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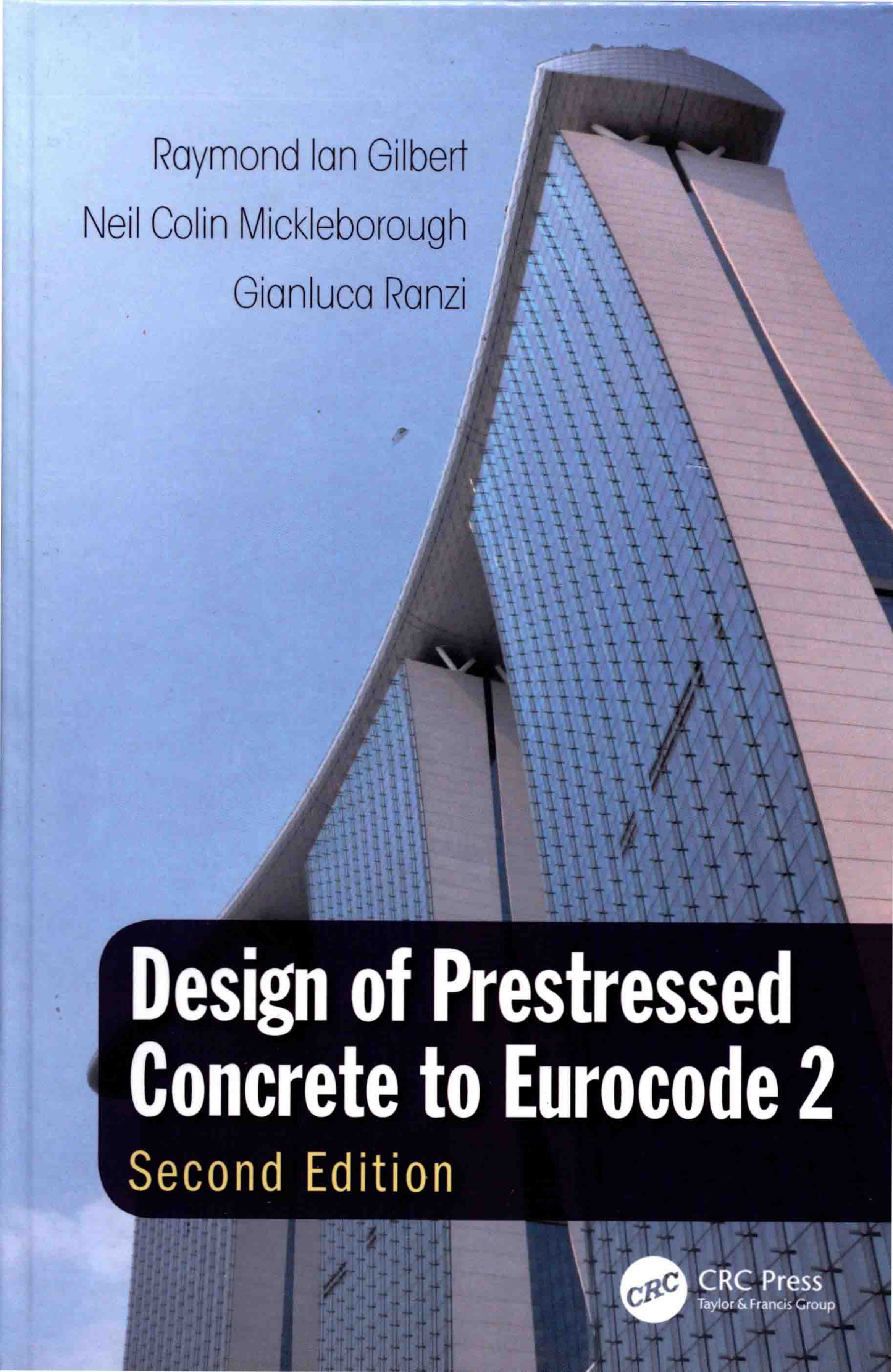

Design of Prestressed Concrete to Eurocode 2

Second Edition

CRC Press
Taylor & Francis Group

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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed on acid-free paper
Version Date: 20161209

International Standard Book Number-13: 978-1-4665-7310-9 (Hardback)
International Standard Book Number-13: 978-1-3153-8952-3 (eBook)

Library of Congress Cataloging-in-Publication Data

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

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FSC www.fsc.org FSC® C013604

