

# REINFORCED CONCRETE

**A Fundamental Approach**

by  
Dr. Edward G. Nawy, P.E.

TU 371

# REINFORCED CONCRETE

**A Fundamental Approach**

by

**Dr. Edward G. Nawy, P.E.**

Distinguished Professor and Chairman

Department of Civil and Environmental Engineering  
Rutgers University  
The State University of New Jersey

RBR17/03

With collaboration from Dr. Perumaisamy N. Balaguru, Associate Professor

**Prentice-Hall Inc.**  
**Englewood Cliffs, New Jersey 07632**

87.1608



*Library of Congress Cataloging in Publication Data*

Newby, Edward G.

Reinforced concrete.

Includes bibliographies and index.

1. Reinforced concrete. 2. Reinforced concrete construction. I. Title.

TA444.N38 1984 620.1'37 84-9985

ISBN 0-13-771643-5

Editorial/production supervision: Aliza Greenblatt

Frontmatter and chapter opening design: A Good Thing, Inc.

Cover design: George Cornell

Manufacturing buyer: Anthony Caruso

**PRENTICE-HALL INTERNATIONAL SERIES IN CIVIL ENGINEERING AND ENGINEERING MECHANICS**  
**WILLIAM J. HALL, EDITOR**

© 1985 by Prentice-Hall, Inc., Englewood Cliffs, New Jersey 07632

All rights reserved. No part of this book may be reproduced, in any form or by any means, without permission in writing from the publisher.

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-771643-5 01

Prentice-Hall International, Inc., *London*

Prentice-Hall of Australia Pty. Limited, *Sydney*

Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*

Prentice-Hall Canada Inc., *Toronto*

Prentice-Hall of India Private Limited, *New Delhi*

Prentice-Hall of Japan, Inc., *Tokyo*

Prentice-Hall of Southeast Asia Pte. Ltd., *Singapore*

Whitehall Books Limited, *Wellington, New Zealand*

## Preface

Reinforced concrete is a widely used material for constructed systems. Hence graduates of every civil engineering program must have, as a minimum requirement, a basic understanding of the fundamentals of reinforced concrete. Additionally design of the members of a total structure is achieved only by trial and adjustment: assuming a section then analyzing it. Consequently design and analysis were combined to make it simpler for the student first introduced to the subject of reinforced concrete design.

The text is an outgrowth of the author's lecture notes evolved in teaching the subject at Rutgers University over the past twenty-five years and the experience accumulated over the years in teaching and research in the areas of reinforced and prestressed concrete up to the Ph.D. level. The material is presented in such a manner that the student can be familiarized with the properties of plain concrete and its components prior to embarking on the study of structural behavior. The book is uniquely different from other textbooks at this level in that most of its contents can be covered in one semester in spite of the in-depth discussions of some of its major topics.

The concise discussion presented in Chapters 1 through 4 on the historical development of concrete, the proportioning of the constituent materials, the long-term basic behavior, and the development of safety factors should give an adequate introduction to the subject of reinforced concrete. It should also aid in developing fundamental laboratory experiments and essential knowledge of mix proportioning, strength and behavioral requirements, and the concepts of reliability of performance of structures to which every engineering student should be exposed. The discussion of quality control and quality assurance should also give the reader a good introduction to the systematic approach needed to administer the development of concrete structural systems from conception to turnkey use.

Since concrete is a nonelastic material, with the nonlinearity of its behavior starting at a very early stage of loading, only the ultimate strength approach, or what is sometimes termed the "limit state at failure approach," is given in this book. Adequate coverage is given of the serviceability checks in terms of cracking and deflection behavior as well as long-term effects. In this manner, the design should satisfy all the service-load-level requirements while ensuring that the theory used in the analysis (design) truly describes the actual behavior of the designed components.

Chapters 5, 6, 7, and 8 cover the flexural, diagonal tension, and serviceability behavior of one-dimensional members: beams and one-way slabs. Full emphasis has been placed on giving the student and the engineer a feeling for the internal strain distribution in structural reinforced concrete elements and a basic understanding of the reserve strength and the safety factors inherent in the design expressions. Chapter 9, on the analysis and design of columns and other compression members, treats the subject of strain compatibility and strain distribution in a similar manner as in Chapter 5, on flexural analysis and design of beams. It includes a detailed discussion of how to construct interaction diagrams for columns as well as proportioning columns subjected to biaxial bending and buckling. With Chapter 10, on bond and development length in reinforcement, and Chapter 12, on the design of foundations and footings, the sequence of design steps of all elements except two-way floors is complete.

It is important to mention that Chapter 6, on diagonal tension, also contains detailed coverage of the behavior of deep beams, corbels, and brackets, with sufficient design examples to supplement the theory. This topic has been included in view of the increased use of precast construction, the wider understanding of the effects of induced horizontal loads on floors, and the frequent need for including shear walls and deep beams in today's multilevel structures. Additionally, Chapter 7 treats the topic of torsion in some detail considering the space constraints of the book. The discussion ranges from the basic fundamentals of pure torsion in elastic and plastic materials to the design of reinforced concrete members subjected to combined torsion, shear, and bending. The material presented and the accompanying illustrative examples should give the background necessary for pursuing more advanced studies in this area, as listed in the selected references.

Chapter 11 presents an extensive coverage of the subject of analysis and design of slab and plate floor systems. Following a discussion of fundamental behavior, it gives detailed design examples using both the ACI procedures and yield-line theory for the flexural design of reinforced concrete floors. It also includes ultimate load solutions to most floor shapes and possible gravity loading patterns. Detailed discussion of the deflection behavior and evaluation of two-way panels as well as the cracking mechanism of such panels, with appropriate analysis examples, makes this chapter another unique feature of this concise textbook.

