



# STRUCTURAL DESIGN FOR **FIRE SAFETY**

ANDREW H. BUCHANAN  
ANTHONY K. ABU

SECOND EDITION

WILEY



# **STRUCTURAL DESIGN FOR FIRE SAFETY**



# STRUCTURAL DESIGN FOR FIRE SAFETY

**Second Edition**

**Andrew H. Buchanan & Anthony K. Abu**  
*University of Canterbury, New Zealand*

**WILEY**

This edition first published 2017  
© 2017 John Wiley & Sons, Ltd

First Edition published in 2001

*Registered Office*

John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at [www.wiley.com](http://www.wiley.com).

The right of the author to be identified as the author of this work has been asserted in accordance with the Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. It is sold on the understanding that the publisher is not engaged in rendering professional services and neither the publisher nor the author shall be liable for damages arising herefrom. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

*Library of Congress Cataloging-in-Publication Data*

Names: Buchanan, Andrew Hamilton, 1948– author. | Abu, Anthony Kwabena, 1980– author.

Title: Structural design for fire safety / Andrew H. Buchanan, Anthony K. Abu.

Description: Second edition. | Chichester, West Sussex, United Kingdom : John Wiley & Sons Inc., 2017. |

Includes bibliographical references and index.

Identifiers: LCCN 2016032579 | ISBN 9780470972892 (cloth) | ISBN 9781118700396 (epub)

Subjects: LCSH: Building, Fireproof. | Structural engineering.

Classification: LCC TH1065 .B89 2017 | DDC 693.8/2–dc23

LC record available at <https://lccn.loc.gov/2016032579>

A catalogue record for this book is available from the British Library.

Cover image: AUSTRIA FIRE RETIREMENT HOME

(Media ID: 20080209000077529215)

Credit: EPA | Source: APA | Trans Ref: EGG03

Set in 10/12pt Times by SPi Global, Pondicherry, India

10 9 8 7 6 5 4 3 2 1

# Contents

<b>Preface</b>	<b>xv</b>
<b>List of Notations</b>	<b>xvi</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Objective and Target Audience	1
1.2 Fire Safety	2
1.3 Performance-based Design	2
1.3.1 <i>Fundamentals of Performance-based Design</i>	2
1.3.2 <i>Documentation and Quality Control</i>	4
1.3.3 <i>Risk Assessment</i>	4
1.4 Structural Fire Engineering	5
1.5 Purpose of this Book	5
1.6 Units	6
1.7 Organization of Chapters	6
<b>2 Fire Safety in Buildings</b>	<b>8</b>
2.1 Fire Safety Objectives	8
2.1.1 <i>Life Safety</i>	8
2.1.2 <i>Property Protection</i>	9
2.1.3 <i>Environmental Protection</i>	9
2.2 Process of Fire Development	9
2.2.1 <i>Fire Behaviour</i>	10
2.2.2 <i>Human Behaviour</i>	11
2.2.3 <i>Fire Detection</i>	12
2.2.4 <i>Active Control</i>	12
2.2.5 <i>Passive Control</i>	12
2.3 Conceptual Framework for Fire Safety	13
2.3.1 <i>Scenario Analysis</i>	13
2.3.2 <i>Quantitative Risk Assessment</i>	13
2.3.3 <i>Fire Safety Concepts Tree</i>	14

2.4	Fire Resistance	17
2.4.1	<i>Examples of Fire Resistance</i>	17
2.4.2	<i>Objectives for Fire Resistance</i>	19
2.4.3	<i>Fire Design Time</i>	20
2.4.4	<i>Trade-offs</i>	21
2.4.5	<i>Repairability and Reserviceability</i>	22
2.5	Controlling Fire Spread	22
2.5.1	<i>Fire Spread within Room of Origin</i>	22
2.5.2	<i>Fire Spread to Adjacent Rooms</i>	23
2.5.3	<i>Fire Spread to Other Storeys</i>	25
2.5.4	<i>Fire Spread to Other Buildings</i>	27
2.6	Building Construction for Fire Safety	29
2.6.1	<i>Fire during Construction and Alterations</i>	29
2.6.2	<i>Fire following Earthquake</i>	30
2.7	Assessment and Repair of Fire Damage	31
2.7.1	<i>Inspection</i>	32
2.7.2	<i>Steel</i>	32
2.7.3	<i>Concrete and Masonry</i>	33
2.7.4	<i>Timber</i>	33
<b>3</b>	<b>Fires and Heat</b>	<b>35</b>
3.1	Fires in General	35
3.2	Combustion	37
3.3	Fire Initiation	39
3.3.1	<i>Sources and Mechanisms</i>	39
3.3.2	<i>Pilot Ignition and Auto-ignition</i>	39
3.3.3	<i>Flame Spread</i>	39
3.4	Pre-flashover Fires	40
3.4.1	<i>Burning Items in Open Air</i>	40
3.4.2	<i>Burning Items in Rooms</i>	42
3.4.3	<i>t-Squared Fires</i>	44
3.4.4	<i>Fire Spread to Other Items</i>	46
3.4.5	<i>Pre-flashover Fire Calculations</i>	46
3.5	Flashover	48
3.5.1	<i>Conditions Necessary for Flashover</i>	48
3.6	Post-flashover Fires	49
3.6.1	<i>Ventilation Controlled Burning</i>	49
3.6.2	<i>Fuel Controlled Burning</i>	53
3.6.3	<i>Fire Temperatures</i>	54
3.6.4	<i>Computer Models</i>	58
3.7	Design Fires	60
3.7.1	<i>Hand Methods</i>	60
3.7.2	<i>Published Curves</i>	61
3.7.3	<i>Eurocode Parametric Fires</i>	62



