torsion reinforcement, f_y shall not exceed 60,000 psi. For special seismic systems, f_y is limited to 80,000 psi for moment frames and 100,000 psi for structural walls.
- 20.3 Prestressing Reinforcement:
  - Design Properties (20.3.2): f_{pu} (specified tensile strength) is limited based on the material type (e.g., 270,000 psi for low-relaxation strand). f_{ps} (stress at nominal strength) is calculated based on strain compatibility or using approximate formulas.
- 20.5 Durability of Steel Reinforcement:
  - Concrete Cover (20.5.1): This is the primary method of corrosion protection. Minimum specified cover is detailed in Table 20.5.1.3.1.
    - Concrete cast against and permanently in contact with ground: 3 in.
    - Concrete exposed to weather or in contact with ground:
      - No. 6 to No. 18 bars: 2 in.
      - No. 5 bar, W31/D31 wire, and smaller: 1-1/2 in.
    - Concrete not exposed to weather or in contact with ground:
      - Slabs, joists, walls: 3/4 in. (for No. 11 bar and smaller).
      - Beams, columns: 1-1/2 in.
- 20.6 Embedments:
  - Prohibited Materials (20.6.3): Aluminum embedments shall be coated or covered to prevent reaction with concrete and electrolytic action with steel.

Visual Elements Analysis

Figure R20.4.1: Configurations of stud heads (Page 383)

- Description: This figure compares the geometry of headed shear studs per AWS D1.1 with those specified by ASTM A1044.

- Technical Details: It visually shows that the head of an ASTM A1044 stud is much larger relative to its shank diameter (`≥ √10 * shank diameter`) compared to an AWS D1.1 stud (`(√2.5 to 2) * shank diameter`).
- Relationship to Text: This figure supports the commentary (R20.4.1), explaining why AWS D1.1 studs are not suitable for use as headed shear reinforcement under the ACI code—their smaller heads do not provide sufficient anchorage.

Calculations and Formulas

- Stress-Strain Relationship (Nonprestressed Steel):
  - Formula (Elastic): $f_s = E_s * \varepsilon_s$ (for $\varepsilon_s < \varepsilon_y$)
  - Formula (Plastic): $f_s = f_y$ (for $\varepsilon_s \geq \varepsilon_y$)

BOQ Implications

- Concrete Cover and Formwork: The specified concrete cover from Table 20.5.1.3.1 directly impacts the overall dimensions of members. Increased cover requirements for durability (e.g., in corrosive environments) will increase the concrete volume and formwork dimensions in the BOQ.
- Reinforcement Grade: The specified grade of steel (f_y) is a primary cost component. The BOQ must clearly state the grade (e.g., Grade 60, Grade 80), as higher-strength steels have higher material costs.
- Coatings: If corrosion protection beyond standard cover is required (e.g., epoxy-coated or galvanized reinforcement), this represents a significant additional material and fabrication cost that must be included as a separate line item in the BOQ.

Critical Notes and Warnings

- Cover is to Transverse Steel: The commentary (R20.5.1.1) clarifies a critical point: specified cover is measured to the outermost surface of reinforcement, which for beams and columns is typically the outside of the stirrups or ties, not the main longitudinal bars. This is a common point of error in detailing.
- Yield Strength Limit for Shear: Section 20.2.2.4 limits f_{yt} (yield strength of transverse reinforcement) to 60,000 psi for most shear design. The commentary explains this is to control the width of diagonal shear cracks at service load levels. Using higher-strength steel for stirrups without meeting other specific code provisions is not permitted.

Chapter 21: Strength Reduction Factors

Overview

This chapter specifies the strength reduction factors (ϕ) that must be applied to the calculated nominal strength (S_n) of a member to obtain the design strength (ϕS_n). The ϕ factor accounts for uncertainties in material properties, dimensions, and design equations, as well as the ductility and failure consequences of the member. The value of ϕ varies depending on the type of action (flexure, shear, etc.) and, for columns, on the net tensile strain (ε_t) in the extreme tension steel.