It is important to emphasize that in this field, the use of computers prevails today. Access to transportable personal computers and handheld computers, due to their affordable cost, has made it possible for almost every student to be equipped with such a tool. Hence Chapter 13 presents programming procedures and computer programs written for both the handheld HP41C/CV/CX and in BASIC language for the Apple IIe and IIc transportable computers for the analysis (design) of sections in flexure, shear, torsion, combined loading (including compression), and members subjected to biaxial loading, as well as deep beams and corbels. As a result, the use of handbook charts was kept to a bare minimum. The inclusion of extensive flowcharts with logical steps in each relevant topic will make it possible for the reader to develop or use, without difficulty, such programs with any handheld or desktop computer.

Selected photographs of various areas of structural behavior of concrete elements at failure are included in all the chapters. They are taken from the published research work by the author with many of his M.S. and Ph.D. students at Rutgers University over the past two decades. Additionally, photographs of landmark structures, mainly in the United States, are included throughout the book to illustrate the versatility of design in reinforced concrete.

The textbook conforms to the provisions of ACI 318-83 with an eye to stressing the basics rather than tying every step to the code, which changes once every six years. Consequently, no attempt was made to tie any design or analysis step to the particular equation numbers in the code, but rather, the student is expected to gain the habit of getting familiar with the provisions and section numbers of the ACI code on a separate basis. In this manner, the student should not only master the fundamentals presented in the textbook, but should also become well versed with the ACI code as a dynamic, ever-changing document. Conversions to SI units are included in the illustrative examples throughout the book.

The various topics have been presented in as concise a manner as possible without sacrificing the need for the instructional details of an introductory course in the subject. Hence the topic of prestressed concrete has been left for more advanced works. The major portions of this book are intended for a first course at the junior or senior level of the standard college or university curriculum in civil engineering. The contents should also serve as a valuable guideline to the practicing engineer who has to keep abreast of the state of the art in concrete, as well as the designer who is interested in a concise treatment of the fundamentals.

Rutgers University  
The State University of New Jersey  
New Brunswick, New Jersey

Edward G. Nawy



## Acknowledgments

Grateful acknowledgment is due to Dr. Edward J. Bloustein, President of Rutgers University, for his continuous support and encouragement over the years, to the American Concrete Institute for contribution to the author's accomplishments and for permitting generous quotations of its ACI 318 Code and the illustrations from other ACI publications, and to his original mentor, Professor A. L. Baker of London University's Imperial College of Science and Technology who inspired him with the affection that he has developed for systems constructed of concrete. Grateful acknowledgment is also made to the author's many students, both undergraduate and graduate, who had much to do with generating the writing of this book, to the many who assisted in his research activities over the years, shown in the various photographs of laboratory tests throughout the book; and to his colleague at Rutgers University, Dr. P. N. Balaguru, for his valuable contributions, specifically to Chapters 9 and 13, and to the flowcharts.

Special thanks are due to the distinguished panel of authoritative reviewers: Professor William J. Hall of the University of Illinois at Urbana, Engineering Editor of Prentice-Hall Advanced Series, for his valuable input and recommendations; Professor Vitelmo V. Bertero of the University of California at Berkeley; Professor Dan E. Branson of the University of Iowa; Professor Thomas T. C. Hsu of the University of Houston; and Mr. Gerald B. Neville, Manager, Structural Codes, Portland Cement Association—with deep gratitude for agreeing to review the manuscript and for contributing extensive suggestions and advice which considerably improved the content.

Thanks to M.S. candidate Mark J. Cipolloni for his diligence and input to the manuscript, particularly for his contribution to Chapter 13, on computer programs and to its flow charts; to M.S. candidate Regina Silveira Rocha Souza for her diligent and continuous work on reviewing the computational process, details, and logic, and generating many ideas for the various chapters; to Robert M. Nawy, Rutgers engineering class of 1983, for his valuable work on the solutions, and to engineer Abe Daly and Ph.D. candidate Lily Sehayek for their critical contributions to the computer programs in BASIC. Thanks also to Mr. Charles M. Iossi, Executive Editor and Vice-President, Ms. Alice Dworkin, Executive Assistant, and Ms. Aliza Greenblatt, Production Editor, Prentice-Hall Inc., for their patience and the continuous cooperation and help received in developing the manuscript. Last, but not least, grateful acknowledgment is due to Ms. Suzanne Iazzetta, Executive Assistant, Department of Civil and Environmental Engineering at Rutgers, for her superior work on the manuscript and the invaluable help she rendered throughout.

# Contents

Preface xv

Acknowledgments xvii

Introduction 1

1.1 Historical Development of Structural Concrete / 1.2 Basic Hypothesis of Reinforced Concrete / 1.3 Analysis versus Design of Sections

Concrete-Producing Materials 7

2.1 Introduction / 2.2 Portland Cement / 2.2.1 Manufacture / 2.2.2 Strength / 2.2.3 Average Percentage Composition / 2.2.4 Influence of Fineness of Cement on Strength Development / 2.2.5 Influence of Cement on the Durability of Concrete / 2.2.6 Heat Generation during Initial Set / 2.3 Water and Air / 2.3.1 Water / 2.3.2 Entrained Air / 2.3.3 Water/Cement Ratio / 2.4 Aggregates / 2.4.1 Coarse Aggregate / 2.4.2 Fine Aggregate / 2.4.3 Grading of Normalweight Concrete Mixes / 2.4.4 Grading of Lightweight Concrete Mixes / 2.4.5 Grading of Heavy-Weight and Nuclear-Shielding Aggregates / 2.4.6 Unit Weights of Aggregates / 2.5 Admixtures / 2.5.1 Accelerating Admixtures / 2.5.2 Air-Entraining Admixtures / 2.5.3 Water-Reducing and Set-Controlling Admixtures / 2.5.4 Finely Divided Admixtures / 2.5.5 Admixtures for No-Slump Concrete / 2.5.6 Polymers / 2.5.7 Superplasticizers / Selected References