---

3.8	Other Factors	66
3.8.1	<i>Additional Ventilation Openings</i>	66
3.8.2	<i>Progressive Burning</i>	66
3.8.3	<i>Localized Fires</i>	69
3.9	Heat Transfer	69
3.9.1	<i>Conduction</i>	69
3.9.2	<i>Convection</i>	72
3.9.3	<i>Radiation</i>	72
3.9.4	<i>Design Charts for Fire Resistance Calculation</i>	74
3.10	Worked Examples	75
<b>4</b>	<b>Fire Severity and Fire Resistance</b>	<b>84</b>
4.1	Providing Fire Resistance	84
4.1.1	<i>Background</i>	84
4.1.2	<i>Fire Exposure Models</i>	88
4.1.3	<i>Design Combinations</i>	89
4.2	Fire Severity	89
4.3	Equivalent Fire Severity	90
4.3.1	<i>Equal Area Concept</i>	90
4.3.2	<i>Maximum Temperature Concept</i>	91
4.3.3	<i>Minimum Load Capacity Concept</i>	92
4.3.4	<i>Time Equivalent Formulae</i>	92
4.4	Fire Resistance	95
4.4.1	<i>Definition</i>	95
4.4.2	<i>Assessing Fire Resistance</i>	95
4.5	Fire Resistance Tests	96
4.5.1	<i>Standards</i>	96
4.5.2	<i>Test Equipment</i>	97
4.5.3	<i>Failure Criteria</i>	97
4.5.4	<i>Standard of Construction</i>	101
4.5.5	<i>Furnace Pressure</i>	101
4.5.6	<i>Applied Loads</i>	101
4.5.7	<i>Restraint and Continuity</i>	102
4.5.8	<i>Small-scale Furnaces</i>	103
4.6	Specifying Fire Resistance	103
4.6.1	<i>Approved Fire Resistance Ratings</i>	103
4.6.2	<i>Fire Resistance by Calculation</i>	104
4.7	Fire Resistance of Assemblies	107
4.7.1	<i>Walls</i>	107
4.7.2	<i>Floors</i>	108
4.7.3	<i>Beams</i>	108
4.7.4	<i>Columns</i>	108
4.7.5	<i>Penetrations</i>	109
4.7.6	<i>Junctions and Gaps</i>	110

4.7.7	<i>Seismic Gaps</i>	110
4.7.8	<i>Fire Doors</i>	110
4.7.9	<i>Ducts</i>	111
4.7.10	<i>Glass</i>	112
4.7.11	<i>Historical Buildings</i>	112
4.8	Worked Examples	113
<b>5</b>	<b>Design of Structures Exposed to Fire</b>	<b>115</b>
5.1	Structural Design at Normal Temperatures	115
5.2	Loads	116
5.2.1	<i>Types of Load</i>	116
5.2.2	<i>Load Combinations</i>	116
5.2.3	<i>Structural Analysis</i>	116
5.2.4	<i>Non-linear Analysis</i>	117
5.2.5	<i>Design Format</i>	117
5.2.6	<i>Working Stress Design Format</i>	118
5.2.7	<i>Ultimate Strength Design Format</i>	119
5.2.8	<i>Material Properties</i>	120
5.2.9	<i>Probability of Failure</i>	121
5.3	Structural Design in Fire Conditions	122
5.3.1	<i>Design Equation</i>	123
5.3.2	<i>Loads for Fire Design</i>	124
5.3.3	<i>Structural Analysis for Fire Design</i>	125
5.4	Material Properties in Fire	126
5.4.1	<i>Testing Regimes</i>	126
5.4.2	<i>Components of Strain</i>	127
5.5	Design of Individual Members Exposed to Fire	130
5.5.1	<i>Tension Members</i>	130
5.5.2	<i>Compression Members</i>	130
5.5.3	<i>Beams</i>	131
5.6	Design of Structural Assemblies Exposed to Fire	135
5.6.1	<i>Frames</i>	135
5.6.2	<i>Redundancy</i>	135
5.6.3	<i>Disproportionate Collapse</i>	136
5.6.4	<i>Continuity</i>	136
5.6.5	<i>Plastic Design</i>	142
5.6.6	<i>Axial Restraint</i>	143
5.6.7	<i>After-fire Stability</i>	149
5.7	Worked Examples	149
<b>6</b>	<b>Steel Structures</b>	<b>154</b>
6.1	Behaviour of Steel Structures in Fire	154
6.1.1	<i>Structural Steel Design Process</i>	155

---

6.2	Steel Temperature Prediction	157
6.2.1	<i>Fire Exposure</i>	157
6.2.2	<i>Calculation Methods</i>	158
6.2.3	<i>Section Factor</i>	158
6.2.4	<i>Thermal Properties</i>	159
6.2.5	<i>Temperature Calculation for Unprotected Steelwork</i>	161
6.2.6	<i>Temperature Calculation for Protected Steelwork</i>	163
6.2.7	<i>Typical Steel Temperatures</i>	164
6.2.8	<i>Temperature Calculation for External Steelwork</i>	165
6.3	Protection Systems	166
6.3.1	<i>Concrete Encasement</i>	167
6.3.2	<i>Board Systems</i>	167
6.3.3	<i>Spray-on Systems</i>	169
6.3.4	<i>Intumescent Paint</i>	169
6.3.5	<i>Protection with Timber</i>	170
6.3.6	<i>Concrete Filling</i>	170
6.3.7	<i>Water Filling</i>	171
6.3.8	<i>Flame Shields</i>	171
6.4	Mechanical Properties of Steel at Elevated Temperature	171
6.4.1	<i>Components of Strain</i>	171
6.4.2	<i>Thermal Strain</i>	172
6.4.3	<i>Creep Strain</i>	173
6.4.4	<i>Stress-related Strain</i>	174
6.4.5	<i>Proof Strength and Yield Strength</i>	174
6.4.6	<i>Design Values</i>	175
6.4.7	<i>Modulus of Elasticity</i>	178
6.4.8	<i>Residual Stresses</i>	179
6.5	Design of Steel Members Exposed to Fire	179
6.5.1	<i>Design Methods</i>	179
6.5.2	<i>Design of Steel Tensile Members</i>	180
6.5.3	<i>Design of Simply Supported Steel Beams</i>	181
6.5.4	<i>Lateral-torsional Buckling</i>	184
6.5.5	<i>Design for Shear</i>	184
6.5.6	<i>Continuous Steel Beams</i>	185
6.5.7	<i>Steel Columns</i>	186
6.6	Bolted and Welded Connections	187
6.7	Cast-iron Members	188
6.8	Design of Steel Buildings Exposed to Fire	188
6.9	Worked Examples	188
<b>7</b>	<b>Concrete Structures</b>	<b>195</b>
7.1	Behaviour of Concrete Structures in Fire	195
7.2	Concrete Materials in Fire	196
7.2.1	<i>Normal Weight Concrete</i>	196

