An ACI Manual

ACI Reinforced Concrete Design Handbook

A Companion to ACI 318-19

Volume 1: Member Design

MNL-17(21)

American Concrete Institute
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ACI MNL-17(21)

ACI REINFORCED CONCRETE DESIGN HANDBOOK

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VOLUME 1

VOLUME 2

ACI MNL-17(21)
Volume 1

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DEDICATION

This edition of *The ACI Reinforced Concrete Design Handbook*, MNL-17(21), 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 MNL-17. His oversight and review comments were instrumental in the development of the ninth edition of the 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 at 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 ACI 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 318-19).

The ACI Reinforced Concrete Design Handbook 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 318-19 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 ACI Reinforced Concrete Design Handbook* contain a general discussion of the related ACI 318-19 chapter.

This edition of *The ACI Reinforced Concrete Design Handbook* was updated and enhanced by ACI staff engineers under the auspices of the ACI Technical Activities Committee (TAC). Each chapter was reviewed by at least two reviewers, who provided valuable comments, suggestions, and insights. The following reviewers are gratefully acknowledged and thanked:

Michael E. Ahern	Christopher C. Ferraro	Ian S. McFarlane	Brandon Ross
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Special thanks are due to a number of outside contributors to this Manual. Dirk Bondy and Kenneth Bondy provided software used to analyze and design the post-tensioned beam example, in addition to their valuable comments and suggestions. StructurePoint and Computers and Structures, Inc. (SAP 2000 and Etabs) provided use of their software to perform analyses of structure and members. The Bridge Software Institute (BSI) provided use of their software and their expertise in the development of the design examples on deep foundations.

The ACI 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/MNL1721Download1
https://www.concrete.org/MNL1721Download2

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

Trey Hamilton
Managing Editor

VOLUME 1: CONTENTS

CHAPTER 1—INTRODUCTION

1.1—Introduction

This Manual is intended to assist with the design of reinforced concrete structures using ACI 318-19 (hereinafter referred to as the Code). The focus is on the application of the Code requirements to the individual members with respect to both structural design requirements and detailing provisions. As with the Code, the design procedures and detailing practices illustrated in this Manual do not replace sound professional judgment or the licensed design professional's (LDP's) knowledge of the specific factors surrounding a project.

To illustrate the procedures and details, it is necessary to generate the member actions for which the design will be conducted. Although this Manual provides background and context regarding the analysis of structural concrete systems, it is assumed that the user of this Manual has a basic understanding of structural analysis and the development of the member design actions from such an analysis.

This chapter describes the overall organization of this Manual and additionally describes the loads, geometry, and other details of the example building used to generate actions for member or component design illustrated in subsequent chapters.

Table 1.2—Member chapters

Volume No. ACI MNL-17(21)	Chapter name ACI MNL-17(21)	Chapter No.	
		ACI 318-19	ACI MNL-17(21)
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 13	12
	Serviceability	24	13
	Strut and tie	23	14
	Anchoring to concrete	17	15

1.2—Organization and use

A structural system consists of members, joints, and connections, each performing a specific role or function. 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.

This Manual is organized into chapters listed below that follow the general progression of the structural design of a building. The early chapters describe the overall building configuration, loads, and development of actions from structural analysis followed by chapters devoted to the design of the individual members within the example structure.

(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 1.2, Code chapters are correlated with the chapters in Volumes 1 and 2 of this Manual.

The fictitious example building depicted in Fig. 1.2a through 1.2d was created to demonstrate how, by various examples in this Manual, to design and detail a typical structural concrete building according to the Code. This example building is seven stories above ground and has a one-story basement. The building has evenly spaced columns along the grid lines in both directions. One column has been removed along Grid C on the second level to provide 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 10 ft high and has an extra column 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.

A single specific gravity load system is not specified herein but rather is left unknown to enable demonstration of the design of several structural systems including nonprestressed and prestressed one-way beam and slab systems; nonprestressed and prestressed two-way slab systems; nonprestressed and prestressed transfer girder to accommodate column removal; and nonprestressed and prestressed beams of various types and sizes. Lateral loads are resisted by concrete shear walls in the north/south direction and concrete moment frames in the east/west direction; both systems are designated as *ordinary* for the purposes of seismic design and detailing. In some cases, member examples are expanded to demonstrate the change in design and detailing procedures when elements or systems are designated as *intermediate* or *special*, but using the results from the original structural

