STRUCTURAL DESIGN FOR FIRE SAFETY

ANDREW H. BUCHANAN
ANTHONY K. ABU

SECOND EDITION

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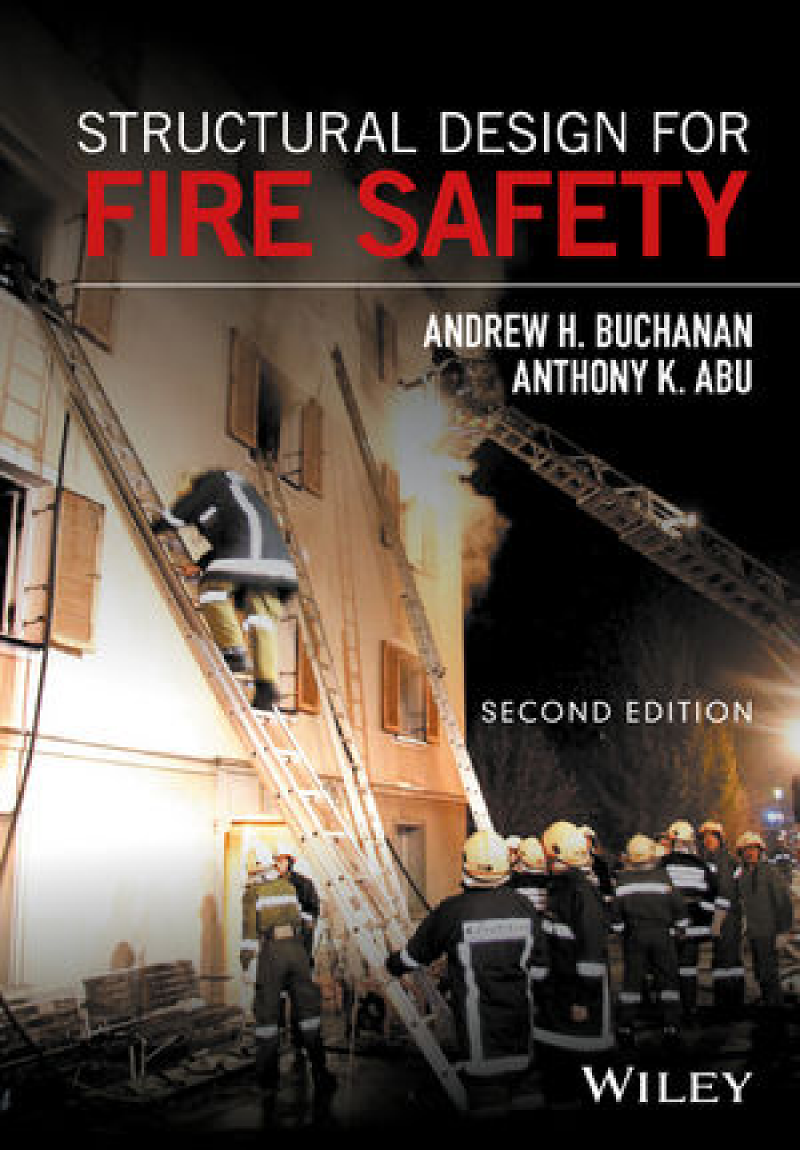

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Second Edition

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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.

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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_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^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

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

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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).

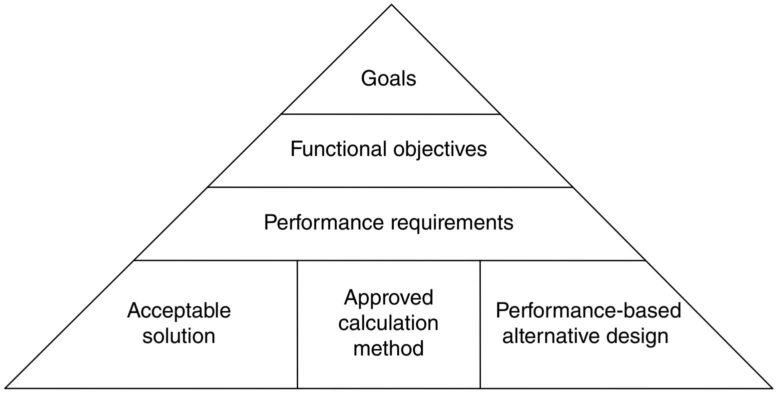

Figure 1.1 Typical hierarchical relationship for performance-based design

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).