Printed and bound by CPI Group (UK) Ltd, Croydon, CR0 4YY

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Preface

For the design of prestressed concrete structures, a sound understanding of structural behaviour at all stages of loading is essential. Also essential is a thorough knowledge of the design criteria specified in the relevant design standard, including the rules and requirements and the background to them. The aim of this book is to present a detailed description and explanation of the behaviour of prestressed concrete members and structures both at service loads and at ultimate loads and, in doing so, provide a comprehensive guide to structural design. Much of the text is based on first principles and relies only on the principles of mechanics and the properties of concrete and steel, with numerous worked examples. Where the design requirements are code specific, this book refers to the provisions of Eurocode 2 (EN 1992–1–1:2004) and other relevant EN Standards, and, where possible, the notation is the same as in the Eurocode. A companion edition in accordance with the requirements of the Australian Standard for Concrete Structures AS 3600–2009 is also available, with the same notation as in the Australian Standard.

The first edition of the book was published over 25 years ago, so a comprehensive update and revision is long overdue. This edition contains the most up-to-date and recent advances in the design of modern prestressed concrete structures, as well as the fundamental aspects of prestressed concrete behaviour and design that were well received in the first edition. The text is written for senior undergraduate and postgraduate students of civil and structural engineering and also for practising structural engineers. It retains the clear and concise explanations and the easy-to-read style of the first edition.

Between them, the authors have almost 100 years of experience in the teaching, research and design of prestressed concrete structures, and this book reflects this wealth of experience.

The scope of the work ranges from an introduction to the fundamentals of prestressed concrete to in-depth treatments of the more advanced topics in modern prestressed concrete structures. The basic concepts of prestressed concrete are introduced in Chapter 1, and the limit states design philosophies used in European practice are outlined in Chapter 2. The hardware required to pretension and post-tension concrete structures is introduced in Chapter 3, including some construction considerations. Material properties relevant to design are presented and discussed in Chapter 4. A comprehensive treatment of the design of prestressed concrete beams for serviceability is provided in Chapter 5. The instantaneous and time-dependent behaviour of cross-sections under service loads are discussed in considerable detail, and methods for the analysis of both uncracked and cracked cross-sections are considered. Techniques for determining the section size, the magnitude and eccentricity of prestress, the losses of prestress and the deflection of members are outlined. Each aspect of design is illustrated by numerical examples.

Chapters 6 and 7 deal with the design of members for strength in bending, shear and torsion, and Chapter 8 covers the design of the anchorage zones in both pretensioned and post-tensioned members. A guide to the design of composite prestressed concrete beams is provided in Chapter 9 and includes a detailed worked example of the analysis of a composite through girder footbridge. Chapter 10 discusses design procedures for statically determinate beams. Comprehensive self-contained design examples are provided for fully-prestressed and partially prestressed, post-tensioned and pretensioned concrete members.

The analysis and design of statically indeterminate beams and frames is covered in Chapter 11 and provides guidance on the treatment of secondary effects at all stages of loading. Chapter 12 provides a detailed discussion of the analysis and design of two-way slab systems, including aspects related to both strength and serviceability. Complete design examples are provided for panels of an edge-supported slab and a flat slab. The behaviour of axially loaded members is dealt with in Chapter 13. Compression members, members subjected to combined bending and compression, and prestressed concrete tension members are discussed, and design aspects are illustrated by examples. Guidelines for successful detailing of the structural elements and connections in prestressed concrete structures are outlined in Chapter 14.

As in the first edition, the book provides a unique focus on the treatment of serviceability aspects of design. Concrete structures are prestressed to improve behaviour at service loads and thereby increase the economical range of concrete as a construction material. In conventional prestressed structures, the level of prestress and the position of the tendons are usually based on considerations of serviceability. Practical methods for accounting for the non-linear and time-dependent effects of cracking, creep, shrinkage and relaxation are presented in a clear and easy-to-follow format.

The authors hope that *Design of Prestressed Concrete to Eurocode 2* will be a valuable source of information and a useful guide for students and practitioners of structural design.

Ian Gilbert
Neil Mickleborough
Gianluca Ranzi

Authors

Raymond Ian Gilbert is emeritus professor of civil engineering at the University of New South Wales (UNSW) and deputy director of the UNSW Centre for Infrastructure Engineering and Safety. He has more than 40 years of experience in structural design and is a specialist in the analysis and design of reinforced and prestressed concrete structures. Professor Gilbert has taught successive generations of civil engineering students in Australia on subjects related to structural engineering, ranging from statics and structural analysis to the design of reinforced and prestressed concrete structures. His research activities are in the field of concrete structures, with a particular interest in serviceability. Professor Gilbert has published six books, including *Structural Analysis: Principles, Methods and Modelling* and *Time-Dependent Behaviour of Concrete Structures* which are also published by CRC Press, and more than 350 technical papers and reports. He was awarded Honorary Life Membership of the Concrete Institute of Australia in 2011.

