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An ACI Handbook

The Reinforced Concrete Design Handbook

A Companion to *ACI 318-14*

Volume 1: Member Design

SP-17(14)

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ACI SP-17(14)

THE REINFORCED CONCRETE DESIGN HANDBOOK

A Companion to *ACI 318-14*

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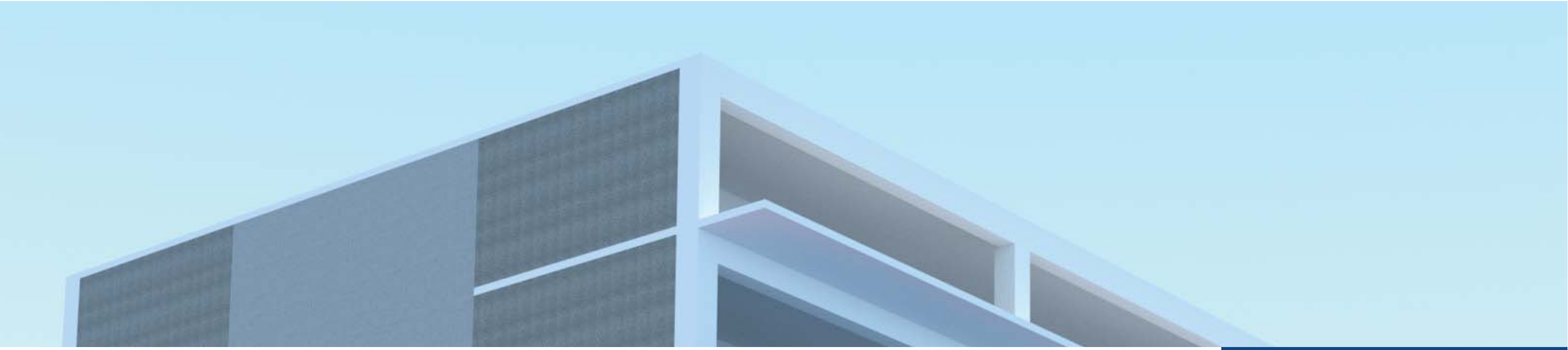

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38800 Country Club Drive
Farmington Hills, MI 48331 USA
+1.248.848.3700
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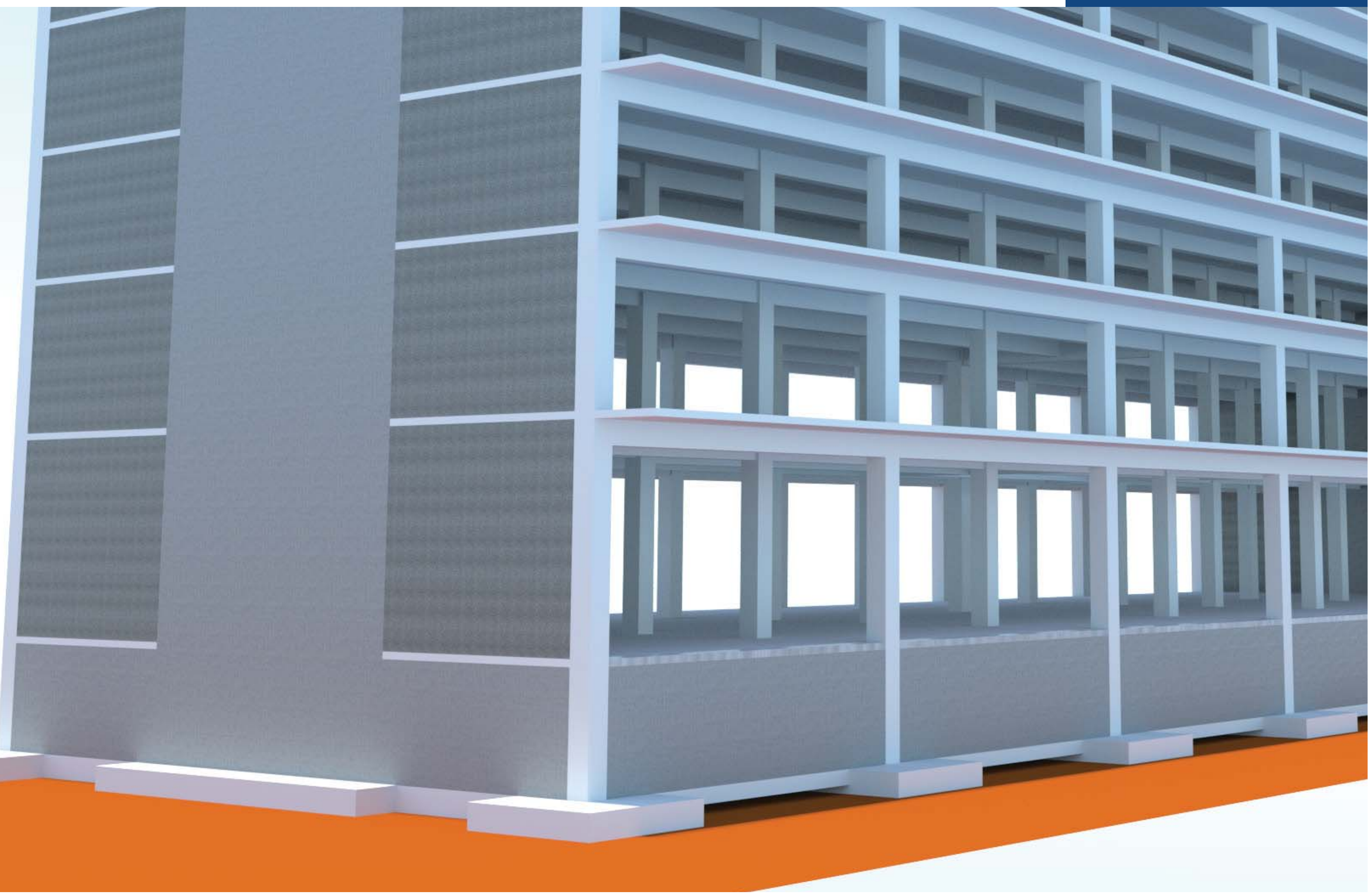

ACI SP-17(14)
Volume 1

THE REINFORCED CONCRETE DESIGN HANDBOOK

A Companion to *ACI 318-14*

Editors:
Andrew Taylor
Trey Hamilton III
Antonio Nanni

American Concrete Institute
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Volume 1 ~ Ninth Edition

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American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331 USA
+1.248.848.3700

Managing Editor: Khaled Nahlawi
Staff Engineers: Daniel W. Falconer, Matthew R. Senecal, Gregory M. Zeisler, and Jerzy Z. Zemajtis
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DEDICATION

This edition of *The Reinforced Concrete Design Handbook, SP-17(14),* is dedicated to the memory of Daniel W. Falconer and his many contributions to the concrete industry. He was Managing Director of Engineering for the American Concrete Institute from 1998 until his death in July 2015.

