

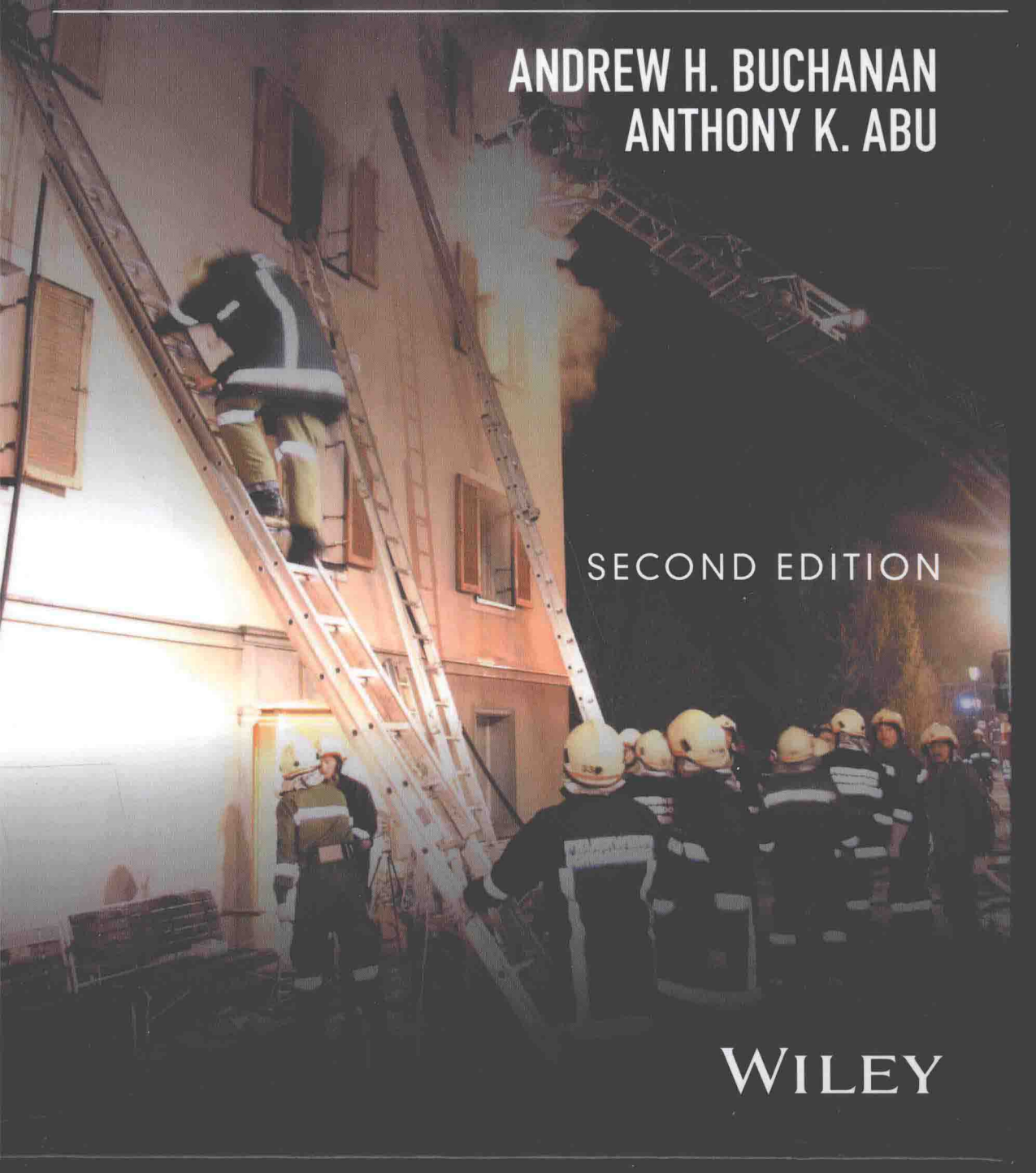
# STRUCTURAL DESIGN FOR **FIRE SAFETY**

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ANDREW H. BUCHANAN  
ANTHONY K. ABU

SECOND EDITION

WILEY



# 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

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*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

Printed and bound in Malaysia by Vivar Printing Sdn Bhd

10 9 8 7 6 5 4 3 2 1

# 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>
$a$	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>
$A_p$	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
$D_h$	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
$f_{bf}$	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
$f_{tw}$	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 ( $A_v\sqrt{H_v}/A_f$ )	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
$\Delta H_{c,eff}$	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/√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	
$k_{mem}$	Factor to convert allowable stress to mean failure stress	
$k_{e,T}$	Reduction factor for concrete strength	
$k_{E,T}$	Reduction factor for modulus of elasticity	

$k_{y,\bar{r}}$	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
$m_v$	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
$M^{\text{cold}}$	Design bending moment in cold conditions	kN.m
$M^{\text{fire}}$	Design bending moment in fire conditions	kN.m
$M^{\text{fire,red}}$	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
$M_n$	Moment capacity	kN.m
$N$	Axial load, axial load capacity	kN
$N_c$	Crushing strength capacity	kN
$N_{\text{crit}}$	Critical buckling strength	kN
$N_n$	Axial load capacity	kN
$N_w$	Axial tensile force for working stress design	kN
$N_n$	Axial load capacity	kN
$N_f$	Axial load capacity in fire conditions	kN
$N^{\text{a}}$	Design axial force	kN
$N^{\text{a,fire}}$	Design axial force in fire conditions	kN
$p$	Perimeter of fire exposed cross section	m
$q$	Surface burning rate	kg/s/m <sup>2</sup>
$\dot{q}^{\text{a}}$	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
$\bar{r}$	Distance from radiator to receiver	m
$R_{load}$	Load ratio	
$R$	Load capacity	
$R_n$	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
$T_s$	Tensile force at yield	kN
$U$	Load effect	

$U_f$	Load effect in fire conditions	
$U^*$	Design force for ultimate limit state design	
$U^{*}_{fire}$	Design force in fire conditions	
$V$	Volume of unit length of steel member	$m^3$
$V_f$	Shear capacity in fire conditions	kN
$\bar{V}$	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
$W$	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
$\bar{x}$	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	$mm^3$

# 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