Technical Specifications

- Table 21.2.1: Provides the primary ϕ factors for different actions.
  - Shear: $\phi = 0.75$
  - Torsion: $\phi = 0.75$
  - Bearing on concrete: $\phi = 0.65$
  - Post-tensioned anchorage zones: $\phi = 0.85$
  - Strut-and-tie models: $\phi = 0.75$
  - Plain concrete: $\phi = 0.60$
- Flexure and Axial Load (ϕ from Table 21.2.2): The ϕ factor for columns and beams varies based on the net tensile strain (ε_t) to reflect the ductility of the section.
  - Tension-controlled sections ($\varepsilon_t \geq \varepsilon_{ty} + 0.003$): $\phi = 0.90$. These are ductile sections that exhibit large deformations before failure.
  - Compression-controlled sections ($\varepsilon_t \leq \varepsilon_{ty}$):
    - With spirals: $\phi = 0.75$.
    - With ties: $\phi = 0.65$. These are brittle sections with little warning of failure.
  - Transition region ($\varepsilon_{ty} < \varepsilon_t < \varepsilon_{ty} + 0.003$): ϕ is linearly interpolated between the compression-controlled and tension-controlled limits.

Visual Elements Analysis

Figure R21.2.2a: Strain distribution and net tensile strain in a nonprestressed member (Page 395)

- Description: A diagram showing the assumed linear strain distribution across a column section at nominal strength.
- Technical Details: The diagram shows the concrete at the extreme compression fiber at its ultimate strain ($\varepsilon_{cu} = 0.003$). The strain at the level of the extreme tension steel is ε_t. The neutral axis depth is c.
- Relationship to Text: This figure is the basis for calculating ε_t, which is the controlling parameter for determining the ϕ factor for columns from Table 21.2.2.

Figure R21.2.2b: Variation of ϕ with net tensile strain in extreme tension reinforcement, εt (Page 396)

- Description: A graph plotting the strength reduction factor ϕ versus the net tensile strain εt.
- Technical Details: The graph visually shows the three zones:
  - A flat portion at $\phi = 0.65$ (or 0.75 for spirals) for compression-controlled sections ($\varepsilon t \le \varepsilon ty$).
  - A sloping line representing the linear interpolation for the transition region.
  - A flat portion at $\phi = 0.90$ for tension-controlled sections ($\varepsilon t \ge \varepsilon ty + 0.003$).
- Relationship to Text: This is a direct graphical representation of the values and interpolation procedure specified in Table 21.2.2.

Calculations and Formulas

- Transition Region ϕ Factor (for tied columns):
  - Formula: $\phi = 0.65 + 0.25 * [(\varepsilon t - \varepsilon ty) / 0.003]$
  - Procedure: This linear interpolation formula is used to calculate ϕ when the section's strain εt falls between the compression-controlled and tension-controlled limits.

BOQ Implications

- Indirect Cost Impact: The ϕ factors do not directly appear in a BOQ. However, they have a major impact on the final design and thus the required material quantities. A lower ϕ factor (e.g., 0.65 for a large column) reduces the usable strength, which may necessitate a larger column cross-section or more reinforcement to meet the $\phi Sn \ge U$ requirement, thereby increasing BOQ quantities.
- Ductility and Cost: The code incentivizes ductile design. By detailing a member to be tension-controlled ($\phi = 0.90$), the designer can use a smaller section than if it were compression-controlled ($\phi = 0.65$) for the same required strength U. This can lead to material cost savings.

Critical Notes and Warnings

- Ductility and Reliability: The commentary (R21.1.1) explains the rationale for varying ϕ: compression-controlled sections (like large columns) are less ductile and their failure can affect a larger portion of the structure, so a lower ϕ factor is used to provide a higher margin of safety. Tension-controlled sections (like most beams) are more ductile and provide warning of failure, so a higher ϕ is permitted.
- Shear is Critical: Shear failure is brittle. Therefore, the ϕ factor for shear is a constant, low value ($\phi = 0.75$) and there is no transition region. This reflects the need for a higher safety margin against brittle shear failure.

Chapter 22: Sectional Strength

Overview

This chapter provides the core equations for calculating the nominal strength (S_n) of member cross-sections for all primary actions: flexure, axial load, one-way shear, two-way shear, torsion, and bearing. These are the fundamental "engine" of concrete design, used to determine the capacity side of the $\phi S_n \geq U$ equation. The chapter is built on the design assumptions established in 22.2.

