

REINFORCED CONCRETE

A Fundamental Approach

Fifth Edition

Edward G. Nawy

Distinguished Professor

Department of Civil and Environmental Engineering

Rutgers, The State University of New Jersey



Pearson Education, Inc.
Upper Saddle River, New Jersey 07458

CONTENTS

PREFACE **xiii**

1

INTRODUCTION **1**

- 1.1 Historical Development of Structural Concrete 1
- 1.2 Basic Hypothesis of Reinforced Concrete 2
- 1.3 Analysis versus Design of Sections 3

2

CONCRETE-PRODUCING MATERIALS **7**

- 2.1 Introduction 7
- 2.2 Portland Cement 8
- 2.3 Water and Air 11
- 2.4 Aggregates 12
- 2.5 Admixtures 15
- Selected References 19

3

CONCRETE **20**

- 3.1 Introduction 20
- 3.2 Proportioning Theory—Normal Strength Concrete 22
- 3.3 High-Strength High-Performance Concrete Mixtures Design 29
- 3.4 PCA Method of Mixture Design 40
- 3.5 Estimating Compressive Strength of a Trial Mixture Using the Specified Compressive Strength 40
- 3.6 Mixture Designs for Nuclear-Shielding Concrete 45
- 3.7 Quality Tests on Concrete 45
- 3.8 Placing and Curing of Concrete 46
- 3.9 Properties of Hardened Concrete 48
- 3.10 High-Strength Concrete 59
- Selected References 65
- Problems for Solution 67

4

REINFORCED CONCRETE **68**

- 4.1 Introduction 68
- 4.2 Types and Properties of Steel Reinforcement 69
- 4.3 Bar Spacing and Concrete Cover for Steel Reinforcement 70
- 4.4 Concrete Structural Systems 73
- 4.5 Reliability and Structural Safety of Concrete Components 74
- 4.6 ACI Load Factors and Safety Margins 79
- 4.7 Design Strength versus Nominal Strength: Strength Reduction Factor ϕ 81
- 4.8 Quality Control and Quality Assurance 82
- Selected References 89

5

FLEXURE IN BEAMS 91

- 5.1 Introduction 91
- 5.2 The Equivalent Rectangular Block 95
- 5.3 Strain Limits Method for Analysis and Design 100
- 5.4 Analysis of Singly Reinforced Rectangular Beams for Flexure 103
- 5.5 Trial-and-Adjustment Procedures for the Design of Singly Reinforced Beams 108
- 5.6 One-Way Slabs 112
- 5.7 Doubly Reinforced Sections 114
- 5.8 Nonrectangular Sections 123
- 5.9 Analysis of T and L Beams 124
- 5.10 Trial-and-Adjustment Procedure for the Design of Flanged Sections 131
- 5.11 Concrete Joist Construction 140
- 5.12 SI Expressions and Example for Flexural Design of Beams 141
 - Selected References 144
 - Problems for Solution 145

6

SHEAR AND DIAGONAL TENSION IN BEAMS 149

- 6.1 Introduction 149
- 6.2 Behavior of Homogeneous Beams 151
- 6.3 Behavior of Reinforced Concrete Beams as Nonhomogeneous Sections 152
- 6.4 Reinforced Concrete Beams without Diagonal Tension Reinforcement 154
- 6.5 Diagonal Tension Analysis of Slender and Intermediate Beams 157
- 6.6 Web Steel Planar Truss Analogy 159
- 6.7 Web Reinforcement Design Procedure for Shear 163
- 6.8 Examples of the Design of Web Steel for Shear 164
- 6.9 Deep Beams 169
- 6.10 Brackets or Corbels 181
- 6.11 Strut-and-Tie Model Analysis and Design of Concrete Elements 190
- 6.12 SI Design Expressions and Example for Shear Design 201
 - Selected References 204
 - Problems for Solution 205

