Prestressed concrete is one of the most reliable, durable, and widely used construction materials in building and bridge projects around the world. It has made significant contributions to the construction industry, the precast manufacturing industry, and the cement industry as a whole. It has led to an enormous array of structural applications, including buildings, bridges, nuclear power vessels, TV towers, and offshore drilling platforms.

Main Features:
This book was written to serve as a thorough teaching text, a comprehensive source of information, and a basic reference. It is intended for advanced students, professional engineers, and researchers. It emphasizes the fundamental concepts of analysis and design of prestressed concrete structures, providing the user with the essential knowledge and tools to deal with everyday design problems, while encouraging the necessary critical thinking to tackle more complex problems with confidence.

This updated edition
- Integrates the provisions of the 2011 ACI Building Code in text and examples
- Offers an extensive treatment of bridge analysis and design according to the 2010 AASHTO LRFD Specifications
- Offers a rigorous treatment of fundamentals as applied to serviceability and ultimate strength limit states for bending, shear, composite action, compression and tension members, and introduces some simple optimum design approaches
- Includes a large number of logical design flow charts and design examples
- Covers the basics and provides examples of applications comparing both the 2011 ACI and 2010 AASHTO LRFD code approaches to bending, shear and torsion, prestress losses, and interface shear
- Presents a chapter on strut-and-tie modeling according to the ACI Building Code with examples of anchorage zone design
- Covers slenderness effects in prestressed concrete columns, and provides load-moment interaction diagrams for prestressed columns and poles
- Offers a comprehensive treatment of the design of one- and two-way prestressed slabs
- Presents a unique treatment of prestressed tensile members by optimum design, including the design of wall for circular tanks
- Covers the time-step procedure to compute prestress losses and long-term deflections
- Offers a rigorous treatment of prestressed continuous beams
- Presents a comprehensive treatment of prestressed composite beams
• Contains more than four hundreds illustrations and photographs
• Covers sufficient material for a two-semester course on the subject
• Contains a large number of examples, an extensive updated bibliography, and an appendix with answers to study problems
• Uses consistent notation and consistent sign convention
• Uses dual units (US and SI) throughout for key equations and reference data

Chapter 1  Principle and Methods of Prestressing
Chapter 2  Prestressing Materials: Steel and Concrete
Chapter 3  The Philosophy of Design
Chapter 4  Flexure: Working Stress Analysis and Design
Chapter 5  Flexure: Ultimate Strength Analysis and Design
Chapter 6  Design for Shear and Torsion
Chapter 7  Deflection Computation and Control
Chapter 8  Computation of Prestress Losses
Chapter 9  Analysis and Design of Composite Beams
Chapter 10  Continuous Beams and Indeterminate Structures
Chapter 11  Prestressed Concrete Slabs
Chapter 12  Analysis and Design of Tensile Members
Chapter 13  Analysis and Design of Compression Members
Chapter 14  Prestressed Concrete Bridges
Chapter 15  Strut-and-Tie Modeling
Appendix A  List of Symbols
Appendix B  Unit Conversions
Appendix C  Typical Post-Tensioning Systems
Appendix D  Answers to Selected Problems
Appendix E  Typical Precast / Prestressed Beams

CONTENTS

Preface xxiii
Acknowledgments xxix

Chapter 1  Principle and Methods of Prestressing 1
1.1  Introduction 1
1.2  Examples of Prestressing 2
1.3  History of Prestressed Concrete 4
1.4  Prestressing Methods 12
  1.4.1  Pretensioning 12
  1.4.2  Posttensioning 17
  1.4.3  Self-Stressing 22
1.5  Prestressing Systems 24
1.6  Particular Prestressing Techniques 25
  1.6.1  External Prestressing 25
  1.6.2  Circular Prestressing 27
5.19 Example: Analysis or Investigation Checking for All Ultimate Strength Design Criteria
5.20 Reinforcement Design for Ultimate Strength
5.20.1 Example: Reinforcement Design for Nominal Resistance – Rectangular Section
5.20.2 Example: Reinforcement Design for Nominal Resistance – T Section

