FIRE SAFETY CONCERNS FOR NEW ARCHITECTURAL FEATURES

HUNG WING YAN

A thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy

Department of Building Services Engineering
The Hong Kong Polytechnic University

August 2005

ABSTRACT

As experienced, many buildings with new architectural features have difficulties in complying with the prescriptive fire codes in Hong Kong. Active updating to the existing prescriptive codes and adopting the new approach of performance-based design are essential in the new century. However, both approaches cannot be achieved with a good understanding on the problems inside. Therefore, fire safety concerns associated with the new architectural features was studied and being the focus of this thesis.

Four popular innovative architectural features including atrium design, double-skin façade (DSF), internal building void (IBV) and ultra high-rise building design were identified to study their hidden fire risks. Methodology included analysis of numerical experiments, critical review on fire codes and fire incidents, application of fire engineering tools including fire models, and full-scale burning tests at a remote site in Northeastern China.

The current fire regulations, particularly requirements on fire resisting construction such as providing intumescent protective coating for steel structure were reviewed first with their deficiencies identified. The rationale behind the development and some standard fire tests and equal area hypothesis of the fire codes for high-rise buildings were analyzed. The review study would give a basis for revising existing codes.

It was found that the existing prescriptive-based fire codes with objectives only on protecting against accidental fires. There might not be adequate for some premises as shown in the World Trade Center (WTC) incident. Further, it would take time, say a few years, on revising current codes and developing new codes. An immediate action is to protect those buildings with higher chance to have non-accidental fires. A new fire risk assessment scheme was proposed to identify those different buildings for immediate upgrading their fire safety provisions. The contrast to other common fire safety assessment scheme, the total fire safety concept is included in this new system. The likelihood of a building in having non-accidental fires can be assessed.

In this thesis, fire safety aspects of atrium buildings were discussed. By studying the configuration of an atrium in a site survey, it was revealed that fire and smoke could spread rapidly in the huge atrium space and adjacent levels, leading to life losses, human injuries and property damaged. After the review on the existing codes, it was found that there are no tailor-made codes or regulations specifying the fire safety requirements for atrium. Having considered three fire scenarios, including fire at the atrium level; fire at a shop adjacent to the atrium at lower levels; and fire at a shop adjacent to atrium at upper levels, high headroom sprinkler following the fire services installation code was found not necessarily be capable of controlling an atrium fire.

Fire safety of the IBV design for high-rise buildings was studied by covering the following three areas, including fire in a room adjacent to the internal void; spreading of smoke from the fire level to adjacent levels; and fire resistance provisions for windows. For a typical bathroom in a domestic building in Hong Kong, of size 2.25 m x 1.55 m x 3 m with an opening 0.6 m wide and 1 m high, the heat release rate (HRR), from Thomas equation, needed for such small room is only 0.5 MW which is a value easily obtained by materials stored inside the room. Fire models including application of Computational Fluid Dynamics (CFD) were used for the analysis of an IBV connected with 2 levels of bathroom. The CFD study from the literature includes five scenarios varied with opening conditions and pressure differential. The most undesirable fire scenarios happened when there was a negative pressure imposed at the door of the upper room. Results of the study indicated that there might be possibility of spreading hot smoke or even flame from the fire level to adjacent levels through the IBV. Further studies should be carried out to investigate the problem.

Fire hazard of another new architectural feature – DSF was examined experimentally. Flame impingement onto the inner glass panes on the adjacent floors and cracking appeared on the internal layer of a DSF would be the most undesirable scenario. Full-scale burning tests on part of a full-scale DSF design were carried out in a facility developed in Northeast of China. A total of four sets of tests were performed to demonstrate how the depth of cavity of a DSF affects the smoke movement. Cavity depths of 1.5 m, 1 m and 0.5 m were examined. Surface temperature and heat flux received on the test panels were recorded. By comparing the measured surface temperature of the inner and outer glass panels, the possible smoke movement pattern inside the air cavity could be estimated. Cracking patterns found on the glass panels were also observed. The first cracking occurred when the bulk glass temperature was ranging from 120 °C to 350 °C and the heat flux was higher than 3 kWm^{-2}. It has good agreement with the overseas studies in which the first cracking occurred when the bulk glass temperature was at about 110 °C and the heat flux was about 3 kWm^{-2}. Results showed that a deeper cavity might give better safety under the scenario studied. The outer glass panel would be broken rapidly for the cavity of 0.5 m deep but DSF with a cavity of 1.0 m deep appeared to be the most risky as glass panels above broke the most frequent among the different cavity depths. The inner glass panel might be broken before the outer panel, leading to an undesirable fire scenario.

Possible collapse scenarios of the WTC twin towers assessed by local and international experts were studied and reported. Investigational results on the collapse mechanism were reviewed. Failure of end connections, dislodgment of fireproofing, insufficient thickness of insulation materials and higher heat release rate than a normal accidental fire were considered to be the possible factors to give total failure within one and a half hours. The fire resistance provided for the structural steel members were discussed. Uncertainties in the standard practice on fire testing conditions were pointed out. The mass needed for four fireballs generated at the twin towers was 12,000 kg of jet fuel. The possible heat release rate of the big fire triggered by burning huge amount of fuel was also estimated. The jet fuel carried by the planes would lead to HRR of up to 8 GW, a thousand time of a common design fire, on the typical floor area of WTC. Consequent to the WTC incident, the existing standards and codes were discovered to have problems in dealing with non-accidental fires. Further investigations are urged to carry out. Prior to that, a fire risk assessment scheme was proposed to identify buildings requiring more fire safety provisions.

Having studied the four new architectural features of interest in this thesis by full-scale experiment, application of fire engineering tools, critical reviews on statutory requirements and literatures, and analysis of fire incidents, it was revealed that the new generation of architecture was usually associated with some hidden fire risks which had not been paid adequate attention before.

By analyzing the development and establishment of the existing codes, including the standard fire tests and equal area hypothesis, their inadequacy in protecting new buildings against fires was unveiled. The fire safety objectives of the existing codes only taking accidental fires into account were evident to be insufficient in defeating non-accidental fires. In view of these findings, the existing fire codes would require major revisions and performance-based codes are needed to take non-accidental fires into consideration to protect new architectural features against fires.

As these exercises would take time, a Fire Risk Assessment Scheme, including total fire safety concept, was therefore proposed in this thesis to provide quicker estimate for those buildings most likely to encounter non-accidental fire risks. By making reference to the prevailing fire risk indexing system and considering total fire safety concept, 24 parameters in the areas including passive building design, fire services installation, fire safety management, political stability and social stability were included in the assessment. From which, the relative fire risk the building encountered could be evaluated and prompt remedial measures for improving fire safety provisions could be thus determined.

The diversified investigation results of this study can be unified to provide a checklist for designers' consideration when planning for innovative designs for which fire safety aspects should be paid extra attention. The checklist could become a good start in handling the brand new building designs and maintaining the fire safety level of our built environment.

CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written nor material which has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

_______________________ (Signed)

Hung Wing Yan (Name of student)

ACKNOWLEDGEMENTS

I would like to express my sincere thanks to my supervisor, Professor W.K. Chow, for his supervision, encouragement and support throughout my research studies.

Heartfelt gratitude would be also given to Professor K.T. Yang for his patient guidance and heartfelt hospitality during my short-term training at the University of Notre Dame in USA.

I also wish to thank my grandmother and Mr. C.H. Wu, to whom this thesis is dedicated, for their unconditional support and affection for me.

CONTENTS

Abstract		i
Certificate of Originality		vii
Acknowledgements		viii
Table of Contents		ix
List of Tables		xiv
List of Figures		xv
Chapter 1	**Introduction**	
1.1	Objectives	1
1.2	Hypothesis	3
1.3	Methodology	4
1.4	Outline of Each Chapter	6
Chapter 2	**New Architectural Features**	
2.1	Introduction	10
2.2	Green and Sustainable Buildings	13
2.3	Extensive Use of Glass	15
2.4	Selected New Architectural Features	18
2.5	Atrium Design	20
2.6	Internal Building Void	21
2.7	Double-skin Facade	23
2.8	Ultra High-rise Building Design	25
2.9	Summary	27

Chapter 3 Current Fire Safety Requirements on High-rise Buildings

3.1 Introduction 28

3.2 Local Fire Safety Requirements 30

3.3 Comparison among Codes in HK, China, UK and USA 36

3.4 Some Recommendations 39

Chapter 4 Atrium Design

4.1 Introduction 42

4.2 Evolution of Atrium 43

4.3 Architectural Aspects 47

4.4 Environmental Aspects 50

4.5 Economic Aspects 53

4.6 Design Considerations 55

4.7 Local Examples 57

4.8 Fire Safety Aspect 60

Chapter 5 Internal Building Void

5.1 Introduction 64

5.2 Fire in a Room Adjacent to the Internal Void 67

5.3 Fire Resistance for Windows 71

5.4 Discussions on the Simulation Results 73

5.5 Summary 75

Chapter 6 Double-skin Facade

6.1 Introduction 76

6.2 Review on Current Regulations Governing the Use of Glass 78

6.3 Fire Safety Considerations in the Use of Glass 80

6.4 Fire Safety Problems Associated with the Construction of Double-skin Facade 83

6.5 Recommendations 84

Chapter 7 Experimental Study on Double-skin Facade

7.1 Introduction 86

7.2 Full-scale Burning Tests 87

7.3 Test Results and Discussions 90

7.4 Effects of Cavity Depth 105

7.5 Factors Affecting Fire Risk 107

7.6 Summary 110

Chapter 8 Ultra High-rise Building Design

8.1 Introduction 112

8.2 Concerns Arising from the Latest Big Fire Incidents 118

8.3 Fire Safety for Ultra High-rise Buildings 120

8.4 Collapse Scenarios of World Trade Centre Twin Towers 123

8.5 Fire Resistance of Floor Truss System 135

8.6 Heat Release Rate inside the Twin Towers 139

8.7 Recommendations 143

Chapter 9 Fire Resisting Construction

9.1 Introduction 149

9.2 Fire Resisting Construction in Hong Kong 150

9.3 FRP in a Compartment 152

9.4 Standard Tests for Fire Resistance 155

9.5 The Equal Area Hypothesis 157

9.6 Existing Requirements on Fire Resistance Period in UK 158

9.7	Local Requirements on Fire Resistance Period	161
9.8	Inadequacies of the Current Requirements on FRP	163
9.9	Engineering Performance-based Fire Codes	166
9.10	Recommendations	167
Chapter 10	**Intumescent Coating for Steel Structure**	
10.1	Introduction	170
10.2	Intumescent Coating	171
10.3	Application of Intumescent Coating	174
10.4	Determination of the Thickness of Intumescent Coating Required for a Specific Element	176
10.5	Local Regulations on Intumescent Coating	180
10.6	Deficiencies Associated with Intumescent Coating	181
10.7	Summary	182
Chapter 11	**Fire Risk Assessment Scheme for Non-accidental Fires in High-rise Buildings**	
11.1	Introduction	185
11.2	Necessity of a Fire Risk Assessment Scheme	188
11.3	Fire Risk Indexing System	192
11.4	Proposed Fire Risk Assessment Scheme (FRAS)	195
11.5	Risk Parameters of the FRAS	198
11.6	Risk Index	202
11.7	Summary	205
Chapter 12	**Conclusions**	208

Tables		T-1
Figures		F-1
Appendix A	Benefits and Limitations of Using Glass	AA-1
Appendix B	Definitions of Terms in Codes and Standards	AB-1
Appendix C	Fire Safety Requirements in Mainland, UK and USA	AC-1
Appendix D	Consumption of Oxygen by Gas Appliances	AD-1
Appendix E	Numerical Experiments on Smoke Spreading in Internal Building Void	AE-1
Appendix F	Preliminary Experimental Study of Double-Skin Façade	AF-1
Appendix G	Suggested Upgrades on Fire Safety Protection	AG-1
Appendix H	Evolution of the Requirements on Fire Resisting Construction	AH-1
Appendix I	Fire Protective Coatings for Structural Steel Elements	AI-1
Appendix J	Classifications of Severity for Parameters of Severity	AJ-1
Appendix K	Classifications of Probability for Parameters of Probability	AK-1
Appendix L	Design Checklist	AL-1
References		R-1
Publications Arising from this Thesis		P-1

LIST OF TABLES

Table 3-1	Requirements on Fire Resistance Period (FRP) (in hours)	T-1
Table 3-2	Requirements on Compartment Size	T-2
Table 3-3	Requirements on Escape Routes in Local Codes	T-3
Table 3-4	Requirements on Escape Stairways	T-4
Table 3-5	Requirements on Travel Distance	T-5
Table 3-6	Comparisons between Fire Safety Codes	T-7
Table 7-1	Tests G2 to G5	T-8
Table 7-2	Positions of Maximum Temperature	T-9
Table 7-3	Glass Damages	T-10
Table 9-1	Differences in Other Fire Tests for Building Materials from BS 476	T-11
Table 9-2	General Grades of Fire Resistance Period (in hours) of Major Elements of Construction	T-12
Table 9-3	Comparison of FRP Requirement between Building (Construction) Regulation 1966 and London Building By-laws 1972	T-13
Table 11-1	Risk Parameters for the Proposed Fire Risk Assessment Scheme	T-15
Table 11-2	Sample Risk Index Evaluation Worksheet	T-16
Table 11-3	Risk Assessment Matrix	T-17
Table 11-4	A Sample Risk-based Control Plan	T-18

LIST OF FIGURES

Figure 2-1	Different Generations of Commercial Premises in Hong Kong	F-1
Figure 2-2	Different Window-to-wall Ratio Shown on Residential Buildings	F-2
Figure 4-1	Stacked Atrium	F-3
Figure 4-2	Covered Central Court: Atrium	F-4
Figure 4-3	Four Types of Atrium	F-5
Figure 4-4	Availability of Daylight	F-6
Figure 4-5	Bank of China Tower, Hong Kong, 1989	F-7
Figure 4-6	Hongkong Bank Headquarters, Hong Kong, 1985	F-8
Figure 4-7	The Palace Mall, Hong Kong, 1996	F-9
Figure 4-8	Fire and Smoke Spreading through the Atrium	F-10
Figure 4-9	Activation of Sprinkler Head at Atrium	F-11
Figure 4-10	Staircase Pressurization	F-12
Figure 5-1	Traditional Floor Plan	F-13
Figure 5-2	New Design with Internal Void	F-14
Figure 6-1	Flame and Smoke Movement	F-15
Figure 7-1	External View of the Burning Hall (16.5 m wide and 6 m high) in Lanxi	F-16
Figure 7-2	Area of Interest in the Experimental Study	F-17
Figure 7-3	Schematic Diagram of the Experimental Setup	F-18
Figure 7-4	Pictures of Test Rig	F-19

Figure 7-5	Locations of Thermocouples and Heat Flux Meters	F-20
Figure 7-6	Flame Coming out from the Fire Chamber	F-21
Figure 7-7	Maximum Temperature on Test Panel TPO	F-22
Figure 7-8	Maximum Temperature on Test Panel TPI	F-23
Figure 7-9	Temperature Profiles of Test Points on the Same Height for Test G2	F-24
Figure 7-10	Temperature Profiles of Test Points on the Same Height for Test G3a	F-25
Figure 7-11	Temperature Profiles of Test Points on the Same Height for Test G3b	F-26
Figure 7-12	Temperature Profiles of Test Points on the Same Height for Test G4a	F-27
Figure 7-13	Temperature Profiles of Test Points on the Same Height for Test G4b	F-28
Figure 7-14	Temperature Profiles of Test Points on the Same Height for Test G5a	F-29
Figure 7-15	Temperature Profiles of Test Points on the Same Height for Test G5b	F-30
Figure 7-16	Maximum Temperature Difference ΔT_{max} Varied with Cavity Depth d	F-31
Figure 7-17	Estimated Smoke Movement Influenced by the Depth of Cavity	F-32
Figure 7-18	Maximum Temperature and Damages Recorded in Test G2	F-33

Figure 7-19 Maximum Temperature and Damages Recorded in Test G3 F-34

Figure 7-20 Maximum Temperature and Damages Recorded in Test G4 F-35

Figure 7-21 Maximum Temperature and Damages Recorded in Test G5 F-36

Figure 7-22 Incident Heat Flux Profile on TPO F-37

Figure 8-1 Scenario Guessed from the Consultancy Report (TVB 2003) F-38

Figure 8-2 Diagrammatic Illustration Showing the Impact on the Lower Part of the Building F-39

Figure 8-3 Progressive Collapse F-40

Figure 8-4 Building Tilted Sideway (Real News 24/7 2005) F-41

Figure 9-1 Heating and Pressure Applied on Test Specimen in BS 476 F-42

Figure 9-2 Comparison of Different Standard Temperature/Time Curves F-43

Figure 9-3 The Equal Area Hypothesis F-44

CHAPTER 1 INTRODUCTION

1.1 Objectives

Many new architectural features appear in the construction industry lately. As experienced, they are difficult in complying with prevailing fire codes. This study aims to explore the hidden fire risks in some popular new architectural features. As the existing fire codes are prescriptive-based and only accidental fires are taken into consideration, they appear inadequate to protect the new innovative building designs. This would be also addressed in this study by reviewing the current fire codes. Insufficiencies in current regulations would lead to time-consuming code revision. A simpler approach is essential and thus suggested to facilitate the fire safety upgrades in advance of the new codes established.

Most of these designs are aiming at providing environmental consciousness, aesthetic quality and symbolic appearance. Not only energy consumption can be greatly reduced, the investment return, say sales and rental price, can be also extensively promoted with the integration of environmental-responsive design and marvelous appearance of the development. They can easily demonstrate their advantages in terms of investment cost or energy cost. However, very few attentions are paid on understanding the potential hazards associated with these popular design features before extensively applying in the new buildings. For example, providing daylight by using large pieces of glass on the exterior might give problems when a fire occurs. Cracking of glass panes would increase the air supply rate to sustain combustion to give higher heat release rate.

Existing building regulations in most of the countries, developed decades ago, are prescriptive-based. In local area, fire regulations and codes would be revised each time only after big fires occurred. This becomes a question on whether these codes are adequate or not to achieve necessary fire safety level.

Moreover, the existing codes only protect buildings against accidental fires. Fire led by non-accidental causes, including arson fire, terrorist attack fire and natural disaster fire, is out of consideration. The existing premises compliant with the building codes in which the maximum fire load density is laid down should be able to control the fire size of an accidental fire. In considering the past record, the existing codes demonstrate satisfaction in protection against accidental fires. However, arson fire and terrorist attack fire with external fire load added would bring about unpredictable damages. As shown in World Trade Center incident (FEMA 2002), the extraordinary amount of jet fuel brought by the hijackers gave rise to the total collapse of the famous twin towers. It is, therefore, necessary to review the current regulations to understand the rational behind the establishment of the existing codes and explore their deficiencies to provide a basis for development of new codes to meet the current need.

Authorities of most of the countries now are paying the greatest effort in considering whether non-accidental fires should be included in the building fire codes. However, not all buildings are required with such high level of protection especially in places neither politically nor socially unstable. Indeed, code revision requires considerable time to complete. An intermediate remedial measure is vital and a fire safety indexing system is aimed to propose for this purpose.

As a whole, this thesis is dedicated to demonstrate, from architectural point of view, the fire risk behind the new architectural features by integrating results investigated from different methodologies. Useful data, including the analysis results and recommendations, is then provided as a checklist of design considerations for architects when they are planning for similar or innovative designs.

1.2 Hypothesis

Since many popular new architectural features have a number of advantages and contributions in terms of environmental conservation, aesthetics quality and investment return, they are popular designs lately in either commercial or residential premises. However, insufficient attention was received on their fire safety aspects. The hypothesis of this thesis is that there are potential fire hazards associated with the new architectural features from either the characteristics of the building designs or the current fire codes governing these buildings.

1.3 Methodology

The target of study should be clarified prior to in-depth investigations. Popular designs in the well-developed region, say Hong Kong, are selected to be the target of investigation. Popular designs of interest include atrium design, internal building void, double-skin façade and high-rise building. They may be either constructed with commercial or domestic developments. Only high-rise buildings (above 30 m high as defined in local code) were taken into considerations.

To discover there are potential fire hazards from these new building designs, various methodologies were applied. They included critical reviews on codes, literature and sites, application of fire engineering tools and full-scale burning tests. All these were applied to study the potential fire risks of the new architectural feature.

First of all, literatures concerning to the architectural features of interest, the WTC incident, the development of the existing codes, such as fire resistance construction, the standard fire tests, the intumescent coating for steel structure, the prevailing fire risk indexing systems were reviewed. All these provided the fundamental and background information for further study and analysis.

Together with literature review, survey on codes for high-rise buildings was also carried out. The requirements in terms of fire resisting construction, means of escape, means of access and fire services installations were reviewed. Building uses and size the requirements based on were also identified. It was aimed to understand the adequacy and applicability of the existing codes and regulations in governing the new architectural features.

Three site surveys were carried out to identify the dimensions and characteristics of a real construction of atrium, internal building void and double-skin façade. For example, the size of a DSF was essential for the setup of the full-scale experimental study and layout plan of a domestic flat unit with IBV design was used to estimate the fire hazard of having a flashover fire adjacent to the IBV.

After carrying out the above reviews, some common fire engineering tools were applied. An example is on the fire resistance requirements. The empirical equations and the equal area hypothesis governing the required FRP were examined. The required FRP, expressed by Law's correlation (Law 1971), was determined by the total fire load, the floor area, the area of window openings and the area of internal surfaces to which heat is lost excluding windows. The equal area hypothesis, based on the concept of equivalent severity, demonstrated that equal areas under two temperature/time curves would have identical fire severity. The fire severity and the required FRP of a real fire curve can be determined by comparing with the standard temperature/time curve. These were used to figure out the key parameters missed out from the standard practice and hence the room for improvement. Computational Fluid Dynamics (CFD) was also used as a tool for analyzing the fire risks of IBV with real dimensions and layout acquired from the site survey. Two adjacent levels were studied and five scenarios with different pressure differentials across the test rooms were identified.

A full-scale burning study was also carried out in Northeast of China to study the feature of DSF. It was an active personal collaboration work of Professor Chow with Harbin Engineering University in Heilongjiang, China. Part of the DSF including two stories was constructed according to the dimensions measured from site survey. The cavity depth, up to 2 m, was adjusted in four sets of tests to study smoke and fire spreading in the cavity between the two glazed panels. By evaluating the temperature difference between the measured surface temperatures on the outer glass panel and on the inner glass panel and observing the cracking patterns of glass, the possible smoke movement pattern inside the air cavity could be estimated.

1.4 Outline of Each Chapter

This chapter introduced the background of this thesis while the new architectural features of interest were briefly discussed in Chapter 2. In Chapter 3, it was focused on fire safety requirements in terms of fire resisting construction, means of escape, means of access and fire services installation, for high-rise buildings which is believed to possess higher fire risk. Statutory instruments in Hong Kong and some other nations were reviewed and briefly compared. Deficiencies of the existing prescriptive building codes were emerged from this review and some suggestions were made for future revisions.

It would be directed to the area of new architectural features appearing lately in the city in the following chapters. First of all, attention would be paid on atrium design in Chapter 4, in which the reason for its popularity would be discussed together with its limitations, especially in fire safety aspect. Some local examples were also introduced.

It was concerned about the feature of internal building void in Chapter 5. Configurations of the building design and the reason leading to such design initiative were analyzed with its possible fire hazards brought about. Computer modeling carried out for a real residential development in the local area was discussed. It was followed by the simulated scenarios and the respective numerical results.

Extending the idea of using glass, double-skin façade becomes popular in the local area. The evolution of this architectural feature was discussed together with the fire safety problems associated with it in Chapter 6. Experimental study was carried out in two phases to examine the fire hazard of this design feature. Details and results of the full-scale burning tests was disclosed in Chapter 7.

Other than the new architectural features aiming to achieve green and sustainability, skyscrapers, especially the ultra high-rise buildings should be provided with additional fire protection in view of the World Trade Center disaster. Collapse scenarios and mechanisms of the incident were reviewed and discussed in Chapter 8. Recommendations on several aspects were laid down for immediate actions before the current fire and building codes have been upgraded accordingly.

How long a structure can stand without collapsing under post-flashover fire is critical in providing life safety. Fire resisting construction, in particular the requirements of fire resistance period, was focused in Chapter 9, where development of fire resisting construction, factors affecting the required fire resistance period, standard tests, existing regulations, etc. would be reviewed and discussed.

In view of the steel structure in WTC, the intumescent coating for structural steelworks, which appears widespread in high-rise buildings, was discussed in Chapter 10. It plays one of the key role in maintaining the structural stability of a steel structure. Application and determination of the thickness of intumescent coating were included and it was followed by the drawbacks of this kind of protective coating.

Performance-based fire codes currently under development is crucial in providing appropriate fire safety provisions to each single building in particular to those with innovative features. In considering the deficiencies of the existing codes and the vulnerability of the existing buildings in dealing with non-accidental fires, a fire risk assessment scheme is urged to establish in prior to the time-consuming development of performance codes. The scheme should be able to figure out the fire risk level a building encountering in a simple and speedy approach, and provide a basis for upgrades of fire safety measures for the existing buildings. A proposed assessment scheme was developed and included in Chapter 11.   Conclusion of this study was put into Chapter 12.

CHAPTER 2 NEW ARCHITECTURAL FEATURES

2.1 Introduction

The word “architecture” was first given definition by human being’s need for security, shelter and comfort (Pothorn 1983). For these simple functions, premises have similar design and their configuration could easily comply with the prescriptive statutory requirements which were developed decades ago, specified for several common building uses at that time.

However, the latest definition of architecture is changing with the sophisticated societal development as well as the advanced technology. Sheltering and security are no longer the only purposes for building construction. It is also expected that aesthetic quality be expressed with the old functional requirements in order to gain reputation by distinguishing itself from the ordinary designs. Having symbolic exterior, emphasizing verticality and transparency is one of the means to successfully promote the investment return. On the other hand, concerns on environmental protection and energy saving has been aroused among the construction industry due to the greenhouse effect and the abuse of energy consumption (Fordham 2000). Environmental responsive buildings are therefore widespread in most of the countries. Using less energy for thermal comfort and artificial light might lead to transformation on the physical appearance of the development, say higher window-to-wall ratio. Building constructions are therefore different from before, with varieties showing on the external appearance and also interior space.

To create an admirable building exterior and internal special quality, most designers like to manipulate the development with the transparent building material. Concrete buildings with windows of certain area ratio to the wall according to the building codes were commonly constructed years ago. However, commercial buildings with extensive use of glass appeared to be standard design lately in the financial districts, such as in Hong Kong. Not only aesthetic quality could be achieved, they would also satisfy one of the criteria on assessing the industry-wide green or sustainable building by maximizing natural lighting and reducing electricity consumption. As discussed in the literature (e.g. LEED 2002), green or sustainable buildings are designed to promote occupants' health with energy and resources efficiency, process started from design, construction, usage to maintenance.

In Hong Kong, a wide variety of building designs using glass, in the form of full height glass curtain wall, atrium, double-glazing, double-skin façade and etc, are standing in the urban area. Glass is recognized as a favorable building material due to its transparency and lightlessness. Glass curtain wall was commonly employed since decades ago and it was followed by the evolution of other types of glass design with environmental responsive consideration - double-skin façade to be the latest innovation. Extensive use of glass in terms of a wide variety of designs can be regarded as one of the green building types defined in the latest green building movement. There are many advantages in using transparent building material. Examples are provision of better views, introduction of natural lighting, reduction on energy consumption in temperate areas, promotion of productivity (Gratia & Herde 2003) and etc. For the developers' standpoint, not only the energy cost can be reduced, investment return can be also promoted by the favorable design.

Other than using extensive of glass, developers and designers are also trying to maximize the environmental performance of building and sales or rental price by other means. Internal building void, commonly found in the latest residential premises, is one of the examples. The bathrooms of such building are placed connecting to enclosed space instead of open to external air in order to increase the window size of living room through which more daylight and pleasant views can be introduced. The visual quality for the occupants can be promoted whilst the reliance on artificial lighting can be minimized. Similar to the glass design, it also takes both aesthetic and environmental issue into consideration.

Apart from using glass, outstanding appearance can be emphasized by the extreme height of a building. Ultra high-rise buildings are of particular interest in this study. Due to the high land price in the financial areas or limited land area in cities like Hong Kong, developments, both commercial and domestic, usually change the skyline by surpassing the original tallest building The symbolic appearance, sometimes with full height glass curtain wall, can stimulate the sales and rental price and also attract overseas investment to local area. The top position of the tallest building list is repeatedly revised by the newly-erected skyscrapers throughout the world.

However, too much emphasis is put on the environmental issue and investment return while the fire safety is suspected to be overlooked. Dangerous fire scenarios, threatening our lives to an immeasurable extent would be led by inadequate attention paid on fire safety of the new building designs. This point would be addressed in this thesis in order to ask for higher level of fire safety protection to our living space.

2.2 Green and Sustainable Buildings

Building green and sustainable is a hot topic in the construction industry lately. In the latest standard (ASTM 2005), green building or sustainable building is defined as:

A building that provides the specified building performance requirements while minimizing disturbance to and improving the functioning of local, regional, and global ecosystems both during and after its construction and specified service life.

Due to the extensive use of energy among the advanced and sophisticated societies, some adverse effects, like abuse of unrenewable resources, damage to natural environment and disturbance to ecology system, are found. Global warning on gas house emission has been announced. Buildings are one of the major users of energy, consuming about half of the fossil fuel (Fordham 2000). All these urge the need to construct the environmental responsive buildings. In fact, global movement for building “green” or “sustainable” has been processed and numerous organizations are initiated to promote the objective of it which encompasses energy and resources efficiency, materials selection, health protection, environment protection and so on (e.g. LEED 2002). Its importance in Hong Kong has been addressed by the Policy Address (HKSAR Government 2001) on environmental protection.

Green and sustainable buildings are two similar but different concepts, with one on regional basis while the other on global basis. To be more concise, the ranking of green is based on regional settings. A prototype which is a typical building in that particular region is utilized as a reference for assessment as well as the levels of “green”. Different nations have their own rating systems, say GBTool (GBTool 2005), an application developed in Canada by Green Building Challenge, and LEED Green Building Rating System (LEED 2002) developed by US Green Building Council.

However, it is thought that assessment by comparing to prototype is too slow in progress. Another approach which is termed as sustainability based on an absolute value is evolved. Energy and mass transfer are determined and made comparison to the absolute value that is evolved from taking account of, economic and politics issues, in addition to engineering and technology which are only considered in building green. However, both of them are trying to reduce consumption of energy and fossil fuel and minimize the harmful effect on natural environment.

Artificial lighting is the main electricity consumption in commercial premises while cooling load is found to be major energy killer in domestic sectors (Fordham 2000). The most direct means to cut down building used energy is by applying natural means instead of mechanical means to provide lighting or thermal comfort. Building designs aiming to effectively decrease the use of energy emerge throughout the world. Some of these innovative design features are selected in this study to demonstrate the beneficial and detrimental aspects. Examples include atrium, internal building void and double-skin façade. Note that glass is an extensively applied building material for building green due to its transparent characteristic and aesthetic quality.

2.3 Extensive Use of Glass

Symbolic buildings furnished with full-height glass curtain wall can be seen throughout the world. Hong Kong, being an international city and a financial centre in Asia, also possesses numerous landmark buildings with glazed exterior. However, because of the high land price buildings have to be built vertically upward to become ultra high-rise buildings (understood to be over 40 levels in Hong Kong). A state-of-the-art ultra high-rise building, surpassing the others to be the tallest locally and framing a new skyline of the city, is also furnished with full-height glass curtain wall, as shown in Figure 2-1a. An obvious comparison on the use of glass on commercial buildings is indicated in Figure 2-1a and 2-1b.

Extensive use of glass is not only found in commercial buildings, but also widespread at the latest residential developments, most of which are located in the new urban areas, as shown in Figure 2-2a. In contrary, domestic buildings in the old districts have a lower window-to-wall ratio than those in the new premises, as shown in Figure 2-2b. The use of concrete was popular decades ago on account of its price, availability, strength and fire resistance. The application of the glass panels at that time might be mainly for the sake of compliance to the building regulations (Laws of Hong Kong 1997a), where the minimum size of fixed lights and openings for providing daylight and ventilation were specified. Building designs in recent years would, however, consider a wide range of issues, including environmental contribution, architectural aesthetics and investment returns, and their interrelations. Glass is the material able to achieve all of these so that it is in favor by the building designers. Though there are requirements on the protection of openings where a barrier below them should be constructed of not less than 1.1 m high (Laws of Hong Kong 1997a), glass can also be used as the protective barrier which makes full-height glass external walls possible provided that the lower part is fixed. This gives flexibility to the innovative designs, such as atrium and double-skin façade.

Safety problems would be brought about by excessive stresses from wind loading or heat flux due to a fire on glass panels. Glass breakage is an important issue on building safety since shattered glass would cause injuries of occupants and also pedestrians. The breakage area provides an opening, supplying fresh air to give flashover or giving backdraft (Beason 1984) in case of a fire. Smoke or even flame can spread out to the adjacent areas through those openings.

Therefore the fire safety problems associated with excessive use of glass panels should be investigated.

The benefits and limitations of using glass as building materials are summarized in Appendix A.

There are a wide range of glass types in use, say clear glass, heat strengthened glass, wired glass, fully tempered glass and annealed glass, of which different characteristics are presented but no clear specifications are shown in the existing codes. It is necessary to understand thoroughly their properties before stipulating their uses in local buildings. Numerous works on mechanical or thermal performances of glass were reported in the literature (Beason 1984; Behr 1998; Cuzzillo & Pagni 1998; Shields, Silcock & Flood 2001) for overseas countries. Those data might be inapplicable to local buildings because of different living styles, climatic environment and convention of construction. In-depth studies for local practices should be carried out by making reference to the overseas investigatory results.

To comprehend further the current practice and fire safety problems on extensive use of glass, innovative designs originated from using glass are investigated. Atrium and double-skin façade are focused in the Chapter 4 and 6 respectively since they appear frequently in the latest designs and its contribution to the natural environment is assured.

2.4 Selected New Architectural Features

More attention should be paid to existing or future new designs which are not yet included in the existing prescriptive codes. Four new architectural features are selected for detailed discussion in this thesis. They are atrium design, internal building void, double-skin façade and ultra high-rise building design. A brief introduction on them is included in this section. Atrium design and ultra high-rise building design are not new idea in the construction industry when compared with internal building void and double-skin façade which appeared for several years only. The existing fire safety requirements are specified for designated building uses in the local codes (BD 1995, 1996a, 1996b) which were implemented ten years ago. It is not clear whether the existing codes will be revised for new features.

In this thesis, new architectural features are defined as those building designs appearing in the construction industry after the establishment of the existing fire codes, and having no additional considerations on their fire safety requirements.

With many innovative architectural features appeared, associated fire safety problems should not be overlooked. Some of them even hardly comply with the existing prescriptive codes. For example, green buildings are highly recommended to diminish the abuse of unrenewable fossil fuel in the world and also minimize damage to the global ecology system. Glass curtain wall can be one of the green building types due to its transparent property where solar radiation and natural lighting can be transmitted into the occupied space and thus decrease the consumption on heating load as well as artificial lighting. However, literatures (e.g. Shields, Silcock & Flood 2001) showed that glass might be a vulnerable building material when exposed to high heat environment. Excessive thermal stress on the glass surface and air pressure inside well sealed offices as in curtain walled building would break the glass. It becomes more dangerous to the occupants and also pedestrians in the street. Further, breaking the windows might give adequate intake air flow rate to burn up all combustibles to give a mass fire (e.g. Chow 2003b).

In addition, occupant load in some places such as shopping mall always exceed the design value. If smoke and flame spread through the atrium in case of fire, crowd movement and inadequacy on means of escape would give disaster. Ultra high-rise buildings like the World Trade Center twin towers would give difficulty in evacuation. Fire safety in those ultra high-rise buildings was pointed out recently (Chow 2004; 2004b). Additional fire safety provisions should be considered with great cautions for each special case.

Though existing building fire codes usually lag behind the development of new building design, the imposed fire risk resulted from the innovative ideas should be examined in advance to determine the provisions of additional fire safety measures. Potential fire risks associated with these new architectural features were the core of this thesis and were discussed in Chapter 4 to 8.

2.5 Atrium Design

Large-scale buildings often use "atrium" as a design concept. Atrium buildings have been applied frequently in the recent decades.

Atrium, an architectural feature in favor for decades, is also an extended idea from the use of glass with which architectural aesthetics, economic and environmental contributions are usually associated. Office buildings are commonly constructed with atrium all over the world. This will continue to be developed and applied to modern architecture, in particular, to large-scale buildings. There are many advantages in having an atrium. With appropriate design of glazed area of the atrium, heat transfer through atrium can benefit the thermal comfort of the internal occupied space (e.g. Ho 1996). Utilizing daylight would provide better visual quality and reduce the energy use on operating artificial lighting. Investment return can be also benefited from its environmental performance and favorable appearance.

However, atria also have their disadvantages and fire risks hidden behind. In respect of the open feature of atrium design, it arouses a disastrous issue that requests for cautious consideration in the design process. Smoke emitted from an accidental fire would spread rapidly through the atrium void and affect other areas, leading to immeasurable human and property losses. Therefore, fire safety aspects for atria should be paid adequate attention.

The openness of atrium could successfully create spatial quality which encourages human interaction. However, fire hazards are accompanying with this characteristic. The void spanning several stories would become an effective channel for the spread of smoke and hot gases in case of a fire. Smoke and flame are stopped spreading by the compartmentation walls which are specified in the local codes. It is envisaged as an effective means for this purpose in the traditional building with small compartmentation sizes. As regarding, atrium is often used as a social area where occupant load should be considerable. The rapid spreading of heat and toxic gases can cause life losses, human injuries and property damaged.

Though sprinklers are often installed at the atrium ceiling for those buildings constructed after 1987 when the FSI Codes (FSD 1998) required that sprinklers be installed in a wide range of building occupancies, it is ineffective for high headroom atrium especially when the fire occurs at atrium level or in the shops adjacent to the atrium space. Performance of atrium sprinkler were reviewed (Chow 1999b) in Chapter 4.

2.6 Internal Building Void

As stated in Building (Planning) Regulations Cap. 123F Part IV (Laws of Hong Kong 1997a), it is required to construct one or more windows in every room used for habitation in a building. In a traditional design, all rooms are arrayed on the perimeter of the floor area to achieve this requirement. In the latest years, designers advance the floor plan layout where kitchen and bathroom are placed in the middle of the floor area leaving more space for the living rooms and bedrooms. The required openings of kitchen and bathroom are therefore open to a shaft known as "internal building void" which connected all the floors and run through the full building height at the centre of the building. This design allows more desirable views and natural lighting be introduced to the living rooms and bedrooms.

There are concerns that internal building void would become a vertical channel to assist spreading of smoke or even flame. The stack effect inside the internal building void with small cross sectional area in multi-level buildings is significant.

For example, the cross sectional area of typical internal building voids is of the order of 3 to 7 m^2, with more than 100 m height. Stack effect induced by temperature differential between outside and inside would be significant enough to affect air flow.

Fire load in the bathrooms can be high enough to create a flashover fire, leading to a more risky scenario. In light of the existing building code (BD 1996a), window of the bathroom of the simulated building is not required to provide any FRP protection. When there is a fire, the internal building void, connecting all floors, acts like a fire drain (Harmathy & Oleszkiewicz 1987) through which flame and smoke might be able to spread from one level to the adjacent levels by pressure differential.

From the legislative and investment points of view, the design feature appeared satisfactory. Fire safety problem is, therefore, easily neglected. The potential fire hazards associated with the channel-like internal building void will be demonstrated by numerical experiment in Chapter 5 in this thesis. This can be one of the strong supports showing the hidden fire hazards in connection with the innovative architectural designs.

2.7 Double-skin Facade

Overheating may occur when solar radiation transmitting through the external glazed wall is trapped inside the occupied space. "Double-skin façade" is designed to minimize the shortcoming brought about by the use of glass on the external wall.

Use of glass is a kind of green building feature bringing higher percentage of daylight and pleasant views to the occupied interiors. With such advantages, it is expected that productivity of office workers can be promoted (Gratia & Herde 2003) and the rental price can also be raised provided that an optimum glazed area is figured out.

In a double-skin façade, apart from the glass panel enclosing the internal space, one more layer of glass wall is constructed externally with a distance in the range between 0.8 m to 2 m from the inner one. The cavity space shaped by the double glass skins becomes a vertical shaft connecting stories. Air flow induced by either natural or mechanical force is applied to bring away the heat built up at the cavity.

Similar to the internal building void design, the cavity space acting as an effective channel would assist in flame and smoke spreading which may be probable to endanger the occupants in area other than fire room. With two sides constructed of glass, a double-skin façade is appeared more hazardous than internal building void where only the window open to the shaft is of glazing material. Shattered glass pieces created from glass breaking under fire exposure already put pedestrians and occupants at risk.

Under certain circumstances, smoke and flame coming out from a fire room would probably impinge the inner glass wall of the upper floor, leading to the breaking of glass and endanger the adjacent occupied space. This happens to be the most severe fire risk.

There is not any requirement in dealing with such innovative design feature and lack of study concerning the thermal behavior of glass in a double-skin façade. However, this popular domestic design feature should receive further attention and in-depth study should be worked out when prohibitive resources are available. The glass types used for inner and outer skins should be taken into consideration in a cautious manner.

The depths of cavity, revealed to be a factor in affecting smoke movement inside the cavity, will be examined by a series of full-scale experimental tests. Other factors affecting the fire risks should be studied by full-scale burning tests when resources are available.

2.8 Ultra High-rise Building Design

Significant financial centres all over the world are standing with a large number of famed ultra high-rise buildings which maintain an eye-catching skyline and usually a marvelous night scene. Eight of the top ten tallest buildings in the world are built in Asia and Hong Kong is one of great examples possessing about one-tenth of the 100 tallest buildings around the world as reported (Emporis 2005).

In Hong Kong, premises, especially in the financial district, are compacted in the limited land area, which is also the reason for the increasing height of the latest developments. Most of these commercial buildings and sometimes domestic buildings are furnished with full-height glass curtain wall for its aesthetic quality and provision of natural lighting. As mentioned, glass would break and fall out under some fire scenarios, and hence the safety of pedestrians and vehicles in the street would be threatened.

Though ultra high-rise buildings (some are of over 400 m) somewhat symbolize advancement and affluence of the city, they would create some vulnerabilities in terms of safety aspect. The unforgettable World Trade Center (WTC) incident in 2001 has been the most serious catastrophe of ultra high-rise buildings. Concerns on the ultra high-rise buildings are aroused consequent to the disaster

(Chow 2004b). It is anxious that the super tall structure would be threatened again by terrorist attack. The collapse mechanism of the WTC incident will be discussed in Chapter 8 in order to understand the weakest point or deficiencies in the existing building design as a basis for the enhancement for fire requirements in the future.

It appears that most of the existing ultra high-rise buildings have been remained in good situation since they were being built. However, WTC twin towers were one of the exceptional examples. The investigations throughout the world (e.g. FEMA 2002) showed that the buildings were not designed against such kind of attack in which exaggerated collision force and fire load were imposed on the structures simultaneously. To provide higher protective level, building structure and fire safety protection must be extensively improved and upgraded. In fact, including non-accidental fires into the fire safety objectives is required for selective buildings before upgrading the existing building and fire codes. As excessive fire protection on buildings with lower fire risks would lead to unfavorable appearance or investment cost, the extent of fire safety provisions required should be decided carefully.

The collapse scenarios and possible mechanisms leading to the total structural failure of WTC twin towers will be also reviewed and discussed. Based on which, the priority of improvement for the ultra high-rise buildings in the areas of structure, passive building design and active fire protection systems is expected to be figured out.

2.9 Summary

Four new architectural features had been selected for further study. Some of them appear while studying this project. Some are found in existing buildings years ago but still without receiving careful considerations on fire safety requirements. New architectural features in this thesis are not necessarily coming out to the construction industry for only one or two years.

As reviewed, little attention was paid on their fire safety issue. There might be difficulties for the innovative designs to comply with the existing fire codes. It is necessary to carry out risk analysis for those building features preliminarily identified with additional fire risk, say using computational modeling and full-scale studies for verification. Upgrades of the prescriptive codes are essential and the developing performance-based codes become more appropriate in dealing with innovative building designs where fire risk analysis might be needed.

In this chapter, the general benefits achieved from new architectural features, of atrium, internal building void, double-skin façade and ultra high-rise buildings was outlined. Their potential fire risks were highlighted. Fire safety measures for the new architectural features were suggested to be updated.

CHAPTER 3 CURRENT FIRE SAFETY REQUIREMENTS ON HIGH-RISE BUILDINGS

3.1 Introduction

As discussed in Chapter 2, efforts were made on environmental performance of the new architectural features. The fire aspects of these features are not considered sufficiently. As experienced in many projects (Chow 2003a), there are possible conflicts between fire safety and environment protection. For example, double-skin façade would give better daylight illumination with less cooling energy in tropical area. However, there is a potential fire risk in spreading smoke through the air gap. In this chapter, fire safety of these features was discussed.

Fire safety requirements for the new architectural features are not yet taken care in current codes. Consequent to the tragedy in New York World Trade Center (WTC) in 2001 (FEMA 2002), fire safety requirements for high-rise buildings become a concern among the public.

High-rise buildings are defined in local regulations as (FSD 1998):

A building of which the floor of the uppermost storey exceeds 30 m above the point of staircase discharge at ground floor level.

Low-rise buildings are believed to be less risky when compared to high-rise counterparts since occupants can easily access a safe place. Therefore, focus is put on high-rise buildings in this chapter.

The well-known WTC twin towers were witnessed able to stand for about 1 and 1-3/4 hours respectively even they were strike by enormous impacts from the civil jetliners. Unfortunately, they were unable to arrest collapse from the extraordinary fire loading. Total collapse resulted from the big fire in the incident claimed thousands of human lives. Fire hazards from an ultra high-rise building, which is understood as buildings of more than 40 storeys locally, are especially severe as much more occupants are staying inside the building. Though the existing regulations and codes are only specified for high-rise buildings, they are also applied on ultra high-rise buildings. It is doubted that whether enforcing buildings with different dimensions by the same statutory requirements is appropriate or not.

The current prescriptive-based fire codes, therefore, should be reviewed to disclose whether they are inadequate for protecting the new innovative design and ultra high building structure.

Fire codes are now under reviews in most of the countries to find out whether the existing fire regulations are sufficient in protecting high-rise building, especially those ultra high-rise buildings, from the incident like WTC incident. In fact, several big fires (e.g. SCMP 1996, 1997; HKS 1997) occurred in the latest years already triggered some revisions on the local codes (e.g. Laws of Hong Kong

1998). If it is necessary to take account of terrorist attack fire as that in WTC incident, some more works should be carried out. For places like Hong Kong, as one of the busiest financial centres globally and possessing about one-tenth of the 100 tallest buildings in the world (Emporis 2005), it is of ultimate importance to review the local fire safety requirements to provide better safety environment.

In this chapter, fire safety regulations for new high-rise buildings in Hong Kong were reviewed. Codes and standards in China Mainland, UK and USA are also reviewed in order to make comparisons among different countries. These would be helpful in suggesting improvements and reconsiderations on the existing fire regulations. The definitions for different terms are reviewed and listed in Appendix B.

3.2 Local Fire Safety Requirements

Fire safety provisions are usually divided into "passive" and "active" measures. "Passive" ones means passive building design which include fire resisting construction (FRC) (BD 1996a), means of escape (MOE) (BD 1996b) and means of access (MOA) (BD 1995). Their functions are to provide sufficient means of egress from the building and sufficient means of access for fire fighting and rescue; maintain integrity of the building structure and prevent fire and smoke spreading when there is outbreak of fire. For the passive building construction, they are basically enforced by the government Buildings Department (BD). On the other hand, "active" means active fire protection engineering or fire services installation (FSI), such as fire alarm system, detection system, sprinkler system, emergency lighting, and fire hydrant/hose reel system. They are used to extinguish attack, prevent or limit a fire; provide access to any premises for extinguishing, attacking, preventing or limiting a fire. This part is taken charge by the government Fire Services Department (FSD).

There were several fatal fire incidents in commercial high-rise buildings in Hong Kong (e.g. SCMP 1996, 1997). In order to provide better protection from the risk of fire for occupants and users to certain kinds of commercial premises and commercial buildings, a Fire Safety (Commercial Premises) Ordinance (Laws of Hong Kong 1998) was issued. It covered the aged commercial premises where the fire safety provisions were installed based on the old fire codes. By upgrading or improving the MOE, MOA, fire services installations and equipment, the current codes can then be met.

Other than upgrading for the commercial buildings, there is Fire Safety (Buildings) Ordinance (Laws of Hong Kong 2003) for aged composite buildings and domestic buildings. It also aims at providing better protection from the risk of fire for occupants to certain kinds of composite buildings and domestic buildings by provision of or improvements in MOE, MOA, fire services installations and equipment.

Basically, other than the two key areas passive building design and fire services installation, fire safety management is considered to be important as addressed by the Chief Secretary of the government in 1998 (GIC 1998). Currently, fire safety management only focuses on maintenance requirements for various fire services installations and keeping escape routes free from blockage (Tsui & Chow 2004). Other aspects in fire safety management, such as staff training, fire action and fire prevention, are not yet established except for few building uses, say schools, homes for elderly and karaoke establishments.

3.2.1 Local requirements on passive building construction

Passive building construction includes FRC, MOE and MOA. In the local Code of Practice for Fire Resisting Construction by BD (1996a), the requirements for fire resistance period (FRP) and compartment volume are specified. Whilst, the minimum number required and dimensions of the elements of MOE and MOA are specified in the code of practices for MOE and MOA (BD 1996b, 1995).

- Requirements for fire resisting construction

FRP is an important factor for fire safety. The general grades of FRP are 1 hour, 2 hours and 4 hours which were developed from overseas researches decades ago (e.g. HMSO 1946). In local code (BD 1996a), the required FRPs for every construction elements, compartment walls and floors within each compartment are specified for different building uses, as listed in the code. For domestic buildings, hotel bedrooms and offices, a minimum FRP of 1 hour should be provided. On the other hand, at least 2 hours should be provided for industrial buildings and warehouses. For compartments in basements, the FRP should not be less than 4 hours.

Elements of MOE and MOA are specified with adequate FRP. All the enclosure of liftwell should be separated from other parts of the building by a minimum of 2-hour FRP. Any door to a liftwell wall should have an FRP of not less than 1 hour in terms of integrity and insulation.

All required staircases and lobbies connected to the accommodation of the story should have an FRP of not less than that for the construction elements of the compartments next to them. “Non-combustible” materials should be used for staircases enclosure. Internal corridor and balcony approach corridor serving rooms in separate occupancies should be protected by an FRP of not less than 1 hour. The doors on them should have an FRP longer than half an hour. Comparisons with other codes were made in section 3.3 of this chapter. Requirements on the fire resisting constructions are compared first in Table 3-1.

Buildings with a big space volume should be divided into different compartments by structural elements in order to limit the spread of fire and reduce the number of persons exposed to the fire. As stated in the code, the maximum compartment size is specified according to their cubical extent. The maximum compartment volume allowed is 28000 m^3 for spaces above ground, but it is reduced to 7000 m^3 for underground spaces. The above fire compartment size is allowable to increase if an equivalent fire safety standard is achieved. The requirements on compartment size for local premises and overseas buildings are listed in Table 3-2.

- Requirements for means of escape

The number of staircases required in local high-rise commercial buildings is determined by the occupant load of each story, which can be assessed by prescribed factors for different occupancies stated in the code (BD 1996b). The various intended uses of a building or a story are categorized by a factor, namely the usable floor area per person A_{per}. It varies from 0.5 m^2 per person for assembly halls to 30 m^2 per person for warehouses. Normally, it is not acceptable for buildings having more than six stories or more than 17 m high to have just one single staircase; at least two staircases must be provided. For non-domestic single-use buildings, occupants should be able to gain access to the other staircase without passing through some private areas, when they are using one of them. Staircases are not permitted to continue down to any basement levels. At least two exits are required in each basement. In Table 3-3, the requirements on escape routes, including the minimum number of exit doors and exit routes, are listed according to the capacity of the room or storey. In addition, a comparison on the minimum width and number of staircases among all codes is shown in Table 3-4. Discussions on these will be carried out in section 3.3.

The minimum width of exit routes, determined by the occupant load, is also shown in Table 3-3. Where at least two exit routes should be provided in a premise, the width for the exit route or stairway should be at least 1050 mm. More specifically, stairways serving not more than 300 persons from a story should be at least 1.2 m wide, while for those serving more than 300 persons, their width should be at least 1.5 m. The clear height of all staircases is 2 m.

The distance of escape route is a key issue in the MOE code. The measurement of it is divided into 2 parts:

- Direct distance: measured from any part in a room to the centre of the exit door of the room;
- Travel distance: measured from the exit door of the room to the centre of the fire door of an exit stairway.

The requirements on the distance of escape route are different when it is applied on different uses of the premises and three different exit route approaches including the balcony approach (with ventilation), internal corridor (without ventilation) and a type other than those mentioned above. The first approach deserves the largest travel distance and direct distance. For offices, shops and schools, the maximum sum of the two distance measurements is 45 m, 36 m and 30 m for the three approaches respectively. In all other cases, they should be 36 m, 36 m and 30 m instead. The travel distance limitation is shown in Table 3-5, with comparison made to the other codes.

- Requirements for means of access

Other than the means of escape, there are requirements for the means of access. For high-rise buildings, at least two access staircases for the access of firefighters should be provided (BD 1995). The number of access staircases required is identical to that of the escape staircases. Staircases, in this respect, can serve for these two purposes. At least one fireman's lift is prescribed to construct within 60 m from any floor for buildings with two or more lifts.

3.2.2 Local requirements on fire services installations

Fire hydrant/hose reel systems must be provided in high-rise buildings and located within 30 m from any part of the building. The actuating point of the fire alarm system should be located at each hose reel point with the installation of an audio warning device.

Sprinkler systems are required in most of the non-residential buildings and they should be installed at every part of the building, including staircases and corridors. For a ventilation system in the building, an automatic cut-off system should be provided to stop the mechanically induced air movement.

An independent emergency generator should be provided. In the whole building and at all escape routes, emergency lighting and exit signs should be available. Artificial lighting is required to reach 30 lux at floor level of the exit routes. In case of the normal lighting fails, emergency lighting should provide a minimum of 2 lux at floor level.

3.3 Comparison among Codes in HK, China, UK and USA

The requirements in Mainland China, UK and USA are included in Appendix C.

A brief comparison is made among the building and fire codes in the Mainland, Hong Kong, USA and UK after review. A summary is shown in Table 3-6. The following are the key points:

- Mainland codes, local codes and the US codes have explicit definitions on high-rise buildings. The critical height for a building classified as high-rise is 24 m for the Mainland, 30 m for Hong Kong and 22.9 m and 23 m for USA; those in UK are 18.2 m and 30.5 m.

- On the classification of high-rise buildings, there are two well-defined types with specified fire safety in the Mainland (GB 50045-95 2001; Ma 1995). In contrast, high-rise buildings in other codes and regulations are classified according to their intended usage for determining the fire safety provisions.

- FRP requirements of construction elements are defined according to the classified building types (GB 50045-95 2001) in the Mainland. However, an FRP of 2 hours is the basic requirement for construction elements in Hong Kong (BD 1996a). Values of FRP might be different and be specified individually for special cases. FRP requirements in Approved Document B and Fire Precautions Act are defined by purpose groups or their intended functions instead of structural elements. In the IBC (ICC 2000), FRP requirements are based on types of construction and occupancy groups. However, NFPA 101 specifies FRP for elements of construction according to NFPA 220, in which each construction element is further classified by different materials.

- Building compartments are specified in terms of floor area in the Mainland codes, Approved Document B and NFPA 101 (GB 50045-95 2001; Ma 1995; ODPM 2004; NFPA 2000a), but in terms of space volume in Hong Kong (FSD 1998). In all of the places, separation of usage is applied for different compartments. No compartmentation requirements are mentioned in Fire Precautions Act (HMSO 1989a) and IBC (ICC 2000).

- The required number of staircases is determined by the number of fire compartments in the Mainland (GB 50045-95 2001; Ma 1995). The number of persons in a floor is used to determine the required number of exit routes (staircases) in Hong Kong, UK and USA. The required number of staircases is also dependent on the travel distance as prescribed in Fire Precautions Act (HMSO 1989a) and IBC (ICC 2000).

- The required number of fireman's lifts is determined by the floor area of a storey and a maximum of three are required in the Mainland (GB 50045-95 2001; Ma 1995). The exact locations of the lifts are not specified, only suggestions were made in the codes. In Hong Kong, only one fireman's lift is required in buildings having two lifts (BD 1995). The maximum travel distance between any position in a building and the lift is specified to be 60 m. In Approved Document B, the number of firefighting shafts which contain firefighting stairs, lobbies and lifts is determined by the floor area. Only buildings with a floor higher than 20 m above ground or basement at 10 m below ground should have firefighting shafts including firefighting lifts. At least one firefighting shaft is required by a floor area of less than 900 m^2. There is no requirement of firefighting lift specified in Fire Precautions Act (HMSO 1989a), IBC (ICC 2000) and NFPA 101 (NFPA 2000a).

- As specified in the local codes, Mainland codes and Approved Document B, the air-conditioning and mechanical ventilation system of the fire compartment must be shut down in coordinate operations with the smoke control system (FSD 1998). However, it was not mentioned in Fire Precautions Act (HMSO 1989a), IBC (ICC 2000) and NFPA 101 (NFPA 2000a).

3.4 Some Recommendations

Fire safety codes for high-rise buildings in different places were reviewed. Comparisons with the fire regulations in Mainland China, UK and USA were made. These are useful in understanding the present fire regulations for fire safety in high-rise buildings.

In the local codes, alternative approaches other than prescriptive one offering the same fire safety are accepted (BD 1996a) for the buildings of special hazards due to their size, height, use, design, construction or location. However, prescriptive-based is still the main approach (Walters & Hastings 1998).

Minimum requirements based on the size and building uses are specified. The incremental legislation is developed after each time a big fire had occurred. The new requirements will be added as an extension to the existing building codes.

In this sense, the traditional prescriptive-based codes might not give a safe environment when the building is under fire exposure. Some considerations might be taken into account to promote fire safety and enhance existing requirements.

- Fire behaviour of materials should be considered. Results measured from fire tests on building materials and products such as the cone calorimeter (Babrauskas & Grayson 1992) and the ISO 9705 room-corner fire tests (ISO 1997) should be referred to. These tests give information on burning materials including heat release rate, flame spread, and their contributions to flashover. They are the modern fire test methods much more suitable than those older flammability standards in assessing new materials and products.

- Full-scale burning tests should be carried out when necessary. For instance a PolyU/USTC atrium was constructed (Chow et al 2001) for performing experimental studies. From which, the actual smoke filling process, transient development of smoke layer thickness, smoke extraction rate, the performance of fire protection design and so on were achieved.

- Establishment of engineering performance-based fire codes in Hong Kong (e.g. Chow 1999) is urged to be accelerating. For example, operating a sprinkler system in a high headroom atrium will give smoke logging and produce large quantity of steam. The system should not be installed without a careful planning in evacuation. Overseas codes (e.g. BS 2001) can be made reference to facilitate the development of our local code.

- Currently, fire safety management only focuses on maintenance requirements for various fire services installations and keeping escape routes free from blockage (Tsui & Chow 2004). Implementation of fire safety management should be more comprehensive. A fire safety plan should be worked out. There should be a maintenance plan, a staff training plan, a fire action plan and a fire prevention plan (Malhotra 1987) including information, such as safety management structure; actions to be taken in a fire emergency; fire drills; housekeeping; staff training; record-keeping and so on (BS 2001). Respecting the fire safety plan by following the scheme closely is of ultimate importance. Training of fire safety managers and wardens; and regular tests on all fire safety measures should be executed. It is dangerous to keep the fire safety plan in shelf rather than to put it into operation.

CHAPTER 4 ATRIUM DESIGN

4.1 Introduction

Buildings in advanced countries consume too large an amount of energy for human comfort. Most of the energy is unrenewable and the consumption of them produces greenhouse gas. These will eventually affect the global environment adversely. Therefore, it is of top urgency to develop sustainable buildings. Energy abuse would also dramatically increase the expenses for operation and maintenance if natural ventilation, daylighting and thermal control of the building are not designed carefully.

Atrium is regarded as an environmental friendly design and become popular in the recent decades (Saxon 1986). They are commonly found in large-scale building development like shopping malls or office tower. It is one of the earliest strategies for getting better comfort for internal space by using less energy. For example, warming effect in winter and utilization of natural lighting for glazed roof together with appropriate design would reduce energy consumption (Saxon 1986). Except its environmental responsive contributions, there are also other beneficial reasons, from architectural and economic viewpoints, for its increasing use. The advantages and the potential problems of this design feature will be outlined in this chapter, following the discussion on its development history in section 4.2. After reviewing the existing types of atrium, some design considerations are proposed for improvements in new projects with atria with some local examples included.

Behind the favorable contribution atrium would have to the sustainability of buildings, fire safety should not be neglected. The open feature of atrium would allow smoke spreading easily through the space where social activities are common as designated and to the adjacent levels. The fire safety problem brought about will be discussed at the end of this chapter.

4.2 Evolution of Atrium

The term "atrium" was first used in the Roman house for a large central space open to the sky (Kent 1989). It has come, gone and come around again in the history. The Roman Atrium was composed by a grand entrance space, a focal courtyard and a sheltered semi-public area. Building materials used were limited to masonry and timber. As pointed out in the literature (Kent 1989), the Roman house was isolated from outside, but with some interaction. This is a complex and contradictory concept. The house left the facade blank and turned inward to the courtyard where noise and dirts were isolated. Inhabitants in houses opened to the atrium needed to pass through that common space to go inside or outside. There must be many reasons for its periodic rebirth. Social qualities and architectural sense of liberation may be one of them. An "atrium" is a tall indoor open space, with part of it connected to the outside environment (Process Architecture 1989). Its development can be divided into four periods:

4.2.1 Early 19th Century

The atrium consisting of a covered court, arcade, galleria and wintergarden came into use in the western world in the 19th century (Saxon 1986). New technology for constructing the roof over the picture gallery at Attingham Park, Shropshire was developed by the innovative architect, John Nash (Saxon 1986), in 1806. There, iron and glass technology were used to build the first “modern” atrium.

Greenhouses, utilizing solar radiation passing through glasses, also appeared early in the 19th century. This technological development is an illustration of industrialization of construction and artificial control of climate. Basic passive solar storage techniques, shading, insulation shutters and blinds, and auxiliary hearing systems were developed. The empirical thinkers approach to the idea of large glass enclosures had greatly influenced the development history of atrium buildings.

The Industrial Revolution had given rise to buildings with huge, open and glazed spaces to create dramatic effect in stores, markets, railway stations, conservatories and exhibition halls, such as the Crystal Palace (1850-51) (Kent 1989), by Joseph Paxton in England.

4.2.2 Late 19th Century

A new type of atrium emerged in America near the end of the 19th century. Burnham and Root’s Rookery atrium (1886) in Chicago (Kent 1989) was transformed from an ordinary light well to make better use of the natural light.

It thus became a lively interior street with shops at the ground floor and mezzanine.

4.2.3 Early 20th Century

In 1905, Frank Lloyd Wright (Kent 1989) arranged the office space of the Larkin Building in Buffalo, New York (1903) with four open-sided levels around a sky-lit court, and introduced filtered air into it. The whole building had a single interior volume, and was turned inward away from the city to give an uplifting space for the office workers.

Wright remained interested in the flow of space from level to level. He bridged the gap between the first modern atrium period and the second. There was a top-lit space, with two or three levels of galleries around the entrance lobby and main office space in the Johnson Wax headquarters in Racine, Wisconsin (1936) (Saxon 1986). At that time, Wright was almost alone in using that concept. The V C Morris store in San Francisco (1949), and the Guggenheim Museum in New York (1959) are also top-lit buildings with focal central spaces.

The definition of atrium changed as construction technology developed to give longer span, better enclosure and shelter. New atria without glass ceiling but sit beneath towers were built. There were atria found at higher levels of skyscrapers rather than building from the ground (Kent 1989). A new idea is to have atrium that can be stacked, off the ground and not open to the sky as in Figure 4-1.

4.2.4 Late 20th Century

Two buildings announced the second revival of atrium. One of them is the Ford Foundation by Kevin Roche John Dinkeloo and Associates (1967), and the other one, which is a more influential one, is the Hyatt Regency in Atlanta (1968) by John Portman (Kent 1989). A covered central court was first called an atrium (Saxon 1986) as in Figure 4-2.

The former has a square plan with a 8,500-ft^2 internal garden. Offices occupy two sides all the way up to the 12 levels, forming an L-shape on the perimeter. Some offices are facing the atrium with the other sides facing the city. Glass was put at the other two sides to provide natural lighting; and to give an effect of opening to Manhattan. The sense of accessibility was reinforced by constructing the elements as in above.

The architect of Hyatt Hotel, John Portman, who was much inspired by the John Wax headquarters, the V C Morris store and the Guggenheim Museum, intended to provide a socially stimulating environment. A sun and rain canopy was put over courts but with natural ventilation provided simultaneously. There are areas for catering and sight-seeing. On the other hand, Portman was also the pioneer to adopt the wall-climber elevator. That was not enclosed in a shaft, but exposed to the atrium, giving the atrium a dynamic quality as the lift cars travelling up and down. The Hyatt Hotel, introducing a sense of joy and spirit, deserved much appreciation on the entertaining atmosphere and had achieved great commercial success.

Architects afterwards were inspired by Portman and tried to simulate the social atmosphere to their shopping mall design (Kent 1989). The number of enclosed centres then increased rapidly. At the same time, they made compact and multi-level atrium design to save money on climate control (Saxon 1986). In order to anchor attractions at the top of the multi-level shopping centres, architects had to shift the visual emphasis from the horizontal (galleria) to the vertical (atria) and provide eye-catching transport in the open wells. Parking, food courts, leisure uses or department stores were being used as the attractions at the top. A high placing of these elements gave the occupants potential views and much more interactions with the atrium well.

4.3 Architectural Aspects

4.3.1 Merits

Atrium building contributes numerous possibilities to urban design. It can deal with an awkward site easily as an atrium inserted allows any creative shape of the building in order to incorporate harmoniously with the site. In addition, for the use of land, the same floor-space could be presented in relatively low buildings by arranging them around the perimeter of a site. That is to say, if two sites have the same built volume on them, the tower stands on its own at the centre will be three times higher than the court one sitting on the verges. This results in more efficient use of land with less expense and discomfort.

Apart from the above, atrium is also regarded as a tool for revitalizing the aged buildings. As mentioned in the previous section, atrium can be put into an existing building, or a roof could be put over several buildings to link them up and end up with unification. Connections may also be made at the levels above ground to separate the pedestrian and traffic on the ground level, thus decreasing the possibility of accidents. Meanwhile, it enables preserving the cultural heritage instead of demolishing some treasures thoughtlessly.

Moreover, the concept of revitalization can be expanded outwards to the local area. Apart from redeveloping the buildings one by one, designers have another innovative idea: building an atrium in a redevelopment area as a device to stimulate the revival of the surrounding areas. This also leads to the result of mixed-use development. One of the examples is The Winter Garden, Niagara Falls, by Cesar Pelli (Saxon 1986). A big greenhouse was designed (Saxon 1986) to give a typical atrium surrounded by other types of buildings developed later. To a large extent, this atrium successfully tied the whole city back and became the city centre.

By renewal of buildings or adding a roof appropriately, an atrium could already provide urban comfort, which largely depends on the pleasure of human interchange. Sheltered area and a place to gather can promote the interaction of the occupants. For example, the great popularity of Regency Hyatt Hotel designed by John Portman, as described in the previous section, was stimulated by the creative design of covered courtyard located in the centre of the building. People were much attracted by the intimate and pleasant atmosphere created deliberately. In an information society, cities are a place where information is produced, exchanged and processed. With the advancement of technology, information exchange seems to be proceeded via electronic media much more than by face-to-face human contact (Process Architecture 1989). Therefore, an atrium must devise a means for people to gather and exchange information and knowledge to create a humanistic environment to recover from technology-induced stress. Besides providing a comfortable spacious area, musical performances, exhibitions, shows and some other events can be held at the atrium, which may consequently turn it into a cultural centre as well. It is also the focus of activity in the building itself. The openness of the atrium gives occupants an excellent visibility to look all around in the atrium and the adjacent spaces, and also a more clear perception of the accessibility to every space. For the occupants, they prefer to look over the controlled interior environment rather than the exterior view i.e. awkward parking lots outside.