Dan was instrumental in the reorganization of *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)* as he served as ACI staff liaison to ACI Committee 318, Structural Concrete Building Code; and ACI Subcommittee 318-SC, Steering Committee. His vision was to simplify the use of the Code for practitioners and to illustrate the benefits of the reorganization with this major revision of *SP-17*. His oversight and review comments were instrumental in the development of this Handbook.

An ACI member since 1982, Dan served on ACI Committees 344, Circular Prestressed Concrete Structures, and 373, Circular Concrete Structures Prestressed with Circumferential Tendons. He was also a member of the American Society of Civil Engineers. Prior to joining ACI, Dan held several engineering and marketing positions with VSL Corp. Before that, he was Project Engineer for Skidmore, Owings, and Merrill in Washington, DC. He received his BS in civil engineering from the University of Buffalo, Buffalo, NY and his MS in civil and structural engineering from Lehigh University, Bethlehem, PA. He was a licensed professional engineer in several states.

In his personal life, Dan was an avid golfer, enjoying outings with his three brothers whenever possible. He was also an active member of Our Savior Lutheran Church in Hartland, MI, and a dedicated supporter and follower of the Michigan State Spartans basketball and football programs. Above all, Dan was known as a devoted family man dedicated to his wife of 33 years, Barbara, his children Mark, Elizabeth, Kathryn, and Jonathan, and two grandsons Samuel and Jacob.

In his memory, the ACI Foundation has established an educational memorial. For more information visit http://www.scholarshipcouncil.org/Student-Awards. Dan will be sorely missed for many years to come.

FOREWORD

The Reinforced Concrete Design Handbook provides assistance to professionals engaged in the design of reinforced concrete buildings and related structures. This edition is a major revision that brings it up-to-date with the approach and provisions of *Building Code Requirements for Structural Concrete (ACI 318-14).* The layout and look of the Handbook have also been updated.

The Reinforced Concrete Design Handbook now provides dozens of design examples of various reinforced concrete members, such as one- and two-way slabs, beams, columns, walls, diaphragms, footings, and retaining walls. For consistency, many of the numerical examples are based on a fictitious seven-story reinforced concrete building. There are also many additional design examples not related to the design of the members in the seven story building that illustrate various *ACI 318-14* requirements.

Each example starts with a problem statement, then provides a design solution in a three column format—code provision reference, short discussion, and design calculations— followed by a drawing of reinforcing details, and finally a conclusion elaborating on a certain condition or comparing results of similar problem solutions.

In addition to examples, almost all chapters in the *Reinforced Concrete Design Handbook* contain a general discussion of the related *ACI 318-14* chapter.

All chapters were developed by ACI staff engineers under the auspices of the ACI Technical Activities Committee (TAC). To provide immediate oversight and guidance for this project, TAC appointed three content editors: Andrew Taylor, Trey Hamilton III, and Antonio Nanni. Their reviews and suggestions improved this publication and are appreciated. TAC also appreciates the support of Dirk Bondy and Kenneth Bondy who provided free software to analyze and design the post-tensioned beam example, in addition to valuable comments and suggestions. Thanks also go to JoAnn Browning, David DeValve, Anindya Dutta, Charles Dolan, Matthew Huslig, Ronald Klemencic, James Lai, Steven McCabe, Mike Mota, Hani Nassif, Jose Pincheira, David Rogowski, and Siamak Sattar, who reviewed one or more of the chapters.

Special thanks go to StructurePoint and Computers and Structures, Inc. (SAP 2000 and Etabs) for providing a free copy of their software to perform analyses of structure and members.

Special thanks also go to Stuart Nielsen, who provided the cover art using SketchUp.

The Reinforced Concrete Design Handbook is published in two volumes: Chapters 1 through 11 are published in Volume 1 and Chapters 12 through 15 are published in Volume 2. Design aids and a moment interaction diagram Excel spreadsheet are available for free download from the following ACI webpage links:
https://www.concrete.org/store/productdetail.aspx?ItemID=SP1714DAE
https://www.concrete.org/store/productdetail.aspx?ItemID=SP1714DA

Keywords: anchoring to concrete; beams; columns; cracking; deflection; diaphragm; durability; flexural strength; footings; frames; piles; pile caps; post-tensioning; punching shear; retaining wall; shear strength; seismic; slabs; splicing; stiffness; structural analysis; structural systems; strut-and-tie; walls.

Khaled Nahlawi
Managing Editor

VOLUME 1: CONTENTS

CHAPTER 1—BUILDING EXAMPLE

1.1—Introduction

The building depicted in this chapter was developed to show how, by various examples in this Handbook, to design and detail a common concrete building according to ACI 318-14. This example building is seven stories above ground and has a one story basement. The building has evenly spaced columns along the grid lines. One column has been removed along Grid C on the second level so that there is open space for the lobby. The building dimensions are:

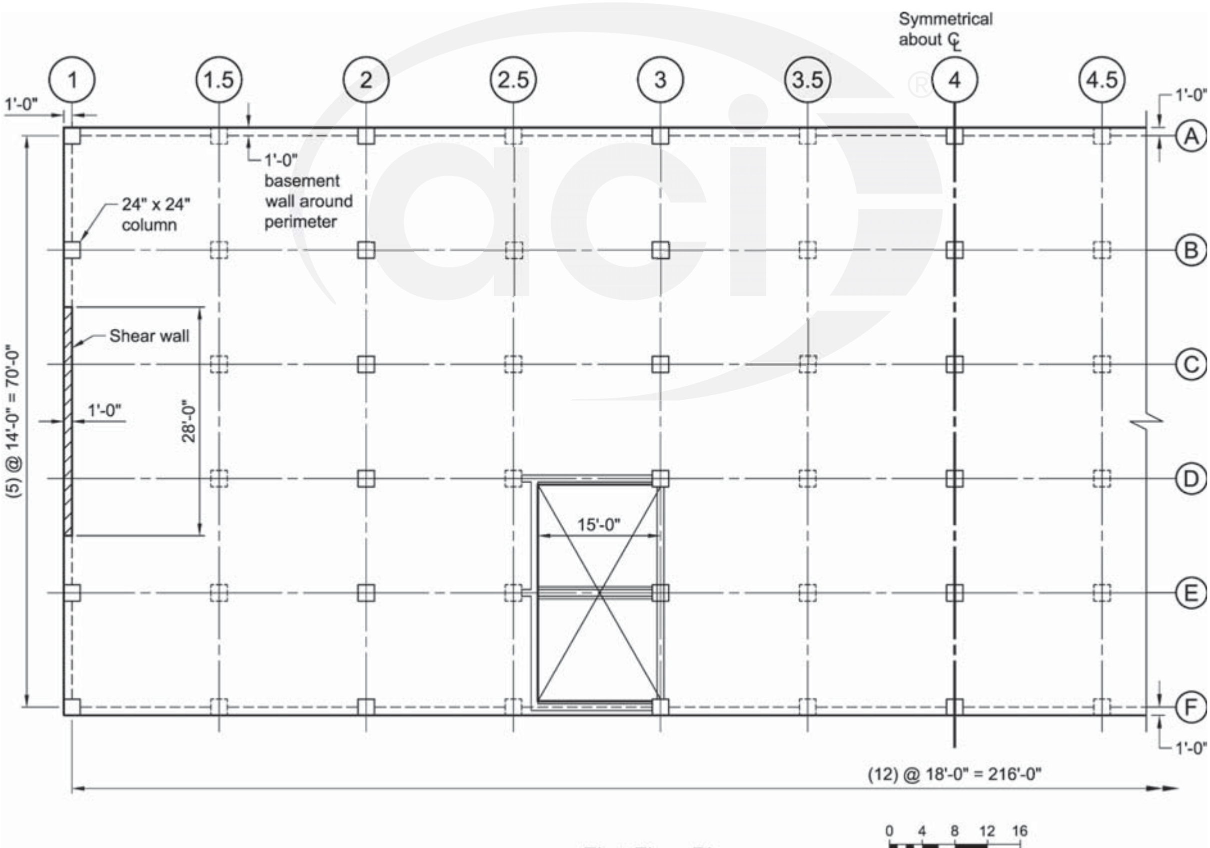
- Width (north/south) = 72 ft (5 bays @ 14 ft)
- Length (east/west) = 218 ft (6 bays @ 36 ft)
- Height (above ground) = 92 ft
- Basement height = 10 ft