Technical Specifications

- 22.2 Design Assumptions:
  - Plane Sections: Strain in concrete and reinforcement is assumed to be proportional to the distance from the neutral axis (22.2.1.2).
  - Maximum Concrete Strain: Maximum usable strain at the extreme concrete compression fiber is assumed to be 0.003 (22.2.2.1).
  - Equivalent Stress Block (22.2.2.4): The complex nonlinear stress distribution in the compression zone can be replaced by an equivalent rectangular stress block with a uniform stress of $0.85f_c'$ and a depth of $a = \beta_1 \cdot c$. The factor β_1 is 0.85 for $f_c' \leq 4000$ psi and reduces by 0.05 for each 1000 psi of strength above 4000, but not less than 0.65.
- 22.5 One-Way Shear Strength (V_c):
  - Nonprestressed Members (Table 22.5.5.1): Provides multiple equations for V_c depending on the amount of shear reinforcement. The simplified equation is: $V_c = 2 \cdot \lambda \cdot \sqrt{f_c'} \cdot b_w \cdot d$. A more complex formula accounts for the reinforcement ratio ρ_w and the moment-to-shear ratio M_u/V_ud.
- 22.6 Two-Way Shear Strength (v_c):
  - Nonprestressed Members (Table 22.6.5.2): v_c is the least of:
    - $4 \cdot \lambda_s \cdot \lambda \cdot \sqrt{f_c'}$
    - $(2 + 4/\beta) \cdot \lambda_s \cdot \lambda \cdot \sqrt{f_c'}$
    - $(2 + \alpha_s \cdot d/b_o) \cdot \lambda_s \cdot \lambda \cdot \sqrt{f_c'}$
  - λ_s: A size effect factor, $\lambda_s = \sqrt{2 / (1 + 0.1d)} \leq 1.0$, which reduces shear strength for slabs with $d > 10$ in.
- 22.7 Torsional Strength:
  - Threshold Torsion (T_{th}): Torsion can be neglected if $T_u < \phi T_{th}$. T_{th} is calculated based on section properties.
  - Nominal Torsional Strength (T_n): $T_n = (2 \cdot A_o \cdot A_t \cdot f_{yt} / s) \cdot \cot(\theta)$, where A_o is the area enclosed by the shear flow path.

Calculations and Formulas

This chapter is almost entirely composed of formulas. Key examples:

- Nominal Moment Strength (M_n):
  - Formula: $M_n = A_s * f_y * (d - a/2)$ (for a rectangular section with tension steel only)
  - Variables: A_s = area of tension steel, f_y = yield strength, d = effective depth, a = depth of equivalent stress block.
- Nominal One-Way Shear Strength (Simplified):
  - Formula: $V_c = 2 * \lambda * \sqrt{f_c'} * b_w * d$
- Nominal Two-Way Shear Strength (Simplified):
  - Formula: $v_c = 4 * \lambda_s * \lambda * \sqrt{f_c'}$
- Nominal Torsional Strength (T_n):
  - Formula: $T_n = (2 * A_o * A_t * f_{yt} / s) * \cot(\theta)$
  - Variables: A_o = area enclosed by shear flow path, A_t = area of one leg of a closed stirrup, s = stirrup spacing, θ = angle of compression diagonals.

BOQ Implications

- Direct Impact on Quantities: The formulas in this chapter are used to directly size members and determine required reinforcement. For a given factored load V_u, the shear strength formula for V_s ($V_s = A_v*f_y*d/s$) is rearranged to solve for the required area of stirrups per unit length (A_v/s). This value is then used to select the stirrup size and spacing, which is a direct input for the steel quantity takeoff in the BOQ.
- Trade-offs: The design process involves trade-offs that affect the BOQ. For shear, a designer can either use a larger concrete section to increase V_c or add more shear reinforcement (V_s). The relative cost of concrete versus reinforcing steel and labor will influence this decision.

Critical Notes and Warnings

- Size Effect in Shear: The commentary (R22.5.5.1, R22.6.5.2) highlights the "size effect," where the nominal shear stress at failure decreases as member depth increases. The factor λ_s was introduced to account for this phenomenon in two-way shear, making designs for thick slabs safer than in previous code editions.
- Combined Actions: The commentary (R22.7.7.1) explains how shear and torsional stresses are combined. For solid sections, they are combined using a "square root of the sum of the squares" approach, while for hollow sections, they are added directly. This distinction is critical for the design of members like spandrel beams.

Chapter 23: Strut-and-Tie Method

Overview

This chapter provides a powerful analysis and design tool for regions of a structure where the basic assumption of linear strain distribution is invalid. These are known as "D-regions" (Disturbed or Discontinuity regions) and occur near concentrated loads, reactions, or geometric changes. The method involves modeling the complex flow of forces as a simplified truss, consisting of concrete compression struts, reinforcing steel tension ties, and nodal zones where they intersect.