4.3.2 Demerits

As architects redirected their attention onto atria as spaces that they can control, the outside environment and the outer edge of the space seemed to be disregarded (Jackson 1997). Efforts were paid on designing the interior by turning it into a covered street, making it become a weather-protected public space. Entertaining elements were put into it. People were “pulled” to the atrium due to its attractive and elegant features. As a result, designers only leave the facade blank or leave it as not matching with the interior space, therefore, downgrading the architectural features of the exterior (Jackson 1997). People are then discouraged to go outdoors and the reality of outside world is being blocked out. This creates a discontinuous and unbalancing district. In this sense, atria become harmful in the urban environment if they are designed in such an “introverted” way.

4.4 Environmental Aspects

4.4.1 Merits

In order to attract people to go into an atrium and enjoy the space, spatial quality and relaxing atmosphere are not the whole. Thermal comfort and daylighting are, on the other hand, the most influential factors for this issue.

In passive atrium design, the building form primarily affects the amount of heat transfer between the atrium and the surrounding environment. Four types of atria, namely centralized, semi-enclosed, attached and linear forms are shown in Figure 4-3. Among the four generic types, centralized and linear atria have the greatest capability in reducing the temperature fluctuations and their overall temperature performance remains closest to the neutral temperatures (Ho 1996).

With the roofing of spaces between buildings, the more comfortable “outdoor” spaces were created. A study by Hastings and Rubery (Saxon 1986) on putting glass canopies across streets found that the canopies can cut the heat loss of the adjacent buildings dramatically. They store the solar heat at the building surfaces and the street pavement in winter while, on the other hand, provide shades on the walkway and induce air movement with the application of ventilators in the canopy. This kind of beneficial effect is called "buffer effect" (Saxon 1986).

By covering a court and converting it into an atrium, the temperatures of the atrium are higher than the ambient temperatures throughout the year. The marked increase in the space air temperature is important when designing heating systems in winter. However, the thermal comfort is also greatly contributed by the glazing. Glazed areas in the internal atrium facades affect heat and light transmission between the atrium and the adjacent buildings. By increasing the glazing area in the internal atrium facades, the atrium air temperatures will increase slightly in winter. It is due to the heat and mass (of air) transfer induced by temperature differences between the warmer building and the cooler atrium. In summer, there might be air motion and heat transfer from the warmer atrium to the cooler main building. It has greater effect on the more enclosed atrium. A more efficient way to achieve thermal comfort by using glazing is to vary the amount of glazing according to the solar gains on the internal atrium facades. More glazing can be placed at the corners and at lower levels where daylight and solar gain might be small due to self-shading from the main building and shading effect from adjacent buildings (Ho 1996).

Daylighting is an important issue, in particular, in non-domestic buildings, for visual comfort and energy saving. Despite lighting efficiency has been gradually increased, lighting is still the major source of energy consumption in many large-scale buildings. Atrium can be a source of daylight as its high transmittance glazing material transmits light into the interior space. The availability of daylight in an atrium and in a traditional building is compared in Figure 4-4. Furthermore, the light will be reflected by the highly reflective atrium wall, or some obstructions and external building surfaces, to the adjacent rooms (Baker 1988). For a working plane in an office, illumination level should be between 300 and 500 lux. Good availability of daylight would give a value close to the requirement. Integrating daylighting with artificial lighting system and the reflected internal finishes of the occupied space would provide visual comfort with less energy.

4.4.2 Demerits

Huge atrium would give a lower air temperature in winter and a higher air temperature in summer (Ho 1996). The total heat loss through the external glazing is higher than the solar heat gain in winter, leading to an increase in winter heating load without providing thermal radiation to the glazing. However, atrium will also be overheating in summer time. Mechanical air-conditioning systems are required to cool down the high air temperature due to solar gain. Therefore, a balance is often needed between the optimum amount of glazing for passive solar heating purposes and that required to limit heat loss. On top of that, large glazing ratio will result in glare, which will make occupants feel uncomfortable too.

4.5 Economic Aspects

4.5.1 Merits

Atrium buildings cost less to build than ordinary buildings of the same size as they use less construction elements, fewer elevators and stairs. Also, they can be built in a shorter period of time, thus reducing the effect of inflation due to long-term construction and reducing the amount of interest to be paid. Apart from the capital cost mentioned above, revenue cost and investment value are the essential factors to be considered (Saxon 1986).

Energy cost is the only one of those comprising operating costs that will vary materially. It will be lower in well-designed atrium buildings. As discussed earlier, artificial lighting is currently the largest single energy user, introducing daylight effectively and integrating it with artificial lighting instead of leaving the lighting on all the time can reduce the electric power considerably. As reviewed, the overall energy needed for atrium buildings is only about one-half to two-thirds of that for other buildings.

There might be size limits on sites due to urban planning for traffic and services accommodation. Atrium would give a better gross floor-space (or plot area ratio in Hong Kong) (Laws of Hong Kong 1997a).

In addition, the return of atrium design is reinforced by the potential of using some of the floor space for retailing. Public plaza can be provided in an atrium building or a podium atrium grafted onto a tower. Some levels of the building may be able to sustain shops and restaurants, that adds to the attraction of the office space and even the whole development, and thus gaining more profits.

Moreover, atrium has a longer building perimeter so that more offices can have better views in comparing with other types of buildings. This leads to higher rental price.

Hotels, trade marts, office buildings, shopping malls and, especially, combined and multi-use developments, have exploited the atrium concept since the late 1960s. Atrium office building is, thereby, proved to be the most prevailing type of building with its outstanding returns discussed above.

4.5.2 Demerits

Though the atrium form seems to have brought many economical advantages to the building owners, it does have some disadvantages. First, atrium is not suitable for smaller sites. Secondly, it is not common for the atrium floor to have long-term tenants, apart from short-term renting for exhibitions and performance shows. Also, the access corridors will be too long, which is distracting for the small office tenants. It actually results in poor net/gross area efficiencies (Benyon 1982). All these are the points that designers have to further consider in future designs.

4.6 Design Considerations

As discussed in the above sections, beneficial points contributed by atrium buildings and the interests of the designers have led to continued use of the atrium concept in the sophisticated urban cities. Nevertheless, there are still some problems affecting the efficiency in the existing atrium buildings. It is of utmost significance to tackle all the detrimental factors that lower the adaptability of an atrium building because of the rapidly growing amount of atrium design throughout the world. These are discussed below and suggestions are made.

Modern development has been a disaster for the characters of most established urban cities. Original well-defined streets were changed (Saxon 1986).

Disregarding the outside world of an atrium is actually destroying the harmony of an urban face, and that results in a hotchpotch of disparate elements. People are not living inside a building only, but are moving around in the whole city. Architects should make sure that their exterior architecture does not just equal to the interior, but has a slight edge over what they did inside, so that people would be encouraged to stay outdoors also. The façade has to match with its own interior space, and contribute to the public.

Environmental aspects have to be considered at the design stage. Utilization of daylight and natural ventilation through windows might lead to higher solar gain and more discomfort glares. So, in practice, in the real world outside, the aesthetic aspect becomes the main determinant of a building design rather than the actual functions. An atrium can be shaped as a daylight collector and distributor, with space arranged around it to take this advantage. Similarly, an atrium can be oriented and shaped to give shade or collect heat as required for thermal and ventilation benefits. The huge space volume can be used intelligently with an optimum air-handling strategy.

Determinations on the location of an atrium should be dependent on whether a warming or cooling atrium is required, and the climate which it has to stand. Most light is available from the top, in all latitudes, and a skylight will be the most cost-effective way to collect daylight. Solar collection will be simple through a skylight, but the most heat will be collected when least needed, in summer. In cool temperate climate, an equator-facing glazed side wall used to collect lower-angle sunlight is desirable while, on the other hand, a roof-light which can be shaded from high-angle solar-penetration and deliver considerable quantities of reflected light is preferable in warmer regions.

It is not recommended to construct east- and west-facing atria because they admit low-angle sunlight in summer and are hard to shade. In winter, their heat loss is much more than the equator-oriented equivalent. Polar-oriented walls are adversely valuable in tropical areas at lower latitudes as they receive skylight without solar penetration.

Apart from the orientation of the atrium, landscaping as well as internal walls and light shelves will introduce diffuse and reflected light to the interior spaces. Architects should pay more attention to these elements, especially the reflective walls. Light intensity will be diminished at the bouncing process too (Saxon 1986).

Furthermore, active shading devices, louvres, blinds, extractable roof and low-E glass, etc. are means to solve the problem of overheating. However, solar-shading to prevent overheating of occupied spaces is better provided on the windows inside the atrium. Shading in the roof itself would reduce the transmission of diffuse light under overcast skies.

The most important concern for building owners is, of course, the budget for the development. For the site limitation, it may not be easily overcome. However, if designers can put more effort in the energy-saving design, the decrease in energy costs may already compensate the excessive expenses in construction. Retailing space also has the potential to enhance the return from the atrium design. It either produces a far higher return for the same investment, or it can be built at a cost higher than the tower and still gets the same return.

4.7 Local Examples

Over hundreds of atrium buildings have been built in Hong Kong in the last two decades. Developers favor this new architectural design feature because on top of the advantages discussed earlier, it not only satisfies the permitted plot ratio, but it also creates dramatic indoor public spaces for social functions. They are found in banks, hotels, commercial buildings and shopping malls.

There are lots of famous buildings constructed with an atrium:

- Bank of China Tower (Building Journal Hong Kong China 1990), designed in the 1980s, had once been the tallest building in Hong Kong. This 70-story skyscraper as shown in Figure 4-5a has no internal column but supported by the building envelope. An ingenious steel and concrete megastructure is composing one loadbearing and one wind-resisting structural system, all the loads of the building are being channelled to the four reinforced concrete corner columns finally. Not only can an unobstructed open space be created, the resistant capability to wind loading can also be reinforced by the structure. Using less structural elements resulted in dramatic reduction in construction time and use of materials (Building Journal Hong Kong China 1990). The vertical void inside the tower creates a 17-story high atrium as in Figure 4-5b that ends with a 8-story high sloped skylight. Natural light filters into the interior spaces through the heat-reflective glass curtain-wall mounted onto the entire building surface. This specific glass is used to maximize natural lighting while cutting off the undesired heat gain which will lead to an increase in cooling load.

- Daylight was attempted to provide into the deep-plan of Hong Kong Bank

Headquarter (outside view as in Figure 4-6a) at the beginning of the design process. Finally, the project ended up with a 10-story high atrium (as in Figure 4-6b) in the centre of the building, being underneath office floors but not open to the sky. A "sunscoop" device (as in Figure 4-6c) was utilized to direct daylight into the interior building (Building Journal Hong Kong China 1985; Magnago Lampugnani 1993).

- Another excellent built project The Palace Mall as shown in Figure 4-7 is a grand underground retail complex with a glass entrance hall on the ground level. It is the foremost shopping mall buried in the ground in Hong Kong. A double-story atrium space is located underneath the glass house and so daylight can penetrate the glass hall and reach the atrium and the nearby shopping arcade. However, the atrium is attached to one side of the whole shopping mall and thus the opposite side is unable to enjoy natural lighting. It can only rely on artificial lighting (HKIA Journal 1998).

  The splendid curvilinear roof and entrance hall are completely made up of glass structure and there may be glares irritating occupants. Trees in Salisbury Garden surrounding the glasshouse could provide sunshade to it. The articulation of atrium and the retail area of this project, as a result, creates a monumental landmark and somehow energy conservative building if daylight and artificial lighting can be well integrated.

As observed, natural ventilation is not provided in most of the local atrium buildings. Dense urban environment means buildings are erected too close to one another that it is difficult to design good strategies for wind-induced air movement. Stack effect is not so significant in comparing with temperate countries like Canada as the temperature difference between internal and external air is not so high. Winter temperature of 5°C outdoor, and indoor temperature of 18°C would give a stack pressure difference of 17 Pa for a vertical height difference of 30 m. For Canada, stack pressure difference might be 54 Pa for the same 30 m height difference as temperature outside might be -20°C, and indoor temperature 18°C. Air draft due to hot glazed roof might not be welcome. In addition, poor outdoor air quality discourages the use of outside air without suitable treatment. All these create problems to the architects on using natural ventilation, and so atria are still relying on mechanical ventilation and air-conditioning system.

4.8 Fire Safety Aspect

Although atrium design is beneficial in the architectural, environmental and economic aspects, there are problems on fire safety. "Open" through many levels is not good design in comparing with conventional buildings with compartmentation design. Fire and smoke can spread rapidly (as shown in Figure 4-8) in the huge atrium space and adjacent levels, leading to life losses, human injuries and property damaged. Note that most of the life losses in fire were due to smoke rather than heat (Hansell 1987).

However, atrium is not classified as a special type of building in the local prescriptive codes. There, fire safety requirements are prescribed by building type (Chow & Wong 1998). There are no tailor-made codes or regulations specifying the fire safety requirements for atria. Hong Kong government is now open-minded and allows the application of engineering performance-based fire codes for cases where the existing fire codes are not adequate.

Further, different levels of the atrium would be used for different functions such as a food court or an exhibition. Both the fire load density and occupant loads would be different. The evacuation pattern at the atrium floor may be changed by installing display boards if the space is used for exhibition. Therefore, fire safety management should be worked out carefully (BS 1999a).

Fire services installation (FSI), such as fire detection, fire hydrant/hose reel systems, sprinklers system, and emergency lighting might not necessarily be capable of controlling an atrium fire. Sprinklers are often installed at the atrium ceiling for those buildings constructed after 1987 when the FSI Codes (FSD 1998) required that sprinklers be installed in a wide range of building occupancies. However, it is not effective for high headroom atrium. There might be three scenarios as shown in Figure 4-9:

- Scenario 1: Fire at the atrium level.
- Scenario 2: Fire at a shop adjacent to the atrium at lower levels.
- Scenario 3: Fire at a shop adjacent to atrium at upper levels.

Scenario 1 is unlikely as it is difficult to have a big fire unless the space is used for exhibition. Earlier studies on stadium fires indicated that a 20 MW fire can only be achieved by burning a tank of propane (Corbett 1998-99). Scenarios 2 and 3 are possible due to the probable high fire load density in shops.

It would take a long time to activate the sprinkler head if the smoke reaching the atrium ceiling is not hot enough for scenarios 1 and 2 as shown in Figures 4-9a and 9b. Even after the sprinklers system has started to operate due to a fire in a high level shop, water discharged might cool down the smoke layer, reduce its buoyancy and pull it downward. Steam production gives additional problems. Earlier theoretical studies indicated that sprinklers should not be installed at the atrium roof. This will be confirmed by full-scale burning tests (Chow et al 2001).

Since the atrium space is normally opened to the adjacent levels, smoke management (Hansell 1987; NFPA 2000b) is important. Smoke curtain and fire shutter, one of the solutions to overcome the adverse effect of the open feature of atrium, can be installed at each level to isolate the atrium space but, at the same time, leaving the entrances of each floor open. On the other hand, smoke extraction system has to be installed so as to comply with the local codes. Its integration with sprinkler system has to be watched carefully. Depressurization of atrium space should be considered as smoke might spread into the adjacent occupant spaces.

Apart from removing smoke from the atrium to maintain a clear escape route in case of fire, staircase pressurization system is one of the solutions. Pressure in the staircase shaft can be kept higher than the atrium or other occupied space by supplying large quantity of air as in Figure 4-10. Smoke would be unable to flow to the escape routes from the fire compartment. Another alternative is to use air curtain for smoke control in atria of open design (Chow 1999b).

Fire safety management also plays an important role. Security guards should be well-trained in taking appropriate action in an accidental fire (Lui & Chow 2000).

More important, fire safety should be considered carefully. As there is not yet clear local guidelines available, those available elsewhere (Hansell 1987; BS 1999a; NFPA 2000b), including the new Australian publication for shopping centres (Fire Code Reform Research Program 1998) are useful references. Full-scale burning tests should be carried out if necessary (e.g. Chow et al 2001).

CHAPTER 5 INTERNAL BUILDING VOID

5.1 Introduction

In Hong Kong, it is required to construct one or more windows in every room used for habitation in a building as stated in Building (Planning) Regulations Cap. 123F Part IV (Laws of Hong Kong 1997a). They are believed to be provided for sake of psychological and physiological effects, including the following:

- Provide natural lighting;
- Offer better views, say the Victoria Harbour view for the deluxe premises;
- Provide natural ventilation before installation of air-conditioning system was popular;
- Supply fresh air for gas cooker and water heater installed in kitchens and bathrooms respectively so as to remove toxic gases generated, such as carbon monoxide (CO). In Appendix D, an example is used to demonstrate the air speed requirement of windows varied with the thermal power of gas appliances with the oxygen consumption method (Babrauskas & Grayson 1992).

Due to the abovementioned regulation, flat units in most of the residential buildings are placed on the perimeter of the floor area in order to comply with it. As a result, some units or rooms are unable to face a pleasant view, such as a sea view, on the limited length of perimeter. As illustrated in Figure 5-1, flat unit D and E are forced to face hill side and this might lead to a dramatic drop on their selling price when compared with those facing harbour view. Moreover, to maximize the utilization of the buildable area, some rooms may be located closely with rooms of the opposite unit, just as rooms in unit A and H. It might be necessary to draw curtains to maintain privacy.

Since not all flat units are able to face desired panoramic views and thus they are of lower market value, such layout plan is not in favor by developers and end-users. Innovative building designers then create new form of floor plan layout so called “internal building void” with which all units are located side by side to get the desirable outside views, as shown in Design I in Figure 5-2a. For a smaller floor area like Design II in Figure 5-2b, bathroom and kitchen are placed inside the floor area instead of facing open air. The internal building void, extending through the whole building height, to which windows of kitchen and bathrooms are open, is created to comply with the legislation (Laws of Hong Kong 1997a). It appears that this design satisfies both legislative and investment demands.

However, from the fire engineering viewpoint, fire safety aspects should be watched out with great caution. If a fire breaks out in a kitchen which is open to the internal void, smoke and flame would probably spread to the adjacent floors through the internal void. For a fire scenario like this, the innovative building feature would become an effective channel for smoke spread. Smoke (Klote & Milke 1992; Tamura 1994) is found to be the major killer in fire incidents since it is composed of numerous toxic gases and particles, including carbon monoxide (CO), carbon dioxide (CO_2), hydrogen cyanide (HCN) and hydrogen chloride (HCl), which will lead to eye irritation and also adversely affect the respiratory system, and the most serious, would lead to suffocation of the occupants.

It is, therefore, crucial to understand the factors affecting smoke movement. It is in fact led by air flow which is driven by the following natural means (Tamura 1994):

- Stack effect
- Wind-induced action
- Buoyancy of hot smoke

The aspect of smoke spreading would be studied by Computational Fluid Dynamics (CFD) in the following section. In fact, there is also possibility of fire spreading through the internal void, acting like a “fire drain” (Harmathy & Oleszkiewicz 1987).

In this chapter, three main areas are focused on to study the fire safety aspect of this new architectural feature:

- Fire in a room adjacent to the internal void.
- Fire resistance for windows.
- Spread of smoke from the fire room to adjacent levels.

A residential building Y of more than 40 storeys high, with total eight units built on each floor is taken as an example in the study, as shown in Figure 5-2b. For a typical floor plan, bathrooms of every two adjacent are open to the same full building-height internal building void, with an openable window. The four internal voids are of dimensions 1525 mm × 4600 mm, 1475 mm × 2200 mm, 1475 mm × 2200 mm and 2050 mm × 2950 mm, with the bottom open and the top fully or partially covered. The walls of bathroom connected to the internal voids are without fire resistant protection.

5.2 Fire in a Room Adjacent to the Internal Void

The worst scenario might be a fire occurring in the room adjacent to the internal building void. Smoke is believed easily move out through the opening and internal shaft to other storeys. Therefore, potential fire hazards at the room open to an internal void should be investigated. For the sake to maximize attractive views to the living area in a flat unit, service room, like bathroom and kitchen, is most likely to be put inside the sellable area, as discussed before. However, combustibles stored in a room might lead to ignition. The duration of a fire is dependent on the fire load and air supply.

Possible fire load inside bathroom and kitchen is one of the concerns:

- In Hong Kong, most of the building designs in the latest years do not provide places for drying clothes since there is limited floor area and a tendency to keep building façade tidy. Hanging space is designated outside the window of kitchen to solve this problem, as shown in Figure 5-1. However, oily substances and grease exhausted from kitchen discourage the use of the hangers. As a result, apparels are hanged inside bathroom after laundry at most families. It is noted that nearly all garments are fabricated by combustible materials, like cotton and polyester, which would be ignited easily. Other storages, say toilet papers, are also highly combustible.

- Kitchen is appeared in a higher risk since fuels are present for cooking. For instance, Liquefied Petroleum Gas (LPG) cooker is still popular in the old public housing estates. Household LPG cylinders are stored in the kitchen. Improper use of LPG cooker or a lack of safety checks would cause an event of fire or even explosion. An older kerosene stove is even more dangerous in using. A fire would be also caused by carelessness, for example, combustibles are put near the cooking fire.

Natural ventilation can be provided by the openable windows facing internal building void. Inflow of air would assist in combustion if there is enough fuel and ignition occurs. In such a small room, the upper smoke layer temperature can be increased easily to give flashover phenomenon which is defined as a rapid spread of burning from the fire origin to all the combustible surfaces throughout the compartment and all the combustibles reach their ignition temperature (Drysdale 1999). Criteria of flashover are found to be:

- Gas temperature near the ceiling reaches 500 to 600 °C;

- Total heat flux at floor level is above 20 kWm^{-2}; and
- Flame is flowing out from the opening.

A bathroom of size 2.25 m x 1.55 m x 3 m in an example building Y with an opening 0.6 m wide and 1 m high is chosen to study the required heat release rate (HRR) to reach flashover. From Thomas equation (Thomas 1981), the HRR needed for such small room is only 0.5 MW which is a value easily obtained by materials stored inside the room. A fully developed fire would generate a large amount of smoke, probably moving out of the opening driven by air flow with hot flames.

5.2.1 Fire hazard from apparels

Material of apparel is influential to the fire safety aspect in building with internal building void. In UK, The Nightwear (Safety) (Amendment) Regulations 1987 (HMSO 1987b) was stipulated to deal with this issue.

The most widely used textile fibres for apparel are cotton, polyester, acrylic and nylon fibres. Among all, cotton becomes the most popular because it is inexpensive and highly available (Miller 1992). As a natural fibre material, thin cotton fabrics is found easily ignited and thus producing flame. Other materials, polyester, acrylic and nylon, are made by synthesis. When compared to cotton, these synthetic fibres would not ignite easily, however, they would melt and give a faster burning rate once ignited.

In order to decrease the production cost, natural and synthetic materials blended or mixed together can give a lower price for fabric products. Nevertheless, the untreated natural fibres would burn even more rigorously with the assistance of synthetic fibres, which would give rise to a more severe scenario than from burning of a pure material (The Textile Institute 1999; Pasadena Fire Department 2001).

Apart from the textile fibres, fire risk in bathroom also depends on the gesture of clothing. They may be suspended vertically or folded horizontally, flammability of the apparels are then largely varied. Hanging vertically is believed to give a higher burning rate since a larger surface area of fabric is exposed to the atmosphere. Flashover is therefore easily reached by such rapid burning in the small room. Hanging a row of clothing, commonly found in local domestic flat units, should be paid extra attention in studying the fire safety aspects of internal void.

5.2.2 Smoke movement

When a fire breaks out in the room open to internal building void, smoke would be produced and probably move out of the fire room to the internal shaft through the opened windows and thus jeopardize the adjacent floors in a very short period of time. Depending on driven forces of air flow, including buoyancy of hot smoke, wind-induced action, stack effect and mechanical ventilation system, smoke and hot gases produced by a fire in the other rooms would also move to the room next to internal void and spread outwards.

How much smoke was generated becomes influential to the severity of the fire. The rate of smoke production depends on factors like fire size (e.g. Klote & Milke 1992; Tamura 1994). A two-layer zone model named FIREWIND (FIREWIND 2000) was used to assess the quantity of smoke flowing out of the fire compartment to the internal void. By assuming an NFPA slow t^2-fire with a cut-off value of 300 kW for a bathroom with an opened door 0.8 m wide and 2 m high, the mass flow rate of smoke flowing out of the bathroom to the internal building void is 0.53 kgs^{-1}. This small fire would not lead to flashover as discussed before. Though the selection of "slow" fire might not be realistic, it is sufficient to demonstrate that a more severe scenario would be resulted from a fire of higher growth rate.

5.3 Fire Resistance for Windows

If window of the room connected to internal building void is in a closed state, it is believed better fire protection could be achieved when compared to an open state. Regarding to this, fire resistance period (FRP) of the glass window should be considered carefully. According to the local requirements (BD 1996a), window of the bathroom of example building is not required to provide any FRP protection. FRP of construction elements in local area are tested in accordance with BS 476: Parts 20 to 24: 1987. To watch it out carefully, it is necessary to understand the criteria of acceptance of the fire resistance tests.

According to BS 476 (BS 1987a, 1987b, 1987c), there are three criteria to determine FRP:

- Loadbearing capacity: The ability of a specimen of a loadbearing element to support its test load, where appropriate, without exceeding specified criteria with respect to either the extent of, or rate of, deformation or both.
- Integrity: The ability of a specimen of a separating element to contain a fire to specified criteria for collapse, freedom from holes, cracks and fissures and sustained flaming on the unexposed face.
- Insulation: The ability of a specimen of a separating element to restrict the temperature rise of the unexposed face to below specified levels.

A critical temperature is used to determine the acceptance performance of insulation criterion. If the average temperature of the unexposed face increases by 140 °C of its initial value, it is deemed to unsatisfy to the insulation criterion.

Different construction elements are required to meet different criteria. For instance, a loadbearing wall must satisfy all of the three criteria (BS 1987b) whilst glazed element should satisfy both the integrity and insulation criteria to avoid flame, smoke and heat transmitting to the unexposed side (BS 1987c).

In America, the standard fire test of American Society for Testing and Materials (ASTM) also established three criteria for fire resisting construction, including transmission of heat, transmission of hot gases and load-carrying ability of the elements. According to ASTM E119 (ASTM 2000) they are tested by fire endurance and hose stream tests, from which the critical temperature for the criterion of transmission of heat is 139 °C. Also, a loadbearing wall should be able to satisfy all the criteria while the protective membrane should only meet the heat transmission criterion.

Accounting for the example building Y, both the protected shafts and windows should meet the criteria of integrity and insulation and the loadbearing wall should have all three criteria satisfied. Usually, there is no requirement on FRP on the window opening of a bathroom in local domestic building since they are facing an open space. However, the situation as in the example building is dissimilar, the windows are open to a vertical shaft which should be protected in order to avoid smoke and flame spreading. It is concluded that windows of adequate FRP should be provided in such room.

5.4 Discussions on the Simulation Results

As discussed, when flashover is arisen in the bathroom with opened window, smoke and even flame would move out to the adjacent internal void through the opening, driven by forces like stack effect, wind-induced force, buoyancy of hot gases and thermal expansion caused by the fire. Usually, smoke would rise up due to buoyancy except adverse effects, say strong wind action, take place. Traveling along the internal building void, the temperature of smoke would gradually decrease with the increase in travel distance. Movement of smoke would stop when its temperature is equal to the ambient temperature.

A fire hazard assessment using computational fluid dynamics (CFD) was carried out (Chow 2001c) to examine the spreading of smoke from a room adjacent to the internal building void in the example building Y. The CFD geometry and the simulation results are referred to as in Appendix E. The results demonstrating the potential fire risks will be discussed here.

As shown in Figure E-2, it was shown that hot smoke from the fire room A would move up the internal building void without spreading into the upper levels where windows are closed, i.e. scenario 1. While traveling along the internal void, rising plume would entrain air towards the plume and thus its temperature would gradually drop, say after moving up one level, the smoke temperature is at about 100 °C.

When window is opened at room B and other conditions remains the same, i.e. scenario 2, hot smoke moving along the internal building void would not spread into room B, as shown in Figure E-3.

When window and door are both opened at room B and other conditions remains the same, i.e. scenario 3, hot smoke also would not spread into room B and the air outside room B would be even drawn out of its window as shown by the zoom-up view in Figure E-4a.

Nevertheless, if a pressure difference of -50 Pa is imposed at the door of room B, i.e. scenario 4 in Figure E-5, air movement towards room B from internal building void would be resulted with high velocity. Under the negative pressure, smoke, hot gases and even flame would spread into room B and even other area of this unit. This is the most undesirable scenario of the study of this building feature. The high pressure differential might be resulted by mechanical system. Even when the pressure difference is reduced to – 5 Pa, i.e. scenario 5, the immediate upper room is still suffered, as demonstrated in Figure E-6.

5.5 Summary

The internal building void, connected to the rooms with window openings, is acting like a fire drain (Harmathy & Oleszkiewicz 1987) which would allow flame and smoke spreading through it to other compartment by pressure differential.

The results of CFD simulation showed that there is possibility of smoke spreading from the fire level to the adjacent levels under some scenarios. Dimension of the internal building void, wind-induced action, operation of MVAC systems and whether a flashover stage is reached in the fire room would be critical to the fire severity.

However, whether there is a fire hazard is not assured. Further in-depth studies by full-scale burning tests or fire modeling are necessary to carry out fire hazard assessment. Full-scale burning tests should be carried out with a setup of at least five storeys high in order to justify the design and verify the numerical analysis.

CHAPTER 6 DOUBLE-SKIN FACADE

6.1 Introduction

Building features derived from the use of glass are believed to have those potential hazards brought about by the extensive use of glass as discussed before. Building with double-skin façade (DSF), also named glass double façade in some countries, gaining affection in the local construction industry, is selected for further investigation in this study.

Buildings furnished with glass curtain wall are standing everywhere in cities of Far East (Hung & Chow 2003). High transmittance of solar radiation through glass panels leads to the use of shading devices and indoor illumination by artificial lighting. This put the cooling load of those buildings a burden which results in investigations on new techniques helping reduce heat gain. As a result, double-skin façade are proposed to overcome the problems inherent in glazed wall and for environmental benefits (Jones et al. 2000; Kragh 2002). By adding an extra layer of glass, solar heat gain coefficient and thermal transmittance are found to be reduced. Mechanical systems can be employed to induce convection inside the cavity space between the two layers of glass so as to remove solar heat gain. In addition, acoustic attenuation can be achieved by the double façade system.

Glass has been in favor by building designers since it was first created as building material. However, glass is found to be less resistant to heat than opaque wall such as concrete. Studies on glass performance were reported (e.g. Shields, Silcock & Flood 2002; Shields, Silcock & Hassani 1997/98) throughout the world from which safety of glass becomes a query since the capacity of glass to resist thermal stress is not high enough. Breakage of glass would easily occur under heat exposure. Previous works are useful as references on the scenarios of breaking glass. It is noted that double-skin façade is different from double-glazing system as investigated in most of the previous works, though there are two layers of glass pane in both systems. The distance between two layers of glass can be as far away as 2 m and the cavity between them is extended vertically through stories or even the whole building height. It was revealed from the literature (Shields, Silcock & Flood 2002) that a single glazing would probably break and fall out under certain conditions, say about 400 °C to cause fallout of a 6 mm clear float glass pane. If the inner glass panel of a double-skin façade is broken at fire condition, smoke and flame moving out to the cavity would further damage the other part of the construction, say the adjacent stories.

Since the feature of double-skin façade has been employed frequently in the local area in recent years, fire safety (Hung & Chow 2002b; Chow 2003a) is a concern that should be dealt with great cautions. There are not yet clear regulations nor design guidelines. Existing regulations governing the use of glass in Hong Kong will be reviewed in the next section. The fire safety problems associated with the use of glass and double-skin façade will be discussed in section 6.4 before going through a more in-depth investigation in next chapter by carrying out a full-scale experimental study.

6.2 Review on Current Regulations Governing the Use of Glass

In Hong Kong there is not explicit and stringent requirement for the design and materials on using glass in the existing regulations, though curtain wall and large glazed wall are widespread in use. Usually, requirements are made reference to the national standards (BD 1999). A list of standards commonly used for the design and construction of curtain wall and window wall accepted by the local Building Authority are specified in the practice note (BD 2001b) where British Standards (BS) (BS 1994, 1995) are primarily referred to. From which classifications of glass, available thicknesses, pane sizes and the breakage characteristics are clearly laid down. In the local codes, glass types and the corresponding nominal thicknesses used at the window and window wall are not yet specified, but only with the required FRP (BD 1996a). However, structural details and design calculations should be submitted to assure the strength and stability of the selected materials provided that it is used to resist a design wind stress of at least 3.4 kPa on the external wall, with the least dimension and area of at least 1.8 m and 6 m^2 (BD 2000a).

According to Laws of Hong Kong (1997b), glass curtain wall should be constructed of non-combustible materials and able to show the ability to prevent condensation, moisture, corrosion and so on. The capability of wind resistance of the window glass should be also verified by safety tests stated clearly in the practice note (BD 1999), where either of the two tests, cyclic test or static load test, should be satisfied. In the cyclic test, which is made reference to the BS 5368: Part 3 (BS 1978), specified positive and negative pressures are imposed on the specimen in specified sequence and duration. The material should not be broken and its deflection and recovery of deformation should meet the specific values as stated in the document. On the other hand, static load test is simplified from the former test, where the test load is maintained at 1.25 times the design wind stress for not less than 15 minutes and the other conditions remain the same.

The tests stipulated in the local legislations are only concerned about the performance of glass against wind load but none is about thermal behavior and impact from wind-borne debris. Lacking tests examined thermal response of a glazed element in local area turns out that national standards are referred to. Generally, for window opening on a wall, the required FRP of the glazed area is not less than ½ hour. The glazing elements are tested in accordance with BS 476: Parts 22 (BS 1987c), in which the integrity and insulation criteria should be satisfied to determine its corresponding FRP. Criteria of integrity means the ability of a specimen of a separating element to contain a fire to specified criteria for collapse, freedom from holes, cracks and fissures and sustained flaming on the unexposed face. On the other hand, insulation is the ability of the specimen to restrict the average temperature rise more than 140 °C above its initial value of the unexposed face.

There are three classifications of safety glass specified for impact tests as described in BS 6202 (BS 1981), namely Class A, B and C, according to the behavior against impact with detailed performance described in the standard. Similar guidance is also expected in the local area.

6.3 Fire Safety Considerations in the Use of Glass

Breakage of window glass plays a key role in compartment fire as the characteristic of window is changed from a barrier to an opening vent during the course of fire. Numerous works on thermal behavior of glazing assembly in an enclosure fire, including installations with single-pane and double-pane glazing were carried out throughout the world. An experimental study carried out under room corner fire (Shields, Silcock & Flood 2001) demonstrated that cracking on a single glazing would be initiated when incident heat flux is at least 3 kWm^{-2} or the heat release rate (HRR) in the enclosure is at 100 kW. The glass panes would fall out if they are suffered from a more severe environment, like heat flux of at least 35 kWm^{-2} or HRR approaches 500 kW. It is noted that HRR larger than 100 kW is easy to arrive when burning some combustibles in a typical room of a local flat unit with a window opening. Breaking glass is, therefore, most likely to take place in an enclosure fire and the panes located at the higher level are likely to fall out since they are in touch with the hotter gas layer. Moreover, glass pane of larger area undergoes such kind of breakage more rapidly.

A bench-scale experimental study on double glazing system (Shields, Silcock & Hassani 1997/98) demonstrated the thermal behavior of the double glazed window units, which are widespread in the construction industry. In that study, two layers of large and small glass panes were tested where cracking was resulted but fallout rarely occurred. Double-glazing system appears more robust than the single-glazing counterpart. Exposed surface temperatures were found dependent on the distance between the fuel bed and the window panes, and also the available ventilation. Gas temperatures of about 400 °C were found nearby the cracking area of the inner glass panes for different setups. Though there were crack bifurcation pattern on both the inner and outer glass layers at different times, the entire unit remained intact. The thermal performance of the system seemed satisfactory as desired. However, experimental exposed surface temperature of the glass panes was higher in the middle part at the earlier stage, indicating that radiative heat transfer dominant at that time. Bench-scale tests cannot reveal the real scenarios in this respect since radiation are unable to be scaled down by modeling studies. Full-scale burning tests should be carried out since the larger pane would yield more easily in the single-pane test abovementioned.

Computer modeling was also used to predict the performance of a double-glazing system under fire by Cuzzillo & Pagni (1998). It was indicated by the results on the temperature profile on both sides of the two layers that the temperature rise on the pane further away from the fire was insignificant. After the pane near at the exposed side has broken, the outer pane would start to heat up rapidly. However, the system remained intact since fallout of the outer pane did not occur. This study well demonstrated that double-glazing system has higher strength than the single-glazing counterpart. Since the heat transfer mechanism between the two panes were believed to be mainly by radiation, the study also exhibited that the fire resistance of the double-glazing unit would be increased as long as a low-emissivity coating is applied on the inner surface of the inner pane. Different fire protective coatings can be provided on different types of glass panes. Profound investigation on thermal behavior of different types of glass at the design stage of building allow enhancement of the whole system.

Once window breakage has been arisen in the enclosed fire compartment, an opening is created and fresh air would be supplied from the ambient. The worst scenario would cause the most severe consequences. The fire services installations, such as sprinkler system, might not be actuated prior to the window breakage. It might be affected by a number of factors, say the fire location, severity of the fire, the geometry of glazing, thickness of glass and area of fire room. Due to direct incidence of thermal radiation, the surface temperature of the glass panes may be higher than the upper hot layer. Once the glass breaks, fresh air moving in lower the room temperature to certain extent so that the activation time of the systems would be delayed. Even worst, if lots of combustibles are stored without any active protection systems, flame would spread rapidly with large generation rates of smoke and toxic gases. Wind action may also assist in the spreading of smoke and flame, leading to serious consequences before flashover fire is developed. If, however, there is only limited fire load, drawing air through the broken window might reduce the development rate of the fire

Lethal gases, smoke and flame might escape from the fire room through the newly-created channel towards the adjacent levels and compartments. If a negative pressure difference is induced across those rooms, fatal gases would be drawn towards them. As a result, occupants will be exposed to higher risks because of increasing damaged areas resulted from breaking windows.

The most undesirable situation would be a fire breaking out near the glass window. Very high heat flux incident onto the glass would result in cracking due to the unendurable thermal stresses on the surface. The heat performance of window glass should be studied for fire hazard assessment. Fire safety management is a key element in giving total fire safety. The safety plan to keep combustibles clear of the glazed area; and keeping fire load density to lower values are useful.

6.4 Fire Safety Problems Associated with the Construction of Double-skin Facade

Smoke movement is the key issue on fire safety of double-skin facade, from which the thermal performance of the glass panels on the adjacent floors and on the outer skin would be affected in different ways. As revealed in Figure 6-1, the smoke movement inside the cavity between the two layers of glass would be determinant to the fire risks resulted. The direction of smoke movement depends on a number of factors, say heat release rate (HRR), the opening to cavity, the geometry of the cavity and the applied airflow rate and pressure of the ventilation system. Numerous possible scenarios would occur under other circumstances.

If hot smoke moves towards the outer skin, as in scenario I illustrated in Figure 6-1b, the outer glass panel might be cracked or even broken by heat or high pressure. On the other case, the upper glass panel would be affected if smoke (or even flame) moves upwards, as in scenario II shown in Figure 6-1b. Breaking the outer glass panel is not as disastrous as breaking the upper one in giving a channel for spreading of smoke and flame to upper stories. For ordinary curtain wall with one layer of glass pane, smoke and toxic gases can be diluted and cooled down by the ambient air whilst they are trapped inside the vertical air cavity which is at higher temperature than in the open space for double-skin façade. In addition, pressure gradient inside the cavity would have significant effects on glass. For better understanding on the fire behavior of such architectural feature, full-scale experimental study should be carried out.

6.5 Recommendations

Using a great deal of glass panels on the exterior of a building would lead to unpredictable safety problems and this has already stimulated extensive concern from the construction industry. However, as reviewed, there are not detailed specifications on the glass type and configuration in the existing building codes for design consideration. Appropriate regulations for local premises are urged to stipulate in order to safeguard human life.

In advance to drafting out the statutory requirements, further works should be carried out to comprehend fully the characteristics of every types of glass commonly in use in local area. A wide variety of glass types available in the market, such as annealed glass, heat strengthened glass, tempered glass, float glass, laminated glass and so on, have diversified thermal behavior, but unique specification on each configuration is missing. Tempered glass, taken as an example, is found to be as strong as four times the strength of annealed glass. It is classified as a safety glass because it would only be broken into small harmless particles whilst the heat-strengthened glass, which is also relatively robust, would shatter into harmful large fragments (BS 1994). In view of these advantages, it is often employed for large window panes to resist strong wind load in local area. Nevertheless, the occurrence of spontaneous breakage of tempered glass would in turn encourage the use of other glass types as the alternatives (BD 2000a). Comprehension on the properties of all glass types is, therefore, of great significance for achieving the highest safety level as well as economic efficiency. Though there are plentiful overseas studies on glass behavior in various approaches, including experimental tests or computer simulations (e.g. Shields et al. 1997/98, 2001; Cuzzillo & Pagni 1998; Saxe et al. 2002), not all the types of glass were being tested. Glass types or combination commonly used in local practice should be investigated on their properties and installation methods by in-depth studies which should be carried out accordingly while the examination methods and some of the results from other nations could be selected and made references.

However, glazed elements on one story or at one compartment were focused in most of the previous works. Further works should be carried out for multiple stories to reveal the air movement and the thermal response on the upper or adjacent floors once hot gas has been coming out from the fire room. It can recognize whether it would endanger the adjacent occupied spaces. It is necessary to set up compartments of consecutive stories to give the whole picture of the detrimental effect of this building feature to human being and property.

CHAPTER 7 EXPERIMENTAL STUDY ON DOUBLE-SKIN FACADE

7.1 Introduction

As discussed in the last chapter, a full-scale burning test for double-skin façade is strongly desired to better understand the fire hazard associated with this new architectural feature. However, additional attention should be paid in carrying out full-scale burning tests. Due to high land price and stringent environmental protection regulations in Hong Kong (now the Hong Kong Special Administrative Region), it seems impossible to execute this plan in local area. Toxic gases and particles generated from the tests would be harmful to the citizens. Therefore, a remote site should be relied on, but it should be easily accessed for delivery of goods and samples, and water and electricity supply must be ready as well.

Collaboration on scientific developments with China becomes enhanced after smooth reunification to China. An abandoned hall in a small town Lanxi in Harbin in Northeast China was rented as the laboratory to carry out the experimental study with a total of 18 tests performed in the past two years. The hall of an abandoned disco building of 6 m high, 16.5 m long and 16 m deep, with a view shown in Figure 7-1. Inside the hall, full-scale burning facilities on a double-skin façade were constructed.

The objectives of this test are to study experimentally the behavior of glass panels and smoke movement in the air cavity of a double-skin façade in relation to the depth of cavity. Surface temperature and heat flux received on the test panels are presented. Cracking patterns found on the glass panels are also described. Results give the possible smoke movement pattern inside the air cavity. Tests with wood panels and one glass test were used for preliminary tests, results of which can be referred to Appendix F.

7.2 Full-scale Burning Tests

Full-scale burning tests on DSF (Chow et al 2004a, 2004b) were carried out in a site in Northeast China. An abandoned hall, 6 m high, 16.5 m long and 16 m deep, in a small town Lanxi at the outskirt of the province capital Harbin was selected.

Part of a full-scale DSF feature was constructed to give an L-shape configuration, as illustrated in Figure 7-2. There was a fire room and a cavity space with two levels. The cavity space was 2 m wide and 4 m high, formed by two glass panels as illustrated in Figure 7-3. The fire chamber, taken as the room with a fire broken out, was constructed of bricks with width 2 m, depth 1.5 m and height 2 m. The test construction is shown in Figure 7-4. An opening to the cavity of 1.5 m by 0.8 m was assigned, say resulted from breaking of the inner glass panel. The depth of the cavity was identified to be the key factor in fire hazard assessment.

Four sets of burning tests carried out were chosen for further analysis in this chapter. Glass panels of 2 m wide, 1.5 m high and thickness 3.5 mm commonly used for curtain walls were installed to give the curtain walls of full height. Three different depths of cavity *d* of 1.5 m, 1 m and 0.5 m were tested.

The four sets of tests were:

- G2 and G3 (G3a and G3b): glass panels, *d* = 1.5 m.
- G4 (G4a and G4b): glass panels, *d* = 1 m.
- G5 (G5a and G5b): glass panels, *d* = 0.5 m.

Two test panels, namely TPO and TPI respectively, on the outer skin and inner skin of the upper story as shown in Figure 7-3 were studied carefully.

Type K thermocouples were fixed to metal wires at designated locations on the inner face of the test panels (TO1 to TO7 and TI1 to TI3) and the ceiling of the fire chamber (TC1 and TC2) to measure their surface temperature. The temperature range of the thermocouples is from 0 °C to 1100 °C. An H-201 digital heat flux meter was also installed on the inner surface to examine the heat flux received on the test panel. The highest output level of which was 10 kWm^{-2}. The number of thermocouples and flux meters used in the study were limited by resources allocated. Thermocouples were placed with identical intervals along the centre line of the glass panels in order to measure the temperature differential varied with height while the heat flux meter was placed at the point TO5 where highest incident heat flux from the fire chamber can be measured. The locations of the thermocouples and heat flux meters are illustrated clearly in Figure 7-5.

A 0.5 m diameter pool fire at the centre of the chamber was set up by burning 5000 ml of gasoline for tests with glass panels. Such amount was verified in the preliminary test, as discussed in Appendix F, to be good enough to give a flashover fire in the chamber. Heat release rate was determined to be 550 kW separately in a room calorimeter by the oxygen consumption method.

Different openings were assigned on the test rig to give different ventilation conditions in a DSF. There was a front vent FV of area 0.3 m^2 (0.15 m by 2.0 m), a back vent BV of 1 m^2 (0.5 m by 2.0 m), a side vent SV of 0.5 m^2 (0.5 m by 1.0 m) and a top vent of 4 m^2 (2.0 m by 2.0 m). The top of the cavity was left open to a hood with an exhaust duct for removing smoke out of the rig by natural ventilation. The back vent of the fire chamber was open for supplying air required for combustion. In a real construction, cavity of double-skin façade would be extended upwards for many stories instead of being partitioned. As constrained by the height of the laboratory, a vertical cavity space of a few levels was impossible. The 15-cm high front vent FV was assigned to entrain air as experienced in real DSF cavity due to natural or mechanically induced air movement.

Data logged in the burning tests lasted for 10 to 15 minutes for all the tests except test G2 where data were recorded for 30 minutes. The burning time for the tests lasted for about 4 to 7 minutes.

Different testing conditions are listed together with the maximum measured surface temperature and heat flux in Table 7-1. Thermal performance of glass in the test rig was studied. Surface temperature, heat flux and cracking patterns (if any) were measured. The results were applied for studying fire spread under different cavity depths.

By observation, smoke and hot gases were flowing upwards, affecting either the upper part of the outer test panel TPO or the inner test panel TPI. Large quantity of smoke was generated in the tests, which is the reason for the installation of a hood and exhaust duct on top of the test rig. The movement of them happened to be similar to the arrangement of fire place with a chimney. Mechanical extraction system was not provided and thus the fire-induced flow was not affected by it. Moreover, flame was coming out from the fire chamber to the cavity as shown in Figure 7-6.

7.3 Test Results and Discussions

The test results of the four sets are summarized in Table 7-1. During the tests, surface temperature and heat flux were recorded and the glass behavior under the particular heat environment was observed.

7.3.1 Surface temperature

The profile of highest temperature on both tests panels is shown in Figure 7-7 and 7-8 respectively and points of highest temperature are listed in Table 7-2.

Among all the temperature measuring points on TPO and TPI, the highest temperature appeared at point TI3 in tests G2, G3a and G3b; TI2 in test G4a; TO4 in tests G4b and G5a; and TO2 in test G5b. It was noted that the maximum temperatures in tests G5a and G5b were much larger than those in the other tests whilst the one in test G2 was the smallest.

To reach the maximum temperature, test G2 took about 3’30” while both tests G3a and G3b took about 2 minutes since they had identical setup. For the other tests, they spent less than 2 minutes to arrive the summit. Tests G4a, G5a and G5b used about 1’50” and test G4b took about 1’37”.

Tests G2 with the open back vent spent the longest time since there was not flashover fire inside the chamber. It was found that the time required decreased with the depth of cavity except that test G4b took the shortest time which might be attributed by the early collapse of TPI. The breakage of glass is thought to have a considerable influence on the fire severity.

Temperatures measured from the ceiling of the fire chamber were extremely high in all the tests except G2 in which the back vent was open. It was believed there were flashover fires in the other tests.

A detailed discussion on the measured surface temperatures in tests of different cavity depth is as follows:

- Tests G2, G3a and G3b

On the outer test panel TPO, the highest temperatures at points TO1 to TO7 increased with height. That means point TO1 had the highest temperature among the seven points on TPO. It should be noted that point TO1 was located on the upper composite pane; TO2 to TO4 were located on the middle one; and TO5 to TO7 were on the bottom pane. On the inner test panel TPI, the highest temperatures decreased with height.

On the inner test panel TPI, the highest temperatures decreased with height in general, as shown in Figure 7-8. Points TI2 and TI3 were placed on the bottom composite pane. TI3 suffered the hottest environment in tests G2 through G3b.

As shown in Figures 7-3a and 7-5, TO1 and TI1; TO2 and TI2; and TO3 and TI3 were pairs of points at the same height from the ground on the test panel TPO and TPI. In all the three tests, it appeared quite consistent that temperatures of points on TPI were higher than those on TPO, as illustrated in Figures 7-9 to 7-11. The temperature profile and temperature difference between each pair were similar in tests G3a and G3b since their back vents were closed while test G2 had an open back vent in the fire chamber. The temperature differences between each pair decreased with height, that means points TO1 and TI1 had the smallest difference.

Consistency has been shown in the tests with a cavity depth of 1.5 m, where the highest temperature on TPO was at point TO1 and that on TPI was at point TI3, as shown in Table 7-2. Test panel TPI was hotter than TPO. The temperature differences between the two panels decreased with height. It may be concluded that the smoke and hot gases coming out from the fire chamber might tilt upwards due to buoyancy and disperse along the upward path. Thus, point TO3 or lower points were being affected to a lesser extent. In addition, a 15 cm high bottom vent was created to introduce natural ventilation into the cavity to act as if air moved from the floors below. Air moving up would also cool down the internal space of the cavity. The depth of cavity in tests G2 to G3b might be wide enough that the outer panel was not affected severely by the flowing out of smoke. The surface temperatures decreased with height on TPI might indicate the temperature varied with the distance from the fire chamber opening. Therefore, point TI3 suffered the hottest environment not only in the tests G2, G3a and G3b, but also tests G4b and G5b.

- Tests G4a and G4b

For cavity depth of 1.0 m, the highest temperature appeared at points TO2 and TO4 for test G4a and G4b respectively. In test G4b, the highest temperatures decreased with height on inner test panel TPI. However, TI2 suffered the hottest environment in test G4a.

Temperatures on both TPO and TPI had similar profiles in which their differences were very small. The three pairs of points had similar difference in test G4a, as in Figure 7-12. Once cracking or collapse happened, the temperature dropped slightly. In test G4b, the temperature profiles at the beginning in each pair were similar to those in test G4a. However, they became different after the cracks or collapse appeared. Temperature profile of test points at the same height in test G4b is shown in Figure 7-13. Temperature difference was enlarged between points at the same level right after the first collapse of glass panel in test G4b which occurred at the uppermost pane on TPO. Point TO1 became cooler than TI1 until the second collapse at the middle pane on TPO. However, Points TI2 and TI3 dropped more than TO2 and TO3. The enlarged temperature differences might be caused by the collapse of glass panels. All of the composite panes on TPO and the bottom pane on TPI underwent collapse in test G4b while only the middle and bottom pane on TPO fell down in test G4a. It was noted that points TO2 and TO3, of similar temperature, were higher than TO1 in these two tests. On TPI, the highest point TI1 also experienced the lowest temperature when compared to the lower points.

In test G4a with a narrower cavity, points TO2 and TI2 were the points having the highest temperature whilst in test G4b, points TO4 and TI2 had the highest temperature. In comparing with the tests with a cavity of 1.5 m deep, the smoke was estimated to be moving in a different direction or at a inclined angle. Indeed, the temperatures on the two layers were so close that the difference was only of several degrees. As shown in Figures 7-8 and 7-9, temperatures on TPO in tests G4a and G4b were higher than those in tests G2 to G3b but those on TPI were lower than those in tests G3a and G3b. Also, the temperature at points TO2 and TO3 were higher than that at TO1, different from that in the tests with a 1.5 m cavity. It is believed that the smaller distance between the two layers of glass was attributed to the change. It appeared that smoke clung to TPI in tests G2 to G3b but it was moving more or less in the middle of the cavity in the next two tests. Since the bottom part of the test panel TPI in test G4b fell out at some time unknown, cool air might lower the surface temperature measured at points of TPI. The temperature profile of test G4b was, therefore, different at the later stage, where points TI2 and TI3 became much cooler than points TO2 and TO3. Even though the time of fallout of TPI was not recorded, it could be told by the substantial drop of temperature of the two points.

- Tests G5a and G5b

On test panel TPO, point TO4 had the highest temperature in test G5a while point TO2 was the hottest in test G5b. On test panel TPI, TI1 and TI3 suffered the hottest environment in test G5a and G5b respectively.

The temperature profiles in the two tests G5a and G5b were dissimilar, as shown in Figures 7-14 and 7-15. In test G5a, the surface temperatures at points TO2 and TO3 were found to be higher on TPO than on TPI at the beginning. Again, the temperature differences between each pair decreased with height, that means points TO1 and TI1 had the smallest difference. All the six test points experienced the highest temperature before any collapse appeared. After the middle and bottom panes on TPO had fallen down, temperatures at points TO2 and TO3 dropped quite a lot more than those points on TPI at the same level. Points TO2, TO3 and TI1 had the highest temperature among the six points. In test G5b, all of the three points on TPO were higher than those on TPI at the same level and the temperature differences decreased with height before any collapse. In this period, the highest temperatures of points TO1, TO2 and TI3 were not reached. After the first collapse on TPO, temperature at point TO3 dropped substantially. However, point TO1 rose to its maximum temperature after a drop of about 100 °C and the temperature difference from point TI1 was enlarged from about 5 °C at the beginning to about 370 °C. Temperature at point TO2 also increased extensively to widen the temperature difference with point TI2 to about 350 °C. The lowest pair TO3 and TI3, however, had completely different profile in which TI3 had risen and TO3 had dropped extensively. A temperature gap as large as 270 °C was created. Points TO1, TO2 and TI3 had the highest temperature among the six points.

Temperature profiles in tests G5a and G5b were different. It was believed that the first collapse occurred at different fire stages in the two tests led to the disparity. It took place before and after complete burning in the former and latter test respectively. Temperature at points TO2 and TO3 were higher than those on TPI at the same level before the collapse of the panel on TPO. However, point TO1 was cooler than point TI1 and point TO4 was the hottest on the two test panels. It might imply that smoke and hot gases were first traveling towards TPO and then bounced back by the outer panel within the narrow cavity space. In view of the small depth of the cavity, smoke moving out from the opening of the fire chamber must inevitably touch the point facing the opening, i.e. TO4. The fire in test G5a was too severe that a flashover occurred inside the chamber. The momentum of the hot gases would be large enough to rebound them back to the inner panel once they hit on the outer panel. After the occurrence of the first fallout, temperature on TPO became lower than those on TPI at the same level because fresh air would probably flow into the cavity through the breakage at the middle and bottom part of TPO.

The scenario in test G5b was totally different from test G5a. At the beginning, temperatures on TPO were all higher than those on TPI and the temperature difference decreased with height. Smoke moving out from the fire chamber would also directly punch onto TPO and it led to the very high temperature at point TO3. It was estimated that the horizontal momentum pushed the smoke and hot gases flowing towards the outer pane and they were then moving along the outer panel. This is coincident with the scenario in test G5a. The horizontal momentum of smoke was not as high as in test G5a since burning was not yet completed. The highest temperatures of points TO1, TO2 and TI3 were reached after the first occurrence of fallout. The temperature of them rose up extensively after breakage was created on TPO. Large quantity of fresh air enhanced the combustion of the ventilation-controlled fire in the fire chamber, so that temperature increased considerably after the breakage of glass. As the middle and bottom part of the outer panel collapsed, large quantity of cool air moved into the cavity. However, the upward force of cool air was less than the buoyancy of hot gases generated by complete combustion, only point TO3 could be cooled down.

7.3.2 Estimated smoke movement

In comparing all the tests, point TI3 has the highest temperature among the points on both panels in tests G2 to G3b, and point TI2 was the hottest in test G4a. It indicated that TPI would experience a hotter environment in a wider cavity whilst TPO would be hotter when the cavity is very narrow. Tests G4a and G4b were different in this aspect though they had identical setup. It might be due to the breakage of glass panel on TPI at an earlier period of time. The temperature of TPI was thus lowered to a certain extent.

A large amount of smoke was moving out from the fire chamber to the cavity in the tests. Fire hazard of a DSF depends on the direction of smoke and flame spreading out from the fire chamber to the cavity. As discussed in the last chapter, smoke moving upwards with flame impinged on the upper inner surface as in scenario II shown in Figure 6-1b is more dangerous. Calculating the temperature difference ΔT between the measured surface temperatures T_{TPO} and T_{TPI} on TPO and TPI respectively at the same height would give some indication on how smoke spreads inside the cavity.

Defining ΔT as:

$$\Delta T = T_{TPO} - T_{TPI} \qquad \ldots(7\text{-}1)$$

The value of ΔT is positive when TPO is hotter than TPI; and negative when TPI is hotter than TPO.

As shown in Figure 7-5, there are three pairs of measuring points located at the same height from tests G2 to G5:

- Uppermost at TO1 and TI1
- Middle at TO2 and TI2
- Lowest at TO3 and TI3

The maximum temperature differences ΔT_{max} of each pair during the transient heat environment are plotted with *d* in Figure 7-16. Two ΔT_{max} are plotted for each pair, including the positive value (when TPO was hotter than TPI) and the negative value (when TPI was hotter than TPO). The points with maximum surface temperature in each test are summarized in Table 7-2.

The smoke movement pattern can be estimated from each test.

- Tests G2, G3a and G3b

  - The hottest points were at the uppermost part of TPO and the lowest points on TPI, as shown in Table 7-2.
  - Surface temperatures at points on TPI were higher than those on TPO at the same height, with typical result of G3a shown in Figure 7-10.
  - ΔT_{max} was the smallest at the uppermost level.

Smoke and even flame might move up along the inner surface after coming out from the fire chamber as in scenario II shown in Figure 6-1b.

- Tests G4a and G4b

    - The highest temperature was found at different points on TPO and TPI in the two tests with identical *d*. However, the topmost part on TPO was not the hottest in these tests.
    - TPO and TPI had similar temperature profiles with little differences, especially for test G4a. The temperature profile became different at later periods of time where the temperature of TPI dropped considerably in test G4b.
    - As shown in Figure 7-16, ΔT_{max} in both directions (positive or negative values) are similar in test G4a. This is not the case for the middle pair in test G4b as the inner panel collapsed.

Smoke movement pattern was different from those with a wider cavity. Smoke would move at the centre of the cavity, rather than along the wall.

- Tests G5a and G5b

    - The highest temperatures were found at different points on TPO and TPI in the two tests of the same *d*. The uppermost part of TPO was not the hottest point. On TPO, the surface temperature was higher at TO4 in test G5a but at TO2 in test G5b; while on TPI, TI1 and TI3 were the hottest in the two tests respectively.

- TPI was hotter than TPO at the uppermost and the lowest pair in test G5a and G5b respectively.
- Temperature differences between each pair decreased with height in test G5a.
- In test G5b, all of the three points on TPO were higher than those on TPI at the same level and the temperature differences decreased with height before any collapse.
- As shown in Figure 7-16, the temperature differences in test G5b deviated from those in test G5a.

In view of the results, the smoke and hot gases would spread towards TPO first in test G5a. Smoke was then bounced back from the outer panel. The difference in the two tests might be due to breaking of the glass panel at different time. After the glass panels TPO collapsed in test G5b, there might be "complete combustion" in the fire chamber due to the air supplied. Air entrained might cool down the lower point TO3 with temperature much lower than that at TI3. The movement of hot gases in test G5b would then be very different from G5a.

As a summary, test panel TPI would be eventually heated up to higher temperature for wider cavities. TPO would be hotter when the cavity is too narrow.

For the same heat release rate (HRR) of fire, the smoke flow induced by buoyancy is believed to be the same. As the outer skin of the cavity comes closer, smoke spreading out from the fire chamber would unavoidably touch it. The estimated smoke movements in cavity depth of 1.5 m, 1 m and 0.5 m are varied with the changing location of the hotter surface, as illustrated in Figure 7-17.

7.3.3 Thermal behavior of glass panels

Glass performance under heat exposure was observed in all tests. Cracking and fallout were found on the outer panel TPO. The incident heat flux on TPO facing the opening of fire chamber in each test was all higher than 3 kWm^{-2} and the highest was above 10 kWm^{-2}. The temperature measured at the first crack in each test was ranging from 120 °C to 350 °C. It has good agreement with the overseas studies (Shields, Silcock & Flood 2001) in which it demonstrated that the first cracking occurred when the bulk glass temperature was at about 110 °C and the heat flux was about 3 kWm^{-2}.

However, the severity of glass damages was shown diversified in the study. The middle composite pane was suffered from the most serious cracking where it was initiated at the bottom of that pane in test G1 but the time to give the first crack was not recorded. Cracking was found on all the outer panels TPO and inner panels in tests G3b to G5b. Tests G3a and G3b were similar as their bottom pane on TPO collapsed. Both the middle and bottom one on TPO fell down in tests G4a, G5a and G5b, but only cracks appeared on TPI in the former two tests while fallout happened in G5b. The bottom one on TPI of test G5b also collapsed at some time later. Among all the tests, glass in test G4b suffered the most serious damage, where all the panes on TPO cracked and fell out and the bottom of panel TPI also collapsed. The bottom pane on TPO was the most severely damaged. Fallout of it was encountered in five out of the seven tests with glass panels. The middle one of TPO was also severely devastated. They were described as follows:

- Tests G2, G3a and G3b

    - Cracks were only observed on the lower part of TPO in test G2.
    - Cracks appeared mainly on TPO in test G3a and G3b.
    - The lower panel on TPO was observed to collapse in test G3a and G3b.
    - A crack was found at the bottom part of TPI in test G3b.

- Tests G4a and G4b

    - Very serious damage was observed among all tests.
    - Cracks were found on TPO and the bottom part of TPI.
    - Bottom and middle panels collapsed in test G4a.
    - All panels collapsed except the top one of TPI in test G4b.

- Tests G5a and G5b

    - All except the upper panels of TPO cracked and finally fell down.

- Cracks were found at the bottom part of TPI first, and then collapsed in the two tests.

The time to give the first crack, the corresponding temperature and collapse area are shown in Table 7-3. The maximum temperatures and glass damages are clearly illustrated in Figures 7-18 to 7-21.

The distribution of damage patterns together with the measured surface temperature can be used to estimate the smoke movement in the cavity.

Glass sheets of a smaller area appeared to have better thermal behavior than those of a larger area. The glass area fallen down from the bigger ones was much larger than from the smaller glass panels (Shields, Silcock & Flood 2002). The composite glass panes of smaller size in this experiment would probably affect the glass performance under the heat exposure. Theoretically, large piece of glass would suffer larger temperature difference between the edge and the centre and higher thermal stress would be resulted. Even the composite ones in this study could not endure high heat environment. Cracks must be generated and fallout of pieces is likely to occur on the glass panel of original size, which would cause risks to the neighboring environment in reality. The ordinary glass panes of 3.5 mm used in the study might not be identical to those used in local development. The type and thickness of glass both play key role in glass behavior, for instance, tempered glass has four times the strength of annealed glass (BS 1994), but there is also cost implication. Different glass types on both inner and outer skin should be used to provide desirable fire safety.

7.3.4 Heat flux profile

Heat flux meter was located at point TO5 on the outer test panel TPO as illustrated in Figure 7-5. It was at the same level with the top of the chamber opening. The highest incident heat flux onto the outer test panel from the fire chamber can be measured. The heat flux profiles of the tests are shown in Figure 7-22. The maximum heat flux measured was about 10 kWm^{-2} in test G4a and G4b.

7.4 Effects of Cavity Depth

Breaking of the glass panels of a DSF due to smoke spreading out from the fire room is not a desired consequence as in Figures 6-1a and 6-1b. Breaking of the inner skin would have the fire spreading up to the adjacent levels and exposed more occupants to fire.

Cavity depth *d* was identified to be a key area in the earlier study (Chow et al 2004a; 2004b), values of 2 m, 1.5 m, 1 m and 0.5 m were tested. The biggest *d* of 2 m used to be taken as the maximum cavity depth in DSF constructions.

The driving forces of smoke movement in a DSF include the buoyancy of hot smoke and the stack effect induced by the temperature difference between the cavity space and the ambient. Buoyancy of hot smoke generated by the same fire in each test described above is roughly the same. The stack effect in this arrangement would not be significant due to the small height.

Heat would be extracted from the top vent and air temperature would be reduced to a certain extent inside a deeper cavity. Thus, it is estimated that temperature difference between the outer and inner space would be further reduced to give insignificant stack effect. Buoyancy is, therefore, believed to be the primary driving force for the movement of smoke and hot gases.

A summary of the temperatures at TPI and TPO for the tests is illustrated in Figures 7-18 to 7-21. Cracks and collapse of glass panels are also shown. Smoke spread along the inner skin for *d* of 1.5 m, the inner skin did not collapse even though the temperatures were higher. Air temperature inside the cavity space was not as high as in the other tests with a narrower cavity. Smoke did not attach to the inner panel for *d* of 0.5 m or 1 m, as indicated by the lower surface temperature. However, the inner panel collapsed and fell down.

Cavity depth *d* of 1 m appeared to be a more dangerous design as so many fractures and breakages of glass were observed. As the measured surface temperatures on both sides were similar in the tests, smoke spread upwards through the gap. The effects on both panels were the same, with either one cracked or collapsed quicker than the other. If the inner panel fell down first as in test G4b, the consequence would be hazardous. Other glass panels also cracked and fell out successively.

On the other hand, a narrow gap with *d* of 0.5 m would function as a channel in directing smoke to travel along. Smoke moving out from the opening of the fire chamber as a ceiling jet would impinge on point TO4 with higher momentum, making it to be the hottest point. The first crack was found there and glass collapsed. The momentum of the ceiling jet would be large enough to have smoke rebound back to the inner panel upon hitting the outer panel. Since smoke and even flame were spreading towards the outer panel at the beginning, cracks were first shown on TPO. The time for cracking was much faster than those in tests G4a and G4b.

7.5 Factors Affecting Fire Risk

Apart from the cavity depth, the direction of smoke movement depends on a number of factors, say heat release rate (HRR), the opening to cavity, the geometry of the cavity and the applied airflow rate and pressure of the ventilation system. In this study, only the depth of cavity was examined. Further studies on other parameters are strongly required to fully understand the potential fire risks associated with this architectural feature.

Fire size is given in terms of HRR, which plays a key role in determining the quantity of smoke generated and thus the movement of hot smoke and toxic gases. The vertical momentum of smoke movement would be increased with the volume of smoke. By varying HRR, the inclination of hot gases would be also affected to give different pictures, as illustrated in Figure 6-1. Gasoline of 5000 ml, applied in the last 3 tests, was recorded to give a maximum HRR of about 0.55 MW.

Since hot gases would form a layer at the ceiling of the fire room after an outbreak of fire, breaking glass should most probably appear near the ceiling of the story due to direct incidence. It is believed that smoke coming out from the broken part near the ceiling could influence the glass panel on the adjacent floor easily. The opening across fire chamber and cavity, acting as a broken part of the inner skin, was created 0.5 m below the ceiling of the fire chamber, the height of which was 2 m. The 0.5 m high wall above the opening would become barrier to the spreading of flame and smoke and act like a reservoir screen. The spreading was obstructed and thus the upward force was also hindered.

