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Prestressed Concrete
A Fundamental Approach

预应力混凝土

[美] Edward G. Nawy 著
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PEARSON Education

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Edward G. Nawy
Prestressed Concrete: A Fundamental Approach, 5/E
ISBN: 0-131-49759-6

版贸核渝字 2005 第 114 号

图书在版编目(CIP)数据

预应力混凝土/(美)内伊(Nawy,E.G.)著;李英民缩编.—重庆:重庆大学出版社,2007.4
缩编国外精品教材
ISBN 978-7-5624-3827-4

Ⅰ.预... Ⅱ.①内...②李... Ⅲ.预应力混凝土—高等学校—教材—英文 Ⅳ.TU528.571

中国版本图书馆 CIP 数据核字(2006)第 106055 号

Prestressed Concrete: A Fundamental Approach
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出 版 者:重庆大学出版社 **地 址**:重庆市沙坪坝正街 174 号重庆大学(A 区)内
网 址:http://www.cqup.com.cn **邮 编**:400030
电 话:(023) 65102378 65105781 **传 真**:(023) 65103686 65105565
出 版 人:张鸽盛
责任编辑:刘秀娟 **版式设计**:刘秀娟
责任校对:夏 宇 **责任印制**:赵 晟
印 刷 者:重庆华林天美印务有限公司
发 行 者:全国新华书店经销
开 本:787×1092 1/16 **印张**:33.25 **字数**:982 千
版 次:2007 年 4 月第 1 版 2007 年 4 月第 1 次印刷
书 号:ISBN 978-7-5624-3827-4
印 数:1—3 000
定 价:45.00 元

缩编说明

本书详尽介绍了预应力混凝土的基本理论、设计方法及其在工程中的运用，可作为结构工程及相关专业高年级本科生及研究生教材，也是从事预应力混凝土领域科研人员的实用工具。

本书第1章介绍了预应力理论的发展历史和预应力的基本概念。第2章介绍钢筋、混凝土等预应力材料的性能，分析了预应力系统的组成，阐述了预应力作用原理。第3章着重分析了预应力混凝土构件的预应力损失，并讨论了预应力损失的影响。第4章讨论了预应力混凝土构件的抗弯设计方法。第5章重点介绍了预应力混凝土构件的抗剪和抗拉设计方法。第6章讨论了超静定结构中的预应力体系，通过对连续梁和桥梁中连续构件预应力作用机理的分析，给出了设计方法。第7章阐述了预应力构件中反拱、翘曲及裂缝产生的机理并给出了控制方法。第8章探讨了预应力柱和桩的设计方法以及细长柱中的二阶效应的影响。第9章介绍了施加预应力的双向板体系，对施工荷载下预应力板的屈服行为进行了深入的分析。第10章介绍了预应力构件之间的相互连接问题。

本书作者Edward G. Nawy是美国新泽西州州立大学土木与环境工程系教授，美国土木工程师学会（ASCE）和预应力混凝土协会（PCI）资深会员，美国混凝土协会（ACI）荣誉会员。Edward G. Nawy教授是预应力混凝土领域的专家，在混凝土领域和预应力混凝土领域发表过上百篇学术论文和专著，对混凝土和预应力混凝土学科的发展有着重大贡献。

李英民

2006年10月

ABOUT THE AUTHOR

Dr. EDWARD G. NAWY is a distinguished professor in the Department of Civil and Environmental Engineering at Rutgers. The State University of New Jersey, has been active in the ACI and PCI since 1959 and is internationally recognized for his extensive research work in the fields of reinforced and prestressed concrete, particularly in the areas of serviceability and crack control. Dr. Nawy's work has been published in technical journals worldwide (over 170 technical papers). He is the author of Simplified Reinforced Concrete (1986), Prestressed Concrete (3rd Ed., 2000), both published by Prentice Hall, High Strength High Concrete Construction Engineering Handbook (1998) published by CRC Press. He is recipient of several major awards, including the Henry L. Kennedy Award of the American Concrete Institute, is a licensed Professional Engineer in the States of New York, New Jersey, Pennsylvania, California and Florida, Evaluator for the Accreditation Board for Engineering and Technology (ABET), and has been a consultant in structural engineering throughout the United States.