7.2.2	<i>High Strength Concrete</i>	196
7.2.3	<i>Lightweight Concrete</i>	198
7.2.4	<i>Steel-fibre Reinforced Concrete</i>	199
7.2.5	<i>Masonry</i>	199
7.2.6	<i>Prestressed Concrete</i>	199
7.2.7	<i>External Reinforcing</i>	200
7.3	Spalling of Cover Concrete	201
7.3.1	<i>Cover</i>	201
7.3.2	<i>Spalling</i>	201
7.4	Concrete and Steel Reinforcing Temperatures	202
7.4.1	<i>Fire Exposure</i>	202
7.4.2	<i>Calculation Methods</i>	202
7.4.3	<i>Thermal Properties</i>	204
7.5	Mechanical Properties of Concrete at Elevated Temperatures	207
7.5.1	<i>Test Methods</i>	207
7.5.2	<i>Components of Strain</i>	207
7.5.3	<i>Thermal Strain</i>	208
7.5.4	<i>Creep Strain and Transient Strain</i>	209
7.5.5	<i>Stress Related Strain</i>	209
7.6	Design of Concrete Members Exposed to Fire	213
7.6.1	<i>Member Design</i>	215
7.6.2	<i>Simply Supported Concrete Slabs and Beams</i>	215
7.6.3	<i>Shear Strength</i>	217
7.6.4	<i>Continuous Slabs and Beams</i>	218
7.6.5	<i>Axial Restraint</i>	220
7.6.6	<i>Reinforced Concrete Columns</i>	223
7.6.7	<i>Reinforced Concrete Walls</i>	223
7.6.8	<i>Reinforced Concrete Frames</i>	224
7.7	Worked Examples	224
<b>8</b>	<b>Composite Structures</b>	<b>234</b>
8.1	Fire Resistance of Composite Elements	234
8.2	Assessing Fire Resistance	237
8.2.1	<i>Tabulated Data for Beams and Columns</i>	237
8.2.2	<i>Simple Calculation Methods</i>	237
8.2.3	<i>Advanced Calculation Methods</i>	238
8.3	Behaviour and Design of Individual Composite Members in Fire	238
8.3.1	<i>Composite Slabs</i>	238
8.3.2	<i>Composite Beams</i>	240
8.3.3	<i>Composite Columns</i>	243
8.4	Design of Steel and Composite Buildings Exposed to Fire	248
8.4.1	<i>Multi-storey Steel Frame Buildings</i>	248
8.4.2	<i>Car Parking Buildings</i>	251
8.4.3	<i>Single-storey Portal Frame Buildings</i>	252
8.5	Worked Example	255

<b>9</b>	<b>Timber Structures</b>	<b>257</b>
9.1	Description of Timber Construction	257
9.1.1	<i>Heavy Timber Construction</i>	257
9.1.2	<i>Laminated Timber</i>	258
9.1.3	<i>Behaviour of Timber Structures in Fire</i>	259
9.1.4	<i>Fire Resistance Ratings</i>	260
9.1.5	<i>Fire Retardant Treatments</i>	261
9.2	Wood Temperatures	261
9.2.1	<i>Temperatures Below the Char</i>	262
9.2.2	<i>Thermal Properties of Wood</i>	262
9.3	Mechanical Properties of Wood	264
9.3.1	<i>Mechanical Properties of Wood at Normal Temperatures</i>	264
9.3.2	<i>Mechanical Properties of Wood at Elevated Temperatures</i>	266
9.4	Charring Rate	273
9.4.1	<i>Overview of Charring</i>	273
9.4.2	<i>Corner Rounding</i>	275
9.4.3	<i>Charring Rate of Protected Timber</i>	276
9.4.4	<i>Effect of Heated Wood Below the Char Line</i>	277
9.4.5	<i>Design for Realistic Fires</i>	279
9.5	Design for Fire Resistance of Heavy Timber Members	280
9.5.1	<i>Design Concepts</i>	280
9.5.2	<i>Timber Beams</i>	280
9.5.3	<i>Timber Tensile Members</i>	283
9.5.4	<i>Timber Columns</i>	283
9.5.5	<i>Empirical Equations</i>	284
9.5.6	<i>Timber Beam-columns</i>	285
9.5.7	<i>Timber Decking</i>	286
9.5.8	<i>Hollow Core Timber Floors</i>	288
9.5.9	<i>Timber-concrete Composite Floors</i>	288
9.5.10	<i>Cross Laminated Timber</i>	288
9.5.11	<i>Reinforced Glulam Timber</i>	289
9.5.12	<i>Post-tensioned Timber Structures</i>	289
9.6	Timber Connections in Fire	290
9.6.1	<i>Geometry of Timber Connections</i>	291
9.6.2	<i>Steel Dowel-type Fasteners</i>	292
9.6.3	<i>Connections with Side Members of Wood</i>	293
9.6.4	<i>Connections with External Steel Plates</i>	295
9.6.5	<i>Glued Timber Connections</i>	296
9.7	Worked Examples	297
<b>10</b>	<b>Light Frame Construction</b>	<b>301</b>
10.1	Summary of Light Frame Construction	301
10.2	Gypsum Plaster Board	304
10.2.1	<i>Manufacture</i>	304

---

10.2.2	<i>Types of Gypsum Board</i>	305
10.2.3	<i>Chemistry</i>	306
10.2.4	<i>Thermal Properties</i>	306
10.2.5	<i>Fire Resistance</i>	306
10.2.6	<i>Ablation</i>	308
10.2.7	<i>Cavity Insulation</i>	308
10.3	<b>Fire Behaviour</b>	309
10.3.1	<i>Walls</i>	310
10.3.2	<i>Floors</i>	310
10.3.3	<i>Buildings</i>	310
10.4	<b>Fire Resistance Ratings</b>	311
10.4.1	<i>Failure Criteria</i>	311
10.4.2	<i>Listings</i>	312
10.4.3	<i>Generic Ratings</i>	312
10.4.4	<i>Proprietary Ratings</i>	312
10.4.5	<i>Typical Fire Resistance Ratings</i>	312
10.4.6	<i>Fire Severity</i>	313
10.5	<b>Design for Separating Function</b>	314
10.5.1	<i>Temperatures Within Light Frame Assemblies</i>	314
10.5.2	<i>Insulation</i>	315
10.5.3	<i>Component Additive Methods</i>	316
10.5.4	<i>Finite Element Calculations</i>	317
10.6	<b>Design for Load-bearing Capacity</b>	318
10.6.1	<i>Verification Methods</i>	318
10.6.2	<i>Calculation Methods</i>	318
10.6.3	<i>Onset of Char Method</i>	318
10.6.4	<i>Fire Test Performance</i>	319
10.6.5	<i>Timber Stud Walls</i>	320
10.6.6	<i>Calculation of Structural Performance</i>	320
10.6.7	<i>Buckling of Studs</i>	322
10.6.8	<i>End Restraint</i>	323
10.6.9	<i>Steam Softening</i>	324
10.6.10	<i>Finite Element Calculation Methods</i>	324
10.7	<b>Steel Stud Walls</b>	325
10.7.1	<i>Design of Steel Stud Walls</i>	325
10.8	<b>Timber Joist Floors</b>	327
10.9	<b>Timber Trusses</b>	328
10.10	<b>Construction Details</b>	329
10.10.1	<i>Number of Layers</i>	329
10.10.2	<i>Fixing of Sheets</i>	329
10.10.3	<i>Resilient Channels</i>	331
10.10.4	<i>Penetrations</i>	332
10.10.5	<i>Party Walls</i>	333
10.10.6	<i>Fire Stopping, Junctions</i>	334
10.10.7	<i>Conflicting Requirements</i>	335