5.21 Composite Beams
5.22 Continuous Beams and Moment Redistribution
5.23 Author’s Recommendations for the Design of RC, PC, and PPC Beams at Ultimate
5.23.1 Using \( \varepsilon_t \) and \( d_e \) instead of \( \varepsilon_t \) and \( d_t \)
5.23.1.1 Example of Error in Using the Net Tensile Strain in Extreme Layer of Reinforcement
5.23.2 T-Section Behavior
5.23.3 Stress \( f_p \) in Bonded Tendons at Ultimate
5.23.4 Stress \( f_{ps} \) in Unbonded Prestressing Tendons at Ultimate

5.24 Additional Design Examples Based on USD
5.24.1 Example 1: Analysis with Unbonded Tendons Illustrating Eq. (5.103)
5.24.2 Example 2: Given \( A_{ps} \), Design for \( A_s \) Based on USD – Unbonded Tendons
5.24.3 Example 3: Given \( A_s \), Design for \( A_{ps} \) Based on USD – Unbonded Tendons
5.24.4 Example 4: Given \( A_s \), Design for \( A_{ps} \) Based on USD – Bonded Tendons

5.25 Concluding Remarks

Chapter 6 Design for Shear and Torsion
6.1 Introduction
6.2 Shear Design
6.3 Prestressed Versus Reinforced Concrete in Shear
6.4 Diagonal Tension in Uncracked Sections
6.5 Shear Stresses in Uncracked Sections
6.6 Shear Cracking Behavior
6.7 Shear Reinforcement after Cracking
6.8 ACI Code Design Criteria for Shear
6.8.1 Basic Approach
6.8.2 Shear Strength Provided by Concrete
6.8.2.1 Conservative Design Method to Estimate \( \nu_c \) or \( V_c \)
6.8.2.2 Elaborate Design Method to Estimate \( \nu_c \) or \( V_c \)
6.8.3 Required Area of Shear Reinforcement
6.8.4 Limitations and Special Cases
6.8.5 Critical Sections for Shear
6.9 Design Expedients
6.10 Example: Design of Shear Reinforcement (ACI Code)
6.10.1 Conservative Method to Determine \( \nu_c \)
6.10.2 Elaborate Method to Determine \( \nu_c \)
6.10.3 Design for Increased Live Load: Partially
### Chapter 6  Prestressed Beam

