

Analysis and Design of Steel and Composite Structures



CRC Press
Taylor & Francis Group

Qing Quan Liang

Analysis and Design of Steel and Composite Structures

Qing Quan Liang



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

© 2015 by Qing Quan Liang
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed on acid-free paper
Version Date: 20140707

International Standard Book Number-13: 978-0-415-53220-4 (Paperback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Library of Congress Cataloging-in-Publication Data

Liang, Qing Quan, 1965-
Analysis and design of steel and composite structures / Qing Quan Liang.
pages cm
Includes bibliographical references and index.
ISBN 978-0-415-53220-4 (paperback)
1. Building, Iron and steel. 2. Composite construction. I. Title.

TA684.L5176 2014
624.1'821--dc23

2014024460

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

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

This book is dedicated to the memory of my parents, Bo Fen Liang (1928–1981) and Xing Zi He (1936–1987), and to my wife, Xiao Dan Cai, and my sons, Samuel Zhi De Liang, Matthew Zhi Cheng Liang and John Zhi Guo Liang.

Preface

Steel and composite steel–concrete structures are widely used in modern bridges, buildings, sport stadia, towers and offshore structures. The analysis and design of steel and composite structures require a sound understanding of the behaviour of structural members and systems. This book provides an integrated and comprehensive introduction to the analysis and design of steel and composite structures. It describes the fundamental behaviour of steel and composite members and structures and the latest design criteria and procedures given in Australian Standards AS/NZS 1170, AS 4100, AS 2327.1, Eurocode 4 and AISC-LRFD specifications. The latest research findings on composite members by the author's research teams are also incorporated in the book. Emphasis is placed on a sound understanding of the fundamental behaviour and design principles of steel and composite members and connections. Numerous step-by-step examples are provided to illustrate the detailed analysis and design of steel and composite members and connections.

This book is an ideal course textbook on steel and composite structures for undergraduate and postgraduate students of structural and civil engineering, and it is a comprehensive and indispensable resource for practising structural and civil engineers and academic researchers.

Chapter 1 introduces the limit state design philosophy, the design process and material properties of steels and concrete. The estimation of design actions on steel and composite structures in accordance with AS/NZS 1170 is described in Chapter 2. Chapter 3 presents the local and post-local buckling behaviour of thin steel plates under in-plane actions, including compression, shear and bending of steel plates in contact with concrete. The design of steel members under bending is treated in Chapter 4, which includes the design for bending moments and the shear and bearing of webs to AS 4100. Chapter 5 is devoted to steel members under axial load and bending. The analysis and design of steel members under axial compression, axial tension and combined axial load and bending to AS 4100 are covered. In Chapter 6, the design of bolted and welded steel connections, including bolted moment end plate connections and pinned column base plate connections, is presented. Chapter 7 introduces the plastic analysis and design of steel beams and frames.

The behaviour and design of composite slabs for strength and serviceability to Eurocode 4 and Australian practice are treated in Chapter 8. Chapter 9 presents the behaviour and design of simply supported composite beams for strength and serviceability to AS 2327.1. The design method for continuous composite beams is also covered. The behaviour and design of short and slender composite columns under axial load and bending in accordance with Eurocode 4 are given in Chapter 10. This chapter also presents the nonlinear inelastic analysis of thin-walled concrete-filled steel tubular short and slender beam-columns under axial load and biaxial bending. Chapter 11 introduces the behaviour and design of composite

connections in accordance with AISC-LRFD specifications, including single-plate and tee shear connections, beam-to-composite column moment connections and semi-rigid composite connections.

Qing Quan Liang
Associate Professor
Victoria University
Melbourne, Victoria, Australia