10.11	Lightweight Sandwich Panels	335
	10.11.1 Description	335
	10.11.2 Structural Behaviour	335
	10.11.3 Fire Behaviour	336
	10.11.4 Fire Resistance	337
	10.11.5 Design	339
<b>11</b>	<b>Advanced Calculation Methods</b>	<b>340</b>
11.1	Types of Advanced Calculation Methods	340
11.2	Fire Models	341
	11.2.1 Plume Models	342
	11.2.2 Zone Models	342
	11.2.3 CFD Models	343
	11.2.4 Post-flashover Fire Models	343
11.3	Thermal Response Models	344
	11.3.1 Test Data and Simple Calculation Methods	344
	11.3.2 Thermal Modelling with Advanced Calculation Methods	344
11.4	Advanced Structural Models	348
11.5	Advanced Hand Calculation Methods	349
	11.5.1 Steel-concrete Composite Floors	349
	11.5.2 Tensile Membrane Action	349
	11.5.3 The Membrane Action Method	350
	11.5.4 The Slab Panel Method	353
	11.5.5 Failure Mechanisms of Composite Slabs	353
11.6	Finite Element Methods for Advanced Structural Calculations	355
	11.6.1 Structural Behaviour Under Fire Conditions	355
	11.6.2 Finite Element Analysis Under Fire Conditions	358
	11.6.3 Material Properties	359
	11.6.4 Structural Properties	364
11.7	Software Packages for Structural and Thermal Fire Analysis	369
	11.7.1 Generic Software Packages	369
	11.7.2 Specific Structural Fire Engineering Software	370
<b>12</b>	<b>Design Recommendations</b>	<b>371</b>
12.1	Summary of Main Points	371
	12.1.1 Fire Exposure	371
	12.1.2 Fire Resistance	372
12.2	Summary for Main Materials	372
	12.2.1 Structural Steel	372
	12.2.2 Reinforced Concrete	373
	12.2.3 Steel-concrete Composite Construction	374
	12.2.4 Heavy Timber	374
	12.2.5 Light Frame Construction	375
12.3	Thermal Analysis	375
12.4	Conclusions	376

<b>Appendix A: Units and Conversion Factors</b>	<b>377</b>
<b>Appendix B: Section Factors for Steel Beams</b>	<b>381</b>
<b>References</b>	<b>394</b>
<b>Index</b>	<b>411</b>



# Preface

Fires in buildings have always been a threat to human life and property. The threat increases as larger numbers of people live and work in bigger buildings throughout the world. Professor Buchanan's interest in structural fire engineering was initiated by Professor Brady Williamson in the 1970s at the University of California at Berkeley, and developed during his subsequent career as a practising structural engineer, then as an academic. Dr Abu was introduced to the subject by Professor Ian Burgess and Professor Roger Plank at the University of Sheffield in 2004, and has since worked with a number of consultants in the field.

New Zealand became one of the first countries to adopt a performance-based building code in the late 1980s, stimulating a demand for qualified fire engineers. This led to the establishment of a Master's Degree in Fire Engineering at the University of Canterbury, where one of the core courses is structural fire engineering, now taught by Dr Abu. The lecture notes for that course have grown into this book. Many masters and PhD students have conducted research which has contributed to our knowledge of fire safety, and much of that is reported here.

Professor Buchanan and Dr Abu have both been involved in many problems of fire safety and fire resistance, designing fire resisting components for buildings, assisting manufacturers of fire protecting materials, and serving on national fire safety committees.

Preparation of this book would not have been possible without the help of many people. We wish to thank Charley Fleischmann, Michael Spearpoint, Peter Moss, Rajesh Dhakal and other colleagues in the Department of Civil and Natural Resources Engineering at the University of Canterbury, and a large number of graduate students.

Many people provided helpful comments on the text, figures, and underlying concepts, especially Philip Xie, Melody Callahan, and a large number of friends and colleagues in the international structural fire engineering community.

This book is only a beginning; the problem of fire safety is very old and will not go away. We hope that this book helps to encourage rational improvements to structural fire safety in buildings throughout the world.

The second edition has been a long time coming because of devastating earthquakes in Christchurch and other unforeseen difficulties. We hope that it has been worth the wait.

Andrew H. Buchanan and Anthony K. Abu  
*University of Canterbury, New Zealand*

# List of Notations

$\alpha$	Fire intensity coefficient	MW/s <sup>2</sup>
$\alpha$	Thermal diffusivity	m <sup>2</sup> /s
$\alpha$	Ratio of hot wood strength to cold wood strength	
$\alpha_h$	Horizontal openings ratio	
$\alpha_v$	Vertical openings ratio	
$\beta$	Target reliability	
$\beta$	Measured charring rate	mm/min
$\beta_1$	Effective charring rate if corner rounding ignored	mm/min
$\beta_n$	Nominal charring rate	mm/min
$\beta_{par}$	Charring rate for parametric fire exposure	mm/min
$\delta$	Beam deflection	mm
$\Delta$	Deflection	mm
$\Delta_L$	Maximum permitted displacement	mm
$\Delta_0$	Mid-span deflection of the reference specimen	mm
$\chi$	Buckling factor	
$\varepsilon$	Strain	
$\varepsilon_i$	Initial strain	
$\varepsilon_\sigma$	Stress-related strain	
$\varepsilon_{cr}$	Creep strain	
$\varepsilon_{th}$	Thermal strain	
$\varepsilon_{tr}$	Transient strain	
$\varepsilon$	Resultant emissivity	
$\varepsilon_e$	Emissivity of the emitting surface	
$\varepsilon_r$	Emissivity of the receiving surface	
$\phi$	Configuration factor	
$\Phi$	Strength reduction factor	
$\Phi_f$	Strength reduction factor for fire design	
$k$	Elastic curvature	1/m
$\gamma_M$	Partial safety factor for material	
$\gamma_G$	Partial safety factor for dead load	
$\gamma_Q$	Partial safety factor for live load	