Neil Colin Mickleborough is professor of civil engineering and the director of the Center for Engineering Education Innovation at Hong Kong University of Science and Technology. He has been actively involved in the research, development and teaching of prestressed and reinforced concrete, structural analysis and tall building and bridge design in Australia, Asia and the Middle East for the past 30 years. He has acted as an expert design consultant on tall buildings and long-span bridge projects in both Dubai and Hong Kong. In addition, he is a chartered structural engineer and a Fellow of the Hong Kong Institution of Engineers.

Gianluca Ranzi is professor of civil engineering, ARC Future Fellow and director of the Centre for Advanced Structural Engineering at the University of Sydney. Gianluca's research interests range from the field of structural engineering, with focus on computational mechanics and the service behaviour of composite steel–concrete and concrete structures, to architectural science.

Acknowledgements

The authors acknowledge the support given by their respective institutions and by the following individuals and organisations for their assistance:

Mr Brian Lim (VSL International Limited, Hong Kong)
Mr Brett Gibbons (VSL Australia, Sydney)

Notation and sign convention

All symbols are also defined in the text where they first appear. Throughout the book we have assumed that tension is positive and compression is negative and that positive bending about a horizontal axis causes tension in the bottom fibres of a cross-section.

Latin upper-case letters

A	Cross-sectional area or accidental action
A_c	Cross-sectional area of concrete
$A_{c,eff}$	Effective area of concrete in tension surrounding the tendons with depth $h_{c,ef}$ equal to the lesser of $2.5(h\text{-}d)$, $(h\text{-}x)/3$ or $h/2$
A_{ct}	Area of the concrete in the tensile zone just before cracking
A_{c0}	Bearing area
A_{c1}	Largest area of the concrete supporting surface that is geometrically similar to and concentric with A_{c0}
A_g	Gross cross-sectional area
$\bar{A}_k$	Area of the age-adjusted transformed section at time t_k
A_p	Cross-sectional area of prestressing steel
$A_{p(i)}$	Cross-sectional area of the prestressing steel at the i-th level
A_{pc}	Cross-sectional area of the precast member
A_s	Cross-sectional area of non-prestressed steel reinforcement or cross-sectional area of a single bar being anchored
$A_{s(i)}$	Cross-sectional areas of non-prestressed steel reinforcement at the i-th level
A_{sb}	Area of transverse reinforcement in the end zone of a pretensioned member (Equation 8.6)
A_{sc}	Cross-sectional area of non-prestressed steel reinforcement in the compressive zone

A_{st}	Cross-sectional area of non-prestressed transverse steel reinforcement *or* cross-sectional area of non-prestressed reinforcement in the tension zone
$A_{s,min}$	The minimum area of bonded longitudinal reinforcement in the tensile zone (Equation 14.9) *or* minimum area of longitudinal reinforcement in a column (Equation 14.16)
A_{sw}	Cross-sectional area of the vertical legs of each stirrup *or* area of the single leg of transverse steel in each wall of the idealised thin-walled section in torsion
$A_{sw,max}$	Maximum cross-sectional area of shear reinforcement (Equations 7.13 and 7.14)
$A_{sw,min}$	Minimum cross-sectional area of shear reinforcement (Equation 7.17)
A_0	Area of the transformed section at time t_0
B_c	First moment of the concrete part of the cross-section about the reference axis
$\bar{B}_k$	First moment of the age-adjusted transformed section at time t_k
B_0	First moment of area of the transformed section about the reference axis at time t_0
C	Strength class of concrete *or* carry-over factor *or* Celsius
$\mathbf{D}_0$	Matrix of cross-sectional rigidities at time t_0 (Equation 5.42)
E (subscript)	Effect of actions
$E_{c,eff}(t, t_0)$, $E_{c,eff}$	Effective modulus of concrete at time t for concrete first loaded at t_0 (Equations 4.23 and 5.56)
$\bar{E}_{c,eff}(t, t_0)$, $\bar{E}_{c,eff}$	Age-adjusted effective modulus of concrete at time t for concrete first loaded at t_0 (Equations 4.25 and 5.57)
E_{cm}	Secant modulus of elasticity of concrete
$E_{cm,0}$	Secant modulus of elasticity of concrete at time t_0
E_p	Design value of modulus of elasticity of prestressing steel
$E_{p(i)}$	Design value of modulus of elasticity of the *i*-th level of prestressed steel
E_s	Design value of modulus of elasticity of reinforcing steel
$E_{s(i)}$	Design value of modulus of elasticity of the *i*-th level of non-prestressed steel
F_{bc}	Transverse compressive force due to bursting moment in a post-tensioned end block
F_{bt}	Transverse tensile force due to bursting in a post-tensioned end block (the bursting force)
F_c	Force carried by the concrete
F_{cc}	Compressive force carried by the concrete
F_{cd}	Design force carried by the concrete *or* design compressive force in a strut