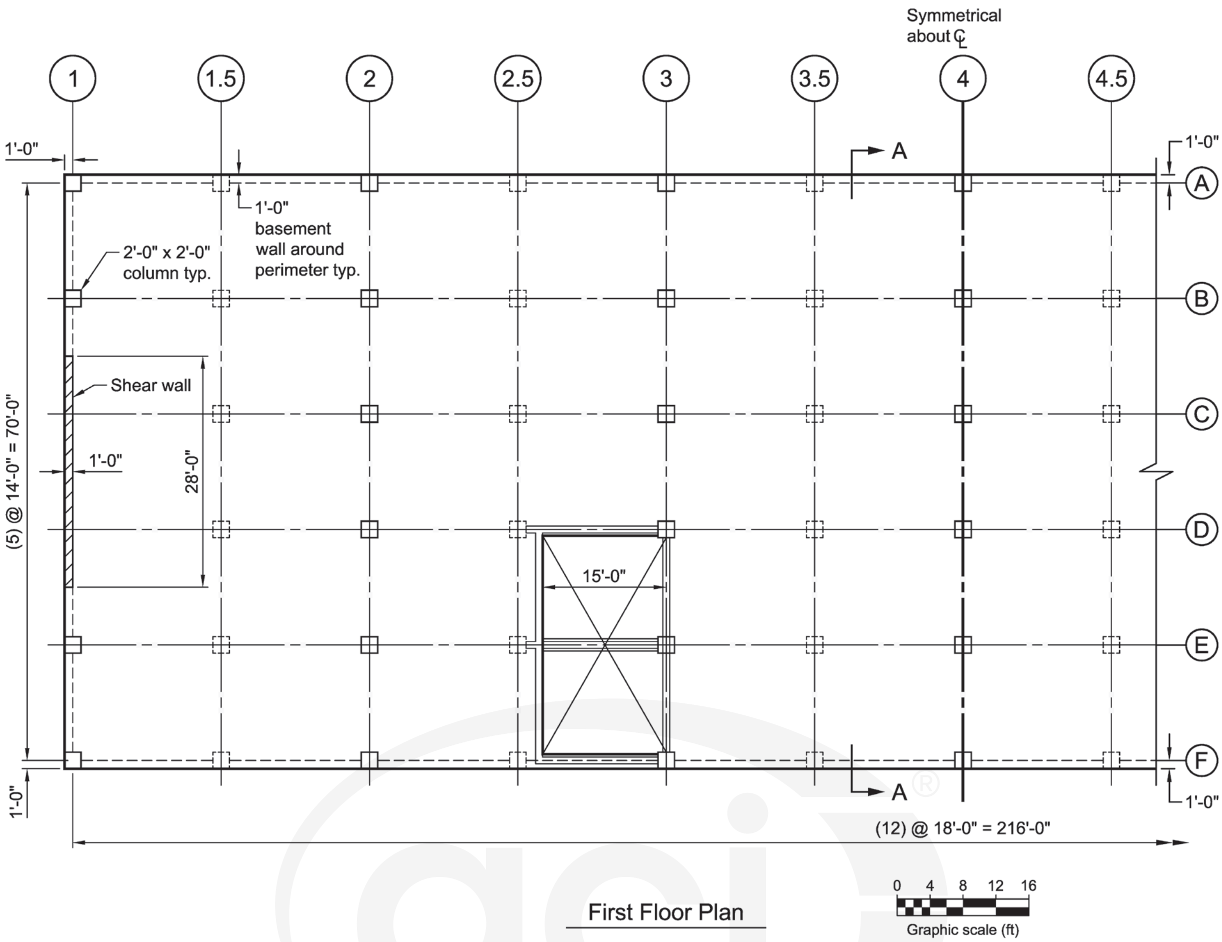

Fig. 1.2a—Example building first floor plan.

analysis. Those examples may modify this initial data to demonstrate some specific code requirement.

This building example was created for the purpose of illustrating design of structural concrete members and systems. Other aspects of building design that may affect the structural layout such as occupancy, egress, fire protection, or other architectural constraints have not been addressed.

1.3—Building plans and elevation

The following building plans and elevation illustrate the structural layout and some details of the example building.

1.4—Loads

The following loads for the example building are generated in accordance with ASCE/SEI 7. Risk Category II is assumed.

Gravity Loads

Dead Load, D:

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

Live Load:

- First and Second 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

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

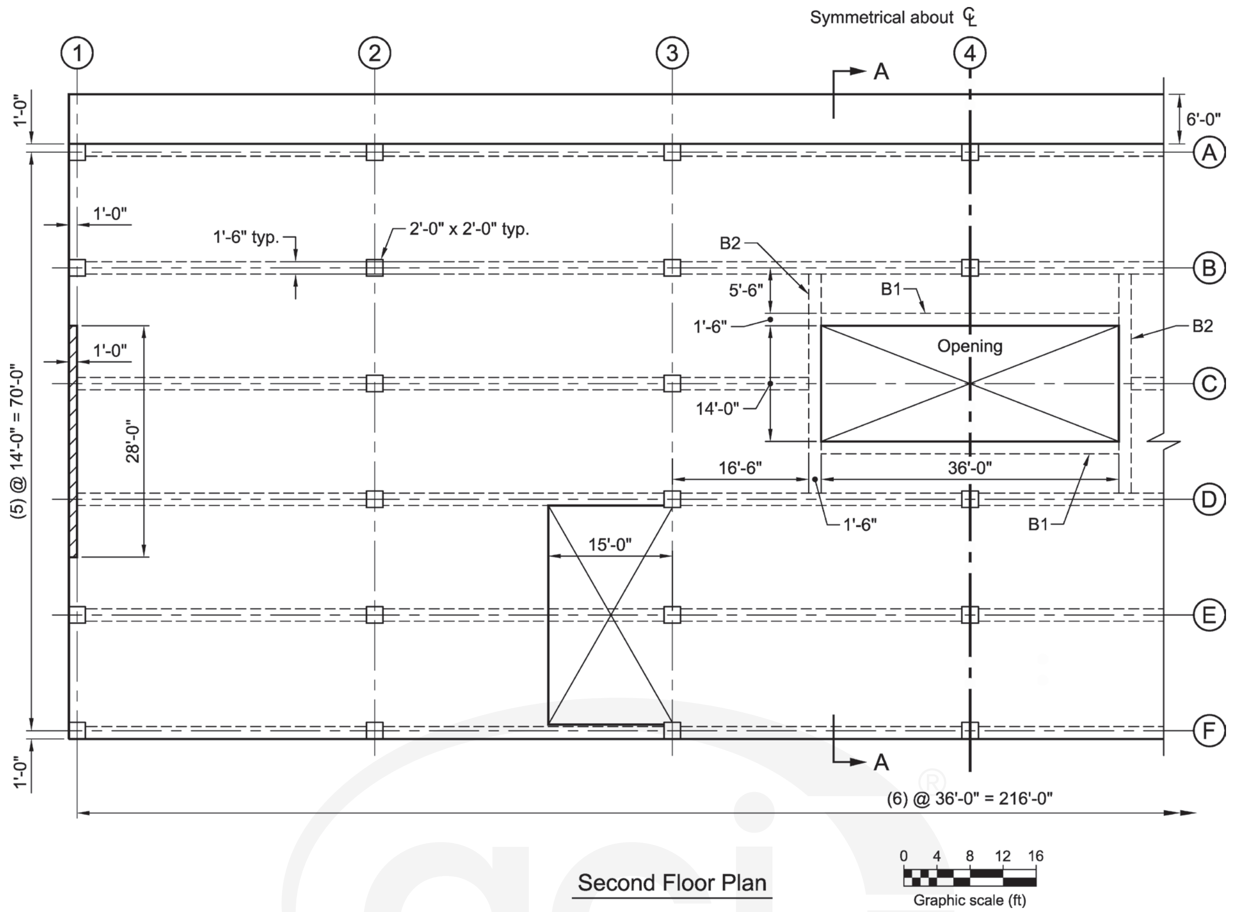

Fig. 1.2b—Example building second floor plan.

- Ordinary reinforced concrete shear walls in the north-south direction
  - $R = 5$
  - $C_s = 0.046$
- Ordinary reinforced concrete moment frame in the east-west direction
  - $R = 3$
  - $C_s = 0.032$

1.5—Material properties

The designer should investigate and acquire a reasonable knowledge of locally available concrete and steel materials. Concrete properties are typically selected based on both mechanical properties and durability. Code Chapter 19 provides limitations, requirements, and guidance on the selection of f_c'. The chapter also provides requirements for durability of concrete, which will be discussed further in Chapter 4 of this Manual.

Code Table 19.2.1.1 provides minimum f_c' for use with a variety of structural systems and seismic design categories (SDCs). Minimum required strength for general use in SDC A, B, or C is 2500 psi. For typical floor spans and loads, however, an f_c' of 4000 psi is usually sufficient to satisfy strength requirements. For the example used in this Manual, the building height is moderate and the loads are typical. Assume that 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 Code Table 19.3.2.1 shows that 5000 psi will satisfy minimum f_c' for all exposure classes. The following concrete material properties are chosen:

- $f_c' = 5000$ psi
- Normalweight $w_c = 150$ lb/ft^3
- $E_c = 4{,}030{,}000$ psi (Code Eq. (19.2.2.1b))
- $\nu = 0.2$
- $e_{th} = 5.5 \times 10^{-6}$/F (ACI 209R)

To minimize space occupied by heavily loaded columns and walls in multi-story buildings, the designer may choose to use a larger f_c' for columns than is 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. This results in column loads being transferred through the lower-strength concrete of the floor system. It may be desirable to specify f_c' of the floor system to be greater than $0.7 \times f_c'$ of the vertical members to avoid having to place higher-strength concrete in the floor system in the area of contact between floor and column (Code Sections 15.5.1 and 15.5.1a). Usually this situation only becomes an issue for taller buildings.

The most common and most available nonprestressed reinforcement is ASTM A615 Grade 60. Higher grades are