In the real construction of double-skin façade, there is either natural or mechanical ventilation inside the cavity to remove the accumulated heat (Kragh 2002). The natural ventilation introduced by the 15 cm high front vent FV in the tests was suspected unable to reach the amount in a realistic convective force, which is believed pushing up and affecting the direction of smoke movement. Moreover, the airflow rate and pressure induced by a mechanical ventilation system could have far different effect where the inclination of the smoke might be much larger.

Other than the abovementioned functions affecting the movement of the escaped hot gases and smoke, glass types would also alter the fire scenarios. Glass species would be significant to the glass behavior under heat exposure. For instance, tempered glass has four times the strength of annealed glass (BS 1994).

Thickness of glass is also determinant; the strength of glass is increased with its thickness. Of course, price is also a function of the strength. Combinations of appropriate glass types at inner and outer skins, together with the optimum width of cavity are important to the fire safety of this building feature and cost-effectiveness.

As stipulated in the existing requirements (BD 1996a), a vertical spandrel of not less than 900 mm high should be constructed below the opening for the sake of fire safety protection. It is believed that the upper floor can effectively evade from the attack of hot smoke. Inner glass wall of a double-skin façade can be visualized as a single-glazing where the same protection should be taken into account. Materials of higher strength, say tempered glass, could be used to construct the vertical spandrel. However, the temperature and pressure gradient between the two layers of glass in a double-skin façade are different from that exposed to the ambient. Smoke coming out from the fire chamber cannot be diluted and cooled down. As discussed, the inclination of smoke would be totally different from a single-glazing unit. Inner skin of the double-skin system might be unable to endure the heat environment and, therefore, higher risk is resulted.

Based on the information from this study, further works can be carried out in order to have an in-depth understanding of double-skin façade.

7.6 Summary

A full-scale burning test carried out before is aimed to comprehend the fire safety aspect of the new architectural feature which is getting popular in the local area. The two-story test facility was used to demonstrate the smoke and flame spreading inside the cavity of a double-skin façade with variable depth of cavity. The cavity between two skins appears as an effective channel for spreading of smoke and flame in case of fire, with the assistance of natural or mechanical ventilation applied in the space to take away accumulated solar heat gain. An undesirable scenario is flame impingement onto the inner glass panes on the adjacent floors, either upper or lower floor depending on pressure gradient. Flame impingement causing glass breaking on the inner skin of double-skin facade would put more occupants at risk. The inclination of hot gases inside the cavity is therefore a key factor to the detrimental effect of this building feature. Whether it is moving vertically upwards from the fire room or tilting towards the outer skin at an angle would lead to different consequence.

Wider cavities appeared safer in the tests. To avoid breaking of the inner glass panels, as in scenario II in Figure 6-1b, larger cavity space might be a solution. However, the gross or the rentable floor area will be reduced and so not welcomed by the developers. Among the different cavity depths, including 1.5 m, 1 m and 0.5 m, 1 m might be the most risky value. An undesirable fire scenario that caused the breakout of the inner skin was resulted. Further studies on the intermediate values between those applied in this study should also be carried out to have a clearer understanding of the critical value. Other factors affecting the smoke spreading should be also studied thoroughly to give whole picture of the fire risks of this architectural feature.

It was presumed that the height of the cavity space in the test facility was not tall enough to induce significant stack effect inside the space. Further study using a setup matching better with the actual double-skin façade feature is proposed to verify this. Prohibitive resources are required for such experiments with a full-scale setup, say with tens of stories. Experimental correlations derived from some validated modeling techniques (e.g. Stec & Paassen 2002) have to be applied and relied upon.

Prescriptive-based codes are still dominant in the existing regulations in Hong Kong. Engineering performance-based fire codes, still under development in local area, is thought to be more appropriate for the fast-track development of the construction technology where innovative designs are often associated with potential fire safety problems (Chow 1999). Fire safety engineering approach allows tailor-made design of fire safety provisions to a particular building. Database containing the temperature of glass breakage should be acquired to help establishing the new codes. The ISO 9705 room-corner fire test (Babrauskas & Grayson 1992) is one of the approaches to give the required information, such as gas and glass surface temperature profiles, heat flux distribution profiles, time to first crack and cracking patterns, as demonstrated in overseas works (e.g Shields, Silcock & Flood 2001). The full-scale international-standardized test is preferable than the bench-scale tests since radiative heat transfer is not able to be scaled down which may result in a significant error.

CHAPTER 8 ULTRA HIGH-RISE BUILDING DESIGN

8.1 Introduction

Due to limited area of land and high land price, many well-developed region including Hong Kong have built with numerous ultra high-rise buildings, of which the elevators had been considered as a means of escape in case of fire (Favro 1995). In the local area, ultra high-rise building has been understood to be building having more than 40 levels. Another term “mega-high-rise building” refers to a building in excess of 75 floors and with one or more sky lobbies (Fortune 1997). It is found that about one-tenth of the 100 tallest buildings are possessed by Hong Kong (Emporis 2005). Some of them in Asia are higher than 400 m.

Breaking glass of the tallest building in Hong Kong due to a fire incident happened years ago (Oriental Daily News 2002). At that time, the glass panels were being installed on the exterior. As the building was still under construction and the sprinkler systems were not yet commissioned, high temperature associated with the fire made the glass panels unendurable to the thermal stress and thus fractured and dislodged from a height. Fortunately, no injuries were resulted from the accident. Safety implication of ultra high-rise buildings is already indicated by the occurrence of this incident.

Consequent to WTC incident in 2001, extensive concerns (e.g. Chow 2004) have been aroused for the fire safety of skyscrapers, in particular the ultra high-rise buildings. This incident has led to the largest damages, in terms of human lives and property loss, ever seen in the building disaster history. The tragedy claimed some 2,800 people and tens of billions US dollars. The follow-up works dealing with the incident and the building site have not yet finished even after 3 years of the disaster. The collapse released thousands of tons of cement dust, glass fibers, asbestos, lead and other compounds into the air. These pollutants are threatening the health of the local residents and workers who were found having developed symptoms like coughing, wheezing and shortness of breath. Babies born by women exposed to dirt and soot from the attacks were appeared smaller than usual. The hazards of the incident are still present and it seems keep going on to the next generation. These suggest an urgent need to safeguard our living environment more securely from the similar attack.

Various disciplines including structural engineers, building designers, fire engineering professionals and law makers are paying great effort on studying the adequacy of the existing building design and requirements. As reviewed, the existing fire regulations for high-rise buildings are not specified for different height. Fire codes on fire resisting construction, means of escape, means of access and active fire protection systems in most countries (e.g. BD 1995, 1996a, 1996b; FSD 1998) are basically designed for protecting against accidental fires in buildings having fewer stories. Though there have been hot arguments on protecting old high-rise building fires against careless actions such as removing fire doors for lift shafts while refurbishing as in the big Garley Building fire (Chow 1998); and protecting karaokes against arson fires (Chow 2001a) consequent to some big fires, concerns are aroused on whether these codes are safe enough (Chow 2004; Hung & Chow 2002a) as non-accidental fires are frequently seen. The human losses, injuries and damages to property in such fires are totally different in scale from those caused by an accidental fire. Several of them in Hong Kong, South Korea, Russia, Spain and China happened lately will be reviewed in this chapter.

The current fire regulations on fire resisting construction (BD 1996a), means of escape (BD 1996b), means of assess (BD 1995) and active fire protection systems (FSD 1998) should be revisited. The total fire safety concept (Chow 2002b) with these hardware provisions (BD 1995; 1996a; 1996b; FSD 1998; BOCA 1996; BS 2001) should be enhanced together with fire safety management (Malhotra 1987; Chow 2001d; Tsui & Chow 2004) for buildings, especially the ultra high-rise, to withstand non-accidental fires.

The WTC incident is one of the biggest events in the building history, lessons from which should be paid serious attention so as to avoid the recurrence of tragedy as such incident. On 11 September 2001, two hijacked aircrafts were piloted towards the landmark WTC twin towers in New York, USA. One tower was hit in the middle of one of the elevations, whilst the other was hit near the corner; both were on the upper stories (FEMA 2002). Both aircrafts were found filling with about 38,000 liters of jet fuel, a full capacity of the fuel tank. After the giant impact by the aircrafts, the skyscrapers, constructed of steel, were able to stand for quite a long time before collapse. The steel structure was thought to be more robust in comparing with that of concrete as shown in bomb attack in the Oklahoma city, in 1995 (Wearne 1999), where the concrete building was incapable of resisting the explosive impact and collapsed almost immediately. On the other hand, the 1362-ft and 1368-ft WTC twin towers were able to stand for 1 hour and 1¾ hours respectively under the exposure of huge fires resulted from the extraordinary fuel content.

A report (FEMA 2002) showed that the structure was able to arrest collapse from the planes, but not the collapse due to the ensuing big fires acting to the damaged structure right after the impact. The jetliners carrying with substantial liquid fuel would meet the US federal criteria for weapons of mass destruction (WMD) (e.g. Asker 2001). As a very high heat release rate (HRR) would be resulted from the liquid fire, indoor air was heated up rapidly to over 1000 °C; and temperature of steel members might also be heated up above their critical temperature. Huge fireballs were also observed at the impact zone immediately after the impact. Intensive thermal radiation might be resulted to ignite all combustibles inside. Breaking large area of glass pane would supply adequate air for sustaining the combustion.

Since the building structure and fire safety provisions were not designed for resisting against such a big fire, total collapse was therefore resulted. The failure of the fire safety provisions, including passive building construction and fire engineering systems (designed only for fighting against accidental fires), under the conflagration is thought to be the main cause leading to the tragedy. As reported, there are a number of estimations on the collapse scenarios from professionals around the world. They will be discussed in the next sections.

It was believed that the mega structures would not collapse if either one of the extreme loadings added to the towers. A higher collaboration between the structural engineers and fire experts is pursued consequent to this unprecedented building disaster. Various professionals (e.g. Usmani, Chung & Torero 2003) are now concerned about protection of structural elements against fires which might give rise to substantial revision on the fire safety requirements for the structural members.

The fire resistance tests carried out in the federal investigations also exposed uncertainties in the standard fire tests used in current practice. Clarifying the unclear issues about the standard fire tests the existing codes based on is of ultimate importance for upgrade of existing skyscrapers and safety level for future buildings.

The heat release rate of the big fires at the twin towers can be better estimated upon releasing more data. Anyway, design fire in most buildings would not be so high as observed. Burning a car without liquid fuel might give only 7 MW! The extremely high heat release rate as estimated is far beyond the normal design value in building fire. The existing fire safety requirements are only for protection against accidental fires. This point should be reviewed for symbolic buildings to protect against extreme events like this. Whether and how to include protection against terrorist attack fires in ultra high-rise buildings in the fire safety objective would leave a big task for forthcoming research. Prior to its establishment, a fire risk assessment scheme taking into consideration non-accidental fires, symbolic buildings and new architectural features that are incompliant with the existing prescriptive codes would be useful in making decisions on the improvements of the current fire safety provisions.

Professionals and authority officers throughout the world are paying great efforts on the building and fire investigations so as to provide concrete basis for the enhancement and development of the building and fire codes and practices. Some suggestions for the fire safety design of ultra high-rise buildings are included in this chapter.

The collapse scenarios estimated by some leading professionals throughout the world will be also reviewed. Understanding which would help the safety design of buildings, especially the ultra high-rise in the coming future. Stability of the steel structure has become a concern in testing fire resistance for structural members. As examined by the official investigation department (NIST 2004a), some uncertainties in the conventional practice of the standard tests were exposed and to be further investigated. The possible heat release rate was estimated. The high value is suspected to be a key factor causing the total failure.

Collapse of WTC twin towers was so shocking. Since then, building designers had paid more attention and efforts on fire safety of ultra high-rise buildings. This incident has been selected as a case study to disclose the potential fire risks associated with ultra high-rise buildings and to provide information regarding fire safety consideration.

8.2 Concerns Arising from the Latest Big Fire Incidents

There were a number of big fires resulted deliberately throughout the world in recent years. By reviewing these incidents, it was revealed that the current prescriptive codes might be insufficient for protection against malicious fires. The non-accidental attacks brought about substantial injuries and fatalities. Some of the more serious examples are listed below:

- In January 1994, a bank in Shek Kip Mei, Hong Kong was firebombed and it claimed 4 human lives and injured another 9 people (HKS 1994). The branch was found complied with fire regulations, but the provisions were still not enough to avoid the nightmare.
- In January 1997, an arson fire started by a petrol bomb killed 15 people and injured another 15 in a karaoke bar in Tsim Sha Tsui, Hong Kong (HKS 1997). Karaoke Bar was one of the newly popular businesses at the time of being attacked. It was not included in local codes as one of the building usage having specified requirements though it has unusual layouts and design in the occupancy.
- In September 2001, the renowned WTC twin towers were crashed and knocked down by the most disastrous terrorist attack ever seen. Thousands of human lives were also claimed in this extreme event. The fire safety provisions, designed for accidental fire only, were found unable to resist and control a big fire size like that.

- In October 2002, terrorist attack in Bali, Indonesia, a famous tourist visiting area, gave rise to a death toll of 202, among which there were tourists from 21 countries (BBC news 2003a).
- In February 2003, a man setting fire in an underground train in Daegu, South Korea, killed at least 120 people and another 134 injured (BBC news 2003b).
- In January 2004, arson fire was set in the busiest mass transit railway at rush hour in Hong Kong (SCMP 2004). A total of 14 people were injured.
- In February 2004, the bomb attack in Moscow metro subway caused at least 39 people died and more than 100 injuries (BBC news 2004a). Many of them were suffered from smoke inhalation and burns. Tracing back the history, there were many suicide bomb attacks in the city, believed to be plotted by political dissidents.
- In March 2004, ten terrorist bombings hit Madrid's train systems, leading to at least 190 people dead and 1200 injuries (BBC news 2004b).

In local area, there were proposals to revise the fire codes after having a big fire. Better fire protection should be provided to existing or new premises. However, the ad-hoc revisions only benefit the community after the big incidents. Provisions of safety measures should precede every catastrophe to avoid claiming human lives or causing injuries. Fire safety provisions are normally designed for fighting against accidental fires (although some accidental fire (SCMP 1996) might give big disaster due to whatever unknown reasons), explaining why there are undesired consequences. Since the frequency of occurrence of arson fires and even terrorist attack fires appears to be increasing, non-accidental fires are urged to be included in the fire safety objectives in some areas.

8.3 Fire Safety for Ultra High-rise Buildings

Fire safety provisions in typical buildings were only designed to protect against accidental fires. The prescriptive fire regulations which have been used for decades are demonstrated to be good enough for such protection. However, they are not enough for protecting against fire attack of larger-scale. It was apparent that from the study on collapse scenarios of WTC incident, both the building structure as well as fire protection provisions were inadequate for the extreme event like this. The extraordinary loading added or the uneven distributed loading had already exceeded the upper limit of design value even though there were redundant structural elements inherent in the twin towers. Or, the huge fire had substantially undermined the strength of the structural members. Originally, the whole structure might be able to resist either the big impact or the conflagration but not the resultant loading from both of them since it might be too large that the whole structure could hardly endure. Structural response under non-accidental fires should be profoundly investigated. This will be relied on a higher degree of collaboration between the structural engineers and fire engineering professionals.

Extremely high heat release rate is found to be one of the probable root causes of the incident. The heat release rate should be the first parameter to review. For example, design fires used locally for shopping malls and atriums are 5 MW and 7 MW respectively, but there was thousands of megawatts as evaluated for the incident. These should be further reconsidered to include flashover (e.g. Chow 2001a).

Indeed, the big heat release rate due to burning liquid fuel as analyzed in the WTC incident is far higher than the typical value used for designing fire safety provisions such as sprinkler system in normal operation. After the enormous crash by the aircrafts, sprinkler pipeworks might be damaged. Even if the sprinkler system was not damaged, water discharged from the sprinkler would give a faster spreading rate of the liquid fuel fire. Design fires should be reconsidered and developing a new database of heat release rate might be necessary after the WTC tragedy.

Carrying out full-scale burning tests might not be feasible in Hong Kong. The high cost and low repeatability make it even more difficult. Fortunately, such a facility was developed in China at a remote area (Chow 2001a). In addition to the costly full-scale burning test, other methods (e.g. Morgan & Hansell 1984/85) to determine the design fire should be considered to give a good database.

Database of heat release rate from other nations might not be applicable for local use. This is especially true in China where so many new materials have been developed in the past decade. Different living styles make it inappropriate for application to buildings in different regions. Measurement on elements for local applications should be carried out (Chow 2002c).

It should be noted that fire risk level can be varied with a number of factors, such as location of building, the social environment, political stability and so on. It is important and useful to determine the necessary reinforcement for the corresponding buildings and thus devote appropriate investment to attain the necessary fire safety level. Using exaggerated protection or construction elements may, otherwise, add load and lead to adverse effects to the natural environment, say additional waste disposal and extra consumption of unrenewable energy. Design of ultra high-rise buildings (e.g. Chow 2004) should be considered carefully.

A fire risk assessment scheme should be proposed to determine the risk level that a building may encounter. The hazard scenarios, consequence of scenarios, and the probability of occurrence vary with the building location where political, economic and social environment may be entirely dissimilar. The building itself would also affect the severity of incident, for example green buildings with extensive use of glass appear too vulnerable to the huge crash. All these should be included into this scheme to evaluate the fire risk. The evaluated risk level by the scheme can provide a basis for the upgrading of current fire safety provisions for existing or new buildings.

Authorities and professionals have also started to review the fire safety provisions for special buildings, such as skyscrapers, against conflagrations like terrorist attacks. Fire safety provisions including passive building designs such as fire resisting construction, means of escape and means of access; fire engineering systems and fire safety management should be upgraded in local area. If non-accidental fires including terrorist attack fire are included, the following should be upgraded and enhanced.

- Structural stability against a big fire
- Evacuation
- More effective fire engineering systems
- Well-implemented fire safety management

Some suggestions on the above areas are included in Appendix G.

8.4 Collapse Scenarios of World Trade Centre Twin Towers

Two civil jetliners Boeing 767 were hijacked by terrorists and hit at WTC in the morning of 11 September 2001. They were full-loaded with maximum number of passengers together with about 38,000 liters (10,000 gallons) of liquid jet fuel (FEMA 2002). The WTC North tower and South tower were hit between the 94th and 98th floors floor in the middle of one façade and between the 78th and 84th floors floor towards the corner respectively. The two buildings were able to stand for about 1 hour and 1¾ hours correspondingly prior to their eventual progressive collapse. Other than wars or natural disasters, the WTC incident has caused the largest damages in terms of human lives and property loss ever seen.

Consequent to the total structural failure, investigations were initiated by many organizations, including government departments, engineering institutes and private sectors. To reconstruct the fire and collapse scenarios would help to understand the factors leading to the collapse, so that further works can be focused on the vulnerability of these factors. A safe built environment with a number of ultra high-rise buildings in the future is also relied on these studies. Understanding this is of ultimate significance for the design of ultra high-rise buildings in the future. Collapse scenarios assessed by various professional parties and in the latest official reports are reviewed and reported. Fire scenarios and structural response modeled and analyzed are also discussed (e.g NIST 2004a).

There are two phases of the US federal investigations. Right after the tragedy, the Federal Emergency Management Agency (FEMA) of the US government and the Structural Engineering Institute of the American Society of Civil Engineers (SEI/ASCE) formed a Building Performance Study (BPS) Team to perform the work of data collection on the tremendous event, and to make preliminary observations and recommendation on the further research. Their 7-month study was reported in May 2002 (FEMA 2002). In August 2002, the National Institute of Standards and Technology (NIST) started an official federal investigation after being funded (Quintiere 2004a). The investigational study was planned to last for 2 years and it was supposed to be completed at the end of 2004. Other leading fire safety experts' views and analysis will be also included. An engineering firm has also proclaimed their effort on the investigation of the structural failure occurring in WTC, as announced to the general public via television broadcasting (TVB 2003). In fact, a rough estimation (Chow 2002a) was reported to the local professionals years ago after the incident. All these will be included in this chapter.

8.4.1 Building performance study from FEMA

In the World Trade Center Building Performance Study (FEMA 2002), all relevant information about the WTC complex, in terms of structural design, fire safety provisions, observations of the incident and the fire behaviors of the steel members were clearly described.

The FEMA Building Performance Study (FEMA 2002) showed that there are redundant structural systems in each of the towers, the perimeter tubular structure, the gravity loadbearing central core and the outrigger trusses system on the upper floors. After being crashed by the hijacked civil liners, the structure kept standing for about 1 hour and 1¾ hours respectively for the two towers. It was believed loadings on the damaged elements were successfully transferred through the structural systems to the adjacent ones, making those members bear gradually increased loading which were probably near, but not over the ultimate capacities. It was anticipated that the towers could remain standing if there were only impact but not an ensuing fire. Therefore, fire was presumed to play a more significant role in leading to the collapse.

Since fireballs were observed at the impacted zone immediately after the aircraft's impact to the twin towers, the jet fuel carried by the aircrafts was partly consumed by the fireballs. It was estimated that three fireballs, of diameter as wide as the length of the tower, consumed about 3000 gallons of fuel whilst 4000 gallons were flowed away. The jet fuel left inside the floor area was about 4000 gallons. With a high burning rate of liquid jet fuel, the fire duration was estimated of less than 5 minutes. However, the ignition of the ordinary combustibles inside the office space was triggered by the liquid pool fires, giving rise to the fires burning for the entire time. The average fuel load used was 40 kg/m^2. A peak heat release rate of 1.0 to 1.5 GW was estimated using a Computational Fluid Dynamics (CFD) (Rehm et al 2003). Temperatures within the floor area, depending on the changed geometry and fuel loading upon the aircrafts entry into the interior, were estimated as high as 900 to 1000 °C in some areas while 400 to 800 °C in other areas.

No clear conclusion was made in the report on the root cause of the collapse disaster. However, it spelled out that the floor truss system should be further examined and the connections between floors and columns were the weak link (FEMA 2002).

Several collapse scenarios resulted by the substantial degradation from the impact of the aircraft and the big fires were addressed in the report. Some spray-applied fire protective materials were peeled off due to the impact. Exposing part of the protected members would heat up the floor framing and slabs, which then expanded and gave thermal stress on some other members. Higher temperature on floor slabs would reduce their strength and lead to a catenary action. If the end connections failed to support, the floors would fall onto the floors below and the unsupported columns would buckle. On the other hand, the modulus of elasticity of the columns would decrease with their elevated temperature. They would buckle even when the lateral support is present. It was believed that this effect outweighed those of the floor slabs.

8.4.2 Building Performance Study (BPS) team member

One of the team members (Milke 2003) also estimated that less than one minute was required to burn up all the jet fuel inside the floor area, excluding those used up by the three fireballs. He also suggested three failure mechanisms, two of which were the same as in the FEMA report talking about catenary action leading to falling floors and the columns' buckling phenomenon. Another mechanism he addressed was about the outrigger truss system at the roof the twin towers, which was designed to transfer loads between interior and exterior columns. The stresses in the truss elements increased with a decrease of the strength of the columns. When these stresses exceeded the truss capacity, load could not be transferred, leading the collapse of the interior columns.

8.4.3 Report from an engineering consultancy firm

In a report from an American engineering corporation as broadcasted two years ago (TVB 2003), it was pointed out that the major reason for the progressive collapse of the WTC towers was the insufficiency of fire safety provisions. The structural members of the central core were found to be weakened substantially by the big fires and explosions. As a result, the central portion of the buildings was incapable of withstanding the giant mass of the structure. Loads were transferred between the inherent redundant structural systems. Originally, the outrigger trusses system between the uppermost 106th and 110th floors was designed to stiffen the building frame against wind forces. It was also able to transfer the gravity loads from the central core. The analysis of the report illustrated that the loads were mobilized to the perimeter columns right after structural failure had occurred at the centre of the building, leading to a giant force pulling the whole structure down to the ground level, as illustrated in Figure 8-1. It was asserted that the catastrophe of total collapse was attributed to the inadequacy of fire safety provisions. The structure was believed to be able to resist an impact force of 500,000 pounds at the time of being hit. It was contrary to the explanation of FEMA from which it was discovered that the structure was too weak to resist the forces imposed.

8.4.4 An earlier estimation in Hong Kong

Based on the limited information available immediately after the attack (basically from television and newspapers), an estimation from the viewpoint of structural force was computed. Since both the interior and exterior steel columns were destroyed and unable to resist the loading, by calculating the force increased due to the impact at the short time interval might explain (Chow 2002a) why the floors fell one by one as observed in the television. In this estimation, the exaggerated value of the whole mass from the stories above the impact area punching onto the floor below was assessed.

As shown in Figure 8-2, the downward force can be estimated by the mass of floors above a certain level *m*, the height of that level *h*, acceleration due to gravitation *g* (taken as 9.8 ms^{-2}) and the impact time for change of momentum Δt:

$$\frac{\text{Increase in force}}{\text{Downward weight}} = \frac{m\sqrt{2gh}/\Delta t}{mg} \times 100\,\%$$

$$= \sqrt{\frac{2h}{g(\Delta t)^2}} \times 100\,\% \qquad \text{… (8-1)}$$

If Δt is 1 s and one storey of 3.5 m high is assumed to be collapsed at the beginning, the total force would be increased by 85 % of its downward weight for each impact resulted from the collapse of each floor.

Since the structural steel columns and beams were heated up to high temperatures, the lower floors could not support the substantially increased downward force from the upper floors. The floors immediately below the giant mass continuously fell on the stories below together with the heavy weight of the debris from the upper floors. The weight of the falling mass increased considerably from each impact. The force increased due to subsequent impacts of the collapse of the n^{th} floor is therefore $(1.85)^n$ of the downward weight! A "domino-like" progressive collapse was resulted at last as all the floors underneath were unable to support the weight of the falling mass. The progressive collapse was illustrated in Figure 8-3.

As discussed, diversified findings were revealed from different reports. One of which claimed the disaster the responsibility of structural failure whilst the other claimed that inadequacy of fire safety provisions should take the major liability, however they both suggested that the existing buildings are incapable of bearing huge fires like this. Further investigations and studies are urged to carry out.

From the viewpoint of fire engineering, many works can be carried out for the upgrading of fire safety provisions. One of the critical parts is to review the current fire safety objective in which buildings are only protected against accidental fires only. If arson fires and even terrorist attack fires are to be included into the fire safety objective, fire safety provisions in terms of passive building construction, fire services installation and fire safety management including the egress system should be enhanced. However, exaggerated cost would be involved if all buildings require the same degree of enhancement. Perhaps, an assessment scheme should be worked out to appraise the risk level of the particular building and the different extent of fire protection needed. Simultaneously, ultra high-rise buildings should be designed and considered carefully to safeguard human life.

8.4.5 National Institute of Standards and Technology (NIST) investigations

A lot of efforts have been paid on the investigations of the WTC disaster in order to recommend improvements for ultra high-rise buildings' design, construction and maintenance. After having collected additional findings (NIST 2004a), the federal investigation by NIST has carried out a more in-depth analysis on the

WTC incident. They paid a great deal of effort individually on analyzing the structural fire response (NIST 2004b), the fire resistance of WTC floor system (NIST 2004d), the aircraft impact damage (NIST 2004e) and so on to reconstruct the probable fire scenario (NIST 2004c). It concluded that the fires, but not aircraft impact, played the major role in initiating the collapse (NIST 2004f). However, aircraft impact also contributed the entire failure. Fireproofing materials on top of the steel members were believed being dislodged by debris from the impact, otherwise, the temperature rise of the structural members was not high enough to cause global collapse (NIST 2004c).

The analysis on aircraft indicated the number of columns severed and damaged and the damages to floor slabs, floor trusses and core beams by computer calculations (NIST 2004e). For WTC1, other than the north face which was directly impacted by aircraft, exterior columns were failed at bolted connections. Due to the impact, a large amount of fuel and aircraft debris was also deposited in certain areas. The characteristics of the aircraft damage on WTC2 were similar to those on WTC1.

The floor truss system with the protection of spray-applied insulation materials were an innovative construction at the time of the building being built but there was a lack of technical basis supporting the thickness of the fireproofing materials (NIST 2004f). In view of that, NIST has carried out a series of fire resistance tests of WTC floor systems (NIST 2004d). Two tests were conducted with scaled truss spanning 17 ft whilst the other two spanning 35 ft which was representative of a short-span floor system in WTC towers. For the 35 ft span tests with ¾ in fireproofing, the fire resistance rating should be laid between 1.5 hours and 2 hours shown from results of the restrained and unrestrained tests. The required fire resistance rating for floor system should be 2 hours and 3 hours as specified by the New York City building code at the time of construction and 2000 International Building Code respectively.

The results were found contradictory to the expectation based on conventional testing procedure where unrestrained rating will be lower than restrained rating and the restrained tests are usually used in practice. These tests, however, showed the unrestrained one got a higher rating than the restrained one. The ratings might be lower in general.

By carrying out a range of studies varied from the property of the structural elements, the structural performance after aircraft impact, the fire behavior of structural members and collapse analysis, leading hypotheses for the collapse of WTC1 and WTC2 were also developed (NIST 2004c) according to all the evidence from which collapse scenarios were reconstructed. Both towers were supposed to have fallen down in a similar approach (NIST 2004b) except that floor sagging also appeared in WTC2.

The hijacked civil jetliner was piloted and hit towards the centre of north face of WTC1, passing through from north face, the central core to the south side. The enormous weapon extensively ruined the fireproofing on the steel structure. Along with the big fire broken out in the floor area afterwards, the critical temperature of the exposed steel columns in the central core near the south side was exceeded. High heat exposure softened and shortened the columns where the loadbearing capacity was diminished. As discussed, there were redundant structural systems in the buildings. Load at these core columns were then transferred through the floor systems to the adjacent core columns. Being further heated up, more core columns softened with the increasing degree of shortening led to downward displacement of core area which induced load transfer through the hat truss on the upper floors to the perimeter columns.

The fireproofing of the floor systems was also removed due to the great impact. Deflection was occurred at the impact area and floor slab expanded due to temperature increase. The expansion of the slabs created horizontal pulling force onto the perimeter columns on the south face. In addition to the horizontal force, the vertical loading and the extreme high temperature added together to pull the perimeter columns bowing inward and buckled which were observed 5 to 10 minutes before the collapse of the tower. The whole structure became instable due to the buckling of the vertical members above which the downward displacement of the building mass changed the potential energy which exceeded what the structure could bear and total collapse was consequently resulted.

Collapse mechanism of WTC2 was alike but the location of the impacted area was different. WTC2 was crashed near the southeast side by the aircraft. Fireproofing materials on the structural steel was also removed. Due to the fire ensued, the unprotected core columns near the east side were softened and shortened. It was also followed by load transfer to adjacent core columns through the floor system. As increasing number of core columns being weakened, downward displacement occurred at the core area which led to significant load transfer through the hat truss to the east perimeter. The floor systems, especially at the impact zone and east side, sagged significantly after the big fires occurred and fireproofing had been removed. They expanded and pushed outward on the perimeter columns except those on the southeast which were, on the other hand, pulled inward due to connection loss. Again, instability induced by these buckling events. The building mass above the impact zone went beyond which the structure below could endure then fell down accordingly.

8.4.6 A leading fire expert's analysis

A leading fire expert also gave insightful analysis to this event as well as on the NIST results. He suggested that insufficient fireproofing on the floor truss system to be the ultimate cause of collapse of the twin towers (Quintiere, Marzo & Becker 2002; Quintiere 2005), and the fire was more significant than the aircraft impact to the global collapse. The fire duration of the substantial jet fuel he estimated was 79 s, excluding the amount for the consumption of four fireballs in each tower. For the building contents, based on the fuel load of 37 kg/m^2 (from the general literature) rather than a comparatively low value of 20 kg/m^2 used in the NIST investigations, fire durations of about 90 to 125 minutes were estimated. By using CIB correlation, the fire temperature ranging from 800 to 1000 °C and the peak heat release rate of 2.5 GW were evaluated. He also estimated the time to failure and the corresponding temperature of the steel rods by carrying out a conduction analysis on steel elements with insulation on top. The results gave good agreement between the actual insulation thicknesses and the actual collapse times at the WTC twin towers. Indeed, he concluded that total failure induced by core columns are not more likely than by the floor truss which was in less protection.

8.5 Fire Resistance of Floor Truss System

The New York City building code specified the requirements of 3-hour fire resistance rating for columns and 2-hour fire resistance rating for floors (NIST 2004d) at the time the WTC twin towers being built. The provisions of WTC twin towers were compliant with the local building code at the time being built. However, both skyscrapers fell down entirely much less than 2 hours after the crashes of aircrafts.

To achieve 2-hour rating, only 13 mm fireproofing materials was needed as stated in the code. The floor truss systems of WTC were coated with 19 mm fireproofing when they were built. However, the spray-applied fireproofing was an innovative technology at that time and there was no technical basis on the determination of the thickness of the material (NIST 2004f). A necessary full-scale fire resistance test for this innovative floor system was not conducted to determine the required thickness for a 2-hour fire resistance rating.

NIST also found that there was an interesting history in relation to the thickness of insulation for the floor system required for WTC twin towers (NIST 2004d). Different thickness was pursued at different time to meet the 2-hour fire resistance requirement. In 1963 when the twin towers were erected, 13 mm thick insulation was deemed to be sufficient. Some of them were upgraded to have 38 mm thick in 1993 and that was why the impact area of WTC1 had a layer of 38 mm thick fireproofing whilst all but one level at WTC2 had the original thickness. Later in 2001, a model code claimed that 2 inches (50 mm) of fireproofing was required for 2 hour rating but a consultant report found that 13 mm was adequate based on their analysis.

The results of NIST study revealed that some fireproofing coated on the structural steel members were found to be knocked down when the aircrafts crashed into the floor area (NIST 2004c). Since the critical temperature of steel is at 550 °C, over which the modulus of elasticity would be decreased by 50 % (ASFPCM et al 1992). The unprotected fully stressed steel verified having half an hour fire resistance (ASFPCM et al 1992) was unable to stand for the conflagration inside the twin towers. The protection of fireproofing materials was significant in offering enough fire resistance periods for evacuation.

To explore the fire behavior of the floor system as constructed in WTC is constructive to reconstruct the fire and collapse scenario. Full-scale and scaled fire resistance tests for composite concrete-steel trussed floor systems as applied in the WTC twin towers were carried out by the NIST (NIST 2004d) to re-examine the fire resistance ratings of such structural system. A total of four tests were conducted, including thermally-restrained and -unrestrained 11-meter floor system with 19 mm fireproofing material, thermally-restrained 5-meter truss with 19 mm fireproofing and thermally-restrained 5-meter truss with fireproofing thickness of 13 mm. The common practice for the test specimen in the fire tests in US is under thermally restrained condition which means the thermal expansion is prevented. 11-meter was representative of the typical floor span inside the twin towers whilst 5-meter was the common size in the standard tests. Fireproofing of 19 mm was the thickness originally applied in the twin towers but 13 mm was the specified thickness in the code at the time WTC being built.

The test results showed that the restrained 11-m floor assemblies was 1.5-hour fire rated, lower than the 2-hour fire rated unrestrained one, contrary to the general expectation that an unrestrained floor system could not perform as well as the restrained counterpart. The fire rating of the structural members in buildings like WTC might be underestimated. On the other hand, the truss system of 5 m gave a 2-hour fire rating when the fireproofing thickness was of 19 mm. It is different from the result achieved from that of 11-meter floor span. The fire resistance rating of real construction determined based on the test using smaller specimen size in standard fire tests becomes query. The 13 mm thick fireproofing, as specified in the building code at the time of construction, on the 5 m long floor assemblies only gave fire rating of 0.75 hour which was far less than the expected rating.

These fire tests on floor system raised questions on the uncertainties found in the standard practice which has been applied for decades. Not using full-scale test specimen is certainly a problem which has been discussed before (Hung & Chow 2002a). The perception on the unrestrained and restrained construction elements have to be revised with appropriate experimental verifications. The underestimated fire ratings on other existing buildings should be reinforced to provide sufficient fire protection.

A leading fire expert has commented on NIST analysis (Quintiere 2004b). He found query on the scale of the fire resistance tests carried out by NIST. A full-scale, representative floor truss system instead of the scaled one as used by the study should be studied. Moreover, the test constructions did not collapse in the tests and the deflection limitation was used to determine the fire ratings, which seemed incomparable to the actual performance of the WTC floor system. He also pointed out that with the limited recovered steel elements, the actual thickness of fireproofing applied in WTC should be figured out carefully for this kind of analysis. In fact, he suggested the root cause of the global collapse was due to inadequate fireproofing rather than dislodgement of the insulation materials. His conduction analysis correlated well the thickness difference to the actual collapse time difference between the twin towers (Quintiere 2005).

The current building and fire codes were designed only for protection against accidental fires but not the extreme events as the terrorist attack at WTC twin towers where WMD was employed to attack the symbolic buildings. Even ordinary combustible content, say furniture and paper, would give high fire load. The buildings and fire safety provisions could already hardly survive the extraordinary heat release rate which is much higher than the design fire size.

In addition, the enormous impact of the aircrafts, damaging severely the fireproofing materials and keeping the steel members exposed, contributed significantly to the subsequent fires and the final progressive collapse. The existing building and fire codes only took a single issue into account; say impact or physical damage was not considered in a fire scenario. Closer collaboration of structural and fire engineers are therefore expected in the future.

It was observed from videos available on web that WTC2 was tilting aside while WTC1 was more likely punching straightly on the floors below. If tearing off the fireproofing materials was the main reason, the extent of damages on the different elements would be different. This might lead to non-uniform stress distribution. The buildings would then collapse sideway as a domino, not as observed to be only slightly tilted as in Figure 8-4 (Real News 24/7 2005). Note that there were two towers, not just one!

8.6 Heat Release Rate inside the Twin Towers

In light of the collapse scenario, big fires following the exaggerated impact further weakened the structural steel members. The substantial jet fuel carried by the civil jetliners was able to create extremely high HRR which is of the order of thousands of megawatts (Hung & Chow 2004b). However, fireballs, being observed outside the perimeter wall at the impact zone, believed to use up considerable amount of liquid fuel (FEMA 2002). Moreover, some fuel was spilled out to the exterior through the vents. The jet fuel left inside leading to big fires damaging the building structure should be evaluated by eliminating the fuel spilled out and fireball consumption.

The fuel used for civil aviation is of kerosene type called “Jet A-1” (Shell Canada Limited 2004). The flash point of which is 38 °C minimum as specified in the standard (ASTM 2001). The two civilian jet planes employed in the terrorist attack carrying a large amount of aviation fuel were regarded as the WMD which caused the most destructive building incident ever seen in this century. From the images of the WTC incident shown in the news reports, several fireballs were generated outside the external walls at the impact zone. The huge crash damaged seriously both the targeted building and the plane itself. The sudden release of the originally pressurized fuel was evaporated into vapor; ignited and burned in form of sphere moving up due to buoyancy (NFPA 1995).

Fireballs can be as large as about 100 m in diameter and the duration of it is of the order of a few seconds only since the mixing with air is rapid (NFPA 1995). In the WTC incident, the diameter of the fireballs observed at WTC2, the second tower being hit, was wider than the width of the building (about 63 m) right after the aircraft’s impact. The mass of fuel used by those fireballs can be calculated by the experimentally based correlations from the literatures (Zalosh 1995; Milke 2003). The mass of fuel vapor m (kg) used for a fireball of particular diameter D (m) can be expressed as:

$$D = 5.25\, m^{0.314} \qquad \ldots(8\text{-}2)$$

Therefore, the mass needed for each fireball generated at the twin towers is approximately 3,000 kg. The earlier FEMA building study (FEMA 2002) found out there were three fireballs for each tower while there were four in a later study (Quintiere 2005). If there were four fireballs, then a total of 12,000 kg of jet fuel was consumed. Both skyscrapers were assumed to be similar.

The jet fuel carried by the planes was about 38,000 liters (FEMA 2002) which correspond to about 30,400 kg. The fuel found outside of the towers was about 3,000 kg and 4,800 kg respectively at WTC1 and WTC2 (NIST 2004e), either flowing down the outside of the towers or passing through the building. Consequently, the jet fuel entered the floor area and gave rise to the ensuing big building fires after the impact are estimated at about 15,400 kg and 13,600 kg to WTC1 and WTC2 respectively. Based on the mass loss rate of kerosene at about 0.05 kg/m^2s, the burning rate of 200 kg/s for the total floor area would be resulted provided that the fire burned in a homogenous way. The duration for burnout of jet fuel would be 77 s and 68 s respectively for WTC1 and WTC2. The fire, as observed, was burning for the entire period until the symbolic buildings collapsed. The burning of liquid fuel, though burning for a very short period of time, triggered the ignition of the building contents by its exaggerated HRR.

Though the calculated fire load density (FLD) of the jet fuel is only about 460 MJ/m^2, which is much lower than the upper limit of the local code (FSD 1998), it cannot give any physical insight of the fire size. HRR, however, is the answer to “how big is a fire?”. As reported in the literature (Hung & Chow 2004b), the

HRR of up to 8 GW was computed for burning liquid fuel on the typical floor area of WTC. For typical retail shops of area 9 m^2, a 5 MW design fire is commonly used. However, the value can be up to 19 MW for a liquid pool fire. The intensive radiative heat flux can lead to severe devastation in terms of structural stability, human lives and property. The whole content inside the impact areas must be ignited promptly and a well-developed fire would be resulted.

After the planes had crashed into the towers, broken areas on the external walls would give large quantity of fresh air for faster fire growth. The peak HRR of 1 to 1.5 GW was evaluated in the study of FEMA by using a CFD code Fire Dynamics Simulator (FDS) (Rehm et al 2003). On the other hand, Quintiere (Quintiere 2005) evaluated the peak HRR of 2.5 GW based on the CIB correlations (Thomas & Heselden 1972) and the size of vent created by aircraft impact as reported in the FEMA building study (FEMA 2002). He has also demonstrated the applicability of the CIB data correlations to the large building fires like the WTC incident. However, the CIB data is related to wood cribs fire. For other fuel type as in WTC twin towers, the burning rate and thus the peak HRR would be higher.

The claim on the insufficient thickness of fireproofing might be inappropriate. In that analysis, only temperatures but not heat fluxes were evaluated (Quintiere 2005). With such extremely high HRR, it is suspicious that nothing can be endured inside the building. The unexposed steel members might be heated up rapidly by the strong incident heat flux even with a protective coating. Indeed, the existing building and fire codes only protect building against accidental fires which are of the order of several megawatts. Fire size of thousand of megawatts is never taken into consideration or protection for this is infeasible in terms of cost efficiency and technology.

8.7 Recommendations

There are several fire types, including accidental fires, arson fires, terrorist attack fires and natural disaster fires. For building fires, terrorist attack fire might be of the largest scale in terms of damages as demonstrated in the WTC tragedy. Considering the existing fire codes, only accidental fires taken into account is certainly insufficient.

Efforts have been paid throughout the world after the tragedy of World Trade Center which is a kind of incidents receiving inadequate attention before. Fire safety provisions in local practice are currently under review and considered to be upgraded. From the fire engineering viewpoint, to provide total fire safety in a building, there must be three components, namely passive building design, fire services installation and fire safety management. To protect against the extreme events such as terrorist attacks, the existing requirements of fire provisions should be revisited. Recommendations laid down before certainly need some time to come into sight. However, fire safety management, software to provide fire safety, can be implemented immediately to mitigate the potential hazards to a considerable extent. It is, therefore, influential and critical to the fire safety level in existing buildings.

When all hardware failed to perform due to the mass destruction, software is the last defense line to protect human life safety. As discussed before, many improvements should be made on the implementation of fire safety management. The key area urged to achieve is the perception of this software provision for fire safety. There are only hardware provisions stated in the existing codes in the past decades, people thereby regarded them as the mere essential elements for fire safety. The new idea to provide total fire safety by introducing fire safety management still paid inadequate attention in this respect. More works, such as setting up strict requirements on the implementation of fire safety management, should be carried out by the Government in order to elevate the public sense on its significance.

Measures to protect against accidental fires and terrorist attack fires are of completely different approach. For example, water sprinklers are powerful enough for small fires but foam sprinkler systems or water mist systems might be essential to suppress liquid fuel fires or fires with a high heat release rate. However, it is harmful to the escaping occupants if the foam sprinklers are actuated in a short period of time after the breakout of the fire. Another example is that the refuge floor can act as a rest place and safe destination in a small-scale fire, but on the other hand, it would impede the escape process at the breathtaking moment when total structural failure is most probably to occur.

Fire safety design is the liability of the developer or the owner of the property as they determine how much initial cost would be granted. As a result, designs oriented either for accidental fires or terrorist attack fires only would be resulted. Fire safety provisions to protect against both of them may be considered among some of the premises. In light of this, a fire safety plan is essential, in which a variety of fire safety modes are worked out for particular fire incidents, such as accidental fire mode or terrorist attack fire mode. For example, phased evacuation should be performed in an accidental fire and total evacuation should be undergone in a severe terrorist attack. Steps and actions to be taken should be premeditated and stated clearly in the fire safety plans for different modes. After a fire has broken out and the fire scenario has been recorded and analyzed, appropriate mode and actions can thus be selected and followed without hesitation.

Apparently the WTC twin towers were incapable of withstanding simultaneous damage from physical impact and big fires. Existence of either one might not lead to entire collapse of the buildings. The renowned WTC twin towers were designed to resist impact of a Boeing 707 and the significant wind forces (FEMA 2002); and also they were provided with fire safety provisions as specified in the building and fire codes, so that the structure should be able to resist either the big impact or conflagration. However, the resultant loading from both of them was too severe and the inherent protection was damaged so that the whole structure can hardly endure. The steel members and redundant structural systems, able to survive the big impact originally, were significantly weakened by the high heat environment. The exaggerated HRR resulted by the substantial jet fuel and building contents led the buildings to an untenable condition promptly after the aircraft impact. Both of them gave rise to the vulnerability of the structure as shown in the incident but the fire is generally accepted to be dominant in this respect.

Fire attacks might be accompanied by physical damage occasionally as in WTC incident. Fire loading is not the only concern in considering the necessary fire safety protection. Structural behavior under non-accidental fires should be also investigated. Higher degree of collaboration between the structural engineers and fire engineering professionals is urged to advance the current practice.

A series of fire resistance tests on typical floor assemblies in WTC conducted lately (NIST 2004d) showed results out of original expectation. Fire resistance ratings on standard tests might not be appropriate for such terrorist attack fire (NIST 2004g). Whether the fire resistance of the structure performed as told by the standard tests becomes doubtful. Full-scale burning tests are thought to give results of higher accuracy. Repeatability and reproducibility of such tests require prohibitive resources. It is rather impossible to reconstruct a fire scenario as in the WTC incident. The current step is to work out and clear the uncertainties in the standard tests and practice.

A study on the impact analysis on the tallest building in Hong Kong (TVB Pearl 2004) has come up with an encouraging result which proved the landmark building is robust enough to stand after an impact as in WTC incident. It was also found that the steel column protected with concrete would be much more resistant than bare steel column itself. The new buildings to be built at the site of WTC twin towers would also use concrete cores instead of steel structure which commonly appeared in New York City years ago.

Ultra high-rise buildings are popular throughout the world. The WTC incident became an alarm to all ultra high-rise building designs. Spelling out the collapse scenario of the WTC twin towers and possible root causes on the observed structural failure would give a better understanding on the potential fire risk associated with an ultra high-rise building. Further, inadequacies in terms of structural stability or fire safety protection under current statutory requirements are illustrated. The WTC incident is a lesson to the building designers to aware of fire safety while planning for tall buildings.

Upgrading the fire safety provisions is essential but it is necessary to know that scenarios and consequences are totally different in an arson fire and terrorist attack fire. To protect structure against extreme events as in WTC incident would involve substantial construction cost. Determining the fire risk and providing corresponding fire safety measures for particular buildings are helpful to devote appropriate investment on the necessary fire safety level. Using exaggerated protection or construction elements would have adverse effect, say adding load to the natural environment. Terrorist attack fire will be more likely to happen in nations which are both politically and socially unstable. To optimize the capital cost and fire safety level, a fire risk assessment scheme should be proposed to determine the risk level a building would likely encounter before the new fire codes have been established locally. It might be varied with a number of factors, say political, economic and social environment, and the characteristic of the building itself. Green buildings (Hung and Chow 2003) and skyscrapers (Chow 2004; 2004b) with additional fire risk should also be worked out carefully.

In such scheme, risk parameters can be identified with a risk index designated. Possible risk level can then be evaluated for the assessed building. Corresponding fire safety upgrades can be provided on the particular buildings accordingly and appropriate investment can be devoted on the necessary fire safety level. Details of a proposed scheme will be discussed in Chapter 11.

CHAPTER 9 FIRE RESISTING CONSTRUCTION

9.1 Introduction

Buildings with new architectural features might have difficulties in complying with the prescriptive fire codes in Hong Kong (e.g. BD 1995, 1996a, 1996b) as the codes developed decades ago may be unable to catch up with the newly developed technologies and materials. Engineering performance-based fire codes (EPBFC) are therefore considered to implement. However, prescriptive-based fire codes are still primarily relied on.

Basically, there are accidental fires, arson fires, terrorist attack fires and natural disaster fires. Existing fire safety provisions are basically for accidental fires only. Non-accidental fires, such as arson fire and terrorist attack fire, sound much more severe in terms of fire size and damages resulted, the necessary fire protection for them should be further enhanced compared to the existing requirements. Current requirements and aspects related to fire resistance period (FRP) will be focused and investigated.

How long a structure can stand a fire without collapsing is one of the main concerns in providing safety under accidents, especially after the total collapse of the World Trade Center (WTC) Twin Towers in New York (ABCnews 2001). The structural response under fire should be also watched carefully. The requirements for structural members will be discussed in this respect.

In this chapter, development of FRP requirements is reviewed first. Factors affecting FRP are then analysed. The standard fire tests, determining FRP of the construction elements, are also included. The prescriptive codes of FRP in the United Kingdom (UK) and Hong Kong are discussed. It is followed by the identification of some inadequacies of current requirements. A brief discussion on the structural fire response to non-accidental fire will also expose the deficiencies of the existing codes. At last, implementation of engineering performance-based fire codes along with some recommendations are discussed.

All these will be useful for understanding what should be assessed in implementing engineering performance-based fire code for fire resisting construction; and in upgrading the existing prescriptive codes before the performance-based codes are valid.

9.2 Fire Resisting Construction in Hong Kong

The Code of Practice for Fire Resisting Construction 1996 (FRC code) (BD 1996a) published by Buildings Department (BD), and Part XV of the Building (Construction) Regulations (Laws of Hong Kong 1997b) described the need for fire resisting construction. In the local code (BD 1996a), buildings are required to be broken down into smaller compartments or to have adequate fire resistance period (FRP) for preventing the spread of smoke and flame and ensuring the stability, insulation and integrity of the structural elements.

FRP requirements are different for different intended uses of buildings with the specified compartment volume in the local code. All the elements of construction, such as walls, floors, beams and columns, should follow the requirements for their building types. Elements of construction should be examined by British Standard BS 476: Parts 20-22: 1987 (BS 1987a, 1987b, 1987c) as stated in the definition of FRP in local code (BD 1996a):

The period of time for which any element of construction, wall, fixed light, door, fire shutter or other component of a building is capable of resisting the action of fire when tested in accordance with BS 476: Parts 20 to 22: 1987 or as specified in tables A to F in the local Code.

In the standard fire tests, three criteria are to be examined, including loadbearing capacity, integrity and insulation. Basically, loadbearing capacity of the structural elements is the ability to resist the applied loading without collapsing; integrity is the ability to prevent flame from spreading to adjacent compartments and insulation is to keep the temperature rise on the unexposed side controlled. The FRP in local code is specified in hours; 1-hour, 2-hour and 4-hour are common grades for Hong Kong premises. Reasons for selecting those values will be discussed. Before doing so, rationale behind which should be fully understood so that safe enough buildings can be constructed. The development of the requirements on fire resisting construction has been included in Appendix H.

9.3 FRP in a Compartment

It was indicated that FRP requirements were only based on the fire load in the Fire Grading of Buildings. It implied equal fire loads would give identical fire severities, however some of the researches on fire growth showed that fire load is not the only factor which affects fire severity (Malhotra 1987).

In the later studies, it was discovered that the severities of fires can vary in a wide range even if they are of equal amount of fire load. Different materials of the same weight and the same calorific value may still have distinctive fire risks, since they may differ in their ease of ignition and burning rate (HSMO 1946).

One of the factors influencing fire severity of a compartment fire is the ventilation available, which is determined by the dimensions of the openings. It would influence the development and the temperature of the fire, since sufficient air supply and amount of fuel may lead to flashover, which is an uncontrollable fire stage.

Another factor is the thermal property of compartment enclosure. Enclosures with high heat capacity may absorb excessive heat generated and so the temperature of the fire can be kept under control. It might avoid ignition of some combustible contents inside the compartment.

The air supply through the openings for the combustion process and the thermal properties of the enclosures would affect the temperature reached while the quantity of fuel would control the duration of combustion. The occupants' familiarity with the environment and the occupancy level are also the determinants of the requirements of FRP (Malhotra 1987).

Fire load in dwellings may be higher than that in hotels, but the occupancy level is comparatively lower and their occupants are more familiar with the environment. Therefore, it is inappropriate to regard dwellings as having higher fire hazard than hotels. Other than fire severity, potential hazard can be affected by a number of factors, such as occupants' familiarity to the environment, the ability of the occupants to evacuate quickly, the degree of awareness of fire conditions and so on, which should be also taken into account in considering the required FRP.

The required FRP denoted by t_f (in minutes) in a compartment can be expressed in terms of the total fire load L (in kg - equivalent of wood); floor area A_F (in m^2); area of window openings A_w (in m^2) and area of internal surfaces to which heat is lost excluding windows A_T (in m^2) (Law 1971):

$$t_f = \frac{L}{(A_w A_T)^{1/2}} \qquad \text{…(9-1)}$$

which can be written as:

$$t_f = \frac{L}{A_F} \frac{A_F}{(A_w A_T)^{1/2}} \qquad \text{…(9-2)}$$

The term in numerator L/A_F denotes the fire load density, which was perceived as the unique parameter for determining FRP. The significance of ventilation and compartment size and shape is expressed exhaustively by the denominator $A_F /(A_w A_T)^{½}$.

However, the thermal properties of the envelope materials were not included in the above correlation. Studies on fully-developed fire in a compartment have shown that heat generated by combustion might be transferred to the internal surfaces, including walls, floors and ceiling. Later on, this factor has also been taken into account in the evaluation of equivalent fire resistance t_e by adjusting the "ventilation factor" as well as fire load density (Malhotra 1982) in terms of the total internal surface area of the compartment A_t, height of the window opening H and q_f:

$$t_e = \quad 0.067\, q_f \left(\frac{A_t}{A_w\sqrt{H}}\right)^{1/2} \qquad \ldots(9\text{-}3)$$

Rewriting the above for q_f expressed as a density L/A_t:

$$t_e = \quad 0.067 \frac{L}{\left(A_t A_w \sqrt{H}\right)^{1/2}} \qquad \ldots(9\text{-}4)$$

The equivalent fire resistance for a compartment can be evaluated provided that the fire load, dimensions of the compartment and window openings are known. The structural elements of the compartment encountering the same severity would follow the FRP required in that compartment.

In practice, the required FRP for structural elements are specified according to the usages/occupancies of the compartments (Hung & Chow 2001). In Hong Kong, it would be upgraded if the compartment volume exceeds the specified value of 28,000 m^3 (BD 1996a). The classification of FRP by building usages was given by the historical development, such as in Fire Grading of Buildings.

9.4 Standard Tests for Fire Resistance

Elements of construction in local premises are required to be examined by British Standard fire tests (BS 1987a, 1987b, 1987c) to consider their FRPs as specified in the local FRC code. Therefore, it is valuable to study these standard fire tests to understand how the FRP is labeled onto the various elements of construction. The constraints of the tests may also be figured out to appraise their accuracies.

Full-scale test is more desirable in general terms since it can offer higher accuracy without the errors created by uncertainty parameters of the scaling-down conditions. In the standard tests, the test specimen is to be accommodated in a furnace with fixed size, so that the scale of the test specimen is dependent on whether it can be placed inside the furnace. Too large a test construction will be scaled down to a specified size as described in the standards (BS 1987a, 1987b, 1987c). Heating and pressure will be applied onto the test specimen inside the furnace, as in Figure 9-1. Thermocouples are used to measure the temperature of the internal environment of the furnace. The heating conditions will be controlled by limiting the input rate of fuel to follow the standard temperature/time curve which can be expressed in terms of the mean furnace temperature above the initial furnace temperature (taken as 20 °C) T (in °C) and the heating time t (in minutes):

$$T = 345 \log_{10}(8t + 1) + 20 \qquad \ldots(9\text{-}5)$$

Performance criteria are key issue in the standard tests. There are three performance criteria, namely loadbearing capacity, integrity and insulation, used to examine the fire resistance of structural elements. The details of them are clearly stated in the standard. Heat will be applied until failure presented in any one of the criteria. The required FRP for that construction is taken from the heating time.

Different nations have their own system of standard tests. Those in UK, USA, Japan, Germany and International Organization for Standardization are briefly reviewed and compared. The standard test methods of interest are as follows:

- British Standard BS 476: Parts 20-22 (BS 1987a, 1987b, 1987c)
- International Organization for Standardization ISO 834 (ISO 1999)
- American Society for Testing & Materials ASTM E119 (ASTM 2000)
- Japanese Industrial Standard JIS A 1304 (JIS 1994)
- Deutsches Institut Fur Normung DIN 4102: Part 2 (DIN 1977)

Their approach to assess the fire resistance of constructions is identical and similarity is shown in the curves, as in Figure 9-2. However, they are slightly diverted in the following areas:

- Size of test specimen
- How the specimen is heated
- Standard temperature/ time curve
- Test methods
- Performance criteria

They are summarised in Table 9-1.

In order to standardize the different tests across the European Union (EU) countries, European Commission has created a new system harmonising the existing national tests among the EU countries (Warrington 2002). The BS EN 1363 to 1366 and 1634-1 are the new European Standards (ENs) adopted as British Standards. Standards in other EU countries, such as France, German, will have the same operation. A new classification of fire resistance and performance criteria are generated (BS 2003) as a European Standard. Those existing standard tests in conflicting with the new system will be withdrawn.

9.5 The Equal Area Hypothesis

In 1920s, an “equal area hypothesis” was raised by Ingberg (Drysdale 1999) to relate the fire load and fire severity. By carrying out a large number of experimental works, it was demonstrated that equal areas under two temperature/time curves (with a baseline of 300 °C) will have identical fire severity as shown in Figure 9-3. The fire severity and the required FRP can be determined for a fire curve T_{real} of a real scenario by comparing with the standard temperature/time curve T_{stand}. If the areas under the real fire curve and the standard temperature/time curve above a base level are identical, the severities of them are considered equal. The correlation can be expressed as:

$$\int_0^{FRP} T_{stand}\, dt = \int_0^{t_1} T_{real}\, dt \qquad \ldots(9\text{-}6)$$

Again, the heat flux received by the construction elements is not taken into account. The fire severity is considered as a function of temperature only.

Curves of real fire based on either 150 or 300 °C were used in the equal area concept and it was discovered that the difference between using either of the temperatures is insignificant when compared to the variation between tests (Malhotra 1982). Though the hypothesis was not comprehensive enough, it has been utilized by many building regulating authorities in assessing the required FRP to withstand a complete burnout of a fire compartment.

9.6 Existing Requirements on Fire Resistance Period in UK

9.6.1 The Building Regulations 2000

The Building Regulations 2000, one of the principal regulations in UK, is empowered by the Building Act 1984. The Approved Document B: Fire Safety (ODPM 2004) is a practical guide compliant with the requirements in Schedule 1 to and regulation 7 of the Building Regulations 2000 for England and Wales in which technical requirements are expressed in functional form.

The minimum FRP for elements of structure are also specified for purpose groups (i.e. building uses) of the building. In general, structural elements within a building deserve an FRP of 0.5 hour, such as floors, roofs, corridors, protected stairways and vertical shafts. A 1-hour FRP is specified for compartment walls separating different purpose groups. Four grades of FRP, including 0.5-hour, 1-hour, 1.5-hour and 2-hour, are generally based on in the requirements on each special purpose group as defined in the Document. The general grades of FRP along with those in other statutory instruments are listed in Table 9-2. The required FRP will be increased with the height of the top floor above ground in the building. In most of the purpose groups, structural elements of their basements are required to have an FRP of either 1 hour or 1.5 hours. A 2-hour FRP is required when the compartments are used as industrial occupancy or storage.

9.6.2 Fire Precautions Act 1971

The Fire Precautions Act 1971 (HMSO 1989a) controls the fire safety at work at designated premises, including hotel or boarding houses; factories; offices; shops and railway premises, which require a fire certificate. The minimum FRP is defined for different construction elements. Floor slabs should have an FRP of not less than 0.5 hour. Compartment enclosures in offices and shops should have at least 0.5 hour while factories need 1-hour FRP.

9.6.3 Greater London Council (GLC) The London Building Acts (Amendment) Act 1939 and London Building (Constructional) By-laws 1972

Other than Building Regulations, there are local Acts in operation within the area of Inner London. The London Building Acts (Amendment) Act 1939 and the building by-laws apply to Inner London and are integrated into the Building (Inner London) Regulations 1985.

The London Building Act (The Architectural Press 1983) and By-laws (GLC 1972) are similar to the FRC code in the classification of FRP since they are specified for the intended functions of the building or occupancy and varied with the cubical extent. Compartments with a greater volume deserve a higher FRP. The general FRP grades include 0.5 hour, 1 hour and 2 hours. Elements of construction of basement storey require an FRP of not less than twice that required for the elements of construction of the building. However, in no case the FRP can be greater than 2 hours.

9.7 Local Requirements on Fire Resistance Period

By reviewing the UK regulations and statutory instruments, the post-war Fire Grading reports in 1946 are said to be the most significant document throughout the century. The afterwards Model By-laws, London Building (Constructional) By-laws and the Building Regulations are all influenced by the reports.

Building Ordinance in Hong Kong was first issued in 1955. It was also influenced by the Fire Grading of Buildings since it had made reference to the London Building (Constructional) By-laws as London was the advocate of fire safety since the historical Great Fire of London.

New materials and building techniques have been evolved with the growing demand for residential and commercial premises by the increasing population in Hong Kong. Higher buildings are erected on the limited usable land, which lead to more stringent fire safety requirements (e.g. BD 1996a) in order to protect the occupants and properties.

9.7.1 FRC code

In local FRC code (BD 1996a), the FRP requirements are specified for the intended uses of buildings. The grades used are 1 hour, 2 hours and 4 hours. Those for the major elements of construction within a compartment, such as walls, beams, columns, floors, roofs and basements are prescribed to follow those for the various building uses, as shown in the following:

- 1-hour FRP is required in domestic buildings, hotel bedrooms, offices;
- 2-hour FRP is required in shops, restaurants, hospitals, assemblies, industrial buildings;
- 4-hour FRP is required for warehouses and basements.

Some of the FRP requirements can be slightly adjusted provided that their compartment volume does not exceed the specified value. For example, FRP can be reduced to 1 hour for shops, restaurants and hospitals if their cubical extent is less than 7000 m^3.

9.7.2 Building Ordinance 1966

The first Building Ordinance in Hong Kong was issued in 1955. Some revisions were made until 1966, the Building (Construction) Regulations were presented and the requirement of fire resisting construction was shown in Part XIII. The technical requirements, as in the current code of practice, were listed in Table XVI. The definition of FRP pointed out that the requirement had made reference to BS 476: 1932 and LCC (the predecessor of GLC) London Building (Constructional) By-laws 1952.

The general grades of fire resistance in the 1966 edition are 0.5, 1 and 2 hours, which are dependent on the intended uses and also the volume or floor area of any one storey. The walls separating any adjoining buildings are required to have an FRP of not less than 4 hours while those separating compartments should have at least 2 hours. The construction elements of basements, on the other hand, should have twice the FRP required for those of the compartment in which the basement is located, but in no case, it should exceed 2 hours. Moreover, elements of construction in buildings with at least 4 stories should be provided an FRP of not less than 1 hour. The details of the FRP requirement are listed in Table 9-3, with the comparison with that of London Building (Constructional) By-laws 1972, the principal By-laws in Inner London. Both of them are similar in the grade of fire resistance, the classification of the building uses and the cubical extent of the compartment, however, they are divergent in the measuring units and the number of divisions in volume. The requirements on FRP of some building uses are classified by floor area of any one storey.

9.8 Inadequacies of the Current Requirements on FRP

Standard fire tests are commonly referred to in the fire regulations. Since the development of building materials and technologies is getting into a fast track with the growing demand for buildings, these standard fire tests operated tens of years ago may not be able to adapt to the changes of the market. It was believed that these tests can provide adequate fire safety since big fires seldom occur. The fire resistance period might be overestimated as reviewed in above. This would increase the capital cost. From the review of standard tests, it is also discovered that the real fire scenarios are not taken into account. Some full-scale fire tests carried out overseas have indicated that the structural fire protection is overrated by the standard tests.

The BS 476: Parts 20 to 22 only examine one single element in each test. That means the structural stability gained from the connections with the adjacent elements of construction is not taken into account. However, it is believed to be able to increase the loadbearing capacity and integrity of the tested element to a large extent. The reduced specimen size resulted by the limited furnace capacity and also the ignorance of ventilation and thermal properties of compartments in the standard temperature/time curve would divert the fire performance far away from the real fire scenario. Either overestimated or underestimated fire resistance design will be resulted from all these errors. Cost-effectiveness and fire safety can neither be ensured consequently.

As reviewed, temperature matching the standard temperature/time curve is the furnace temperature instead of surface temperature of the test specimen. It is believed that temperature would be different between the two points. Heat transfer characteristics are varied by a number of factors, such as the types of fuel, thermal properties of the furnace walls, and the location of burners (Malhotra 1982). Two individual furnaces following the same standard temperature/time curve will also give different heat fluxes (Castle 1974). Therefore, the temperature received at the surface of test specimen is not necessarily equal to the internal temperature of furnace (Malhotra 1979).

Moreover, total heat flux is the sum of convective and radiative heat flux. The latter will be significant in the case that the furnace wall of low thermal inertia is used. However, flames, which give considerable amount of radiative heat flux, are excluded in the standard tests (Morris, Read & Cooke 1988).

For the code itself, there are only 10 classes of buildings classified in the local FRC code. Some of the building features which may have higher potential hazard are not required to have higher FRP. For instance, the popular atrium buildings are not included in the classification of building uses, but this design feature has been utilized in many large-scale complexes. The grand elegant space created in an atrium would impose extra fire hazard since smoke and flame would easily spread through different levels which are connected by the atrium.

On the other hand, the total collapse of WTC Twin Towers on 11 September 2001 made the adequacy of the current fire safety measure doubtful. It was otherwise suspected that the structural fire protection is underestimated. In fact, both situations would take place depending on the fire types, such as commonly-seen accidental fires and terrorist attack like WTC incident. As the fire size under circumstances like WTC incident would be of the order of thousands megawatts (Chow 2002a), which is much higher than the small-scale accidental fires, the necessary fire safety protections are completely different.

Existing fire safety codes are only designed for protection against accidental fires, it is now under review among some nations that other types of fires should be taken into account in the codes and regulations. Of course, not all buildings need to upgrade fire safety measures to a level able to protect against terrorist attack fire. With the fast track development of building technology and innovative design, some latest projects might be unable to comply with existing prescriptive building codes. These problems request fire engineering design which enables peculiar building designs and provides suitable fire safety measures to the particular building evaluated from hazard and risk analysis.

9.9 Engineering Performance-based Fire Codes

A new performance-based approach for those buildings unable to comply with the current prescriptive codes are now under development in Hong Kong. A tailor-made assessment method for the unique building is offered in this approach so that no exaggerated fire protection systems have to be installed. Fire safety design is examined by the appropriate assessment tool. The limitation of the standard fire tests can then be eliminated.

Performance-based fire codes are already adopted by a number of advanced countries. Performance criteria and design fire are the most important parts in the fire design under the code (BS 1999a; NFPA 2003). For the fire resistance requirements, performance criteria for structural elements should be set to examine the fire design under the design fires.