Concrete 22

3.1 Introduction / 3.1.1 Compactness / 3.1.2 Strength / 3.1.3 Water/Cement Ratio / 3.1.4 Texture / 3.1.5 Parameters Affecting Concrete Quality / 3.2 Proportioning Theory / 3.2.1 ACI Method of Mix Design / 3.2.2 Example 3.1: Mix Design of Normalweight Concrete / 3.3 Portland Cement Association Method / 3.4 Mix Design for Structural Lightweight Concrete / 3.5 Estimating Compressive Strength of a Trial Mix Using the Specified Compressive Strength / 3.5.1 Recommended Proportions for Concrete Strength  $f'_{cr}$  / 3.5.2 Trial Mix Design for Average Strength When Prior Field Strength Data Are Available / 3.5.3 Example 3.2: Calculation of Design Strength for Trial Mix / 3.6 Mix Designs for Nuclear-Shielding Concrete /

**3.7 Quality Tests on Concrete** / 3.7.1 Workability or Consistency / 3.7.2 Air Content / 3.7.3 Compressive Strength of Hardened Concrete / 3.7.4 Flexural Strength of Plain Concrete Beams / 3.7.5 Tensile Splitting Tests / **3.8 Placing and Curing of Concrete** / 3.8.1 Placing / 3.8.2 Curing / **3.9 Properties of Hardened Concrete** / 3.9.1 Compressive Strength / 3.9.2 Tensile Strength / 3.9.3 Shear Strength / 3.9.4 Stress-Strain Curve / 3.9.5 Modulus of Elasticity / 3.9.6 Shrinkage / 3.9.7 Creep / 3.9.8 Creep Effects / 3.9.9 Rheological Models / Selected References / Problems for Solution

## 4

### **Reinforced Concrete 57**

**4.2 Introduction** / **4.2 Types and Properties of Steel Reinforcement** / **4.3 Bar Spacing and Concrete Cover for Steel Reinforcement** / **4.4 Concrete Structural Systems** / 4.4.1 Floor Slabs / 4.4.2 Beams / 4.4.3 Columns / 4.4.4 Walls / 4.4.5 Foundations / **4.5 Reliability and Structural Safety of Concrete Components** / **4.6 ACI Load Factors and Safety Margins** / **4.7 Design Strength versus Nominal Strength: Strength Reduction Factor  $\phi$**  / **4.8 Quality Control and Quality Assurance** / 4.8.1 The User / 4.8.2 Planning / 4.8.3 Design / 4.8.4 Materials Selection / 4.8.5 Construction / Selected References

## 5

### **Flexure in Beams 81**

**5.1 Introduction** / **5.2 The Equivalent Rectangular Block** / **5.3 Balanced Reinforcement Ratio  $\bar{\rho}_b$**  / **5.4 Analysis of Singly Reinforced Beams for Flexure** / 5.4.1 Example 5.1: Flexural Analysis of a Single Reinforced Beam / 5.4.2 Example 5.2: Nominal Resisting Moment in a Singly Reinforced Beam / **5.5 Trial-and-Adjustment Procedures for the Design of Singly reinforced Beams** / 5.5.1 Example 5.3: Design of a Singly Reinforced Simply Supported Beam for Flexure / 5.5.2 Arrangement of Reinforcement / **5.6 One-Way Slabs** / 5.6.1 Example 5.4: Design of a One-Way Slab for Flexure / **5.7 Doubly Reinforced Sections** / 5.7.1 Example 5.5: Analysis of a Doubly Reinforced Beam for Flexure / 5.7.2 Trial-and-Adjustment Procedure for the Design of Doubly Reinforced Sections for Flexure / 5.7.3 Example 5.6: Design of a Doubly Reinforced Beam for Flexure / **5.8 Nonrectangular Sections** / **5.9 Analysis of T and L Beams** / 5.9.1 Example 5.7: Analysis of a T Beam for Moment Capacity / **5.10 Trial-and-Adjustment Procedure for the Design of Flanged Sections** / 5.10.1 Example 5.8: Design of an End-Span L Beam / 5.10.2 Example 5.9: Design of an Interior Continuous Floor Beam for Flexure / Selected References / Problems for Solution

## 6

### **Shear & Diagonal Tension in Beams 142**

**6.1 Introduction** / **6.2 Behavior of Homogeneous Beams** / **6.3 Behavior of Reinforced Concrete Beams as Nonhomogeneous Sections** / **6.4 Reinforced Concrete Beams without Diagonal Tension Reinforcement** / 6.4.1 Modes of Failure of Beams without Diagonal Tension Reinforcement / 6.4.2 Flexural Failure / 6.4.3 Diagonal Tension Failure / 6.4.4 Shear Compression Failure / **6.5 Diagonal Tension Analysis of Slender and Intermediate Beams** / **6.6 Web Steel Planar Truss Analogy** / 6.6.1 Web Steel Resistance / 6.6.2 Limitations on Size and Spacing of Stirrups / **6.7 Web Reinforcement Design Procedure for Shear** / **6.8 Examples on the Design**



