Fourth Edition

PRESTRESSED CONCRETE ANALYSIS AND DESIGN

Fundamentals

Antoine E. Naaman | Shih-Ho Chao

Antoine E. Naaman and Shih-Ho Chao **Fourth Edition**

PRESTRESSED CONCRETE ANALYSIS AND DESIGN: Fundamentals

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 developing the necessary critical thinking and training to tackle more complex problems with confidence.

This updated edition integrates the provisions of the 2019 ACI Building Code in text and examples; offers an extensive treatment of bridge analysis and design according to the 2020 AASHTO LRFD Specifications; includes a large number of logical design flow charts and detailed design examples; provides an extensive updated bibliography; includes an appendix with answers to study problems; uses consistent notation as well as consistent sign convention; and uses dual units (US and SI) for key equations and reference data. The book contains sufficient material to cover four targeted courses dealing with: a) prestressed concrete fundamentals and applications, b) advanced PC analysis and design, c) post-tensioned concrete structures (including continuous beams, one- and two-way slab systems and slabs on ground), and d) PC bridges. Unique topics addressed include slenderness effects in column, optimum design of water tanks, prestress losses by the time-steps procedure, anchorage design by strut-and-tie modeling, and design for shear and torsion. The material is presented in 16 chapters, with1432 pages, and more than 650 illustrations and photographs. Contents include:

Antoine E. Naaman, Professor Emeritus, University of Michigan, Ann Arbor, USA.
Shih-Ho Chao, Professor, University of Texas at Arlington, USA.

TECHNO PRESS 3000
5115 Flicker Field Circle
Sarasota, Florida 34231
USA
www.technopress3000.com

ISBN 978-0-9674939-5-4
90000>
9 780967 493954

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Antoine E. Naaman
Professor Emeritus
University of Michigan, Ann Arbor

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Professor
University of Texas at Arlington

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Publisher's Cataloging-In-Publication Data
(Prepared by The Donohue Group, Inc.)

Names: Naaman, Antoine E., author. | Chao, Shih-Ho, author.
Title: Prestressed concrete analysis and design : fundamentals / Antoine E. Naaman, Professor Emeritus, University of Michigan, Ann Arbor [and] Shih-Ho Chao, Professor, University of Texas at Arlington.
Description: 4th edition. | Sarasota, Florida, USA : Techno Press 3000, [2022] | Includes bibliographical references and index.
Identifiers: ISBN 9780967493954 (hardcover)
Subjects: LCSH: Prestressed concrete construction.
Classification: LCC TA683.9 .N3 2022 | DDC 624.1/83412--dc23

LCCN: Library of Congress Control Number: 2022907946

Copy editor: *Ingrid Naaman*
Cover design: *Allison Reich*

Prestressed Concrete Analysis and Design: Fundamentals – 4th Edition

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

Techno Press 3000
5115 Flicker Field Circle
Sarasota, Florida, 34231, USA
www.technopress3000.com

ISBN 978- 0-9674939-5-4

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PREFACE

PREFACE TO THE FOURTH EDITION

Although historically Prestressed Concrete has experienced a slower start than Reinforced Concrete and its development has followed a different path, it has evolved into a reliable technology and has established itself as a major structural material in par and in association with reinforced concrete and steel. Prestressed concrete, has made significant contributions to the precast manufacturing industry, the cement industry, and the construction industry as a whole. This has led to an enormous array of structural applications from bridges to nuclear power vessels, from buildings serving every use and occupancy to ships, and from lowly products, such as rail-road ties and piles, to monumental TV towers, and offshore petroleum platforms. Seldom is a major construction project planned today without prestressed concrete being considered as one of the viable alternative solutions. A careful analysis of future trends indicates a substantial increase in the use of prestressed concrete. This is also supported by developments in partially prestressed concrete, which integrates both reinforced and prestressed concrete and treats them as the extreme boundaries of the same system. It has become almost inevitable to consider each material separately without considering their combination. The term structural concrete is increasingly used to include both.