A design fire should be determined (Bukowski 1995) and there are some proposals (e.g. BS 1999b) in fitting the heat release rate Q (in kW) by a quadratic function in time t (in s) in terms of a fire growth constant α (in kWs^{-2}):

$$Q = \alpha t^2 \qquad \ldots(9\text{-}7)$$

It will reach a steady value then and later on go through a decay phase (NFPA 2000b, 2003). All possible fire scenarios should also be investigated. They include building environment, configuration and thermal properties of the compartments, fire protection systems, air supply, probability of fire occurrence from past experiences and occupant factor. A “worst credible fire scenario” will be selected to act as the upper limit of fire risk analysis.

An evaluating tool, such as a computer modelling or mathematical analysis, is necessary to assess the performance of the fire safety design and determine whether it is satisfactory to the performance criteria. The one sufficient to protect the building can be used to replace the prescriptive requirements.

To establish an EPBFC, design fire, fire scenarios, performance criteria, assessment tools are all areas requiring more effort in local area (e.g. BD 1998). Detailed guidance on all those have to be provided in the fire code. For instance, the assessment method should be developed and achieve a sophisticated standard to ensure the accuracy and reliability of the judgment. Moreover, full-scale burning tests for those new materials in local industry should also be carried out and compiled as a database (Chow 2001a).

9.10 Recommendations

In the local FRC code, the FRP of structural elements are examined by the BS

476 according to the definition. However, it is found that the British Standards may be outdated or too conservative in coping with the new technologies. It is also necessary to revise the requirement on the load-bearing structural members since structural failure is not impossible as demonstrated in the WTC incident. The current focus on the control of spread of fire is only suitable for protection against accidental fire which is of smaller fire size comparatively.

Reform on the current fire codes system should therefore be carried out. The currently dominant prescriptive fire codes may be still applicable to some of the buildings after revision. In the meantime, EPBFC should be developed, following the global trend, to meet the demand of the complex buildings which cannot easily comply with the prescriptive codes.

In Hong Kong, though EPBFC is still under development, the performance-based approach has been adopted for those new building designs having difficulties to comply with the prescriptive code, as stated in the local code (BD 1996a). The traditional buildings should still follow the requirements in the prescriptive approach. A practice note (BD 1998) has illustrated the steps to perform this alternative approach in order to provide guidance for the Authorized Persons and the designers since it is a new idea to the local industry. In this stage, only outlines but not details are provided. For establishing the EPBFC, fire safety objectives should be firstly worked out so as to determine the steps followed, such as performance criteria. The sophistication of assessment tools, including computer models, laboratory tests or even hand calculations, should also be achieved or the accuracy of assessment will become a query. Numerous nations have already adopted EPBFC in their legislation system (e.g. BS 2001). It is possible to make reference to their experience in working out the performance-based codes. However, not all the elements are suitable for the local environment. It should intelligently integrate those appropriate with our effort, say a useful database on full-scale burning tests of the local materials (Chow 2001a), to complete this task. The professionals and fire engineers should also equip themselves with appropriate skills and knowledge to assist in the transition of fire codes.

Construction elements rated in fire resistance period can ensure fire confinement in the fire room and protect the neighboring compartment from the effect of fire. Occupants can then have enough time for evacuation. It is mainly concerned about the post-flashover fire (Chow 2001b). However, the pre-flashover fire should not be ignored. Flame spreading over wall-linings or carpets would definitely worsen the fire scenario at a much earlier stage. Aspects of flame spreading are not yet included in local codes on passive building design, though included in FSI code.

A study carried out before (Chow 2001b), estimating the effect of the surface linings and carpets with different ignitability on the heat release rate showed that flashover is likely to occur in small karaoke cubicles when non- fire-rated partition materials or retardant treatment are chosen. Studies showed that flame spreading would occur on painted surfaces (Murrell 1998). Therefore, pre-flashover fire is also an important issue even it is not included in this study.

CHAPTER 10 INTUMESCENT COATING FOR STEEL STRUCTURE

10.1 Introduction

Steel is one of the most popular materials for building construction due to its stiffness and slimness (Malhotra 1982). Ultra high-rise buildings constructed of steel are able to stand strong wind load. There might also be glazing materials covering on the steel frameworks. This type of full-height glass curtain wall would give good views, and is thus attractive for high-class commercial premises (Hung & Chow 2003). Consequent to the World Trade Center incident, there might be risks of having non-accidental fires including terrorist attack for the symbolic buildings. There are concerns on the fire behavior of the structural steel buildings.

At room temperature the thermal conductivity of steel is about 50 W/m°C. Such a high value would heat up the entire steel structure in normal size evenly within a short time (Hung & Chow 2003). The temperature of steel structure would rise up promptly upon heating, in comparing to another commonly-used building material. Concrete is able to stand a fire up to several hours due to its high heat capacity and low conductivity. The strength of steel would be reduced by half when heated up to about 600 °C (SCI 1999). The failure temperature of steel is lying between 550 °C to 700 °C where the lower value is commonly utilized in many standards (ASFPCM et al 1992). With the high thermal conductivity, adequate fire protection must be provided for steel structures. Though it was verified (ASFPCM et al 1992) that unprotected fully stressed steel would have half an hour fire resistance, better protection by giving longer FRP is necessary for most of the construction elements (BS 1987a).

One of the methods for enhancing fire safety of steel structure is by applying fire protective coating to elongate the fire resistance period of the structure. Fire protective systems used for structural steelwork are discussed in Appendix I. Intumescent coating is focused on as the product becomes popular recently. The fire retardancy mechanisms are different from traditional coatings and might be regarded as reactive fire protection system. The principle, components, application and determination of the applied thickness will be discussed. Local legislations and guidelines governing the use of this type of fire resisting products will also be reviewed. The inherent weaknesses should be understood for advising appropriate fire protection.

10.2 Intumescent Coating

Intumescent coating is regarded as a reactive fire protection system since such coating will have chemical reactions under fire and new substances will be formed upon heating up. It was defined in BS 8202: Part 2, (BS 1992), as follows:

Coating which reacts under the influence of heat by swelling in a controlled *manner to many times its original thickness and typically producing a layer of carbonaceous char or foam which acts as an insulating layer for the substrate.*

Two classifications of intumescent coatings, including thin film intumescent coatings and thick film intumescent coatings, in the market provide different FRPs (ASFP 2001b). The thin ones would be varied from 0.25 mm to 6 mm to give 30 to 120 minutes FRP whereas the thick ones of 2 mm to 32 mm would give 30 to 240 minutes FRP, Ham (SCI 1999). The latter gives a higher fire rating but the former one is more often used. It can be either solvent- or water-based.

In Hong Kong, the steel section with certain thickness of protective coating is tested in accordance with BS 476: Part 21: 1987 by accredited laboratories to determine the fire resistance of that coating material in relation to the protection thickness and section factor.

Due to the unique characteristics, intumescent coating can be obviously distinguished from the other types of fire protective methods by its thermal reaction upon exposure to fire. For the spray protection, board and casing protection and the generic materials, their applied thickness is theoretically unchanged throughout the whole period of protection including the time they are reacting to the heat exposure unless they are mechanically damaged. However, intumescent coating presents its uniqueness at its intumescence phenomenon which occurs when it is being heated up. Thinner layer is one of the benefits given by intumescent coating where less floor area is occupied. Upon heat exposure, a temperature differential between the outside and inside would give a temperature gradient across the protective material. Of the same kind of material, a thicker layer would definitely give a slower change of temperature to the substrate whilst a thin layer might only give a short delay of temperature rise on the unexposed face. Though the applied intumescent coating is far thinner than the other protection methods, the "swollen" form of the material could offer, on the other hand, a much thicker layer, of up to 50 times the original thickness, and thus the variation of temperature increases too. It is noted that the heated intumescent coating would be suffered not only physical change but also chemical one. The temperature gradient is dependent not only on the thickness but also the thermal conductivity of the material. Thermal conductivity of nonmetallic solids, liquids and gases are much lower than that of metals. Gases created during the intumescence reaction would further lower the thermal conductivity of the intumescent coating.

According to BS 8202: Part 2, intumescent coating contains some active components to give its thermal reaction known as intumescence (BS 1992). A catalyst and a carbohydrate react to form a carbonaceous char while a binder, or resin and a spumific agent would liberate a large amount of non-flammable gases binding the foam and thus provide a thick insulating layer. Low thermal conductivity of the layer is resulted from the gases being trapped within the char.

The insulating carbonaceous char would act as a physical barrier which protects the steel substrates from being exposed to the fire. Heat transfer through the insulation to the steel sections can be effectively reduced, followed by the impediment of their temperature rise and hence their loadbearing capacity and integrity could be prolonged. The FRP is also lengthened. Typically, a thin film coating would swell to 50 times the thickness of the coating when subjected to a temperature of about 200 °C to 250 °C (ASPF 2001b, 2002). After all the reactions inside the coating material have been completed, the insulating layer would be degraded by the fire and it may likely slip off from the surface. Consequently, the substrate would be exposed and attacked by the fire. Therefore, the thickness of the coating (ASPF 2001b), is a key factor in providing fire protection to the structural elements.

10.3 Application of Intumescent Coating

Thin film intumescent coating appears like the traditional paint so it can be applied on the surface of substrate by roller, brush and airless spray. An intumescent coating system usually consists of three layers:

- A primer: applied directly onto the surface of the substrate to prevent corrosion of the steel elements and acts as a bonding agent between the basecoat and the substrate. Prior to the application of primer, the steel surface should already be blasted and primed.
- An intumescent basecoat: reacting to the fire action and creating the insulating carbonaceous char to protect the structure.
- A sealer coat: exposed to the ambient and applied to prevent environmental degradation (ASFP 2001a).

To achieve a better appearance after the application of protective coating, a decorative coat can be used, where a variety of color finish is provided for decoration purposes. It is an attractive alternative when compared to the sprayed-applied coating on which a messy look is always presented. Both the primer and the sealer coat should be fully compatible to the intumescent basecoat so as to ensure that they would not weaken the performance of the whole system.

It is commonly intended for internal use whilst there are also occasions for use in external environment. For the layer of unknown paint appeared on the steel sections, it is appropriate to remove the entire paint coating preceding the primer application, otherwise, the FRP provided becomes ambiguous and the heat performance of the protective coating might also be deteriorated.

A sealer coat or decorative coat is considered as a protective layer under which the intumescent basecoat would last for lifelong where no special maintenance work is needed for this intermediate layer. Two to five years guarantee on the intactness would generally be offered. However, the sealer top coat might be damaged or degraded by the daily use where traditional painting might be applied on the deteriorated areas.

In Hong Kong, there are three to four popular brands of protective coatings in use. There are solvent-based thin film intumescent coatings with DFT ranging from 0.32 to 6.15 mm, which can provide an FRP of 30 to 120 minutes with respect to particular section factors. As investigated, its cost, including material and labor, is estimated to be around $800 to $1,200 per unit area for a fire resistance of 2 hours. An increase of 20 % is subject to external application.

Another type of thin film solvent-based coatings providing an FRP up to 2 hours (Firetherm 1998), with DFT ranging from about 0.5 to 3.5 mm is available. It can be applied by brush, roller or spray. A range of top seals in special color is also provided by the same manufacturer or other top seals can also be applied under their approval.

10.4 Determination of the Thickness of Intumescent Coating Required for a Specific Element

Fire safety requirements for buildings in UK are specified in Building Regulations 2000 (HMSO 2000) and the Approved Document B: Fire Safety (ODPM 2004), in which technical details compliant with the Building Regulations are provided. The fire resistance rating required for elements of construction in different uses of buildings are specified. To achieve adequate FRP on steel structure, applying fire protective coating is the essential way where the specifications on them are referred to the "Yellow Book" *Fire Protection for Structural Steel in Buildings* (ASFPCM et al 1992), by Association of Specialist Fire Protection Contractors and Manufacturers (ASFP, formerly ASFPCM) as referenced in Appendix A of Approved Document B and Steel Designers' Manual.

In the aforesaid Yellow Book, the protection methods on steelwork, concept of section factor and determination of appropriate thicknesses are discussed. Data sheets of a wide variety of protective materials on the corresponding thicknesses determined by the required FRP and section factor are attached. It gives a handy guidance on the application of fire protective coating including the passive ones.

10.4.1 Section factor

Prior to checking out the suitable thickness of the intumescent coating, the calculation of section factor should be understood. Section factor, defined as H_p/A (in m^{-1}) with perimeter of section exposed to fire H_p (in m) and cross-sectional area of the steel member A (in m^2) (BS 1992), is an important parameter for a steel section where the extent of heat sink of the particular section could be revealed by its value. A big value of H_p/A representing small heat sink means the steel section is heated up rapidly and the critical temperature is easily reached whereas a large heat sink with a small value means the member would be heated up slowly. It was demonstrated that the sections without protection could withstand high temperature for up to half an hour due to large heat sink (ASFPCM et al 1992).

The significance of the section factor for steel members is revealed. There are dissimilar profiles of steel section such as I-section and hollow section and various protection is needed for different construction elements, say three-sided protection for beams and four-sided protection for columns. Basically, intumescent coating is only applied as profile protection instead of box protection since it is a thin and paint-like material. When evaluating the section factor, it is essential to learn the accurate depth, width, thickness of the section and the sectional area. For example, for three-sided protection in case of a beam attached to the ceiling, the upper width of the flange should not be included in H_p and attention should also be paid to the calculation of other profiles and exposures.

10.4.2 Thickness in data sheets from manufacturers

After evaluating H_p/A and checking the required fire resistance rating from the Approved Document B for the particular building usage, the required thickness of various proprietary intumescent coatings could be found in the data sheets of the "Yellow Book" as shown in barchart format. The manufacturers are responsible for the appraisal of their proprietary products which are tested in accordance with the fire resistance tests BS 476: Part 20-22 (BS 1987a, 1987b, 1987c).

The thin film coating type usually gives an FRP of up to 2 hours and the thickness lies between 0.25 mm to 6 mm. For the thick film, its thickness could be ranged from 3 mm to 65 mm. Such thickness would probably frustrate the use of it since it would apparently be accompanied with a high cost.

10.4.3 Volume solids

The manufacturers of proprietary are used to provide DFT in specifying the necessary thickness corresponding to the required FRP for a given steel structure. Note that there are volatile components in the coating and the layer would be shrunk upon drying. The term “volume solids” (VS) is defined to describe the percentage volume of dry film given from a volume of liquid coating (Brooks 2003; ISO 1998). In applying intumescent coating, the values of the wet film thickness (WFT) should be known. WFT is the thickness of the coating in wet form at the time when it is applied onto the substrate; and is given by:

$$WFT = \frac{DFT}{VS} \qquad \ldots(10\text{-}1)$$

VS is used to calculate WFT, but the accuracy of the values quoted by the manufactures becomes a question. For example, 1 hour FRP requires 1 mm DFT of a proprietary intumescent coating. The quoted value of VS is 70 %, putting in numerical values of DFT would give WFT of 1.43 mm.

Generally, two approaches are used to establish VS: calculating from the coating formulation; or measuring the density of the applied dry coating. Any incorrect declaration on VS may give much thinner layer of dry coating. The FRP is then shortened. Going back to the above example, if VS is 60 % instead of 70 %, DFT would be smaller at 0.86 mm. This would reduce the FRP by 14 % as pointed out in the literature, giving higher risk and bigger potential damages. More reliable methods for unifying the calculation of VS should be worked out (Brooks 2003).

10.5 Local Regulations on Intumescent Coating

In Hong Kong, the requirement of FRP is specified in the Code of Practice for Fire Resisting Construction (BD 1996a). The minimum thicknesses of protection on steel columns and beams are stated clearly in the Table of the code for FRP of 1, 2 and 4 hours respectively. The mentioned protections include only some generic materials like concrete, solid brick and gypsum plaster. However, there are not technical details on using the protective coatings. As reviewed, the evolution of the local regulations is originated from those in UK, for instance, the FRP of the construction elements used in local premises should be tested in accordance to the BS fire tests.

A practice note (BD 2001a), regarding the acceptability of building materials and proprietary fire resisting products was issued to govern the application of new materials. Authorized Persons and Registered Structural Engineers are relied on to give advice on the compliance with standards. Tests should be carried out in accredited laboratories which are recognized by the Hong Kong Laboratory Accreditation Scheme. The test or assessment reports should be prepared by those laboratories and examined by the Authorized Persons or Registered Structural Engineers who are responsible to ensure that the reports are valid and legitimate.

Since the thickness required for a specific fire rating on a particular steel section is already given by the manufacturers, the application of the intumescent coating in local area can make use of the data sheets they provide once having checked out the required FRP in the local code.

10.6 Deficiencies Associated with Intumescent Coating

Glass is usually used in conjunction with a steel structure, but this combination might be too vulnerable when suffered from a high heat environment. When exposed to heat, intumescent coating would expand ten times to give fire protection. It is doubtful whether the intumescence phenomenon would impose high stresses on the adjacent glass elements and crack or break the glass. As discussed, the thin layer of coating would swell as much as 50 times its original thickness within a short time once they experienced high temperature of about 200 °C. It would then create very high pressure which may exceed the yield strength of the glass piece. The performance of resisting the stress may be largely dependent on the connection between the steel sections and glazed elements. For instance, silicone sealant, used to bridge the structural frame and glass panels and seal the leakage, might allow certain tolerance in three-dimensional movements of the adjacent elements which are subjected to external environment. Therefore, with the use of intumescent protective coating, design considerations should be paid on the whole system, including structural framework, glass panes, protective coating and connections. For the additional application of coating after building is in use for some time, it should be considered with great caution. Direct spraying on the surface of the structural members may cause further safety problems.

On the other hand, after the intumescent coating has reacted under high heat exposure, the material itself would change its ingredient and slip off the surface. The residue left after the fire has to be cleared. There are some follow-up works for this fire protection system, and additional maintenance fee is required.

The conductive substrate would be exposed if the coating is degraded or knocked off from the steelworks. Heat would then easily transfer through the framework and soften the whole structure.

The collapsed WTC twin towers were erected with steel structure, which became focus consequent to the tragedy. Substantial investigations on the structural performance have been carried out (e.g. FEMA 2002; NIST 2004a, 2004b; Quintiere, Marzo & Becker 2002). Some results found that the insulation coating on top of the structural elements was dislodged at the aircraft impact otherwise the temperature was not high enough to cause structural failure (NIST 2004c). The dislodgment of insulation material would lead to an uncontrollable and risky situation since the thermal conductivity of steel is so high that even a small unprotected area can heat up the whole structure promptly. Good maintenance is important to keep the protection at the designed level.

10.7 Summary

For the structural steelworks, even though half an hour fire resistance can be achieved with fully stressed unprotected steel in certain conditions, additional fire protection must be provided on top of the steel structure in order to comply with the statutory requirements. Usually, coating or casing is used to wrap up the steel members since it appears to be easier in application when compared with those "fill-in" types. However, being situated outside the sections make them inevitably exposed to vigorous environment where damages on them are not rare. As discussed, a small unprotected area on the steel structure could give rise to severe situation which might be equal to heating up bare steel members. It was thought that the protective coating in the twin towers of WTC was unable to resist the impact of the jetliners and fell over at the very beginning. The impact resistance of those protective coatings is therefore asking for further consideration. Intumescent coating can be as thin as 0.25 mm where its robustness is a query. Taking good care of them should be a section in the maintenance plan for good implementation of fire safety management.

It is also suspected that the protective coating is unable to withstand the high HRR from a non-accidental fire as in WTC incident even though it is remained intact with the structural elements. For protection against non-accidental fires, design considerations should be put on not only impact resistance but also heat flux of a fire of extraordinary fire size.

Further, when designing buildings with the use of intumescent coating as well as glass material, it is urged to give thought to the whole system, including glass panes, steel member, coating and connections in between, instead of tactlessly spraying the coat onto the framework. Without good considerations, glass panes would break under high pressure induced by ten times of intumescence of the reacting basecoat.

CHAPTER 11 FIRE RISK ASSESSMENT SCHEME FOR NON-ACCIDENTAL FIRES IN HIGH-RISE BUILDINGS

11.1 Introduction

On 11 September 2001, the prominent twin towers of the World Trade Center (WTC) in New York, USA were crashed rigorously by two different hijacked aircrafts. One of them was hit at the centre of one facade, while the other one was hit nearby the corner. The crash points were both on the upper stories (FEMA 2002). After the enormous impact, it was evident that the towers could stand for an adequately long time. The 110-story WTC twin towers were able to stand under such huge fires for 1 hour and 1¾ hours respectively. Since the hijacked airliners were filled with a large quantity of jet fuel (approximately 38,000 liters), extremely big fires was also resulted. The fire safety provisions, both passive building construction and active fire protection systems (designed only for fighting against accidental fires) appeared vulnerably under the huge fires. Inadequacy of fire protection was alleged to be one of the main factors leading to the disaster.

Investigations and reports were announced throughout the world. There have been various estimations on the collapse scenarios, including structural deficiency or insufficient fire safety provisions. However, taking no account of non-accidental fires might be the most critical factor. Actually, both the structure and fire protection systems were not designed to stand against such a big fire and also the strong resultant load from impact and conflagration, thus the consequence of total collapse.

In fact, there is an increasing number of building fires started on purpose since 1994. Examples are the bank fire (HKS 1994) and karaoke fire (HKS 1997) in Hong Kong, arson fires in the mass transit railway in Korea and Hong Kong (SCMP 2004) and at two universities in Beijing (CNN news 2002), and also the big blast in Madrid (BBC news 2004b).

Proposals to revise the fire codes appeared each time after having a big fire. Better fire protection should be provided to existing or new premises. However, the ad-hoc revisions only benefit the community after the big incidents. Provision of safety measures should precede every catastrophe to avoid claiming human lives or causing injuries. Fire safety provisions (BD 1995, 1996a, 1996b; FSD 1998) are normally designed for fighting against accidental fires (although some accidental fire (Chow 1998) might give big disaster due to whatever unknown reasons), explaining why there are undesired consequences. Since the frequency of occurrence of arson fires and even terrorist attack fires appears to be increasing, non-accidental fires are suggested to be included in the fire safety objectives in some areas, such as the karaoke establishment ordinance in Hong Kong (Laws of Hong Kong 2003b), as the first step to upgrade the safety level.

Revisions on the current fire codes and new fire codes are under development in order to give community a better protection. Enhancement should be provided for both existing and new premises to withstand the attack of non-accidental fires. However, not all the buildings throughout the world are likely to be under the threat of terrorist attack. The frequency of occurrence would be differed among nations and cities. A larger-scale fire is only likely to occur in places with social or political instability.

A ranking system is proposed in this chapter to determine the potential fire risk of having non-accidental fires in high-rise buildings and hence the corresponding actions in connection to fire protection upgrade. As in other risk indexing systems (e.g. NFPA 2001; Hultquist & Karlsson 2000), a wide range of technological issues covering building design, fire safety provisions and some other characteristics of the building itself are included. In addition, social and political issues are also incorporated into the scheme to reflect the "non-accidental fire" component. As risk is an expression of the likelihood and consequence(s) of a specified hazardous event (SSS 1997; BS 2004), the technological issue is responsible to decide the level of severity when there is a big fire. The social and political issues will determine the chance of having non-accidental fires.

A total of 24 risk parameters concerning the abovementioned areas are identified. In which, the technological issue and the risk parameters commonly adopted in some existing fire risk evaluation systems (e.g. NFPA 2001; Hultquist & Karlsson 2000) will be used. There are 19 parameters on this issue. The rest of the parameters are concerned with the social and political issues. From the viewpoint of fire engineering, the technological components would be divided in a more detailed manner in this preliminary scheme with the other two components left for in-depth investigations in the coming future.

Risk parameters are derived based on a number of well-established fire risk indexing systems (e.g. NFPA 2001). The evaluation of risk index is discussed in the following sections. The necessary additional fire safety provisions on top of the existing requirements can be determined based on the result. Performance-based fire codes are still under development in some of the countries. It takes time to train an adequate number of fire engineers and officers approving the design (Chow 2004c). Prescriptive codes should be relied on in the coming few years. This scheme would be helpful for regular updating of the prescriptive-based fire codes. As this scheme is only a preliminary proposal, further work is necessary. Anyway, setting up and implementing such a risk assessment scheme would help the authority concerned to have an idea on how to determine appropriate fire safety provisions for protection against non-accidental fires.

11.2 Necessity of a Fire Risk Assessment Scheme

In general, there are four types of fires, namely accidental fires, arson fires, terrorist attack fires and natural disaster fires. Fire safety provisions in most of the existing fire regulations are designed to protect buildings against accidental fires only. For example, buildings are taken to be empty without movable fire load. They are demonstrated to be adequate before having big unexpected fires, such as the big Garley Building fire (SCMP 1996) in Hong Kong. There might be some controversies on their inapplicability to the new architectural features. Natural disaster fire can be envisaged as another type of accidental fire which is not man-made, for example, the fire induced by an earthquake. Similar to an accidental fire, the fire size depends on the combustibles and how they burnt inside the buildings. The fire damaged area might be much bigger to give higher total loss. For example the fire breaking out after earthquake would involve not only one building as occur in the other types of fire, but a large urban area. This is the scope of urban mass fire but not building fire on which the study focuses.

Arson fires and terrorist attack fires can be classified as non-accidental fires since they are caused by man-made offence. In non-accidental fires, additional fire load is often put in by the arsonist or terrorist so that huge devastation would be resulted. For instance, in the 911 incident, fully-loaded civil liners were used as weapons of mass destruction (WMD) where the amount of liquid fuel was found able to create heat release rate (HRR) of exaggerated value. The fire size in a non-accidental fire can therefore be up to thousand times that in an accidental fire. Very few buildings, such as nuclear power stations, are able to resist fire attack caused by arsonists and terrorists (Kitipornchai 2001).

Technology nowadays can provide fire safety for protecting against terrorist attack. Adequate defense of an aircraft carrier can be provided against missile attack! However, the cost would be high and it is not necessary to be provided for all buildings.

Usually, arson fires and terrorist attack fires are caused by social and political problems where the latter seems to be involved more often in terrorist attack fires that often lead to more severe destructions. The most impressive example is the World Trade Center disaster (FEMA 2002). Unstable political situation in Middle East might be one of the most influential factors on the terrorist activities in the world. Competition of the sovereignty between races or countries may lead to military action as well as premeditated terrorist attack; say suicide bombing can be seen frequently in the news report in Middle East region. Bali bombing (BBC news 2003a) was another incident with deep sorrow throughout the world which was also resulted from terrorist activity. Arson fires can be caused by some other social problems, say economic downturn together with high unemployment rate, dissatisfaction with local government's policy, triad activities or even commitment of suicide.

Terrorist attack seems to be the most serious destruction in terms of structural damage, human and property loss. All the buildings can be protected against terrorist attack in order to ensure total fire safety; however, it would lead to exaggerated cost. Since different countries and regions have totally divergent political, social and economic situations, fire safety provisions should be provided accordingly. Some nations would be in low possibility of being attacked by terrorists whilst some are in high risk. There should be a balance between cost and safety protection.

With most innovative architectural features emerged, the associated fire safety problems should not be neglected. For instance, green buildings are highly recommended to diminish the abuse of unrenewable fossil fuel in the world and also minimize damage to the global ecology system. Glass curtain wall can be one of the green building types due to its transparent property where solar radiation and natural lighting can be transmitted into the occupied space and thus decrease the consumption on heating load as well as artificial lighting. However, literatures (e.g. Shields, Silcock & Flood 2001) showed that glass might be a vulnerable building material when exposed to high heat environment. Excessive thermal stress on the glass surface and fire-induced air pressure inside well-sealed offices as in curtain-walled building would break the glass. It becomes more dangerous to the occupants and also pedestrians in the street. Further, breaking the windows might give adequate intake air flow rate to burn up all combustibles to give a mass fire (e.g. Chow 2003b). In addition, the occupant load in some places such as shopping malls always exceeds the design value. Crowd movement and the possible inadequacy on means of escape would give disaster. Therefore, additional fire safety provisions should be considered for each special case.

A simple and rapid analysis approach appeared as a good basis in quickly determining the enhancement of existing fire safety provisions for all high-rise buildings. An assessment scheme evaluating the fire risk in terms of severity and probability is therefore proposed to help decide the risk level of a building encountering non-accidental fire. It should include the following issues though further investigations are required on them:

- Social stability;
- Political stability;
- Characteristics of the building;
- Location of the building;
- Fire safety measures.

A risk index worked out from the assessment scheme is useful in determining additional fire safety provisions to safeguard the building against non-accidental fires.

11.3 Fire Risk Indexing System

A fire risk assessment scheme (FRAS) is proposed to assess the risk level of the new or existing buildings, especially taking account of non-accidental fires, for additional fire safety provisions. As discussed, buildings are likely to be jeopardized with different scales of attack, such as accidental fires, arson fires, terrorist attack fires and even natural disaster fires. The possibility of occurrence of each type varies with a number of aspects including building characteristics, location of the building, and political/social issues of the city where the building is located. Engineering assessment can provide the most accurate and detailed risk analysis; however, it would not be cost-effective to carry out risk assessment for every single building to examine their risk level based on non-accidental fires. Under some circumstances, detailed risk assessment is considered to be inappropriate (Watts 2002; Watts & Kaplan 2001) when the data are sparse and uncertain; the interaction of them are complex; greater sophistication is not required; and so on. Moreover, they are costly and labour-intensive.

A number of risk indexing systems concerning about fire safety have been prevailing in the industry. Some of the dominant examples are the Fire Safety Evaluation System (FSES) (NFPA 2001) (to give equivalent safety level as that in Life Safety Code (NFPA 1994)), BOCA National Building Code Section 3406 (BOCA 1996), Central Office Fire Risk Assessment (COFRA) (Parks et al 1998) and a Fire Risk Index Method for Multi-storey Apartment Buildings (FRIM-MAB) (Hultquist & Karlsson 2000) with detailed development of the index method revealed.

Generally, these fire risk indexing systems (Watts 2002) based on relative or comparative risk rather than absolute risk, using a single numerical value to measure the risk associated with a facility, could analyze and score the concerned attributes to come up with a rapid and simple estimate of relative fire risk. In general, a list of attributes is generated to represent positive and negative fire safety features that account for an acceptably large portion of the total fire risk. They would be assigned values, usually with both weight and grades, in a fire risk indexing system; however, they are usually not measurable especially for the existing buildings where there is only little information available. These values are then operated by some combination of arithmetic functions, usually a linear additive model, to give a single value.

These well-established indexing systems are valuable for the derivation of the proposed risk assessment scheme, which, however, will also consider facets other than technology to have a broader coverage.

On the other hand, there are a large number of risk assessment tools and techniques for system safety as stated in the literature (SSS 1997). They are usually used to identify hazards, causes of failure, fault modes and their frequency of a system. Selection of different techniques depends on the systems of different industries or conditions. Among which, risk assessment matrix is extensively applied (e.g. BS 2004; Military Standard 1993; Geronsin 2001).

To carry out risk analysis, the severity and probability should be figured out after the hazards are identified since risk is a function of severity and probability of specified hazardous event (SSS 1997; BS 2004). A series of categories for severity and levels of probability are, therefore, developed to determine risks. As demonstrated in the literature (Military Standard 1993), the hazard severity categories can provide a qualitative measure of the worst credible mishap resulted from personal error, design deficiencies, system failure and etc., leading to death, injury, occupational illness, of damage to, or loss of, equipment or property; whilst the hazard probability level can be reported in either qualitative or quantitative terms, such as frequent and occasional or at least once every ten years (1×10^{-1}/year) and once in a hundred years (1×10^{-2}/year). Certainly, the definition of the categories and levels should be clearly stated in the analysis documents for ease of application and maintenance of consistency.

Risks are then estimated by combining the evaluated severity category and probability level into a matrix. The result, named a risk index, should indicate the tolerability level or qualitative priority factors for assigning corrective or preventive measures to enhance safety (e.g. BS 2004; Military Standard 1993).

These risk indexing systems provide a good basis in the development of the proposed fire risk assessment scheme for protection against non-accidental fires.

11.4 Proposed Fire Risk Assessment Scheme (FRAS)

Risk analysis is an important step to ensure safety for any system, facility or building. Its objective is to provide corrective or preventive measures to lower the risks (Redmill 2002). In view of the gloomy WTC incident, the existing and future high-rise building designs based on the current prescriptive codes should be reviewed on their fire safety protection against non-accidental fires in a speedy approach in order to safeguard our built environment under the threat of terrorism or man-made damages. A fire risk assessment scheme is, therefore, proposed to achieve this target. Detailed engineering analysis is not capable of giving prompt actions (Watts 2002). A risk indexing system appeared to be a more appropriate alternative to cover the whole built environment.

Among a wide range of risk indexing systems applicable for risk assessment, a technique used in the early stages of system design or when there is basic or incomplete information is referred to as the blueprint of the proposed FRAS (SSS 1997; US Coast Guard 2005). Instead of identifying the hazards inherent in the building, a list of attributes representing the building features and the social and political environment are assigned to evaluate the fire severity and the probability of occurrence of non-accidental fires. This is similar to a multiattribute evaluation technique (Watts 1997), widely used in life safety evaluations, which simplifies the work to evaluate all the buildings including the existing premises for a risk level by coming up with a risk index.

There is a wide range of issues which would affect potential fire risks. The attributes, or risk parameters, covering aspects affecting the risk level of the assessed building are identified in this proposed scheme.

Advancement of technology and social demand on new style of living give new architectural features where most of the existing prescriptive codes (developed decades ago) are difficult to comply. With many symbolic buildings and innovative architectural features evolved, various potential fire risks are emerging. For example, ultra high-rise buildings like the World Trade Center twin towers would give difficulty in evacuation. Fire safety in those ultra high-rise buildings (or super tall buildings) was pointed out recently (Chow 2004). Moreover, sophisticated urban cities attracting more people moving towards the cities would stimulate some of the social problems say, high unemployment rate. These aspects would all be included in the scheme as the risk parameters.

Comparison of parameters employed in each system was made prior to the determination of the risk parameters used in FRAS. Some parameters from the prevailing systems are selected and integrated into the new scheme. Risk parameters showing the characteristics of the evaluated buildings, the fire safety provisions and the personnel concerned are made reference to the sample risk assessment systems since they are often included in common. These will be used to evaluate the fire severity or the response of the building when there is a big fire. However, there is one big difference of the proposed FRAS from the existing risk indexing systems. The chance of having non-accidental fire is included in the new scheme. In this respect, attributes with regard to non-accidental fires are therefore encompassed in the proposed scheme. These parameters, however, will be used to determine the probability of occurrence of a non-accidental fire in the assessed building. Therefore, there are two groups of risk parameters, namely parameters of severity and parameters of probability.

Each risk parameter will be scored with different systems for two groups of parameters. By combining the individual highest "score" on severity and probability from the risk parameters, a single term will become a Risk Index based on which decision can be made on whether additional fire safety provisions are required for the assessed building. Further actions should be implemented accordingly to protect the high-rise buildings from the attack of man-made fires.

11.5 Risk Parameters of the FRAS

There are 24 risk parameters determining the risk level of non-accidental fires in buildings. Parameters in six areas are covered including passive building design (PBD), fire services installations (FSI), fire safety management (FSM), social issue and political issue. As discussed, not all high-rise buildings are likely to be threatened by non-accidental fires. Different buildings should be protected by different degree of fire safety provisions, in considering the safety level as well as the construction cost. The risk parameters are then divided into two main groups, parameters of severity (S_1 to S_{19}) and parameters of probability (P_1 to P_5), dealing with the two determinants of a risk. The former group determines the fire severity of the building whilst the latter determines the probability of having non-accidental fires in relation to the social and political stability of the place where the building is situated.

11.5.1 Parameters of severity

On the technological aspect, the newly proposed total fire safety concept (Chow 2002b; 2004d) on passive building construction, fire services installation and fire safety management are used. Attributes concerning the technological aspect commonly adopted in some existing fire risk evaluation systems (e.g. NFPA 2001; Hultquist & Karlsson 2000) are adopted. Other aspects on building geometry affecting severity are used to assess the fire severity or the response of the building features under exposure of a big fire. The parameters of severity are:

- PBD
  - S_1: Building height
  - S_2: Load-bearing structural elements
  - S_3: Compartmentation
  - S_4: Windows
  - S_5: Façade
  - S_6: Means of escape
  - S_7: Linings
  - S_8: Installations for escape route
- FSI
  - S_9: Ventilation system
  - S_{10}: Detection system
  - S_{11}: Signal system
  - S_{12}: Smoke control system
  - S_{13}: Sprinkler system
  - S_{14}: Fire service
- FSM
  - S_{15}: Hardware maintenance
  - S_{16}: Information for occupants
  - S_{17}: Special hazard
  - S_{18}: Neighborhood
  - S_{19}: Occupants

11.5.2 Parameters of probability

The social and political problems which play a key role in affecting the probability of having non-accidental fires compose the parameters of probability.

Social and political stability would trigger some offences like arson fires, and even worse, well-organized attack from terrorism. As listed in Table 11-1, unemployment rate and wealth gap are included as social issue while social inequity phenomenon, war and military action and target of terrorist are grouped under political issue. All of these are essential in reflecting the ingredient of "non-accidental fires" in the fire safety objectives.

Economic downturn would lead to high unemployment rate and people may commit crimes to reflect their dissatisfaction or to earn a living illegally. Setting fire might be one way they express their dissatisfaction to the government. Some people may also suffer from mental disorder under unendurable pressure. They may commit suicide and create conflagration. Citizens' reactions led by high unemployment rate were also publicized frequently in Hong Kong since the economic recession in 1997. Protests and marches are the positive ones while there might sometimes be law-breaking wrongdoings.

Extreme distribution of wealth might lead to dissatisfaction of the poor who might commit offenses to express their feelings and arouse public concern. For those who are not sensible, setting fires might be one of the possibilities. Income inequality between the rich and the poor can be measured by the Gini coefficient (The World Bank Group 2004), ranging from 0 to 1. A measure of 1 indicates complete inequality and, on the other hand, 0 means perfect equality.

According to the local government statistics, the Gini coefficient was climbing from 0.43 in 1971 to 0.525 in 2001. The situation of wealth inequality is deemed to be serious when compared to other nations. The Gini coefficients are 0.45, 0.35, 0.35, 0.31 and 0.25 in Singapore, USA, Australia, South Korea and in Japan respectively (Hong Kong Christian Council 2004).

War and military action are often seen in some politically unstable countries, like those in Middle East. Weapons of mass destruction (WMD) might be used sometimes, leading to disastrous consequences to the buildings, human beings and the even whole country.

Extreme religious beliefs might be one of the driving forces leading to terrorism. America and its alliances who support American's anti-terrorist policy would be topped in the list of target of terrorist attack. Since the largest devastation in the WTC incident, some other nations co-operating with United States have also been announced to be the next target. The recent train bombing attack in Madrid (BBC news 2004b) was claimed of responsibility by one of the suspected terrorists.

Political instability can be resulted by numerous social inequity phenomena other than these. Other causes, like sex discrimination, racial inequity and religious bias are also included.

The parameters of probability include:

- Social issue
  - P_1: Unemployment rate
  - P_2: Wealth gap
- Political issue
  - P_3: Social inequity phenomenon
  - P_4: War and military action
  - P_5: Target of terrorist

The list of parameters and groupings can be found in Table 11-1.

11.6 Risk Index

As in a multiattribute assessment and hazard analysis (BS 2004; US Coast Guard 2005; Watts 1997), each parameter will be evaluated with a “score” based on their different properties, performance or criteria. A severity category and a probability level will be assigned for parameters of severity and parameters of probability respectively.

11.6.1 Severity categories and probability levels

For the parameters of severity, there are four severity categories in the scale of 1 to 4 indicating the most risky to the less risky, namely Catastrophic, Critical, Marginal and Negligible, when the building is under the threat of a fire. The definitions of them are:

- Catastrophic (1): death or severe damage of property
- Critical (2): severe injury or major damage of property
- Marginal (3): minor injury or minor damage of property
- Negligible (4): less than minor injury or less than minor damage of property

On the other hand, there are five probability levels ranging from A to E, termed as Frequent, Probable, Occasional, Remote and Improbable, for the parameters of probability. They indicate the likelihood of the building to have non-accidental fires. Their definitions are:

- Frequent (A): likely to occur frequently
- Probable (B): will occur several times in the life of the building
- Occasional (C): likely to occur some time in the life of the building
- Remote (D): unlikely but possible to occur in the life of the building
- Improbable (E): so unlikely, it can be assumed occurrence may not be experienced

To ensure the consistent application of the scheme by different users, it is important to define the categories and levels with enough precision and detailed interpretation. The classifications of severity category for each parameter are set out clearly in Appendix J and K.

11.6.2 Risk index and risk assessment matrix

A sample risk index evaluation worksheet is shown in Table 11-2. To evaluate a building, all parameters of severity will be assigned with a "category" individually while all parameters of probability will be assigned with a "level". Unlike the common fire risk indexing systems (e.g. NFPA 2001; Hultquist & Karlsson 2000), the final "score" is not come up with the addition of individual "scores". On the other hand, the highest category and the highest level (category 1 and level A to be the highest) is determined by making comparison of the same group of parameters, for example 1 and A. The combination of these (1A) will be regarded as a "risk index" (BS 2004; Military Standard 1993), which gives indication on the non-accidental fire risk of the assessed building. Note that the risk indexing system only gives relative or comparative risk rather than absolute risk. The relationship between the severity categories, the probability levels and the risk indexes can be tabulated in a matrix form as shown in Table 11-3.

Tolerability criteria should be established as a basis to determine additional fire safety provisions. Each risk index corresponds to a tolerability of risk which decides whether the risk is acceptable or not. In the proposed FRAS, four levels of tolerability are suggested, including unacceptable, undesirable, acceptable with review and acceptable without review. Appropriate actions to control or reduce risks are to be decided according to the tolerability of risk (BS 2004), as demonstrated in a sample risk-based control plan in Table 11-4.

The more unacceptable of tolerability, the higher fire risk of that building would be resulted under a non-accidental fire attack. More stringent fire safety requirements should be provided. The current fire safety regulations were designed only for accidental fires. Appropriate fire safety requirements for protecting against arson fires and terrorist attack fires should be worked out in the next step.

11.7 Summary

Consequent to different fire scenarios can be worked out according to the frequency of occurrence and severity of damage. The starting size of an accidental fire would not be very large when compared to an arson fire. However, more cases of arson fire was reported to give bigger initial fire size (Chow et al. 2004). The number of terrorist attack fire is observed to be increasing. Protection against accidental fire is the fire safety objective in the existing fire regulations. It appears necessary to revise the objectives to protect some buildings against other types of fires. More fire safety provisions are expected. However, cost is another concern and not all buildings might have a risk of arson and terrorist attack. Therefore, a Fire Risk Assessment Scheme was proposed in this chapter to assess the likelihood of different buildings having arson or terrorist attack fires. A relative fire risk based on a scoring system can be evaluated.

Fire safety measures in terms of PBD, FSI and sometimes FSM are usually included as parameters in the widely used fire risk indexing systems. To address the objective of the proposed FRAS, additional risk parameters concerning political and social issues are incorporated into the system. As a result, 24 parameters in the areas including PBD, FSI, FSM, political stability and social stability are included in the assessment. A risk index representing the fire risk level is resulted after following the simple procedure of evaluation. In this preliminary scheme, parameters are proposed to allow future refinement and justifications since the current version is derived based on the regional areas and local legislations. Modifications should also be made once the technical knowledge in this area is advanced.

The fire risk index and the corresponding tolerability of risk accomplished from the proposed FRAS should be provided for upgrades or enhancement of the fire safety provisions, which should be carefully worked out to give equivalent fire safety level as pursued in the current statutory requirements. In light of the risk indexes, different degree of reinforcement of the fire safety provisions should be granted for the assessed premises. For example, with the “unacceptable” risk level, the building should be substantially upgraded in terms of PBD, FSI and FSM to avoid catastrophic events and the building operation might be ceased before the improvements are done. For an “acceptable with review” building, the enhancement of fire safety provisions can be focused on the single risk parameter of the highest “score” or enforced on the whole building provided that the cost is acceptable.

Apart from the concerns on fire safety, the security system of the properties is also extremely important to prevent the occurrence of this sort of attack. Skyscrapers or super high-rise buildings are thought to be too vulnerable to terrorist attack. Though it is not impossible to provide full protection to a building against mass destruction such as from a terrorist attack, the huge investment and undesirable look are not what investors and designers desire and neither the occupants would like to use it. What can be done more might be on the security and management of the property. For instance, secure entrance and restriction to the vehicle access. The structural elements should not be altered without recognizing the influence to the structure. Aircraft manufacturers can develop a protective system to prevent the plane from being hijacked, say a protective "bubble" plan is being developed to shield the skyscrapers (The Engineer 2001). The cockpit should also be prohibited by all means from trespassing of terrorists eventhough they can get on board (Kitipornchai 2001).

CHAPTER 12 CONCLUSIONS

The advancement of technology and creativity in the construction industry introduced many landmark buildings and development of highest admiration in the cities. Behind the glamorous appearance, buildings with new architectural features sometimes have difficulties in complying with the prescriptive fire codes. Study has been carried out on the fire safety of the new architectural features in cities, like Hong Kong.

First of all, the existing prescriptive fire regulations and codes were reviewed. It is followed by the studies on four innovative building designs, the potential fire hazards of which were investigated with in-depth study. From these studies, the existing legislations appeared lagging behind the innovative demand of the construction industry as it takes time to carry out research and development works.

The existing prescriptive-based fire codes, taking account of accidental fires only, are considered inadequate. In connection with the WTC incident, the fire resistance requirements and fire protective coatings for structural steel elements were discussed. In the local codes, the prescriptive codes developed based on technology and information from tens of years ago might be out-of-date. Revision and extension on existing codes only made each time after a big fire. The current codes are inherent with some other problems, say only accidental fire is included in the fire safety objective; the standard fire tests may overestimate or underestimate the fire ratings; the structural stability under fire exposure is not taken into consideration and so on. Shortages are also exposed when they are dealing with the innovative building designs. They may have difficulties in complying with the codes or they get compliant with the codes with some fire hazards hidden.

Investigating by various methodologies throughout this study, potential fire risks behind the new architectural features and the inadequacies of the existing fire codes have been unveiled. With the analysis results and suggestions arisen from the study, this thesis can provide some useful data or information for architects' planning for innovative designs in the future. The investigations appear diversified among different architectural features but they can be unified to compile a checklist for designers' consideration. An example was illustrated in Appendix L.

The study on the new architectural features, including atrium design, double-skin façade, internal building void and ultra high-rise building design, was the core part of this thesis and it has presented some new knowledge to the construction industry. It has demonstrated there are potential fire hazards in some non-traditional building designs. For example, a huge open space created at an atrium facilitates smoke spreading through different levels. The fire safety aspect in relation to the open design was pointed out with examination of the advantages and disadvantages of an atrium. Design considerations were suggested for this popular design.

The internal building void, connected to the rooms with window openings, is acting like a fire drain (Harmathy & Oleszkiewicz 1987) which allows flame and smoke spreading through it to other compartment by pressure differential. The results of CFD simulation showed that there is possibility of smoke spreading from the fire level to the adjacent levels through the internal building void under some scenarios. It is urged that further studies should be carried out to justify the popular building design and verify the numerical analysis. Full-scale burning tests with a setup of at least five storeys high are highly recommended for this purpose provided that sufficient resources are granted.

On the other hand, a full-scale experimental study on a double-skin façade has demonstrated that smoke spreading inside the cavity between the two layers of glass panels would vary with the depth of cavity. A wider cavity appeared to be a more desirable design in terms of the inclination of smoke spreading. Further studies on the intermediate values of cavity depths between those applied in this study should also be carried out to have a clearer understanding of the critical value. Other factors affecting the smoke spreading should be also studied thoroughly to give whole picture of the fire risks of this architectural feature.

Consequent to the WTC disaster, more attention should be paid to fire safety of ultra high-rise buildings. Reviews on collapse scenarios of WTC incident analyzed from various professionals were aimed to have a clearer picture on the fire behavior of an ultra high-rise building under exposure of terrorist attack fire. Insufficient fire insulation is suspected to be a root cause to the structural failure. On the other hand, the extreme high HRR as evaluated could make everything inside the towers untenable and is also considered as a main cause. The current building and fire codes were appeared inadequate to protect ultra high-rise buildings. Major revisions are required. The relationship between fire resistance requirements and structural stability should be also reconsidered. In-depth study on understanding the event and the possible cause for the collapse is therefore required to keep architects alert on the fire safety issue of the ultra high-rise buildings.

It has been verified that the existing building and fire codes are unsatisfactory for protecting high-rise buildings against non-accidental fire attack. Their inadequacy was spelt out in this thesis and major revisions were urged. Professionals and experts throughout the world are now paying substantial effort on revisions of current codes and establishment of performance-based fire codes (e.g. Chow 1999). However, it would take some time for this big task. Whether or not to include non-accidental fires is a difficult decision as not all buildings are under the threat of such attack. If it is included, structural stability should be watched carefully. For accidental fires, separation of compartment or control on fire spread is the most important issue while structural stability would be compromised under high HRR from non-accidental fires. In this sense, a higher collaboration between structural engineers and fire experts is expected.

To safeguard our built environment before the new codes established, some interim work should be carried out. Only selective buildings, in places with unstable social and political environment, are required for protection against non-accidental fires. A fire risk assessment scheme was, therefore, proposed in this study to assess the likelihood of having non-accidental fires. By grading every existing or newly constructed building with a single “score”, further work, say enhancing the existing fire safety provisions or providing higher building security, can be worked out promptly for each building of “unsatisfied” risk level.

Further, better fire safety protection is expected by the establishment of the engineering performance-based fire codes, of which the development and application require expertise judgment. Adequate fire engineering professionals to take up this task would entirely rely on extensive education and training in the coming future.

TABLES

Table 3-1: Requirements on Fire Resistance Period (FRP) (in hours)

Constructions	**Hong Kong***	**Mainland**		**Approved Document B***	**Fire Precautions Act***	**IBC&**	**NFPA 101#,%**
		First Class	**Second Class**				
Fire resisting wall	1, 2, 4	3	3			2, 3, 4	0.5, 1, 2
Load bearing wall	1, 2, 4	2	2	1, 1.5, 2		0, 1, 2, 3	2, 3, 4
Floor slab	1, 2, 4	1.5	1	1, 1.5, 2	0.5	0, 1, 2	2, 3
Columns	1, 2, 4	3	2.5	1, 1.5, 2		1, 2, 3	2, 3, 4
Beams	1, 2, 4	2	1.5	1, 1.5, 2		0, 1, 2	2, 3, 4
Roof	1, 2, 4	1.5	1	1, 1.5, 2		0, 1, 1.5	1.5, 2
Lift well	2	2	2	0.5	0.5		
Stair enclosure	1, 2, 4	2	2	0.5	0.5		
Compartment wall	1, 2, 4	0.75	0.5	1, 1.5, 2	0.5, 1		
Non-load bearing external walls of escape route	1, 2, 4	1	1	0.5	0.5	0, 1, 2, 3	
Hanging roof		0.25	0.25^				

* FRP depends on the intended functions of the building.

^ Materials which made of hard − combustible component which is difficult to ignite or treated with fire retardants.

% Subject to different materials.

\# Elements are of Type 1 approved noncombustible or limited-combustible materials.

& FRP depends on types of construction and occupancy groups.

Table 3-2: Requirements on Compartment Size

	Classifications		Maximum compartment size	Remarks
Local code	Above ground		28000 m^3	Defined by volume.
	Underground		7000 m^3	
Mainland code	Type1		1000 m^2 2000 m^2 (s)	Defined by floor area.
	Type 2		1500 m^2 3000 m^2 (s)	
	Underground		500 m^2 1000 m^2 (s)	
Approved Document B	Offices		No limit	Defined by floor area.
	Institutional		2000 m^2	
	Assembly & recreation, shop & commercial		2000 m^2 4000 m^2 (s)	
	Industrial	Not more than 18 m	7000 m^2 14000 m^2 (s)	
		More than 18 m	2000 m^2 4000 m^2 (s)	
	Storage & other non-residential	Not more than 18 m	20000 m^3 40000 m^3 (s)	Defined by volume.
		More than 18 m	4000 m^3 8000 m^3 (s)	
NFPA 101	Assembly, day-care, detention and correctional, hotels and dormitories, apartment, residential board and care, industrial, storage		Not mentioned.	Defined by floor area.
	Educational		2800 m^2	
	Health care, ambulatory health care		2100 m^2	
	Mercantile, business		No requirement.	
Fire Precaution Act	No requirements.			
IBC	No information.			

(s) Represents sprinklered building

Table 3-3: Requirements on Escape Routes in Local Codes

Capacity of room or storey	Minimum number of exit doors (from room) or exit routes (from storey)	Minimum total width/mm		Minimum width/mm	
		exit doors	exit routes	exit doors	exit routes
4 - 30	1			750	1050
31 - 200	2	1750	2100	850	1050
201 - 300	2	2500	2500	1050	1050
301 - 500	2	3000	3000	1050	1050
501 - 750	3	4500	4500	1200	1200
751 - 1000	4	6000	6000	1200	1200
1001 - 1250	5	7500	7500	1350	1350
1251 - 1500	6	9000	9000	1350	1350
over 1500	7 or higher as required by the Authority	to be calculated at the rate of 300 mm per 50 persons		1500	1500

Table 3-4: Requirements on Escape Stairways

	Minimum requirements	
	Number of staircases	Width of staircases (m)
Local code	2	1.1
Mainland code	2	1.1
Approved Document B	2	0.8
Fire Precautions Act	2	0.75
IBC	2	1.1
NFPA 101	2	0.91

Table 3-5: Requirements on Travel Distance

	Use of premise		Maximum travel distance(m)	Remarks
Local code	Office, school and shop		36	The travel distance is for cases with more than 1 escape routes. The distance from any point within a room to the corridor door is defined as "direct distance". It is the maximum sum of the direct distance and travel distance. Apply to internal corridor only.
	Others		36	
Mainland code	Hospital	wards	24	The travel distance is for cases with more than 1 escape routes. Measured from room door to story exit.
		others	30	
	Educational building, hotel and exhibition hall		30	
	Others		40	
Approved Document B	Institutional, bedrooms, building for handicapped		18	The travel distance is for cases with more than 1 escape routes.
	Bedroom corridor		35	
	Assembly and recreation Areas with seating in rows		32	
	Office, shop and commercial, storage, industrial, schools		45	
Fire Precautions Act	Factory		45	The travel distance is for cases with more than 1 escape routes. Normal fire risk.
	Shop		30	
	Office		45	
IBC 2000	Assembly, educational, factory and industrial F-1, institutional I-1, mercantile, residential, storage S-1, business		76	The travel distance is for cases with more than 1 escape routes. Sprinklered buildings.
	Business B		91	
	Factory and industrial F-2, storage S-2, utility		122	
	Institutional I-2, I-3, I-4		61	

NFPA 101	Assembly, educational, day-care, ambulatory health care, detention and correctional	45	All are for new buildings and; Non-sprinklered buildings.
	Hotels and dormitories, apartments, board and care	53	
	Business, industrial, storage	60	
	Mercantile	30	

[a] Result obtained by multiplying the direct distance by 1.5
[b] Measured from any point in a corridor to the nearest story exit

Table 3-6: Comparisons between Fire Safety Codes

	Local codes	Mainland codes	Approved Document B	Fire Precaution Act	IBC	NFPA 101
Definition of high-rise buildings	Height ≥ 30 m	Residential buildings ≥ 10 stories. Public buildings ≥ 24 m. Further classified into 2 types.	No definition but 18 m to be a critical value.	No definition.	Height ≥ 22.8 m	Height ≥ 23 m
Fire safety measures (provisional requirements)	Depends on usage of buildings.	Depends on types of high-rise building.	Depends on usage of buildings.	All premises.	Depends on usage of buildings.	Depends on usage of buildings.
FRP	Depends on the functions in the building.	Depends on the construction elements of the type of the high-rise building.	Depends on the functions in the building.	Depends on the functions in the building.	Depends on the types of construction and occupancy groups.	Depends on structural elements defined by different materials.
Compartmentation	Defined by volume.	Defined by area.	Defined by area and volume.	Not mentioned.	No information.	Defined by area.
Number of staircases/exits/ routes	Depends on number of occupants in a storey.	Depends on number of fire compartment.	Depends on number of occupants in a storey.	Depends on occupant load and travel distance.	Depends on occupant load and travel distance.	Depends on number of occupants in a storey.
Number and location of Fireman's lift	1 if more than 1 lifts installed. ≤ 60 m from any point of the floor.	Depends on floor area. No prescribed requirements on the location.	Depends on floor area.	Not mentioned.	No information.	Not mentioned.
Control on HVAC systems in the fire compartment	Shut down in case of fire.	Shut down in case of fire.	Shut down in case of fire.	Not mentioned.	No information.	Not mentioned.

Table 7-1: Tests G2 to G5

Test		Cavity depth *d* (m)	Max. heat flux (kWm^{-2})	Maximum surface temperature of test panel (°C)											
				TPO							TPI			Ceiling	
				TO1	TO2	TO3	TO4	TO5	TO6	TO7	TI1	TI2	TI3	TC1	TC2
G2		1.5	5.91	140	120	115	96	83	75	72	157	173	184	215	216
G3	G3a	1.5	5.93	187	164	165	161	132	138	117	265	289	305	604	562
	G3b		6.67	193	172	171	169	142	139	119	254	292	310	548	524
G4	G4a	1.0	10.22	256	271	271	251	201	138	88	246	274	259	472	445
	G4b		10.43	246	260	258	282	250	158	95	243	256	264	500	468
G5	G5a	0.5	6.77	231	282	332	409	369	259	149	250	233	247	625	602
	G5b		3.55	474	489	350	488	481	375	193	259	246	381	646	620

Table 7-2: Positions of Maximum Temperature

Test		Cavity depth *d* (m)	TPO		TPI		Both test panels	
			Point	Maximum temperature (°C)	Point	Maximum temperature (°C)	Point	Maximum temperature (°C)
G2		1.5	TO1	140	TI3	184	TI3	184
G3	G3a	1.5	TO1	187	TI3	305	TI3	305
	G3b		TO1	193	TI3	310	TI3	310
G4	G4a	1.0	TO2	271	TI2	274	TI2	274
	G4b		TO4	282	TI3	264	TO4	282
G5	G5a	0.5	TO4	409	TI1	250	TO4	409
	G5b		TO2	489	TI3	381	TO2	489

Table 7-3: Glass Damages

Test no.		Burning Time (s)	Time Temperature/fallout area									
			TPO						TPI			
			Top pane		Middle pane		Bottom pane		Top pane		Bottom pane	
			Crack	Collapse	Crack	Collapse	Crack	Collapse	Crack	Collapse	Crack	Collapse
G2		6'19"	-	-	-	-	3'37"	-	-	-	-	-
							(127 °C)					
G3	G3a	4'	-	-	3'30"	-	2'25"	2'50"	-	-	-	-
					(90 °C)		(120 °C)	upper part				
	G3b	3'56"	3'50"	-	2'20"	-	2'13"	3'25"	-	-	1'25"	-
			(63 °C)		(130 °C)		(110 °C)	upper part			(250 °C)	
G4	G4a	4'34"	3'05"	-	1'42"	2'13"/ 3'38"	2'32"	unknown	-	-	unknown	-
			(200 °C)		(250 °C)	upper/ whole	(120 °C)	partial			unknown	
	G4b	4'39"	2'26"	2'26"	3'37"	3'03"	3'	unknown	-	-	-	unknown*
			(180 °C)	unknown	(240 °C)	whole	(180 °C)	partial				whole
G5	G5a	5'18"	-	-	51"	1'57"	1'25"	1'59"	-	-	unknown	-
					(300 °C)	whole	(190 °C)	middle			unknown	
	G5b	4'50"	-	-	52"	1'45"	1'45"	1'47"	-	-	-	4'41"
					(350 °C)	whole	(450 °C)	whole				partial

* estimated to be before 2’26” from temperature profile

Table 9-1: Differences in Other Fire Tests for Building Materials from BS 476

Tests	BS 476	ISO 834	ASTM E119	JIS A 1304	DIN 4102
Size of test specimen	Full size if applicable, otherwise, provide at least the minimum size prescribed.	As in BS 476.	Full size if applicable, otherwise, proportionately reduce the specimen size.	Not in full size but prescribed size.	As in BS 476.
How the specimen is heated	Wall: one side Floor: underside Beam: 4 sides Column: 4 sides	Wall: more than one side Beam: 3 or 4 sides	Wall: both sides	Beam: underside	No information.
Standard temperature/ time curve	$T = 345 \log_{10}(8t + 1) + 20$ T is in °C.	As in BS 476.	No mathematical expression provided. T is in °C.	No mathematical expression provided. T is in °C.	$\theta - \theta_o = 345 \log_{10}(8t + 1)$ θ is in K.
Test methods	Heating for loadbearing, insulation and integrity; Cotton pad for integrity.	As in BS 476.	Hose stream test and cotton pad test for integrity.	As in BS 476.	As in BS 476.
Performance criteria	Loadbearing: deflection or collapse Insulation: 140 °C (temp. rise) Integrity: cotton pad ignited	Insulation: 140 K (temp. rise)	Insulation: 139 °C (temp. rise)	Insulation: 260 °C (exact temp.)	Insulation: 140 K (temp. rise)

Table 9-2: General Grades of Fire Resistance Period (in hours) of Major Elements of Construction

Elements of construction	Local FRC code[#]	Building (Construction) Regulations 1966[*]	Approved Document B: Fire Safety 2000[%]	Fire Precautions Act 1971	GLC London Building Act and By-laws[#]
1. Wall	1, 2	0.5, 1, 2	0.5, 1, 1.5, 2	0.5, 1	0.5, 1, 2
Separating wall	2	4	1, 1.5, 2	-	4
2. Beam	1, 2	0.5, 1, 2	0.5, 1, 1.5, 2	-	0.5, 1, 2
3. Column	1, 2	0.5, 1, 2	0.5, 1, 1.5, 2	-	0.5, 1, 2
4. Floor	1, 2	0.5, 1, 2	0.5, 1, 1.5, 2	0.5, 1	0.5, 1, 2
5. Roof	1, 2	0.5, 1, 2	0.5, 1, 1.5, 2	-	0.5, 1, 2
6. Basement	4	1, 2	0.5, 1, 1.5, 2	-	1, 2

[#] FRP depends on the intended functions of the building and cubical extent.
[*] Buildings having more than 3 stories should have at least 1-hour FRP.
[%] FRP depends on the intended functions of the building and height of top floor above ground or depth of the lowest basement.

Table 9-3: Comparison of FRP Requirement between Building (Construction) Regulation 1966 and London Building By-laws 1972

Uses	Building (Construction) Regulation 1966		London Building By-laws 1972	
	Volume / area*	FRP	FRP	Volume
Warehouse	708-1417 m^3	0.5	0.5	≤ 710 m^3
			0.5	710-1420 m^3
	1417-3542 m^3	1	0.5	1420-2130 m^3
			1	2130-3550 m^3
	3542-7083 m^3	2	2	3550-7080 m^3
Trade or manufacture	-	-	0.5	≤ 710 m^3
	-	-	0.5	710-1420 m^3
	1417-3542 m^3	0.5	0.5	1420-2130 m^3
			1	2130-3550 m^3
	3542-7083 m^3 ≤ 697 m^2 > 697 m^2	 1 2	2	3550-7080 m^3
Office or domestic	-	-	Nil	≤ 710 m^3
	-	-	Nil	710-1420 m^3
	1417-3542 m^3 or 93-332 m^2	0.5	0.5	1420-2130 m^3
			0.5	2130-3550 m^3
	> 3452 m^3 or > 232 m^2	1	1	≥ 3550 m^3
Partly for office & partly for trade or manufacture	-	-	0.5	≤ 710 m^3
	-	-	0.5	710-1420 m^3
	≤ 1813 m^3 or ≤ 232 m^2	0.5	1	1420-2130 m^3
	1813-3542 m^3 or 232-464 m^2	1	1	2130-3550 m^3
	3542-7083 m^3 or > 464 m^2	2	2	3550-7080 m^3
Partly for domestic & partly for trade or manufacture	≤ 907 m^3 or ≤ 93 m^2	0.5	0.5	≤ 710 m^3
	907-1813 m^3 or 93-232 m^2	1	0.5	710-1420 m^3

	> 1813 m^3 or > 232 m^2	2	1	1420-2130 m^3
	-	-	1	2130-3550 m^3
	-	-	2	3550-7080 m^3
Transformer	-	2	2	-
Garage	≤ 46 m^2	0.5	0.5	≤ 710 m^3
	46-93 m^2	1	1	710-1420 m^3
			1	1420-2130 m^3
	> 93 m^2	2	2	2130-3550 m^3
			2	3550-7080 m^3

* The original measuring unit is transformed to metric system.

Table 11-1: Risk Parameters for the Proposed Fire Risk Assessment Scheme

Areas	Parameters of Severity	
PBD	S_1	Building Height
	S_2	Load-bearing Structural Elements
	S_3	Compartmentation
	S_4	Windows
	S_5	Façade
	S_6	Means of Escape
	S_7	Linings
	S_8	Installations for Escape Route
FSI	S_9	Ventilation System
	S_{10}	Detection System
	S_{11}	Signal System
	S_{12}	Smoke Control System
	S_{13}	Sprinkler System
	S_{14}	Fire Service
FSM	S_{15}	Hardware Maintenance
	S_{16}	Information for Occupants
	S_{17}	Special Hazard
	S_{18}	Neighborhood
	S_{19}	Occupants
Areas	**Parameters of Probability**	
Social Issue	P_1	Unemployment Rate
	P_2	Wealth Gap
Political Issue	P_3	Social Inequity Phenomenon
	P_4	War and Military Action
	P_5	Target of Terrorist

Table 11-2: Sample Risk Index Evaluation Worksheet

Risk Parameters		Category (1-4)	Level (A-E)
Parameters of Severity			
S_1	Building Height		
S_2	Load-bearing Structure Elements		
S_3	Compartmentation		
S_4	Windows		
S_5	Façade		
S_6	Means of Escape		
S_7	Linings		
S_8	Installations for Escape Route		
S_9	Ventilation System		
S_{10}	Detection System		
S_{11}	Signal System		
S_{12}	Smoke Control System		
S_{13}	Sprinkler System		
S_{14}	Fire Service		
S_{15}	Hardware Maintenance		
S_{16}	Information for Occupants		
S_{17}	Special Hazard		
S_{18}	Neighborhood		
S_{19}	Occupants		
Parameters of Probability			
P_1	Unemployment Rate		
P_2	Wealth Gap		
P_3	Social Inequity Phenomenon		
P_4	War and Military Action		
P_5	Target of Terrorist		
Highest Category/Level* (Risk Index):			
Tolerability:			

* Category 1 and Level A to be the highest respectively

Table 11-3: Risk Assessment Matrix

Severity / **Probability**	Catastrophic (1)	Critical (2)	Marginal (3)	Negligible (4)
Frequent (A)	1A	2A	3A	4A
Probable (B)	1B	2B	3B	4B
Occasional (C)	1C	2C	3C	4C
Remote (D)	1D	2D	3D	4D
Improbable (E)	1E	2E	3E	4E

Table 11-4: A Sample Risk-based Control Plan

Risk Index	Tolerability	Necessary Action
1A, 1B, 1C, 2A, 2B, 3A	Unacceptable	The risk level is unacceptable. Substantial improvements on fire safety measures are required, so that the risk can be reduced to an acceptable level. Building operation should be stopped until improvements are implemented to reduce the risk to an acceptable level.
1D, 2C, 2D, 3B, 3C	Undesirable	The risk level is undesirable. Substantial improvements on fire safety measures should be implemented urgently within a defined time period. Building operation should be suspended or interim risk control should be applied.
1E, 2E, 3D, 3E, 4A, 4B	Acceptable with review	The risk level is acceptable but consideration should be given to lower the risk. Costs of additional fire safety provisions should be also taken into account. The improvement work should be implemented within a defined time period.
4C, 4D, 4E	Acceptable without review	The risk level is considered acceptable. No further action is necessary other than to ensure that the controls are maintained.