7

TORSION 209

- 7.1 Introduction 209
- 7.2 Pure Torsion in Plain Concrete Elements 212
- 7.3 Torsion in Reinforced Concrete Elements 219
- 7.4 Shear–Torsion–Bending Interaction 224
- 7.5 ACI Design of Reinforced Concrete Beams Subjected to Combined Torsion, Bending, and Shear 225
- 7.6 SI Metric Torsion Expressions and Example for Torsion Design 251
 - Selected References 255
 - Problems for Solution 257

8

SERVICEABILITY OF BEAMS AND ONE-WAY SLABS 260

- 8.1 Introduction 260
- 8.2 Significance of Deflection Observation 261
- 8.3 Deflection Behavior of Beams 261
- 8.4 Long-Term Deflection 268

- 8.5 Permissible Deflections in Beams and One-Way Slabs 270
- 8.6 Computation of Deflections 271
- 8.7 Deflection of Continuous Beams 276
- 8.8 Operational Deflection Calculation Procedure and Flow Chart 286
- 8.9 Deflection Control in One-Way Slabs 287
- 8.10 Flexural Cracking in Beams and One-Way Slabs 291
- 8.11 Tolerable Crack Widths 297
- 8.12 ACI 318 Code Provisions for Control of Flexural Cracking 297
- 8.13 SI Conversion Expressions and Example of Deflection Evaluation 299
 - Selected References 302
 - Problems for Solution 302

9

COMBINED COMPRESSION AND BENDING: COLUMNS 305

- 9.1 Introduction 305
- 9.2 Types of Columns 306
- 9.3 Strength of Short Centrally Loaded Columns 309
- 9.4 Strength of Eccentrically Loaded Columns: Axial Load and Bending 312
- 9.5 Strain Limits Method to Establish Reliability Factor ϕ and Analysis and Design of Compression Members 315
- 9.6 Whitney's Approximate Solution in Lieu of Exact Solutions 330
- 9.7 Column Strength Reduction Factor ϕ 337
- 9.8 Load–Moment Strength Interaction Diagrams (P – M Diagrams) for Columns Controlled by Material Failure 339
- 9.9 Practical Design Considerations 346
- 9.10 Operational Procedure for the Design of Nonslender Columns 348
- 9.11 Numerical Examples for Analysis and Design of Nonslender Columns 348
- 9.12 Limit State at Buckling Failure (Slender or Long Columns) 356
- 9.13 Moment Magnification: First-Order Analysis 360
- 9.14 Second-order Frame Analysis and the P – Δ Effect 364
- 9.15 Operational Procedure and Flow Chart for the Design of Slender Columns 365
- 9.16 Compression Members in Biaxial Bending 371
- 9.17 SI Expressions and Example for the Design of Compression Members 388
 - Selected References 390
 - Problems for Solution 390

10

BOND DEVELOPMENT OF REINFORCING BARS 394

- 10.1 Introduction 394
- 10.2 Bond Stress Development 395
- 10.3 Basic Development Length 399
- 10.4 Development of Flexural Reinforcement in Continuous Beams 410
- 10.5 Splicing of Reinforcement 416
- 10.6 Examples of Embedment Length and Splice Design for Beam Reinforcement 418
- 10.7 Typical Detailing of Reinforcement and Bar Scheduling 422
 - Selected References 432
 - Problems for Solution 432

11

DESIGN OF TWO-WAY SLABS AND PLATES 434

- 11.1 Introduction: Review of Methods 434
- 11.2 Flexural Behavior of Two-Way Slabs and Plates 437
- 11.3 The Direct Design Method 438

- 11.4 Distributed Factored Moments and Slab Reinforcement by the Direct Design Method 442
- 11.5 Design and Analysis Procedure: Direct Design Method 452
- 11.6 Equivalent Frame Method for Floor Slab Design 474
- 11.7 SI Two-Way Slab Design Expressions and Example 485
- 11.8 Direct Method of Deflection Evaluation 494
- 11.9 Cracking Behavior and Crack Control in Two-Way-Action Slabs and Plates 500
- 11.10 Yield-Line Theory for Two-Way Action Plates 507
 - Selected References 521
 - Problems for Solution 522