The basement is used for storage, building services and mechanical equipment. It is ten feet high and has an extra column added in every bay along Grids A through F to support a two-way slab at the second level. There are basement walls at the perimeter.

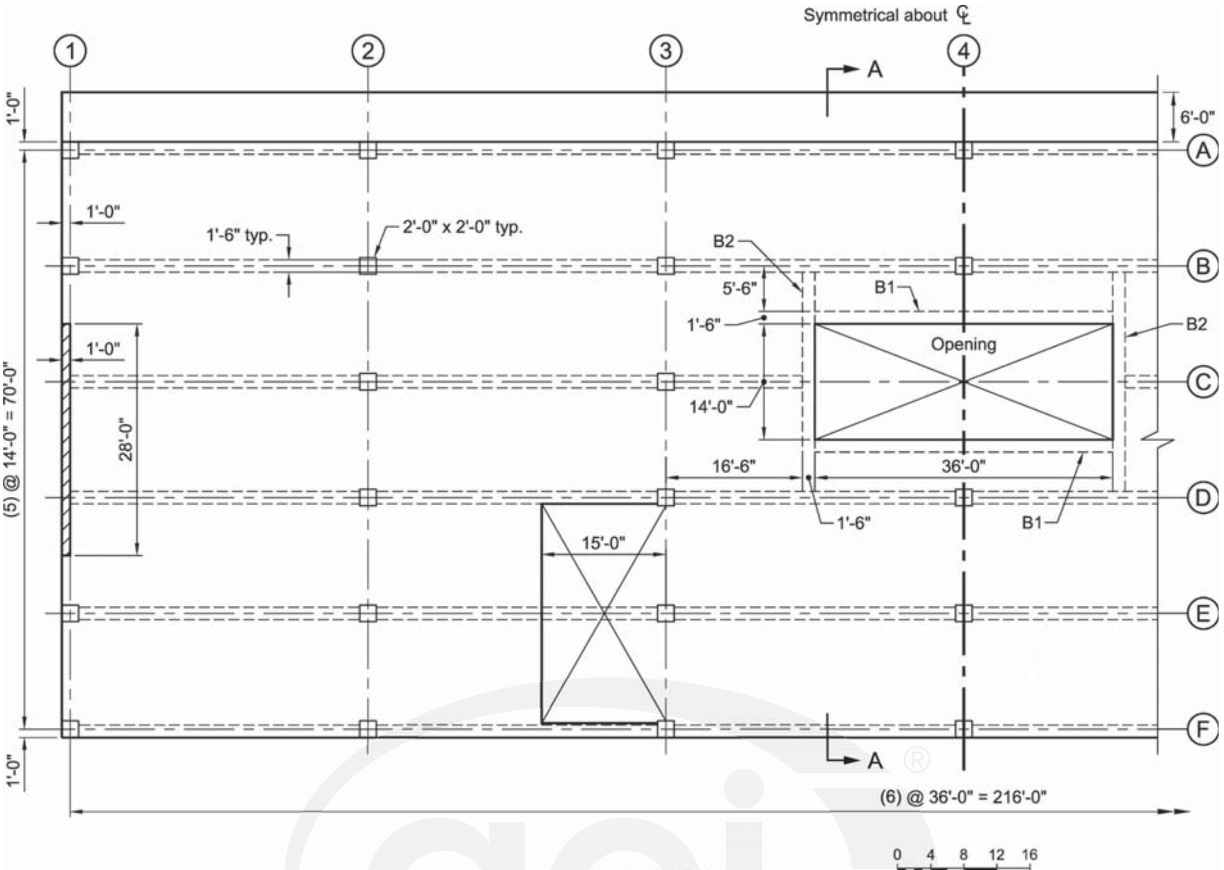
The structural system is an ordinary concrete shear wall in the north/south direction and an ordinary concrete moment frame in east/west direction. These basic systems were chosen as a starting point for the examples. Member examples may be expanded to show how they may be designed in intermediate or special systems but a new structural analysis is not done. The following analysis results provide the moments, shears, and axial loads given in the examples in other chapters in the manual. Those examples may modify this initial data to demonstrate some specific code requirement.