$\eta$	Temperature ratio	
$\theta$	Plastic hinge rotation	rad
$\theta$	Radiating angle	rad
$\rho$	Density	kg/m <sup>3</sup>
$\sigma$	Stefan–Boltzmann constant	kW/m <sup>2</sup> K <sup>4</sup>
$\sigma$	Stress	MPa
$\nu_p$	Regression rate	m/s
$\xi$	Reduction coefficient for charring of decks	
$a$	Depth of heat affected zone below char layer	mm
$a$	Depth of rectangular stress block	mm
$a$	Distance of the maximum positive moment from the support	m
$a_f$	Depth of stress block, reduced by fire	mm
$a_{fi}$	Thickness of wood protection to connections	mm
$A$	Cross-sectional area	mm <sup>2</sup> , m <sup>2</sup>
$A_f$	Floor area of room	m <sup>2</sup>
$A_{fi}$	Area of member, reduced by fire	mm <sup>2</sup> , m <sup>2</sup>
$A_{fuel}$	Exposed surface area of burning fuel	m <sup>2</sup>
$A_h$	Area of horizontal ceiling opening	m <sup>2</sup>
$A_1$	Area of radiating surface 1	m <sup>2</sup>
$A_r$	Cross-sectional area reduced by fire	mm <sup>2</sup> , m <sup>2</sup>
$A_s$	Area of reinforcing steel	mm <sup>2</sup>
$A_t$	Total internal surface area of room	m <sup>2</sup>
$A_w$	Window area	m <sup>2</sup>
$b$	Breadth of beam	mm
$b_f$	Breadth of beam reduced by fire	mm
$b$	$\sqrt{\text{Thermal inertia}} = \sqrt{(k\rho c_p)}$	Ws <sup>0.5</sup> /m <sup>2</sup> K
$b_v$	Vertical opening factor	
$B$	Breadth of window opening	m
$c$	Thickness of char layer	mm
$c_p$	Specific heat	J/kg K
$c_v$	Concrete cover to reinforcing	mm
$C$	Compressive force	kN
$C$	Contraction	mm
$d$	Depth of beam, effective depth of concrete beam	mm
$d$	Thickness of timber deck	mm
$d$	Diameter of circular column or width of square column	mm
$d_f$	Depth of beam reduced by fire	mm
$d_i$	Thickness of insulation	mm
$D$	Length of short side of compartment	m
$D$	Deflection	mm
$D$	Thickness of slab of burning wood	m
$D_b$	Reinforcing bar diameter	mm
$e$	Eccentricity	mm
$e_f$	Fuel load energy density (per unit floor area)	MJ/m <sup>2</sup>
$e_t$	Fuel load energy density (per unit area of internal room surfaces)	MJ/m <sup>2</sup>
$E$	Modulus of elasticity	GPa
$E$	Total energy contained in fuel	MJ

$E_k$	Characteristic earthquake load	
$f$	Factor in concrete-filled steel column equation	
$f$	Stress	MPa
$f^m$	Calculated stress in member	MPa
$f_t^m$	Calculated tensile stress for working stress design	MPa
$f_a$	Allowable design stress for working stress design	MPa
$f_b$	Characteristic flexural strength	MPa
$f_{b,f}$	Characteristic flexural strength in fire conditions	MPa
$f_c$	Crushing strength of the material	MPa
$f_c^*$	Characteristic compressive strength	MPa
$f_{c,T}^*$	Compressive strength at elevated temperature	MPa
$f_t^*$	Characteristic tensile strength	MPa
$f_{tv}$	Long term allowable tensile strength	MPa
$f_{t,f}^*$	Characteristic tensile strength in fire conditions	MPa
$f_y$	Yield strength at 20 °C	MPa
$f_{y,T}$	Yield strength at elevated temperature	MPa
$F$	Surface area of unit length of steel	m <sup>2</sup>
$F_c$	Crushing load of column	kN
$F_{crit}$	Critical buckling load of column	kN
$F_v$	Ventilation factor ( $A_v\sqrt{H_v/A_t}$ )	m <sup>0.5</sup>
$g$	Acceleration of gravity	m/s <sup>2</sup>
$g$	Char parameter	
$G$	Dead load	
$G_k$	Characteristic dead load	
$h$	Slab thickness	mm
$h$	Initial height of test specimen	mm
$h$	Height from mid-height of window to ceiling	m
$h_c$	Convective heat transfer coefficient	W/m <sup>2</sup> K
$h_r$	Radiative heat transfer coefficient	W/m <sup>2</sup> K
$h_t$	Total heat transfer coefficient	W/m <sup>2</sup> K
$H$	Height of radiating surface	m
$H_p$	Heated perimeter of steel cross section	m
$H_r$	Height of room	m
$H_v$	Height of window opening	m
$\Delta H_c$	Calorific value of fuel	MJ/kg
$\Delta H_c$	Heat of combustion of fuel	MJ/kg
$\Delta H_{c,n}$	Effective calorific value of fuel	MJ/kg
$I$	Moment of inertia	mm <sup>4</sup>
$jd$	Internal lever arm in reinforced concrete beam	mm
$k$	Growth parameter for t <sup>2</sup> fire	s/ $\sqrt{MW}$
$k$	Thermal conductivity	W/mK
$k_i$	Thermal conductivity of insulation	W/mK
$k_a$	Ratio of allowable strength to ultimate strength	
$k_b$	Compartment lining parameter	min m <sup>2</sup> /MJ
$k_c$	Compartment lining parameter	min m <sup>2.25</sup> /MJ
$k_f$	Strength reduction factor for heated wood	
$k_{mean}$	Factor to convert allowable stress to mean failure stress	
$k_{c,T}$	Reduction factor for concrete strength	
$k_{E,T}$	Reduction factor for modulus of elasticity	