Technical Specifications

- Applicability (23.1.1): Applies to regions where the load or geometry causes a nonlinear distribution of longitudinal strain.
- Model Components (23.2):
  - Struts: Compression members. Can be prismatic, bottle-shaped, or fan-shaped.
  - Ties: Tension members, consisting of reinforcement.
  - Nodal Zones: The intersection points of struts and ties.
- Design Strength (`ϕFns`, `ϕFnt`, `ϕFnn`): The design strength of each strut, tie, and nodal zone must be greater than or equal to the factored force (`Fus`, `Fut`) in that element (23.3.1).
- Strength of Struts (`fce`) (23.4.3): The effective compressive strength of a strut depends on its type and confinement.
  - `fce = 0.85 * βs * fc'`. The factor `βs` is 1.0 for prismatic struts, 0.75 for bottle-shaped struts with reinforcement, and can be as low as 0.4 for unreinforced tension zones.
- Strength of Nodal Zones (`fce`) (23.9.2): The effective compressive strength of a nodal zone depends on the types of elements framing into it.
  - `fce = 0.85 * βn * fc'`. The factor `βn` is 1.0 for C-C-C nodes (compression-compression-compression), 0.80 for C-C-T nodes, and 0.60 for C-T-T nodes.

Visual Elements Analysis

Figure R23.1: D-regions and discontinuities (Page 438)

- Description: This figure shows examples of D-regions in various structural members, such as a beam with a hole, a dapped-end beam, and a beam with a concentrated load near a support.

- Technical Details: The D-region is shaded and shown to extend a distance `h` (the member depth) from the source of the discontinuity. The regions outside the shaded area are B-regions, where standard beam theory applies.
- Relationship to Text: This figure is crucial for identifying where the strut-and-tie method is required. It visually defines the boundaries between B-regions and D-regions.

Figure R23.2.1: Description of strut-and-tie model (Page 439)

- Description: A diagram of a simple-span deep beam showing a typical strut-and-tie model.
- Technical Details: It shows two inclined compression struts transferring the load from the top of the beam to the supports. A horizontal tension tie (the bottom reinforcement) connects the base of the struts. Nodal zones are shown at the load application point and at the supports.
- Relationship to Text: This figure is the classic illustration of the strut-and-tie method, showing how the internal truss is conceptualized.

Figure R23.2.6a,b,c: Hydrostatic nodes, extended nodal zones, and classification of nodes (Pages 442-443)

- Description: These figures provide detailed views of the nodal zones.
- Technical Details:
    - Hydrostatic Node: A simple node where forces are in equilibrium.
    - Extended Nodal Zone: Shows that the "node" is not a point but a volume of concrete over which forces are distributed. It illustrates how the geometry of the node depends on the width of the struts and the anchorage length of the tie.
    - Classification: Shows the three main types of nodes: C-C-C, C-C-T, and C-T-T.
- Relationship to Text: These figures are essential for correctly detailing the reinforcement at the nodes, which is often the most critical part of a strut-and-tie design.

BOQ Implications

- Reinforcement Detailing: The strut-and-tie method leads to non-standard reinforcement patterns. The BOQ will include quantities for specifically placed bars that act as tension ties, which may be oriented at various angles and require special anchorage details (e.g., large-radius bends, mechanical heads).
- Formwork for D-regions: For members like deep beams or dapped ends, the geometry is complex, leading to higher formwork design and construction costs that must be captured in the BOQ.

Critical Notes and Warnings

- Angle Between Struts and Ties (23.2.7): The angle between the axes of any strut and any tie entering a single node shall be at least 25 degrees. The commentary explains this is to avoid incompatibilities from strut shortening and tie elongation occurring in nearly the same direction.
- Minimum Distributed Reinforcement (23.5): The commentary (R23.5) explains that while the strut-and-tie method is based on lower-bound plasticity theory, which doesn't strictly require it, minimum distributed reinforcement (a mesh of bars) must be provided in D-regions to control cracking at service loads and promote ductile behavior. This is a mandatory requirement that must be followed.

Chapter 24: Serviceability

Overview

This chapter focuses on requirements that ensure a structure performs acceptably under normal service loads, distinct from the strength requirements for ultimate loads. The primary serviceability concerns addressed are deflections and cracking. The chapter provides methods for calculating immediate and long-term deflections and sets limits on reinforcement spacing to control the width of flexural cracks.