FIGURES

(a) Ultra high-rise office tower with full-height glass curtain wall

(b) Old high-rise commercial buildings

Figure 2-1: Different Generations of Commercial Premises in Hong Kong

(a) New residential building

(b) Aged residential building

Figure 2-2: Different Window-to-wall Ratio Shown on Residential Buildings

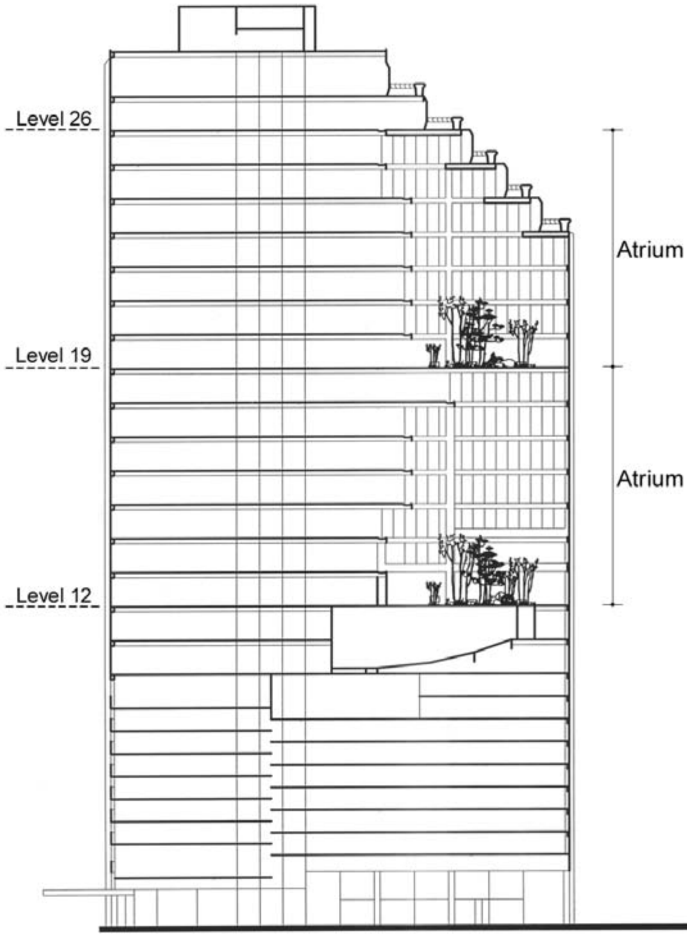


Figure 4-1: Stacked Atrium

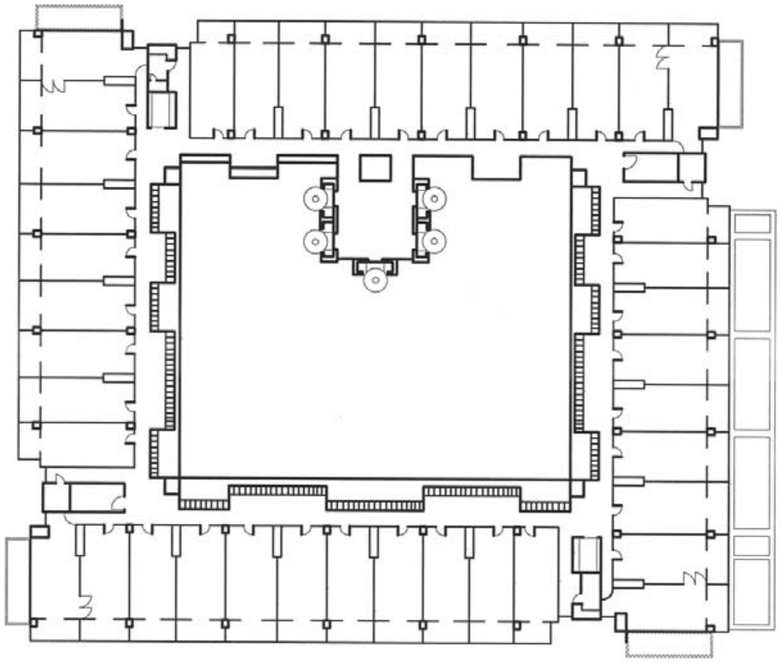


Figure 4-2: Covered Central Court: Atrium

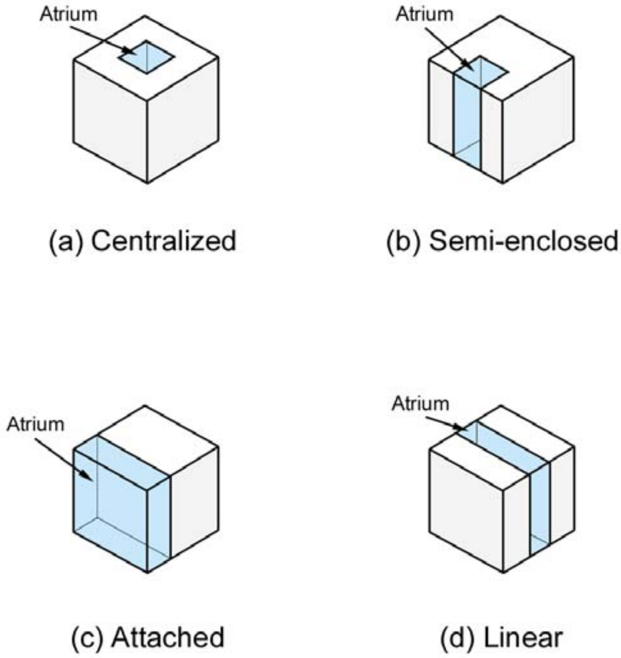


Figure 4-3: Four Types of Atrium

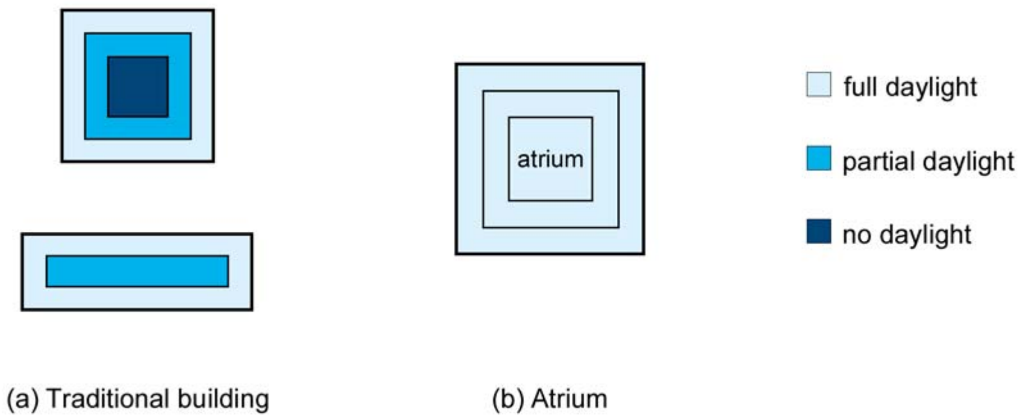


Figure 4-4: Availability of Daylight

(a) Outside view

(b) Atrium

Figure 4-5: Bank of China Tower, Hong Kong, 1989

(a) Outside view

(b) The 10-story high atrium
(availability of daylight)

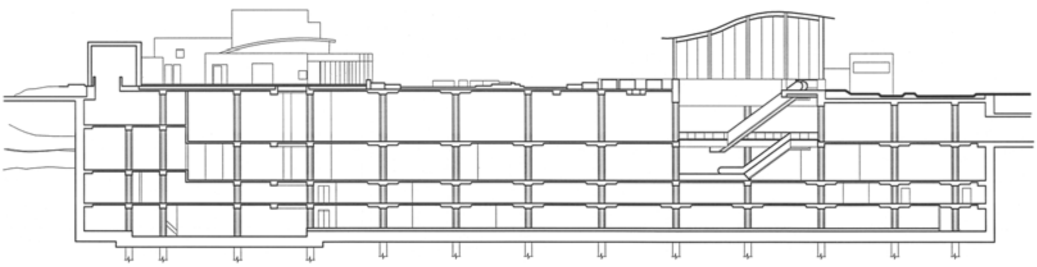
(c) "Sunscoop" device
(directing sunlight into the atrium)

Figure 4-6: Hongkong Bank Headquarters, Hong Kong, 1985

(a) Outside view

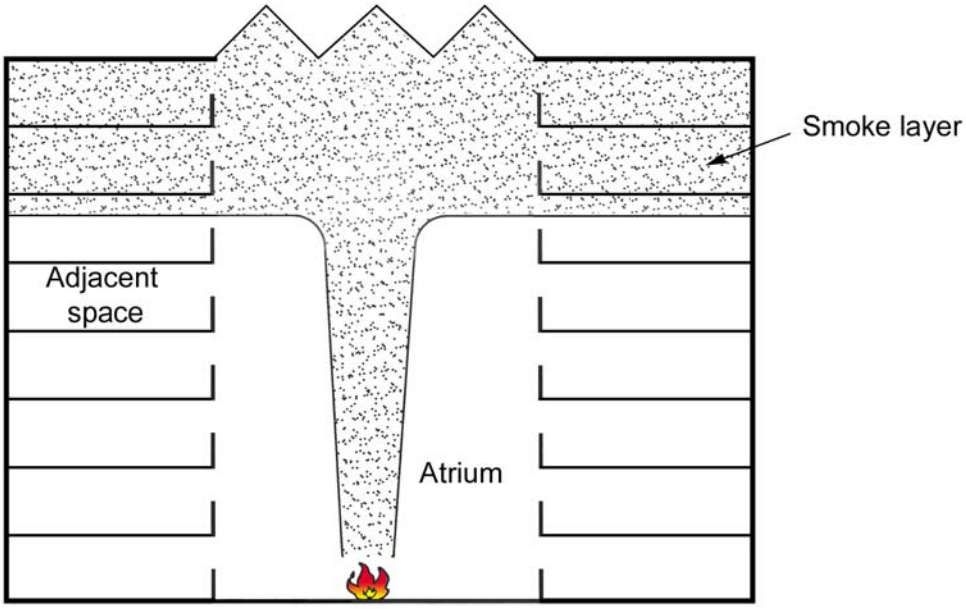
(b) The glass curvilinear roof

(c) The atrium

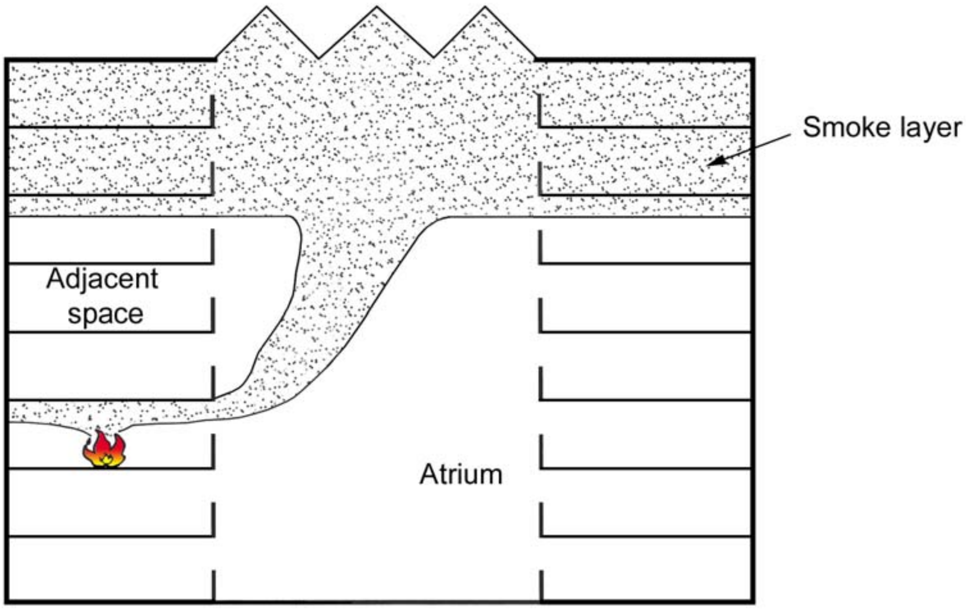


(d) Schematic view

Figure 4-7: The Palace Mall, Hong Kong, 1996

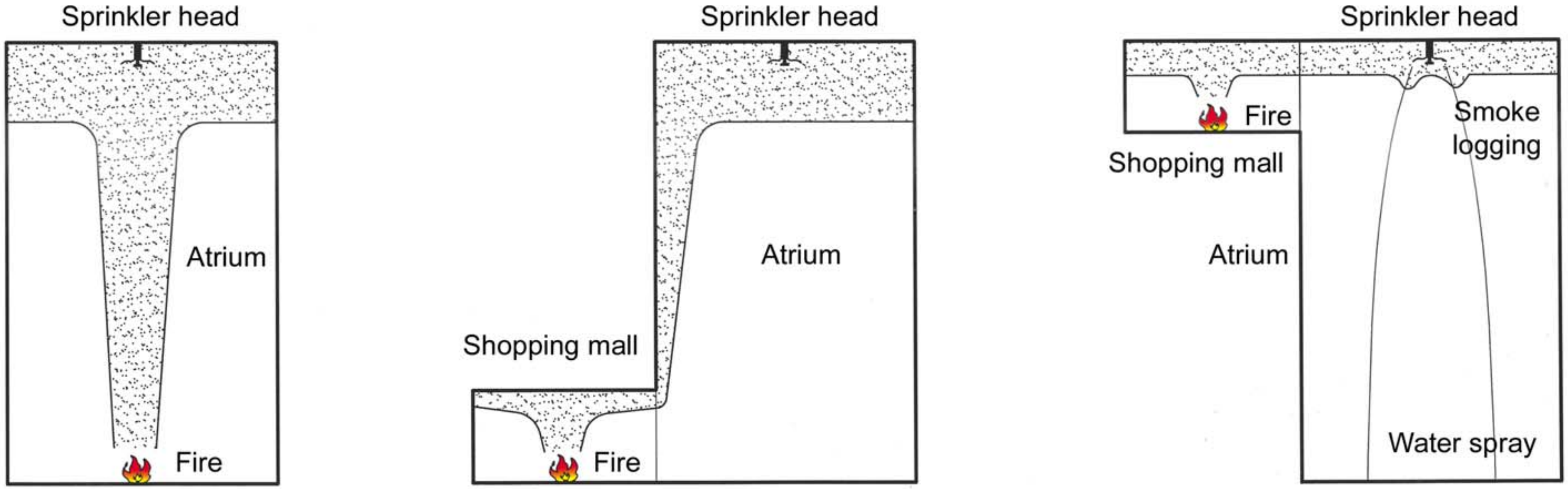


(a) Fire at the atrium floor



(b) Fire at adjacent shops

Figure 4-8: Fire and Smoke Spreading through the Atrium



(a) Scenario 1 (b) Scenario 2 (c) Scenario 3

Figure 4-9: Activation of Sprinkler Head at Atrium

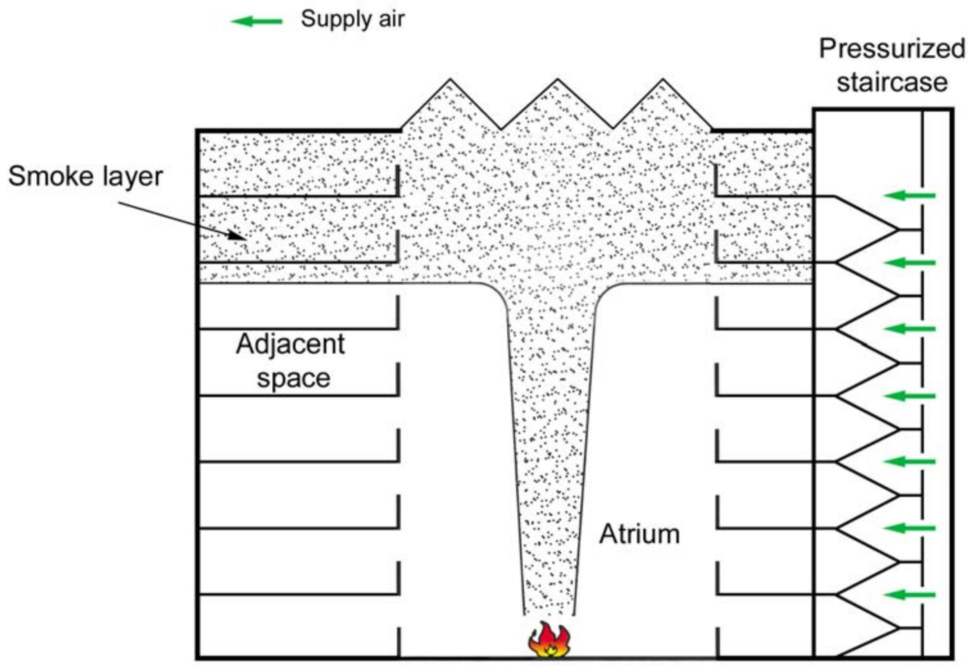


Figure 4-10: Staircase Pressurization

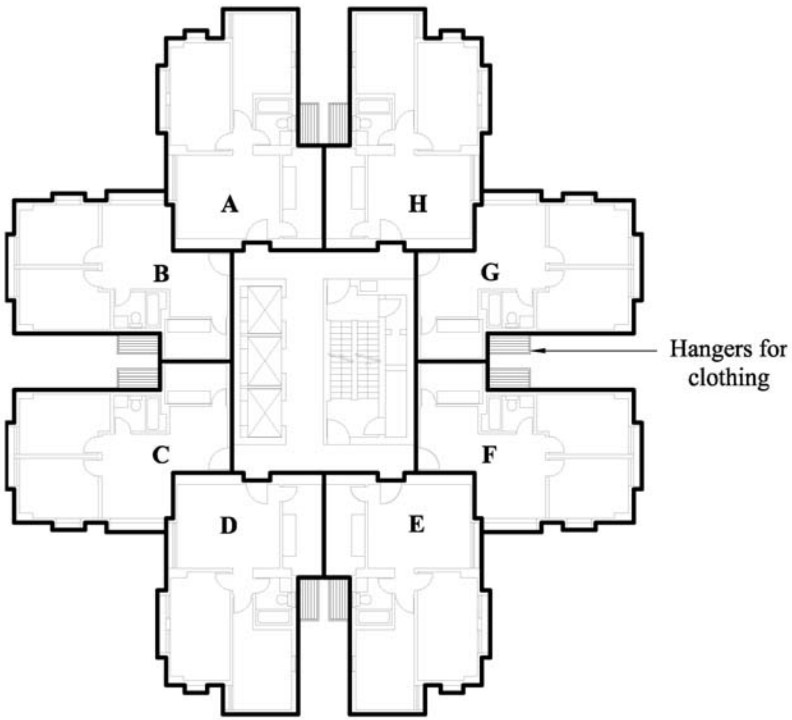
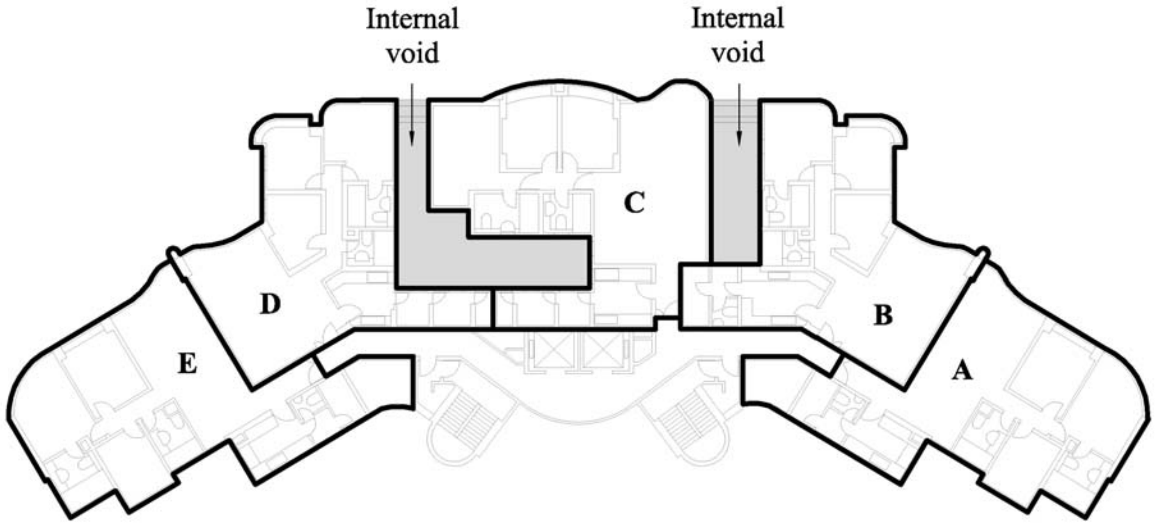
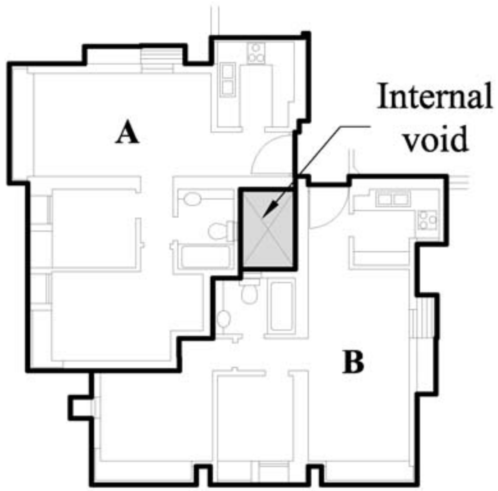


Figure 5-1: Traditional Floor Plan

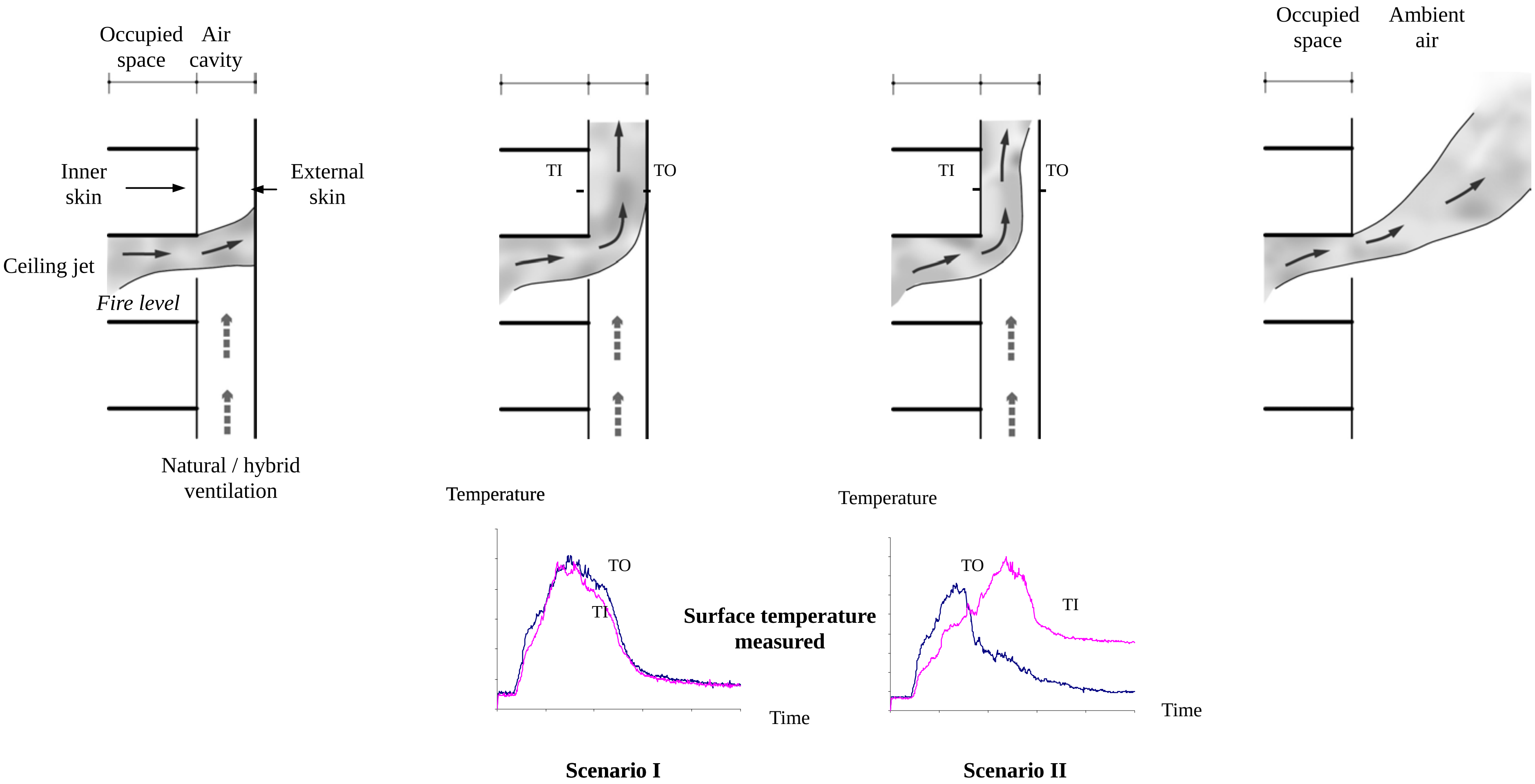


(a) Design I



(b) Design II (Example building Y)

Figure 5-2: New Design with Internal Void



(a) Double-skin façade (initial condition) (b) Double-skin façade (final possibilities) (c) Single Glazing

Figure 6-1: Flame and Smoke Movement

Figure 7-1: External View of the Burning Hall (16.5 m wide and 6 m high) in Lanxi

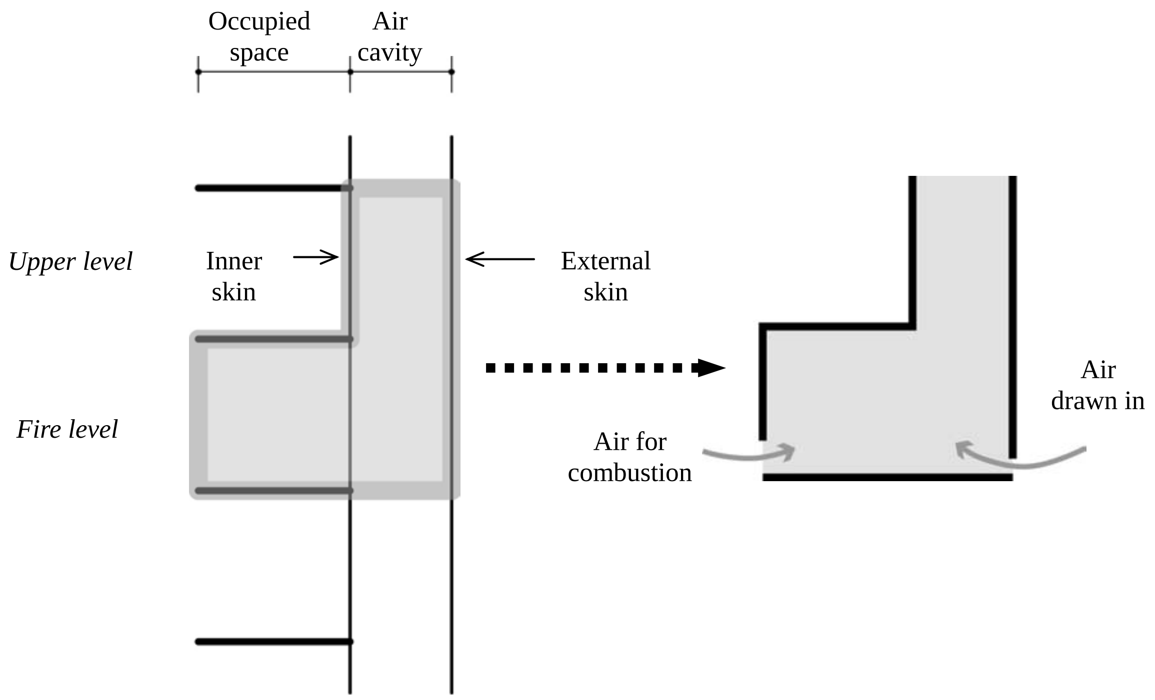
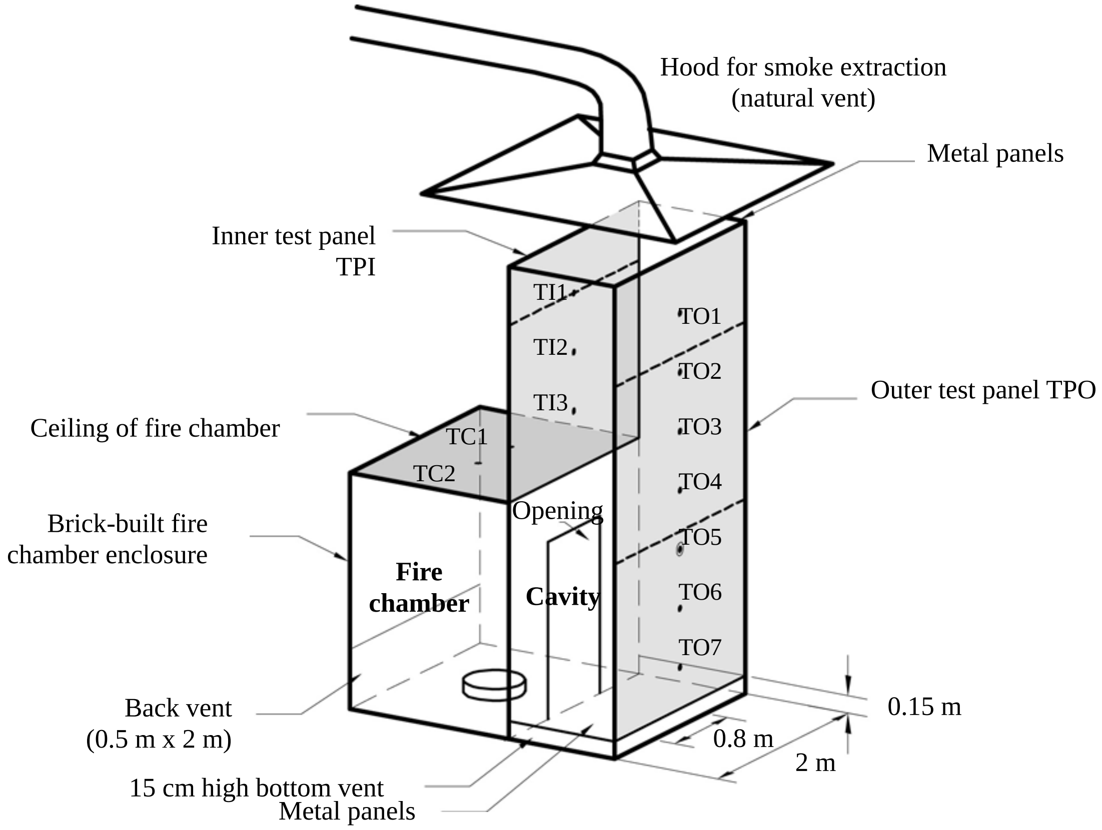
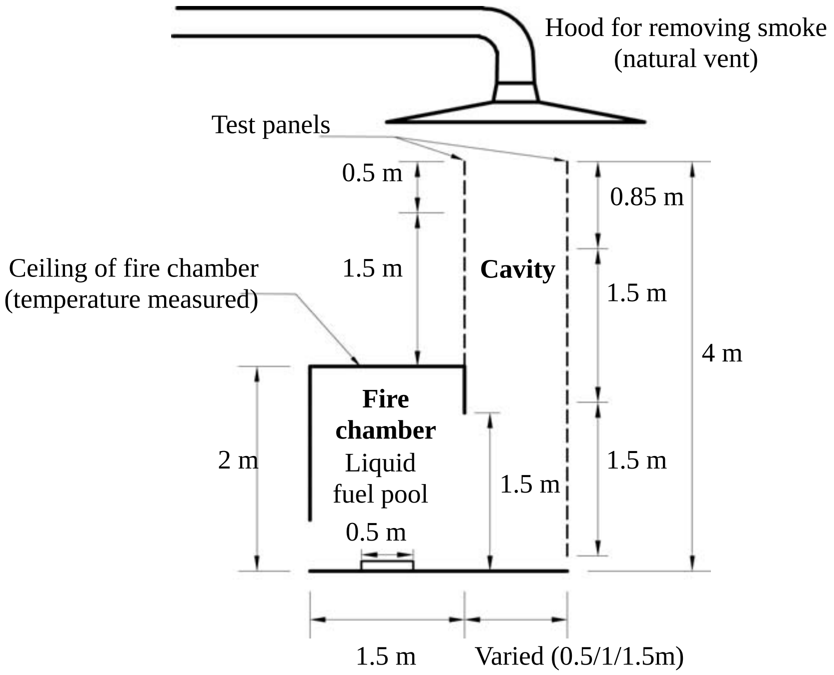


Figure 7-2: Area of Interest in the Experimental Study



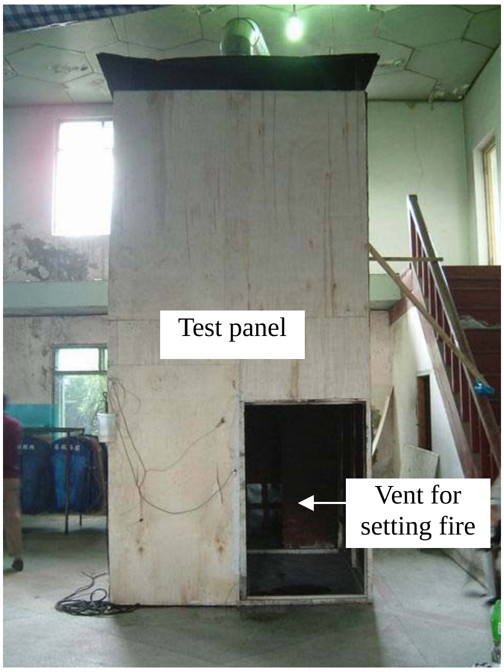
(a) Schematic diagram of test rig

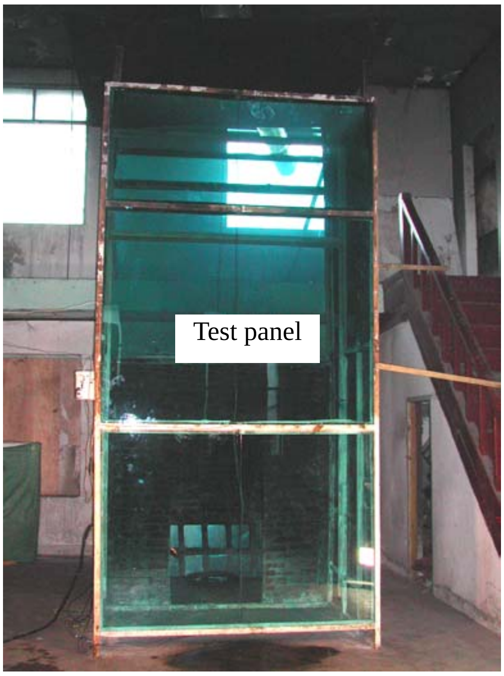


(b) Sectional view

Figure 7-3: Schematic Diagram of the Experimental Setup

(a) Elevation





(b) Wood panel (c) Glass panel

Figure 7-4: Pictures of Test Rig

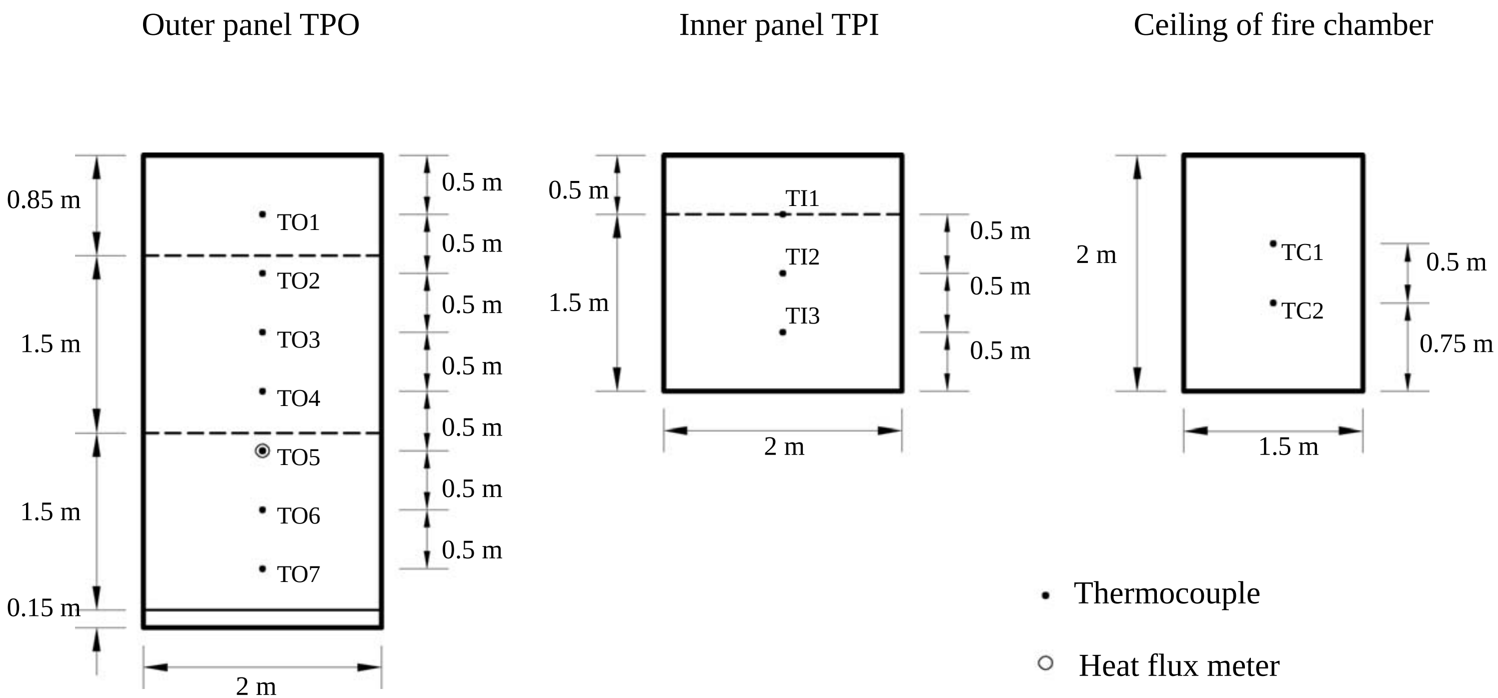


Figure 7-5: Locations of Thermocouples and Heat Flux Meters

Figure 7-6: Flame Coming out from the Fire Chamber

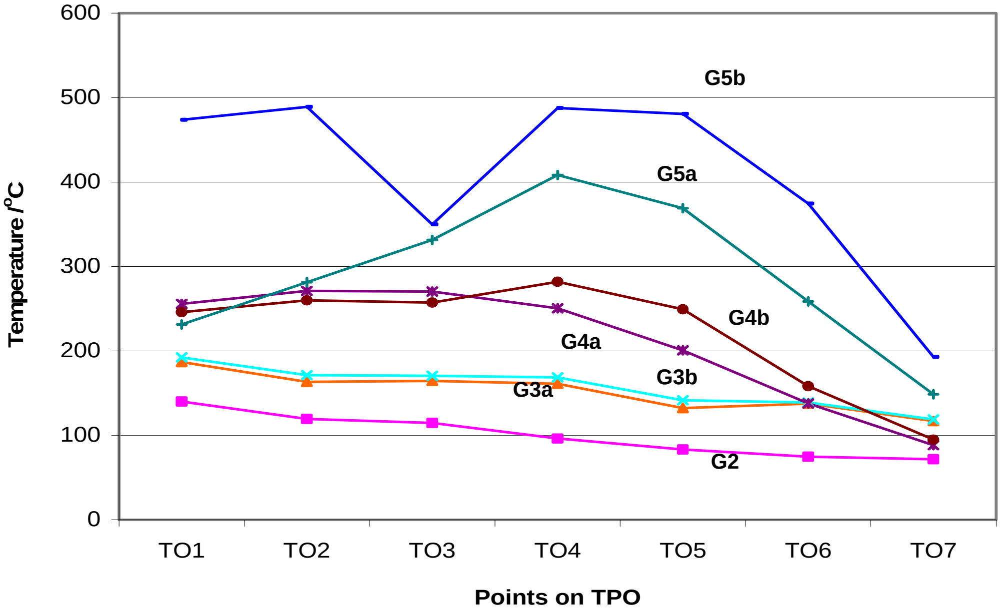


Figure 7-7: Maximum Temperature on Test Panel TPO

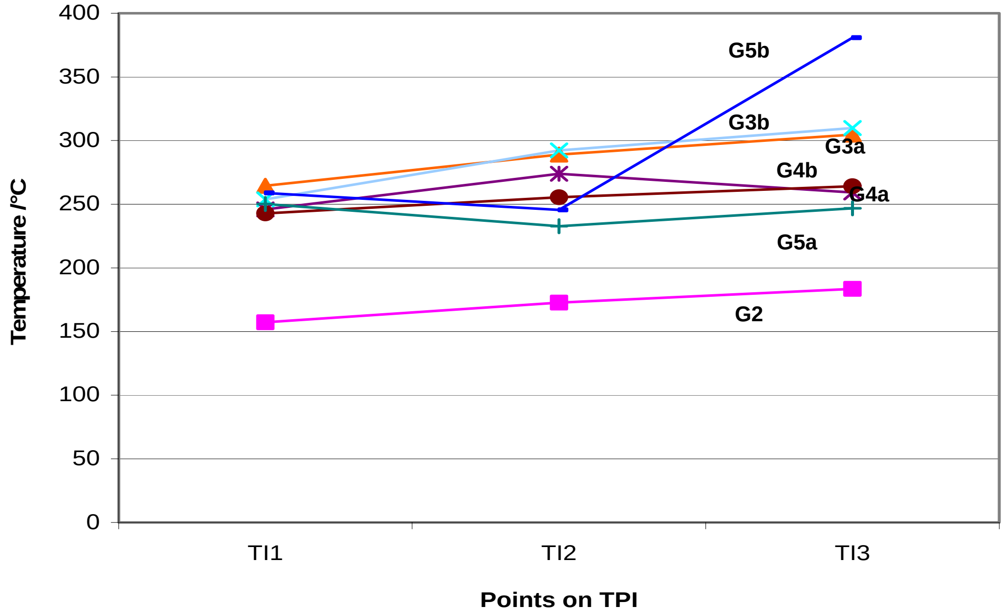


Figure 7-8: Maximum Temperature on Test Panel TPI

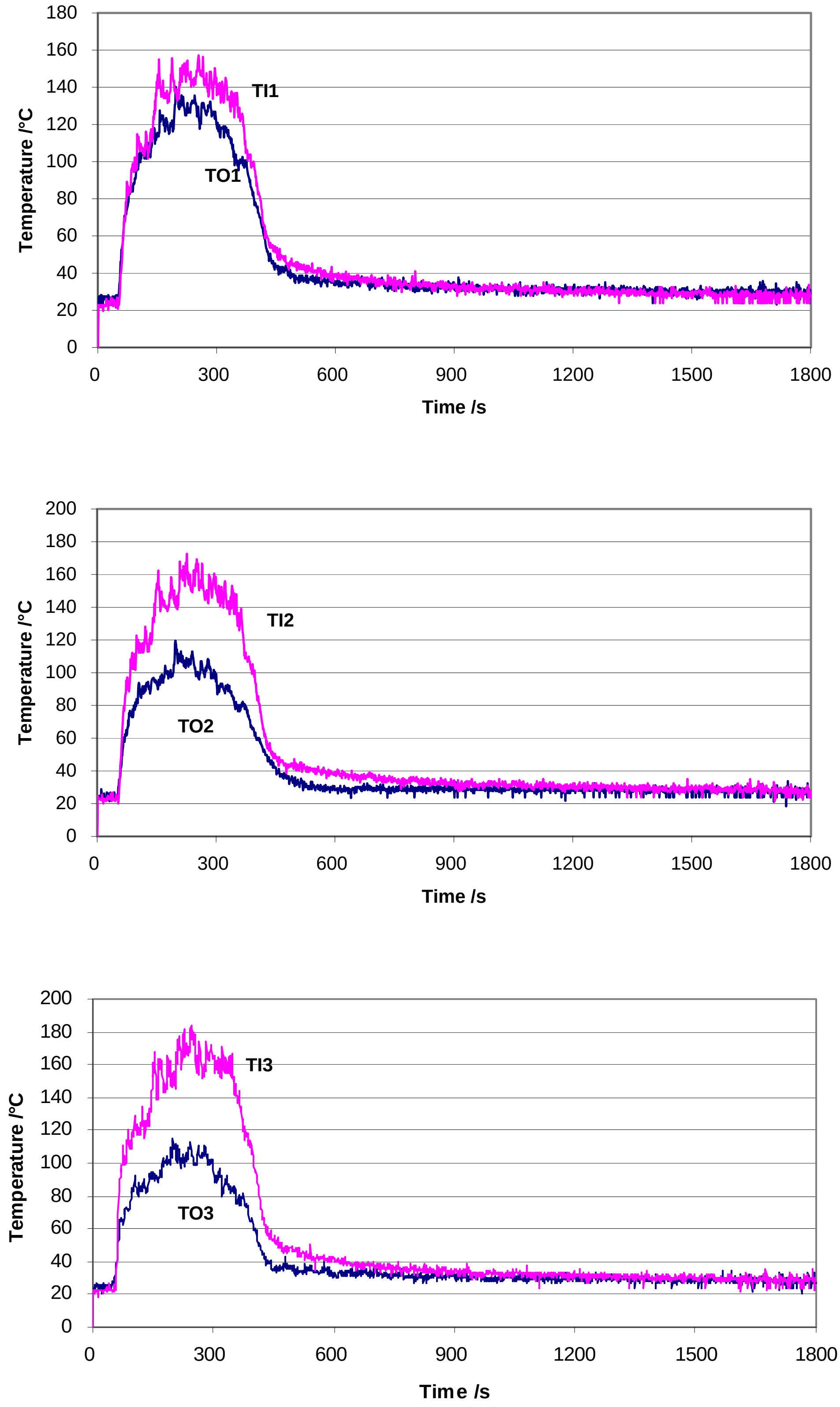


Figure 7-9: Temperature Profiles of Test Points on the Same Height for Test G2

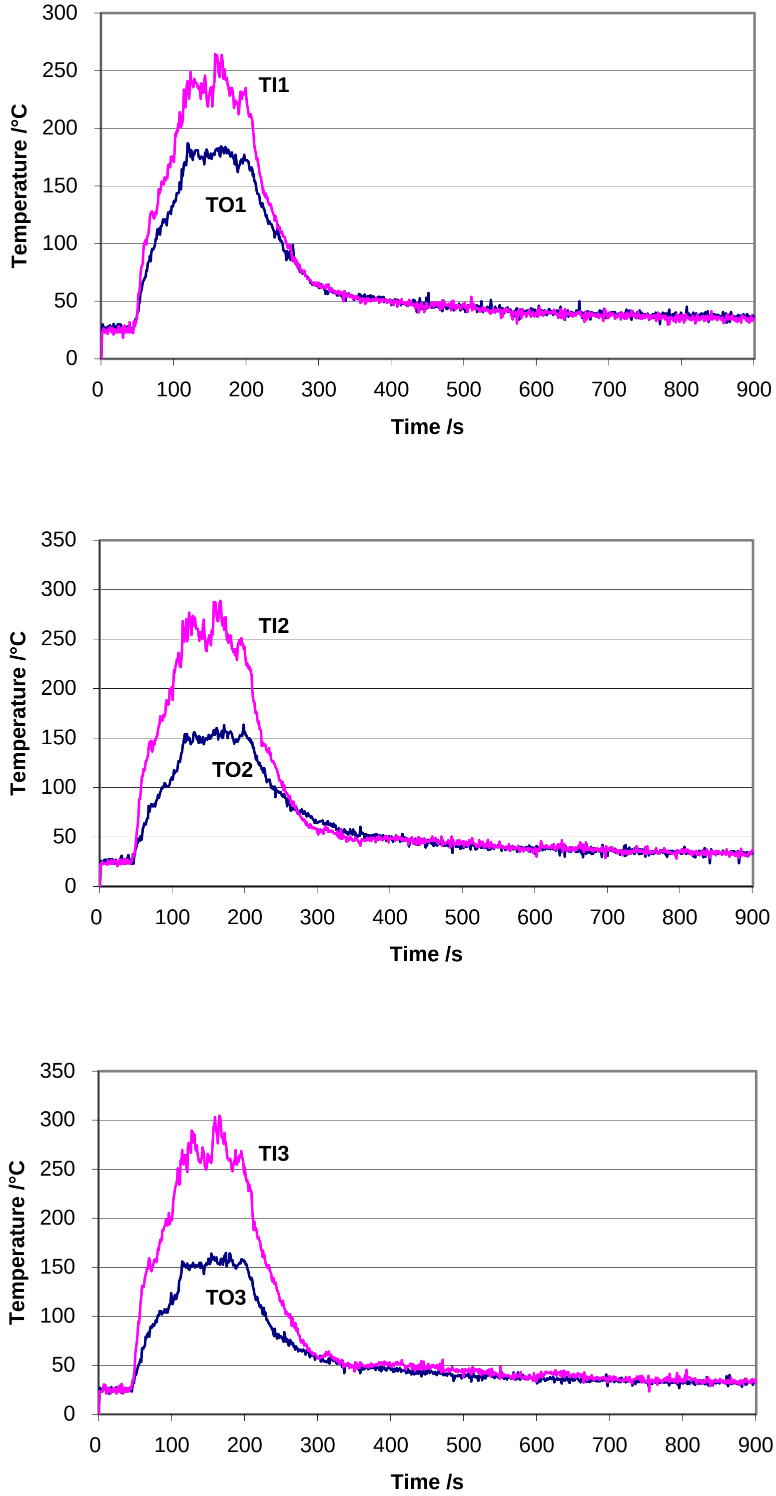


Figure 7-10: Temperature Profiles of Test Points on the Same Height for Test G3a

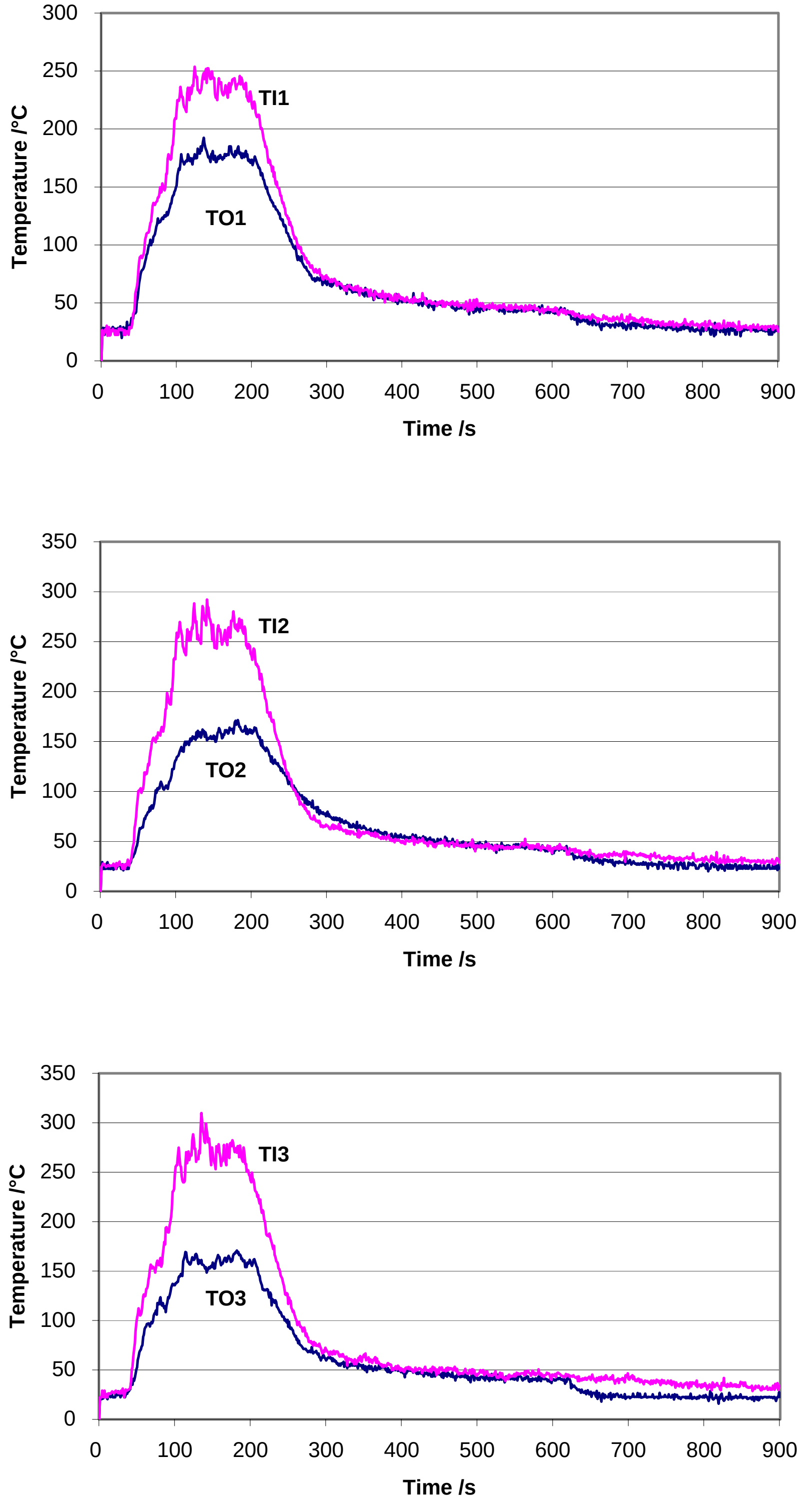


Figure 7-11: Temperature Profiles of Test Points on the Same Height for Test G3b

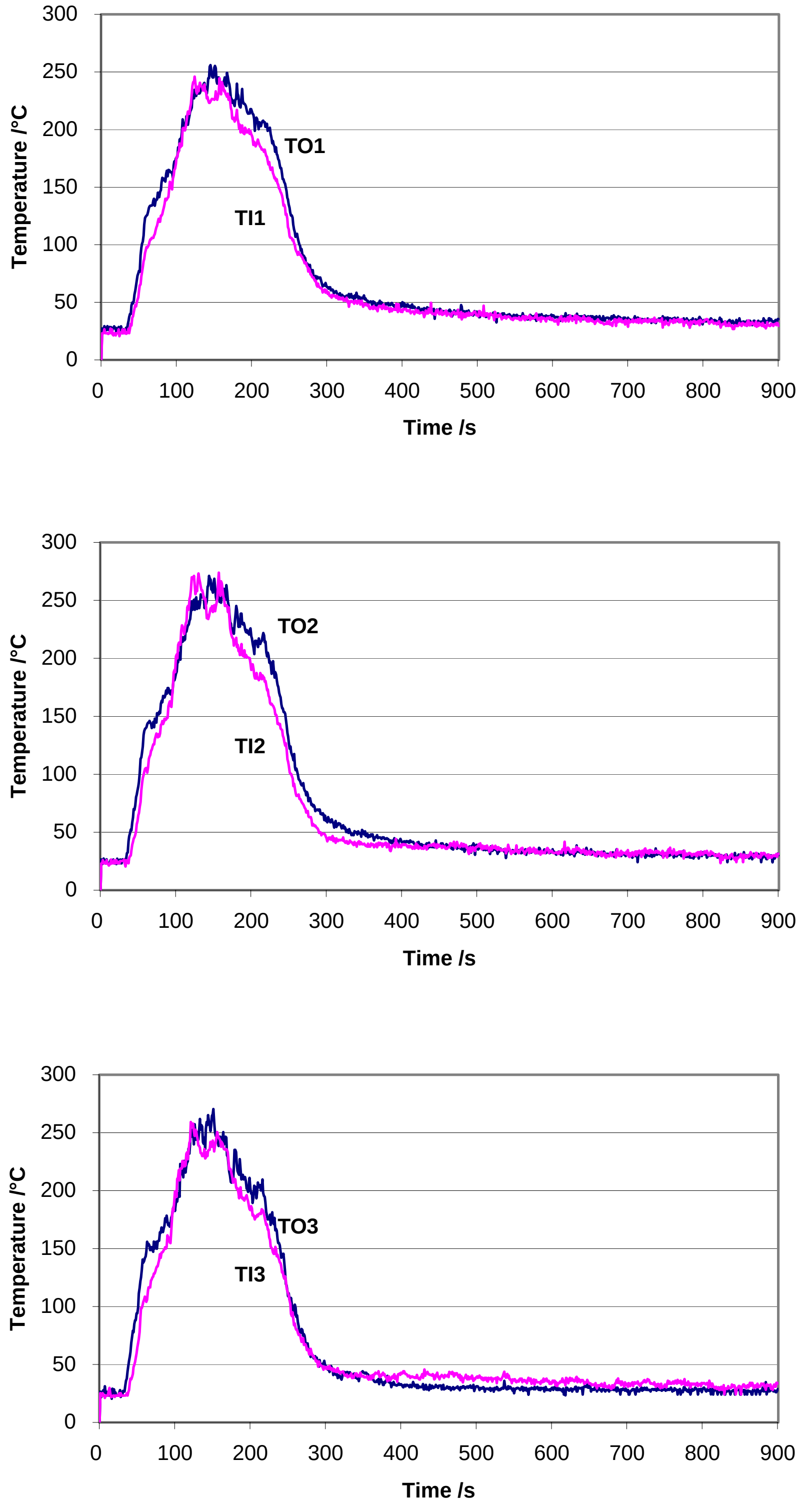


Figure 7-12: Temperature Profiles of Test Points on the Same Height for Test G4a

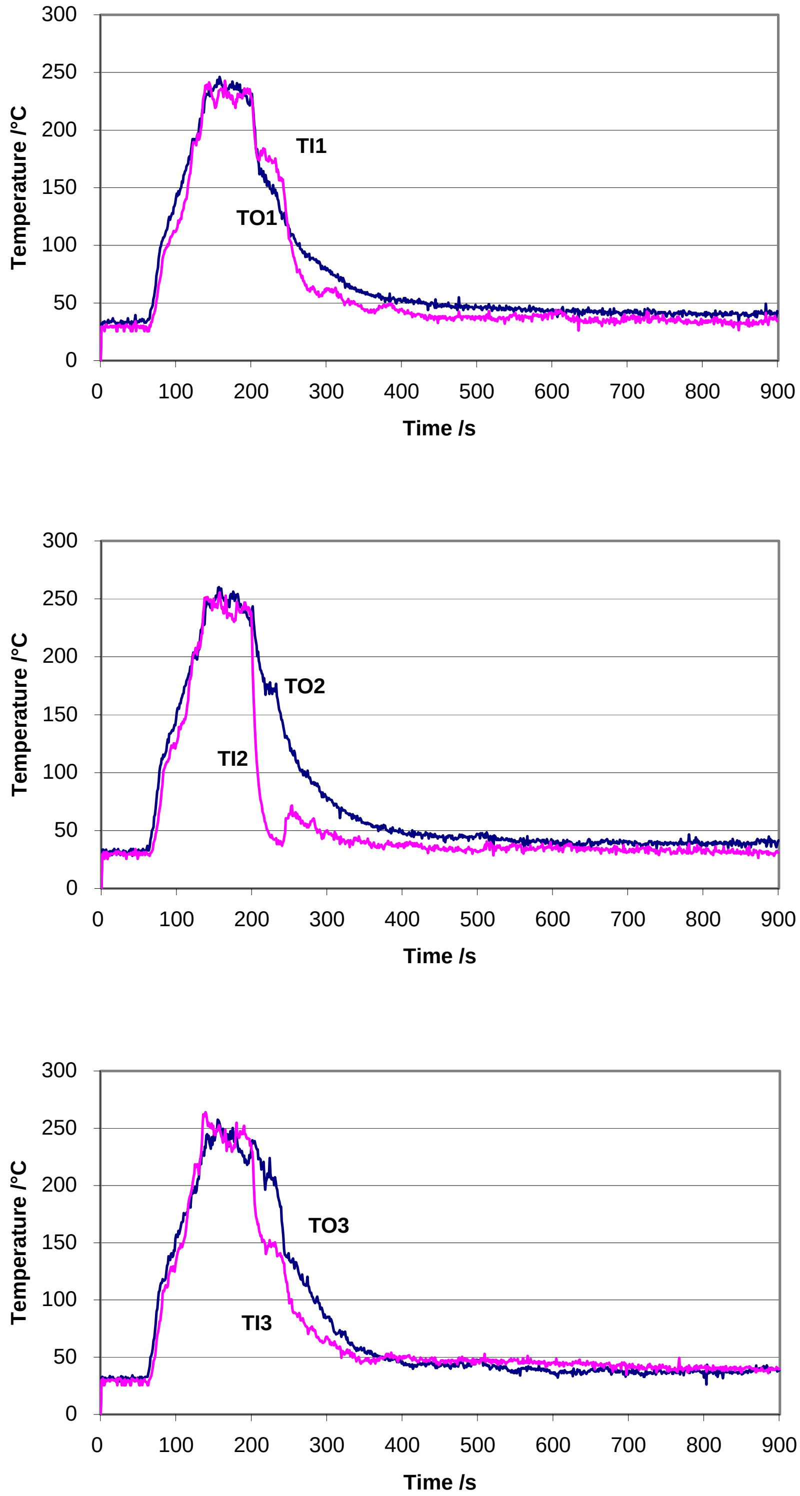


Figure 7-13: Temperature Profiles of Test Points on the Same Height for Test G4b

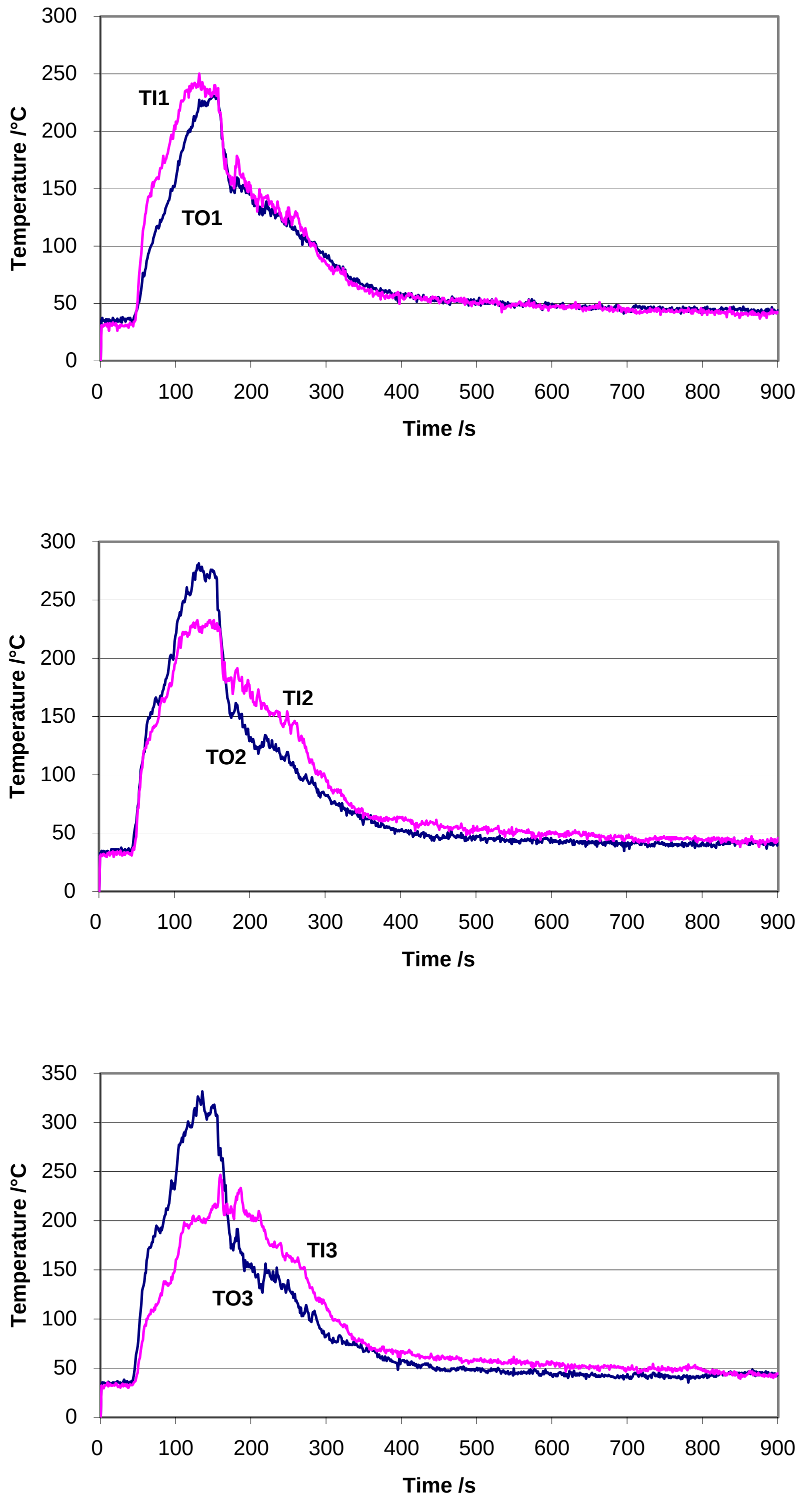


Figure 7-14: Temperature Profiles of Test Points on the Same Height for Test G5a

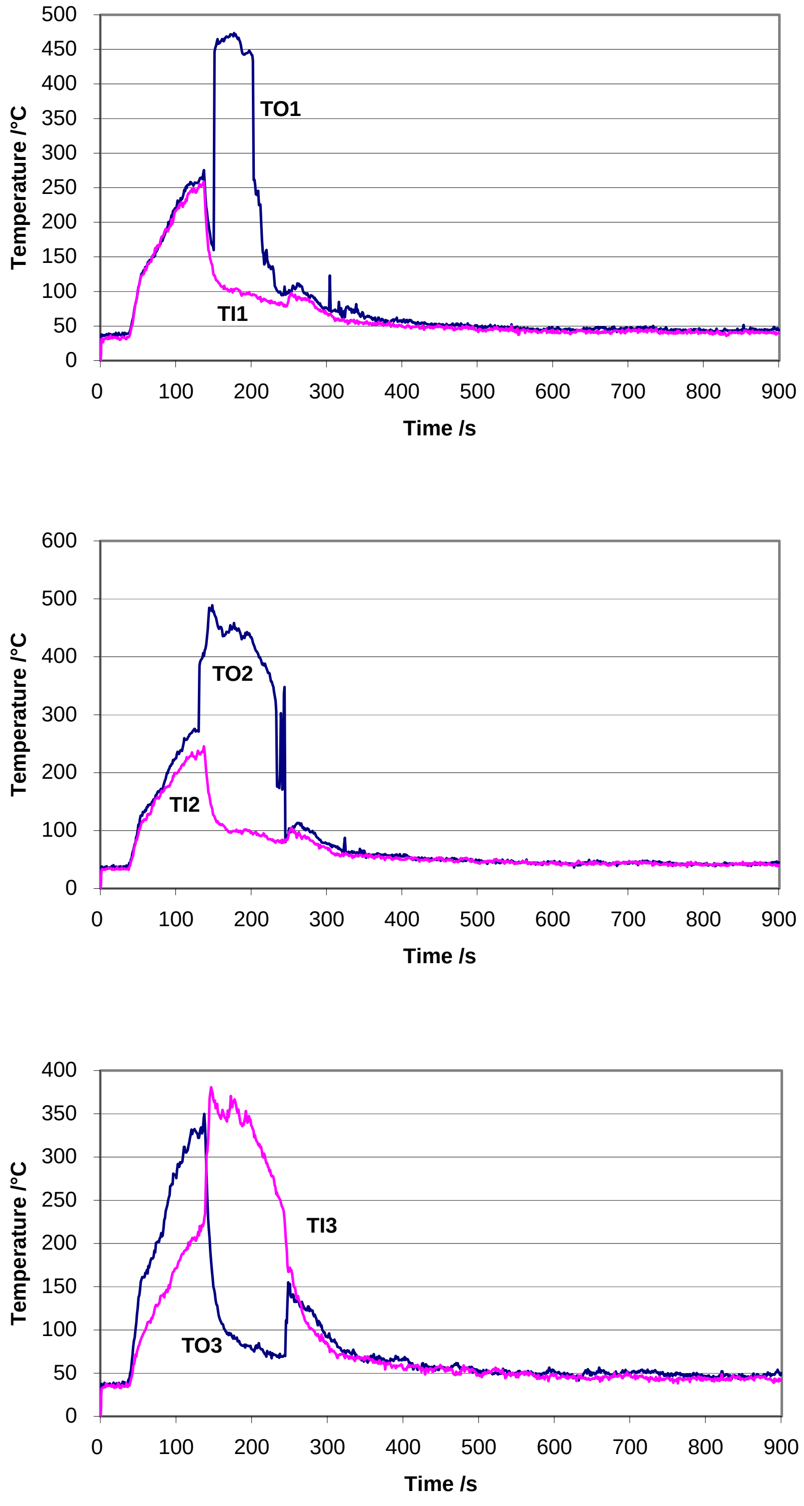
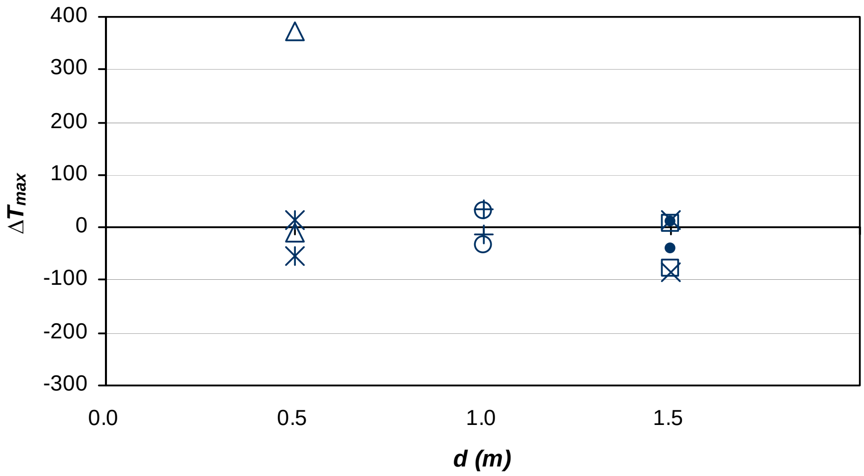
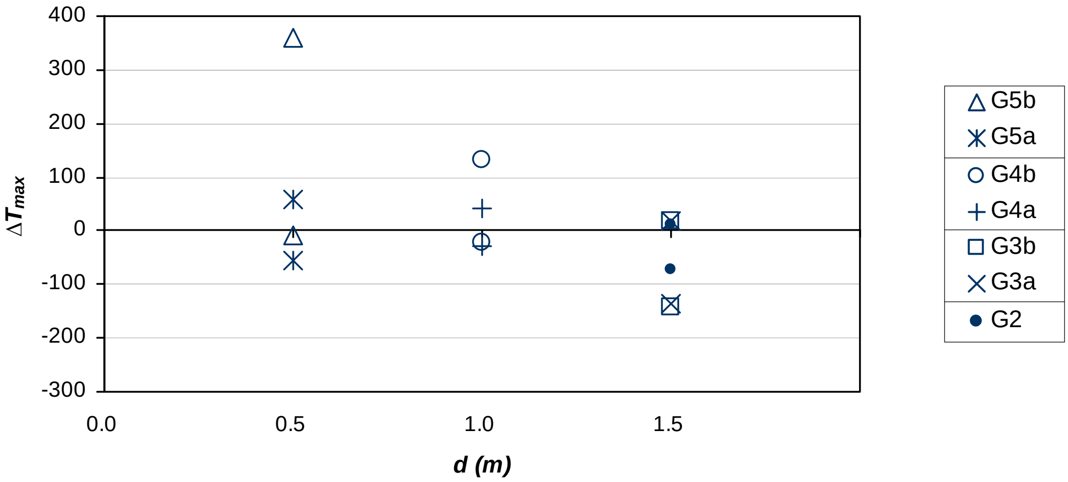