Acknowledgements

The author thanks Professor Yeong-Bin Yang at National Taiwan University, Dr. Anne W. M. Ng at Victoria University in Melbourne, Benjamin Cheung, senior project engineer in Melbourne, and Associate Professor Yanglin Gong at Lakehead University for their invaluable and continued support. The author also thanks all his co-researchers for their contributions to the research work, particularly Associate Professor Muhammad N. S. Hadi at the University of Wollongong, Professor Brian Uy and Professor Mark A. Bradford at the University of New South Wales, Professor Yi-Min Xie at RMIT University, Emeritus Professor Grant P. Steven at the University of Sydney, Professor Jat-Yuen Richard Liew at the National University of Singapore, Emeritus Professor Howard D. Wright at the University of Strathclyde, Dr. Hamid R. Ronagh at the University of Queensland and Dr. Mostafa F. Hassanein and Dr. Omnia F. Kharoob at Tanta University. Thanks also go to Professor Jin-Guang Teng at The Hong Kong Polytechnic University, Professor Dennis Lam at the University of Bradford, Professor Ben Young at the University of Hong Kong, Professor Lin-Hai Han at Tsinghua University, Associate Professor Mario Attard and Professor Yong-Lin Pi and Dr. Sawekchai Tangaramvong at the University of New South Wales, Dr. Zora Vrcelj at Victoria University and Professor N. E. Shanmugam at the National University of Malaysia for their useful communications and support. Grateful acknowledgement is made to the author's former PhD student Dr. Vipulkumar I. Patel for his contributions to the research work on composite columns and to ME students Dr. Sukit Yindeesuk in the Department of Highways in Thailand and Hassan Nashid for their support. Finally, and most importantly, the author thanks his wife, Xiao Dan Cai, and sons, Samuel, Matthew and John, for their great encouragement, support and patience while he was writing this book.

Contents

| | |
|---|-----------|
| <i>Preface</i> | xvii |
| <i>Acknowledgements</i> | xix |
| 1 Introduction | 1 |
| 1.1 <i>Steel and composite structures</i> | 1 |
| 1.2 <i>Limit state design philosophy</i> | 3 |
| 1.2.1 <i>Basic concepts and design criteria</i> | 3 |
| 1.2.2 <i>Strength limit state</i> | 3 |
| 1.2.3 <i>Stability limit state</i> | 4 |
| 1.2.4 <i>Serviceability limit state</i> | 5 |
| 1.3 <i>Structural design process</i> | 5 |
| 1.4 <i>Material properties</i> | 7 |
| 1.4.1 <i>Structural steel</i> | 7 |
| 1.4.2 <i>Profiled steel</i> | 8 |
| 1.4.3 <i>Reinforcing steel</i> | 8 |
| 1.4.4 <i>Concrete</i> | 8 |
| 1.4.4.1 <i>Short-term properties</i> | 8 |
| 1.4.4.2 <i>Time-dependent properties</i> | 11 |
| <i>References</i> | 12 |
| 2 Design actions | 15 |
| 2.1 <i>Introduction</i> | 15 |
| 2.2 <i>Permanent actions</i> | 15 |
| 2.3 <i>Imposed actions</i> | 16 |
| 2.4 <i>Wind actions</i> | 17 |
| 2.4.1 <i>Determination of wind actions</i> | 17 |
| 2.4.2 <i>Regional wind speeds</i> | 19 |
| 2.4.3 <i>Site exposure multipliers</i> | 20 |
| 2.4.3.1 <i>Terrain/height multiplier ($M_{z,cat}$)</i> | 20 |
| 2.4.3.2 <i>Shielding multiplier (M_s)</i> | 20 |
| 2.4.3.3 <i>Topographic multiplier (M_t)</i> | 22 |
| 2.4.4 <i>Aerodynamic shape factor</i> | 22 |
| 2.4.4.1 <i>Calculation of aerodynamic shape factor</i> | 22 |
| 2.4.4.2 <i>Internal pressure coefficient</i> | 23 |

| | | |
|------------|--|----|
| 2.4.4.3 | External pressure coefficient | 23 |
| 2.4.4.4 | Area reduction factor | 24 |
| 2.4.4.5 | Combination factor | 24 |
| 2.4.4.6 | Local pressure factor | 24 |
| 2.4.4.7 | Permeable cladding reduction factor | 24 |
| 2.4.4.8 | Frictional drag coefficient | 24 |
| 2.4.5 | Dynamic response factor | 25 |
| 2.4.5.1 | General | 25 |
| 2.4.5.2 | Along-wind response | 25 |
| 2.4.5.3 | Crosswind response | 27 |
| 2.4.5.4 | Combination of long-wind and crosswind response | 28 |
| 2.5 | Combinations of actions | 28 |
| 2.5.1 | Combinations of actions for strength limit state | 28 |
| 2.5.2 | Combinations of actions for stability limit state | 28 |
| 2.5.3 | Combinations of actions for serviceability limit state | 29 |
| References | | 35 |