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.11</td>
<td>Derivation of Concrete Nominal Shear Strength Equations (ACI Code)</td>
<td>367</td>
</tr>
<tr>
<td>6.12</td>
<td>AASHTO General Procedure for Shear Design</td>
<td>371</td>
</tr>
<tr>
<td>6.12.1</td>
<td>General Sectional Procedure for Shear Design</td>
<td>373</td>
</tr>
<tr>
<td>6.12.2</td>
<td>Special Considerations</td>
<td>380</td>
</tr>
<tr>
<td>6.12.3</td>
<td>Example: Shear Design by AASHTO LRFD Code (Using Modified Compression Field Theory)</td>
<td>384</td>
</tr>
<tr>
<td>6.12.4</td>
<td>Simplified Shear Design Procedure by AASHTO for Prestressed and Non-Prestressed Sections</td>
<td>388</td>
</tr>
<tr>
<td>6.12.5</td>
<td>Example: Using AASHTO Simplified Shear Design Procedure</td>
<td>391</td>
</tr>
<tr>
<td>6.13</td>
<td>Torsion and Torsion Design</td>
<td>392</td>
</tr>
<tr>
<td>6.14</td>
<td>Behavior under Pure Torsion</td>
<td>393</td>
</tr>
<tr>
<td>6.15</td>
<td>Background to Stress Analysis and Design for Torsion</td>
<td>396</td>
</tr>
<tr>
<td>6.15.1</td>
<td>Torsional Stresses</td>
<td>396</td>
</tr>
<tr>
<td>6.15.2</td>
<td>Torsional Cracking Strength</td>
<td>398</td>
</tr>
<tr>
<td>6.15.3</td>
<td>Torsional Resistance after Cracking</td>
<td>399</td>
</tr>
<tr>
<td>6.15.4</td>
<td>Combined Loading</td>
<td>402</td>
</tr>
<tr>
<td>6.15.5</td>
<td>Design Theories for Torsion and Code Related Approaches</td>
<td>404</td>
</tr>
<tr>
<td>6.16</td>
<td>Design for Torsion by ACI Code</td>
<td>406</td>
</tr>
<tr>
<td>6.16.1</td>
<td>Definition of Section Parameters</td>
<td>406</td>
</tr>
<tr>
<td>6.16.2</td>
<td>Basic Assumptions and Design Strategy</td>
<td>407</td>
</tr>
<tr>
<td>6.16.3</td>
<td>Threshold Limit for Consideration of Torsion in Design</td>
<td>408</td>
</tr>
<tr>
<td>6.16.4</td>
<td>Critical Section for Torsion</td>
<td>409</td>
</tr>
<tr>
<td>6.16.5</td>
<td>Maximum Allowable Torsional Moment Strength – Upper Limit</td>
<td>409</td>
</tr>
<tr>
<td>6.16.6</td>
<td>Transverse Reinforcement Design</td>
<td>411</td>
</tr>
<tr>
<td>6.16.7</td>
<td>Longitudinal Torsion Reinforcement</td>
<td>412</td>
</tr>
<tr>
<td>6.16.8</td>
<td>Combining Shear and Torsion Reinforcement</td>
<td>413</td>
</tr>
<tr>
<td>6.16.9</td>
<td>Minimum Torsion Reinforcement</td>
<td>413</td>
</tr>
<tr>
<td>6.16.10</td>
<td>Spacing and Detailing</td>
<td>414</td>
</tr>
<tr>
<td>6.16.11</td>
<td>Type of Torsion Reinforcement</td>
<td>414</td>
</tr>
<tr>
<td>6.16.12</td>
<td>Design Steps for Combined Torsion and Shear</td>
<td>416</td>
</tr>
<tr>
<td>6.17</td>
<td>Example: Torsion Design of a Prestressed Beam</td>
<td>416</td>
</tr>
<tr>
<td>6.18</td>
<td>Shear and Torsion in Partially Prestressed Members</td>
<td>419</td>
</tr>
<tr>
<td>6.19</td>
<td>Importance of Transverse Reinforcement</td>
<td>420</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>421</td>
</tr>
<tr>
<td></td>
<td>Problems</td>
<td>423</td>
</tr>
</tbody>
</table>

### Chapter 7  Deflection Computation and Control

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1</td>
<td>Serviceability</td>
<td>429</td>
</tr>
<tr>
<td>7.2</td>
<td>Deflection: Types and Characteristics</td>
<td>430</td>
</tr>
<tr>
<td>7.2.1</td>
<td>Terminology / Notation</td>
<td>430</td>
</tr>
<tr>
<td>7.2.2</td>
<td>Key Variables Affecting Deflections in a Given Beam</td>
<td>431</td>
</tr>
<tr>
<td>7.3</td>
<td>Theoretical Deflection Derivations</td>
<td>432</td>
</tr>
<tr>
<td>7.3.1</td>
<td>Moment-Area Theorems</td>
<td>434</td>
</tr>
<tr>
<td>7.3.2</td>
<td>Example</td>
<td>436</td>
</tr>
<tr>
<td>7.4</td>
<td>Short-Term Deflections in Prestressed Members</td>
<td>437</td>
</tr>
<tr>
<td>7.4.1</td>
<td>Uncracked Members</td>
<td>437</td>
</tr>
<tr>
<td>7.4.2</td>
<td>Cracked Members</td>
<td>440</td>
</tr>
<tr>
<td>7.5</td>
<td>Background to Understanding Long-Term Deflection</td>
<td>446</td>
</tr>
</tbody>
</table>
### Chapter 7: Long-Term Deflection and Prestress Losses