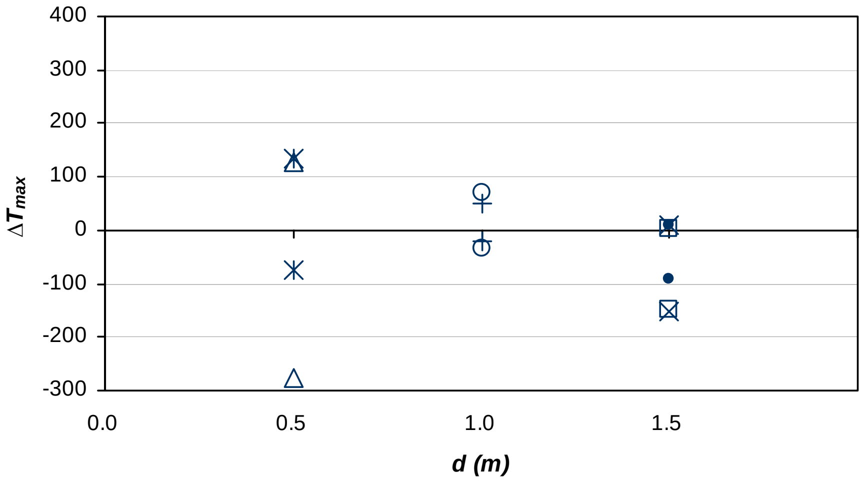
Figure 7-15: Temperature Profiles of Test Points on the Same Height for Test G5b



(a) Uppermost level

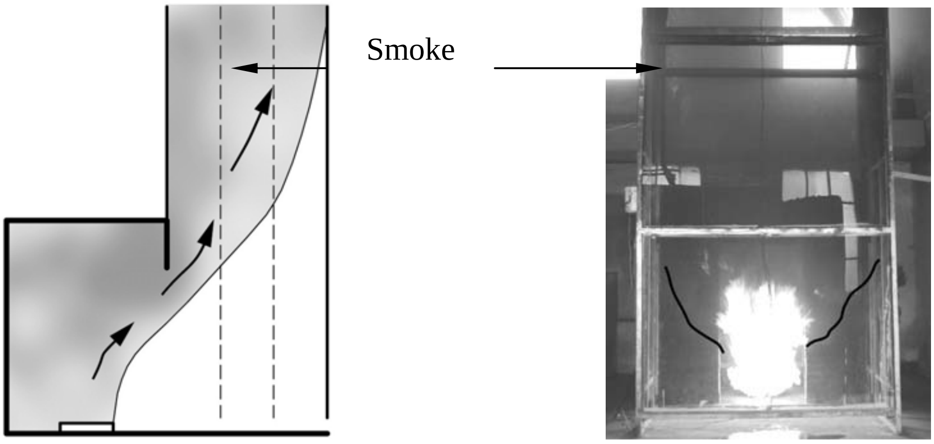


(b) Middle level

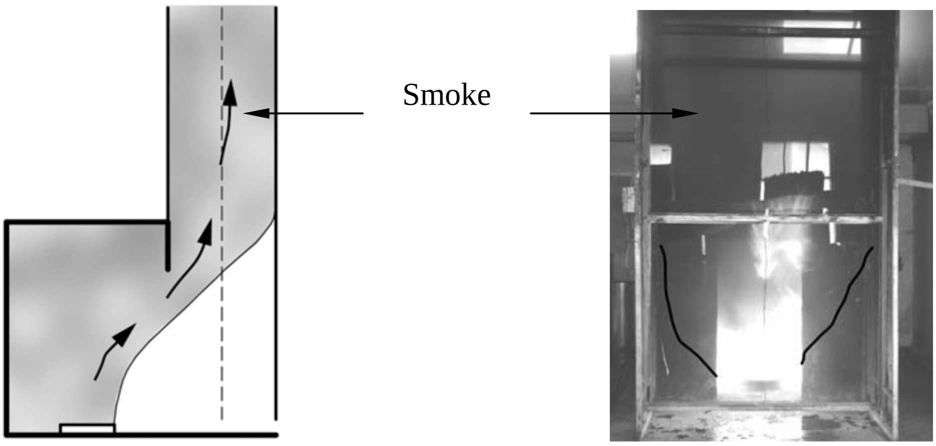


(c) Lowest level

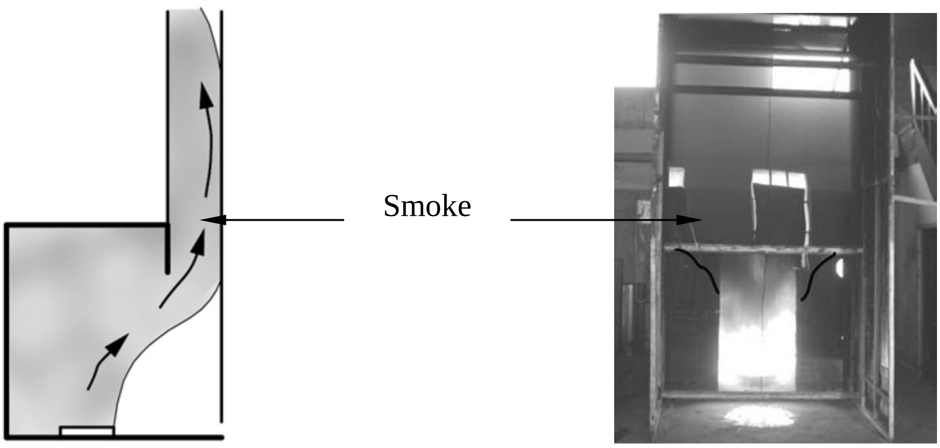
Figure 7-16: Maximum Temperature Difference ΔT_{max} Varied with Cavity Depth *d*



(a) 1.5 m deep cavity



(b) 1 m deep cavity



(c) 0.5 m deep cavity

Figure 7-17: Estimated Smoke Movement Influenced by the Depth of Cavity

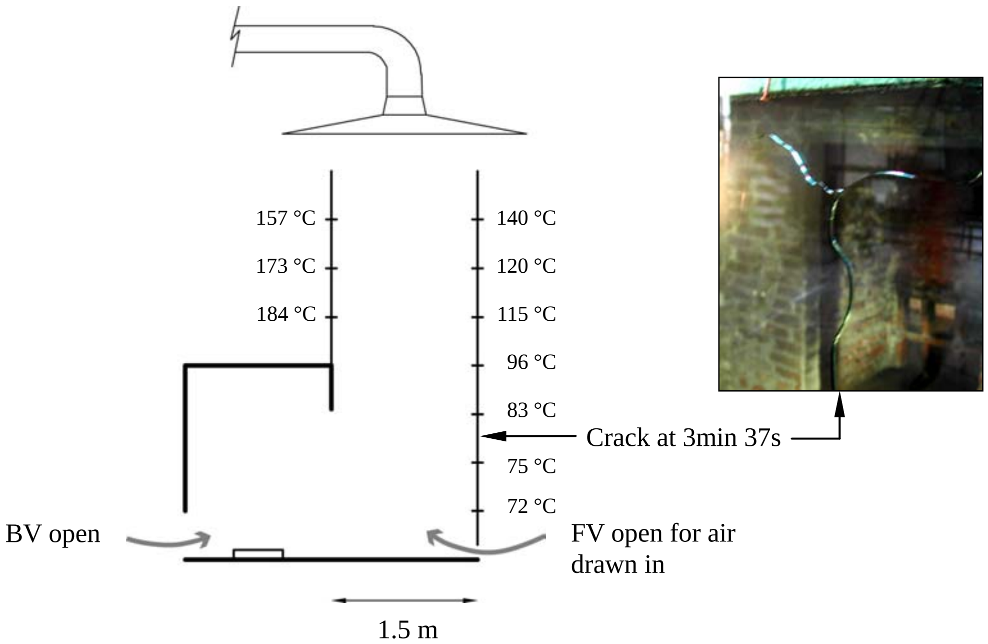


Figure 7-18: Maximum Temperature and Damages Recorded in Test G2

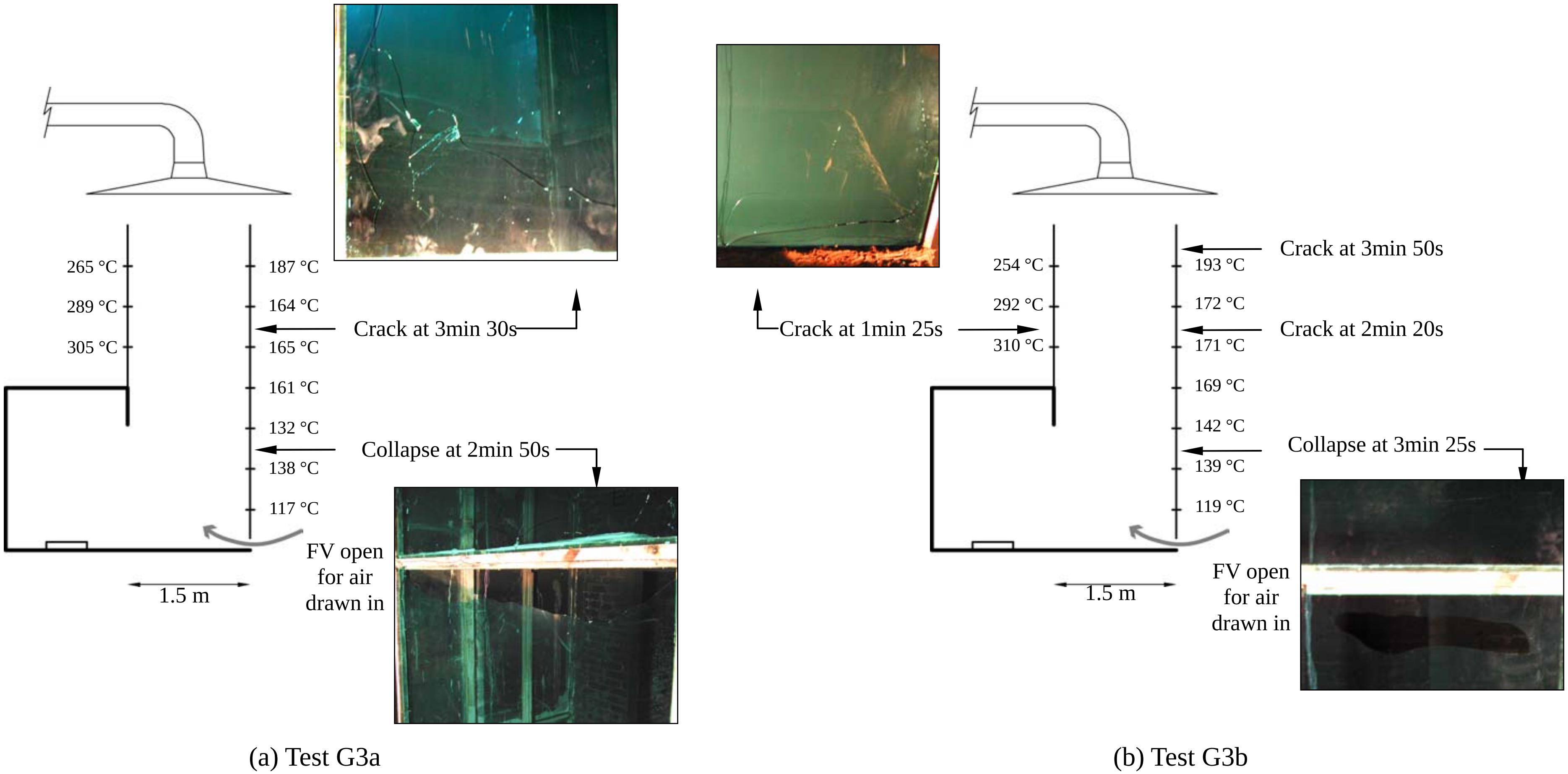


Figure 7-19: Maximum Temperature and Damages Recorded in Test G3

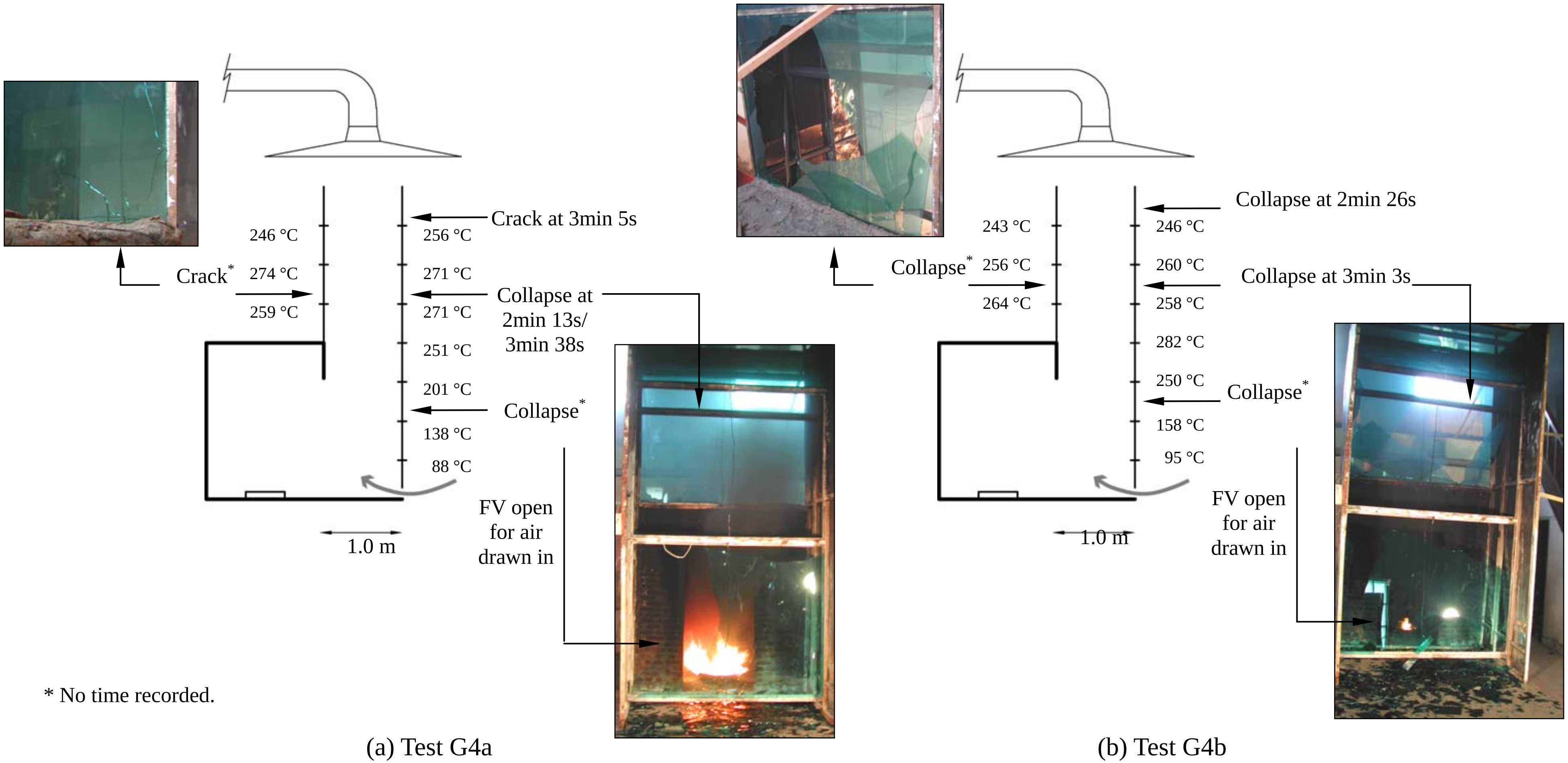
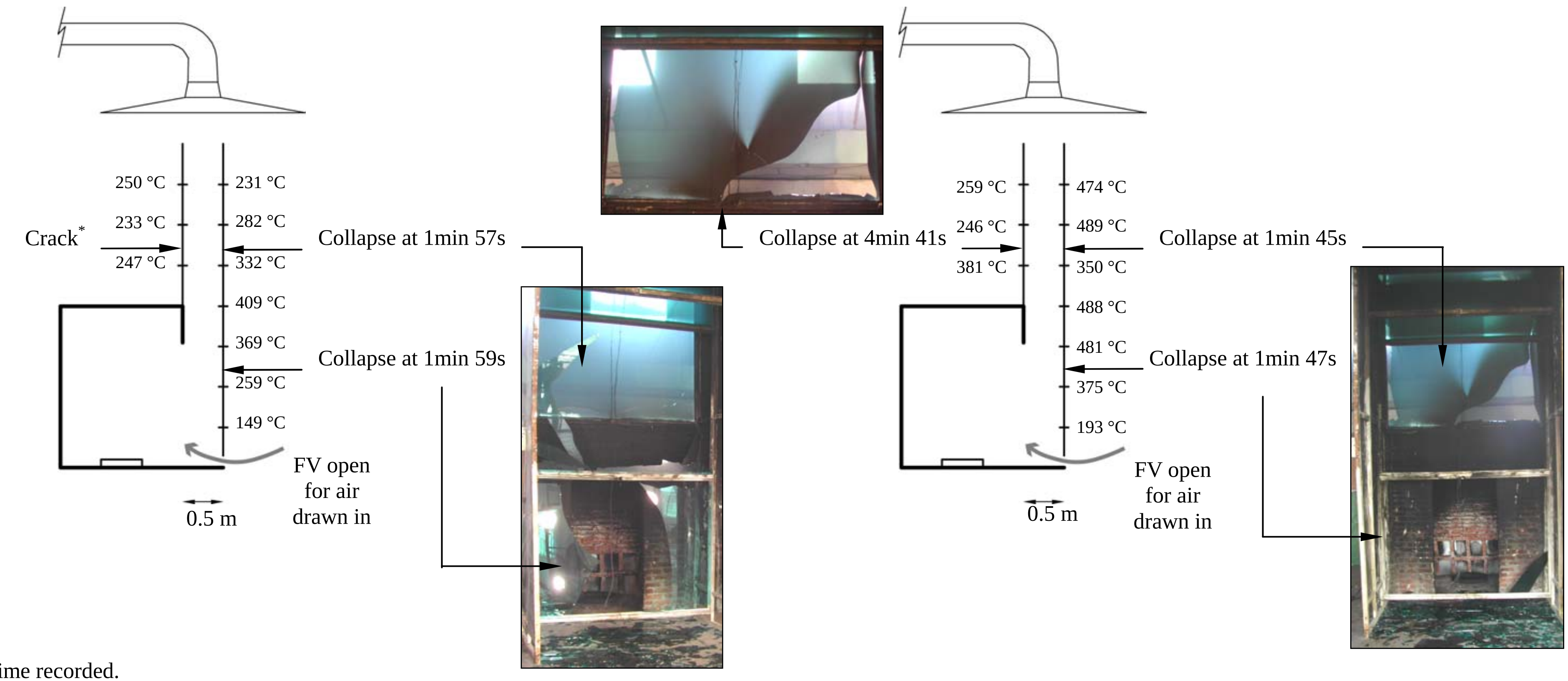


Figure 7-20: Maximum Temperature and Damages Recorded in Test G4



* No time recorded.

(a) Test G5a

(b) Test G5b

Figure 7-21: Maximum Temperature and Damages Recorded in Test G5

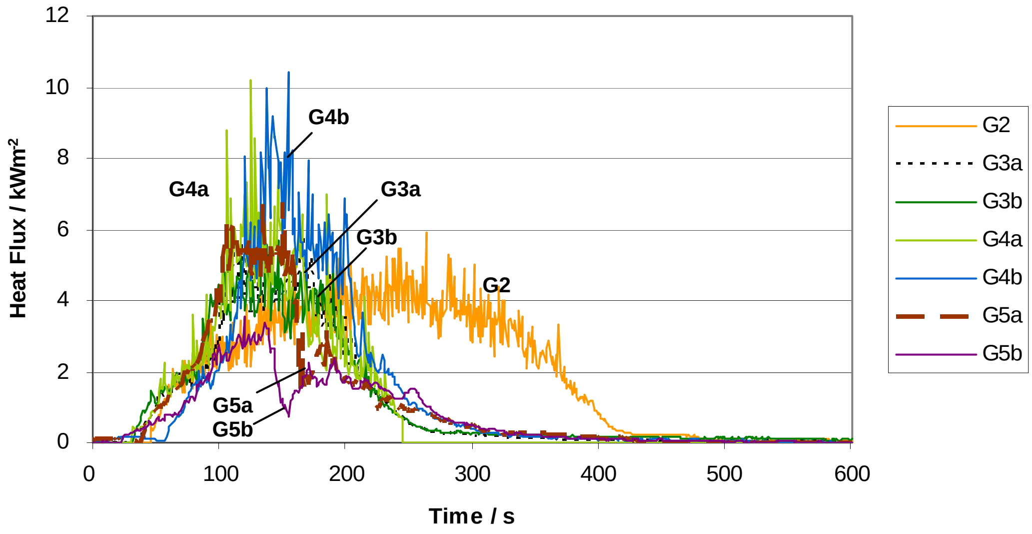


Figure 7-22: Incident Heat Flux Profile on TPO

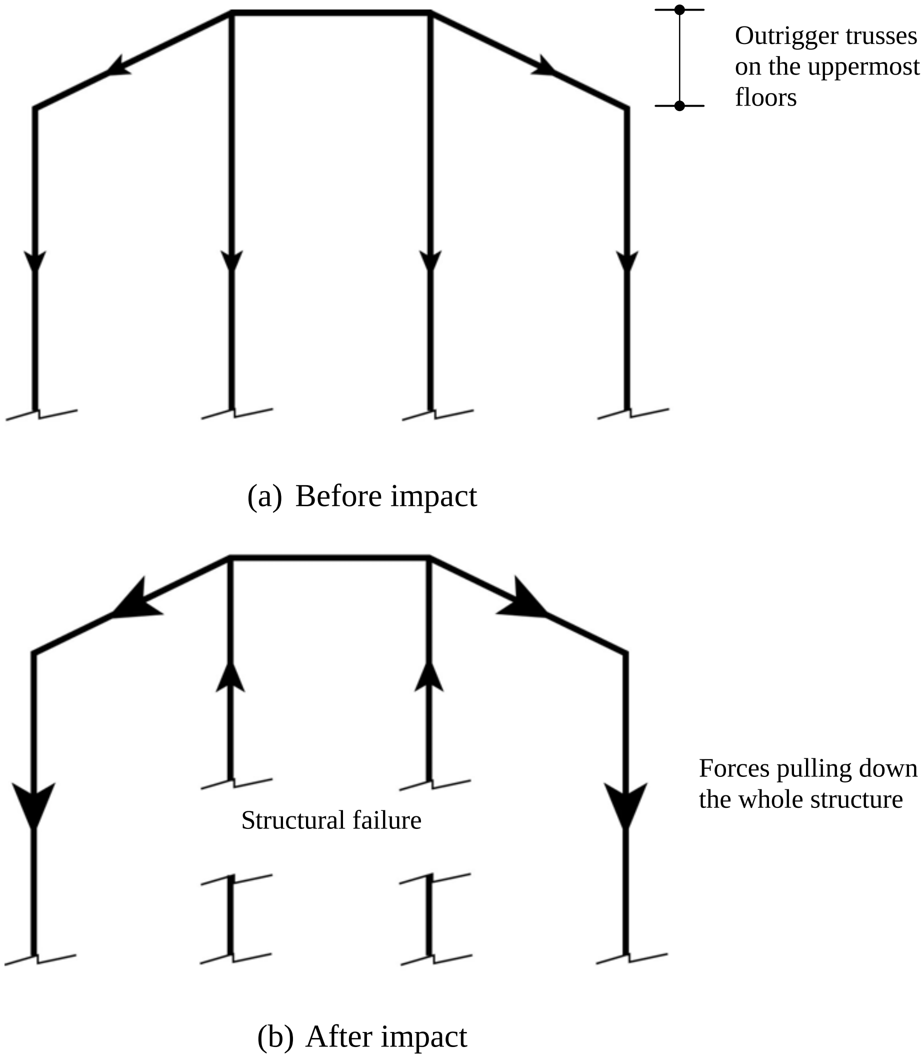


Figure 8-1: Scenario Guessed from the Consultancy Report (TVB 2003)

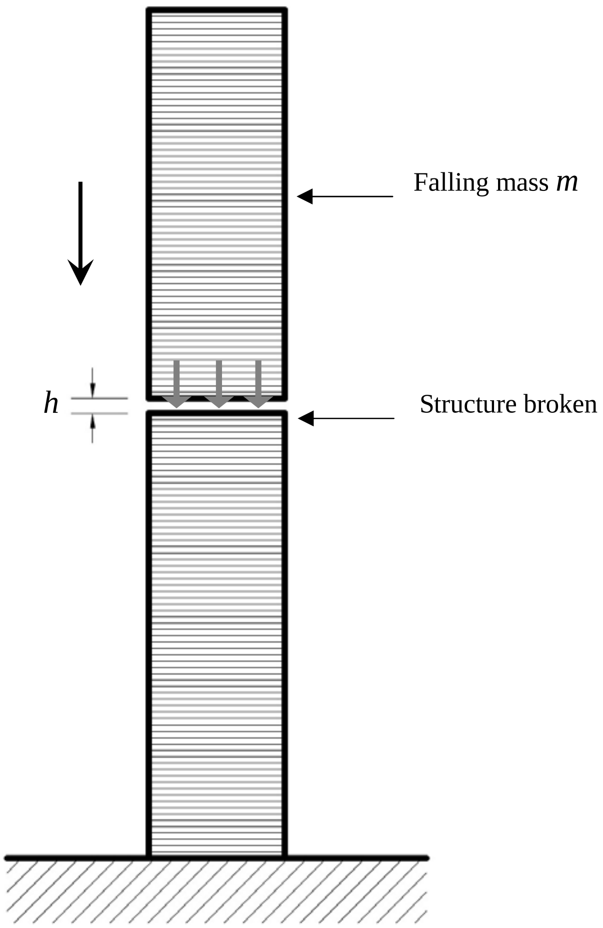


Figure 8-2: Diagrammatic Illustration Showing the Impact on the Lower Part of the Building

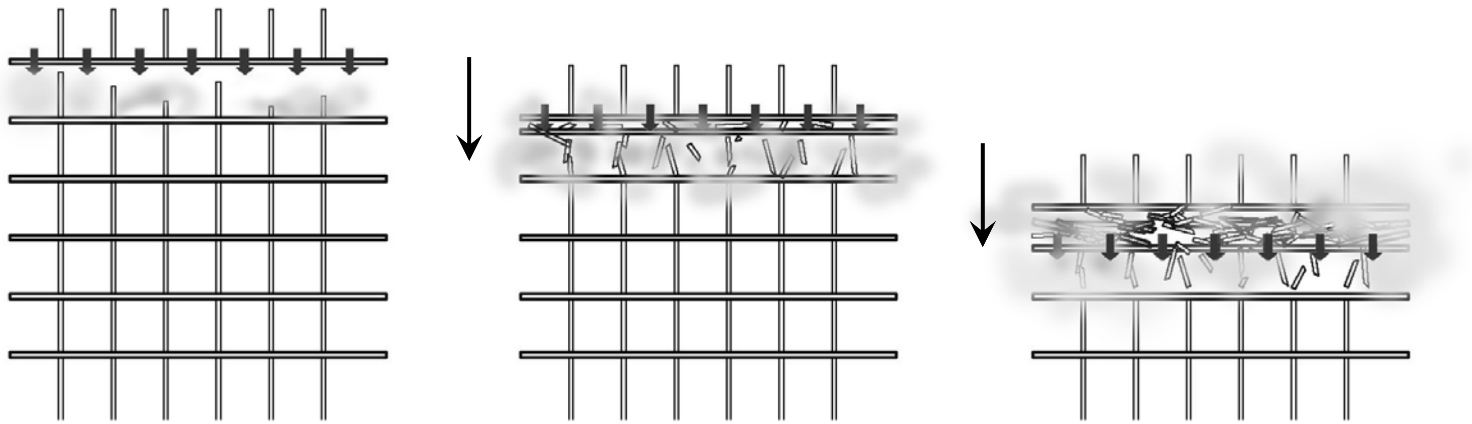


Figure 8-3: Progressive Collapse

Tilted

Figure 8-4: Building Tilted Sideway (Real News 24/7 2005)

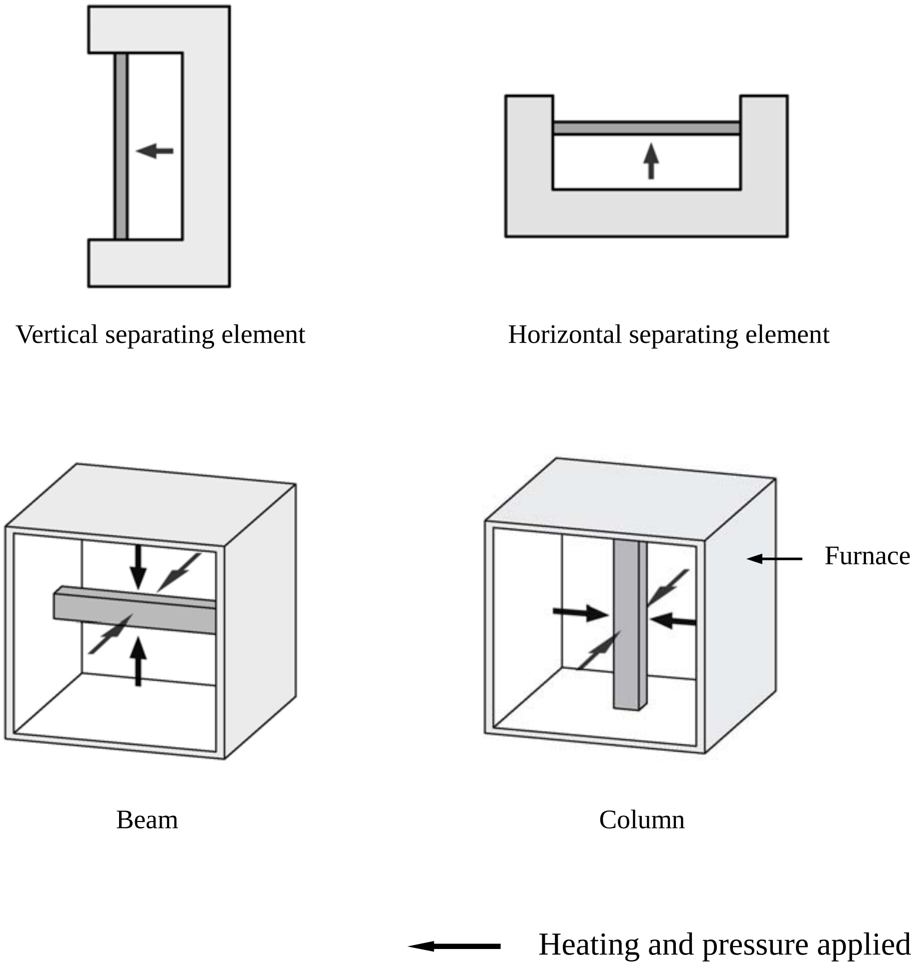
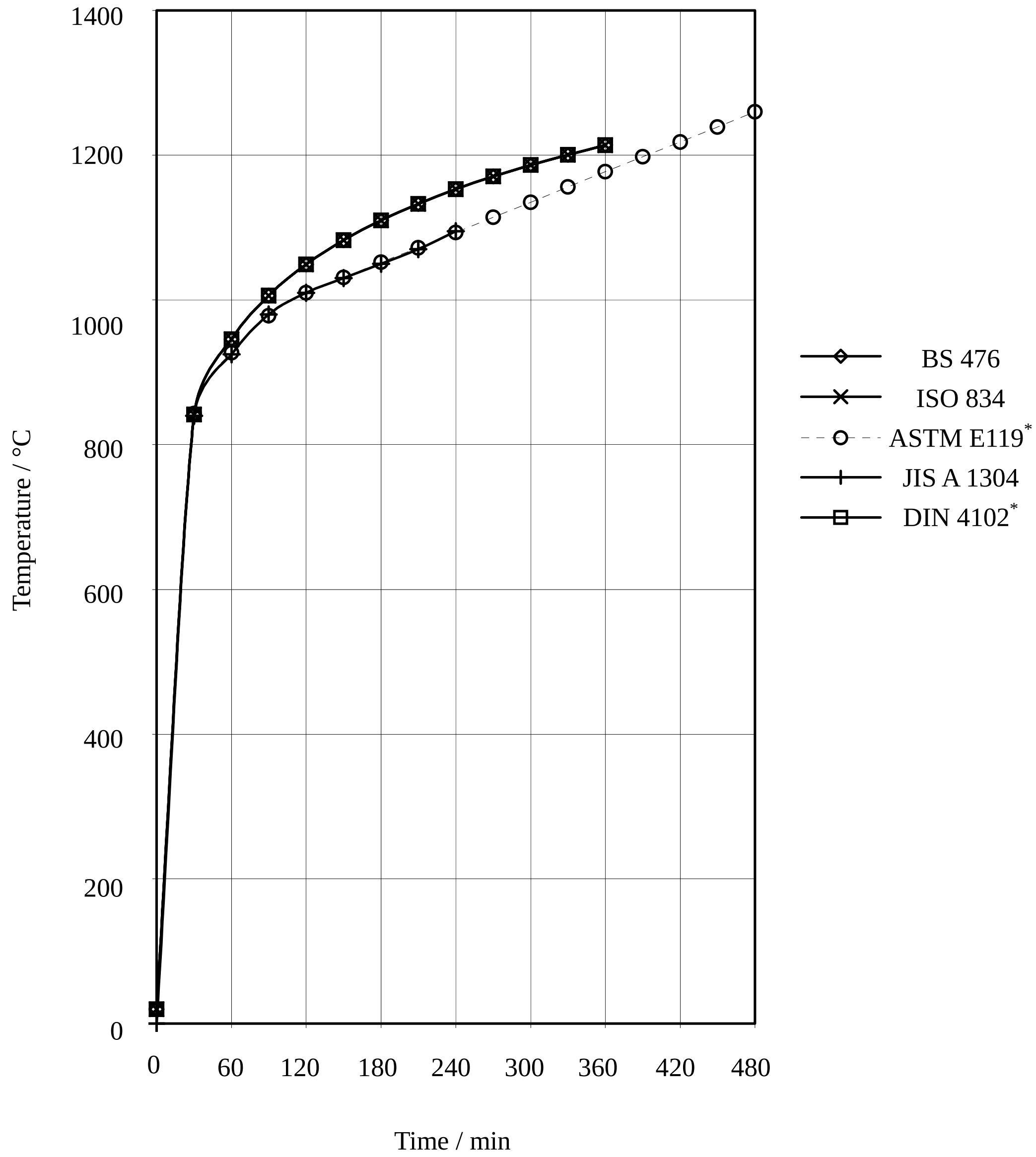


Figure 9-1: Heating and Pressure Applied on Test Specimen in BS 476



* Temperature above 20 °C base.

Figure 9-2: Comparison of Different Standard Temperature/Time Curves

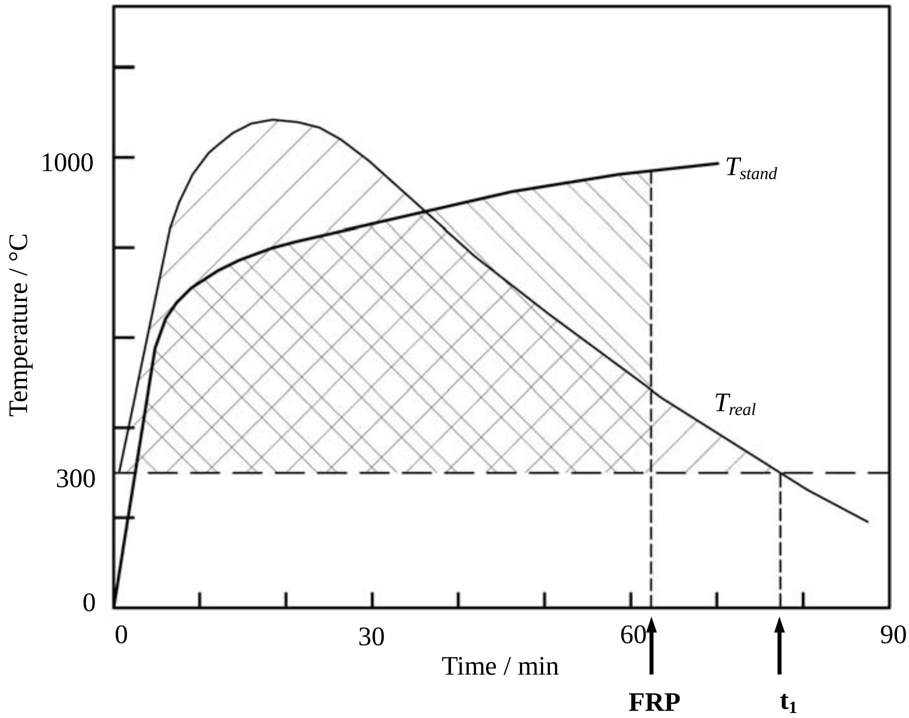


Figure 9-3: The Equal Area Hypothesis

Appendix A Benefits and Limitations of Using Glass

A.1 Benefits from Using Glass

Using glass as building material is beneficial in a number of aspects so that it is adored by the owners and architects. They are briefly discussed as follows:

- Architectural aspects

Among various building materials, glass possesses a characteristic of very high transparency. From the architectural point of view, it can deliver a sense of transparency and weightlessness (Button & Pye 1993) which address modernization and contemporary fashion in architecture.

- Environmental aspects

Higher degree of transparency of building enclosure can maximize natural lighting penetrating into the interior. Some buildings are using more than half of the unrenewable energy on artificial lighting in commercial premises, as shown in study by Fordham (2000). By introducing the solar illuminance into the built space, the lighting load on the perimeter of the floor could be reduced at daytime. For a deep plan, the illuminance at the centre of the floor might be relied on electric lighting, but it is also possible to have daylight tactically diffused into inner areas by using some devices, such as reflector installing at windows.

Openable windows can, on the other hand, introduce air flow which is beneficial to dwelling units since a large portion of electricity consumption is billed on thermal comfort (Fordham 2000). Hong Kong is located in subtropical region where humid and hot climate in summertime is usually unbearable, thus air-conditioning systems is to a large extent relied on. Other than lowering temperature of the occupied spaces, fresh air from the ambient would improve the indoor air quality.

Building green is a worldwide movement in the construction industry in the wake of global warning on greenhouse effect which significantly ruins our ecological system. The abuse of use of fossil fuel would be also harmful to all sorts of energy-dependent activities in the future. Decrease in the consumption of electricity is therefore one of the design considerations in the latest development. Employment of glass becomes one of the green building features under this movement.

- Psychological and physiological aspects

Not only contribute to the natural ecology, providing natural lighting in offices is believed also able to increase the office workers' productivity (Gratia & Herde 2003) to some extent. Attractive panorama can also be drawn through the large windows or curtain walls. The rental price of those offices with panoramic views would be much higher but they could still attract tenants from international corporations and business giants to set up their regional headquarters in the city. The price of residential flat units is also stimulated by provision of views and pleasant visual environment. Flat unit facing sea view would be 30 % higher than that facing hill side. Therefore, the financial district in Hong Kong is built next to the famed Victoria Harbor.

- Economic aspects

Large area of openings and fixed lights could rise up the investment return, by way of incorporating natural and built environment, reducing energy cost and offering better views, which is the primary consideration of the developers. The stunning exterior would be also an attraction beneficial to the rental price.

Though it has been one of the main materials for construction for decades, the trend is still going on because of its multiple contributions.

A.2 Limitations of Using Glass

The popularity of using glass is resulted from the aforesaid benefits in various aspects. However, accident occurred in ultra high-rise building finished with glass curtain wall evidenced that some risks are inherent in this building type. Strength resisting against wind action, seismic force and thermal stress have been studied throughout the world (Beason 1984; Behr 1998; Cuzzillo & Pagni 1998; Shields, Silcock & Flood 2001). The shortcomings related to the glazed wall should be understood in order to minimize undesirable outcomes.

- Radiative heat transfer

First of all, it is necessary to understand how glazed wall affects the interior spaces and thus cooing load. Glass is transparent to short-wave radiation whilst opague to radiation with long wavelength (Lechner 2001). Excessive solar radiation of short wavelength can, therefore, transmit into the building through glass window easily. It would be absorbed by objects inside the occupied spaces with longer waves re-radiated. Part of the radiation would be trapped in the internal space to give greenhouse effect. The inner temperature is thus increased and overheating would be likely resulted in summertime. Cooling load can be reduced by opening windows, otherwise temperature is getting increased if the windows are closed. On the other hand, if the air temperature in winter is higher in the occupied space than in the ambient, heat will move in a reverse direction. Inner air temperature would be decreased where in turn the desired heat is lost towards outside.

Warming up the indoor space by green house effect might reduce the heating load in cold countries. But heat loss would be increased in winter as the window area increased. The optimum window area should be designed by calculating the heat loss and gain terms carefully. In temperate countries, proper design could give warming effect; together with provision of natural daylight means double benefits. As a result, glasses are extensively used in cold climate areas. However, in subtropical region like Hong Kong, effect of overheating is so dominant that air-conditioning systems are largely relied on to preserve the application of full-height glass curtain wall. Usually, curtains are drawn to cut down the strong illumination and glare.

- Wind resistance

External glazed wall at a government building was fiercely damaged by a tropical cyclone of mean wind speed over 25 kmh^{-1} (HKO 2002) years ago (Lee & Wills 2002). It was found that the glass panels are weak in resisting tropical cyclones. Apart from wind action itself, the wind-borne debris generated by loose building components and breaking glass pieces would lead to further damages to the fully glazed towers. The wind-borne particles carried up by a strong wind action might be moved as bullets towards the glass. This should be taken into account when designing the required thickness or strength of the glass (Lee & Wills 2002; Saxe et al. 2002). The fractured pieces fell from the towers would probably cause injuries of pedestrians in the street; even worse human life might be claimed.

- Fire resistance

Fire resistance period (FRP) of glass is a concern. In the local code (BD 1996a), there are minimum thicknesses for some non-combustible materials, like concrete on a specified FRP. Usually, major construction elements in buildings like offices, shops and residence should have a FRP of 1 to 2 hours. For a fixed light on a wall having such FRP, it is only required to have ½ hour FRP. It is suspected that the larger the glass area on the wall, the lower the fire protection. In view of that, a number of investigations on the thermal response of glass panel have been carried out (e.g. Shields, Silcock & Flood 2002). Breakage of glass was probably found under certain conditions, say about 400 °C to cause fallout of a 6 mm clear float glass pane.

Appendix B Definitions of Terms in Codes and Standards

Accessible means of escape

- A continuous and unobstructed way of egress travel from any point in a building or facility that provides an accessible route to an area of refuge, a horizontal exit or a public way. (section 1002.1 chap. 10 of IBC, USA)
- A path of travel, usable by a person with a severe mobility impairment, that leads to a public way or an area of refuge. (3.3.121.1 of NFPA 101, USA)

Balcony approach

- A balcony which is used as an external approach to a common staircase and which serves two or more occupancies. (CoP MoE section 4, HK)

Direct distance

- The distance measured in straight lines along the notional path from any part of a room to the centre of an exit door of the room. (CoP MoE section 4, HK)
- The shortest distance from any point within the floor area, measured within the external enclosures of the building, to the nearest storey exit ignoring walls, partitions and fittings, other than the enclosing walls/partitions to protected stairways. (Appendix E of Approved Document B, UK)
- The shortest distance from any point within the floor area, measured within the external enclosure of the building, to the relevant exit ignoring walls, partitions and fittings other than the enclosing walls/partitions to protected

staircases. (3.01.4 of Code of Practice Means of Escape in Case of Fire, UK)

Exit access

- That portion of a means of egress system which leads from any occupied point in a building or structure to an exit. (section 1002.1 chap. 10 of IBC, USA)
- That portion of a means of egress that leads to an exit. (3.3.61of NFPA 101, USA)

Exit discharge

- That portion of a means of egress system between the termination of an exit and a public way. (section 1002.1 chap. 10 of IBC, USA)
- That portion of a means of egress between the termination of an exit and a public way. (3.3.63 of NFPA 101, USA)

Fire door

- A door or shutter, provided for the passage of persons, air or objects, which together with its frame and furniture as installed in a building, is intended (when closed) to resist the passage of fire and/or gaseous products of combustion, and is capable of meeting specified performance criteria to those ends. (It may have one or more leaves, and the term includes a cover or other form of protection to an opening in a fire-resisting wall or floor, or in a structure surrounding a protected shaft). (Appendix B of Approved Document B, UK)
- A door assembly which if tested under:

a) The conditions of test of door assemblies described in British Standard 476: Part 22; or

b) The conditions of test contained in the British Standard currently in force at the time of the bringing into use of the premises as a factory, office, shop or railway premises; or

c) The conditions of test in the British Standard currently in force at the time the door was manufactured;

would satisfy the criteria for integrity for 20 minutes or for such longer period as may be specified for particular circumstances. (Part II in Fire Precaution Act 1971 Guide to fire precautions in existing places of work that require a fire certificate, UK)

- The door component of a fire door assembly, which is any combination of a fire door, a frame, hardware, and other accessories that together provide a specific degree of fire protection to the opening. (1.4 of NFPA 80, USA and section 702.1 chap. 7 of IBC, USA)

Fire-protection rating

- The period of time that an opening protective assembly will maintain the ability to confine a fire as determined by tests prescribed in Section 714. Ratings are stated in hours or minutes. (section 702.1 chap. 7 of IBC, USA)
- The designation indicating the duration of the fire test exposure to which a fire door assembly or fire window assembly was exposed and for which it met all the acceptance criteria as determined in accordance with NFPA 252or NFPA 257. (3.3.159 of NFPA 101, USA)

Fire resistance period (FRP)

- The period of time for which any element of construction, wall, fixed light, door, fire shutter or other component of a building is capable of resisting the action of fire when tested in accordance with BS 476: Parts 20 to 24: 1987 as specified in tables A to F in the Code. (CoP FRC section 4, HK)
- The period of time from the exposure of a fire to the collapsing of the structure, or a leakage generated for the spread of fire and smoke, or the temperature of the opposite side rises up to 220 ^{o}C for any element of construction. (translated from the mainland HR code Appendix 1)

Fire-resistance rating

- The period of time a building element, component or assembly maintains the ability to confine a fire, continues to perform a given structural function, or both as determined by the tests, of the methods based on tests, prescribed in Section 703. (section 702.1 chap. 7 of IBC, USA)
- The time, in minutes or hours, that materials or assemblies have withstood a fire exposure as established in accordance with the test procedures of NFPA 251. (3.3.160 of NFPA 101, USA)

Fire resisting (or fire resistance)

- The ability of a component or construction of a building to satisfy for a stated period of time, some or all of the appropriate criteria specified in the relevant Part of BS 476. (Appendix E of Approved Document B, UK)
- The construction so designated, including doors, has a minimum standard of fire-resistance of not less than one-half hour in accordance with the relevant Schedules of the current Building By-laws or which achieves such

standard when tested in accordance with BS 476: Part 8: 1972 except that, in the case of door(s): (3.01.6 of Code of Practice Means of Escape in Case of Fire, UK)

a) the rebates to the door frame or the door stops whichever the case may be are not less than 25 mm deep, and; the door is hung on metal hinges having a melting point of not less than 800 ^{o}C, and

b) the door is rendered self-closing.

- That property of materials or their assemblies that prevents or retards the passage of excessive heat, hot gases, of flames under conditions of use. (section 702.1 chap. 7 of IBC, USA)

Fire-resisting construction

- The ability of a component of a building to satisfy some or all of the criteria specified in British Standard 476, Parts 21 to 24 of the conditions of test contained in British Standard 476 in force at the time of the construction or the bringing into use of the building as a factory, office, shop or railway premises, relating to load bearing capacity, integrity and, where appropriate, insulation, for not less than 30 minutes or for such longer period as may be required in the case of that construction. (Part II in Fire Precaution Act 1971 Guide to fire precautions in existing places of work that require a fire certificate, UK)

Fire wall

- A fire-resistance-rated wall having protected openings, which restricts the spread of fire and extends continuously from the foundation to or through the roof, with sufficient structural stability under fire conditions to allow collapse of construction on either side without collapse of the wall. (section 702.1 chap. 7 of IBC, USA)

Horizontal exit

- A path of egress travel from one building to an area in another building on approximately the same level, or a path of egress travel through or around a wall or partition to an area on approximately the same level in the same building, which affords safety from fire and smoke from the area of incidence and areas communicating therewith. (section 1002.1 chap. 10 of IBC, USA)
- A way of passage from one building to an area of refuge in another building on approximately the same level, or a way of passage through or around a fire barrier to an area of refuge on approximately the same level in the same building that affords safety from fire and smoke originating from the area of incidence and areas communicating therewith. (3.3.61.1 of NFPA 101, USA)

Means of egress

- A continuous and unobstructed path of vertical and horizontal egress travel from any point in a building or structure to a public way. A means of egress consists of three separate and distinct parts: the exit access, the exit, and the exit discharge. (section 1002.1 chap. 10 of IBC, USA)
- A continuous and unobstructed way of travel from any point in a building or structure to a public way consisting of three separate and distinct parts:

the exit access, the exit, and the exit discharge. (3.3.121 of NFPA 101, USA)

Means of escape

- Structural means whereby [in the event of fire] a safe route or routes is or are provided for persons to travel from any point in a building to a place of safety. (Appendix E of Approved Document B, UK)
- The structural means whereby a safe route is provided for persons to travel from any point in a building to a place of safety without outside assistance. (Part II in Fire Precaution Act 1971 Guide to fire precautions in existing places of work that require a fire certificate, UK)
- A way out of a building or structure that does not conform to the strict definition of means of egress but does provide an alternate way out. (3.3.122 of NFPA 101, USA)

Occupant capacity

- The occupant capacity is defined as follows: (0.38 of Approved Document B, UK)
  - a) Occupant capacity of a room of storey is the maximum number of persons it is designed to hold (where this is known) or: the number calculated (using the floor space factors given in Table 1 [of the Document] by dividing the area of room or storey (m^2) by the floor space per person (m^2).
  - b) Occupant capacity of a building or part of a building is the sum of the number of occupants of the stories in the building or part.

Occupant load

- The number of persons for which the means of egress of a building or portion thereof is designed. (section 1002.1 chap. 10 of IBC, USA)
- The total number of persons that might occupy a building or portion thereof at any one time. (3.3.136 of NFPA 101, USA)

Smoke stop door

- A door or pair of doors which when fitted in a frame satisfies the requirements of Section 7 of BS 476: Part 8: 1972 as to free from collapse for not less than 30 minutes and resistance to the passage of flame and hot gases for not less than 20 minutes, and which is fitted so that the clearance between the leaf and frame and in the case of double doors also between the two leaves, is as small as is reasonably practical, and except in the case of doors hung to open in both directions, is provided with a rebate to the door frame or with a door stop, which in either case is not less than 25 mm deep. (3.01.13 of Code of Practice Means of Escape in Case of Fire, UK)

Smokeproof enclosure

- An exit stairway designed and constructed so that the movement of the products of combustion produced by a fire occurring in any part of the building into the enclosure is limited. (section 902.1 chap. 9 of IBC, USA)
- A stair enclosure designed to limit the movement of products of combustion produced by a fire. (3.3.186 of NFPA 101, USA)

Travel distance

- The horizontal distance measured on the floor along the centre line of the exit route between the centre of an exit door from a room and
  - d) The centre of the fire-resisting door to the enclosure of any one staircase;
  - e) If there is no such door, the first stair tread of the staircase; or
  - f) If the exit route leads directly to a street of to an open area at ground level, any one of the points of discharge to the street or open area. (CoP MoE section 4, HK)
- (unless otherwise specified, e.g. as in the case of flats) The actual distance to be travelled by a person from any point within the floor area to the nearest storey exit, having regard to the layout of walls, partitions and fittings. (Appendix E of Approved Document B, UK)
- (called the Distance of travel) The actual distance that a person must travel between any point in a building and the nearest final exit; or door to a stairway which is a protected route; or a door for means of escape in a compartment wall. (Part II in Fire Precaution Act 1971 Guide to fire precautions in existing places of work that require a fire certificate, UK)
- The actual distance to be traveled by a person from any point within a floor area to the relevant exit having regard to the layout of walls, partitions and fittings. (3.01.15 of Code of Practice Means of Escape in Case of Fire, UK)
- The length of exit access travel, measured from the most remote point to the entrance to an exit along the natural and unobstructed path of egress travel. (section 1004.2.4 chap. 10 of IBC, USA)
- The distance measured on the floor or other walking surface along the

centerline of the natural path of travel, starting from the most remote point subject to occupancy, curving around any corners or obstructions with a 1-ft (0.3-m) clearance therefrom, and ending at the center of the doorway or other point at which the exit begins. (7.6.2 of NFPA 101, USA)

Appendix C Fire Safety Requirements in Mainland, UK and USA

C.1 Requirements in the Mainland China

The definition of high-rise building is clearly stated in the Codes (GB 50045-95 2001; Ma 1995) of China. High-rise buildings in Mainland China include those residential buildings having more than 10 stories and those public buildings with a floor level higher than 24 m above ground level. More specifically, they are further categorized into two types with respect to their usage, fire hazard class, means of escape and level of difficulty in firefighting and rescue (GB 50045-95 2001; Ma 1995).

Type 1 high-rise building includes:

- High-grade residences.
- Residential buildings having at least 19 stories.
- Hospitals, high-grade hotels.
- Commercial, exhibition, multiple-use, telecom, financial and business-living buildings exceeding 50 m.
- Commercial, exhibition, multiple-use, telecom and financial buildings with each floor area exceeding 1,000 m^2.
- Business-living buildings with each floor area exceeding 1,500 m^2.
- Central and province television broadcast buildings.
- Large-scale power dispatcher's buildings.

- Major province post office buildings and fire command control buildings.
- Big libraries (more than one million books).
- Important office buildings, laboratories and archive buildings.
- Institutional buildings, general hotels, ordinary office buildings, laboratories and archive buildings exceeding 50 m.

Type 2 high-rise building includes:

- Residential buildings having 10-18 stories.
- Commercial, exhibition, multiple-use, telecom, financial, business-living buildings and libraries other than Type 1 high-rise buildings.
- Post office buildings, fire command control buildings, television broadcast buildings and power dispatcher’s buildings other than Type 1 high-rise buildings.
- Institutional buildings, general hotels, ordinary office buildings, laboratories and archive buildings not exceeding 50 m.

C.1.1 Requirements on passive building construction

- Requirements for fire resisting construction

There are two grades of duration of fire resistance in the mainland code. Grade 1 fire resistance is for Type 1 high-rise buildings while Grade 2 fire resistance is for Type 2 high-rise buildings. Basement levels should also be constructed of

Grade 1 fire resistance. Fire resistance ratings are given to the elements of construction. For fire-resisting walls, non-loadbearing walls, walls enclosing escape routes and hanging roofs, the two grades require the same FRP. Other than those mentioned above, Grade 1 is more stringent than Grade 2, that means a longer fire resistance period is required. All these construction elements should be made of noncombustible materials, except Grade 2 hanging roof.

Underground staircases should be protected by an FRP of not less than 2 hours and can directly lead to outdoor area. Other stairway enclosures and lift well should have an FRP of at least 2 hours for both Grade 1 and Grade 2. More details on the fire resistance period for the elements of construction are listed in Table 3-1. Openings, other than fire doors and windows, are not accepted to construct in the staircase. Fire doors should have an FRP longer than 0.9 hour.

Fire compartments are determined by the floor area. The maximum compartment size is 1000 m^2 for Type 1 buildings; 1500 m^2 for Type 2 buildings and 500 m^2 for basements. For premises installed with an automatic sprinkler system, the above compartment size can be doubled.

Retail areas and exhibition areas in tall buildings with the use of non-combustibles or hard-combustible components can be enlarged to a maximum of 4000 m^2 for above ground spaces and 2000 m^2 for underground spaces if an automatic sprinkler system and an automatic fire alarm system are installed.

- Requirements for means of escape

High-rise buildings are required to have at least two escape exits or staircases. For all Type 1 buildings, Type 2 buildings exceeding 32 m above ground, tower type and unit type domestic buildings with more than 18 stories, and balcony-corridor type residential buildings exceeding 11 stories, protected lobbies should be of at least 6 m^2 and 4.5 m^2 in area for public buildings and residential buildings respectively; fire doors, smokeproof enclosures and natural vents or mechanical smoke extraction system are required.

The minimum width of exit doors and corridors are specified according to different uses of the buildings. A minimum of 1.3 m, 1.1 m and 1.2 m are required for exit doors in hospitals, residential buildings and other buildings respectively. Corridors should have 1.4 m, 1.2 m and 1.3 m in width correspondingly for single-sided rooms whilst they should be 1.5 m, 1.3 m and 1.4 m with rooms on both sides. The minimum widths of escape stairs are also specified for the three categories mentioned above. They are respectively 1.3 m, 1.1 m and 1.2 m. Escape routes for 100 persons should be at least 1 m wide.

The maximum travel distance is specified for different uses of the premises usage, which are classified into three categories, as shown in Table 3-5. For general buildings, the maximum travel distance is limited to 40 m, and that for institutional buildings, hotels and exhibition halls is 30 m and that for hospital wards is 24 m. The maximum travel distance in dead-end corridors should be half of those mentioned above.

- Requirements for means of access

For Type 1 buildings, tower type residential buildings, unit type or balcony-corridor type residential buildings with more than 11 stories, and Type 2 buildings higher than 32 m, all are required to have fireman's lifts. The required number of fireman's lift is based on the floor area of the largest story. Only one is required if the largest floor area is less than 1500 m^2; and three are expected for a floor area larger than 4500 m^2. Fireman's lifts can be shared with occupant lifts. It is recommended to locate the fireman's lifts in separate fire compartments. They should be constructed with smoke lobbies and their enclosure of FRP longer than 2 hours.

C.1.2 Requirements for fire services installations

Fire hydrants should be installed at each floor of all high-rise buildings. Automatic sprinkler systems are required for buildings having more than 100 floors and some of the Type 1 buildings, including rooms for public activities, offices, hotel bedrooms, corridors and crowded spaces etc.

Fire alarm systems are required in buildings exceeding 100 storeys, hospital wards, high-grade hotel rooms, commercial buildings, telecommunication buildings, libraries and many other premises including some Type 2 high-rise buildings.

Automatic cut-off devices should be provided for any mechanical ventilation system required for protected staircases, protected lobbies and rooms without natural ventilation.

High-rise buildings should be provided with emergency lighting in areas like all escape staircases, fireman’s lifts and their lobby, services rooms, dense-populated areas, escape routes in public buildings and corridors with more than 20 m in length in residential buildings and so on. The horizontal illuminance measured at floor level should be of at least 0.5 lux in intensity. All escape routes and exits should also be provided with exit signs.

C.2 Regulations in the United Kingdom

The building structure relating to fire safety in UK are governed by two main Acts of Parliament, the Building Act 1984 (HMSO 1984) and the Fire Precautions Act 1971 (HMSO 1989a). The former Act concerns about the requirements for structural fire precautions and means of escape while the latter imposes requirements for means of escape in case of fire and other fire safety measures and issues Fire Certificates to premises having met the fire requirements.

The Building Regulations 2000 (HMSO 2000) is made under the power of the Building Act 1984 and the majority of building projects are required to comply with them. There are not any technical details on the requirement. Approved

Document B: Fire Safety (ODPM 2004) is, therefore, produced to provide particular details compliant with the Building Regulations.

Other than Building Regulations, the Fire Precautions Act 1971 and the Fire Precautions (Workplace) Regulations 1997 as amended in 1999, would apply to certain premises, other than dwellings, simultaneously.

The Fire Precautions Act 1971 (HMSO 1989a), as amended by The Fire Safety and Safety of Places of Sport Act 1987 (HMSO 1987a) and the Health and Safety at Work etc Act 1974, only applies to specified premises in Order. Premises to be designated as hotel or boarding houses; factories; offices; shops and railway premises requiring a fire certificate are required to follow Fire Precautions Act 1971.

C.2.1 Approved Document B: Fire Safety

Approved Document B: Fire Safety ("the Document" hereafter) applies to England and Wales (ODPM 2004). The Approved Document is a practical guide compliant with the requirements of the Building Regulations. No definition of high-rise building is found in this Document. But as reviewed (Nash & Young 1978), high-rise buildings are defined as buildings having the height of 18.2 m and 30.5 m in Scotland, England, Wales Regulations and in GLC Regulations respectively. It is also discovered that 18 m is used as criteria frequently for most of the requirements in the Document. Purpose groups meaning different uses of the buildings are classified in Table D1 in the

Document (ODPM 2004). For some buildings where there may be two or more usages, it is recommended to treat each distinctive use as a purpose group.

Fire safety engineering is accepted as an alternative method to attain the equivalent safety for buildings which appear too complex to satisfy the prescriptive requirements in the Document.

Some requirements on passive building construction are different for flats and maisonettes and buildings other than dwellings.

- Requirements for means of escape for flats and maisonettes

Buildings which have a top floor higher than 11 m and have more than three stories above ground level require at least two staircases in order to evacuate occupants to a safe place when a fire breaks out inside any part of the building. Limitations on the travel distance from the dwelling entrance to the common stairs have also been made. Generally, the maximum travel distance should be no more than 30 m in buildings with at least two common escape routes. Common stairs, constructed with fire resisting enclosure, in flats and maisonettes should be at least 1.1 m wide if they are also used for firefighting purpose.

Higher fire risks are expected in basement. Therefore, separate staircases should be accessed to the ground level.

- Requirements for means of escape and means of access for buildings other than dwellings

All the components of an escape route should be protected by enclosure with specific fire resistance rating, in order to ensure a safe evacuation of occupants. Escape stairs at higher than 18 m should be connected to the protected lobby and corridor. Generally, 30 minutes fire resistance rating is enough for most cases. In addition, escape stairs serving buildings higher than 20 m should be protected by fire-resisting enclosure.

The number of escape routes and exits is determined by number of occupants and travel distance limitation. Every part in a story should normally have access to two or more stairs, as shown in Table 4 in the Document (ODPM 2004). Single escape route is acceptable when the occupant capacity is not more than 60. For composite buildings containing various purpose groups, the means of escape serving different purpose groups should be separated from each other. Buildings with floor level more than 11 m should have more than one escape stairs.

The width of escape routes and exits also depends on the number of occupants. As shown in Table 5 in the Document (ODPM 2004), 50 persons would require escape routes and exits of at least 750 mm wide. From Table 6 in the Document (ODPM 2004), the minimum width of escape stairs is specified. No escape stairs should be wider than 1400 mm if the vertical extent is more than 30 m, otherwise, additional stairs may be desired or a central handrail is needed. All escape routes should have at least 2 m high headroom.

The travel distance is restricted to different purpose groups with one or more than one exits. For instance, the travel distance in office buildings should not be longer than 45 m if there are more than two escape routes. Limitations on the travel distance are shown in Table 3 in the Document (ODPM 2004).

Normally, the lift could not be part of the escape route since there is a risk where people might be trapped inside. However, under some circumstances, it is appropriate to evacuate people with disability by means of the lift. Lifts should be enclosed by fire-resisting construction in general.

Firefighting shafts including firefighting lifts, firefighting stairs and firefighting lobbies have to be constructed in buildings with a story higher than 18 m above fire service vehicle access level or a basement deeper than 10 m below ground. Buildings higher than 7.5 m above fire service vehicle access level and having a story of at least 900 m^2 in floor area should also acquire a firefighting shaft excluding firefighting lifts. It is provided for fire brigade to access and rescue in the building. Buildings without sprinklers installed should provide at least one firefighting shaft for each 900 m^2 floor area on stories higher than 18 m.

- General requirements for fire resisting construction for both types

Fire resistance provides three distinctive ways to withstand fire damage, including loadbearing capacity, integrity and insulation. Details on the fire resistance period of structural elements as well as purpose groups are given in

Appendix A of the Document (ODPM 2004).

In general, structural elements within a building deserve 30 minutes fire resistance rating, such as floors, roofs, protected stairways, lobbies, corridors, lift shafts, service shafts, etc. For compartment walls separating different occupancies, 60 minutes standard is needed. From the standpoint of purpose groups, buildings of most of the groups higher than 18 m require at least 60 minutes as specified. Only office buildings with sprinklers provided can have the fire resistance rating reduced to 30 minutes. On the other hand, industrial and storage buildings without sprinkler system have to increase the standard up to 90 minutes.

In addition to construction with fire resistance rating, the interior of building should be divided into smaller compartments so as to confine the spread of fire and smoke in case of fire. Compartment walls and compartment floors, as defined in the Document (ODPM 2004), should be fire-resistant, and should form a complete barrier to fire between the compartments. For all purpose groups, a wall shared by two or more buildings should be a compartment wall running the full height of the building.

Limitations on compartment area and compartment volume for non-residential buildings are clearly shown in Table 12 of the Document (ODPM 2004). The maximum floor area of the compartment decreases with the floor height above ground but can be enlarged by the installation of an automatic sprinkler system compliant with the recommendations of British Standards BS 5306: Part 2. The maximum allowed compartment floor area (or volume) can be doubled provided that the building is fitted throughout with an automatic sprinkler system. For office buildings, no limitation is enforced on the compartment area while the maximum area for sprinklered and non-sprinklered assemblies, recreation buildings, shops and commercial buildings are 4000 m^2 and 2000 m^2 respectively.