**of Web Steel for Shear** / 6.8.1 Example 6.1: Design of Web Stirrups / 6.8.2 Example 6.2: Alternative Solution to Ex. 6.1 / **6.9 Deep Beams** / 6.9.1 Design Criteria for Shear in Deep Beams Loaded at the Top / 6.9.2 Design Criteria for Flexure in Deep Beams / 6.9.2.1 Simply Supported Beams / 6.9.2.2 Continuous Beams / 6.9.3 Sequence of Deep Beams Design Steps for Shear / 6.9.4 Example 6.3: Design of Shear Reinforcement in Deep Beams / 6.9.5 Example 6.4: Flexural Steel in Deep Beams / Example 6.5: Reinforcement Design for Continuous Deep Beams / **6.10 Brackets or Corbels** / 6.10.1 Shear Friction Hypothesis for Shear Transfer in Corbels / 6.10.2 Horizontal External Force Effect / 6.10.3 Sequence of Corbel Design Steps / 6.10.4 Example 6.5: Design of a Bracket or Corbel / **Selected References** / **Problems for Solution**

## Torsion 195

7

**7.1 Introduction** / **7.2 Pure Torsion in Plain Concrete Elements** / 7.2.1 Torsion in Elastic Materials / 7.2.2 Torsion in Plastic Materials / 7.2.3 Sand-Heap Analogy Applied to L Beams / **7.3 Torsion in Reinforced Concrete Elements** / 7.3.1 Skew-Bending Theory / 7.3.2 Space Truss Analogy Theory / **7.4 Behavior of Concrete under Combined Torsion, Shear, and Bending** / 7.4.1 Combined Torsion and Shear / 7.4.2 Combined Torsion and Bending / 7.4.3 Combined Bending, Shear, and Torsion / **7.5 Design of Reinforced Concrete Beams Subjected to Combined Torsion, Bending, and Shear** / 7.5.1 Torsional Behavior of Structures / 7.5.2 Torsional Web Reinforcement / 7.5.3 Design Procedure for Combined Torsion and Shear / 7.5.4 Example 7.1: Design of Web Reinforcement for Combined Torsion and Shear in a T-Beam Section / 7.5.5 Example 7.2: Equilibrium Torsion Web Steel Design / 7.5.6 Example 7.3: Compatibility Torsion Web Steel Design / **Selected References** / **Problems for Solution**

## Serviceability of Beams & One-Way Slabs 246

8

**8.1 Introduction** / **8.2 Significance of Deflection Observation** / **8.3 Deflection Behavior of Beams** / 8.3.1 Precracking Stage: Region I / 8.3.1.1 Example 8.1: Alternative Methods of Cracking Moment Evaluation / 8.3.2 Postcracking Service Load Stage: Region II / 8.3.2.1 Example 8.2: Effective Moment of Inertia of Cracked Beam Sections / 8.3.3 Postserviceability Cracking Stage and Limit State of Deflection Behavior at Failure: Region III / **8.4 Long-Term Deflection** / **8.5 Permissible Deflections in Beams and One-Way Slabs** / 8.5.1 Empirical Method of Minimum Thickness Evaluation for Deflection Control / 8.5.2 Permissible Limits of Calculated Deflection / **8.6 Computation of Deflections** / 8.6.1 Example 8.3: Deflection Behavior of a Uniformly Loaded Simple Span Beam / **8.7 Deflection of Continuous Beams** / 8.7.1 Deflection of T Beams / 8.7.2 Deflection of Beams with Compression Steel / 8.7.3 Deflection Bending Moments in Continuous Beams / 8.7.4 Example 8.4: Deflection of a Continuous Four-Span Beam / **8.8 Operational Deflection Calculation Procedure and Flowchart** / **8.9 Deflection Control in One-Way Slabs** / 8.9.1 Example 8.5: Deflection Calculations for a Simply Supported One-Way Slab / **8.10 Flexural Cracking in Beams and One-Way Slabs** / 8.10.1 Fundamental Behavior / 8.10.2 Crack-Width Evaluation / 8.10.3 Example 8.6: Maximum Crack Width in a Reinforced Concrete Beam / 8.10.4 Crack-Width Evaluation for Beams Reinforced with

Bundled Bars / 8.10.5 Example 8.7: Maximum Crack Width in a Beam Reinforced with Bundled Bars / 8.10.6 Z Factor for Crack-Control Check in Beams / **8.11 Permissible Crack Widths** / 8.11.1 Example 8.8: Crack Control in a Rectangular Beam / 8.11.2 Example 8.9: Crack Control in a Beam Reinforced with Bundled Bars / Selected References / Problems for Solution