3 Local buckling of thin steel plates

37

| | | |
|---------|--|----|
| 3.1 | Introduction | 37 |
| 3.2 | Steel plates under uniform edge compression | 37 |
| 3.2.1 | Elastic local buckling | 37 |
| 3.2.1.1 | Simply supported steel plates | 37 |
| 3.2.1.2 | Steel plates free at one unloaded edge | 41 |
| 3.2.2 | Post-local buckling | 42 |
| 3.2.3 | Design of slender sections accounting for local buckling | 44 |
| 3.3 | Steel plates under in-plane bending | 48 |
| 3.3.1 | Elastic local buckling | 48 |
| 3.3.2 | Ultimate strength | 49 |
| 3.3.3 | Design of beam sections accounting for local buckling | 49 |
| 3.4 | Steel plates in shear | 52 |
| 3.4.1 | Elastic local buckling | 52 |
| 3.4.2 | Ultimate strength | 54 |
| 3.5 | Steel plates in bending and shear | 55 |
| 3.5.1 | Elastic local buckling | 55 |
| 3.5.2 | Ultimate strength | 55 |
| 3.6 | Steel plates in bearing | 56 |
| 3.6.1 | Elastic local buckling | 56 |
| 3.6.2 | Ultimate strength | 57 |
| 3.7 | Steel plates in concrete-filled steel tubular columns | 57 |
| 3.7.1 | Elastic local buckling | 57 |
| 3.7.2 | Post-local buckling | 61 |
| 3.8 | Double skin composite panels | 65 |
| 3.8.1 | Local buckling of plates under biaxial compression | 65 |
| 3.8.2 | Post-local buckling of plates under biaxial compression | 67 |

- 3.8.3 *Local buckling of plates under biaxial compression and shear* 67
- 3.8.4 *Post-local buckling of plates under biaxial compression and shear* 70

References 70

4 Steel members under bending

73

- 4.1 *Introduction* 73
 - 4.2 *Behaviour of steel members under bending* 73
 - 4.3 *Properties of thin-walled sections* 75
 - 4.3.1 *Centroids* 75
 - 4.3.2 *Second moment of area* 75
 - 4.3.3 *Torsional and warping constants* 75
 - 4.3.4 *Elastic section modulus* 77
 - 4.4 *Section moment capacity* 80
 - 4.5 *Member moment capacity* 81
 - 4.5.1 *Restraints* 81
 - 4.5.2 *Members with full lateral restraint* 82
 - 4.5.3 *Members without full lateral restraint* 84
 - 4.5.3.1 *Open sections with equal flanges* 84
 - 4.5.3.2 *I-sections with unequal flanges* 87
 - 4.5.4 *Design requirements for members under bending* 88
 - 4.6 *Shear capacity of webs* 92
 - 4.6.1 *Yield capacity of webs in shear* 92
 - 4.6.2 *Shear buckling capacity of webs* 94
 - 4.6.3 *Webs in combined shear and bending* 95
 - 4.6.4 *Transverse web stiffeners* 96
 - 4.6.5 *Longitudinal web stiffeners* 98
 - 4.7 *Bearing capacity of webs* 102
 - 4.7.1 *Yield capacity of webs in bearing* 102
 - 4.7.2 *Bearing buckling capacity of webs* 104
 - 4.7.3 *Webs in combined bearing and bending* 104
 - 4.7.4 *Load-bearing stiffeners* 105
 - 4.8 *Design for serviceability* 107
- References* 108