Stairway or any other shafts which pass through more than one compartments should be enclosed in a protected shaft so that the spread of fire from one compartment to another could be delayed.

Fire spread has to be limited not only between compartments, but also between buildings. As a result, the external wall of buildings is required to be constructed of materials of limited combustibility. Where any building is higher than 18 m, or the boundary distance is less than 1 m, the external wall should be constructed in a more stringent way than the reverse case.

- Requirements for fire services installations

Fire mains used for supplying water to hoses are classified as ‘dry’ type and ‘wet’ type. For buildings higher than 60 m above ground, a wet rising mains has to be installed in the building at 60 m level or above, otherwise, both types are appropriate.

Basements tend to be more dangerous than the upper story in case of fire, as smoke and heat would escape through the stairways. It is, therefore, required to discharge the smoke and heat from the basement via the smoke outlets which should be located on the perimeter of the building. The natural smoke outlets should be of at least 2.5 % of the floor area they serve. Mechanical smoke extraction system, as an alternative to the natural one, should provide an extraction rate of at least 10 air changes per hour.

It is necessary to install artificial lighting at the escape routes. Locations in different purpose groups requiring escape lighting are denoted in Table 9 of the Document (ODPM 2004). In addition, every exit to the means of escape should be clearly marked by an exit sign complying with the requirement in BS 5499: Part 1.

In this Document, no specifications are found on sprinkler system. The British Standards BS 5306: Part 2 Fire extinguishing installations and equipment on premises, Specification for sprinkler systems is referred to.

C.2.2 Fire Precautions Act 1971

In the Fire Precautions Act 1971, there is no definition made on high-rise buildings. All the requirements are specified for the four kinds of premises, including factories, offices, shops and railway premises (HMSO 1989a). The Fire Precautions (Factories, Offices, Shops and Railway Premises) Order 1989 (HMSO 1989b) was made under the Fire Precautions Act 1971. Requirements were stated on a guidebook (HMSO 1989a) in which passive building construction and active fire engineering systems are included.

- Requirements for fire resisting construction

Fire resistance period is determinant for fire safety control. The minimum requirement is defined for different construction elements. Most of the elements, including stair enclosure, lift well, escape route enclosure, require a minimum FRP of 30 minutes. Compartment enclosures in offices and shops premises require 30 minutes while those in factories require 60 minutes. Floors should have an FRP of at least 30 minutes. All these above should be in compliance with all major structural elements having not less than 60 minutes fire resistance rate. In order to achieve the most effective fire resistance, all the service ductwork, pipework openings, etc. should be fire-stopped, or fire dampers are required in ventilation ductwork in large-scale buildings. No requirements are stated on compartmentation size in the instrument.

- Requirements for means of escape

Generally, there should be at least two stairways in a building. Only low-rise buildings can be permitted to have single stairway. The minimum width of the staircase should be 750 mm. Staircase, being a component of the means of escape, should be separated from other parts of the building by fire-resisting construction and a self-closing fire door. In high-rise buildings, such as factory buildings higher than 18 m above ground level, and offices or shops premises higher than 24 m above ground level, staircases have to be separated by protected lobbies;

and so should be the buildings with single stair. More than one staircase should be provided if the travel distance at any point in a basement is longer than the requirement. And normally, staircases from upper floors should not extend continuously into the basement, they should be separated from the ground floor by fire doors.

Fire resistance rating is also required in corridors when the corridor exceeds the travel distance of a dead end and extends to alternative routes, the corridor and junction should be protected by fire-resisting construction. The main corridor should not be less than 1.05 m wide. Moreover, for corridors longer than 30 m in shops or 45 m in factory or office buildings, they should be sub-divided by fire doors.

For the rooms in designated buildings, more than one exits should be provided if the room contains more than 60 persons; or if the travel distance to exit exceeds the requirement; or if it is specified as a high fire risk area. The minimum width of such an exit is 750 mm. For an occupant load at 101 to 200 persons, the total width of all exits should be 1.05 m. And then every additional 15 persons require 75 mm more in breadth. The arrangement of the exits in a room is determined by the travel distance and "45-degree" requirement. Routes from any point in a room to the exits should produce an angle greater than 45°.

Travel distance is a pivotal measurement in the means of escape requirements. It affects the number of escape routes and staircases and the dead end length. The maximum travel distance is specified for distinctive fire risk levels in factories, shops and offices and is divergent for one escape direction only and more than one directions. References can be made to the office's requirement on the travel distance of railway premises. For the fire risk category, factory premises are classified into high, normal and low, shop premises are classified into high and normal, and office premises are considered as normal only. Any dead end existing in the premises should not exceed the total travel distance as specified for one direction only. Details of the limitations are stated in Table 2.

Escalator and elevator are generally not accounted as a means of escape. They should be separated by fire-resisting construction or fire doors from other portions of the building. Elevators can be considered as a means of escape when they are designated for physically impaired persons. At the top of the lift well, an openable vent of not less than 0.1 m^2 in area should be given for ventilation. Other openings in the lift well are prohibited.

- Requirements on fire services installations

Fire alarm, either manually or automatically operated, should be installed in all premises. Fire alarm or call points should be installed in accordance with the recommendations of the British Standard.

All the unclear exits should be marked by a "Fire exit" sign. All the escape routes should be illuminated by normal lighting. Escape lighting, capable of lasting for at least 2 hours, should be provided at underground or windowless locations.

C.3 Requirements in the United States

To govern fire safety in high-rise buildings, there are National Fire Protection Association (NFPA) 101 Life Safety Code (NFPA 2000a) (the latest edition is 2003 ed.) and model building codes. International Code Council (ICC) International Building Code (IBC) 2000 (ICC 2000) has been consolidated from the National Building Code (NBC) 1996, Uniform Building Code (UBC) 1997 and Standard Building Codes (SBC) 1997 and used to replace them.

C.3.1 ICC International Building Code 2000

International Building Code covers a wide variety of building aspects, including the provisions of fire safety in terms of fire-resistance-rated construction, fire protection systems and means of egress (ICC 2000). Definition of high-rise building is found in the code where buildings having occupied floor located higher than 22.9 m above the lowest level of fire department vehicle access are deemed to be high-rise buildings.

- Requirements for fire resisting construction

In the International Building Code, there are five types of constriction, namely Type I to V, based on which fire-resistance rating requirements for major building elements are stipulated. Building elements of Type I and II are of noncombustible materials, whilst the interior building elements of Type III can be constructed of any materials permitted by the code. Type IV construction is heavy timber construction in which interior building elements are constructed of wood. For the Type V construction, any material permitted in the code can be used on every structural element, external and internal walls.

General ratings of fire-resistance in the code are 1, 1.5, 2 and 3 hours. The ratings are stipulated according to the type of construction. Type I deserves the highest rating while Type V has the lowest. The fire-resistance rating of exterior nonbearing wall is dependent on the fire separation distance, type of construction and also occupancy group. Fire wall, which restricts the spread of fire and extends from the foundation through the roof, should have higher ratings to achieve complete separation. The ratings are of 4 hours, 3 hours and 2 hours for different occupancy groups as specified I the code. Fire partitions, restricting fire spread, and smoke barrier, limiting smoke movement, should have 1-hour fire-resistance rating in general. Fire resistance rating of fire barrier, including vertical or horizontal assemble, is determined by the location of application, such as vertical exit enclosure, exit passageway, horizontal exit and so on. Requirement of fire protection ratings of fire doors, glazing materials and other opening protectives are also specified in the code.

- Requirements for means of escape

As defined in the code, means of egress consists of three separate elements, namely the exit access, the exit and the exit discharge. Exit access is the portion of means of egress system that leads to an exit from any occupied space; exit discharge is the portion between the termination of an exit and a public way; and exit is the part between the two portions as mentioned.

The fire resistance rating of corridor is prescribed according to different occupancies with or without an automatic sprinkler system. Generally, the fire resistance rating is 1-hour for most of them. Apart from protected by fire-resisting construction, corridors should not be part of the air ducts for supply, return, exhaust and so on.

For the high-rise buildings, a smokeproof enclosure or pressurized stairway should be provided. Either of them should be provided with 2-hour fire resistance rating.

Horizontal exits connected to separate building parts and refuge areas should have an FRP of not less than 2 hours and fire doors should be constructed on it with self-closing or auto-closing devices which can be actuated by smoke detectors.

In general, the requirements of means of egress are determined by the occupants served. The egress width has been specified for each occupant served. The egress width for different occupancies with or without a sprinkler system is listed in the code. For premises without sprinklers, every occupant has to occupy wider space. The total required width is determined by the total occupant load served by the means of egress multiplied by the width per occupant as specified.

The minimum width of doors should be 813 mm and that of stairways and corridors should be 1.1 m. But for an occupant load of less than 50, staircases of 914 mm wide can be accepted. The clear height of them should not be less than 2.03 m. The depth of landing measured in the traveling direction should be identical to the width of the staircases.

The number of required exits for each floor area is based on the occupant load specified and the limitation of travel distance. Generally, at least two exits should be provided. They should be so arranged such that the distance between them is not less than half of the maximum diagonal dimension of the building or not less than one-third of that if the building is sprinklered.

The maximum travel distance is exhaustively listed in Table 1004.2.4 of the Code. It is divergent for buildings with or without a sprinkler system. Details are referred to in Table 3-5. Dead end corridors should not be longer than 6.1 m.

Elevators can only be used as an accessible means of egress, from which an accessible route travels to an area of refuge, a horizontal exit or a public way, rather than a component of the means of escape.

- Requirements for fire services installations

Automatic sprinkler system should be equipped throughout the high-rise buildings. An approved fire alarm system should be also provided.

The means of egress should be illuminated by at least 11 lux at the floor level. If the normal power fails, an emergency power system should be ready for operation for at least 1.5 hours.

At all exits and exit access doors, exit signs should be provided with at least 54 lux illuminance. They should be placed at no more than 30.5 m from any point in an exit access corridor.

C.3.2 NFPA 101 Life Safety Code 2000 Edition

NFPA 101 Life Safety Code, published by the National Fire Protection Association, is an American Standard for fire safety with 2003 edition the latest edition.   In the 2000 edition (NFPA 2000a), it has adopted a performance-based life safety design other than the traditional prescriptive-based option. There, different building uses are classified as different occupancies. The requirements are further specified for new and existing buildings.

In this code, a high-rise building is defined as a building having a height of more than 23 m measured from the access level for fire appliances to the floor of the highest story.   General requirements are provided for all types of occupancies.

- Requirements for fire resisting construction

Every component of the means of egress should be constructed with certain fire resistance rating. For a space having an occupant load of more than 30, the connected corridor should have walls of FRP longer than 1 hour separating from other parts of the building.

A smokeproof enclosure should be permitted to protect the escape stair with a fire resistance rating of 2 hours.

Fire compartments are constructed by fire barriers, which provide separation and protection to the building structure. There are three classes of FRP, including:

- 2-hr fire resistance rating
- 1-hr fire resistance rating
- 0.5-hr fire resistance rating

Openings, such as fire doors and windows, should be provided for opening protection with specified fire resistance rating. For fire doors, they should comply with NFPA 80 and NFPA 252 and be self-closing. Fire window assemblies should comply with NFPA 80 and NFPA 257. The area of them could not be larger than 25% of the area of the fire barrier. Specifications of opening protective to fire barrier are as follows:

- 2-hr fire barrier requires 1.5-hr opening protection
- 1-hr fire barrier requires 1-hr / 0.75-hr opening protection
- 0.5-hr fire barrier requires 20-minute opening protection

Compartmentation size is diversified in accordance with the different occupancies. For instance, the maximum compartment area of educational occupancies is 2800 m^2 and the maximum length of the building is 91 m. But for some of the occupancies, such as business and mercantile occupancies, there is no special requirement on compartment size.

- Requirements for means of escape

The capacity of means of egress depends on the occupant load, which is achieved by dividing the floor area by the occupant load factor specified in the code. The minimum width of the means of egress should be 91 cm and 71 cm for the new and existing buildings respectively.

However, for door openings in the means of egress, the minimum clear width is 81 cm. And for stairs in the means of egress, 91 cm is only applied where the occupant load is smaller than 50, otherwise, the minimum clear width for stairs should be 112 cm wide.

The headroom of means of egress should have a minimum of 2.3 m and also be not less than two-thirds of the ceiling area of any space.

The number of means of egress is specified as not less than two. For an occupant load between 501 to 1000, three should be provided while at least four should be provided for an occupant load more than 1000.

Where there are two exits or exit doors, they should retain a distance from each other of not less than half the diagonal length of the building.

Travel distance is provided in accordance with different occupancies. New business occupancies, for instance, should have a travel distance to exit of not longer than 60 m.

Elevators are generally not permitted to act as a component of the means of egress, however, it is acceptable, in some circumstances, to be an accessible means of egress for people with disability. Every elevator should have a capacity not less than eight persons. Any elevator travelling a distance more than 7.6 m should serve as a firefighting lift as well. The elevator lobby should be protected by a 1-hr fire resistance rated door.

For people with difficulties in mobility, an area of refuge should be provided at a size large enough for one wheel chair (76 cm x 122 cm) for every 200 occupants and at least 91 cm wide. It should be protected by 1-hr fire resistance rated enclosure.

- Requirements for fire services installations

A fire alarm system is required to install within buildings in order to signal an outbreak of fire. The manual fire alarm boxes should be located at anywhere no more than 60 m apart from people at any part within one story. It is not mandatory to actuate alarms by the sprinkler system.

The automatic sprinkler system should meet the requirements of NFPA 13 Standard of the Installation of Sprinkler System. They should be inspected, tested and maintained according to NFPA 25.

In respect to lighting, a minimum of 10 lux lighting level should be provided at the floor surfaces within a means of egress. Emergency lighting, as a backup power, should be provided for a 1.5-hr period if normal lighting has been failed. It should provide an initial illuminance at an average of 10 lux and 1 lux for minimum. Tests on its performance should be carried out regularly.

Exits should be marked clearly by an exit sign compliant with the requirements. The exit sign is recommended to be placed within 30 m from any point of the exit access corridor.

- Additional requirements for high-rise buildings

Some additional fire services installations are recommended to install in high-rise buildings:

- a fire alarm system;
- an approved automatic sprinkler system with a sprinkler control valve and waterflow device provided on every floor;
- a central control station containing control panels; and
- emergency lighting and standby power.

Appendix D Consumption of Oxygen by Gas Appliances

Burning 1 kg of oxygen would give 13 MJ of heat (Babrauskas & Grayson 1992). For a gas water heater of power rating Q (in kW), the mass flow rate M_{ox} (kgs^{-1}) of oxygen required is:

$$M_{ox} = \frac{Q \text{ x } 10^3}{13 \text{ x } 10^6} = \frac{Q}{13} \text{ x } 10^{-3} \qquad \text{...(D-1)}$$

Since 1 mole of oxygen comes with about 3.76 of nitrogen, in 4.76 moles of air. Therefore, 1 kg of oxygen means x kg of air:

$$\frac{\frac{1}{32}}{1} = \frac{\frac{x}{29}}{4.76}$$

$$\therefore \quad x = 4.3 \text{ kg} \qquad \text{...(D-2)}$$

Mass flow rate of air required is:

$$M_{air} = \frac{Q}{13} \text{ x } 10^{-3} \text{ x } 4.3 \qquad \text{...(D-3)}$$

For a window with opening area A_v (in m^2), average air speed perpendicular to the window V (in ms^{-1}), M_{air} is:

$$M_{air} = \rho V A_v \qquad \text{...(D-4)}$$

where ρ is the air density (about 1 kgm^{-3}).

Combining equation (B-3) and (B-4) gives a relationship between Q, V and A_v:

$$\rho V A_v = \frac{Q}{13} \times 10^{-3} \times 4.3 \qquad \ldots\text{(D-5)}$$

A plot of V against typical values of A_v for common power of gas water heater from 1 to 6 kW is shown in Figure D-1.

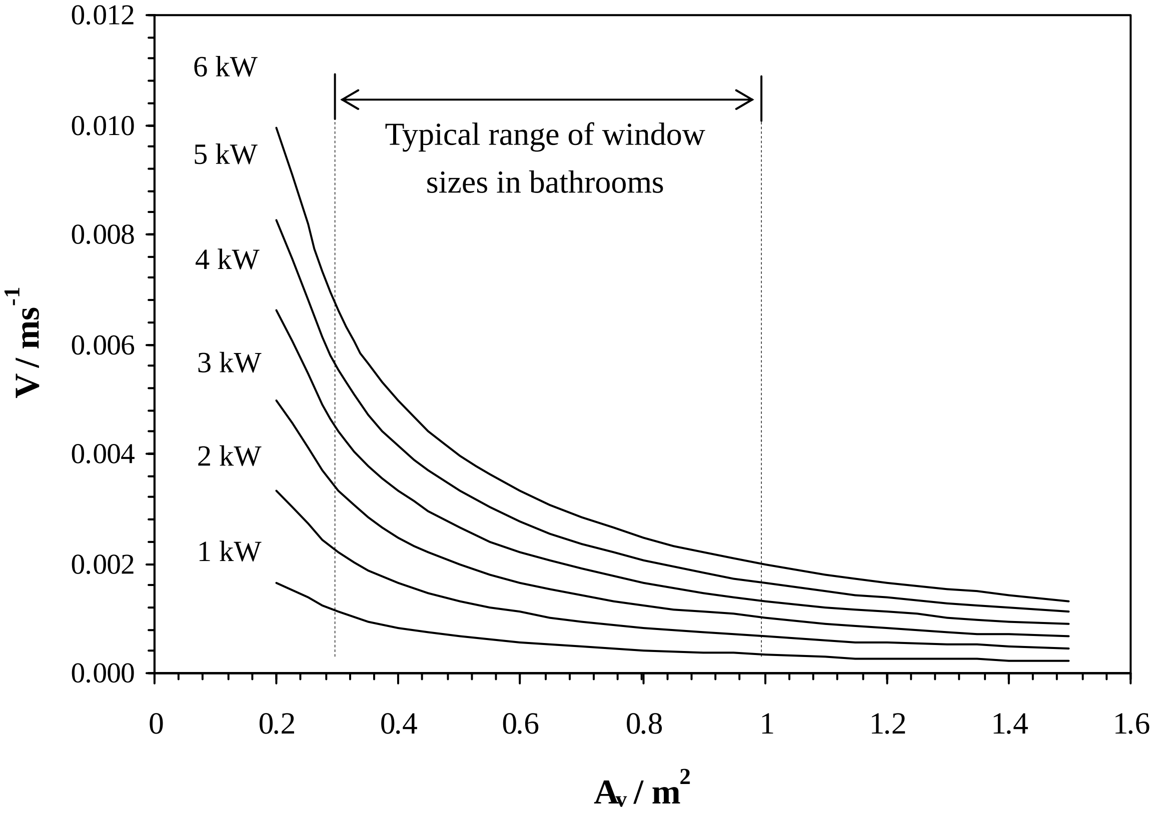


Figure D-1: Air Speed Requirement of Windows

Appendix E Numerical Experiments on Smoke Spreading in Internal Building Void

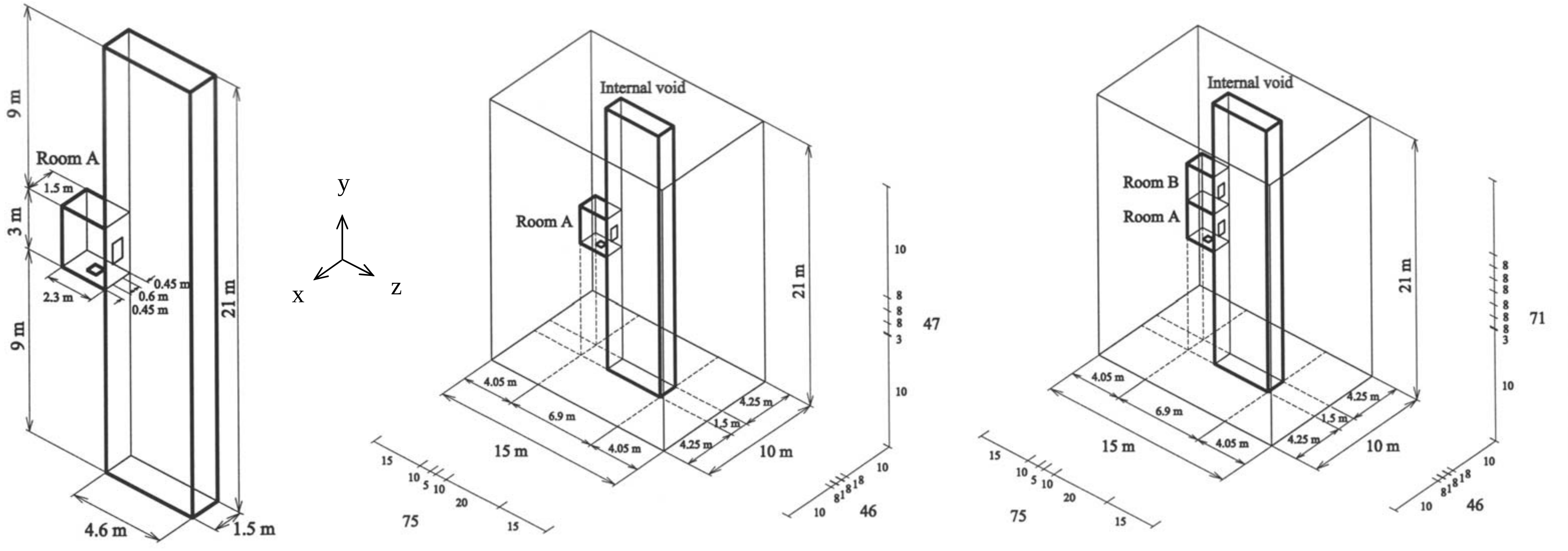
Simulations using computational fluid dynamics (CFD) (Chow 2001c) was carried out to study the smoke spreading phenomenon in the building Y with internal building void. A bathroom (room A) of dimensions 2.3 long, 1.5 m wide and 3 m high with a window of width 0.6 m and height 1 m located 1 m above the floor is taken as the fire room. In order to simplify the simulation, only part of the building Y is considered, as shown in Figure E-1a. An internal void of 21 m high running through the building height is considered. Room A is located on the third level, i.e. 9 m above ground as indicated in the figure. The room right above room A is also considered, as indicated in Figure E-1c. A fire size of 300 kW, which is smaller than minimum size for flashover, is used in the CFD simulator PHOENICS (PHOENICS 2000). Five scenarios considered are listed as follows:

- Scenario 1: Fire room at the 3rd level, all other windows closed.
- Scenario 2: Another room, room B, at an upper level above the fire room with window open.
- Scenario 3: The door of room B open to free space.
- Scenario 4: There is a pressure difference of -50 Pa at the door of room B, due to wind effect or mechanical ventilation and air-conditioning (MVAC) systems.

- Scenario 5: There is a pressure difference of -5 Pa at the door of room B.

In the simulation, the example building is divided into 162,150 parts (75 parts by 47 parts by 46 parts along the x-, y- and z-directions) as in Figure E-1b, for scenario 1 while it is divided into 244,950 parts (75, 71 and 46 along x-, y- and z-directions respectively) for scenarios 2 to 5, as illustrated in Figure E-1c. The y-direction is taken as opposite to the acceleration due to gravity.

The results of simulations are clearly shown from Figure E-2 though Figure E-6 with velocity vectors, temperature and differential pressure contours indicated.

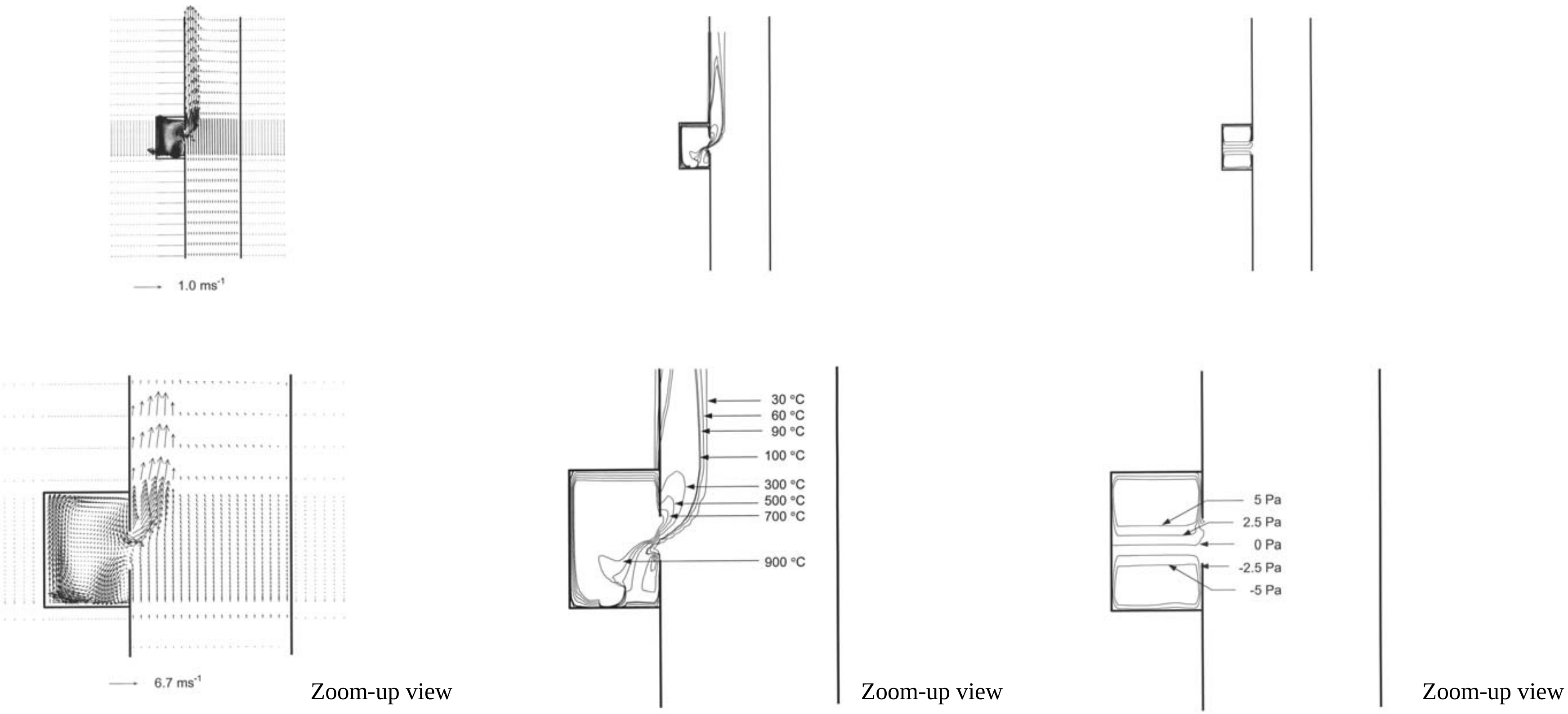


(a) Dimension

(b) CFD geometry for scenario 1

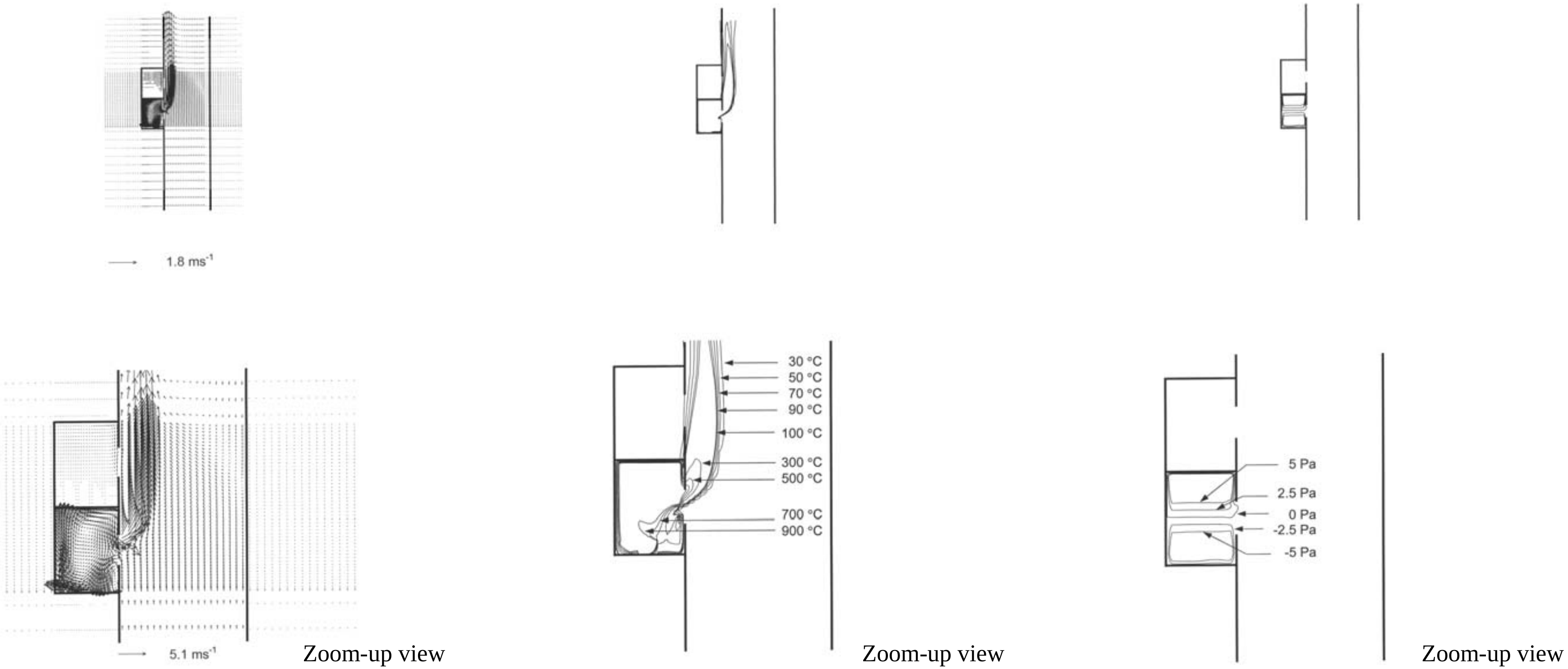
(c) CFD geometry for scenario 2 to 5

Figure E-1: Part of the Example Building Y



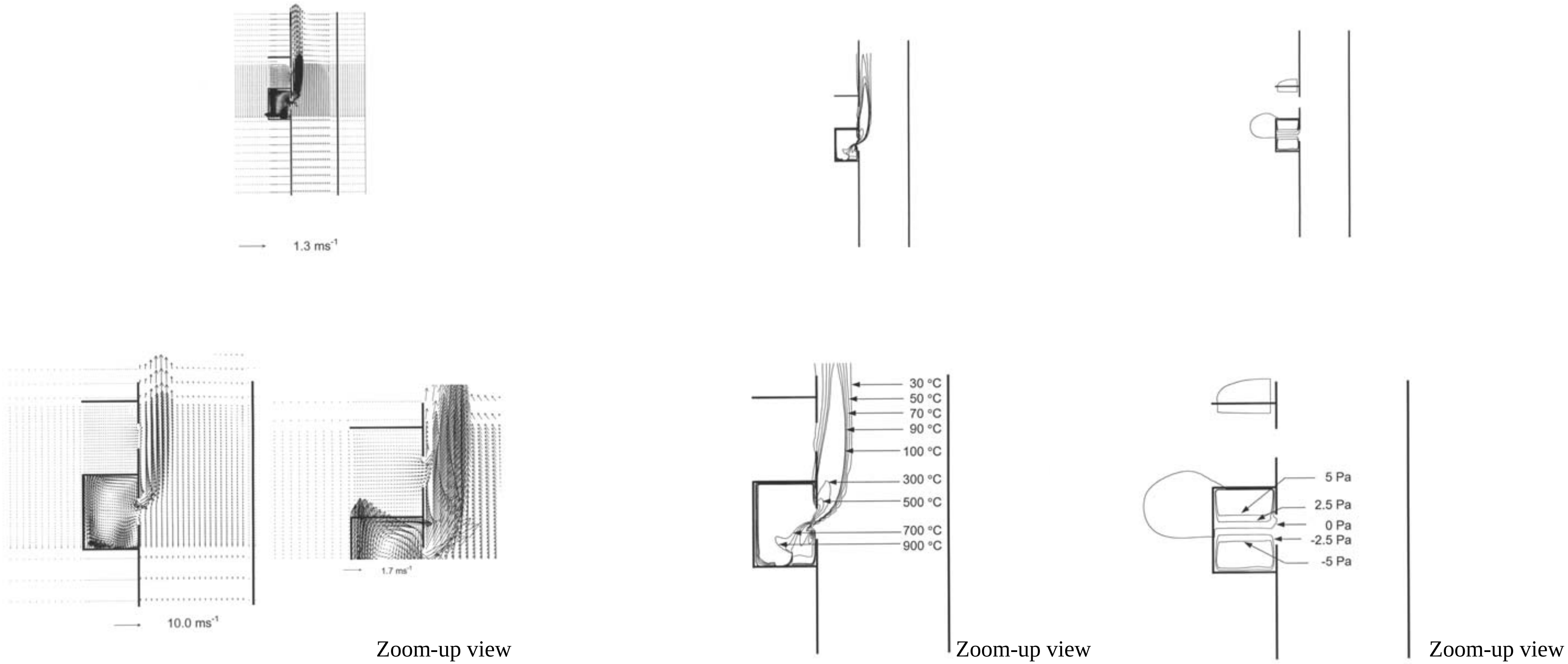
(a) Velocity vectors (b) Temperature (c) Differential pressure

Figure E-2: Scenario 1



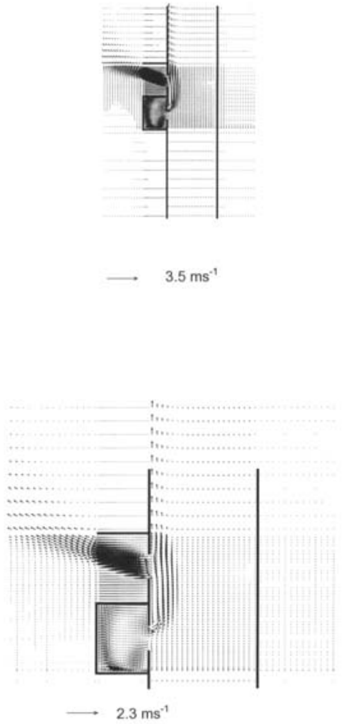
(a) Velocity vectors (b) Temperature (c) Differential pressure

Figure E-3: Scenario 2



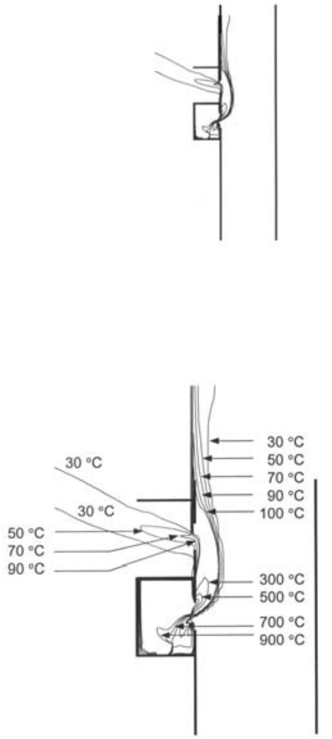
(a) Velocity vectors (b) Temperature (c) Differential pressure

Figure E-4: Scenario 3



Zoom-up view

(a) Velocity vectors



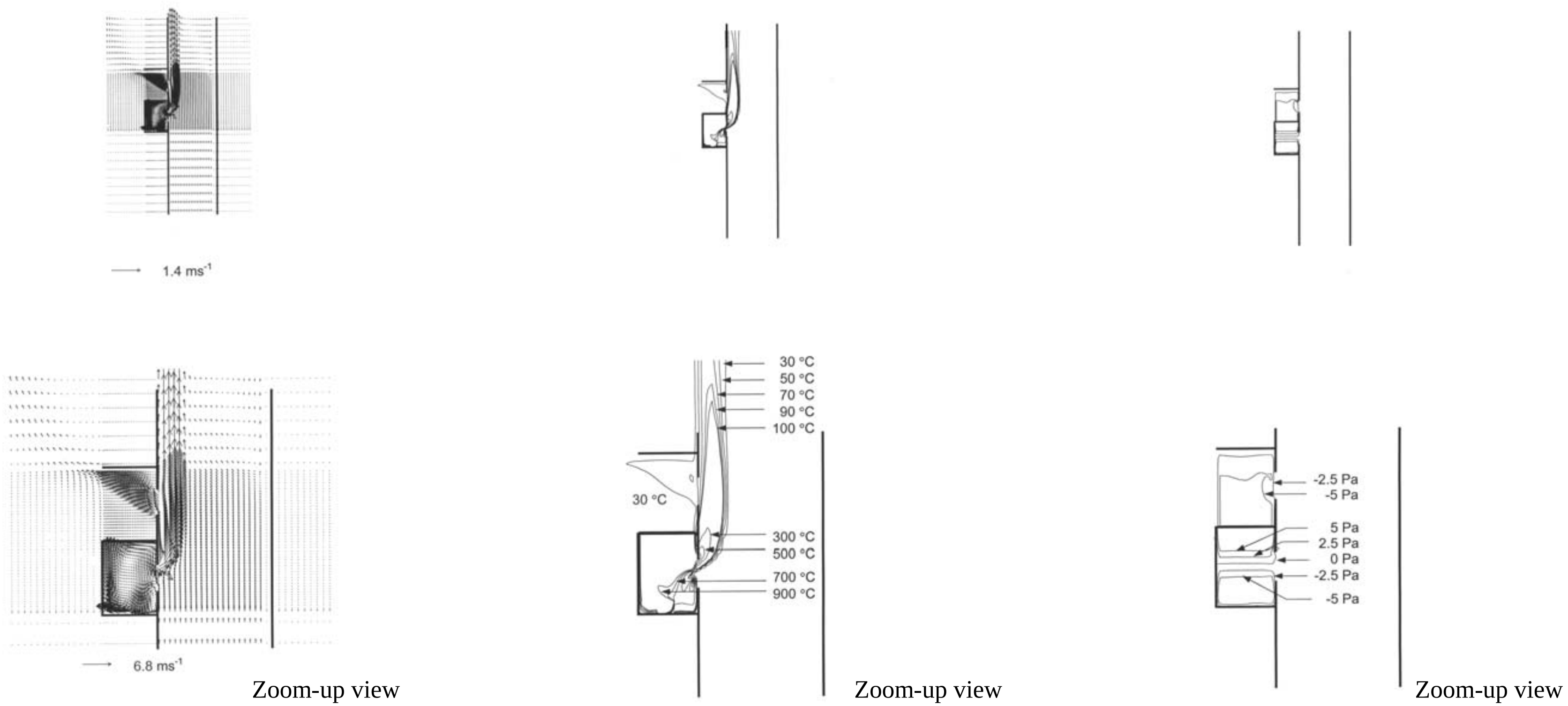
Zoom-up view

(b) Temperature

Zoom-up view

(c) Differential pressure

Figure E-5: Scenario 4



(a) Velocity vectors (b) Temperature (c) Differential pressure

Figure E-6: Scenario 5

Appendix F Preliminary Experimental Study of Double-Skin Façade

F.1 Experimental Facility

The behavior of glass panels and smoke movement in the air cavity of a double-skin façade will be studied experimentally.

The experimental rig used was in an L-shape configuration with one fire room attached to a space demonstrating the cavity between the two glass panes of a double-skin façade, as illustrated in Figure F-1. The fire chamber was 2 m wide, 1.5 m deep and 2 m high and the cavity was 2 m wide, 4 m high and 2 m deep. Test panels TPO and TPI were demonstrating the outer skin and inner skin of the upper story respectively while the fire chamber acted as an occupied space in which a fire broke out.

The opening of the fire chamber opening to the cavity can be taken as a new vent created by the breakage of glazed wall. The window adjacent to the fire origin can be easily broken by excessive absorption of heat. Glass pane would crack once its critical thermal stress is exceeded as reported in the literature (e.g. Shields, Silcock & Flood 2002; Shields, Silcock & Hassani 1997/98).

Fire protective coating was applied onto the inner surface of the wood panels to keep it for a longer time. The top of the cavity was open but a hood and exhaust duct were installed to remove the smoke and hot gases generated to the outside of the building by natural forces.

Thermocouples were attached to metal wires at fixed locations on the inner face of the test glass/wood panels to measure their surface temperature. A heat flux meter was installed on the inner surface of the panes to indicate the heat flux received on the panes. The number of thermocouples and flux meters was subject to their availability. In Figure F-2, the locations of thermocouples and flux meters were illustrated. Points TC1 to TC4 were located on the outer panel TPO; points TC5 and TC6 were located on the inner panel TPI and points TC7 and TC8 were used to measure the temperature at the top of the fire chamber.

As shown in Figure F-3, the enclosure of the fire room was constructed of brick which is not combustible. A vent of size 1.5 m high and 0.8 wide was left open to the cavity so that flame and smoke were able to pass through. The cavity wall was constructed by galvanized sheet steel. The two test wood panels were a species of poplar of 4 mm thickness. The test glass panels, of 3.5 mm thick, were common glass panels used for curtain wall available in the nearby regions. The available glass pane was 2 m wide and 1.5 m high, so that glass panes were cropped to suitable dimensions to compose full height of the walls, as shown in Figure F-2b.

Liquid fuel was chosen for the test due to its reproducibility and ease of access. In the preliminary tests, gasoline of 1000 ml, 2000 ml, 3000 ml and 5000 ml were used and consequently 5000 ml was chosen for the final tests. The fire was of the size reaching flashover fire in such a fire room. Heat release rate of the fires with the same size was determined separately in a room calorimeter measured by the oxygen consumption method. The pool diameter was 0.5 m and it was placed at the centre of the fire chamber.

Because of limited budget, instead of installing glass panes, wood panels were used first to measure the preliminary data including the surface temperature and heat flux. It is known that the heat transfer coefficient of wood is different from that of glass since they have different performances in dealing with radiative heat flux. One is opaque while the other is transparent to thermal radiation. However, by certain assumptions and simulation analysis, it is possible to correlate the data from wood panels and those from glass panes so that some useful data on glass performance can be evaluated. Further, smoke movement can be observed by using wood panels under different chamber opening size, fire load and depth of cavity. Those factors would affect fire safety of this building feature. After obtaining several sets of data by using wood panels, glass panes were installed to investigate the heat performance of glass panels.

F.2 Observations

Ten tests were carried out with nine tests using wood panels (labeled as W1 to W9) and one using glass panel (G1). The first seven burning tests (W1 to W7) were carried out to determine the best setup, such as the location of openings and the fire load. The results are used as references later. The last three tests (W8, W9 and G1) were having identical amount of fuel and opening combinations which were evaluated from the previous tests. Tests W8 and W9 were compared with test G1 since their setups were identical except the panels at the inner and outer surface. Locations of thermocouples and flux meter of the two test panels are different among the ten tests with details shown in Figure F-2. The ceiling of the fire chamber was also fixed with thermocouples. Each burning test lasted for 10 to 15 minutes, starting from the preparation of fuel to burning up of the fuel.

Different openings were arranged on the test rig, namely a front vent FV of area 0.3 m^2 (0.15 m by 2.0 m), a back vent BV of 1 m^2 (0.5 m by 2.0 m), a side vent SV of 0.5 m^2 (0.5 m by 1.0 m) and a top vent of 4 m^2 (2.0 m by 2.0 m), as shown in Figure F-1a. In this way, different opening conditions were used in different tests, as shown in Table D-1. The measured surface temperatures were different under different opening conditions. Different combinations of openings were used in the preliminary tests, say opening the back and top vents in test W1, and opening the side and top vents in test W3. The top of the cavity was left open in all tests. Otherwise, temperatures measured would be extremely high due to the trapped hot gases and smoke inside the cavity. Moreover, they were supposed to move upwards in a continuous cavity which runs through tens of stories in reality.

Smoke and hot gases were observed to be flowing upwards, affecting either the upper part of the outer test panel TPO or the inner test panel TPI. It was noted that opening the vent on wooden TPO was used for the ease of setting off the fire, as shown in Figure F-3c.

Large quantity of smoke was generated in the tests, explaining why a hood and exhaust duct had to be installed on top of the test rig. However, mechanical extraction system was not provided without affecting the fire-induced flow. Moreover, flame was coming out from the fire chamber to the cavity as shown in Figure F-4.

Modification was made after the tests (W1 to W7), i.e. a 15 cm high front vent FV was left at the bottom of the test panel TPO. The purpose of it was to allow entrainment of air since there should be natural or mechanical air movement throughout the cavity in practical case. However, in view of the site constraint, it was unable to raise the whole test rig to achieve this. Leaving an opening at the lowest part became an alternative.

In the last test G1, 3.5 mm thick glass panes of size 2 m x 1.5 m commonly used was utilized by fixing several pieces to give panels of full height. Wood frames were used to stabilize the glass panes. Performance of glass in a double-skin façade exposed under heat was demonstrated and bifurcation pattern could be observed.

F.3 Experimental Results

Surface temperature and heat flux were recorded during the tests and the glass behavior under the particular heat environment was observed.

- Temperature profile of test panels

The results of the ten burning tests are summarized in Table F-1. The temperature at points TC1 to TC4 decreased with height. Point TC1 had the highest temperature in comparing with the other three. On test panel TPI, temperature at TC6 was higher than at TC5 in general. That means the temperature on the inner test panel TPI depends on the distance from the fire chamber. By comparing the temperature on the two test panels, the smoke and flame movement or inclination inside the cavity can be anticipated. For tests W1 to W6, points TC1 to TC6 were located approximately at the same level from the ground. However, temperature at TC1 was higher than at TC6. On the other hand, for tests W7 to G1, TC1 and TC5, and TC2 and TC6 were more or less at the same level. Temperatures at the points on the outer test panel TPO were also higher than those on the inner test panel TPI, as shown in Figures C-5 to C-7, for tests W8, W9 and G1. Moreover, the difference between TC1 and TC5 was larger than that between TC2 and TC6, though their distances were identical. Flame and smoke might move towards the outer skin TPO in this respect.

Among all the temperature measuring points, point TC1 had the highest temperature. Opening the front vent FV in the last three burning tests (W8, W9 and G1) is considered to be a more realistic setup. The maximum temperatures at TC1 in these tests were about 170 °C to 180 °C, giving a temperature rise of

145 °C to 155 °C. The lowest temperature on both panels TPI and TPO was found at TC4, which was the point facing the opening of the fire chamber directly.

The temperature profiles for tests W8, W9 and G1 are shown in Figures C-5 to C-7. Tests W8 and W9 were carried out with wood panels; whilst G1 was conducted using glass panel. It was discovered that the two tests with wood panels took more than 3 minutes to reach the highest temperature. Test G1 with glass took more than 4 minutes to give the highest value. It is noted that the test preparation, such as pouring fuel and setting off the fire, was included in the time measurement.

Temperatures measured from the ceiling of the fire chamber were extremely high in tests W3 to W7 with the back vent BV closed. For the other tests, sufficient air supply was provided by the back vent BV of the fire room which resulted in complete burning. Large quantity of smoke and hot gases moved towards the cavity like the arrangement of fire place with a chimney.

- Heat flux profile

Only one heat flux meter was available in this experiment due to limitation of resources. It was located on the outer test panel TPO as illustrated in Figure F-2. By positioning it directly to face the fire source, the highest incident heat flux onto the outer skin from the fire chamber can be measured. The heat flux profiles of the two tests are shown in Figure F-8. The maximum heat flux measured in tests W8 and W9 was about 5 kWm^{-2}.

- Glass performance

Glass performance was observed in test G1. Cracking occurred on the outer panel TPO. The middle pane suffered the most serious cracking where it was initiated at the bottom of the pane. There were several crack bifurcation patterns, including one loop and some long cracking lines running up to the top of the pane. On the other hand, there was only one cracking line running through the pane on the uppermost one and two running through the lowest one. There was however no observed bifurcation pattern on the glass panel TPI. Fallout of glass pane was not encountered in this test. Cracking patterns are shown in Figure F-9. Time to give the first crack was not recorded in this study.

F.4 Discussion

From the results, points TC1 and TC6 had the highest temperature on TPO and TPI respectively. On the other hand, when comparing points on the same height, outer panel TPO would experience higher temperature than inner panel TPI. It is also shown in Figures C-5 to C-7 that the difference between TC1 and TC5 was larger than that between TC2 and TC6. All these implied that hot gases moved towards the outer skin of the double-skin façade and had an inclination to the upper part, as illustrated in Figure F-10a.

There should be mechanical or natural ventilation inside the cavity of this building feature. A 15 cm high front FV opening was created to introduce natural ventilation into the cavity to act as if air moves from the floors below. Air moving up would cool down the internal space to some extent. In addition, smoke and hot gases coming out from the fire chamber would tilt upwards due to buoyancy and affect TC4 to a lesser extent. Therefore, TC4 had the lowest temperature.

Point TC1 was the hottest point among all the measuring points. The surface temperature was about 170 °C to 180 °C in the three tests W8, W9 and G1. However, it was shown that its temperature would be higher in the burning tests without opening the front and back vents FV and BV. It is because hot gases were trapped inside and there was no air supply to cool down the internal space. A bigger fire size might give higher temperature and more severe damage to the glass panels. It was found that temperature over 400 °C could cause glass fallout (Shields, Silcock & Flood 2002).

It took a bit longer time for test G1 to reach the highest temperature than for tests W8 and W9. Test G1 was carried out by using glass panel which is different from wood panels. Glass is transparent to thermal radiation whilst wood is opaque to it. Therefore, some of the heat might lose to the surroundings through the glass panels and the internal temperature was then decreased.

Thermal stress across test panel TPO would be higher due to higher temperature exposure. As a result, cracking patterns only appeared on TPO. The middle glass panes suffered the most serious damage among the three glass panes on TPO. The cracks were caused by a heat flux of less than 5 kWm^{-2} and temperature of less than 170 °C. Such results were found to be consistent with the overseas studies (Shields, Silcock & Flood 2001) that the first cracking occurred when the bulk glass temperature was at about 110 °C and the heat flux was about 3 kWm^{-2}. Several cracking lines initiated from the edges of the panes and one cracking line at the bottom of the middle pane extended to create a loop where a small piece of glass was about to fall out but remained intact finally. Other long cracking lines extended through the glass panes. Smoke and hot gases were supposed to tilt towards the outer skin with certain inclination from the measured temperature distribution, which is coincident with the distribution of bifurcation patterns.

Due to limited resources, the outer skin of the glass panel was composed by three smaller glass panes, as shown in Figures C-2b and C-4. It is believed that glass pane of smaller area would be stiffer than that of larger area (Shields, Silcock & Flood 2002). Large piece of glass would undergo larger temperature difference between the edge and the centre and higher thermal stress would be resulted. In this experiment, it has already been demonstrated that the glass panels cannot endure high heat environment. Cracks would be generated and fallout of pieces is likely to occur. It would be very risky to the neighboring buildings and environment in reality.

In this study, one scenario was achieved where cracks appeared on the outer skin only but not on the inner skin. The severity should be smaller than that appears on the inner skin since the affected area would not be extended to other stories. The only concern in this case is then the glass pieces would be harmful to the pedestrians. The direction of smoke movement depends on a number of factors, say heat release rate (HRR), the opening to cavity and the depth of the cavity. Many other possible scenarios would occur at other conditions. Further studies are required to fully understand the fire safety environment for this architectural feature.

The depth of cavity in this study was set to 2 m which can be perceived as the maximum typical size in real development. Further study should make it less than 2 m. The depth of the cavity would definitely affect the inclination of the exhausted gases. Narrower cavity should be more influential to the smoke spreading while an oversized shaft would act like an open space. One of the driving forces for air movement is the stack/chimney effect due to temperature difference between the indoor and outdoor space. When fire comes out from the fire floor, the cavity would act like a chimney. Its significance is affected by the height of the vertical shaft or the ratio of the width and height of the cavity. The ratio in this study may be too large that the cavity was not like an enclosed space. The upward force pushing the hot gases was therefore insignificant and thus the horizontal component of momentum appeared in a more dominant way as shown in the smoke movement.

Fire size plays a key role in determining the quantity of smoke produced and thus the movement of toxic hot gases. The vertical momentum would be increased by the quantity of smoke. By varying HRR, it may also give a different picture on the inclination of hot gases. The maximum HRR given by 5000 ml gasoline in this test was about 0.55 MW.

The breakout of glass should most probably appear at the top of the story since hot gases would form a layer at the ceiling of the fire room. Smoke coming out from the vent near the ceiling could easily affect the glass panel on the adjacent floor. In this experimental study, the opening across the fire chamber and cavity was created 0.5 m below the ceiling of the fire chamber which was of 2 m high. The spreading of flame and smoke were obstructed by the vertical wall above the opening which acted like a reservoir screen. The spreading was reduced to a certain extent and the upward force was also affected.

There is ventilation inside the cavity in a real construction to remove the accumulated heat (Kragh 2002). The normal convective force might be higher than that naturally introduced by the 15 cm high front vent FV in the tests. It is believed that it also helps pushing up and affecting the direction of smoke movement.

Glass species would be significant to the glass behavior, for instance, tempered glass has four times the strength of annealed glass (BS 1994). But of course, its cost would be much higher than the ordinary counterparts. Thickness of glass is also determinant but the strength is, again, cost-oriented. Good combinations of different glass types at inner and outer skins, together with the optimum width of cavity are important to the fire safety of this building feature and also the capital cost.

As required by the existing regulations (BD 1996a), a vertical spandrel of not less than 900 mm should be constructed below the opening for the sake of fire safety protection. The upper floor can effectively evade from the attack of hot smoke. Inner glass wall can be visualized as a single-glazing where the same protection should be also taken into account. Materials of higher strength, say tempered glass, could be selected for construction of this barrier. However, the vertical shaft is enclosed by the outer skin, the temperature and pressure gradient are different from the ambient. Smoke coming out from the fire chamber cannot be diluted and cooled down and a higher risk is resulted.

Scenarios are influenced by a number of factors as discussed. A preliminary test as demonstrated in this paper can give some ideas for further studies which are strongly required for an in-depth understanding of double-skin façade.

F.5 Concluding Remarks

Smoke and flame spreading to the cavity of a double-skin façade were studied. The possibility of damaging this building feature was investigated. A probable detrimental situation is flame impingement onto the inner glass panes on the adjacent floors. Cracking on the internal layer of double-skin façade would expand the affected area and thus more occupants would be endangered. The cavity between two layers of glass becomes an effective channel for spreading of smoke and flame, with the assistance of natural or mechanical ventilation in accompany with the space to take away accumulated solar heat gain. A simple experimental setup was used in this study to examine the inclination of gases inside the cavity, whether it is moving vertically upwards from the fire room or tilting towards the outer skin at an angle.

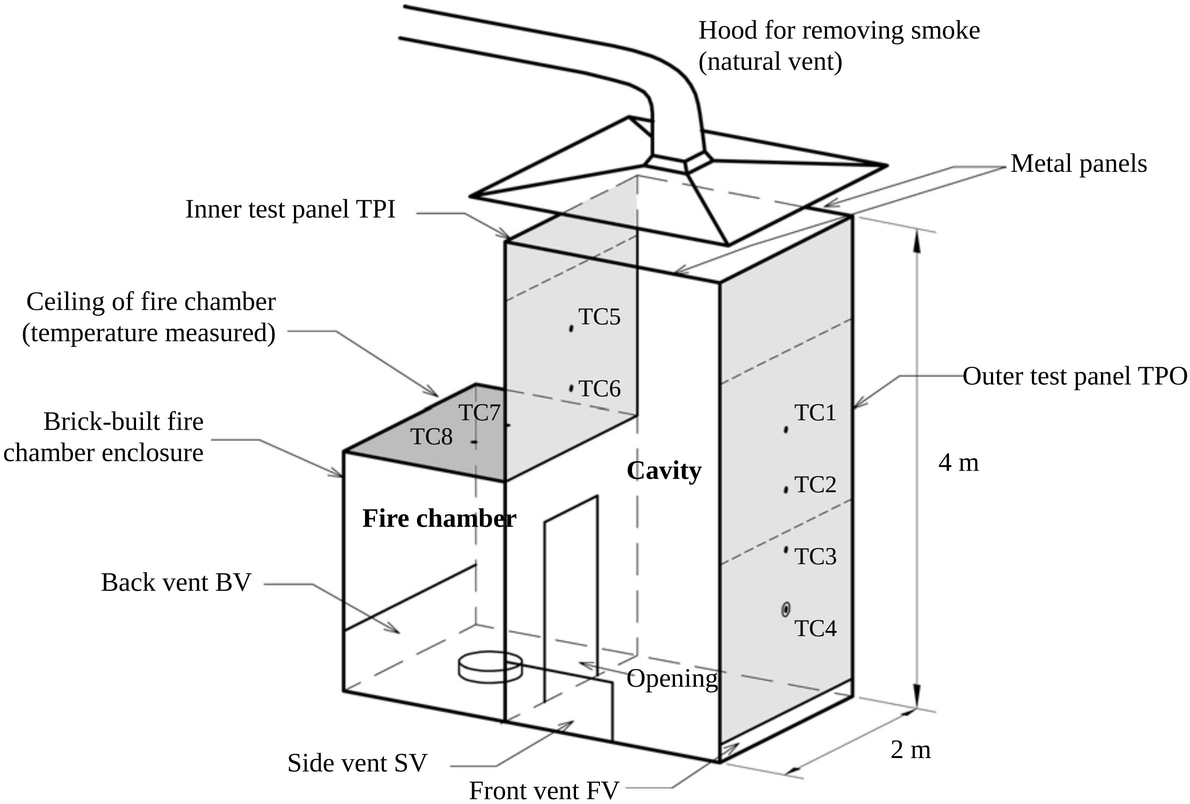
Though a less risky situation was resulted in this study, i.e. the outer skin instead of inner skin was damaged, it was only a very preliminary study which represented a particular scenario. Cavity width of 2 m might be a safe value for this new feature. Undesirable fire scenarios might be caused by a value less than that. The critical value to cause the breakout of the inner skin can be only achieved by future studies.

Through this preliminary study, the potential fire safety problems of double-skin façade are disclosed. In-depth studies are strongly required following the popularity of this new green feature.