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.6</td>
<td>Additional Long-Term Deflection: Simplified Prediction Methods</td>
<td>448</td>
</tr>
<tr>
<td>7.6.1</td>
<td>Additional Long-Term Deflection Using ACI Code Multiplier</td>
<td>450</td>
</tr>
<tr>
<td>7.6.2</td>
<td>Additional Long-Term Deflection Using Branson’s Multipliers</td>
<td>450</td>
</tr>
<tr>
<td>7.6.3</td>
<td>Additional Long-Term Deflection Using Martin’s Multiplier</td>
<td>451</td>
</tr>
<tr>
<td>7.6.4</td>
<td>Additional Long-Term Deflection: Heuristic or “Rule of Thumb” Method</td>
<td>452</td>
</tr>
<tr>
<td>7.6.5</td>
<td>Discussion</td>
<td>452</td>
</tr>
<tr>
<td>7.7</td>
<td>Deflection Limitations</td>
<td>453</td>
</tr>
<tr>
<td>7.8</td>
<td>Strategy for Checking Deflection Criteria</td>
<td>455</td>
</tr>
<tr>
<td>7.9</td>
<td>Example: Deflection of Uncracked or Cracked Prestressed Beam</td>
<td>456</td>
</tr>
<tr>
<td>7.9.1</td>
<td>Fully Prestressed Beam – Uncracked under Full Service Load</td>
<td>457</td>
</tr>
<tr>
<td>7.9.2</td>
<td>Partially Prestressed Beam</td>
<td>459</td>
</tr>
<tr>
<td>7.10</td>
<td>Integrating the Modulus of Concrete into Time-Dependent Deflection Calculations</td>
<td>462</td>
</tr>
<tr>
<td>7.10.1</td>
<td>Age-Adjusted Effective Modulus</td>
<td>462</td>
</tr>
<tr>
<td>7.10.2</td>
<td>Equivalent Modulus</td>
<td>463</td>
</tr>
<tr>
<td>7.10.3</td>
<td>Equivalent Cyclic-Dependent Modulus</td>
<td>464</td>
</tr>
<tr>
<td>7.11</td>
<td>Long-Term Deflection by Incremental Time Steps</td>
<td>464</td>
</tr>
<tr>
<td>7.11.1</td>
<td>Theoretical Approach</td>
<td>464</td>
</tr>
<tr>
<td>7.11.2</td>
<td>Simplified C-Line Approach</td>
<td>465</td>
</tr>
<tr>
<td>7.12</td>
<td>Example: Time-Dependent Deflection Using the C-Line Approach and Comparisons</td>
<td>472</td>
</tr>
<tr>
<td>7.12.1</td>
<td>Standard Precast Prestressed Double-T Beam</td>
<td>472</td>
</tr>
<tr>
<td>7.12.2</td>
<td>Comparison of Long-Term Deflections Predicted from Different Methods</td>
<td>477</td>
</tr>
<tr>
<td>7.13</td>
<td>Time-Dependent Deflection Using C-Line Approach for Example 7.9.1</td>
<td>479</td>
</tr>
<tr>
<td>7.14</td>
<td>Deflection Control</td>
<td>481</td>
</tr>
<tr>
<td>7.15</td>
<td>Effective Moment of Inertia - Revisited</td>
<td>482</td>
</tr>
<tr>
<td>7.16</td>
<td>Concluding Remarks</td>
<td>484</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>485</td>
</tr>
<tr>
<td></td>
<td>Problems</td>
<td>486</td>
</tr>
</tbody>
</table>