5 Steel members under axial load and bending

109

- 5.1 *Introduction* 109
- 5.2 *Members under axial compression* 109
 - 5.2.1 *Behaviour of members in axial compression* 109
 - 5.2.2 *Section capacity in axial compression* 110
 - 5.2.3 *Elastic buckling of compression members* 110
 - 5.2.4 *Member capacity in axial compression* 116
 - 5.2.5 *Laced and battened compression members* 119

| | | |
|-------|---|-----|
| 5.3 | <i>Members in axial tension</i> | 124 |
| 5.3.1 | <i>Behaviour of members in axial tension</i> | 124 |
| 5.3.2 | <i>Capacity of members in axial tension</i> | 124 |
| 5.4 | <i>Members under axial load and uniaxial bending</i> | 127 |
| 5.4.1 | <i>Behaviour of members under combined actions</i> | 127 |
| 5.4.2 | <i>Section moment capacity reduced by axial force</i> | 127 |
| 5.4.3 | <i>In-plane member capacity</i> | 130 |
| 5.4.4 | <i>Out-of-plane member capacity</i> | 131 |
| 5.5 | <i>Design of portal frame rafters and columns</i> | 133 |
| 5.5.1 | <i>Rafters</i> | 133 |
| 5.5.2 | <i>Portal frame columns</i> | 134 |
| 5.6 | <i>Members under axial load and biaxial bending</i> | 139 |
| 5.6.1 | <i>Section capacity under biaxial bending</i> | 139 |
| 5.6.2 | <i>Member capacity under biaxial bending</i> | 141 |
| | <i>References</i> | 146 |

6 Steel connections

149

| | | |
|---------|--|-----|
| 6.1 | <i>Introduction</i> | 149 |
| 6.2 | <i>Types of connections</i> | 149 |
| 6.3 | <i>Minimum design actions</i> | 152 |
| 6.4 | <i>Bolted connections</i> | 152 |
| 6.4.1 | <i>Types of bolts</i> | 152 |
| 6.4.2 | <i>Bolts in shear</i> | 153 |
| 6.4.3 | <i>Bolts in tension</i> | 155 |
| 6.4.4 | <i>Bolts in combined shear and tension</i> | 156 |
| 6.4.5 | <i>Ply in bearing</i> | 156 |
| 6.4.6 | <i>Design of bolt groups</i> | 157 |
| 6.4.6.1 | <i>Bolt groups under in-plane loading</i> | 157 |
| 6.4.6.2 | <i>Bolt groups under out-of-plane loading</i> | 159 |
| 6.5 | <i>Welded connections</i> | 161 |
| 6.5.1 | <i>Types of welds</i> | 161 |
| 6.5.2 | <i>Butt welds</i> | 161 |
| 6.5.3 | <i>Fillet welds</i> | 162 |
| 6.5.4 | <i>Weld groups</i> | 163 |
| 6.5.4.1 | <i>Weld group under in-plane actions</i> | 163 |
| 6.5.4.2 | <i>Weld group under out-of-plane actions</i> | 164 |
| 6.6 | <i>Bolted moment end plate connections</i> | 167 |
| 6.6.1 | <i>Design actions</i> | 167 |
| 6.6.1.1 | <i>Design actions for the design of bolts, end plates and stiffeners</i> | 167 |
| 6.6.1.2 | <i>Design actions for the design of flange and web welds</i> | 169 |
| 6.6.2 | <i>Design of bolts</i> | 170 |
| 6.6.3 | <i>Design of end plate</i> | 170 |
| 6.6.4 | <i>Design of beam-to-end-plate welds</i> | 171 |

- 6.6.5 *Design of column stiffeners* 173
 - 6.6.5.1 *Tension stiffeners* 173
 - 6.6.5.2 *Compression stiffeners* 175
 - 6.6.5.3 *Shear stiffeners* 175
 - 6.6.5.4 *Stiffened columns in tension flange region* 176
 - 6.6.5.5 *Stiffened columns in compression flange region* 177
- 6.6.6 *Geometric requirements* 177
- 6.7 *Pinned column base plate connections* 180
 - 6.7.1 *Connections under compression and shear* 181
 - 6.7.1.1 *Concrete bearing strength* 181
 - 6.7.1.2 *Base plates due to axial compression in columns* 181
 - 6.7.1.3 *Column to base plate welds* 183
 - 6.7.1.4 *Transfer of shear force* 183
 - 6.7.1.5 *Anchor bolts in shear* 184
 - 6.7.2 *Connections under tension and shear* 185
 - 6.7.2.1 *Base plates due to axial tension in columns* 185
 - 6.7.2.2 *Column to base plate welds* 186
 - 6.7.2.3 *Anchor bolts under axial tension* 186
 - 6.7.2.4 *Anchor bolts under tension and shear* 187