Technical Specifications

- 24.2 Deflections:
  - Maximum Permissible Deflections (Table 24.2.2): Provides limits on calculated deflections for various members to prevent damage to nonstructural elements.
    - Immediate deflection due to live load (L): Limited to $\ell/180$ for flat roofs and $\ell/360$ for floors.
    - Long-term deflection: The portion of the total deflection occurring after attachment of nonstructural elements (sum of time-dependent part of dead load deflection and immediate live load deflection) is limited to $\ell/480$ (if likely to be damaged) or $\ell/240$ (if not likely to be damaged).
  - Time-Dependent Deflection (24.2.4): Long-term deflection due to creep and shrinkage is calculated by multiplying the immediate deflection by a factor $\lambda\Delta$.
    - $\lambda\Delta = \xi / (1 + 50\rho')$, where ξ is a time-dependent factor from Table 24.2.4.1.3 (e.g., 2.0 for 5 years or more) and ρ' is the compression reinforcement ratio.
- 24.3 Distribution of Flexural Reinforcement:

- Maximum Spacing (s) (Table 24.3.2): Provides the primary equation for controlling flexural crack width in beams and one-way slabs.
    - $s \le 15 * (40,000/f_s) - 2.5c_c$
    - $s \le 12 * (40,000/f_s)$
    - f_s can be taken as $(2/3)f_y$.

Calculations and Formulas

- Effective Moment of Inertia (I_e):
  - Formula (Branson's Equation): $I_e = (M_{cr}/M_a)^3 * I_g + [1 - (M_{cr}/M_a)^3] * I_{cr} \le I_g$
  - Variables: M_{cr} = cracking moment, M_a = maximum service-load moment, I_g = gross moment of inertia, I_{cr} = cracked moment of inertia.
  - Procedure: This equation provides a transition between the gross (uncracked) and cracked moment of inertia based on the level of applied moment, and is used for calculating immediate deflections.
- Long-Term Deflection Multiplier (λ_Δ):
  - Formula: $\lambda_\Delta = \xi / (1 + 50\rho')$
- Maximum Reinforcement Spacing (s):
  - Formula: $s \le 15 * (40,000/f_s) - 2.5c_c$

BOQ Implications

- Member Sizing: Serviceability, especially deflection limits, can often govern the required depth of long-span beams and slabs. A design governed by deflection will require a deeper section (and thus more concrete) than a design governed by strength alone. This directly impacts the concrete volume in the BOQ.
- Compression Steel: The formula for λ_Δ shows that adding compression reinforcement (ρ') reduces long-term deflections. A designer might choose to add compression steel, which increases the steel quantity in the BOQ, specifically to meet deflection limits without increasing the member depth.

Critical Notes and Warnings

- Deflection is Critical for Finishes: The commentary (R24.2.2) emphasizes that deflection limits are primarily to prevent damage to attached nonstructural elements like drywall, partitions, and windows. The most critical deflection is the portion that occurs *after* these elements are installed.
- Crack Control is for Aesthetics and Durability: The commentary (R24.3.1) explains that the rules for reinforcement spacing are not intended to prevent cracking entirely, but to control the width of cracks to a level that is generally not objectionable aesthetically and, to some extent, to improve durability by limiting ingress of corrosive agents.

Part 10: Reinforcement, Construction, and Evaluation (Chapters 25-27 & Appendices)

Chapter 25: Reinforcement Details

Overview

This chapter is the practical guide to reinforcement detailing, providing the geometric and placement rules essential for ensuring that reinforcement performs as assumed in the design. It covers minimum spacing of bars, the geometry of standard hooks and ties, and the critical requirements for development length (the length of embedment needed to develop a bar's strength) and lap splices (the length of overlap needed to transfer force between bars). These provisions are fundamental to preventing bond and anchorage failures.

Key Standards and Codes Referenced

- ACI Detailing Manual (SP-66): Referenced as a standard for preparing design drawings and fabrication details.
- ACI 408.1R: Source for the empirical basis of the development length equations.

Technical Specifications

- 25.2 Minimum Spacing:
  - Horizontal Layers (25.2.1): Clear spacing between parallel bars in a layer shall be at least the greatest of 1 in., the bar diameter d_b, and (4/3)d_{agg} (nominal maximum aggregate size).
  - Vertical Layers (25.2.2): Clear spacing between layers shall be at least 1 in.
  - Columns (25.2.3): Clear spacing between longitudinal bars shall be at least the greatest of 1.5 in., 1.5d_b, and (4/3)d_{agg}.
- 25.3 Standard Hooks:
  - Geometry (Table 25.3.1): Defines the geometry for standard hooks used in tension development.
    - 90-degree hook: Minimum inside bend diameter of $6d_b$ to $10d_b$ (depending on bar size), plus a straight extension of $12d_b$.
    - 180-degree hook: Minimum inside bend diameter of $6d_b$ to $10d_b$, plus a straight extension of $4d_b$ (but not less than 2.5 in.).
- 25.4 Development of Reinforcement:
  - General (25.4.1.4): The value of $\sqrt{f_c'}$ used in development length calculations shall not exceed 100 psi.