A similar trend is expected at the educational level. Design courses in prestressed concrete will be more widely offered at universities and may be moved from the list of technical electives to the list of required courses in structural engineering curricula, particularly those combining bachelor and master's degrees. It is also likely that reinforced and prestressed concrete will be offered as part of the same general course or course sequence on structural concrete, hence essentially covering partially prestressed (or partially reinforced) concrete.

On Codes for Buildings and Bridges. Unlike an analysis book, a design book must rely by necessity on existing codes for the treatment of examples. The two main U.S. codes for prestressed concrete structures are the ACI Building Code and the

AASHTO LRFD Bridge Design Specifications. These codes have become increasingly lengthy and complex, and undergo relatively frequent updates and changes. Since most computations in the design of large projects are conducted today using powerful software programs, both the ACI and AASHTO codes seem to have shied away from targeting simplicity and brevity in various specifications. Their growing bulk with each new edition is reflected in the length of this book, because, for every example, the related code provisions, exceptions, and limitations must be explained. For example, Chapter 14 on Bridges grew from 57 pages in the first edition of this book, in 1982, to 164 pages in this edition. There may be a time, not too far away, where a textbook will simply deal with the fundamentals and all examples will be treated using existing software programs. This stresses the need to keep the fundamentals as strong as possible, and is the key objective of this book, insuring an in-depth analytical basis necessary to handle any design situation or code provision. Design handbooks, professional guides and codes are not meant to cover the basics in such depth.

Audience and Educational Strategy. This book is written for advanced students, instructors and professionals. It is intended as a thorough teaching text, as well as a reference document for practicing engineers and researchers. It emphasizes the fundamental concepts of analysis and design of prestressed concrete structures and provides students with a sufficiently strong basis for handling everyday design problems, and tackling the more complex problems with confidence. A particular effort is made throughout to synthesize and condense the essential information and to give an overview of the directions in which the design is proceeding. Self-sufficient logical design flow charts summarizing the step-by-step design procedures and containing all necessary design equations are often presented. They reduce the burden of guesswork and iterative try-out encountered in the design process, and are essential when programmable calculators and computers are used. Important formulas and equations are also condensed in tables for ready use. To provide a correlation with reinforced concrete design and to help engineers already familiar with reinforced concrete, the case of partially prestressed (or partially reinforced) concrete is frequently addressed. An extensive selection of references is given at the end of each chapter. An attempt was made to include not only necessary readings but also most recent research conducted in the United States for up-to-date information. Specifications of the 2019 ACI building code and relevant requirements of the 2020 AASHTO LRFD Bridge Design Specifications are integrated in the text. When appropriate guidance is not available in the code, suggestions are made to accommodate the intent of the code. At occasions where the authors' opinion differs from that of the code, the difference is explained and defended.

Whenever possible, widely accepted symbols, such as those used in the ACI code, are adopted and all symbols used in the text are defined and summarized for easy reference in Appendix A. A consistent notation and sign convention is followed throughout, allowing rigorous treatments when needed. This is essential, for instance, in the case of continuous beams where the sign of secondary moments cannot be visualized *a priori* and must be derived from the analysis.

Because of the inevitable future conversion from U.S. customary units to the International System of Units (SI), all important tables, figures, and design information, as well as dimensionally inconsistent equations, are given in dual units. However, since the prestressed concrete industry in the US is not on the verge of change from U.S. customary units to SI units, all examples are treated in U.S. units to allow students and professionals to stay in tune with current practice. In addition, SI conversion factors and SI equivalents for some dimensionally inconsistent equations used in various flow charts are given in Appendix B.

Compared to the previous three editions, this edition is expanded to accommodate the new version of the 2019 ACI and 2020 AASHTO codes in text and examples. New Chapter 15 dealing with prestressed post-tensioned slabs-on-ground (PT-SOG) was added, and Chapter 16 on strut-and-tie modeling and design was updated and extended, allowing the use of this book for a full course targeted to post-tensioned concrete structures. This 4th edition incorporates a countless number of minute improvements based on more than four decades of teaching and research since the printing of the first edition, adding broader knowledge and technical wisdom to the material. Overall, more examples are given, numerous clarifications are provided, the number of figures and photographs has significantly increased, and, when relevant, remarks summarizing the authors' opinion that may differ from the codes, have been added.

