STRUCTURAL DESIGN FOR FIRE SAFETY

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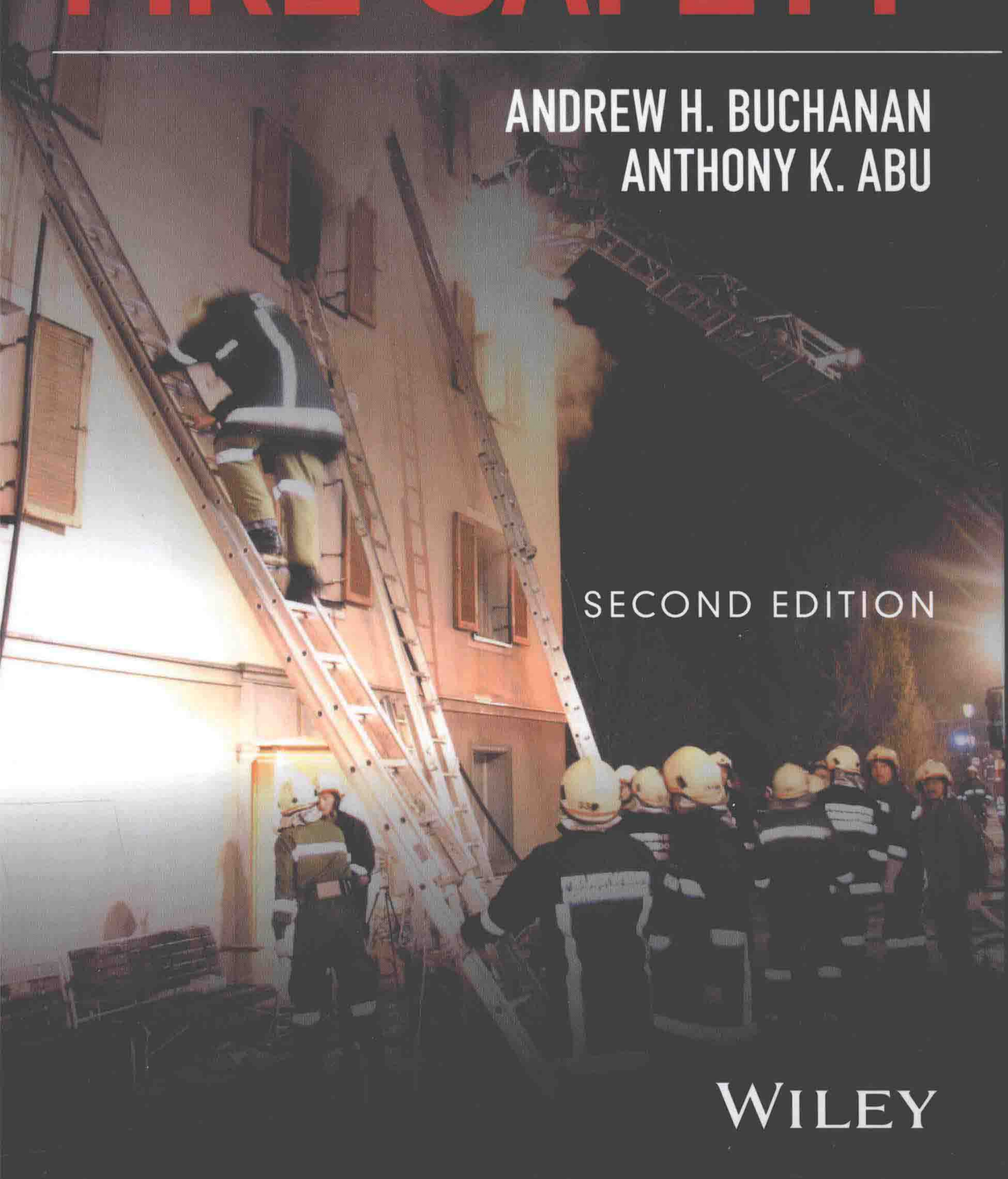

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Preface

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

α	Fire intensity coefficient	MW/s^2
α	Thermal diffusivity	m^2/s
α	Ratio of hot wood strength to cold wood strength	
α_h	Horizontal openings ratio	
α_v	Vertical openings ratio	
β	Target reliability	
β	Measured charring rate	mm/min
β_1	Effective charring rate if corner rounding ignored	mm/min
β_n	Nominal charring rate	mm/min
β_{par}	Charring rate for parametric fire exposure	mm/min
δ	Beam deflection	mm
Δ	Deflection	mm
Δ_L	Maximum permitted displacement	mm
Δ_0	Mid-span deflection of the reference specimen	mm
χ	Buckling factor	
ε	Strain	
ε_i	Initial strain	
ε_σ	Stress-related strain	
ε_{cr}	Creep strain	
ε_{th}	Thermal strain	
ε_{tr}	Transient strain	
ε	Resultant emissivity	
ε_e	Emissivity of the emitting surface	
ε_r	Emissivity of the receiving surface	
ϕ	Configuration factor	
Φ	Strength reduction factor	
Φ_f	Strength reduction factor for fire design	
k	Elastic curvature	1/m
γ_M	Partial safety factor for material	
γ_G	Partial safety factor for dead load	
γ_Q	Partial safety factor for live load	

η	Temperature ratio	
θ	Plastic hinge rotation	rad
θ	Radiating angle	rad
ρ	Density	kg/m^3
σ	Stefan–Boltzmann constant	kW/m^2K^4
σ	Stress	MPa
ν_p	Regression rate	m/s
ξ	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^2, m^2
A_f	Floor area of room	m^2
A_{fi}	Area of member, reduced by fire	mm^2, m^2
A_{fuel}	Exposed surface area of burning fuel	m^2
A_h	Area of horizontal ceiling opening	m^2
A_1	Area of radiating surface 1	m^2
A_r	Cross-sectional area reduced by fire	mm^2, m^2
A_s	Area of reinforcing steel	mm^2
A_t	Total internal surface area of room	m^2
A_v	Window area	m^2
b	Breadth of beam	mm
b_f	Breadth of beam reduced by fire	mm
b	$\sqrt{}$Thermal inertia $=\sqrt{(k\rho c_p)}$	$Ws^{0.5}/m^2K$
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_s	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^2
e_t	Fuel load energy density (per unit area of internal room surfaces)	MJ/m^2
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^*	Calculated stress in member	MPa
f_t^*	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_{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^2
F_c	Crushing load of column	kN
F_{crit}	Critical buckling load of column	kN
F_v	Ventilation factor ($A_v\sqrt{H_v}/A_t$)	$m^{0.5}$
g	Acceleration of gravity	m/s^2
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^2K
h_r	Radiative heat transfer coefficient	W/m^2K
h_t	Total heat transfer coefficient	W/m^2K
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
ΔH_c	Calorific value of fuel	MJ/kg
ΔH_c	Heat of combustion of fuel	MJ/kg
$\Delta H_{c,n}$	Effective calorific value of fuel	MJ/kg
I	Moment of inertia	mm^4
jd	Internal lever arm in reinforced concrete beam	mm
k	Growth parameter for t^2 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^2/MJ
k_c	Compartment lining parameter	min $m^{2.25}$/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	Surface burning rate	kg/s/m^2
$\dot{q}''$	Heat flux	W/m^2
q_i	Incident radiation reaching fuel surface	kW/m^2
$\dot{q}_C$	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^3
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^*	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
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
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