### Chapter 8: Computation of Prestress Losses

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1</td>
<td>Sources of Loss of Prestress</td>
<td>491</td>
</tr>
<tr>
<td>8.2</td>
<td>Total Losses in Pretensioned Members</td>
<td>494</td>
</tr>
<tr>
<td>8.3</td>
<td>Total Losses in Posttensioned Members</td>
<td>497</td>
</tr>
<tr>
<td>8.4</td>
<td>Methods for Estimating Prestress Losses</td>
<td>498</td>
</tr>
<tr>
<td>8.5</td>
<td>Lump Sum Estimate of Total Loss</td>
<td>500</td>
</tr>
<tr>
<td>8.5.1</td>
<td>Background</td>
<td>500</td>
</tr>
<tr>
<td>8.5.2</td>
<td>Lump Sum Estimate of Time-Dependent Prestress Losses: AASHTO LRFD</td>
<td>501</td>
</tr>
<tr>
<td>8.5.2.1</td>
<td>Non Composite Members</td>
<td>501</td>
</tr>
<tr>
<td>8.5.2.2</td>
<td>Composite Members</td>
<td>505</td>
</tr>
<tr>
<td>8.5.2.3</td>
<td>Refined Estimate of Time Dependent Losses</td>
<td>506</td>
</tr>
<tr>
<td>8.6</td>
<td>Separate Lump Sum Estimate of Each Time-Dependent Loss</td>
<td>506</td>
</tr>
<tr>
<td>8.6.1</td>
<td>Total Loss Due to Shrinkage</td>
<td>507</td>
</tr>
<tr>
<td>8.6.2</td>
<td>Total Loss Due to Creep</td>
<td>507</td>
</tr>
</tbody>
</table>
Chapter 10  
Continuous Beams and Indeterminate Structures  

10.1 Advantages and Forms  
10.2 Necessary Analytical Background  
10.3 Sign Convention and Special Notation  
10.4 Secondary Moments and Zero-Load-C (ZLC) Line  
10.5 Example: Secondary Moments and Concordancy Property  
10.6 Linear Transformation  
10.7 Concordant Tendons  
10.8 External Loads Equivalent to Prestressing  
10.8.1 Concept of Equivalent Load  
10.8.2 Application of Equivalent Load to a Continuous Tendon  
10.8.3 Example: Equivalent Load  
10.8.4 Example: Equivalent Load for Circular and Parabolic Tendon Profile  
10.9 Prestressing Moment and Elastic Stresses  
10.9.1 Moment Due to Prestressing,  
10.9.2 Example: Prestressed Moments by the Equivalent Load Method  
10.9.3 Elastic Stresses in a Continuous Beam  
10.10 Design Aids  

References  
Problems
11.9.5 Deflection 745
11.10 Prestressed Flat Plates: Design for Flexure 745
11.10.1 Working Stress Design 745
11.10.2 Allowable Stresses 746
11.10.3 Ultimate Strength Design 747
11.10.4 Minimum Bonded Reinforcement 747
11.10.5 Integrity Tendons and Other Reinforcement 749
11.10.6 Nominal to Cracking Moment Condition 750
11.11 Flat Plates: Design for Shear 750
11.11.1 Concrete Shear Capacity 750
11.11.2 Transfer Moment Between Columns and Slab 753
11.11.3 Maximum Shear Stress in Critical Section 756
11.11.4 Design Tips 761
11.11.5 Shear Reinforcement 761
11.12 Deflection of Flat Plates 764
11.12.1 Elastic Solution 764
11.12.2 Equivalent Frame Approach 768
11.13 Summary of Design Steps for Two-Way Prestressed Flat Plates 771
11.14 Example: Design of a Two-Way Prestressed Flat Plate 772
11.15 Fiber Reinforcement for Punching Shear 790
References 791
Problems 794