References 192

7 Plastic analysis of steel beams and frames 195

- 7.1 *Introduction* 195
- 7.2 *Simple plastic theory* 195
 - 7.2.1 *Plastic hinge* 195
 - 7.2.2 *Full plastic moment* 196
 - 7.2.3 *Effect of axial force* 200
 - 7.2.4 *Effect of shear force* 201
- 7.3 *Plastic analysis of steel beams* 202
 - 7.3.1 *Plastic collapse mechanisms* 202
 - 7.3.2 *Work equation* 202
 - 7.3.3 *Plastic analysis using the mechanism method* 204
- 7.4 *Plastic analysis of steel frames* 208
 - 7.4.1 *Fundamental theorems* 208
 - 7.4.2 *Method of combined mechanism* 208
- 7.5 *Plastic design to AS 4100* 213
 - 7.5.1 *Limitations on plastic design* 213
 - 7.5.2 *Section capacity under axial load and bending* 214
 - 7.5.3 *Slenderness limits* 214

References 215

8 Composite slabs 217

- 8.1 *Introduction* 217
- 8.2 *Components of composite slabs* 217
- 8.3 *Behaviour of composite slabs* 219

| | | |
|--------|--|-----|
| 8.4 | <i>Shear connection of composite slabs</i> | 219 |
| 8.4.1 | <i>Basic concepts</i> | 219 |
| 8.4.2 | <i>Strength of shear connection</i> | 219 |
| 8.4.3 | <i>Degree of shear connection</i> | 221 |
| 8.5 | <i>Moment capacity based on Eurocode 4</i> | 221 |
| 8.5.1 | <i>Complete shear connection with neutral axis above sheeting</i> | 221 |
| 8.5.2 | <i>Complete shear connection with neutral axis within sheeting</i> | 222 |
| 8.5.3 | <i>Partial shear connection</i> | 223 |
| 8.6 | <i>Moment capacity based on Australian practice</i> | 224 |
| 8.6.1 | <i>Positive moment capacity with complete shear connection</i> | 224 |
| 8.6.2 | <i>Positive moment capacity with partial shear connection</i> | 226 |
| 8.6.3 | <i>Minimum bending strength</i> | 228 |
| 8.6.4 | <i>Design for negative moments</i> | 230 |
| 8.7 | <i>Vertical shear capacity of composite slabs</i> | 232 |
| 8.7.1 | <i>Positive vertical shear capacity</i> | 232 |
| 8.7.2 | <i>Negative vertical shear capacity</i> | 233 |
| 8.7.3 | <i>Vertical shear capacity based on Eurocode 4</i> | 234 |
| 8.8 | <i>Longitudinal shear</i> | 234 |
| 8.9 | <i>Punching shear</i> | 235 |
| 8.10 | <i>Design considerations</i> | 235 |
| 8.10.1 | <i>Effective span</i> | 235 |
| 8.10.2 | <i>Potentially critical cross sections</i> | 235 |
| 8.10.3 | <i>Effects of propping</i> | 236 |
| 8.11 | <i>Design for serviceability</i> | 240 |
| 8.11.1 | <i>Crack control of composite slabs</i> | 240 |
| 8.11.2 | <i>Short-term deflections of composite slabs</i> | 241 |
| 8.11.3 | <i>Long-term deflections of composite slabs</i> | 242 |
| 8.11.4 | <i>Span-to-depth ratio for composite slabs</i> | 242 |
| | <i>References</i> | 249 |

9 Composite beams

251

| | | |
|-------|--|-----|
| 9.1 | <i>Introduction</i> | 251 |
| 9.2 | <i>Components of composite beams</i> | 251 |
| 9.3 | <i>Behaviour of composite beams</i> | 253 |
| 9.4 | <i>Effective sections</i> | 254 |
| 9.4.1 | <i>Effective width of concrete flange</i> | 254 |
| 9.4.2 | <i>Effective portion of steel beam section</i> | 256 |
| 9.5 | <i>Shear connection of composite beams</i> | 256 |
| 9.5.1 | <i>Basic concepts</i> | 256 |
| 9.5.2 | <i>Load-slip behaviour of shear connectors</i> | 258 |
| 9.5.3 | <i>Strength of shear connectors</i> | 258 |
| 9.5.4 | <i>Degree of shear connection</i> | 261 |
| 9.5.5 | <i>Detailing of shear connectors</i> | 262 |
| 9.6 | <i>Vertical shear capacity of composite beams</i> | 262 |
| 9.6.1 | <i>Vertical shear capacity ignoring concrete contribution</i> | 262 |
| 9.6.2 | <i>Vertical shear capacity considering concrete contribution</i> | 263 |