    - Tension Development (ℓd) (Table 25.4.2.3): Provides simplified equations for ℓd. For a No. 7 or larger bar with minimum cover and spacing, the basic formula is `ℓd = [fy*ψt*ψe*ψg / (20*λ*√fc')] * db`.
    - Hook Development (ℓdh) (25.4.3.1): The basic formula is `ℓdh = [fy*ψe*ψr*ψo*ψc / (55*λ*√fc')] * db`, but not less than `8db` or 6 in.
    - Headed Bar Development (ℓdt) (25.4.4.2): The basic formula is `ℓdt = [0.016*ψe*ψp*ψo*fy / √fc'] * db`, but not less than `8db` or 6 in.
- 25.5 Splices:
    - Lap Splice Prohibition (25.5.1.1): Lap splices shall not be permitted for bars larger than No. 11.
    - Tension Lap Splices (ℓst) (Table 25.5.2.1): The required length is a multiple of the development length ℓd.
        - Class A splice: `ℓst = 1.0 * ℓd`. Permitted only where the area of steel provided is at least twice that required and no more than 50% of the bars are spliced at one location.
        - Class B splice: `ℓst = 1.3 * ℓd`. Required for all other cases.

Visual Elements Analysis

Figure R25.3.1: Standard hook geometry (Page 471)

- Description: This figure provides clear diagrams illustrating the geometry of 90-degree and 180-degree standard hooks.
- Technical Details: It visually defines the inside bend diameter (`db`) and the straight extension (`ℓext`). It shows how the hook must engage a longitudinal bar. The "point at which bar is developed" is shown at the point of tangency of the hook.
- Relationship to Text: This figure is the visual definition of the standard hooks specified in Table 25.3.1, making the dimensional requirements unambiguous.

Figure R25.5.2.1: Clear spacing of lap-spliced bars (Page 491)

- Description: A diagram showing a plan view of staggered lap splices.
- Technical Details: It clarifies that for staggered splices, the "clear spacing" used to determine confinement effects is the minimum distance between adjacent, non-contact splices. A lapped bar is shown for reference.
- Relationship to Text: This figure provides a critical visual interpretation for applying the splice requirements in Table 25.5.2.1, especially when staggering splices to qualify for a Class A splice.

Calculations and Formulas

- Tension Development Length (`ℓd`):
    - Formula (General): `ℓd = [ (3/40) * (fy / (λ√fc')) * (ψt*ψe*ψs*ψg / ((cb + Ktr)/db)) ] * db`

    - Variables: f_y=yield strength, λ=lightweight factor, f_c'=concrete strength, ψ_t, ψ_e, ψ_s, ψ_g=modification factors for casting position, epoxy coating, bar size, and grade, c_b=cover dimension, K_{tr}=transverse reinforcement index, d_b=bar diameter.
- Tension Lap Splice Length (ℓ_{st}):
    - Formula: $\ell_{st} = (\text{Class Factor}) * \ell_d$, where the Class Factor is 1.0 for Class A or 1.3 for Class B.

BOQ Implications

- Steel Tonnage: Development and splice lengths are a major driver of the total weight of reinforcing steel in a project. Class B splices require 30% more material than Class A splices for the same bar, directly impacting the BOQ.
- Labor Costs: The requirement for hooks on bar ends increases fabrication labor costs compared to straight bars. The need for transverse reinforcement over splice lengths adds to both material and labor costs.
- Mechanical Splices: Using mechanical splices (25.5.7) instead of lap splices is a significant cost trade-off. Mechanical couplers have a high unit cost but can reduce reinforcement congestion and eliminate the extra steel required for a lap, which is a key consideration for the BOQ in heavily reinforced members.

Critical Notes and Warnings

- Do Not Use Excess Steel Factor ($A_{s,req}/A_{s,prov}$) for Splices: The commentary (R25.5.1.4) explicitly states that the development length used to calculate a lap splice length must be based on f_y. You cannot use a shorter ℓ_d calculated based on a lower stress and then apply the lap splice multiplier.
- Splices in Tension Tie Members (25.5.7.4): For critical tension members, lap splices are not permitted. Splices must be made with a full mechanical or welded splice, and adjacent splices must be staggered by at least 30 in.
- No Lap Splices for Large Bars: Bars larger than No. 11 cannot be lap spliced. This is a critical constructibility constraint that necessitates the use of mechanical splices for these large bars.