Functional Organization. The text is organized into 16 chapters, which can be assembled according to their intended function:

- The first three chapters contain essential design information and reference data. They provide general background on materials properties, design philosophy, and codes.
- Chapters 4 to 8 develop the fundamental basis and underlying principles for the analysis and design of prestressed concrete members. They include analysis and design for flexure by the working stress design method with an introduction to optimum design (Chapter 4), analysis and design for flexure by the ultimate strength design (or load and resistance factor design) method with full coverage of partial prestressing (Chapter 5), design for shear and torsion and their combined effects with flexure (Chapter 6), design for deflection control with treatment of partially prestressed cracked sections and the incremental time-step method to predict long-term deflection (Chapter 7), and prediction of prestress losses either by lump sum estimates or by the accurate incremental time-step method (Chapter 8).
- Chapters 9 to 15 address the particular analysis and design aspects of structural elements or systems in various applications of prestressed concrete. They cover composite beams (Chapter 9), continuous beams (Chapter 10), one and two-way slab systems (Chapter 11), prismatic tensile members and cylindrical tanks

(Chapter 12), short and slender columns (Chapter 13), bridges (Chapter 14), and post-tensioned slabs-on-ground (Chapter 15).

- Chapter 16 on strut-and-tie modeling and design addresses a subject that is likely to be more extensively used in future codes and provides a research-oriented path to discontinuity regions and connections. In an advanced course, Chapter 16 could be presented following coverage of shear and torsion in Chapter 6.

Several appendixes are given at the end of the book, including a list of symbols (Appendix A), SI conversion factors (Appendix B), technical information on some post-tensioning systems including tendons and anchorages (Appendix C), answers to selected problems (Appendix D), and examples of precast-prestressed beams (Appendix E) taken from the PCI Handbook.

The material in the book is extensive and can cover up to two semester courses in prestressed concrete spanning from the senior undergraduate level to the advanced graduate level. It also contains sufficient material for a short course on bridge design using the AASHTO LRFD specifications, while several chapters can be used for a course on Post-Tensioned Concrete Structures. Tentative course outlines are suggested next.

Course 1, Part 1: Fundamentals of Prestressed Concrete

In a first course on prestressed concrete the authors recommend the following approach, assuming a semester-long course with 42 lectures of about one hour each:

- *Chapter 1,* introduction: Cover entirely in no more than two lectures.
- *Chapter 2* on materials for prestressing: Cover in less than two lectures; focus mainly on the properties of prestressing steels and their implication for design. Students can read the remaining material on their own as reading assignment and will refer back to these chapters when other topics are covered such as deflection, losses, columns, etc.
- *Chapter 3* on philosophy of design: Cover in about two lectures. Besides explaining the general philosophy of design as applied to prestressed concrete, explain curvature, the C-line or C-force concept, load-balancing concept, and how prestress losses are simply accommodated in preliminary design by using the factor η.
- *Chapters 4 to 7* on working stress analysis and design, ultimate strength analysis and design, design for shear and torsion, and computation of deflections: These chapters should be covered in depth to insure a strong basis in the fundamentals of prestressed concrete and prepare students for detailed design. Depending on time available, parts of certain chapters may be omitted. For instance, the design of anchorage zone in *Chapter 4* may be skipped. In *Chapters 5* and *6*, depending on time and audience, only the approach followed by ACI (or conversely by AASHTO) could be treated and the rest assigned as independent reading. In *Chapter 6*, omit the section on combined shear and torsion. In *Chapter 7*, the long-term deflection by

incremental time steps could be left out to a more advanced treatment. Devote eighteen to twenty lecture hours for *Chapters 4* to *7*.