| | | |
|---------|---|-----|
| 9.7 | Design moment capacity for positive bending | 266 |
| 9.7.1 | Assumptions | 266 |
| 9.7.2 | Cross sections with $\gamma \leq 0.5$ and complete shear connection | 266 |
| 9.7.2.1 | Nominal moment capacity M_{bc} | 266 |
| 9.7.2.2 | Plastic neutral axis depth | 268 |
| 9.7.3 | Cross sections with $\gamma \leq 0.5$ and partial shear connection | 270 |
| 9.7.3.1 | Nominal moment capacity M_b | 270 |
| 9.7.3.2 | Depth of the first plastic neutral axis | 271 |
| 9.7.3.3 | Depth of the second plastic neutral axis | 271 |
| 9.7.4 | Cross sections with $\gamma = 1.0$ and complete shear connection | 272 |
| 9.7.4.1 | Nominal moment capacity M_{bfc} | 272 |
| 9.7.4.2 | Plastic neutral axis depth | 273 |
| 9.7.5 | Cross sections with $\gamma = 1.0$ and partial shear connection | 273 |
| 9.7.5.1 | Nominal moment capacity M_{bf} | 273 |
| 9.7.5.2 | Depth of the first plastic neutral axis | 274 |
| 9.7.5.3 | Depth of the second plastic neutral axis | 275 |
| 9.7.6 | Cross sections with $0.5 < \gamma \leq 1.0$ | 275 |
| 9.7.7 | Minimum degree of shear connection | 276 |
| 9.8 | Design moment capacity for negative bending | 281 |
| 9.8.1 | Design concepts | 281 |
| 9.8.2 | Key levels of longitudinal reinforcement | 282 |
| 9.8.2.1 | Maximum area of reinforcement | 282 |
| 9.8.2.2 | PNA located at the junction of the top flange and web | 283 |
| 9.8.2.3 | PNA located in the web | 283 |
| 9.8.2.4 | PNA located at the junction of the web and bottom flange | 283 |
| 9.8.2.5 | PNA located at the junction of the bottom flange and plate | 283 |
| 9.8.3 | Plastic neutral axis depth | 283 |
| 9.8.4 | Design negative moment capacity | 284 |
| 9.9 | Transfer of longitudinal shear in concrete slabs | 294 |
| 9.9.1 | Longitudinal shear surfaces | 294 |
| 9.9.2 | Design longitudinal shear force | 295 |
| 9.9.3 | Longitudinal shear capacity | 296 |
| 9.9.4 | Longitudinal shear reinforcement | 296 |
| 9.10 | Composite beams with precast hollow core slabs | 304 |
| 9.11 | Design for serviceability | 305 |
| 9.11.1 | Elastic section properties | 305 |
| 9.11.2 | Deflection components of composite beams | 307 |
| 9.11.3 | Deflections due to creep and shrinkage | 308 |
| 9.11.4 | Maximum stress in steel beam | 309 |
| | References | 313 |

10 Composite columns

317

| | | |
|--------|---|-----|
| 10.1 | Introduction | 317 |
| 10.2 | Behaviour and design of short composite columns | 318 |
| 10.2.1 | Behaviour of short composite columns | 318 |