Chapter 26: Construction Documents and Inspection

Overview

This chapter bridges the gap between design and construction. It specifies the minimum information that the licensed design professional shall include in the construction documents (drawings and specifications) to ensure the structure is built as intended. It also outlines the minimum requirements for inspection and testing to verify compliance during construction. This chapter is fundamentally about communication, quality assurance, and responsibility.

Key Standards and Codes Referenced

- ACI 301: Specifications for Structural Concrete (often referenced as a baseline for project specifications).
- ACI 117: Standard Tolerances for Concrete Construction and Materials.
- ASTM C1077: Standard Practice for Agencies Testing Concrete and Concrete Aggregates for Use in Construction.
- ASTM C94: Standard Specification for Ready-Mixed Concrete.
- ACI 308R: Guide to Curing Concrete.
- ACI 306R: Guide to Cold Weather Concreting.
- ACI 305R: Guide to Hot Weather Concreting.

Technical Specifications

- 26.2 Design Criteria: Construction documents must state the name and year of the building code used, design loads, and any delegated design work.
- 26.4 Concrete Materials and Mixture Requirements: The documents shall specify for each concrete mixture:
  - Minimum compressive strength `fc'`.
  - Maximum `w/cm` based on durability exposure class (from Chapter 19).
  - Required cement types, aggregate requirements, and admixture types.
  - Nominal maximum size of coarse aggregate.
- 26.6 Reinforcement Materials and Construction: The documents shall specify:
  - ASTM designation and grade of reinforcement (e.g., ASTM A706, Grade 60).
  - Size, location, detailing, and embedment length of all reinforcement.
  - Location and length of all lap splices.
  - Type and location of all mechanical splices.
- 26.12 Evaluation and Acceptance of Concrete:
  - Strength Test (26.12.1.1): A strength test is defined as the average of at least two 6x12 in. cylinders or three 4x8 in. cylinders.
  - Frequency of Testing (26.12.2.1): Samples must be taken at least: once per day, once per 150 yd^3 of concrete, and once per 5000 ft^2 of slab/wall surface area.
  - Acceptance Criteria (26.12.3.1): Concrete is acceptable if:
    a. Every average of any three consecutive strength tests equals or exceeds `fc'`.

b. No single strength test falls below `fc'` by more than 500 psi (if `fc' ≤ 5000 psi`) or by more than `0.10fc'` (if `fc' > 5000 psi`).

- 26.13 Inspection:
  - Continuous Inspection (26.13.3.2): Required for critical activities like placement of reinforcement for special moment frames and tensioning of prestressing tendons.
  - Periodic Inspection (26.13.3.3): Required for activities like placement of reinforcement, placement of concrete, and installation of post-installed anchors.

BOQ Implications

- Basis of the BOQ: This chapter mandates that all the information necessary to create a complete and accurate BOQ be included in the construction documents. The BOQ is a direct translation of the requirements specified under the rules of this chapter.
- Quality Control Costs: The specified frequency of testing (26.12.2) and the level of inspection (continuous vs. periodic) are direct cost inputs for the Quality Control section of the project budget and must be included in the BOQ or project general conditions.
- Tolerances: The specified placement tolerances for reinforcement (Table 26.6.2.1(a)) set the standard of care for construction. Tighter-than-standard tolerances, if specified by the designer, will increase labor costs and must be accounted for.

Critical Notes and Warnings

- Responsibility: The commentary (R26.1) makes it clear that the intent of the Code is for the construction documents to be a complete set of instructions. The contractor should not be expected to read and interpret the ACI code; all necessary requirements should be explicitly stated in the drawings and specifications.
- Investigation of Low Strength: The code provides a clear, multi-step procedure for what to do when strength tests fail the acceptance criteria (26.12.6). This can involve drilling cores from the structure for testing, which is a costly and time-consuming process.

Chapter 27: Strength Evaluation of Existing Structures

Overview

This chapter provides the procedures for evaluating the strength of an existing structure when its safety is in doubt. This can be due to low strength test results during construction, signs of distress, a change in use, or damage. The chapter outlines two main paths: an analytical evaluation based on as-built conditions and material properties, or a physical load test (either monotonic or cyclic).