PREFACE

Prestressed concrete is a widely used material in construction. Hence, graduates of every civil engineering program must have, as a minimum requirement, a basic understanding of the fundamentals of linear and circular prestressed concrete. The high technology advancements in the science of materials have made it possible to construct and assemble large-span systems such as cable-stayed bridges, segmental bridges, nuclear reactor vessels, and offshore oil drilling platforms—work impossible to undertake in the past.

Reinforced concrete's tensile strength is limited, while its compressive strength is extensive. Consequently, prestressing becomes essential in many applications in order to fully utilize that compressive strength and, through proper design, to eliminate or control cracking and deflection. Additionally, design of the members of a total structure is achieved only by trial and adjustment: assuming a section and then analyzing it. Hence, design and analysis are combined in this work in order to make it simpler for the student first introduced to the subject of prestressed concrete design.

This edition of the book revises the previous text so as to conform to the new ACI 318-05 Code and the International Building Code, IBC 2000-2003, for seismic design, stressing the strain limits approach, sometimes termed as the "unified method" in the code.

The text is the outgrowth of the author's lecture notes developed in teaching the subject at Rutgers University over the past 45 years and the experience accumulated over the years in teaching and research in the areas of reinforced and prestressed concrete inclusive of the Ph. D. level, and the consulting engineering and forensic work that the author has been engaged in over the years. The material is presented in such a manner that the student can become familiarized with the properties of plain concrete, both normal and high strength, and its components prior to embarking on the study of structural behavior. The book is uniquely different from other textbooks on the subject in that the major topics of material behavior, prestress loss, flexure, shear, and torsion are selfcontained and can be covered in one semester at the senior level and the graduate level. The in-depth discussions of these topics permit the advanced undergraduate and graduate student, as well as the design engineer to develop with minimum effort a profound understanding of fundamentals of prestressed concrete structural behavior and performance.

The concise discussion presented in Chapters 1 through 3 on basic principles, the historical development of prestressed concrete, the properties of constituent materials, the long-term basic behavior of such materials, and the evaluation of prestress losses should give an adequate introduction to the subject of prestressed concrete. They should also aid in developing fundamental knowledge regarding the reliability of performance of prestressed structures, a concept to which every engineering student should be exposed today.

Chapters 4 and 5 on flexure, shear, and torsion, with the step-by-step logic of trial and adjustment as well as the flowcharts shown, give the student and the engineer a basic understanding of both the service load and the limit state of load at failure, using the new ACI 318-05 Code requirements for ultimate load design, thereby producing a good feel for the reserve strength and safety factors inherent in the design expressions. Chapter 4 in this edition contains the latest design procedure with numerical examples for the design of end anchorages of post-tensioned members as required by the latest ACI and AASHTO codes.

An extensive Chapter 5 presents, with design examples, the provisions on torsion combined with shear and bending, which include a unified approach to the topic of torsion in reinforced and prestressed concrete members. SI Units examples are included in the text in addition to having equivalent SI conversions for the major steps of examples throughout the book. Additionally, a detailed theoretical discussion is presented on the mechanisms of shear and torsion, the various approaches to the torsional problem and the plastic concepts of the shear equilibrium and torsional equilibrium theories and their interaction. A totally new section is added on the strut-and-tie modeling of forces in deep beams and corbels, with detailed design examples as required by the latest ACI Code provisions.

Furthermore, inclusion in this edition of design examples is SI Units and a listing of the relevant equations in SI format extends the scope of the text to cover wider applications by the profession. In this manner, the student as well as the practicing engineer can avail themselves with the tools for using either the lb-in. (PI) system or the international (SI) system.

Chapter 6 on indeterminate prestressed concrete structures covers in detail continuous prestressed beams as well as portal frames, consistent with the increased use of continuous members in bridge structures. Numerous detailed examples illustrate the use of the basic concepts method, the C-line method and the balancing method presented in Chapter 1. Chapter 7 discusses in detail the design for camber, deflection, and crack control, considering both short- and long-term effects using three different approaches: the PCI multipliers method, the detailed incremental time steps method, and the approximate time steps method. A state-of-the-art discussion is presented, based on the author's work, of the evaluation and control of flexural cracking in partially prestressed beams. Several design examples are included in the discussion. Chapter 8 covers the proportioning of prestressed compression and tension members, including the buckling behavior and design of prestressed columns and piles and the P-Δ effect in the design of slender columns.