1.2—Building plans and elevation

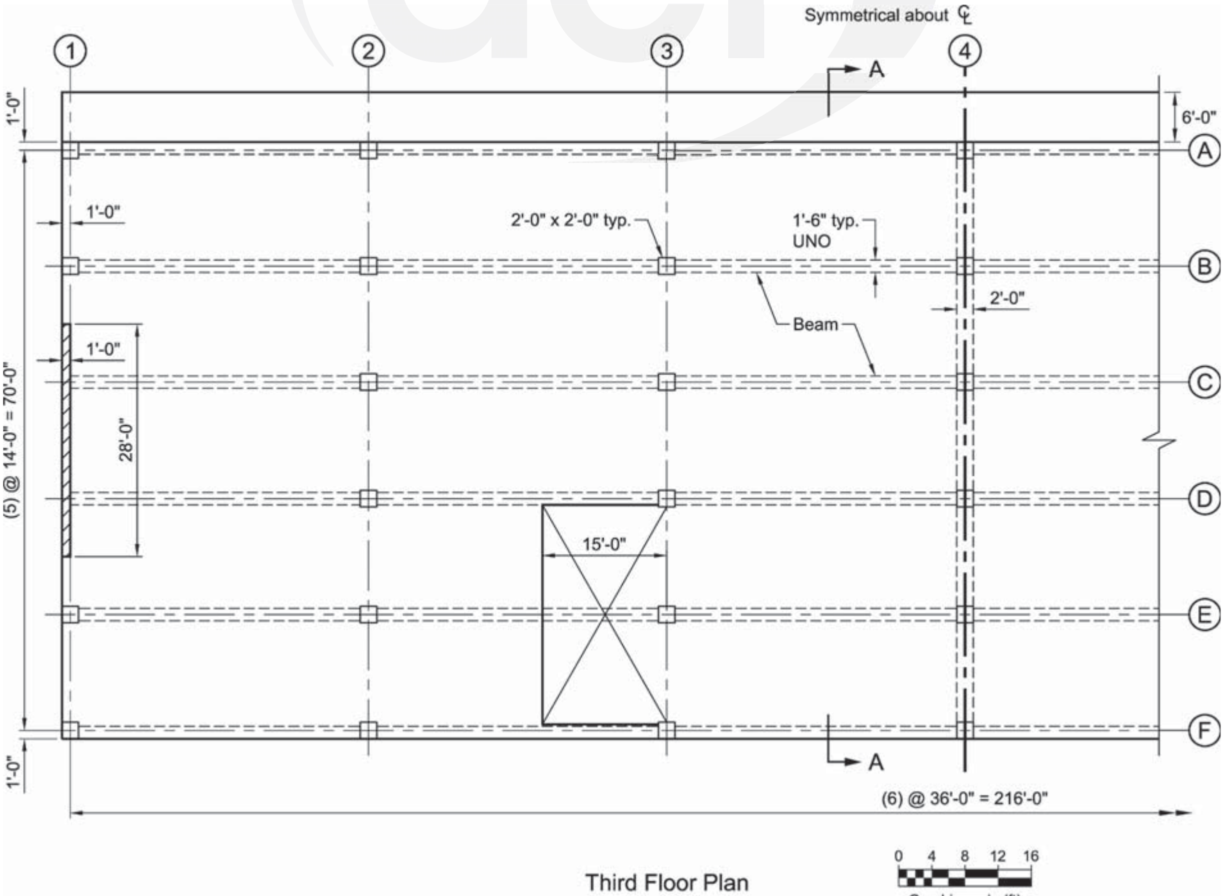
The following building plans and elevation provide the illustration of the example building.



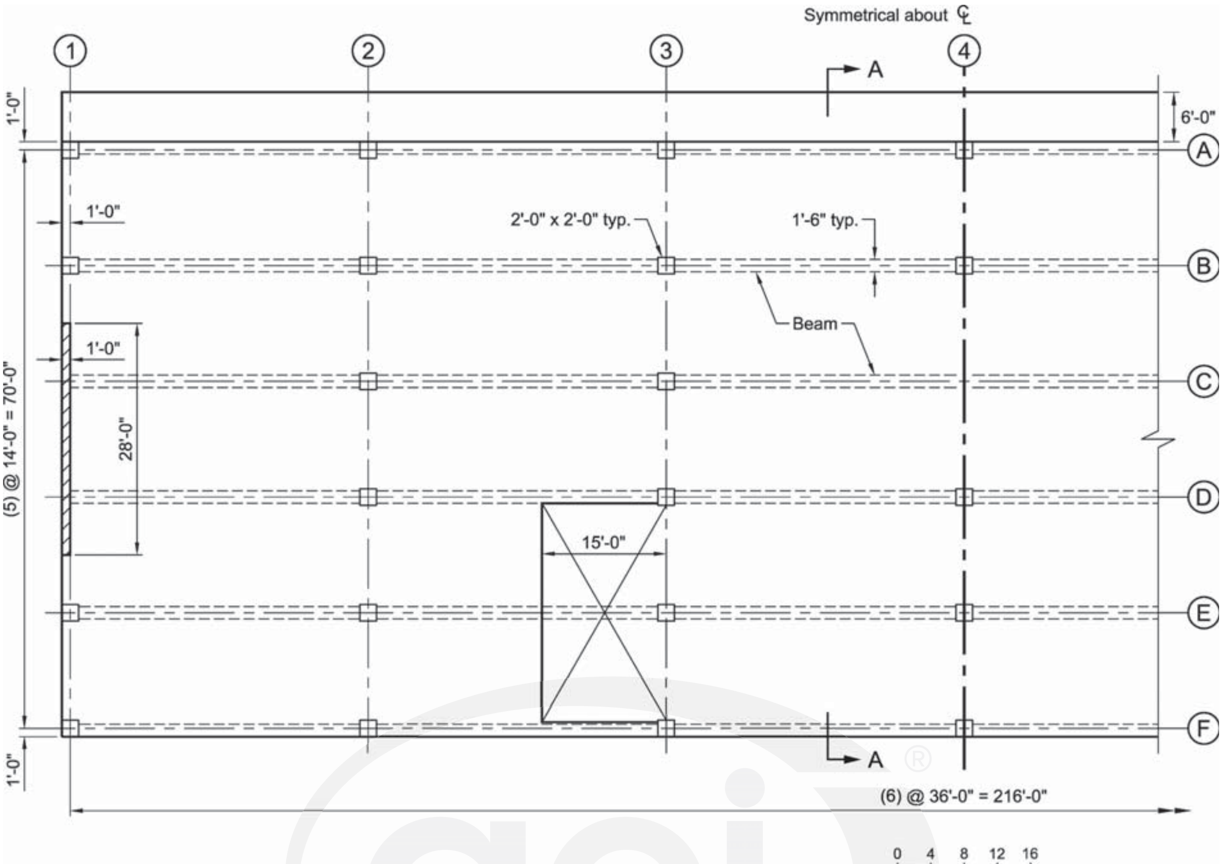
First Floor Plan



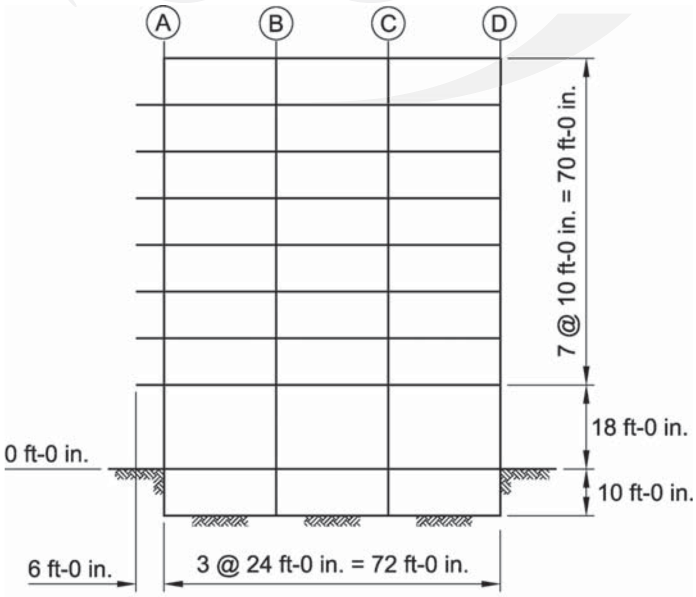
Second Floor Plan



Third Floor Plan



Typical Floor Plan 4th-7th



Elevation A-A

1.3—Loads

The following loads for the example building are generated in accordance with ASCE7-10. The Risk Category is II.