$k_{y,T}$	Reduction factor for yield strength	
$k_d$	Duration of load factor for wood strength	
$k_{sh}$	Correction factor for shadow effect	
$k_{20}$	Factor to convert 5th percentile to 20th percentile	
$K$	Effective length factor for column	
$l_1, l_2$	Dimensions of floor plan	m
$L$	Fire load (wood mass equivalent)	kg
$L$	Length of structural member	mm
$L_f$	Factored load for fire design	
$L_u$	Factored load for ultimate limit state	
$L_w$	Load for working stress design	
$L_v$	Heat of gasification	MJ/kg
$m_c$	Moisture content as percentage by weight	%
$\dot{m}$	Rate of burning	kg/s
$M$	Mass per unit length of steel cross section	kg
$M$	Mass of fuel	kg
$M$	Bending moment	kN.m
$M^-$	Negative bending moment	kN.m
$M^{*cold}$	Design bending moment in cold conditions	kN.m
$M^{*fire}$	Design bending moment in fire conditions	kN.m
$M^{*fire,red}$	Design bending moment of plastic hinge in fire conditions	kN.m
$M_f$	Total mass of fuel available for combustion	kg
$M_f$	Flexural capacity in fire conditions	kN.m
$M_n$	Flexural capacity in cold conditions	kN.m
$M_y$	Moment capacity at the start of yielding	kN.m
$M_p$	Moment capacity of plastic hinge	kN.m
$M_p^+$	Positive moment capacity of plastic hinge	kN.m
$M_p^-$	Negative moment capacity of plastic hinge	kN.m
$M_u$	Moment capacity	kN.m
$N$	Axial load, axial load capacity	kN
$N_c$	Crushing strength capacity	kN
$N_{crit}$	Critical buckling strength	kN
$N_n$	Axial load capacity	kN
$N_w$	Axial tensile force for working stress design	kN
$N_u$	Axial load capacity	kN
$N_f$	Axial load capacity in fire conditions	kN
$N^*$	Design axial force	kN
$N^{*fire}$	Design axial force in fire conditions	kN
$p$	Perimeter of fire exposed cross section	m
$q_p$	Surface burning rate	kg/s/m <sup>2</sup>
$\dot{q}$	Heat flux	W/m <sup>2</sup>
$q_i$	Incident radiation reaching fuel surface	kW/m <sup>2</sup>
$\dot{q}_C$	Heat produced by combustion of fuel	kW
$\dot{q}_L$	Heat carried out of the opening by convection of hot gases and smoke	kW
$\dot{q}_R$	Heat radiated through the opening	kW
$\dot{q}_W$	Heat conducted into the surrounding structure	kW
$Q$	Rate of heat release	MW
$Q_{fo}$	Critical heat release rate for flashover	MW
$Q_p$	Peak heat release rate	MW

$Q_{fuel}$	Rate of heat release for fuel controlled fire	MW
$Q_{vent}$	Rate of heat release for ventilation controlled fire	MW
$Q$	Live load	
$Q_k$	Characteristic live load	
$r$	Radius of gyration	mm
$r$	Radius of charred corner	mm
$r$	Distance from radiator to receiver	m
$r_{load}$	Load ratio	
$R$	Load capacity	
$R_a$	Ratio of actual to allowable load at normal temperature	
$R_f$	Minimum load capacity reached during the fire	
$R_{code}$	Load capacity reached at time $t_{code}$	
$R_{cold}$	Load capacity in cold conditions	
$R_{fire}$	Load capacity in fire conditions	
$s$	Thickness of compartment lining material	m
$s_{lim}$	Limit thickness	m
$s$	Heated perimeter	mm
$S$	Plastic section modulus	mm <sup>3</sup>
$S_k$	Characteristic snow load	
$SW$	Self-weight	
$t$	Thickness of steel plate	mm
$t$	Time	h, min or s
$t^*$	Fictitious time	h
$t_e$	Equivalent duration of exposure to the standard fire to a complete burnout of a real fire in the same room	min
$t_{fail}$	Time to failure of the element when exposed to the standard fire	
$t_b$	Duration of burning	min
$t_d$	Duration of burning period (ventilation controlled)	h
$t_{fo}$	Time to flashover	s
$t_{lim}$	Duration of burning period (fuel controlled)	h
$t_{max}$	Time to reach maximum temperature	h
$t_{max}^*$	Fictitious time to reach maximum temperature	h
$t_{code}$	Time of fire resistance required by the building code	min
$t_r$	Time of fire resistance	min
$t_s$	Time of fire severity	min
$T$	Thermal thrust	kN
$T$	Temperature	°C
$T_e$	Absolute temperature of the emitting surface	K
$T_r$	Absolute temperature of the receiving surface	K
$T_g$	Gas temperature	°C
$T_i$	Initial temperature of wood	°C
$T_{lim}$	Limiting temperature	°C
$T_{code}$	Temperature reached at time $t_{code}$	°C
$T_{fail}$	Temperature of failure	°C
$T_{max}$	Maximum temperature	°C
$T_p$	Temperature of wood at start of charring	°C
$T_0$	Ambient temperature	°C
$T_y$	Tensile force at yield	kN
$U$	Load effect	

$U_f$	Load effect in fire conditions	
$U_f^*$	Design force for ultimate limit state design	
$U_f^*$	Design force in fire conditions	
$V_{fire}$	Volume of unit length of steel member	$m^3$
$V_f$	Shear capacity in fire conditions	kN
$V$	Shear capacity	kN
$V^*$	Design shear force	kN
$V_f^*$	Design shear force in fire conditions	kN
$w$	Ventilation factor	
$w$	Uniformly distributed load on beam	kN/m
$w_c$	Uniformly distributed load on beam, in cold conditions	kN/m
$w_f$	Uniformly distributed load on beam, in fire conditions	kN/m
$\bar{W}$	Length of long side of compartment	m
$W$	Width of radiating surface	m
$W_k$	Characteristic wind load	
$x$	Distance in the direction of heat flow	m
$x$	Height ratio	
$y$	Width ratio	
$y_b$	Distance from the neutral axis to the extreme bottom fibre	(mm)
$z$	Thickness of zero strength layer	mm
$z$	Load factor	
$Z$	Elastic section modulus	$mm^3$
$Z_f$	Elastic section modulus in fire conditions	$mm^3$





# 1

## Introduction

This book is an introduction to the structural design of buildings and building elements exposed to fire. Structural fire resistance is discussed in relation to overall concepts of building fire safety. The book brings together, from many sources, a large volume of material relating to the fire resistance of building structures. It starts with fundamentals, giving an introduction to fires and fire safety, outlining the important contribution of structural fire resistance to overall fire safety.

Methods of calculating fire severity and achieving fire resistance are described, including fire performance of the main structural materials. The most important parts of the book are the design sections, where the earlier material is synthesised and recommendations are made for rational design of building elements and structures exposed to fires.

This book refers to codes and standards as little as possible. The emphasis is on understanding structural behaviour in fire from first principles, allowing structural fire safety to be provided using rational engineering methods based on national structural design codes.

### 1.1 Objective and Target Audience

This book is primarily written for practising structural engineers and students in structural engineering who need to assess the structural performance of steel, concrete or timber structures exposed to unwanted fires. A basic knowledge of structural mechanics and structural design is assumed. The coverage of fire science in this book is superficial, but sufficient as a starting point for structural engineers and building designers. For more detail, readers should consult recognised texts such as Quintiere (1998), Karlsson and Quintiere (2000) and Drysdale (2011), and the Handbook of the Society of Fire Protection Engineers (SFPE, 2008). This book will help fire engineers in their discussions with structural engineers, and will also be

useful to architects, building inspectors, code officials, firefighters, students, researchers and others interested in building fire safety.