F_{cdf}	Design force carried by the concrete flange (Equation 6.36)
F_{cdw}	Design force carried by the concrete web of a flanged beam (Equation 6.37)
$\bar{F}_{e,0}$	Age-adjusted creep factor (Equation 5.60)
F_{pt}	Tensile force carried by the prestressing steel
F_{ptd}	Design tensile force carried by the prestressing steel at the ultimate limit state
F_s	Force carried by non-prestressed steel reinforcement
F_{sc}	Force carried by non-prestressed compressive steel reinforcement
F_{sd}	Design force carried by non-prestressed steel reinforcement
F_{st}	Force carried by non-prestressed tensile steel reinforcement
F_t	Resultant tensile force carried by the steel reinforcement and tendons
$\mathbf{F}_k$	Matrix relating applied actions to strain at time t_k (Equation 5.102)
$\mathbf{F}_0$	Matrix relating applied actions to strain at time t_0 (Equation 5.46)
G	Permanent action
G_k	Characteristic permanent action
I	Second moment of area (moment of inertia) of the cross-section
I_{av}	Average second moment of area after cracking
I_c	Second moment of area of the concrete part of the cross-section about the reference axis
I_{cr}	Second moment of area of a cracked cross-section
I_{ef}	Effective second moment of area after cracking
I_g	Second moment of area of the gross cross-section
I_k	Second moment of area of the age-adjusted transformed section at time t_k
I_{uncr}	Second moment of area of the uncracked cross-section
I_0	Second moment of area of the transformed section about reference axis at time t_0
$J(t,t_0)$	Creep function at time t due to a sustained unit stress first applied at t_0
K	Slab system factor *or* factor that accounts for the position of the bars being anchored with respect to the transverse reinforcement (Figure 14.14)
L_{di}	Length of draw-in line adjacent to a live-end anchorage (Equation 5.150)
M	Bending moment
$\bar{M}$	Virtual moment
M_b	Bursting moment in a post-tensioned anchorage zone

$M_{c,0}$	Moment resisted by the concrete at time t_0
M_{cr}	Cracking moment
M_{Ed}	Design value of the applied internal bending moment
$M_{Ed.x}$, $M_{Ed.y}$	Design moments in a two-way slab spanning in the x- and y-directions, respectively
$M_{ext,0}$	Externally applied moment about reference axis at time t_0
$M_{ext,k}$	Externally applied moment about reference axis at time t_k
M_G	Moment caused by the permanent loads
M_{int}	Internal moment about reference axis
$M_{int,k}$	Internal moment about reference axis at time t_k
$M_{int,0}$	Internal moment about reference axis at time t_0
M_o	Total static moment in a two-way flat slab *or* decompression moment
M_Q	Moment caused by the live loads
M_{Rd}	Design moment resistance
M_s	Spalling moment in a post-tensioned anchorage zone
M_{sus}	Moment caused by the sustained loads
M_{sw}	Moment caused by the self-weight of a member
M_T	Moment caused by total service loads
M_u	Ultimate moment capacity
M_{var}	Moment caused by variable loads
M_0	Moment at a cross-section at transfer
N	Axial force
$N_{c,k}$	Axial forces resisted by the concrete at time t_k
$N_{c,0}$	Axial forces resisted by the concrete at time t_0
N_{Ed}	Design value of the applied axial force (tension or compression)
N_{ext}	Externally applied axial force
$N_{ext,k}$	Externally applied axial force at time t_k
$N_{ext,0}$	Externally applied axial force at time t_0
N_{int}	Internal axial force
$N_{int,k}$	Internal axial force at time t_k
$N_{int,0}$	Internal axial force at time t_0
$N_{p,k}$	Axial force resisted by the prestressing steel at time t_k
$N_{p,0}$	Axial force resisted by the prestressing steel at time t_0
N_{Rd}	Design axial resistance of a column
$N_{Rd,t}$	Design axial resistance of a tension member
$N_{s,k}$	Axial force resisted by the non-prestressed reinforcement at time t_k
$N_{s,0}$	Axial force resisted by the non-prestressed reinforcement at time t_0
P	Prestressing force; applied axial load in a column
P_h	Horizontal component of prestressing force
$P_{init\,(i)}$	Initial prestressing force at the i-th level of prestressing steel