## 9

### **Combined Compression & Bending: Columns 297**

**9.1 Introduction** / **9.2 Types of Columns** / **9.3 Strength of Short Centrally Loaded Columns** / 9.3.1 Example 9.1: Analysis of an Axially Loaded Short Rectangular Tied Column / 9.3.2 Example 9.2: Analysis of an Axially Loaded Short Circular Column / **9.4 Strength of Eccentrically Loaded Columns: Axial Load and Bending** / 9.4.1 Behavior of Eccentrically Loaded Short Columns / 9.4.2 Basic Column Equations 9.6 and 9.7 and Trial-and-Adjustment Procedure for Analysis (Design) of Columns / **9.5 Modes of Material Failure in Columns** / 9.5.1 Balanced Failure in Rectangular Column Sections / 9.5.2 Example 9.3: Analysis of a Column Subjected to Balanced Failure / 9.5.3 Tension Failure in Rectangular Column Sections / 9.5.4 Example 9.4: Analysis of a Column Controlled by Tension Failure; Stress in Compression Steel Equals Yield Strength / 9.5.5 Example 9.5: Analysis of a Column Controlled by Tension Failure; Stress in Compression Steel Less Than Yield Strength / 9.5.6 Compression Failure in Rectangular Column Sections / 9.5.7 Example 9.6: Analysis of a Column Controlled by Compression Failure; Trial-and-Adjustment Procedure / 9.5.8 General Case of Columns Reinforced on All Faces: Exact Solution / **9.6 Whitney's Approximate Solution in Lieu of Exact Solutions** / 9.6.1 Rectangular Concrete Columns / 9.6.2 Example 9.7: Analysis of a Column Controlled by Compression Failure; Whitney's Equation / 9.6.3 Circular Concrete Columns / 9.6.4 Empirical Method of Analysis of Circular Columns / 9.6.5 Example 9.8: Calculation of Equivalent Rectangular Cross Section for a Circular Column / 9.6.6 Example 9.9: Analysis of a Circular Column / **9.7 Column Strength Reduction Factor  $\phi$**  / 9.7.1 Example 9.10: Calculation of Design Load Strength  $\phi P_n$  from Nominal Resisting Load  $P_n$  / **9.8 Load-Moment Strength Interaction Diagrams ( $P$ - $M$  Diagrams) for Columns Controlled by Material Failure** / 9.8.1 Example 9.11: Construction of a Load-Moment Interaction Diagram / **9.9 Practical Design Considerations** / 9.9.1 Longitudinal or Main Reinforcement / 9.9.2 Lateral Reinforcement for Columns / **9.10 Operational Procedure for the Design of Nonslender Columns** / **9.11 Numerical Examples for Analysis and Design of Nonslender Columns** / 9.11.1 Example 9.12: Design of a Column with Large Eccentricity; Initial Tension Failure / 9.11.2 Example 9.13: Design of a Column with Small Eccentricity; Initial Compression Failure / 9.11.3 Example 9.14: Design of a Circular Spirally Reinforced Column / **9.12 Limit State at Buckling Failure (Slender or Long Columns)** / **9.13 Moment Magnification Method** / **9.14 Second-Order Analysis** / **9.15 Operational Procedure and Flowchart for the Design of Slender (Long) Columns** / 9.15.1 Example 9.15: Design of a Slender (Long) Column / **9.16 Compression Members in Biaxial Bending** / 9.16.1 Exact Method of Analysis / 9.16.2 Load Contour Method / 9.16.3 Step-by-Step Operational Procedure for the Design of Biaxially Loaded Columns / 9.16.4 Example 9.16: Design of a Biaxially Loaded Column / Selected References / Problems for Solution

## Bond Development of Reinforcing Bars 380

- 10.1 Introduction** / **10.2 Bond Stress Development** / 10.2.1 Anchorage Bond / 10.2.2 Flexural Bond / **10.3 Basic Development Length** / 10.3.1 Development of Deformed Bars in Tension / 10.3.2 Modifying Multipliers of Development Length  $\rho_d$  for Bars in Tension / 10.3.3 Development of Deformed Bars in Compression and the Modifying Multipliers / 10.3.4 Example 10.1: Embedment Length of Deformed Bars / 10.3.5 Mechanical Anchorage and Hooks / 10.3.6 Example 10.2: Embedment Length for a Standard 90° Hook / **10.4 Development of Flexural Reinforcement in Continuous Beams** / **10.5 Splicing of Reinforcement** / 10.5.1 Lap Splicing / 10.5.2 Splices of Deformed Bars and Deformed Wires in Tension / 10.5.3 Splices of Deformed bars in Compression / 10.5.4 Splices of Deformed Welded Wire Fabric / **10.6 Examples of Embedment Length and Splice Design for Beam Reinforcement** / 10.6.1 Example 10.3: Embedment Length at Support of a Simply Supported Beam / 10.6.2 Example 10.4: Embedment Length at Support of a Continuous Beam / 10.6.3 Example 10.5: Splice Design for Tension Reinforcement / 10.6.4 Example 10.6: Splice Design for Compression Reinforcement / **10.7 Typical Detailing of Reinforcement and Bar Scheduling** / Selected References / Problems for Solution

## Design of Two-Way Slabs & Plates 420

- 11.1 Introduction: Review of Methods** / 11.1.1 The Semielastic ACI Code Approach / 11.1.2 The Yield-Line Theory / 11.1.3 The Limit Theory of Plates / 11.1.4 The Strip Method / 11.1.5 Summary / **11.2 Flexural Behavior of Two-Way Slabs and Plates** / 11.2.1 Two-Way Action / 11.2.2 Relative Stiffness Effects / **11.3 The Direct Design Method** / 11.3.1 Limitations of the Direct Design Method / 11.3.2 Determination of the Factored Total Statical Moment  $M_o$  / **11.4 Distributed Factored Moments and Slab Reinforcement** / 11.4.1. Negative and Positive Factored Design Moments / 11.4.2 Factored Moments in Column Strips / 11.4.3 Factored Moments in Middle Strips / 11.4.4 Effects of Pattern Loading on Increase of Positive Moments / 11.4.5 Shear-Moment Transfer to Columns Supporting Flat Plates / 11.4.5.1 Shear Strength / 11.4.5.2 Shear-Moment Transfer / 11.4.6 Deflection Requirement for Minimum Thickness: An Indirect Approach / **11.5 Design and Analysis Procedures** / 11.5.1 Operational Steps / 11.5.2 Example 11.1: Design of Flat Plate without Beams / 11.5.3 Example 11.2: Design of Two-Way Slab on Beams / **11.6 Direct Method of Deflection Evaluation** / 11.6.1 The Equivalent Frame Approach / 11.6.2 Example 11.3: Central Deflection Calculations of a Slab Panel on Beams / **11.7 Cracking Behavior and Crack Control in Two-Way-Action Slabs and Plates** / 11.7.1 Flexural Cracking Mechanism and Fracture Hypothesis / 11.7.2 Crack Control Equation / 11.7.3 Example 11.4: Crack-Control Evaluation for Serviceability in an Interior Two-Way Panel / 11.7.4 Example 11.5: Crack-Control Evaluation for Serviceability in a Rectangular Panel Subjected to Severe Exposure Conditions / **11.8 Yield-Line Theory for Two-Way-Action Plates** / 11.8.1 Fundamental Concepts of Hinge-Field-Failure Mechanisms in Flexure / 11.8.2 Failure Mechanisms and Moment Capacities of Slabs of Various Shapes Subjected to Distributed or Concentrated