Gravity Loads

Dead Load, *D*:

- Self weight
- Additional D = 15 lb/ft^2
- Perimeter walls = 15 lb/ft^2

Live Load:

- 1st and 2nd Floors: Lobbies, public rooms, and corridors serving them = 100 lb/ft^2
- Typical Floor: Private rooms and corridors serving them = 65 lb/ft^2

Roof Live Load:

- Unoccupied = 20 lb/ft^2

Snow Load:

- Ground load, P_g = 20 lb/ft^2
- Thermal, C_t = 1.0
- Exposure, C_e = 1.0
- Importance, I_s = 1.0
- Flat roof load, P_f = 20 lb/ft^2

Lateral Loads

Wind Load:

- Basic (ultimate) wind speed = 115 mph
- Exposure category = C
- Wind directionality factor, K_d = 0.85
- Topographic factor, K_{st} = 1.0
- Gust-effect factor, G_f = 0.85 (rigid)
- Internal pressure coefficient, GC_{pi} = +/-0.18
- Directional Procedure

Seismic Load:

- Importance, I_e = 1.0
- Site class = *D*
- S_S = 0.15, S_{DS} = 0.16
- S_1 = 0.08, S_{D1} = 0.13
- Seismic design category = *B*
- Equivalent lateral force procedure
- Building frame system; ordinary reinforced concrete shear walls in the north-south direction
  - $R = 5$
  - $C_s = 0.046$
- Moment-resting frame system; ordinary reinforced concrete moment frame in the east-west direction
  - $R = 3$
  - $C_s = 0.032$

1.4—Material properties

The material properties for any building should have a reasonable knowledge of locally available concrete and steel materials. As a preliminary value for this example, a specified concrete compressive strength, f_c', of 4000 psi usually provides for a satisfactory floor design. In the US, reinforcing steel for floor design is usually specified as 60,000 psi.

The f_c' for columns and walls in multi-story buildings may be different than the f_c' used for the floor system. Concrete placement usually proceeds in two stages for each story; first, the vertical members, such as columns, and second, the floor members, such as beams and slabs. It is desirable to keep the concrete strengths of the vertical members within a ratio of 1.4 of the floor concrete strength. Section 15.3.1 in ACI 318-14 states that if this ratio is exceeded, the floor concrete in the area immediately around the vertical members must be “puddled” with higher strength concrete. Usually this situation only becomes an issue for taller buildings.

For this example, the building height is moderate and the loads are typical. The locally available aggregate is a durable dolomitic limestone. Thus, the concrete can readily have a higher f_c' than the initial assumption of 4000 psi. A check of the durability requirements of Table 19.3.2.1 in ACI 318-14 shows that 5000 psi will satisfy the minimum f_c' for all exposure classes. For this concrete, a check of Table 19.2.1.1 in ACI 318-14 shows that all the code minimum limits are satisfied. The following concrete material properties are chosen:

- f_c' = 5000 psi
- Normalweight, w_c = 150 lb/ft^3
- E_c = 4,030,000 psi
- $\nu = 0.2$
- e_{th} =5.5 × 10^{-6}/F

The use of lightweight concrete can reduce seismic forces and foundation loads. Based on local experience, however, this type of building won’t greatly benefit from the use of lightweight. The modulus of elastic for concrete, E_c, is calculated according to 19.2.2 in ACI 318. For normalweight concrete, Eq. 19.2.2.1.b in ACI 318 is applicable. Software programs using finite element analysis can account for the Poisson effect. The Poisson ratio can vary due to material properties, but an average value for concrete is 0.2. Recommendations for the thermal coefficient of expansion, e_{th}, of concrete can be found in ACI 209R.

The most common and most available nonprestressed reinforcement is Grade 60. Higher grades are available but 20.2.2.4 in ACI 318-14 limits many uses of reinforcing steel to 60 ksi. The modulus of elastic for reinforcement, Es, is given in 20.2.2.2 in ACI 318.

Reinforcement Material Properties

- f_y = 60,000 psi
- f_{yt} = 60,000 psi
- E_s = 29,000,000 psi

REFERENCES

American Concrete Institute

ACI 209R-92—Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures

CHAPTER 2—STRUCTURAL SYSTEMS

2.1—Introduction

A chapter on structural systems of reinforced concrete buildings has been introduced into the ACI Code (ACI 318-14). This chapter gives guidance on the relationships among the different chapters and their applicability to structural systems.

A structural engineer's primary concern is to design buildings that are structurally safe and serviceable under design vertical and lateral loads. Prior to the 1970s, reinforced concrete buildings that were of moderate height (less than 20 stories), not in seismically active areas, or constructed with nonstructural masonry walls and partitions, were seldom explicitly designed for lateral forces (ACI Committee 442 1971). Continuing research, advancement in materials science, and improvements in analysis tools have allowed structural engineers to develop economical building designs with more predictable structural performance.

Structural systems and their component members must provide sufficient stability, strength, and stiffness so that overall structural integrity is maintained, design loads are resisted, and serviceability limits are met. The individual members of a building's structural system are generally assumed to be oriented either vertically or horizontally, with the common exception of parking structure ramps. Chapter 4 of ACI 318-14 identifies the structural members and connection types that are common to reinforced concrete building structural systems with design and detailing code provisions (ACI 318-14):

(a) Horizontal floor and roof members (one-way and two-way slabs, Chapters 7 and 8)

(b) Horizontal support members (beams and joists, Chapter 9)

(c) Vertical members (columns and structural walls, Chapters 10 and 11)

(d) Diaphragms and collectors (Chapter 12)

(e) Foundations—isolated footings, mats, pile caps, and piles (Chapter 13)

(f) Plain concrete—unreinforced foundations, walls, and piers (Chapter 14)

(g) Joints and connections (Chapters 15 and 16)

In Table 2.1, code chapters are correlated with the chapters in Volumes 1 and 2 of this Handbook.

Table 2.1—Member chapters

Volume no. ACI SP-17(14)	Chapter name ACI SP-17(14)	Chapter no. ACI 318-14	Chapter no. ACI SP-17(14)
I	Building system	—	1
	Structural systems	4 and 5	2
	Structural analysis	6	3
	Durability	19	4
	One-way slab	7	5
	Two-way slab	8	6
	Beams	9	7
	Diaphragm	12	8
	Columns	10	9
	Walls	11	10
	Foundations	13	11
II	Retaining walls	7 and 11	12
	Serviceability	24	13
	Strut-and tie	23	14
	Anchoring to concrete	17	15

2.2—Materials

The concrete mixture proportion needs to satisfy the design properties and limits in ACI 318-14, Chapter 19, and the reinforcing steel needs to satisfy the design properties and limits in Chapter 20 (ACI 318-14).