A structural engineer who has followed this book should be able to:

- interpret the intentions of code requirements for structural fire safety;
- understand the concepts of fire severity and fire resistance;
- estimate time–temperature curves for fully developed compartment fires;
- design steel, concrete, steel-concrete composite, or timber structures to resist fire exposure;
- assess the fire performance of existing structures.

## 1.2 Fire Safety

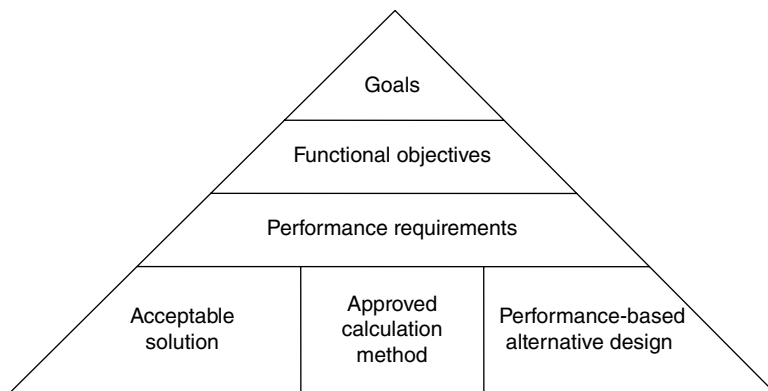
Unwanted fire is a destructive force that causes many thousands of deaths and billions of dollars of property loss each year. People around the world expect that their homes and workplaces will be safe from the ravages of an unwanted fire. Unfortunately, fires can occur in almost any kind of building, often when least expected. The safety of the occupants depends on many factors in the design and construction of buildings, often focusing on the escape of people from burning buildings. Occupant escape and firefighter access is only possible if buildings and parts of buildings will not collapse in a fire or allow the fire to spread. Fire safety science is a rapidly expanding multi-disciplinary field of study. It requires integration of many different fields of science and engineering, some of which are summarized in this book.

Fire deaths and property losses could be eliminated if all fires were prevented, or if all fires were extinguished at the size of a match flame. Much can be done to reduce the probability of occurrence, but it is impossible to prevent all major fires. Given that some fires will always occur, there are many strategies for reducing their impact, and some combination of these will generally be used by designers. The best proven fire safety technology is the provision of automatic fire sprinklers because they have been shown to have a very high probability of controlling or extinguishing any fire. It is also necessary to provide facilities for the detection and notification of fires, safe travel paths for the movement of occupants and firefighters, barriers to control the spread of fire and smoke, and structures which will not collapse prematurely when exposed to fire. The proper selection, design and use of building materials is very important, hence this book.

## 1.3 Performance-based Design

### 1.3.1 *Fundamentals of Performance-based Design*

Until recently, most design for fire safety has been based on *prescriptive* building codes, with little or no opportunity for designers to take a rational engineering approach. Many countries have recently adopted *performance-based* building codes which allow designers to use any fire safety strategy they wish, provided that adequate safety can be demonstrated (Hurley and Bukowski, 2008). In general terms, a prescriptive code states how a building is to be constructed whereas a performance-based code states how a building is to perform under a wide range of conditions (Custer and Meacham, 1997).



**Figure 1.1** Typical hierarchical relationship for performance-based design

Some prescriptive building codes give the opportunity for performance-based selection of structural assemblies. For example, if a code specifies a floor with a fire resistance rating of two hours, the designer has the freedom to select from a wide range of approved floor systems which have sufficient fire resistance. This book provides tools for assessing the fire performance of structural elements which have been tested, as well as those with different geometry, loads or fire exposure from those tested.

In the development of new codes, many countries have adopted a multi-level hierarchical performance-based code format as shown in Figure 1.1. At the highest levels, there is legislation specifying the overall goals, functional objectives and required performance which must be achieved in all buildings. At a lower implementation level, there is a selection of alternative means of achieving those goals. The three most common options are:

1. A prescriptive 'Acceptable Solution' (sometimes call a 'deemed-to-satisfy' solution).
2. An approved standard calculation method.
3. A performance-based 'Alternative Design' which is a more comprehensive fire engineering design from first principles.

Standard calculation methods are still being developed for widespread use, so compliance with performance-based codes in most countries is usually achieved by simply meeting the requirements of the Acceptable Solution, with options 2 and 3 being used for special cases or very important buildings. Alternative Designs can sometimes be used to justify variations from the Acceptable Solution in order to provide improved safety, cost savings, or other benefits.

The code environment in New Zealand (described by Spearpoint, 2008), is similar to that in England, Australia and some Scandinavian countries. Moves towards performance-based codes are being taken in the United States (SFPE, 2000). Codes are different around the world, but the objectives are similar; that is to protect life and property from the effects of fire (ABCB, 2005). It is not easy to produce or use performance-based fire codes for many reasons; fire safety is part of a complex system of many interacting variables, there are so many possible strategies that it is not simple to assess performance in quantitative terms, and there is lack of

information on behaviour of fires and the performance of people and buildings exposed to fires. A number of useful documents have been produced to assist users of performance-based codes, including Custer and Meacham (1997), BS7974 (BSI, 2001), ABCB (2005), Spearpoint (2008) and ISO 23932 (2009). This book provides useful additional information, addressing the design of structures for fire safety, which is a small but important segment of the overall provision of fire safety.

### *1.3.2 Documentation and Quality Control*

As the provision of fire safety in buildings moves away from blind adherence to prescriptive codes towards rational engineering which meets specified performance goals, the need for comprehensive documentation and quality control becomes increasingly important. It is recommended (ABCB, 2005; ISO, 2009) that quantitative calculations be put in context with a 'qualitative design review' which defines the objectives and acceptance criteria for the design, identifies potential hazards and fire scenarios, and reviews the overall design and fire safety features. The review and accompanying calculations should be included in a comprehensive report which describes the building and the complete fire design process (Caldwell *et al.*, 1999). The report should address installation and maintenance of the fire protection features, and management of the building to ensure fire safety, with reference to drawings and documentation from other consultants.