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 (Systéme 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 m/s^2. The basic unit of stress or pressure is the *pascal* (Pa) which is one newton per square metre (N/m^2). It is more common to express stress using the megapascal (MPa) which is one meganewton per square metre (MN/m^2) or identically one newton per square millimetre (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* (°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 whole context of fire safety. Chapter 3 is an elemental review of combustion and heat transfer for those with no background in those subjects, and it also describes fire behaviour in rooms in order to give an indication of the impact of an uncontrolled fire on the building structure. Chapter 4 describes fire severity by comparing post-flashover fires with standard test fires. It further describes methods of achieving fire resistance, including standard tests and calculation methods.

The structural engineering section of the book starts in Chapter 5 where structural design for fire conditions is contrasted with structural design at normal temperatures, and important concepts such as flexural continuity, moment redistribution and axial restraint are introduced. The subsequent chapters address the fire behaviour and design of structural materials and assemblies. Chapters 6, 7 and 8 describe steel, reinforced concrete and composite steel construction, while Chapters 9 and 10 cover timber structures and light frame structures. Advanced calculation methods are covered in Chapter 11, and Chapter 12 gives a summary of the recommended fire design methods for structures of different materials.

2

Fire Safety in Buildings

This chapter gives an introduction to the overall strategy for providing fire safety in buildings, and identifies the roles of fire resistance and structural performance as important parts of that strategy.

2.1 Fire Safety Objectives

The primary goal of fire protection is to limit, to acceptable levels, the probability of death, injury, property loss and environmental damage in an unwanted fire. The balance between life safety and property protection varies in different countries, depending on the type of building and its occupancy. The earliest fire brigades and fire codes were promoted by insurance companies who were more interested in property protection than life safety; this was certainly the case at the time of the great fire of London in 1666.

A recent trend has been for national codes to give more emphasis to life safety than to property protection. Some codes assume that fire damage to a building is the problem of the building owner or insurer, with the code provisions only intended to provide life safety and protection to the property of other people. Many fire protection features such as automatic sprinkler systems provide both life safety and property protection. The distinction between life safety and property protection becomes important if the owner is unaware of the likely extent of fire damage to the building and contents, even if the building complies with minimum code requirements.

2.1.1 Life Safety

The most common objective in providing life safety is to ensure safe escape. To do this it is necessary to alert people to the fire, provide suitable escape paths, and ensure that people are not affected by fire or smoke while escaping through those paths to a safe place. In some

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buildings it is necessary to provide safety for people unable to escape, such as those under restraint, in a hospital, or in a place of refuge within the building. People in adjacent buildings must also be protected, and it is essential to provide for the safety of firefighters who enter the fire building for rescue or fire control.

2.1.2 Property Protection

The objective of protecting property starts with protecting the structure, fabric, and contents of the building. Additional objectives relate to fire protection of neighbouring buildings. An extra level of protection may be necessary if rapid repair and re-use after a fire are important. In many cases an important objective may be to protect intangible items such as possible loss of business or irreplaceable loss of heritage values. A loss disproportionate to the size of the original fire can occur if there is major damage to 'lifelines' such as energy distribution or telecommunications facilities.

2.1.3 Environmental Protection

In many countries an additional objective is to limit environmental damage in the event of a major fire. The primary concerns are emissions of gaseous pollutants in smoke, and liquid pollution in fire-fighting run-off water, both of which can cause major environmental impacts. The best way to prevent these emissions is to extinguish any fire while it is small. All of the above objectives can be met if any fire is extinguished before growing large, which can be accomplished most easily with an automatic sprinkler system.

2.2 Process of Fire Development

Fire safety objectives are usually met with a combination of active and passive fire protection systems. Depending on the design, *Active systems* limit fire development and its effects by some action taken by a person or an automatic device. *Passive systems* on the other hand control the fire or its effects by systems that are built into the structure or fabric of the building, not requiring specific operation at the time of a fire. Some building elements or materials cannot be easily classified as either active or passive systems, for example intumescent coatings which will react automatically in a fire, while fire doors may be shut automatically or by the occupants after a fire is detected. The typical development of a fire in a room is described in Figure 2.1 to emphasize the need for fire protection systems.

Figure 2.1 shows a typical time–temperature curve for the complete process of fire development inside a typical room, assuming no fire suppression. Not all fires follow this development because some fires go out naturally and others do not reach flashover, especially if the fuel item is small and isolated or if there is not enough air to support continued combustion. If a room has very large window openings, too much heat may flow out of the windows for flashover to occur. Complementary to Figure 2.1, Table 2.1 is a summary of the main periods of fire behaviour relative to the active or passive actions that can take place in those periods. The brief discussions that follow relate to Figure 2.1 and Table 2.1, and serve as an introduction to the discussion of fire safety strategies later in this chapter and the description of fire behaviour in Chapter 3.