Chapter 12  Analysis and Design of Tensile Members 797
12.1 Types of Tension Members 797
12.2 Advantages of Prestressed Concrete Tension Members 799
12.2.1 Example: Relative Deformation of Tension Members 800
12.3 Behavior of Prestressed Concrete Tension Members 801
12.4 Analysis of Tension Members 805
12.4.1 Service Stresses, Decompression, Cracking and Ultimate Load 805
12.4.2 Short- and Long-Term Deformations in Linear Members 809
12.4.3 Example: Analysis-Investigation of a Tension Member 811
12.5 Optimum Design of Tension Members 814
12.5.1 Formulation of Design Criteria 814
12.5.2 Design Approximations 819
12.5.3 Minimum Cost Solution 820
12.5.4 Example: Minimum Cost Design of Tensile Member 822
12.6 Circular Structures: Tanks and Pressure Vessels 824
12.6.1 Construction Methods 826
12.6.2 Analysis of Stresses 829
12.6.2.1 Ring Stresses 832
12.6.3 Wall Design 834
12.6.3.1 Design Criteria 834
12.6.3.2 Minimum Wall Thickness 835
12.6.3.3 Minimum Residual Prestress 836
12.6.3.4 Rapid Dimensioning of Wall Thickness and Prestressing 836
12.6.3.5 Radial Deflection 838
12.6.3.6 Additional Design Information 839
12.6.4 Example: Preliminary Design of Cylindrical Tank
Chapter 13  Analysis and Design of Compression Members  853

13.1  Types of Compression Members and Their Advantages  853
13.2  Behavior of Columns  857
   13.2.1  Load-Deformation Response  857
   13.2.2  Classification  858
   13.2.3  Load-Moment Interaction Diagram  858
   13.2.4  ACI Code Design Interaction Diagram  861
13.3  Analysis of Short Columns  863
   13.3.1  Assumptions  863
   13.3.2  Basic Equations for Fully Prestressed Square and Rectangular Sections  865
   13.3.3  Partially Prestressed Square or Rectangular Sections  867
   13.3.4  Circular Hollow-Core and I-Shaped Sections  869
13.4  Example: Column Load-Moment Interaction Diagram  872
13.5  ACI Code Provisions and Other Design Considerations  881
   13.5.1  Minimum Longitudinal Reinforcement  881
   13.5.2  Lateral or Transverse Reinforcement  881
   13.5.3  Minimum Size of Columns  884
   13.5.4  Minimum Eccentricity  884
   13.5.5  Transfer Zone  884
13.6  Slender Columns: Theoretical Background  885
   13.6.1  Critical Buckling Load  885
   13.6.2  Effective Slenderness Ratio  886
   13.6.3  Definition of Braced, Unbraced, Sway and Non-Sway Columns or Frames  887
   13.6.4  Single and Double Curvature  888
   13.6.5  Terminology and Definitions  888
   13.6.6  Flexural Rigidity Under Cracked Conditions for First-Order Frame Analysis  890
13.7  Slenderness Effects: ACI Code Philosophy  891
13.8  ACI Code Design Provisions for Slender Columns by the Moment Magnifier Method  894
   13.8.1  Sway and Non-Sway Conditions  894
   13.8.2  Effective Length Factor $k$  895
   13.8.3  Effective Slenderness Ratio and Slenderness Condition  897
   13.8.4  ACI Moment Magnifier Procedure for Non-Sway Frames  899
   13.8.5  ACI Moment Magnifier Procedure for Sway Frames with $22 < kl_r / r < 100$  901
   13.8.6  Additional Design Checks  905
   13.8.7  Design According to the PCI Committee on Columns  905
13.9  Example: Slender Column Using the PCI Approach  906
   13.9.1  Non-Sway or Braced Column  906
   13.9.2  Sway or Unbraced Column  911
13.10  Design Expedients and Design Aids  914
of Continuous Beams with Equal Spans 1000
14.9 Moments and Shears in Typical Girders 1004
14.10 Example: Composite Bridge with Cast-in-Place Reinforced Concrete Slab on Top of Prestressed I-Girders 1005
14.10.1 Live Load Moments and Shears at Critical Sections 1006
14.10.2 Detailed Design of Prestressed I Beams 1008
14.11 Example: Bridge Deck with Adjacent Precast Pretensioned Box Beams 1022
14.12 Example: Negative Live Load Moment in Two-Span Continuous Bridge Deck 1028
14.13 Slabs for Bridge Decks and Solid Slab Bridges 1031
14.13.1 Equivalent Strip Width for Slab Type Bridges and Distribution Factor for Slabs 1031
14.13.2 Minimum Depth and Clear Concrete Cover 1032
14.13.3 Cast-in-Place One-Way Prestressed Slabs 1032
14.13.4 Traditional Design of Reinforced Concrete Deck Slabs 1033
14.13.5 Empirical Design of Slabs 1034
14.13.6 Temperature and Shrinkage Reinforcement 1035
14.13.7 Moments for Slabs Supported on Four Sides 1036
14.14 Example: Design of a Cast-in-Place Posttensioned Slab Bridge 1036
14.15 Precast Bridge Beams Made Continuous by a Cast-in-Place RC Slab 1040
14.15.1 Example: Prestressed Bridge Beams Made Continuous by Cast-in-Place RC Slab 1042
14.16 Design Charts for Prestressed Bridge Beams 1046
14.17 Preliminary Design Tips for Dimensioning 1047
14.18 Other Design Considerations 1049
14.19 Bridge Engineering: Looking Ahead 1050
References 1053
Problems 1055