Chapter 9 presents a thorough analysis of the service load behavior and yield-line behavior of two-way action prestressed slabs and plates. The service load behavior utilizes, with extensive examples, the equivalent frame method of flexural design (analysis) and deflection evaluation. A detailed discussion is presented on the shear-moment transfer at column support section in two-way action prestressed concrete plates, and on deflection of two-way plates. Extensive coverage is presented of the yield-line failure mechanisms of all the usual combinations of loads on floor slabs and boundary conditions, including the design expressions for these various conditions. Chapter 10 on connections for prestressed concrete elements covers the design of connections for dapped-end beams, ledge beams, and bearing, in addition to the design of the beams and corbels presented in Chapter 5 on shear and torsion. It is revised to accommodate the new load and strength reduction factors required in the ACI 318-05 Code.

This book is also unique in that Chapter 11 gives a detailed account of the analysis and design of prestressed concrete tanks and their shell roofs. Presented are the basics of the membrane and bending theories of cylindrical shells for use in the design of prestressed concrete tanks for the various wall boundary conditions of fixed, semi-fixed, hinged, and sliding wall bases, as well as the incorporation of vertical prestressing, using wrapped wires as well as tendons. Chapter 11 also discusses the theory of axisymmetrical shells and domes that are used in the design of domed roofs for circular tanks.

The extensive Chapter 12 added to the previous edition, has been updated to accommodate the latest LRFD and Standard AASHTO 2003 specifications for the design of prestressed bridge deck girders for flexure, shear, torsion and serviceability, including the design of anchorage blocks. Extensive several examples are given using bulb-tees and box girder sections. It also includes the AASHTO requirements for truck and lane loadings and load combinations as stipulated both by the LRFD and the Standard specifications.

Chapter 13, dealing with the seismic design of prestressed precast structures in high seismicity zones has been updated based on the new ACI 318-05 and the International Building Code, IBC 2000-2003, on seismic design of reinforced and prestressed concrete structures. It contains several design examples and a detailed discussion of ductile moment-resistant connections in high-rise buildings and parking garages in high seismicity zones. A unique approach for the design of such ductile connections in precast beamcolumn joints in high-rise building structures was extended and updated to conform to the new load and strength reduction factors. It also contains examples of the design of shear walls and hybrid connections—all based on the state of the art in this field.

Selected photographs involving various areas of the structural behavior of concrete elements at failure are included in all the chapters. They are taken from research work conducted and published by the author with many of his M. S. and Ph. D. students at Rutgers University over the past four decades. Additionally, photographs of some major prestressed concrete "landmark" structures, are included throughout the book to illustrate the versatility of design in pretensioned and post-tensioned prestressed concrete. Appendices have also been included, with monograms and tables on standard properties, sections and charts of flexural and shear evaluation of sections, as well as representative tables for selecting sections such as PCI double-tees, PCI/AASHTO bulb tees, box girder and AASHTO standard sections for bridge decks. Conversion to SI metric units are included in the examples throughout most chapters of the book.

The topics of the book have been presented in as concise a manner as possible without sacrificing the need for instructional details. The major portions of the text can be used without difficulty in an advanced senior-level course as well as at the graduate level for any student who has had a prior course in reinforced concrete. The contents should also serves as a valuable guideline for the practicing engineer who has to keep abreast of the state-of-the-art in prestressed concrete and the latest provisions of the ACI 318-05 Building Code and PCI Standards , AASHTO 2003 Standards, and the International Building Code (IBC 2000-2003) , as well as the designer who seeks a concise treatment of the fundamentals of linear and circular prestressing.