- *Chapter 8* on prestress losses: At a minimum, cover prestress losses by the total lump-sum estimate of total losses; lump sum estimates of individual losses (including code recommended procedures) could be covered next, and losses by the time-step method could be treated only if time allows. Students involved in research may benefit greatly from the treatment of losses by the time-step method, because it involves a deeper understanding of material behavior (creep and shrinkage of concrete, relaxation of steel) and its implication on structural response. However, generally, most users are less interested in probing prestress losses beyond the minimum needed. For this reason it is suggested to leave the treatment of prestress losses to this later stage in the course. Also, it is recommended to leave the treatment of losses due to friction and anchorage set to a second course. Devote at most two hours to this chapter.

Course 1, Part 2: Applications

In a second part of a first course, analysis and design related to specific applications could be covered. The selection of topics should depend on the interest of the audience and available time. The following sequence is recommended in priority:

- *Chapter 9* on composite beams: Cover entirely in about four lecture hours.
- *Chapter 10* on statically indeterminate structures including continuous beams and one-way slabs; for a first course cover in two lecture hours.
- If time allows and based on students' interest: cover parts of *Chapter 11* on two-way slabs, or *Chapter 14* on bridges, or *Chapter 13* on columns.

Based on years of teaching, it has been the authors' experience that Parts 1 and 2 described above would amply cover a semester-long course on prestressed concrete, assuming time is allocated for one mid-term exam and a final exam. Note however, that in its present form, the book with 16 chapters easily provides sufficient material for two consecutive semester courses on prestressed concrete. Other course options include the following.

Course 2: Prestressed Post-Tensioned Concrete Structures

This course would invariably start with a quick coverage (reminder) of fundamentals taken from *Part 1* of *Course 1*, and then focus on post-tensioned concrete applications starting with One and Two-Ways Slab Systems (*Chapter 11* and review of *Chapter 10*), Post-Tensions Slabs-On-Ground (*Chapter 15*), Bridges (*Chapter 14*), and possibly Strut and Tie Modeling and Design (*Chapter 16*). Anchorage zone design (Chapter 4) and prestress losses due to friction and anchorage set (*Chapter 8*) should also be covered.

Course 3: Prestressed Concrete Bridges
This book contains sufficient material to cover a course on Prestressed Concrete Bridges; indeed, Chapter 14 on bridges, is supported by several sections in *Chapters 5, 6, 7, 8, 9,* and *16* explaining the AASHTO LRFD Bridge Design Specifications with related examples.

Course 4: Advanced Topics in Prestressed Concrete
The following material is suggested for a fourth, more advanced course on prestressed concrete (targeting doctoral students, instructors, and high-level professionals), as has been taught by the first author at the University of Michigan, assuming Course 1 as a prerequisite:

- *Chapter 10* on continuous beams: Cover entirely.
- *Chapter 11* on prestressed one- and two-way slab systems.
- *Book 2 – PPC*: "*Prestressed and Partially Prestressed Concrete*." This book is in progress, but its content could be amassed from research papers. Analysis and design of partially prestressed beams with either *bonded* or *unbonded* tendons in the elastic uncracked, elastic cracked, and ultimate limit state. Particular application to external prestressing with effect of eccentricity variation. Design for serviceability limit states, including fatigue, cracking, and short- and long-term deflections. Nonlinear analysis of prestressed and partially prestressed beams with both *bonded* and *unbonded* tendons; modeling material and sectional behavior (see also Section 2.4); pseudo-nonlinear analysis and compatibility analysis. Concept of ductility and design for minimum ductility. Optimum design concepts and applications to prestressed concrete. Potential use and implications for analysis and design, of prestressed fiber reinforced polymeric tendons. Introduction to earthquake-resistant design and detailing.
- *Chapter 12* on tensile members: Cover entirely and illustrate the application of optimum design to tensile members including walls of cylindrical tanks.
- *Chapter 13* on columns: if non-slender columns were covered in a first course, revisit this chapter with particular attention to slenderness effects in columns.
- *Chapter 16* on strut-and-tie modeling: After revisiting parts of Chapter 6 for shear and torsion, cover this chapter entirely.