2.3—Design loads

ACI 318-14 assumes that ASCE 7-10 design loads are applied to the building's structural system and to individual members, as applicable. Loads are assumed to be applied vertically and horizontally. Horizontal loads are assumed to act in orthogonal directions. Two types of lateral loads are discussed in this chapter:

1. Wind loading (elastic analysis, ACI 318-14, Chapter 6)
2. Earthquake loading (ACI 318-14, Chapter 18)

Wind and earthquake loads are dynamic in nature; however, they differ in the manner in which these loads are induced in a structure. Wind loads are externally applied loads and, hence, are related to the structure's exposed surface. Earthquake loads are inertial forces related to the magnitude and distribution of the mass in the structure.

2.3.1 *Wind loading*—Wind kinetic energy is transformed into potential energy when it is resisted by an obstruction. Wind pressure is related to the wind velocity, building height, building surface, the surrounding terrain, and the location and size of other local structures. The structural response to a turbulent wind environment is predominantly in the first mode of vibration.

The quasi-static approach to wind load design has generally proved sufficient. It may not be satisfactory, however, for very tall buildings, especially with respect to the comfort of the occupants and the permissible horizontal movement, "or drift," which can cause the distress of partitions and glass. Therefore, to determine design wind loads for very tall buildings, wind tunnel testing is not unusual.

2.3.2 *Earthquake loading*—The main objective of structural design is life safety; that is, preserving the lives of occupants and passersby. Serviceability and minimizing economical loss, however, are also important objectives. By studying the results of previous earthquakes on various structural systems, improvements to code provisions and design practices have been achieved. These improvements have led to a reduction in damage of reinforced concrete structures that experience an earthquake. Some code improvements for members that resist significant seismic accelerations are:

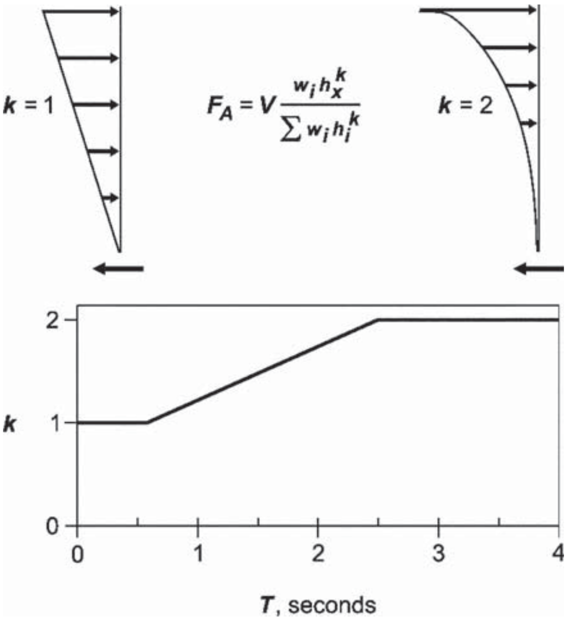


Fig. 2.3.2—Typical distribution of equivalent static lateral forces representing seismic forces "ASCE 7-10."

1. The requirement that columns in a frame are flexurally stronger than beams—the so-called "strong column-weak beam" concept
2. Improve detailing to increase ductility and large energy dissipation capacity (with less deterioration in stiffness and strength)
3. Designing and detailing members to ensure flexural yielding before reaching nominal shear strength
4. Designing and detailing the connections to be stronger than the members framing into them
5. Limiting structural system irregularities.

For most structures, the equivalent lateral force procedure given in ASCE 7-10 is used.

Based on this procedure, the distribution of design forces along the height of a building roughly approximates the building's fundamental mode of vibration (Fig. 2.3.2).

Applying recorded earthquake motions to a structure through elastic dynamic analyses usually result in greater force demands than from the earthquake design forces specified by most codes. This is because codes generally account for force reductions due to inelastic response. For example, ASCE 7-10 applies an *R* factor (response modification factor), which accounts for the ductility of a building, system over-strength, and energy dissipation through the soil-foundation system "ASCE 7-10." It simplifies the seismic design process such that linear static elastic analysis can be used for building designs. The *R* factor reduces the calculated lateral loads and assumes a building may be damaged during an earthquake event, but will not collapse. The higher the R-value, the lower the lateral design load on a structure. R-values range from 1-1/2 for structures with stiff systems, having low deformation capacity, to 8 for ductile systems, having significant deformation capacity. In a design-level earthquake, it is expected that some building members will yield. To promote appropriate inelastic behavior, ACI 318 contains provisions meant to ensure inelastic deformation capacity in regions where yielding is likely, which then protects the overall integrity and stability of the building.

Dynamic (modal) analysis is commonly used for larger structures, important structures, or for structures with an irregular vertical or horizontal distribution of stiffness or mass. For very important and potentially critical structures—for example, nuclear power plants—inelastic dynamic analysis may be used (ACI Committee 442 1988).

2.4—Structural systems

All structures must have a continuous load path that can be traced from all load sources or load application to the foundation. The joints between the vertical members (columns and walls) and the horizontal members (beams, slabs, diaphragms, and foundations) are crucial to this concept. Properly detailed cast-in-place (CIP) reinforced concrete joints transfer moments and shears from the floor into columns and walls, thus creating a continuous load path. The joint design strength (ACI 318-14, Chapter 15) must, of course, adequately resist the factored forces applied to the joint. Refer also to ACI 352R-02, for joint design and detailing information.

Engineers commonly refer to a structure's gravity-load-resisting system (GLRS) and lateral-force-resisting system (LFRS). All members of a CIP reinforced concrete structure contribute to the GLRS and most contribute to both systems. For low-rise structures, the inherent lateral stiffness of the GLRS is often sufficient to resist the design lateral forces without any changes to the design or detailing of the GLRS members. As the building increases in height, the importance of designing and detailing the LRFS to resist lateral loads increases. At some point, stiffness rather than strength will govern the design of the LFRS. In the design process, the type of LFRS is usually influenced by architectural considerations and construction requirements.

There are several types of structural systems or a combination thereof to resist gravity, lateral, and other loads, with deformation behavior as follows:

1. **Frames**—Lateral deformations are primarily due to story shear. The relative story deflections therefore depend on the horizontal shear applied at each story level.
2. **Walls**—Lateral deformations are due to both shear and bending. The behavior predominate mode depends on the wall's height-to-width aspect ratio.
3. **Dual systems**—Dual systems are a combination of moment-resisting frames and structural walls. The moment-resisting frames support gravity loads, and up to 25 percent of the lateral load. The structural walls resist the majority of the lateral loading.
4. **Frames with closely spaced columns, known as cantilevered column system or a tube system**—Lateral deformations are due to both shear and bending, similar to a wall. Wider openings in a tube, however, can produce a behavior intermediate between that of a frame and a wall.