ACKNOWLEDGEMENTS

Grateful acknowledgment is due to the American Concrete Institute, the Prestressed Concrete Institute and the Post-Tensioning Institute for their gracious support in permitting generous quotations from the ACI 318 and other relevant Codes and Reports and the numerous illustrations and tables from so many PCI and PTI publications. Special mention has to be made of the author' s original mentor, the late Professor A. L. L. Baker of London University' s Imperial College of Science, Technology and Medicine, who inspired him with the affection that he has developed for systems constructed of reinforced and prestressed concrete. Grateful acknowledgement is also made to the author' s many students, both undergraduate and graduate, who have had much to do with generating the writing of this book and to the many who assisted in his research activities over the past 45 years. Thanks are also due to the many professors who have been continuously using this textbook since 1988 in major universities in the United States and their valuable comments, and to the engineers worldwide who have adopted this book as a standard reference on the up-to-date analysis and design of prestressed concrete structures.

Acknowledgement is also made to the many experts who reviewed the manuscript of the first edition including Professors Carl E. Ekberg of Iowa State University, Thomas T. C. Hsu of the University of Houston, and A. Fattah Shaikh of the University of Wisconsin; Daniel P. Jenny of the PCI, Clifford L. Freyrmuth of the PTI, and Ib Falk Jorgensen, President, Jorgensen, Hendrikson and Close, Denver. For the third edition of this book, particular thanks are due to Professor Thomas Hsu for again reviewing the revised portions on torsional theory and examples and the shear LRFD section; Professor Alex Aswad of Pennsylvania State University at Harrisburg for his valuable input on precast shear walls in seismic regions; George Nasser, Editor-in-Chief, and Paul Johal. Research Director, both of the Precast/Prestressed Concrete Institute, for their support; Mr. Khalid Shawwaf, Vice President-Engineering, Dywidag Systems International, for his cooperation and advice; and to Dr. Robert E. Englekirk, President, Englekirk Consulting Engineers, and Visiting Professor at the University of California, Los Angeles and San Diego, for his extensive input, discussions and advice on the subject of ductile momentresisting frame connections in high sesimicity zones.

Thanks are also due to Professor A. Samer Ezeldin, formerly of Stevens Institute of Technology, and to Robert M. Nawy, BA, BS, MBA, Rutgers Engineering Class of 1983 who assisted in the work on the first edition of this book, and to Engineer Gregg Romano, MS

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Rutgers'99, for his contribution to last edition's Chapter 15 on the LRFD design of bridge deck structures. Grateful acknowledgement is also made to the Prentice Hall officers and staff: Marcia Horton, Vice president and Editorial Director, Vincent O'Brien, Executive Managing Editor, who both have given me continuous encouragement and support over the years; Managing Editor David A. George for his appreciated efforts in administering the production of the book, staff contact Dolores Mars for her help; and to Patty Donovan, Senior Project Coordinator, Pine Tree Composition, for commendable efforts in bringing to fruition this edition of the book. Grateful acknowledgement is made to former and present graduate students involved: Anand Bhatt, MS, Joe Davis, Ph. D. candidate, James Giancaspro, Ph. D., and last but not least, Mayrai Gindy, Ph. D., for her work on the manuscript.

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CONTENTS

1

BASIC CONCEPTS

1.1 INTRODUCTION

Concrete is strong in compression, but weak in tension: its tensile strength varies from 8 to 14 percent of its compressive strength. Due to such a low tensile capacity, flexural cracks develop at early stages of loading. In order to reduce or prevent such cracks from developing, a concentric or eccentric force is imposed in the longitudinal direction of the structural element. This force prevents the cracks from developing by eliminating or considerably reducing the tensile stresses at the critical midspan and support sections at service load, thereby raising the bending, shear, and torsional capacities of the sections. The sections are then able to behave elastically, and almost the full capacity of the concrete in compression can be efficiently utilized across the entire depth of the concrete sections when all loads act on the structure.

Such an imposed longitudinal force is called a *prestressing force*, i. e. , a compressive force that prestresses the sections along the span of the structural element prior to the application of the transverse gravity dead and live loads or transient horizontal live loads. The type of prestressing force involved, together with its magnitude, are determined mainly on the basis of the type of system to be constructed and the span length and slenderness desired. Since the prestressing force is applied longitudinally along or parallel to the axis of the member, the prestressing principle involved is commonly known as *linear* prestressing.