Loads / 11.8.3 Example 11.6: Rectangular Slab Yield-Line Design / 11.8.4 Example 11.7: Moment Capacity and Yield-Line Design of a Triangular Balcony Slab / Selected References / Problems for Solution

## 12 Footings 500

**12.1 Introduction / 12.2 Types of Foundations / 12.3 Shear and Flexural Behavior of Footings / 12.3.1 Failure Mechanism / 12.3.2 Loads and Reactions / 12.4 Soil Bearing Pressure at Base of Footings / 12.4.1 Eccentric Load Effect on Footings / 12.4.2 Example 12.1: Centrally Loaded Footings / 12.4.3 Example 12.2: Eccentrically Loaded Footings / 12.5 Design Considerations in Flexure / 12.5.1 Reinforcement Distribution / 12.6 Design Considerations in Shear / 12.6.1 Beam Action / 12.6.2 Two-Way Action / 12.6.3 Force and Moment Transfer at Column Base / 12.7 Operational Procedure for the Design of Footings / 12.8 Examples of Footing Design / 12.8.1 Example 12.3: Design of Two-Way Square Isolated Footing / 12.8.2 Example 12.4: Design of Two-Way Rectangular Isolated Footing / 12.8.3 Example 12.5: Proportioning of a Combined Footing / 12.9 Structural Design of Other Types of Foundations / Selected References / Problems for Solution**

## 13 Handheld & Desktop Computer Programming for Analysis & Design of Reinforced Concrete Sections 538

**13.1 Introduction / 13.1.1 Handheld Computers versus Mainframe Computers / 13.1.2 Programming Basics for the Hewlett-Packard HP41 Series / 13.1.2.1 Loading a Program / 13.1.2.2 Running a Program / 13.1.2.3 Writing a Program / 13.2 Rectangular Beams / 13.2.1 Design Equations, Flowchart, and Program Steps / 13.2.2 Instructions to Run the Program / 13.2.3 Numerical Examples / 13.2.3.1 Example 13.1: Flexural Analysis of a Singly Reinforced Beam / 13.2.3.2 Example 13.2: Nominal Resisting Moment in a Singly Reinforced Beam / 13.2.3.3 Example 13.3: Design of a Singly Reinforced Simply Supported Beam for Flexure / 13.2.3.4 Example 13.4: Design of a One-Way Slab for Flexure / 13.2.3.5 Example 13.5: Analysis of a Doubly Reinforced Beam for Flexure / 13.2.3.6 Example 13.6: Design of a Doubly Reinforced Beam for Flexure / 13.3 Flanged Beams / 13.3.1 Design Equations, Flowchart, and Program Steps / 13.3.2 Instructions to Run the Program / 13.3.3 Numerical Examples / 13.3.3.1 Example 13.7: Analysis of a T Beam for Moment Capacity / 13.3.3.2 Example 13.8: Design of an End-Span L Beam / 13.3.3.3 Example 13.9: Design of an Interior Continuous Floor Beam for Flexure / 13.4 Shear and Torsion / 13.4.1 Design Equations, Flowchart, and Program Steps / 13.4.2 Instructions to Run the Program / 13.4.3 Numerical Examples / 13.4.3.1 Example 13.10: Design of Web Stirrups / 13.4.3.2 Example 13.11: Alternative Solution to Ex. 13.10 / 13.4.3.3 Example 13.12: Design of Web Reinforcement for Combined Torsion and Shear in a T-Beam Section / 13.5 Deep Beams / 13.5.1 Design Equations, Flowchart, and Program Steps / 13.5.2 Instructions to Run the Program / 13.5.3 Numerical Examples / 13.5.3.1 Example 13.13: Simply Supported Uniformly Loaded Deep Beam / 13.5.3.2 Example 13.14: Continuous Uniformly Loaded Beam; Deep Beam / 13.5.3.3 Example 13.15: Simply Supported Deep**