Chapter 15 Strut-and-Tie Modeling 1061
15.1 Introduction 1061
15.1.1 Background and Motivation 1061
15.1.2 B- and D-Regions 1062
15.1.3 Trusses and Strut-and-Tie Models 1065
15.1.4 ACI Code Definition 1066
15.2 Elements of Strut-and-Tie Models 1067
15.2.1 Assumptions 1068
15.2.2 Mechanical Requirements and Geometry Rules 1069
15.2.3 Requirements for Nodal Zones 1069
15.2.4 External and Unbonded Prestressing Tendons 1070
15.2.5 Terminology / Notation 1071
15.3 Design Steps to Build a Strut-and-Tie Model (STM) 1071
15.3.1 Initial Checks 1071
15.3.2 Design Steps 1072
15.4 Design Philosophy 1076
15.5 Design of Ties 1076
15.5.1 Prestressing Tendons 1077
15.6 Design of Struts 1078
15.7 Design of Nodal Zones 1081
15.7.1 Assumptions 1081
15.7.2 Dimensioning 1081
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.7.3 Anchorages</td>
<td>1082</td>
</tr>
<tr>
<td>15.7.4 Nominal Strength</td>
<td>1083</td>
</tr>
<tr>
<td>15.8 STM by AASHTO LRFD</td>
<td>1084</td>
</tr>
<tr>
<td>15.9 Anchorage Zones of Prestressed Members</td>
<td>1085</td>
</tr>
<tr>
<td>15.10 Example: Anchorage Zone Design by STM</td>
<td>1087</td>
</tr>
<tr>
<td>15.10.1 Two Spread-Out Anchorages</td>
<td>1088</td>
</tr>
<tr>
<td>15.10.2 Two Anchorages Placed Close to Each Other</td>
<td>1097</td>
</tr>
<tr>
<td>15.11 Dapped-End Beams</td>
<td>1098</td>
</tr>
<tr>
<td>15.12 Example: Dapped-End Beam Design by STM</td>
<td>1100</td>
</tr>
<tr>
<td>15.13 Examples of Applications of Strut-and-Tie Models to Various Structures</td>
<td>1107</td>
</tr>
<tr>
<td>15.14 Concluding Remarks</td>
<td>1113</td>
</tr>
<tr>
<td>References</td>
<td>1113</td>
</tr>
<tr>
<td>Problems</td>
<td>1115</td>
</tr>
</tbody>
</table>

**Appendix A** List of Symbols 1117

**Appendix B** Unit Conversions 1130

**Appendix C** Typical Post-Tensioning Systems 1133

**Appendix D** Answers to Selected Problems 1153

**Appendix E** Examples of Standard Precast / Prestressed Beams 1159

**INDEX** 1167