12

FOOTINGS 524

- 12.1 Introduction 524
- 12.2 Types of Foundations 526
- 12.3 Shear and Flexural Behavior of Footings 527
- 12.4 Soil Bearing Pressure at Base of Footings 530
- 12.5 Design Considerations in Flexure 535
- 12.6 Design Considerations in Shear 536
- 12.7 Operational Procedure for the Design of Footings 538
- 12.8 Examples of Footing Design 541
- 12.9 Structural Design of Other Types of Foundations 554
 - Selected References 554
 - Problems for Solution 555

13

CONTINUOUS REINFORCED CONCRETE STRUCTURES 556

- 13.1 Introduction 556
- 13.2 Longhand Displacement Methods 558
- 13.3 Force Method of Analysis 558
- 13.4 Displacement Method of Analysis 564
- 13.5 Finite-Element Methods and Computer Usage 571
- 13.6 Approximate Analysis of Continuous Beams and Frames 572
- 13.7 Limit Design (Analysis) of Indeterminate Beams and Frames 598
 - Selected References 608
 - Problems for Solution 609

14

INTRODUCTION TO PRESTRESSED CONCRETE 611

- 14.1 Basic Concepts of Prestressing 611
- 14.2 Partial Loss of Prestress 617
- 14.3 Flexural Design of Prestressed Concrete Elements 623
- 14.4 Serviceability Requirements in Prestressed Concrete Members 638
- 14.5 Ultimate-Strength Flexural Design of Prestressed Beams 639
- 14.6 Example 14.5: Ultimate-Strength Design of Prestressed Simply Supported Beam by Strain Compatibility 646
- 14.7 Web Reinforcement Design Procedure for Shear 650
 - Selected References 654
 - Problems for Solution 654

15**LRFD AASHTO DESIGN OF CONCRETE
BRIDGE STRUCTURES 658**

- 15.1 LRFD Truck Load Specifications 658
- 15.2 Flexural Design Considerations 668
- 15.3 Shear Design Considerations 673
- 15.4 Horizontal Interface Shear 678
- 15.5 Combined Shear and Torsion 680
- 15.6 Step-by-Step LRFD Design Procedures 682
- 15.7 LRFD Design of Bulb-Tee Bridge Deck: Example 15.1 685
- 15.8 LRFD Shear and Deflection Design: Example 15.2 697
- Selected References 704
- Problems for Solution 705

16**SEISMIC DESIGN OF CONCRETE STRUCTURES 706**

- 16.1 Introduction: Mechanism of Earthquakes 706
- 16.2 Spectral Response Method 711
- 16.3 Equivalent Lateral Force Method 718
- 16.4 Simplified Analysis Procedure for Seismic Design of Buildings 724
- 16.5 Other Aspects in Seismic Design 725
- 16.6 Flexural Design of Beams and Columns 725
- 16.7 Seismic Detailing Requirements for Beams and Columns 729
- 16.8 Horizontal Shear in Beam–Column Connections (Joints) 733
- 16.9 Design of Shear Walls 735
- 16.10 Design Procedure for Earthquake-Resistant Structures 738
- 16.11 Example 16.1: Seismic Base Shear and Lateral Forces and Moments by the International Building Code (IBC) Approach 747
- 16.12 Example 16.2: Design of Confining Reinforcement for Beam–Column Connections 750
- 16.13 Example 16.3: Transverse Reinforcement in a Beam Potential Hinge Region 754
- 16.14 Example 16.4: Probable Shear Strength of Monolithic Beam–Column Joint 755
- 16.15 Example 16.5: Seismic Shear Wall Design and Detailing 757
- Selected References 763
- Problems for Solution 764

APPENDIX A COMPUTER PROGRAMS IN Q-BASIC 765**APPENDIX B TABLES AND NOMOGRAMS 779****INDEX 813**