Beam with a Concentrated Load / 13.5.3.4 Example 13.16: Design of Shear Reinforcement in Deep Beams / 13.5.3.5 Example 13.17: Reinforcement Design for a Continuous Deep Beam /	<b>13.6 Corbels</b> / 13.6.1 Design Equations, Flowchart, and Program Steps / 13.6.2 Instructions to Run the Program / 13.6.3 Numerical Examples / 13.6.3.1 Example 13.18: Design of a Bracket or Corbel /
<b>13.7 Rectangular Columns: Analysis for a Given Neutral-Axis Depth <math>c</math></b> / 13.7.1 Design Equations, Flowchart, and Program Steps / 13.7.2 Instructions to Run the Program / 13.7.3 Numerical Examples /	13.7.3.1 Example 13.19: Analysis of a Short Rectangular Tied Column / 13.7.3.2 Example 13.20: Analysis of a Column Controlled by Tension Failure; Stress in Compression Steel Less Than Yield Strength / 13.7.3.3 Example 13.21: Design of a Column with Large Eccentricity, Initial Tension Failure / 13.7.3.4 Example 13.22: Design of a Column with Small Eccentricity, Initial Compression Failure / 13.7.3.5 Example 13.23: Construction of a Load-Moment Design Strength Interaction Diagram for a Rectangular Column /
<b>13.8 Circular Columns: Analysis for a Given Neutral-Axis Depth <math>c</math></b> / 13.8.1 Design Equations, Flowchart, and Program Steps / 13.8.2 Instructions to Run the Program / 13.8.3 Numerical Examples /	13.8.3.1 Example 13.24: Analysis of a Circular Column / 13.8.3.2 Example 13.25: Circular Spirally Reinforced Column / 13.8.3.3 Example 13.26: Construction of a Load-Moment Design Strength Interaction Diagram Coordinates for a Round Column /
<b>13.9 Rectangular Columns under Biaxial Bending</b> / 13.9.1 Design Equations, Flowchart, and Program Steps / 13.9.2 Instructions to Run the Program / 13.9.3 Numerical Examples /	13.9.3.1 Example 13.27: Design of a Biaxially Loaded Column /
<b>13.10 Use of Desktop and Transportable Personal Computers</b> / 13.10.1 Programming in BASIC Language /	<b>13.11 Programs for Apple IIe Desktop Personal Computers: Rectangular Beams in Flexure, Shear, and Torsion</b> / 13.11.1 Example 13.28: Flexural Analysis of Singly and Doubly Reinforced Beams / 13.11.2 Example 13.29: Design of Web Stirrups for Shear / 13.11.3 Example 13.30: Design of Web Stirrups for Combined Shear and Torsion /
<b>13.12 Programs for Apple IIe Desktop Personal Computers: Compression Members</b> / 13.12.1 Example 13.31: Analysis of a Rectangular Tied Column / 13.12.2 Example 13.32: Analysis of a Spirally Reinforced Circular Column / 13.12.3 Example 13.33: Load-Moment Design Strength Interaction Plots for Rectangular Columns / 13.12.4 Example 13.34: Load-Moment Design Strength Interaction Plots for Circular Columns / 13.12.5 Example 13.35: Design of a Rectangular Biaxially Loaded Column /	Selected References

## Appendix b89

A-1 Selected Conversion Factors to SI Units / A-2 Geometrical Properties of Reinforcing Bars / A-3 Cross-Sectional Area of Bars for Various Bar Combinations / A-4 Area of Bars in a 1-Foot-Wide Slab Strip / A-5 Gross Moment of Inertia of T Sections
---

## Index b95

# 1

## Introduction





## 1.1 HISTORICAL DEVELOPMENT OF STRUCTURAL CONCRETE

Use of concrete and its cementitious (volcanic) constituents, such as pozzolanic ash, has been made since the days of the Greeks, the Romans, and possibly earlier ancient civilizations. However, the early part of the nineteenth century marks the start of more intensive use of the material. In 1801, F. Coignet published his statement of principles of construction, recognizing the weakness of the material in tension. J. L. Lambot in 1850 constructed for the first time a small cement boat for exhibition in the 1855 World Fair in Paris. J. Monier, a French gardener, patented in 1867 metal frames as reinforcement for concrete garden plant containers, and Koenen in 1886 published the first manuscript on the theory and design of concrete structures. In 1906, C. A. P. Turner developed the first flat slab without beams.

Thereafter, considerable progress occurred in this field such that by 1910 the German Committee for Reinforced Concrete, the Austrian Concrete Committee, the American Concrete Institute, and the British Concrete Institute were already established. Many buildings, bridges, and liquid containers of reinforced concrete were already constructed by 1920 and the era of linear and circular prestressing began.

The rapid developments in the art and science of reinforced and prestressed concrete analysis, design, and construction have resulted in very unique structural