It is important to consider quality control of fire safety throughout the design, construction and eventual use of the building, starting as early as possible in the planning process. Changes to the design often occur during construction, and these may affect fire safety if the significance of the original details is not well documented and well understood on the job site. The approving or checking authorities should also prepare a comprehensive report describing the design and the basis on which it is accepted or rejected. Those taking responsibility for design, approval and site inspection must be suitably qualified. The reliability of active and passive fire protection will depend on the quality of the construction, including workmanship and supervision.

### *1.3.3 Risk Assessment*

Fire safety is all about risk. The probability of a serious fire in any building is low, but the possible consequences of such a fire are enormous. The objectives of design for fire safety are to provide an environment with an acceptably low probability of loss of life or property loss due to fire. Tools for quantitative risk assessment in fire safety are still in their infancy, so most fire engineering design is deterministic. The design methods in this book are deterministic, and must be applied with appropriate safety factors to ensure that they produce an acceptable level of safety.

Fire safety engineering is not a precise discipline, because any assessment of safety requires judgement as to how fire and smoke will behave in the event of an unplanned ignition, and how fire protection systems and the occupants of the building will respond. Design to provide fire safety is based on scenario analysis. For any scenario it is possible to calculate some responses, but the level of accuracy can only be as good as the design assumptions, the input data and the analytical methods available. Fire safety engineering is a very new discipline, so the precision of calculation methods will improve as the discipline matures, but it will always

be necessary to exercise engineering judgement based on experience and logical thinking, using all the information that is available. Analysis of past fire disasters and visits to actual fires and fire damaged buildings are excellent ways of gaining experience.

## 1.4 Structural Fire Engineering

Traditional fire resistance has been simply achieved by designing buildings for room-temperature conditions, then wrapping individual structural elements in protective insulation (for steel construction) or in sacrificial material (for concrete or timber construction). The primary reason for this approach is to limit temperatures in the interior of structural components, so that there is sufficient cold cross-section to provide the required structural resistance in fire conditions.

The new discipline of *structural fire engineering* is leading to major advances in the provision of fire resistance, as an important component of overall building fire safety. Structural fire engineering is an amalgamation of the two older disciplines of *structural engineering* and *fire engineering* to ensure better prediction of building behaviour in the event of a fire, and better overall design for fire safety (Lennon, 2011).

Structural fire engineering follows a scientific approach to the design of any building for fire conditions, requiring the identification of objectives and establishing the criteria that need to be met. Based on the potential fires that can develop, an estimate of material and structural response of the structure is made, ensuring a rational level of sophistication is applied to each design scenario to accurately predict structural behaviour (IStructE, 2003, 2007). The improved understanding of fire and structural behaviour has meant that designers can now take advantage of fire resistance that is inherent in buildings due to their structural form, and use innovative methods and materials to provide structural fire safety at reasonable cost (Newman *et al.*, 2006). The design of structural connections has been largely ignored in the traditional design approach, but the collapse of major buildings such as the World Trade Center towers (Gann, 2008) has shown that it is important to tie buildings together to ensure that failure of one element does not result in collapse of other elements or even collapse of the entire building. An understanding of load paths in structures exposed to fires is critical because these are often different from load paths at ambient temperature, requiring an appreciation of global structural behaviour in all scenarios.

There is increasing international collaboration in the field of structural fire engineering, including development of the Eurocodes, new international journals, and regular international conferences such as the bi-annual Structures in Fire (SiF) conference ([www.structuresinfire.com](http://www.structuresinfire.com)).

With all the advantages of structural fire engineering, it is desirable to incorporate it into building design at the conceptual stage, to ensure economic options that produce safe buildings. This book introduces the fundamentals of structural design for fire conditions and the advantages that structural fire engineering can provide.

## 1.5 Purpose of this Book

Structural design for fire safety concentrates on fire resistance, which is an important part of any design for fire safety. In most buildings, selected structural members and non-structural barriers are provided with fire resistance in order to prevent the spread of fire and smoke, and

to prevent structural collapse during an uncontrolled fire. The provision of fire resistance is just one part of the overall fire design strategy for protecting lives of occupants and fire-fighters, and for limiting property losses. Fire resistance is often described as *passive* fire protection, which is always ready and waiting for a fire, as opposed to *active* fire protection such as automatic sprinklers which are required to activate after a fire is detected. Design strategies often incorporate a combination of active and passive fire protection measures.

Fire resistance is of little significance in the very early stages of a fire, but becomes increasingly important as a fire gets out of control and grows beyond flashover to full room involvement. The importance of fire resistance depends on the size of the building and the fire safety objectives. To provide life safety, fire resistance is essential in all buildings where a fire could grow large before all the occupants have time to escape. This is especially important for large and tall buildings and those where the occupants have difficulty in moving. Fire resistance is also important for Fire Service access and rescue, because firefighters may need to be inside a building well after all the occupants have escaped. Fire resistance is also most important for property protection in buildings of any size, especially if the fire is not controlled with a fire suppression system.

## 1.6 Units

This book uses metric units throughout. These are generally SI (Système International) units. The basic SI unit for length is the *metre* (m), for time the *second* (s), and for mass the *kilogram* (kg). Weight is expressed using the *newton* (N) where one newton is the force that gives a mass of one kilogram an acceleration of one metre per second per second. On the surface of the earth, one kilogram weighs approximately 9.81 N because the acceleration due to gravity is  $9.81 \text{ m/s}^2$ . The basic unit of stress or pressure is the *pascal* (Pa) which is one newton per square metre ( $\text{N/m}^2$ ). It is more common to express stress using the megapascal (MPa) which is one meganewton per square metre ( $\text{MN/m}^2$ ) or identically one newton per square millimetre ( $\text{N/mm}^2$ ).

The basic unit of heat or energy or work is the *joule* (J) defined as the work done when the point of application of one newton is displaced one metre. Heat or energy is more often expressed in thousands of joules [kilojoules (kJ)] or millions of joules [megajoules (MJ)]. The basic unit for rate of power or heat release rate is the *watt* (W). One watt is one joule per second, hence a kilowatt (kW) is a thousand joules per second and a megawatt (MW) is a megajoule per second.

Temperature is most often measured in degrees *Celsius* ( $^{\circ}\text{C}$ ), but for some calculations the temperature must be the *absolute* temperature in *Kelvin* (K). Zero degrees Celsius is 273.15 Kelvin, with the same intervals in each system. A list of units and conversion factors is included in Appendix A. A more extensive list of units and conversion factors can be found in the SFPE Handbook (SFPE, 2008).

## 1.7 Organization of Chapters

This book is organized in a form suitable for teaching a fire safety design course to structural engineering students. Chapter 2 is a discussion of fire safety in buildings, looking at overall strategies and the importance of preventing spread of fire or structural collapse within the