Regardless of the system, a height is reached at which the resistance to lateral sway will govern the design of the

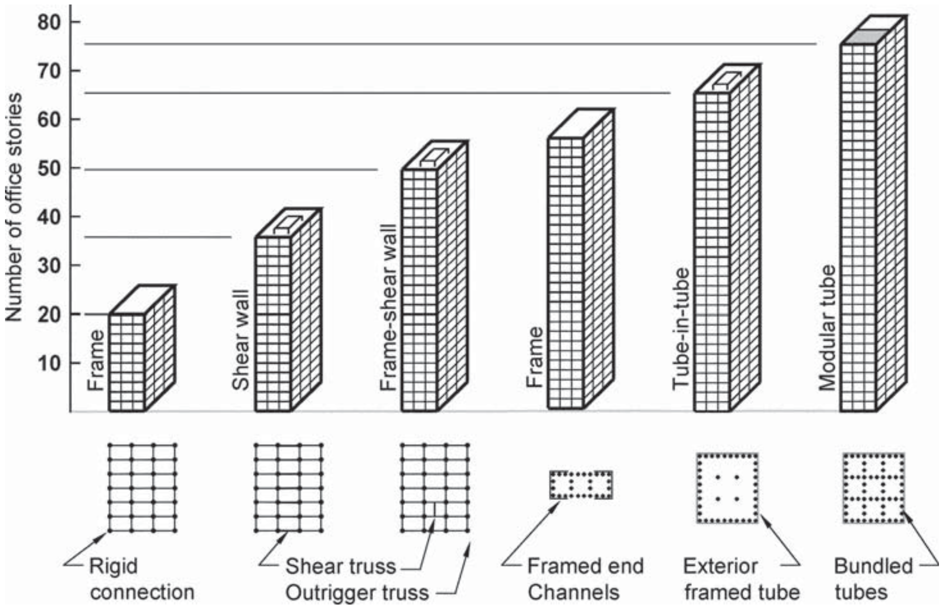


Fig. 2.4—Structural systems and optimum height limitations (Ali and Moon 2007).

structural system. At such a height, stiffness, not strength, controls the building design.

ASCE 7 (2010) provides provisions that determine the Seismic Design Categories (SDC A through F). As a building's Seismic Design Category increases, from A through F, ASCE 7 (2010) requires a progressively more rigorous seismic design and a more ductile system to maintain an acceptable level of seismic performance.

ACI 318 provides three categories of earthquake detailing; ordinary, intermediate, and special. These categories provide an increasing level of system toughness.

Building height limits in ASCE 7 (2010) are related to the LFRS.

For buildings in SDC A and B, wind load will usually control the design of the LFRS.

For buildings in SDC C, seismic loads are likely to control design forces, and seismic detailing is required. LFRSs are not limited in height for most systems for this SDC, but interstory drift limits from ASCE 7 (2010) must be met. Again, stiffness, not strength, will likely control the lateral-force-resisting system design.

For buildings in SDC D, E, and F, seismic loads almost always control design forces, and increased seismic detailing is required. LFRS often have maximum height limitations based on assumed structural performance level behavior. Figure 2.4 shows approximate height limits for different structural systems.

Table 2.4 provides ASCE limits for choosing a structural system for a particular building. The ranges of applicability shown are influenced by occupancy requirements, architectural considerations, internal traffic flow (particularly in the lower floors), the structure's height and aspect ratio, and load intensity and types (live, wind, and earthquake).

2.4.1 *Gravity-resisting systems*—A gravity-load-resisting system (GLRS) is composed of horizontal floor members and vertical members that support the horizontal members. Gravity loads are resisted by reinforced concrete members through axial, flexural, shear, and torsional stiffness and strength. The related deformations are exaggerated and shown in Fig. 2.4.1.

2.4.2 *Lateral-load-resisting system*—A lateral-force-resisting system (LFRS) must have an adequate toughness to maintain integrity during high wind loading and design earthquake accelerations. Buildings are basically cantilevered members designed for strength (axial, shear, torsion, and moment) and serviceability (deflection and creep must be considered for tall buildings).

ACI 318-14, Section 18.2.1, lists the relevant code sections for each SDC as it applies to a specific seismic-force-resisting system. The following lateral-force-resisting systems are addressed as follows.

2.4.2.1 *Moment-resisting frames*—Cast-in-place moment-resisting frames derive their load resistance from member strengths and connection rigidity. In a moment-resisting frame structure, the lateral displacement (drift) is the sum of three parts: 1) deformation due to bending in columns, beams, slabs, and joint deformations; 2) deformation due to shear in columns and joints; and 3) deformations due to axial force in columns.

Yielding in the frame members or the foundation can significantly increase the lateral displacement. The effect of secondary moments caused by column axial forces multiplied by lateral deflections (P-Δ effect) will further increase the lateral deflection.

In buildings, moment-resisting frames are usually arranged parallel to the principal orthogonal axes of the structure and the frames are interconnected by floor diaphragms (ACI 318, Chapter 12). Moment-resisting frames usually allow the maximum flexibility in space planning, and are an economical solution up to a certain height.

Table 2.4—Approximate building height limits for various LFRS

Practical limit of system (ASCE 7-10 limit according to SDC)					
Type of LFRS	SDC				
	A and B	C	D	E	F
Moment-resisting frames (only):					
Ordinary moment frame (OMF)	NL	NP	NP	NP	NP
Intermediate moment frame (IMF)	NL	NL	NP	NP	NP
Special Moment frame (SMF)	NL	NL	NL	NL	NL
Structural walls (only):					
Building frame systems (structural walls are the primary LFRS and frames are the primary GLRS):					
Ordinary structural wall (OSW)	NL	NL	NP	NP	NP
Special structural wall (SSW)*	NL	NL	160 ft	160 ft	100 ft
Bearing wall systems (structural walls are the primary lateral- and gravity-load-resisting system):					
OSW	NL	NL	NP	NP	NP
SSW*	NL	NL	160 ft	160 ft	100 ft
Dual systems (structural walls are the primary LRFS, and the moment-resisting frames carry at least 25% of the lateral load):					
OSW with OMF	NL	NP	NP	NP	NP
OSW with IMF	NL	NL	NP	NP	NP
OSW with SMF	NL	NL	NP	NP	NP
SSW with OMF	NP	NP	NP	NP	NP
SSW with IMF	NL	NL	160 ft	100 ft	100 ft
SSW with SMF	NL	NL	NL	NL	NL

*Height limits can be increased per ASCE 7 (2010), Section 12.2.5.4.

Notes: NL = no limit; NP = not permitted.

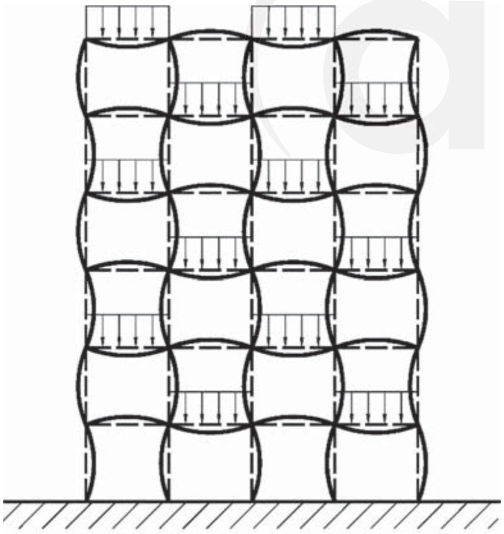


Fig. 2.4.1—Deflections due to gravity load.