Key Standards and Codes Referenced

- ACI 437.2: Code Requirements for Load Testing of Existing Concrete Structures and Commentary.
- ASTM C42: Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete.

Technical Specifications

- 27.3 Analytical Strength Evaluation:
    - Requires determining as-built dimensions, reinforcement locations, and in-place material properties (often through core testing).
    - Increased strength reduction factors (ϕ) from Table 27.3.2.1 are permitted if as-built properties are thoroughly determined. For example, ϕ for a tension-controlled section can be increased from 0.90 to 1.0.
- 27.4 General Requirements for Load Testing:
    - The portion of the structure to be tested shall be at least 56 days old (27.4.4).
- 27.5 Monotonic Load Test:
    - Test Load (T_t) (27.4.6.2): The total test load is the greatest of:
        - $1.0D_w + 1.1D_s + 1.6L + 0.5(L_r \text{ or } S \text{ or } R)$
        - $1.0D_w + 1.1D_s + 1.0L + 1.6(L_r \text{ or } S \text{ or } R)$
        - $1.3(D_w + D_s)$
    - Procedure: The test load is applied in at least four increments and held for 24 hours (27.5.1).
    - Acceptance Criteria (27.5.3):
        - No evidence of failure (spalling, crushing).
        - Deflection Recovery: The residual deflection 24 hours after removing the test load (Δ_r) must be no more than 1/4 of the maximum deflection (Δ_{max}) ($\Delta_r \le \Delta_{max}/4$).
        - If recovery is not met, a second test can be performed. The structure is acceptable if the recovery for the second test satisfies $\Delta_r \le \Delta_{max}/5$.

Calculations and Formulas

- Monotonic Load Test Acceptance:

- Formula (1st Test): $\Delta r \leq \Delta max / 4$
- Formula (2nd Test): $\Delta r \leq \Delta max / 5$
- Variables: Δr = residual deflection, Δmax = maximum deflection under load.

BOQ Implications

- High Cost of Evaluation: Strength evaluations are not part of a standard construction BOQ but represent a significant potential cost if problems arise.
- Load Test Costs: A physical load test is extremely expensive. The BOQ for a load test would include costs for:
    - Engineering analysis to design the test.
    - Shoring and safety measures.
    - The materials used for loading (water tanks, concrete blocks, etc.).
    - Instrumentation (deflection gauges, strain gauges).
    - Labor to conduct the test and monitor the structure for 24+ hours.

Critical Notes and Warnings

- Safety First: The code (27.4.2) mandates that load tests be conducted in a manner that provides for the safety of life and the structure. This requires careful planning and often extensive shoring.
- Load Testing is a Last Resort: The commentary makes it clear that an analytical evaluation is preferred if sufficient information is available. A load test is typically performed only when analysis is not feasible or when the results of an analysis are inconclusive.
- Passing a Load Test Does Not Guarantee Future Performance: The commentary (R27.2.4) warns that for a deteriorating structure, passing a load test only validates its capacity at that moment in time. It may require a program of periodic re-evaluation and inspection to remain in service.

Appendices A, B, and C

- Appendix A: Design Verification Using Nonlinear Response History Analysis:
    - Overview: Provides requirements for a highly advanced, performance-based seismic design method. It is an alternative to the prescriptive rules in Chapter 18.
    - Key Concepts: Actions are classified as either deformation-controlled (ductile, e.g., beam flexure) or force-controlled (brittle, e.g., shear). The design ensures that deformation-controlled actions can sustain large inelastic deformations while force-controlled actions remain essentially elastic.

    - BOQ Implications: This method has massive implications for engineering fees but can potentially lead to a more efficient and less costly structure by optimizing the seismic system.
- Appendix B: Steel Reinforcement Information:
    - Overview: A set of reference tables providing the nominal diameter, area, and weight per foot for standard ASTM reinforcing bars (No. 3 through No. 18) and prestressing strands and wires.
    - BOQ Implications: These tables are the primary source of data used by estimators to convert reinforcement specified on drawings (by bar size) into a total weight for pricing in the BOQ.
- Appendix C: Equivalence Between SI-Metric, MKS-Metric, and U.S. Customary Units of Nonhomogenous Equations in the Code:
    - Overview: A conversion table for the more complex, non-homogenous equations in the code (those that don't scale linearly with units).
    - BOQ Implications: This is a critical tool for estimators working on international projects or converting designs between unit systems, ensuring that calculations for quantities based on these equations are performed correctly.