Circular prestressing, used in liquid containment tanks, pipes, and pressure reactor vessels, essentially follows the same basic principles as does linear prestressing. The circumferential hoop, or "hugging" stress on the cylindrical or spherical structure, neutralizes the tensile stresses at the outer fibers of the curvilinear surface caused by the internal contained pressure.

Figure 1. 1 illustrates, in a basic fashion, the prestressing action in both types of structural systems and the resulting stress response. In (a) , the individual concrete blocks act together as a beam due to the large compressive prestressing force P. Although it might appear that the blocks will slip and vertically simulate shear slip failure, in fact they will not because of the longitudinal force P. Similarly, the wooden staves in (c) might appear to be capable of separating as a result of

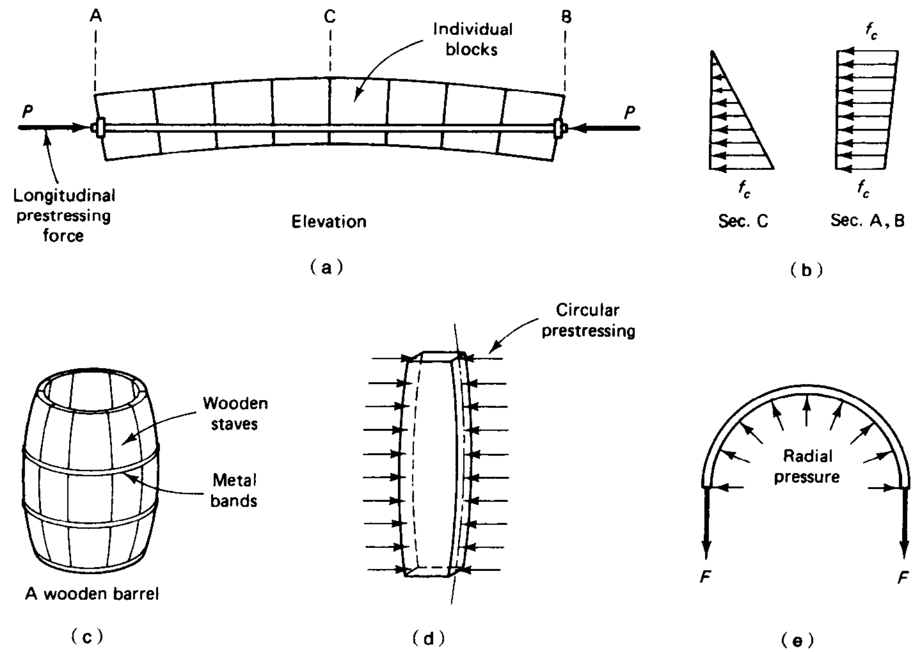

Figure 1.1 Prestressing principle in linear and circular prestressing. (a) Linear prestressing of a series of blocks to form a beam. (b) Compressive stress on midspan section C and end section A or B. (c) Circular prestressing of a wooden barrel by tensioning the metal bands. (d) Circular hoop prestress on one wooden stave. (e) Tensile force F on half of metal band due to internal pressure, to be balanced by circular hoop prestress.

the high internal radial pressure exerted on them. But again, because of the compressive prestress imposed by the metal bands as a form of circular prestressing, they will remain in place.

1.1.1 Comparison with Reinforced Concrete

From the preceding discussion, it is plain that permanent stresses in the prestressed structural member are created before the full dead and live loads are applied, in order to eliminate or considerably reduce the net tensile stresses caused by these loads. With reinforced concrete, it is assumed that the tensile strength of the concrete is negligible and disregarded. This is because the tensile forces resulting from the bending moments are resisted by the bond created in the reinforcement process. Cracking and deflection are therefore essentially irrecoverable in reinforced concrete once the member has reached its limit state at service load.

The reinforcement in the reinforced concrete member does not exert any force of its own on the member, contrary to the action of prestressing steel. The steel required to produce the prestressing force in the prestressed member actively preloads the member, permitting a relatively high controlled recovery of cracking and deflection. Once the flexural tensile strength of the concrete is exceeded, the prestressed member starts to act like a reinforced concrete element.

By controlling the amount of prestress, a structural system can be made either flexible or rigid