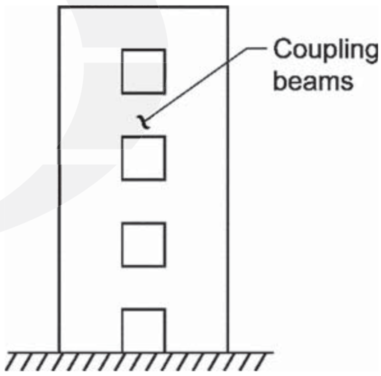


Fig. 2.4.2.2a—Coupled shear walls.

2.4.2.2 *Shear walls*—Reinforced concrete shear walls are often introduced into multistory buildings because of their high in-plane stiffness and strength to resist lateral forces or when the building program is conducive to layout of structural walls. For buildings without a significant moment frame, shear walls behave as vertical cantilevers. Walls can be designed with or without openings (Fig. 2.4.2.2a). Separate walls can be coupled to act together by beams/slabs or deep beams, depending on design forces and architectural requirements. Coupling of shear walls introduces frame action to the LFRS and thus reduces lateral deflection of the system. Reinforced concrete walls are often used around elevator and stair shafts to achieve the required fire rating. For shear wall types and functions, refer to Table 2.4.2.2.

A shear wall building usually consists of a series of parallel shear walls in orthogonal directions that resists lateral loads and supports vertical loads.

In multistory bearing wall buildings, significant discontinuities in mass, stiffness, and geometry should be avoided. Bearing walls should be located close to the plan perimeter if possible and should preferably be symmetric in plan to reduce torsional effects from lateral loading (refer to Fig. 2.4.2.2c).

2.4.2.3 *Staggered wall-beam system*—This system uses story-high solid or pierced walls extending across the entire width of the building and supported on two lines of columns placed along exterior faces (Fig. 2.4.2.3). By staggering the locations of these wall beams on alternate floors, large clear areas are created on each floor.

Table 2.4.2.2—Shear wall types and functions

Structural walls	Behavior	Reinforcement	Remarks
Short—height-to-length ratio does not exceed 2	Lateral design is usually concerned only with shear strength.	Bars evenly distributed horizontally and vertically.	Wall foundation must be capable of resisting the actions generated in the wall. Consider sliding resistance provided by foundation.
Height-to-length ratio is greater than 2	Lateral design must consider both the wall's shear and moment strength.	Evenly distributed vertical and horizontal reinforcement. Part of the vertical reinforcement may be concentrated at wall ends—boundary elements. Vertical reinforcement in the web contributes to the flexural strength of the wall.	Wall foundation must be capable of resisting the actions generated in the wall. Consider overturning resistance provided by foundation.
Ductile structural wall	Lateral design is heavily influenced by flexure stiffness and strength.	Flexural bar spacing and size should be small enough so that flexural cracking is limited if yielding occurs. Over-reinforcing for flexure is discouraged because flexural yielding is preferred over shear failure.	Acceptable ductility can be obtained with proper attention to axial load level, confinement of concrete, splicing of reinforcement, treatment of construction joints, and prevention of out-of-plane buckling.
Coupled walls with shallow coupling beams or slabs (Fig. 2.4.2.2b(a))	Link slab flexural stiffness deteriorates quickly during inelastic reversed loading.	Place coupling slab bars to limit slab cracking at the stress concentrations at the wall ends.	Punching shear stress around the wall ends in the slab needs to be checked.
Coupled walls with coupling beams (Fig. 2.4.2.2b(b))	Depending on span-to-depth ratio, link beams may be designed as deep beams.	Main reinforcement is placed horizontally or diagonally. For coupling beams with main reinforcement placed diagonally from the deep beam's corner to corner may be confined by spiral or closed ties and designed to resist flexure and shear directly.	Properly detailed coupling beams can achieve ductility. Coupling beams should maintain their load-carrying capacity under reverse inelastic deformation.
Infilled frames (structural or nonstructural) (Fig. 2.4.2.2b(c))	Frames behave as braced frames, increasing the lateral strength and stiffness. The infilling acts as a strut between diagonally opposite frame corners, and creates high shear forces in the columns.	Infill walls should either be sufficiently separated from the moment frame (making them nonstructural), or detailed to be connected structurally with the moment frame.	Uneven infilling can cause irregularities of the moment frame. If there are no infills at a given story level, that story acts as a weak or soft story that is vulnerable to concentrated damage and instability.

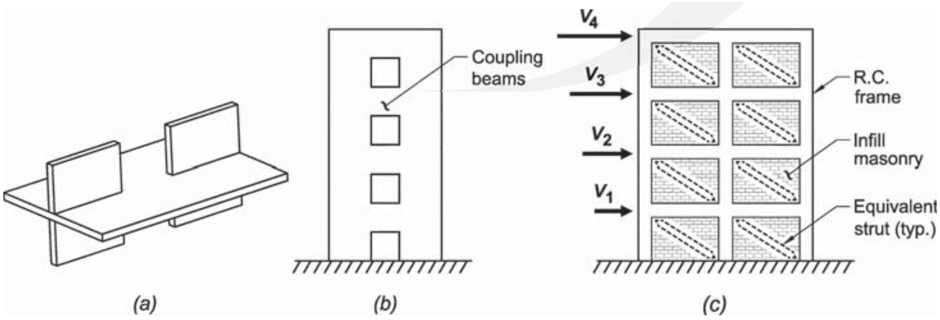


Fig. 2.4.2.2b—Coupled and infill walls: (a) shallow coupling beams or slabs; (b) coupling beams; and (c) infill walls.

The staggered wall-beam building is suitable for multistory construction having permanent interior partitions such as apartments, hotels, and student residences.

An advantage of the wall-beam building is the large open area that can be created in the lower floors when needed for parking, commercial use, or even to allow a highway to pass under the building. This system should be considered in low seismic areas because of the stiffness discontinuity at each floor.

2.4.2.4 *Tubes*—A tube structure consists of closely spaced columns in a moment frame, generally located around the perimeter of the building (Fig. 2.4.2.4(a)).

Because tube structures generally consist of girders and columns with low span-to-depth ratios (in the range of 2 to 4), shearing deformations often contribute to lateral drift and should be included in analytical models. Tubes are often thought of as behaving like a perforated diaphragm.

Frames parallel to direction of force act like webs to carry the shear from lateral loads, while frames perpendicular to the direction of force act as flanges to carry the moment from lateral loads. Gravity loads are resisted by the exterior frames and interior columns.

A reinforced concrete braced tube is a system in which a tube is stiffened and strengthened by infilling in a diagonal pattern over the faces of the building (Fig. 2.4.2.4(b)). This bracing increases the structure's lateral stiffness, reduces the