| | | |
|-------------------|--|-----|
| 10.2.2 | <i>Short composite columns under axial compression</i> | 320 |
| 10.2.3 | <i>Short composite columns under axial load and uniaxial bending</i> | 321 |
| 10.2.3.1 | <i>General</i> | 321 |
| 10.2.3.2 | <i>Axial load–moment interaction diagram</i> | 322 |
| 10.3 | <i>Non-linear analysis of short composite columns</i> | 334 |
| 10.3.1 | <i>General</i> | 334 |
| 10.3.2 | <i>Fibre element method</i> | 334 |
| 10.3.3 | <i>Fibre strain calculations</i> | 334 |
| 10.3.4 | <i>Material constitutive models for structural steels</i> | 336 |
| 10.3.5 | <i>Material models for concrete in rectangular CFST columns</i> | 336 |
| 10.3.6 | <i>Material models for concrete in circular CFST columns</i> | 339 |
| 10.3.7 | <i>Modelling of local and post-local buckling</i> | 340 |
| 10.3.8 | <i>Stress resultants</i> | 342 |
| 10.3.9 | <i>Computational algorithms based on the secant method</i> | 342 |
| 10.3.9.1 | <i>Axial load–strain analysis</i> | 342 |
| 10.3.9.2 | <i>Moment–curvature analysis</i> | 343 |
| 10.3.9.3 | <i>Axial load–moment interaction diagrams</i> | 344 |
| 10.4 | <i>Behaviour and design of slender composite columns</i> | 347 |
| 10.4.1 | <i>Behaviour of slender composite columns</i> | 347 |
| 10.4.2 | <i>Relative slenderness and effective flexural stiffness</i> | 347 |
| 10.4.3 | <i>Concentrically loaded slender composite columns</i> | 348 |
| 10.4.4 | <i>Uniaxially loaded slender composite columns</i> | 350 |
| 10.4.4.1 | <i>Second-order effects</i> | 350 |
| 10.4.4.2 | <i>Design moment capacity</i> | 351 |
| 10.4.5 | <i>Biaxially loaded slender composite beam–columns</i> | 357 |
| 10.5 | <i>Non-linear analysis of slender composite columns</i> | 357 |
| 10.5.1 | <i>General</i> | 357 |
| 10.5.2 | <i>Modelling of load–deflection behaviour</i> | 358 |
| 10.5.3 | <i>Modelling of axial load–moment interaction diagrams</i> | 360 |
| 10.5.4 | <i>Numerical solution scheme based on Müller’s method</i> | 361 |
| 10.5.5 | <i>Composite columns with preload effects</i> | 364 |
| 10.5.5.1 | <i>General</i> | 364 |
| 10.5.5.2 | <i>Non-linear analysis of CFST columns with preload effects</i> | 364 |
| 10.5.5.3 | <i>Axially loaded CFST columns</i> | 364 |
| 10.5.5.4 | <i>Behaviour of CFST beam–columns with preload effects</i> | 365 |
| 10.5.6 | <i>Composite columns under cyclic loading</i> | 365 |
| 10.5.6.1 | <i>General</i> | 365 |
| 10.5.6.2 | <i>Cyclic material models for concrete</i> | 366 |
| 10.5.6.3 | <i>Cyclic material models for structural steels</i> | 368 |
| 10.5.6.4 | <i>Modelling of cyclic load–deflection responses</i> | 369 |
| <i>References</i> | | 371 |