Chapters or parts of chapters that were omitted during the first course, such as bridges, slabs-on-ground, anchorage zone design, prestress losses due to friction and anchorage set, and combined design for shear and torsion, could be covered during this forth course as well. Moreover, it is strongly recommended to assign a term project with some research orientation as a necessary requirement for this course.

In committing to the challenge of writing this book, the authors have attempted to synthesize and convey what they have learned and practically experienced in teaching and working with prestressed concrete over several decades. While they were particularly concerned by the length of this book, they hope that the reader will accept to trade-off length in favor of insuring that the fundamentals are preserved as a reference source and covered in depth, and in order to supplement information that cannot possibly be found in handbooks, professional guides or introductory primers on prestressed concrete. They believe that a current level of knowledge of any topic is only fully understood when a higher level has been attained and exploited. They sincerely hope that those who seek knowledge in this book will not be disappointed.

Antoine E. Naaman - Shih-Ho Chao

The Puente Sobre El Rio Bridge in Lerez, Spain, is a cable stayed bridge with a main span of 129 m (423 ft) and a prestressed concrete single box deck. (*Courtesy Carlos Fernandez Casado S.L.*).

ACKNOWLEDGMENTS

ACKNOWLEDGMENTS TO THE FOURTH EDITION

The acknowledgments to the first, second and third edition remain applicable but are not repeated here for brevity. Although the authors are the main driving force in a textbook writing project, an infinite number of minute tasks contribute to its final creation.

We are indebted to the many students who took our courses on prestressed concrete over almost five decades at the University of Michigan, the University of Illinois at Chicago, and the University of Texas at Arlington, and who have influenced the approach followed in this book by asking pertinent questions and pointing out needed clarification or improvements during course discussions. We are grateful to *Mehrdad Mehraein,* NHTB, Washington State, for his constructive comments on the current chapter on Bridges. The second author would like to extend his sincere appreciation to former students and post-doc who have helped with drawings in this edition: *KyoungSub Park*, *Carmen Diaz-Caneja Nieto*, *Ghassan Almasabha*, *Missagh Shamshiri*, *Bhupendra Acharya*, and *Rahul Rayavarapu*.

We further extend our gratitude to *Allison Reich* who developed the cover design with expert diligence, and *Ingrid Naaman* for editorial oversight throughout.

Material taken and/or adapted from the American Concrete Institute (ACI) Building Code, other ACI Recommended Practices, and the AASHTO LRFD Bridge Design Specifications appears frequently throughout the text. The courteous cooperation of ACI and AASHTO is gratefully acknowledged. Similarly organizations such as the Precast/Prestressed Concrete Institute (PCI) and the Post-Tensioning Institute (PTI) kindly provided photographs and other relevant clips.

Overall, we are particularly grateful to our above-mentioned universities for providing us an environment fostering excellence, and, to all our students who, by giving us the opportunity to teach, also gave us the opportunity to learn and develop.

Antoine E. Naaman and Shih-Ho Chao

The Chuncheon Grand Bridge (Chuncheondaegyo) in South Korea, completed in 2017, is a prestressed concrete cable-stayed bridge with two-spans of 100 meters each and a total length of 1,058 m (3,471 ft); it used an optimized deck with exterior stiffening girders made with an Ultra-High Performance Concrete (UHPC) with a design compressive strength of 180 MPa. *(courtesy Byung-Suk Kim, Korea Institute of Civil Engineering and Building Technology, Goyang, South Korea).*

The Yumekake Bridge in Nara, Japan, is a 3-span continuous extradosed prestressed concrete rigid frame bridge with a main span of 127 m (417 ft). The term "extrados" implies that the stay cables also serve as external prestressing tendons to the deck. *(Courtesy Hiroshi Akiyama, Zenitaka Corp., Japan)*