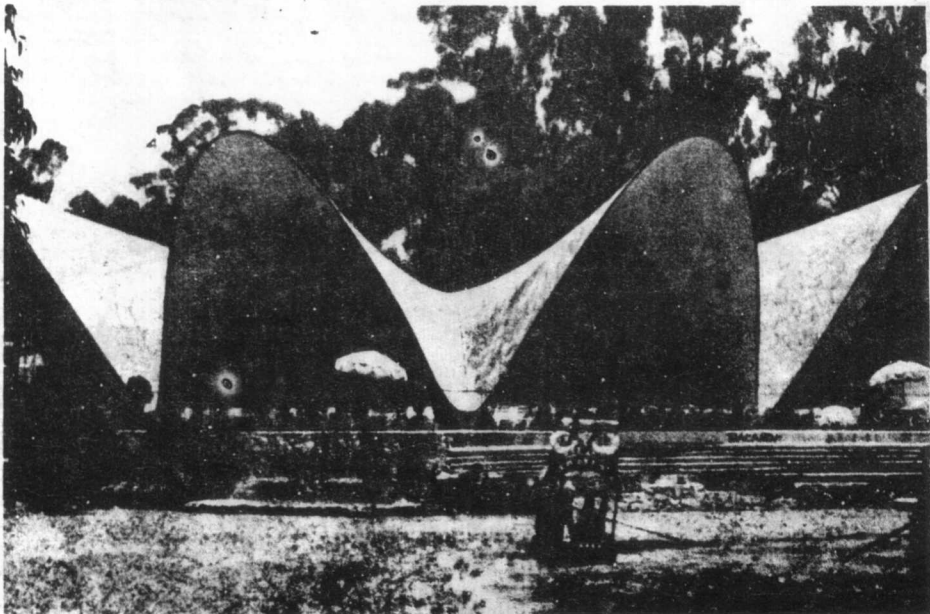
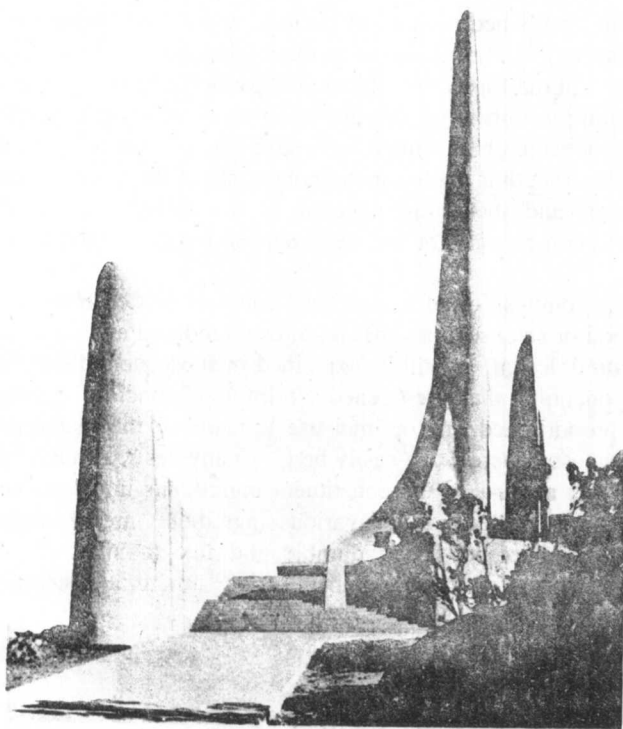


Photo 3 Felix Candela's Xochimilco Restaurant, Mexico.



**Photo 4** Afrikaans Languages Monument, Stellenbosch, South Africa (height of the main dynamically designed hollow columns, 186 ft).

systems, such as the Kresge Auditorium, Boston; the 1951 Festival of Britain Dome; Marina Towers and Lake Point Tower, Chicago; and many, many others.

Ultimate-strength theories were codified in 1938 in the USSR and in 1956 in England and the United States. Limit theories have also become a part of codes of several countries throughout the world. New constituent materials and composites of concrete have become prevalent, including the high-strength concretes of a strength in compression up to 20,000 psi (137.9 MPa) and 1800 psi (12.41 MPa) in tension. Steel reinforcing bars of strength in excess of 60,000 psi (413.7 MPa) and high-strength welded wire fabric in excess of 100,000 psi (689.5 MPa) ultimate strength are being used. Additionally, deformed bars of various forms have been produced. Such deformations help develop the maximum possible bond between the reinforcing bars and the surrounding concrete as a requisite for the viability of concrete as a structural medium. Prestressing steel of ultimate strengths in excess of 300,000 psi (2068 MPa) is available.

All these developments and the massive experimental and theoretical research that has been conducted, particularly in the last two decades, have resulted in rigorous theories and codes of practice. Consequently, a simplified approach has become necessary to an understanding of the fundamental structural behavior of reinforced concrete elements.

## **1.2 BASIC HYPOTHESIS OF REINFORCED CONCRETE**

Plain concrete is formed from a hardened mixture of cement, water, fine aggregate, coarse aggregate (crushed stone or gravel), air, and often other admixtures. The plastic mix is placed and consolidated in the formwork, then cured to facilitate the acceleration of the chemical hydration reaction of the cement/water mix, resulting in hardened concrete. The finished product has high compressive strength, and low resistance to tension, such that its tensile strength is approximately one-tenth of its compressive strength. Consequently, tensile and shear reinforcement in the tensile regions of sections has to be provided to compensate for the weak-tension regions in the reinforced concrete element.

It is this deviation in the composition of a reinforced concrete section from the homogeneity of standard wood or steel sections that requires a modified approach to the basic principles of structural design, as will be explained in subsequent chapters of this book. The two components of the heterogeneous reinforced concrete section are to be so arranged and proportioned that optimal use is made of the materials involved. This is possible because concrete can easily be given any desired shape by placing and compacting the wet mixture of the constituent ingredients into suitable forms in which the plastic mass hardens. If the various ingredients are properly proportioned, the finished product becomes strong, durable, and, in combination with the reinforcing bars, adaptable for use as main members of any structural system.

## **1.3 ANALYSIS VERSUS DESIGN OF SECTIONS**

From the foregoing discussion, it is clear that a large number of parameters have to be dealt with in proportioning a reinforced concrete element, such as geometrical width, depth, area of reinforcement, steel strain, concrete strain, steel stress, and so on. Consequently, trial and adjustment is necessary in the choice of concrete sections, with assumptions based on conditions at site, availability of the constituent materials, particular demands of the owners, architectural and headroom requirements, the applicable codes, and environmental conditions. Such an array of parameters has to be considered because of the fact that reinforced concrete is often a site-constructed composite, in contrast to the standard mill-fabricated beam and column sections in steel structures.

A trial section has to be chosen for each critical location in a structural system. The trial section has to be analyzed to determine if its nominal resisting strength is adequate to carry the applied factored load. Since more than one trial is often necessary to arrive at the required section, the first design input step generates into a series of trial-and-adjustment analyses.

The trial-and-adjustment procedures for the choice of a concrete section lead to the convergence of analysis and design. Hence every design is an analysis once a trial section is chosen. The availability of handbooks, charts, desktop and handheld per-