11 Composite connections

377

- 11.1 *Introduction* 377
- 11.2 *Single-plate shear connections* 377

| | | |
|--------|---|-----|
| 11.2.1 | <i>Behaviour of single-plate connections</i> | 378 |
| 11.2.2 | <i>Design requirements</i> | 379 |
| 11.2.3 | <i>Design of bolts</i> | 379 |
| 11.2.4 | <i>Design of single plate</i> | 380 |
| 11.2.5 | <i>Design of welds</i> | 380 |
| 11.3 | <i>Tee shear connections</i> | 382 |
| 11.3.1 | <i>Behaviour of tee shear connections</i> | 383 |
| 11.3.2 | <i>Design of bolts</i> | 383 |
| 11.3.3 | <i>Design of tee stems</i> | 384 |
| 11.3.4 | <i>Design of tee flanges</i> | 384 |
| 11.3.5 | <i>Design of welds</i> | 384 |
| 11.3.6 | <i>Detailing requirements</i> | 385 |
| 11.4 | <i>Beam-to-CEC column moment connections</i> | 387 |
| 11.4.1 | <i>Behaviour of composite moment connections</i> | 388 |
| 11.4.2 | <i>Design actions</i> | 389 |
| 11.4.3 | <i>Effective width of connection</i> | 390 |
| 11.4.4 | <i>Vertical bearing capacity</i> | 391 |
| 11.4.5 | <i>Horizontal shear capacity</i> | 392 |
| 11.4.6 | <i>Detailing requirements</i> | 394 |
| | 11.4.6.1 <i>Horizontal column ties</i> | 394 |
| | 11.4.6.2 <i>Vertical column ties</i> | 394 |
| | 11.4.6.3 <i>Face-bearing plates</i> | 395 |
| | 11.4.6.4 <i>Steel beam flanges</i> | 395 |
| | 11.4.6.5 <i>Extended face-bearing plates and steel column</i> | 395 |
| 11.5 | <i>Beam-to-CFST column moment connections</i> | 400 |
| 11.5.1 | <i>Resultant forces in connection elements</i> | 400 |
| 11.5.2 | <i>Neutral axis depth</i> | 402 |
| 11.5.3 | <i>Shear capacity of steel beam web</i> | 402 |
| 11.5.4 | <i>Shear capacity of concrete</i> | 403 |
| 11.6 | <i>Semi-rigid connections</i> | 405 |
| 11.6.1 | <i>Behaviour of semi-rigid connections</i> | 406 |
| 11.6.2 | <i>Design moments at supports</i> | 406 |
| 11.6.3 | <i>Design of seat angle</i> | 406 |
| 11.6.4 | <i>Design of slab reinforcement</i> | 407 |
| 11.6.5 | <i>Design moment capacities of connection</i> | 407 |
| 11.6.6 | <i>Compatibility conditions</i> | 407 |
| 11.6.7 | <i>Design of web angles</i> | 408 |
| 11.6.8 | <i>Deflections of composite beams</i> | 408 |
| 11.6.9 | <i>Design procedure</i> | 409 |
| | <i>References</i> | 409 |

Notations

411

Index

431

Introduction

1.1 STEEL AND COMPOSITE STRUCTURES

Steel and composite steel–concrete structures are widely used in modern bridges, buildings, sport stadia, towers and offshore structures. According to their intended functions, buildings can be classified into industrial, residential, commercial and institutional buildings. A steel structure is composed of steel members joined together by bolted or welded connections, which may be in the form of a pin-connected truss or a rigid frame. In comparison with reinforced concrete structures, steel structures have the advantages of lightweight, large-span, high ductility and rapid construction. The rapid steel construction attributes to the fact that steel members and connection components can be prefabricated in a shop. As a result, significant savings in construction time and costs can be achieved. Perhaps, steel portal frames as depicted in Figure 1.1 are the most commonly used steel structures in industrial buildings. They are constructed by columns, roof rafters and bracings, which are joined together by knee, ridge and column base connections. The design of steel portal frames is treated in this book.

The advantages of the rapid and economical steel construction of multistorey buildings can only be utilised by composite steel–concrete structures, which are efficient and cost-effective structural systems. Composite structures are usually constructed by composite columns or steel columns and steel beams supporting composite slabs or concrete slabs. It is noted that steel is the most effective in carrying tension and concrete is the most effective in resisting compression. Composite members make the best use of the effective material properties of both steel and concrete. A composite beam is formed by attaching a concrete slab to the top flange of a steel beam as shown in Figure 1.2. By the composite action achieved by welding shear connectors to the top flange of the steel beam, the steel beam and the concrete slab works together as one structural member to resist design actions. In a composite beam under bending, the concrete slab is subjected to compression, while the steel beam is in tension, which utilises the effective material properties of both steel and concrete. The common types of composite columns include concrete encased composite columns, rectangular concrete-filled steel tubular columns and circular concrete-filled steel tubular columns as presented in Figure 1.3. High-strength composite columns have increasingly been used in high-rise composite buildings due to their high structural performance such as high strength and high stiffness. The fundamental behaviour and the state-of-the-art analysis and design of composite slabs, composite beams, composite columns and composite connections are covered in this book.

The design of steel and composite structures is driven by the limited material resources, environmental impacts and technological competition which demand lightweight, low-cost and high-performance structures. These demands require that structural designers must have a sound understanding of the fundamental behaviour of steel and composite