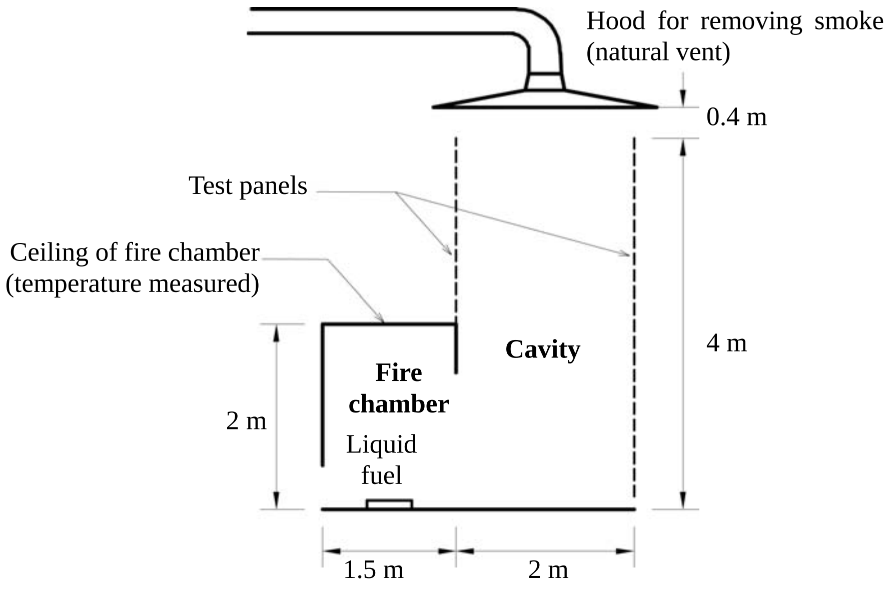
Table F-1: Summary of Results

Test no.	Mass of fuel burnt (ml)	Time (s)	Opening conditions (Closed – C Open – O)			Max. heat flux (kWm^{-2})	Test panel surface temperature (°C)															
							Min.								Max.							
							TPO				TPI		Ceiling		TPO				TPI		Ceiling	
			FV	BV	SV		TC 1	TC 2	TC 3	TC 4	TC 5	TC 6	TC 7	TC 8	TC 1	TC 2	TC 3	TC 4	TC 5	TC 6	TC 7	TC 8
W1	1000	900	C	O	C	1.68	18	14	14	10	17	16	14	18	107	96	71	47	88	88	71	82
W2	2000	600	C	O	C	3.67	16	18	13	17	16	15	15	17	158	147	107	72	119	125	67	73
W3	2000	600	C	C	O	1.57	23	19	20	17	22	22	47	47	127	78	50	44	113	116	494	489
W4	2000	600	C	C	C	0.96	19	20	15	16	18	19	23	21	146	141	117	104	126	127	525	479
W5	3000	600	C	C	C	0.92	18	20	16	20	22	20	41	40	176	170	148	131	154	156	589	545
W6	5000	600	C	C	C	0.98	20	20	18	18	21	20	54	55	243	235	209	183	216	214	669	644
W7	3000	900	C	C	C	N/A	21	19	17	15	19	20	19	17	222	216	178	154	160	181	693	698
W8	5000	676	O	O	C	5.46	23	21	19	19	22	21	21	19	171	150	130	119	124	147	102	85
W9	5000	793	O	O	C	5.11	21	23	20	20	21	17	31	31	180	173	116	107	127	148	122	105
G1	5000	867	O	O	C	N/A	18	18	17	18	16	17	17	17	176	160	116	104	144	138	98	75

Remarks
Fuel type: gasoline
Configuration of fuel container: circular (diameter 0.5 m)
Location of fuel container: centre of fire chamber
Test panel: W1-W9 using wood panels, G1 using glass panel
Openings: FV of area 0.3 m^2 (0.15 m by 2.0 m), BV of area 1 m^2 (0.5 m by 2.0 m) and SV of area 0.5 m^2 (0.5 m by 1.0 m)



(a) Schematic diagram of test rig



(b) Sectional view

Figure F-1: Schematic Diagram of the Experimental Setup

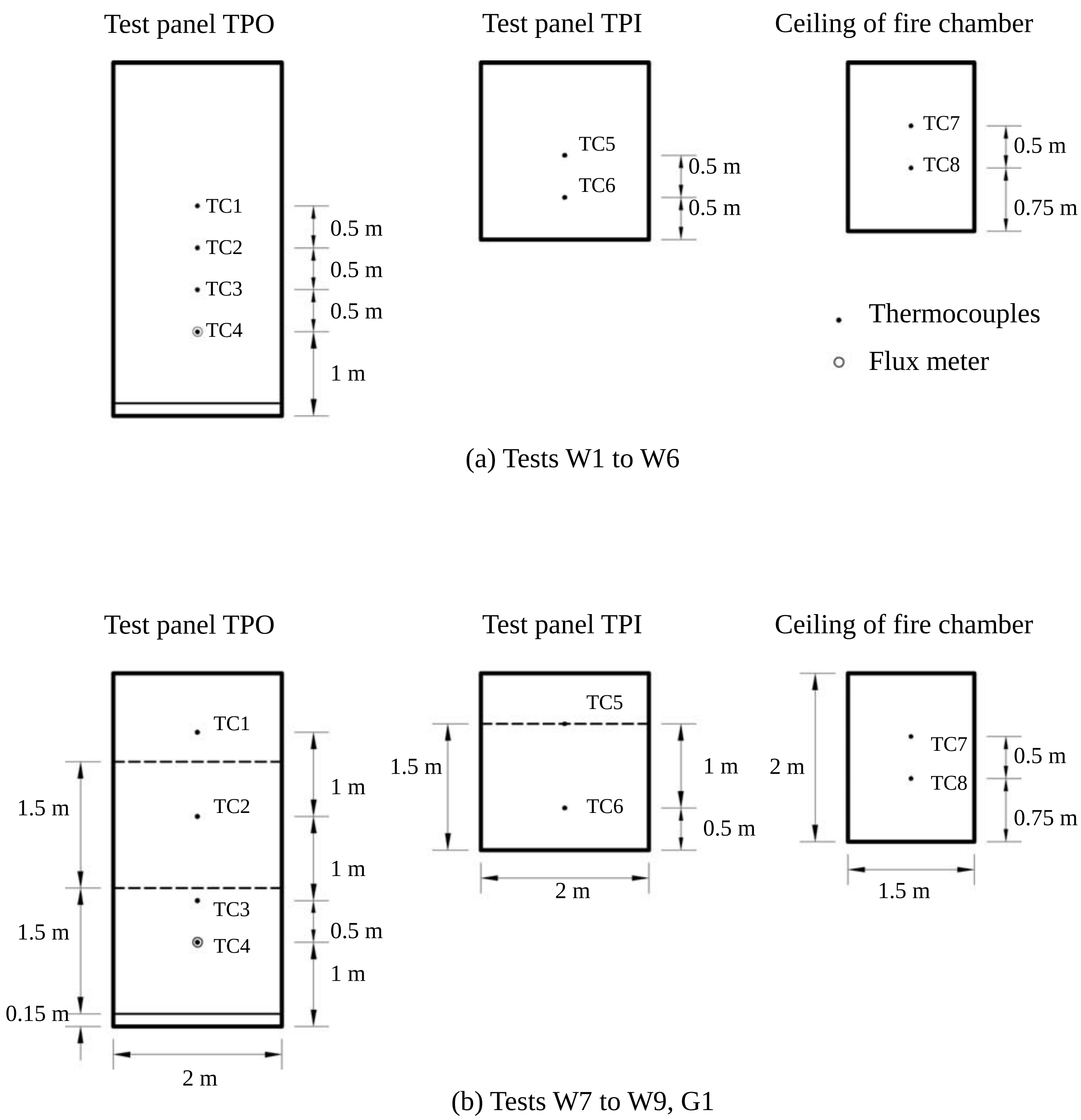


Figure F-2: Locations of Thermocouples and Heat Flux Meters

(a) Appearance

(b) Elevation

(c) Front view

Figure F-3: Pictures of the Test Rig

Figure F-4: Flame Coming out from the Fire Chamber

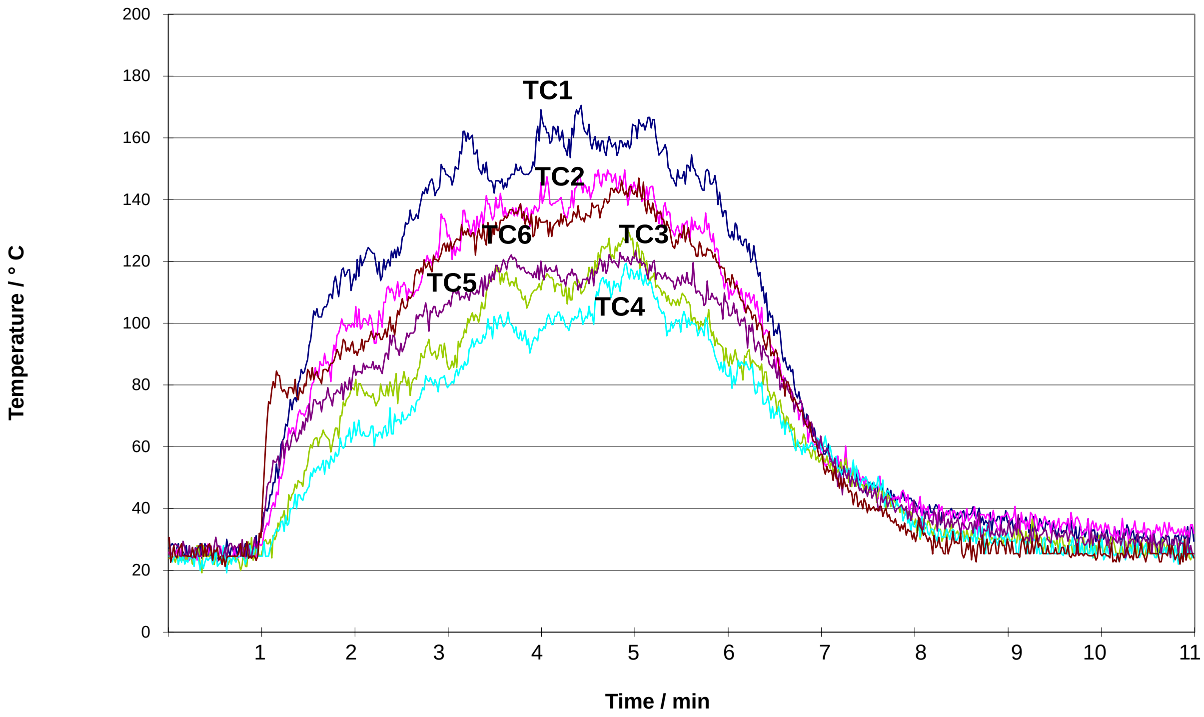


Figure F-5: Temperature Profiles at TC1 to TC6 for Test W8

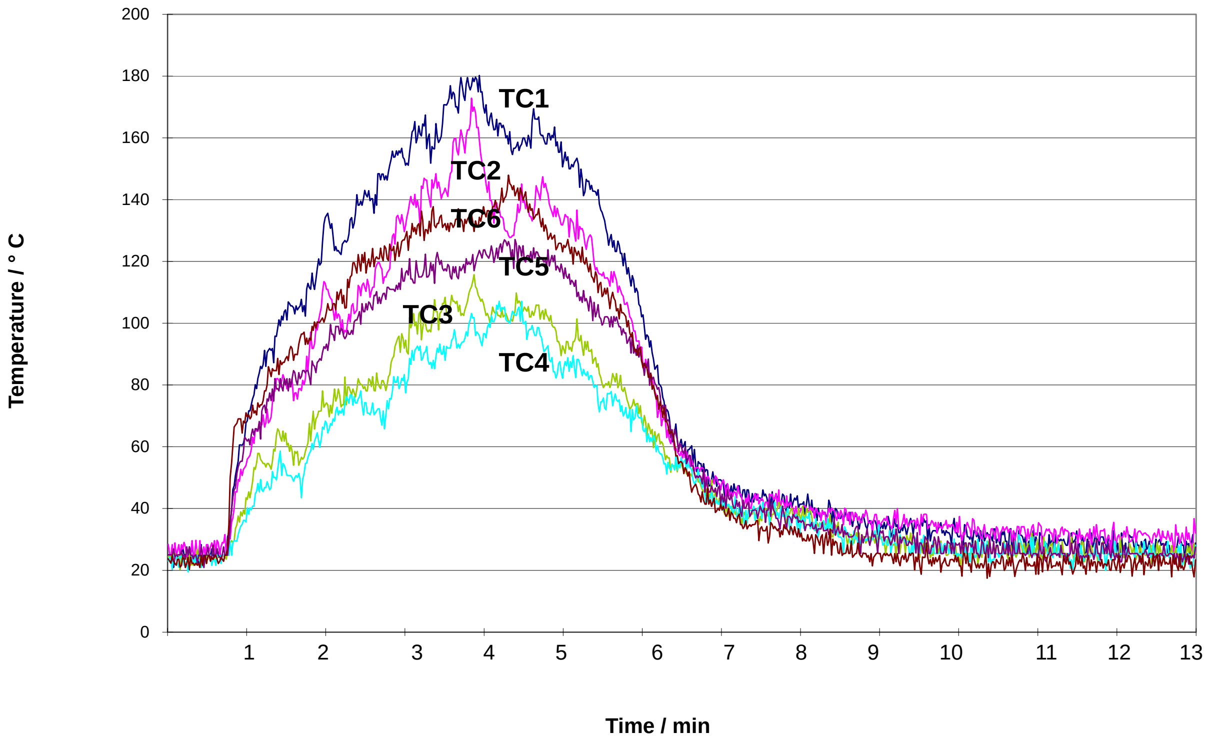


Figure F-6: Temperature Profiles at TC1 to TC6 for Test W9

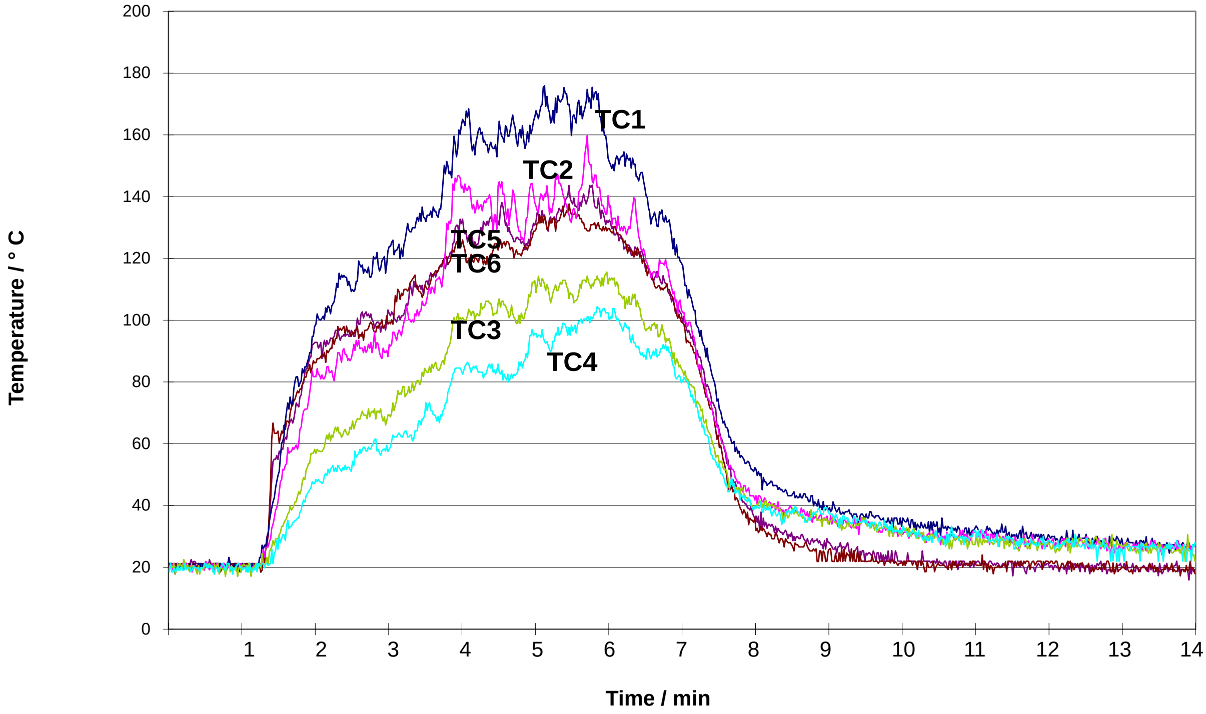


Figure F-7: Temperature Profiles at TC1 to TC6 for Test G1

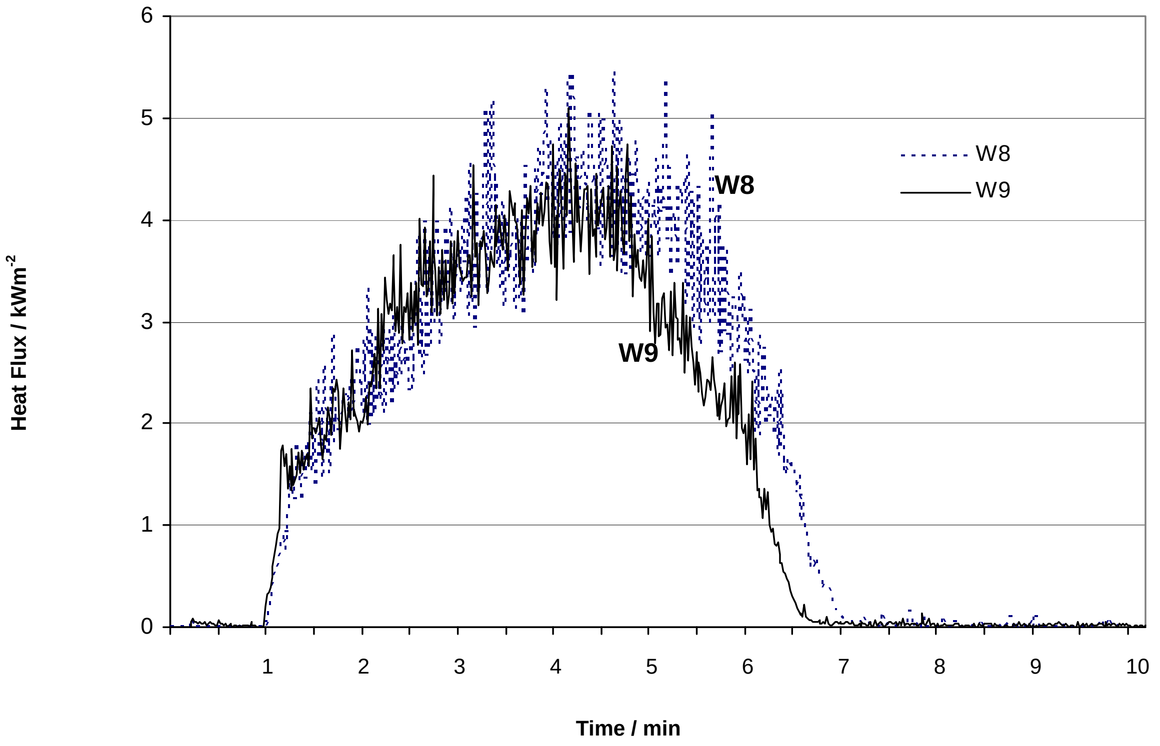
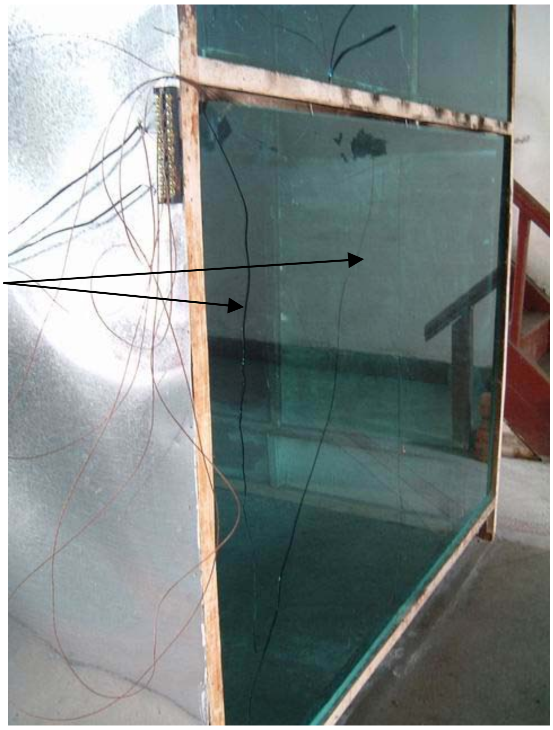


Figure F-8: Heat Flux on TPO

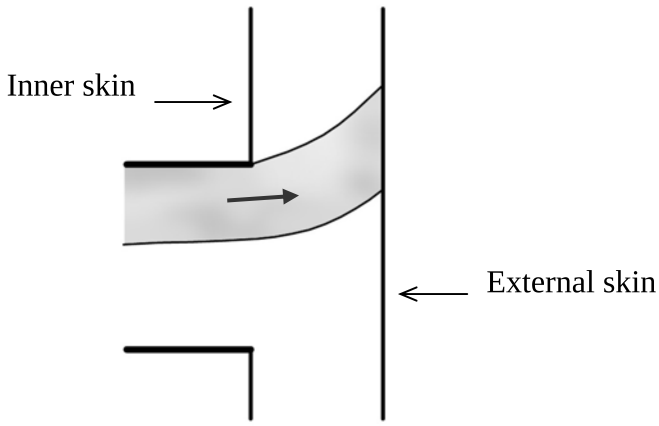
(a) Middle pane



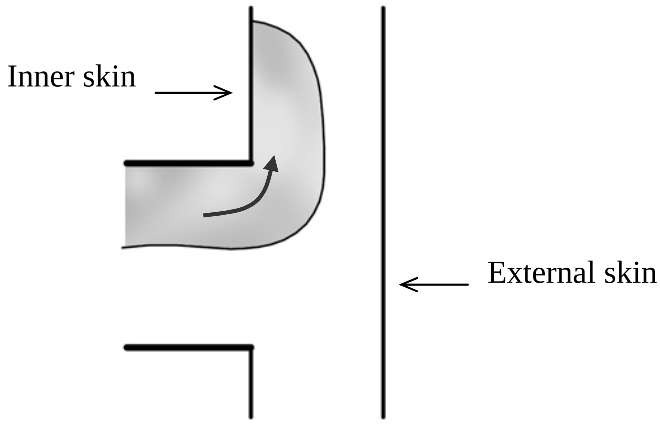
(b) Lower pane

(c) Another view

Figure F-9: Bifurcation Patterns at the Outer Glass Pane



(a) Smoke moves towards outer skin of glass



(b) Smoke moves towards inner skin of glass

Figure F-10: Smoke Movement in Double-Skin Façade

Appendix G Suggested Upgrades on Fire Safety Protection

G.1 Structural Stability against a Big Fire

Though the structures in the two towers stood only for about 1 hour and 1¾ hour respectively, and appeared to be shorter than the claimed fire resistance rating provided at the structural elements (Hung & Chow 2002a), this point should be reviewed. Testing the fire resistance of structural elements by following the standard fire resistance tests (e.g. ASTM 2000) is not for standing against such a big fire. In fact, it is a comparative test with typical room fires. With the advanced development in technologies, fire resistance can be assessed properly through fire basic principle (e.g. Abdullateef et al. 2002), under agreed fire scenarios.

The collapse times in the WTC tragedy were less than the designated evacuation time (Fire 2003; Grimwood 2001), leading to the drastic death toll. Under small accidental fires, 2 hours might be long enough for evacuating the whole building. Phased evacuation, such as evacuating only the fire origin and the adjacent two floors, rather than total evacuation, is preferred. As stated in the local codes including BD 1996b and FSD 1998, refuge floors are required in highrise buildings because it is a protected floor for evacuees of a building to assemble; and to rest temporarily during emergency escape in case of fire. It can act as an enhancement for the escaping process and also the destination for phased evacuation. In addition, it can also avoid vertical smoke spreading since the refuge floor should be separated from the rest of the building and the staircase should be discontinued at that floor. The escape time for total evacuation might be extended considerably in the ultra highrise buildings like the World Trade Center. The value should match with the fire resistance period (FRP) and time to tenability limits.

There are many well-known ultra high buildings up to 400 m. Some of them in the Far East are grouped under the top ten tallest globally. The requirements on FRP and compartmentation in the local code BD 1996a are specified for different uses of buildings, but not yet specially catered for such tall heights. In general, construction elements in most of the premises are required to have an FRP of 1 to 2 hours. The existing provisions are shown to be adequate for protecting against small accidental fires. However, there are criticisms that these are redundant since the regulations are specified for the different building uses without including the building characteristics (Hung & Chow 2002a). This is insufficient for terrorist attacks like the WTC incident. The capability of loadbearing and integrity of the construction element were not demonstrated to stand big impacts. Critical temperature for steel members is about 550 °C. Exposing them to a high heat release rate would have its temperature rise up rapidly and thus lose its strength of bearing load promptly. Though insulation layers had been sprayed on the structural steel members, it appeared that they were knocked down by the rigorous impact. It should be pointed out that the fire resisting construction is able to withstand the enormous hit but not the fire in this disaster. Those existing codes should be reviewed for protecting against such big fires. To achieve a higher FRP, thicker building materials or thicker layers of fireproof coating have to be applied. This would give higher capital cost on the construction, but might not be a big proportion of the total cost due to the high land price. As the frequency of occurrence of terrorist attacks is not so high, a balance has to be attained between the investment cost and the fire safety protection against such big fires. Performance-based designs are acceptable in most of the developed countries (e.g. BS 2001) as prescriptive codes (e.g. BS 1996) might not be applicable for design and construction technologies for this objective.

Some concerns on fire resisting construction are noted below:

- Security

Security is defined to be safeguarding assets including human lives, properties, products, reputation and so on under NFPA 601 (NFPA 2000c). This is different from fire safety, which is defined as to protect the exposed so as to satisfy a specified objective under NFPA 550 (NFPA 2002). Skyscrapers are assumed not capable of withstanding the fire following the huge impact but they should be able to endure a fire only. Security system should be responsible for dealing with the illegal intrusion of terrorists.

- Response of structural components to high heat release rate

The current requirements of FRP on the elements of construction are generally 1 and 2 hours. Heat release rate from that WTC liquid spillage fire is far higher than that from ordinary fire. Structural response under building fires, especially in extreme events with huge damage or big fires should be fully understood. Moreover, the remaining structure, say with the removal of some elements, after impact or explosion, should be studied as well since it would tell a completely different story of the structural behavior. Connections between the structural members also play key role in maintaining the structural stability, its fire behavior should also be well understood. Their performance might be predicted by design tools or modeling techniques validated by good data. However, the users of the tools must have appropriate experience and qualifications. The interdisciplinary training programs provided for structural engineers and fire engineers would be beneficial.

- Frequency of occurrence

As the frequency of occurrence of terrorist attacks appears to be not so high in areas like Hong Kong, considerations should be given on the balance between the capital cost and fire safety provided.

- Fireproof coating

Fireproofing can be very critical to the steel structure, as reviewed (Hung & Chow 2004a). It was found that the fireproofing was vulnerable to the mechanical impact in WTC. Therefore, the impact resistance of fireproofing materials should be developed with suitable performance criteria and test methods. It is worthwhile to consider applying fire retardant coatings for the existing buildings.

- Structural elements and materials

As reported by an engineering consultancy firm, the outrigger system in the WTC towers pulled down the whole mass of the building and led to the collapse. It appeared that diversified structural systems would also give rise to totally different failure mechanism. In view of that, it is necessary to identify the appropriate structural system for some new buildings when carrying out risk assessment. Test methods on the fire behavior of building materials should be standardized to give consistent results and they should include tests in extreme conditions, such as impact, deformation, explosion and fire as in WTC. Current fire resistant tests in use could not tell the actual performance of the structure (Hung & Chow 2002a) as they do not take account of the whole structural frame including the connections between walls, columns and beams. Reconsiderations of the tests might be needed.

- Fire safety management

Fire safety management (Malhotra 1987; Chow 2001d; Tsui & Chow 2004) should be worked out carefully in dealing with terrorist attack fires with fire safety provisions such as fire resisting construction designed for accidental fires only.

G.2 Evacuation

Elements of means of escape and means of access are provided in the towers as required by the model building code in USA (BOCA 1996). Almost all these fire safety provisions were unable to survive after the collision of airliners (FEMA 2002). Elevators and staircases were located in the middle of the floor area in the twin towers. The aircrafts hitting into the skyscrapers were almost as long as the floor width so that the centered vertical shafts were probably ruined severely right after the planes got into the floor area. It was found that the flame and fuel spread to the other stories promptly through the channels of vertical shafts. Vertical shafts should be able to stand against the fire by itself. Separating them by at least 2-hour FRP from the neighboring construction elements in the existing building code might not be sufficient (Hung & Chow 2002a). It sounds enough to protect the escape routes against the action of fire. The possibility of having severe damage by the terrorist attack was not taken into account. It is also regarded as a security problem on which more efforts are urged to be paid. Other parameters, such as travel distance and corridor width, are therefore insignificant under such circumstances.

For buildings taller than 25 stories, other than domestic or composite ones, refuge floors have to be constructed for every 25 stories in Hong Kong (BD 1996b). Refuge floors have to be provided with at least a 2-hour FRP. For a small fire, occupants on the adjacent floors and near the fire origin can escape through the vertical path to access and stay on the refuge floor in a highrise building. An FRP of 2 hours is enough for evacuees to run through the maximum 25 stories to access the safe story. However, total evacuation is essential in the circumstances like the WTC incident. Two hours are thereby not enough for occupants' evacuation. For the limited time to escape, it seems that a rest place is impractical. The existence of refuge floors between certain levels in a building definitely extends the travel distance and thus the egress time, which is detrimental in the case where total collapse is likely to occur. The design approaches towards terrorist attack fires and accidental fires are therefore entirely different.

The following should be considered on evacuation:

- Flow of escape route

The robustness of enclosure of escape route, like staircases, should be enhanced with appropriate assessment on their structural and thermal performance. In addition, the egress system should also be protected from the ingress of smoke where pressurization system might be relied on. Simultaneous evacuation should also be taken into account in the evacuation strategy in which currently phased evacuation is the only consideration. The use of elevators in full evacuation should be reassessed since it must be beneficial to the timely total evacuation. Lifts can be controlled to travel between designated floors in case of emergency situations. If refuge floors are erected inside the premise, being a temporary rest place for total evacuation, it should be big enough to allow smooth flow of the occupants' evacuation when evacuees from multiple stories above are passing from one escape staircase to the other through the refuge floor.

- Horizontal evacuation

"Skybridge", by introducing horizontal evacuation at height to a linked tower, was proposed (Wood, McGrail & Chow 2004) as an alternative to a vertical evacuation strategy. It was found to increase the safety level of the building and commercial value to a "dead" place as a refuge floor.

- Fire safety management

Since the requirements on whether to use refuge floors are undoubtedly dependent on the size of the fire, it is believed fire safety management can help in this respect. Occupants should move to the nearby refuge floors in an accidental fire, and then leave the tower as soon as possible in a huge fire such as that in the WTC incident. Occupants in areas far away from fire origin could not determine by themselves what fire actions are appropriate. Clear instructions given by well-trained fire wardens/managers are of ultimate importance.

Some experts found that enhancing the evacuation system would be more effective than upgrading the structural fire protection in reducing human loss in such extreme events (TVB Pearl 2004). Including elevators as a means of escape might accelerate the evacuation process. However, questions are raised on:

- What happen if there is a power break?

- How about a big fire?

It took at least 20 minutes to evacuate all occupants orderly out of a very tall building even when there is not a fire. Evacuation with lifts should be watched out carefully.

G.3 Effective Fire Engineering Systems

Appropriate fire services installations, including fire detection system, sprinkler system, fire department communication system, standby power and voice/alarm signaling system were provided in places as required in the model building code BOCA 1996. These systems might be damaged as in the passive building designs after such a hitting collision. The fires induced afterwards were therefore uncontrollable. It was demonstrated that they could only protect against small fires comparatively, such as ignition by a lit cigarette, or even arson fires. They are able to resist fire but not impact. Even if the automatic sprinkler system was not damaged by the crash, water discharged might not be able to control such a big liquid spillage fire (FEMA 2002).

Foam sprinklers and water mist systems are effective in suppressing the fire led by liquid fuel. Gas protection system is another alternative to protect the occupied space. To protect the systems inside the building, reinforced perimeter should be built. But common building materials are not capable of withstanding the direct impact of an aircraft. The security system of the airport and flight might be more dominant in avoiding destruction by such kind of Weapons of Mass Destruction.

Some concerns are listed below:

- Sprinkler system

In the WTC incident, they appeared to be too vulnerable to the impact, the rising water supply was found to be broken at the initial crash from the jetliner (FEMA 2002). Enhanced protection should be provided for such fire engineering systems and redundant water supply might be needed.

Foam sprinklers should also be installed for some buildings located in places with high risk to protect against the fire action caused by liquid fuel which might lead to more serious damage.

- Water mist system

Water mist system is designed to create very fine water droplets which have the capability of heat extraction, oxygen depletion and heat attenuation (Damage Control Information Newsletter 1997). It is a water-based fire engineering system having the ability to suppress Class B fuel fires provided with proper design (Butz et al.1994) and it is envisaged as a good substitute for halogenated system. Heat transfer can be largely reduced by the very high concentration of fine droplets, and thus decreasing the liquid fuel vaporization rate.

- Gas protection system

Total flooding gas protection system is in favor since they would not cause water damage to some of the high-value assets in occupied space, for example, damages to computer machines by water are strongly prohibited. The clean agents used in total flooding fire extinguishing systems would not leave a residue upon evaporation (NFPA 2000d).

- Security

Stronger building frame is desirable to protect the fire engineering systems inside the buildings. Nevertheless, full shelter against collision would give rise to a dull appearance and an extremely high cost. Security system should take part in this respect.

G.4 Fire Safety Management

Since the active fire engineering systems and the passive building design were severely ruined by the enormous smash, fire safety management appeared to be crucial in this incident. Thousands of office workers and tenants in the tall buildings indicated that fire drills are essential for the evacuation because of the complicated egress plan. Regular examinations of the fire services installation is of ultimate importance. The announcement given to the occupants inside the towers right after the crash explicitly stated that the broadcasting system was workable. The number of casualties could have extensively reduced if the announcement had made a proper instruction to the occupants in the emergency circumstance. Unfortunately, the instruction of telling tenants to stay calm at desk in the incident has become one of the grounds for the dreadful death toll. However, fire safety management becomes the only safety measure under such circumstance. More attention should be paid to the implementation of fire safety management. It seems that there is a lack of proficiency in the current practice in local organizations (Malhotra 1987; Chow 2001d; Tsui & Chow 2004).

A fire safety plan should be worked out. There should be a maintenance plan, a staff training plan, a fire action plan and a fire prevention plan (Malhotra 1987) including information, such as safety management structure; actions to be taken in a fire emergency; fire drills; housekeeping; staff training; record-keeping and so on (BS 2001).

First of all, a maintenance plan should be prepared, in which maintenance of passive building construction, say fire doors; maintenance of active fire protection systems such as sprinklers, fire hydrants and hosereels; re-verification of system performance; signs and information of escape routes and good housekeeping are included. It is very important since the failure of any one of the systems would lead to unexpected consequences. A serious fire incident happened years ago (HKS 1996) claiming seven human lives was attributed to the improper alarm system and sprinkler system.

A staff training plan should include appointment of fire wardens; description of their duties at usual time or emergency conditions; use of equipments and education on fire dynamics to fire safety management staff.

A fire action plan would be applied when a fire breaks out. It includes reporting to the fire station; leading occupants to a safe place; fighting against the fire and assisting the fire brigade. The effectiveness of it largely depends on the implementation of the staff training plan. Under emergency circumstances, the fire staff should be able to take appropriate actions to protect the occupants or minimize injuries and damages.

The last but not least is the fire prevention plan which is used to identify and eliminate fire hazards. This will be worked out for large organizations such as tunnel management.

Some of the large companies already have their fire safety plans prepared and documented. However, it might not be well implemented, say not following the instructions in the plans or just keeping them inside the shelves. If the fire managers or fire wardens do not understand the fire sciences, they are unable to give appropriate judgment and guidance on what actions should be taken. The egress time may be delayed because the occupants are not able to find the right escape route due to the lack of fire drills. Increase in the loss of life would thus be resulted. Therefore, the significance of a well-prepared and well-executed fire safety plan should be promoted among all the organizations in order to give better safety (Chow 2002b). In addition, to maintain the effectiveness of fire safety management, regular audits according to the building nature should be performed. It may include checking whether the procedures laid down in the fire safety plan are implemented properly, or whether testing of systems is carried out in accordance with the codes (BS 2001).

Some points should be taken into consideration:

- Regulations

Regulations should be established on the implementation of fire safety management by the local government. Currently, fire safety management only focuses on maintenance requirements for various fire services installations and keeping escape routes free from blockage (Tsui & Chow 2004). Other aspects in fire safety management, such as staff training, fire action and fire prevention, are not yet established except for few building uses, say schools, homes for elderly and karaoke establishments.

- Uniqueness

Tailor-made fire safety management should be worked out since different buildings have their own configurations, uses and characteristics of occupants.

- Execution

Respecting the fire safety plan by following the scheme closely is of ultimate importance. Training of fire safety managers and wardens; and regular tests on all fire safety measures should be executed.

- Knowledge of fire sciences

Fire dynamics should be fully understood by the fire safety managers so as to ensure that appropriate actions are taken in case of fire.

- Attitude

Fire safety management can be acted to compensate the inadequacy of the hardware provision so that it is important to provide total fire safety in a premise. The sense towards fire safety management should be promoted.

Appendix H Evolution of the Requirements on Fire Resisting Construction

Hong Kong was under British administration before smooth reunification to China in July 1997. Most of the policies and ordinances had made reference to those in UK. Therefore, reviewing the development of fire safety control in UK would be helpful in understanding the local fire codes. The development of the codes related to structural fire protection in UK was reviewed (e.g. Malhotra 1987; Munro 1970a, 1970b; Read & Morris 1993).

Development of legislation for fire safety in UK has to be traced back to 300 years ago (Munro 1970a, 1970b). In the 17th century, there was no statutory instrument until the big conflagration Great Fire of London, lasting for 4 days and destroyed 80 % of the city, in 1666 (Read & Morris 1993). After that, a Royal Proclamation concerning the building materials, the width of streets and the construction of new buildings was issued. Since then, more attention was paid to fire precautions. Other cities in UK followed suit. Two pragmatic regulations established had become the foundation of fire protection principles including fire resisting construction and fire containment in the future. They are:

- The external walls have to be constructed of brick or stone.
- The thickness of the brick or stone walls is related to the height of the building.

In 1774, Fire Prevention (Metropolis) Act was enacted, in which buildings were classified into seven types with designated thickness of walls and the exposed timber had to be covered by non-combustible materials. Permissible materials for construction of roofs and walls were also laid down in the Act. Some professionals started to develop fire tests in which the fire development in an enclosed room was investigated.

"Fire proof" floors were prescribed in the building regulations since the early 19th century. Meanwhile, other fire-fighting systems were developing as well. In the 1844 Metropolitan Building Act, the building classes were contracted from seven to three, namely dwelling houses, warehouses and public buildings. The concept of compartmentation was introduced. The maximum volume of warehouses was 200,000 ft^3 and elements of construction of public buildings were required to be 'fire-proof'. Concrete was introduced into all public buildings with iron and steel in 1860s. London became the pioneer among the world on the issue of fire protection for the time being, with its legislation prescribing all the major construction elements should be of non-combustible materials and the buildings should be fire resisting.

The legislation was amended in the 1894 London Building Act which constituted some new sessions concerning fire safety, including 250,000 ft^3 to be the maximum volume for warehouses; 80 ft to be the maximum height for any building; and public buildings with cubical extent exceeding 125,000 ft^3 be fire-resisting construction in order to provide at least half an hour for occupants' evacuation and fire fighting by the fire brigade.

The British Fire Protection Committee (BFPC) was instituted (Malhotra 1987) in the following year and became the foremost in standardizing fire-testing techniques. Their work became the foundation of the present-day fire resistance tests and their 25-year effort led to the establishment of fire tests using furnaces.

The revised London Building Acts (Amendment) Act 1905 constituted a new schedule of fire-resisting materials. Elements of means of escape were required to be constructed of fire-resisting materials. Legislations elsewhere in UK were also amended to follow it.

Following the BFPC, the British Engineering Standards Association, the preceding organization of the British Standards Institution (BSI), carried out the fire tests for non-combustibility, non-flammability and fire resistance in considering the previous work of the BFPC and the other countries. The British Standards BS 476: 1932 Fire Tests on Building Materials and Structures (BS 1932), which is still referred to in the codes of Hong Kong and UK at the moment, was then issued.

A Joint Committee collaborated by the Building Research Board and the Fire Offices' Committee in 1938 had published significant reports, the Fire Grading of Buildings (HSMO 1946, 1952), after the war in 1946 regarding the fire precautions in buildings since the enemy attack in the war had made disastrous damage. The post-war reports gave detailed recommendations on the general principles and structural precautions (Part I), fire fighting equipment, personal safety and chimneys and flues (Part II). Part I will be discussed in the later session, with new interpretation on the building grades. Most of the current regulations are influenced by the Reports.

The Model By-laws for England and Wales were revised in 1952, taken into consideration the recommendations in Fire Grading of Buildings Part I. Some new requirements for fire resistance of buildings were stated, for example, specified fire resistance periods should be provided for the elements of construction.

In 1961, the 1400 sets of model by-laws used throughout England and Wales were replaced by the newly established building regulations, which were empowered by the Public Health Act. The first Building Regulations was enacted in 1965 throughout England and Wales with several revisions made up till now. There were no requirements for means of escape until the enactment of Fire Precautions Act 1971.

In 1984, a new set of approved documents was published so as to simplify the complex regulatory systems establishment before and provide practical guidance to the compliance with regulations. For fire safety, Approved Document B illustrated the technical requirements for means of escape, fire resisting construction and fire services installation.

Fire Grading of Buildings (HSMO 1946), published by a joint committee of the

Building Research Board of the Department of Scientific and Industrial Research and the Fire Offices' Committee in 1946, is the most significant study on the development of fire resisting construction in this century. This post-war building study mainly focused on the reconstruction of the damaged houses and new buildings after the war. The general grades for the FRPs used locally are believed originated from this building report.

There are three classifications of fire hazards, namely personal hazard, damage hazard and exposure hazard, in this building report. Personal hazard concerns about the safety of life, while damage hazard concerns about the property and exposure hazard deals with the surrounding buildings.

- Classify fire load

Fire resistance period was developed from damage hazard which was the basis to classify different occupancies. Fire load was used to measure the damage hazard quantitatively. The total weight of combustible material was not used because different materials may exhibit different combustibility. More combustible materials are not necessarily equal to higher potential hazard. In the building report, fire load (B.Th.U's./sq.ft.) is given by multiplying the weight of all combustible materials by their calorific values and dividing by the floor area. It should be noted that 1 B.Th.U's./sq.ft. is equal to 11.35 kJm^{-2}.

After defining the fire load, the means to grade the occupancies, the committee investigated the common occupancies in and outside the country. Some reliable data relating to the fire load of several types of occupancies were obtained. They are summarized as follows:

For residential buildings, hotels, hospitals, schools, offices and similar occupancies, the fire loads usually do not exceed 100,000 B.Th.U's./sq.ft. (or 1,135 MJm^{-2}); for shops and factories, their fire loads exceed 100,000 B.Th.U's./sq.ft. (or 1,135 MJm^{-2}); and for warehouses, the fire load can be up to 1,000,000 B.Th.U's./sq.ft. (or 11,350 MJm^{-2}). In respect to the data, the committee proposed a grading method for the occupancies:

- Low Fire Load: fire load not more than 100,000 B.Th.U's./sq.ft. (or 1,135 MJm^{-2}).
- Moderate Fire Load: fire load more than 100,000 B.Th.U's./sq.ft. (or 1,135 MJm^{-2}) but less than 200,000 B.Th.U's./sq.ft. (or 2,270 MJm^{-2}).
- High Fire Load: fire load more than 200,000 B.Th.U's./sq.ft. (or 2,270 MJm^{-2}) but less than 400,000 B.Th.U's./sq.ft. (or 4,540 MJm^{-2}).

These are also shown in Table H-1.

- Correlate fire load, fire severity and required FRP

The relation between the temperature and duration of a fire and various fire loads was first investigated in America. Matching with the curves of standard test, the equivalent severity of the building fire (expressed in hours) was then assessed. Fire severity was not apparently defined in any standard of code, but it is usually employed to describe the heating conditions and their effect on a structure when exposed to a fire (Malhotra 1982). Since the standard American time-temperature curve is coincident with that of British Standard, the fire severities of different fire loads can also be applied in UK. Low, moderate and high fire load categories are found to match the fire severities of 1, 2 and 4 hours, as shown in Table H-2.

From the above assumption, the committee concluded that in an attempt to resist a complete burn-out without collapse, a building of low fire load should require an FRP of 1 hour in its elements of structure. Likewise, a 2-hour FRP is required for buildings of moderate fire load and a 4-hour FRP is required for buildings of high fire load to resist the complete burn-out without failure in structure, which is called "fully protected construction", as shown in Table H-2.

For convenience, types of construction, designated for different periods of fire resistance and fire protection to the buildings, are classified in the report. Types 1, 2 and 3 constructions are designated for buildings of fully protected construction with elements of structure having not less than 4 hours, 2 hours and 1 hour of FRP respectively, as shown in Table H-3. The remaining Types 4 to 7 constructions are those not capable of resisting a complete burn-out; not having specified fire resistance or having some elements of combustible materials.

- FRP required for elements of construction

After the types of construction have been defined, the required FRP for structural elements of each type are specified. Separating walls, which are used to separate different buildings, should have an FRP of 4 hours in all cases regardless of the types of construction, since the occupancies on each side of the wall would vary with time. Division walls, which separate parts within a building, can follow the types of construction they are situated. In this respect, a 4-hour FRP is deserved for Type 1 construction; 2-hour FRP for Type 2 and 1-hour FRP for Type 3, however, after justification, an FRP of 2 hours should be provided in order to ensure fire safety. For the external walls, they also follow the types of construction. But 2-hour FRP should be provided for those buildings exceeding 50 ft in height. Classification of walls is illustrated in Figure H-1. All columns and beams are awarded an FRP of that required in the walls they are supporting. The required fire resistance period of floors and roofs for Types 1, 2 and 3 construction are 4 hours, 2 hours and 1 hour respectively. As basements impose specially high risk owing to the absence of openings for escape of smoke of high fire load storage, higher grade of fire resistance should be adopted. A minimum of 2 hours FRP should be provided for buildings of low fire load, and 4 hours FRP for moderate fire load. Sufficient fire safety measures should be provided with 4-hour FRP in the high risk basements in this respect. Details are shown in Table H-4.

Table H-1: Classifications of Fire Load (FL) in Fire Grading of Buildings

FL (B.Th.U's./sq.ft.)	FL (MJm^{-2})	Classification of fire load	Example buildings
FL ≤ 100,000	FL ≤ 1,135	Low	Domestic buildings, hotels and offices
100,000 < FL ≤ 200,000	1,135 < FL ≤ 2,270	Moderate	Trade and factory buildings
200,000 < FL ≤ 400,000	2,270 < FL ≤ 4,540	High	Bulk storage buildings

Table H-2: Relationship among Fire Load, Equivalent Severity and FRP of Fully Protected Construction in Fire Grading of Buildings

Classification of fire load	Equivalent severity (hours)	FRP (hours)
Low	1	1
Moderate	2	2
High	4	4

Table H-3: Types of Construction vs FRP in Fire Grading of Buildings

Types of construction	FRP (hours)
1	≥ 4
2	≥ 2
3	≥ 1

Table H-4: Minimum Fire Resistance (in hours) Requirement in Fire Grading of Buildings

<table>
<tr><th colspan="2" rowspan="2">Elements of construction</th><th colspan="3">Types of construction</th></tr>
<tr><th>Type 1</th><th>Type 2</th><th>Type 3</th></tr>
<tr><td rowspan="3">Wall and beam and columns supporting wall</td><td>Separating wall</td><td>4</td><td>4</td><td>4</td></tr>
<tr><td>Division wall</td><td>4</td><td>2</td><td>2</td></tr>
<tr><td>External wall</td><td>4</td><td>2</td><td>2, 1*</td></tr>
<tr><td colspan="2">Floor</td><td>4</td><td>2</td><td>1</td></tr>
<tr><td colspan="2">Roof</td><td>4</td><td>2</td><td>1</td></tr>
<tr><td colspan="2">Basement</td><td>4</td><td>4</td><td>2</td></tr>
</table>

* 1-hour FRP is for buildings not higher than 50 ft.

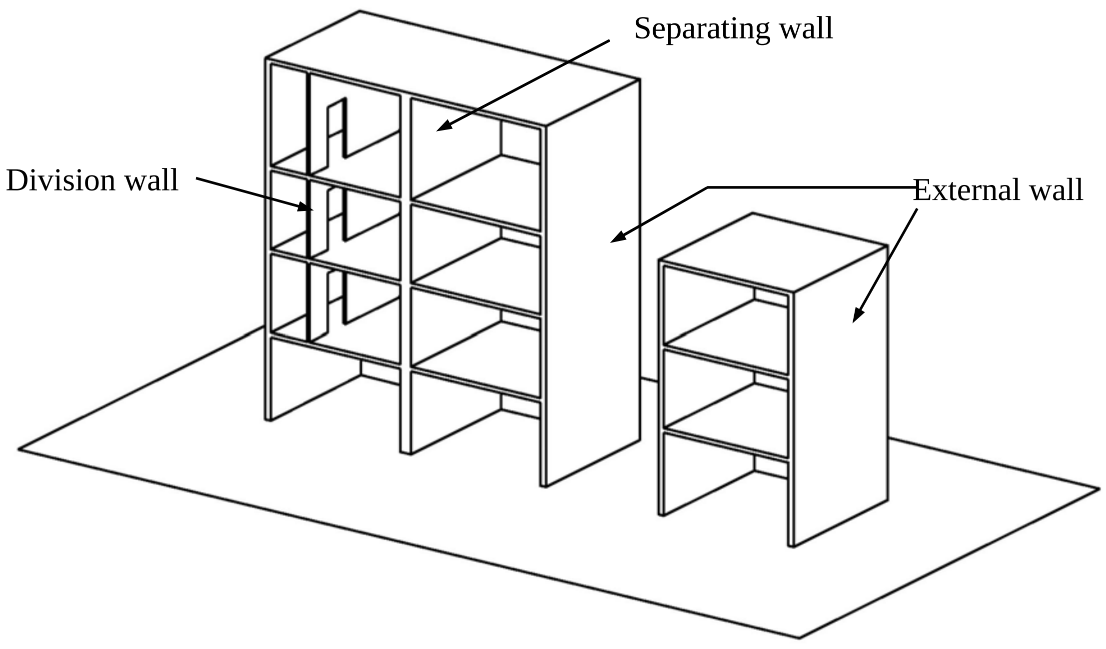


Figure H-1: Separating Wall, Division Wall and External Wall

Appendix I Fire Protective Coatings for Structural Steel Elements

I.1 Fire Protective Coatings for Structural Steel Elements

Consequent to the WTC incident, there are concerns on the fire behavior of structural steel members in those symbolic buildings having risks of non-accidental fires since steel frameworks are commonly used in ultra high-rise buildings in densely populated urban areas.

With the high thermal conductivity, steel members would lose its strength very soon under exposure of heat. Adequate FRP on steel elements of construction must be provided to ensure the structural stability. It can be achieved by four major approaches as stated in standards (ASFPCM et al 1992). The first three kinds are categorized as passive fire protection system while the intumescent coating can be regarded as a reactive fire protection system as defined in Loss Prevention Standards (LPS 1987, 1989). They vary in the ease of application and cost. These four protection systems are briefly introduced as below:

- Spray-applied protection

Sprayed coating is a passive fire protection system which has been the most common type of coatings since the early 30s (ASPF 2002), due to its low cost and easy handling (SCI 2003). Asbestos fibres were the main component at the time of introduction of sprayed coating. They were then substituted by cement or gypsum-based materials containing mineral fibre, vermiculite or perlite which are found to be the least expensive choice with widespread use in the current market (SCI 1999). They can provide fire resistance period (FRP) of up to 4 hours. Their thicknesses correspond to the required FRP range from 10 to 75 mm and the surface of the structural elements after application of the sprayed coating appears to be messy and poor (SCI 1999).

- Board, blankets and casing protection

Dry forms of fire protection include boxed protection or blankets surrounding the steel section to give profile protection, fixed by gluing, screwing or stapling (SCI 2003). Their cost would be higher than the sprayed coating system. They have to be applied in situ. Materials concerned include ceramic fibers, calcium silicate, rock fiber, gypsum and vermiculite (SCI 1999). The heated perimeter could be reduced by the boxed form of appearance when compared to the profile counterpart.

- Generic materials

Generic materials include concrete, brickwork, blockwork or gypsum plaster which can be used to fill up between the flanges of the steel sections or the hollow sections. Once the steel section is protected by the filling, the exposed surface area could be reduced along with the radiative heat transfer. The time to failure temperature is therefore extended. The uneven temperature distribution by the different materials can also induce a higher fire resistance (SCI 2003). For a concrete filled hollow column, steel and concrete could mutually restrict degradation of each other.

- Intumescent coating

The application of intumescent coating, which was initially utilized in UK, is getting more popular in recent years. It is envisaged as a reactive fire protection system (LPS 1989), because an insulating layer is formed only when it is heated up. Now, up to 25 % of fire protection on steelwork in buildings is by intumescent coatings (ASPF 2001a). Comparatively, it is the most expensive one among those mentioned, about 2 to 3 times the cost of its sprayed counterpart (SCI 2003). However, it can leave an appealing surface by applying appropriate decorative or color finish and the coating appears much thinner which is attributed to its peculiar mechanism in forming the insulating layer. There are two types of intumescent coatings, namely thin film and thick film. The thickness of thin film is ranging from 0.25 mm to 6 mm. Dry film thickness (DFT), which is the thickness when coating in the state of hard dry, is usually referred to when specifying the required thickness of intumescent coating. Since the market demand for the product is growing up, investigations of intumescent coating is focused in this study.

I.2 Preliminary Comparisons of Different Coatings

A brief comparison among three approaches of fire protection, namely spray-applied coating, board protection and intumescent coating, on structural steelwork is made in Table I-1. Prior to the comparison, the characteristics of each type of coating are briefly discussed (SCI 2003).

- Spray-applied protection

Its popularity in the last decades is undoubtedly due to its low cost, fast and easy application on complicated sections. The steelwork being protected is not necessarily primed and cleaned. It is also suitable for external environment. The FRP provided is usually up to 4 hours.

On the other hand, its appearance might be too messy to expose on some of the construction elements. It is also envisaged as vulnerable to mechanical damage (SCI 1999).

- Board protection

Up to 4 hours FRP could be offered by the box-like board protection. Tidiness and guarantee on the thickness of the manufactured board could be easily achieved. It is suitable for external use. Priming on steelwork is not needed.

However, it is found to be more expensive and slower in application. The layer would be rather thick, up to 100 mm, that is not in favor by designers or users. However, it might also be too weak to resist mechanical damage (SCI 1999, 2003).

- Intumescent coating

A smooth and colored surface can be obtained by the optional decorative coat. Like the conventional paint, the more commonly used thin film intumescent coating can be applied by brush, roller or airless spray. Thus, it is rapid and convenient at the time of application. Even for the complicated steel sections, it can easily cover up the whole surface.

Comparatively, thin film could only provide a lower fire rating of up to 1 hour and it is also not as cost-effective as the other two forms of protection, with several times the cost of the sprayed coating. Before applying, the surface of steel has to be cleaned and blasted; otherwise the heat performance of the coating may be deteriorated. Application in external environment is only occasionally suitable whilst it is more frequently being used in the interior since it is physically as frail as the traditional paint materials (SCI 1999, 2003).

Table I-1: Comparison among Three Fire Protection Systems (SCI 1999, 2003)

Protection systems	Sprayed-applied coating	Board protection	Intumescent coating
Protection types	Passive	Passive	Active
Cost (£/m^2 surface area in 2001)	4 to 12 (low)	6 to 20 (medium)	5 to 40 (high)
Maximum FRP provided	4 hours	4 hours	Typically 1 hour (thin) 4 hours (thick)
Appearance	Messy or textured	Smooth	Smooth and/or colored
Robustness	Weak	Weak	Very weak (thin) Tough (thick)
Surface primed	Not necessary	Not necessary	Essential
Thickness (mm)	10 to 75	6 to 100	0.25 to 6 (thin) 2 to 32 (thick)
Ease of application	Easy and fast	Slower	Easy and fast
Location of application	Interior and exterior	Interior and exterior	Mainly Interior

Appendix J Classifications of Severity for Parameters of Severity

S_1: BUILDING HEIGHT

Building height (H_B)	**Category**
200 m < H_B	**1**
100 m < $H_B \leq$ 200 m	**2**
30 m < $H_B \leq$ 100 m	**3**
$H_B \leq$ 30m	**4**

S_2: LOAD BEARING STRUCTURAL ELEMENTS

Fire resistance period (FRP) of load-bearing elements	**Category**
1 hr < FRP ≤ 2 hr	**1**
2 hr < FRP ≤ 4 hr	**2**
FRP ≤ 4 hr	**3**

S_3: COMPARTMENTATION

Compartment volume (V_C)		**Category**
Bulk storage and warehouse	28000 m^3 < V_C	**1**
	7000 m^3 < $V_C \leq$ 28000 m^3	**1**
	$V_C \leq$ 7000 m^3	**2**
Industrial undertaking except bulk storage and warehouse	28000 m^3 < V_C	**2**
	$V_C \leq$ 28000 m^3	**3**
Shop, restaurant, hotel foyer, place of public entertainment, hospital place of assembly, carparking	28000 m^3 < V_C	**3**
	7000 m^3 < $V_C \leq$ 28000 m^3	**4**
	$V_C \leq$ 7000 m^3	**4**
Domestic, hotel bedroom, office	$V_C \leq$ 28000 m^3	**4**
	28000 m^3 < V_C	**4**

S_4: WINDOWS

Window FRP	Relative vertical distance R	Category
FRP < 0.5 hr	R < 1	**1**
	R ≥ 1	**2**
0.5 hr < FRP ≤ 1 hr	R < 1	**3**
	R ≥ 1	**4**
1 hr ≤ FRP	R < 1	**4**
	R ≥ 1	**4**

R = vertical distance / window height

S_5: FACADE

Type of void	Category
Continuous void in combustible facade	**1**
Continuous void	**2**
Void with special design solution to prevent fire spread	**3**
No void	**4**

S_6: MEANS OF ESCAPE

Maximum travel distance to an escape route	Minimum total width of exit routes of one story	Category
> 36 m	< 300 mm per 50 persons	**1**
	≥ 300 mm per 50 persons	**2**
30 – 36 m	< 300 mm per 50 persons	**2**
	≥ 300 mm per 50 persons	**3**
< 30 m	< 300 mm per 50 persons	**3**
	≥ 300 mm per 50 persons	**4**

S_7: LININGS

(This refers to the worst lining class (wall of ceiling) that is to be found in a room.)

Lining classes according to Euroclasses	Typical products	Category
Class F	Some plastics	**1**
Class E	Low density wood fibreboard	**1**
Class D	Wood (untreated)	**2**
Class C	Textile wall cover on gypsum board	**2**
Class B	Best FR woods (impregnated)	**3**
Class A2	Gypsum boards	**3**
Class A1	Stone, concrete	**4**

S_8: INSTALLATIONS FOR ESCAPE ROUTE

Exit signs	General lighting	Emergency lighting	Category
None	Manually switched on	Not provided	**1**
		Provided	**1**
	Always on	Not provided	**1**
		Provided	**2**
Normal	Manually switched on	Not provided	**1**
		Provided	**2**
	Always on	Not provided	**2**
		Provided	**3**
Illuminating light	Manually switched on	Not provided	**2**
		Provided	**4**
	Always on	Not provided	**3**
		Provided	**4**

S_9: VENTILATION SYSTEM

Type of ventilation system	Category
No specific smoke spread prevention through the ventilation system.	**1**
Central ventilation system, designed to let smoke more easily into the external air duct than ducts leading to other fire compartments. The ratio between pressure drops in these ducts is in the order of 5:1.	**2**
Ventilation system specially designed to be in operation under fire conditions with sufficient capacity to hinder smoke spread to other fire compartments.	**3**
Ventilation system with a non-return damper, or a smoke detector controlled fire gas damper, in ducts serving each fire compartment.	**3**
Individual ventilation system for each fire compartment.	**4**

S_{10}: DETECTION SYSTEM

Installation of detectors	Detector type	Category
No	-	**1**
Yes	Heat detectors	**3**
	Smoke detectors	**4**

S_{11}: SIGNAL SYSTEM

Installation of light signal	**Installation of sound signal**	**Category**
No	No	**1**
	Alarm bell	**2**
	Spoken message	**3**
Yes	No	**2**
	Alarm bell	**3**
	Spoken message	**4**

S_{12}: SMOKE CONTROL SYSTEM

Activation of smoke control system	**Type of smoke control system**	**Category**
No smoke control system	-	**1**
Manually	Natural ventilation through openings near ceiling	**1**
	Mechanical ventilation	**2**
	Pressurization and natural ventilation for extracting smoke	**2**
	Pressurization and mechanical ventilation for extracting smoke	**3**
Automatically	Natural ventilation through openings near ceiling	**3**
	Mechanical ventilation	**3**
	Pressurization and natural ventilation for extracting smoke	**4**
	Pressurization and mechanical ventilation for extracting smoke	**4**

S_{13}: SPRINKLER SYSTEM

Installation of sprinkler system	**Location of sprinkler**	**Category**
Without sprinkler system	-	**1**
With sprinkler system	In escape route only	**2**
	In compartment only	**3**
	Both in compartment and escape route	**4**

S_{14}: FIRE SERVICE

Response time of fire service to the site (min)	Number of access staircases	Category
> 23	1	**1**
	2	**1**
	> 2	**1**
9 - 23	1	**1**
	2	**2**
	> 2	**2**
6 - 9	1	**2**
	2	**3**
	> 2	**3**
< 6	1	**3**
	2	**4**
	> 2	**4**

S_{15}: HARDWARE MAINTENANCE

Fire engineering systems	Escape routes	Category
More than one year	More than three months	**1**
	At least once every three months	**2**
	At least once per month	**2**
At least once a year	More than three months	**2**
	At least once every three months	**3**
	At least once per month	**3**
At least twice a year	More than three months	**3**
	At least once every three months	**4**
	At least once per month	**4**

S_{16}: INFORMATION FOR OCCUPANTS

Written information	Fire drills	Category
No information	No drills	**1**
	Suppression drill carried out regularly	**1**
	Evacuation drill carried out regularly	**2**
	Suppression and evacuation drills carried out regularly	**2**
Written information available	No drills	**2**
	Suppression drill carried out regularly	**3**
	Evacuation drill carried out regularly	**4**
	Suppression and evacuation drills carried out regularly	**4**

S_{17}: SPECIAL HAZARD

Existence of hazard	Segregation from exit routes	Category
Yes	No	**1**
	Yes	**2**
No	-	**4**

S_{18}: NEIGBORHOOD

Distance to adjacent building (D)	Types of adjacent building	Category
$D < 6$ m	Ultra high-rise building (more than 40 stories)	**1**
	High-rise building (not exceeding 30 m)	**1**
	Low-rise building	**2**
$6 \text{ m} \leq D < 40$ m	Ultra high-rise building (more than 40 stories)	**1**
	High-rise building (not exceeding 30 m)	**2**
	Low-rise building	**3**
$D \geq 40$ m	Ultra high-rise building (more than 40 stories)	**2**
	High-rise building (not exceeding 30 m)	**3**
	Low-rise building	**4**

S_{19}: OCCUPANTS

Major occupant group	**Familiarity to the environment**	**Category**
Disabled	Unfamiliar	**1**
	Familiar	**1**
Aged	Unfamiliar	**1**
	Familiar	**2**
Normal adult	Unfamiliar	**3**
	Familiar	**4**

Appendix K Classifications of Probability for Parameters of Probability

P_1: UNEMPLOYMENT RATE

Unemployment rate (Y %)	Level
$Y \geq 7.5$	**A**
$5 \leq Y < 7.5$	**B**
$2.5 \leq Y < 5$	**C**
$Y < 2.5$	**E**

P_2: WEALTH GAP

(Gini coefficient is a statistical measure of income inequality ranging from 0 to 1.)

Gini coefficient (G)	Level
$G \geq 0.5$	**A**
$0.4 \leq G < 0.5$	**B**
$0.2 \leq G < 0.4$	**C**
$G < 0.2$	**E**

P_3: SOCIAL INEQUITY PHENONMENON

Social inequity problems	Level
More than one of the social problems	**A**
Religious bias	**B**
Racial inequity	**C**
Sex discrimination	**D**
None	**E**

P_4: WAR AND MILITARY ACTION

Latest war and military action	Level
Occurs at present	**A**
Occurred 1 to 5 years ago	**B**
Occurred over 5 years ago	**C**
Occurred over 10 years ago	**D**
Occurred over 50 years ago	**E**

P_5: TARGET OF TERRORIST

Target of terrorist	Level
Attacked by terrorists in the past	**A**
High probability	**B**
Low probability	**C**
Never	**D**

Appendix L Design Checklist

By studying the selected architectural features with different methodologies, the potential fire risks associated with the said features have been unveiled. When planning for the innovative design, building designers should pay more efforts on the fire safety aspect to ensure fire safety level of their works. For example, smoke movement should be watched carefully for the design of an enclosed space similar to the air cavity in a double-skin façade or internal building void. Meeting the minimum requirements in the prescriptive fire codes is certainly insufficient. For the ultra-high rise buildings, non-accidental fires should be taken into account to avoid recurrence of serious structural failure. Fire insulation should be considered with great cautions for steel structure. Any unconventional design might need further study before coming into sight in order to ensure fire safety level.

In light of the investigation results of this thesis, a checklist for architects' design consideration can be compiled as below:

L.1 Building Designs

Building designs appearing in the construction industry after the establishment of the existing fire codes, and having no additional considerations on their fire safety requirements are regarded as new architectural features. They may encounter special fire risks which are yet to be exposed and thus they should be distinguished for further investigations. Whether or not compliant with the existing codes might have diversified treatment.

L.2 Current Prescriptive Fire Codes

The conventional building designs can follow the existing fire safety requirements for fire resisting construction (FRC) (BD 1996a), means of escape (MOE) (BD 1996b) and means of access (MOA) (BD 1995) and fire services installations (FSI) (FSD 1998).

L.3 Code Compliance

For the new architectural features, they may either comply with the existing codes easily by fitting the numerical requirements or otherwise fail to conform the fire regulations. Failing to meet the minimum requirements stipulated in the existing codes would require for fire engineering design which is an alternative accepted in the local code (BD 1996a). However, their counterparts might conceal the potential fire hazards. Further study should be also carried out to unveil their hidden fire risks.

L.4 Fire Engineering Design

In the local codes, prescriptive fire regulations are the main approach and performance-based fire codes are still under development. Alternative approaches other than prescriptive one offering the same fire safety are accepted (BD 1996a) for the buildings of special hazards due to their size, height, use, design, construction or location. Individual fire risk assessment for the problematic building design, say full-scale burning study or numerical simulation, should be carried out to determine the additional fire safety provisions.

L.5 Inadequacies of Current Fire Codes

The existing fire codes developed tens of years ago were found lagging behind the fast development of the construction industry and some requirements might be underestimated or overestimated. For example, from the review of standard fire tests according to which the fire resistance period is determined, it is discovered that the real fire scenarios are not taken into account in the tests. The uncertainties hidden in the existing codes should be cleared even the new architectural design is compliant with the codes.

L.6 New Architectural Features

- Atrium design

Installation of sprinkler heads at high headroom atrium is not effective. The locations of sprinkler head are required for reconsideration. In addition, smoke curtain and fire shutter, one of the solutions to overcome the adverse effect of the open feature of atrium, can be installed at each level to isolate the atrium space in occurrence of a fire. Fire safety management should be also implemented to allow appropriate actions being taken in case of fire.

- Internal building void

Bathroom or kitchen are often constructed connecting the internal building void and it was found that smoke and even flame might spread through an internal building void to endanger adjacent stories. Usually, there is no requirement on FRP on the window opening of a bathroom or kitchen in local domestic building. However, it would be risky if the same is applied for a bathroom or kitchen open to an internal building void which should be protected in order to avoid smoke and flame spreading. Therefore, adequate FRP should be provided for the windows in the room adjacent to the internal building void. Further in-depth studies by full-scale burning tests or fire modeling are necessary for a fire hazard assessment. Full-scale burning tests should be carried out with a setup of at least five stories high in order to justify the design.

- Double-skin facade

The air cavity between two skins of a double-skin façade appears as an effective channel for spreading of smoke and flame in case of fire, with the assistance of natural or mechanical ventilation applied in the space to take away accumulated solar heat gain. A number of factors play a role in affecting smoke movement inside the air cavity, such as heat release rate, the opening to cavity, the geometry of the cavity and the applied airflow rate and pressure of the ventilation system. All of them should be investigated thoroughly before planning for the design.

- Ultra-high rise building design

Consequent to the tragedy of WTC twin towers, the existing requirements of fire safety provisions should be revisited for protection against the extreme events such as terrorist attacks. Non-accidental fires should be taken into account in view of the WTC incident. Fire safety management, software to provide fire safety, can be also implemented immediately to mitigate the potential hazards to a considerable extent, say stating clearing in the fire safety plan what actions should be taken under which circumstances.

In a non-accidental fire attack, physical damage might be accompanied as in WTC incident. Fire loading is not the only concern in considering the necessary fire safety protection. Structural behavior under non-accidental fires should be also investigated. Higher degree of collaboration between the structural engineers and fire engineering professionals is therefore expected.

- Other new building designs

Innovation is accompanied with the sophisticated society. Many brand new building designs would appear in the industry. In consideration of their unknown fire performance, further in-depth study, such as full-scale burning tests, is essential to determine the necessary fire safety measures before they are being erected.

A flow chart in Figure L-1 has summarized the design considerations for the planning of a new development. Necessary actions should be taken appropriately to maintain the fire safety level.

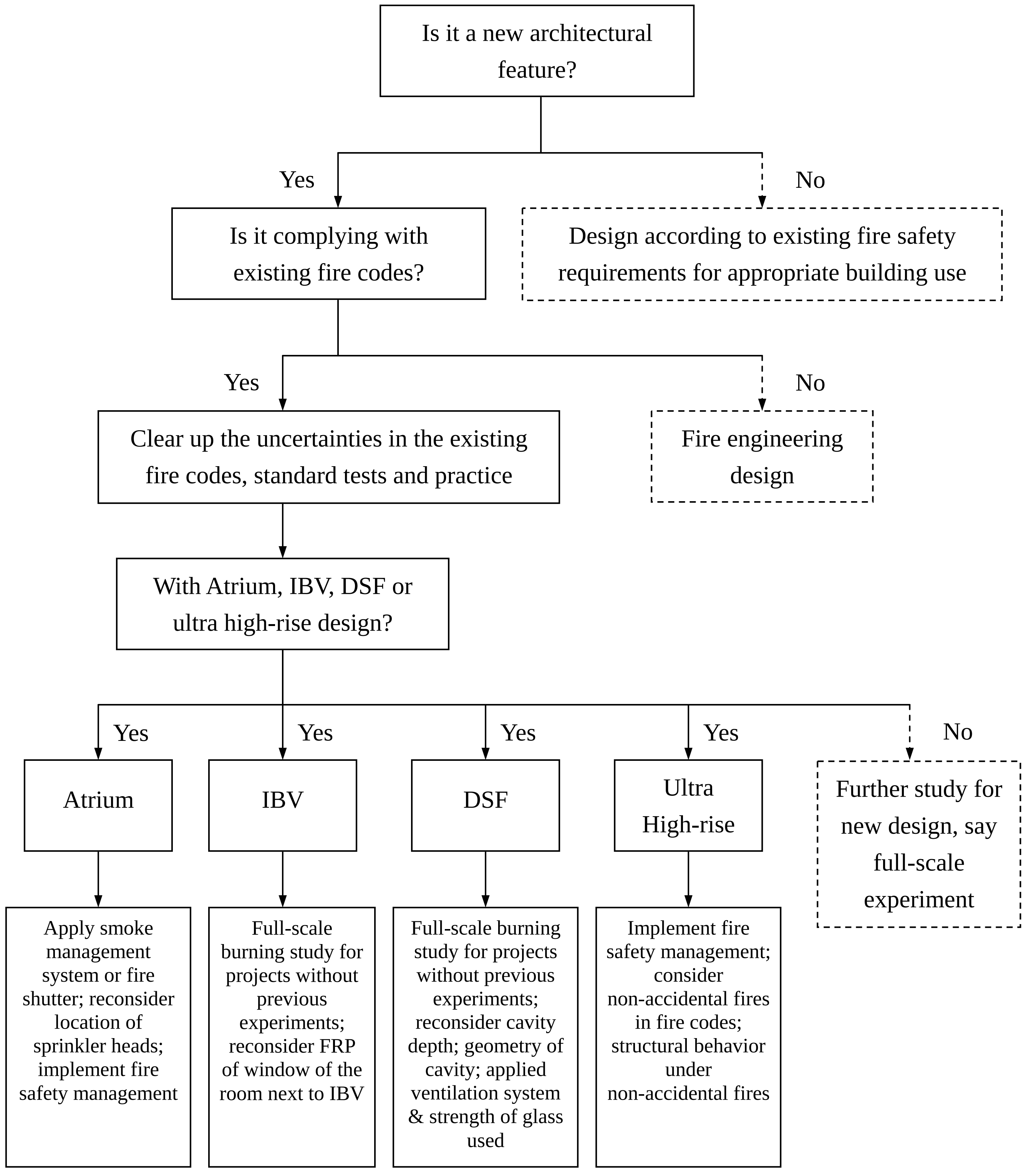


Figure L-1: Flow Chart Showing Design Considerations

REFERENCES

ABCnews. Final collapse, ABCnews.com, 11 September (2001).

Abdullateef M. Al-Khaleefi, Mohammad J. Terro, Alex P. Alex and Yong Wang. Prediction of fire resistance of concrete filled tubular steel columns using neural networks, Fire Safety Journal, Vol. 37, Issue 4, p. 339-352 (2002).

ASFP. TGN 007 On site guidance note for the specification and use of site applied intumescent coating systems. Technical Guidance Note, The Association for Specialist Fire Protection, UK (2001a).

ASFP. The correct application of Intumescent coating, The Association for Specialist Fire Protection (2001b).

ASFP. Application of Fire Resistant Coatings to Structural Steel, The Association for Specialist Fire Protection (2002).

ASFPCM, et al. Fire Protection for Structural Steel in Buildings, 2nd Ed., Association of Specialist Fire Protection Contractors and Manufacturers in conjunction with Fire Test Study Group and Steel Construction Institute, Aldershot, UK (1992).

Asker, J.R. Washington outlook, Aviation Week & Space Technology, September 17, p. 33 (2001).

ASTM. ASTM E 119, Standard test methods for fire tests of building construction and materials, American Society for Testing & Materials (ASTM), USA (2000).

ASTM. ASTM D 1655, Standard specification for aviation turbine fuels, American Society for Testing and Materials (ASTM), USA (2001).

ASTM. ASTM E 2114, Standard terminology for sustainability relative to the performance of buildings, American Society for Testing and Materials (ASTM), USA (2005).

Babrauskas, V. & Grayson, S.J. Heat Release in Fires, Elsevier Applied Science, London and New York (1992).

Baker, N. The atrium environment, Building Technical File, No. 21, p. 39-48 (1988).

BBC news, 19 February (2003a).

BBC news, 18 February (2003b).

BBC news, 6 February (2004a).

BBC news. 11 March (2004b).

BD. Code of practice for means of access for firefighting and rescue, Buildings Department (BD), Hong Kong (1995).

BD. Code of practice for fire resisting construction, Buildings Department (BD), Hong Kong (1996a).

BD. Code of practice for the provision of means of escape in case of fire, Buildings Department (BD), Hong Kong (1996b).

BD. PNAP 204, Guide to fire engineering approach, Practice note for authorized persons and registered structural engineers, Buildings Department (BD), Hong Kong, May (1998).

BD. PNAP 106, Curtain wall systems, Practice Note for Authorized Persons and Registered Structural Engineers, Buildings Department (BD), Hong Kong (1999).

BD. PNAP 239, Window and window wall, Practice Note for Authorized Persons and Registered Structural Engineers, Buildings Department (BD), Hong Kong (2000a).

BD. PNAP 219, Lighting and ventilation for bathrooms and lavatories in domestic buildings, Practice Note for Authorized Persons and Registered Structural Engineers, Buildings Department (BD), Hong Kong (2000b).

BD. PNAP 251, Testing of Building Materials, Practice Note for Authorized Persons and Registered Structural Engineers, Buildings Department (BD), Hong Kong (2001a).

BD. PNAP 256, Structural plans for curtain walls, window walls and cladding, Practice Note for Authorized Persons and Registered Structural Engineers, Buildings Department (BD), Hong Kong (2001b).

Beason, W.L. and Morgan, J.R. Glass failure prediction model, Journal of Structural Engineering, Vol. 110, No. 2, p. 197-212 (1984).

Behr, R.A. Seismic performance of architectural glass in mid-rise curtain wall, Journal of Architectural Engineering, Vol. 4, No. 3, p. 94-98 (1998).

Benyon, M. ,The atrium future forms in an old space, Canadian Architect, Vol. 27, No. 7, p. 14-23 (1982).

BOCA. National Building Code 1996, Building Officials and Code Administrators International (BOCA), USA (1996).

Brooks R. Intumescent Fire Coatings: the Importance of Volume Solids. Fire Safety Engineering, May, 17-19 (2003).

BS. BS 476: 1932, Fire tests on building materials and structures, British Standards (BS), British Standards Institution, UK (1932).

BS. BS 5368: Part 3, Methods of Testing Windows – Wind Resistance Tests, British Standard (BS), British Standards Institution, UK (1978).

BS. BS 6206, Specification for Impact Performance Requirements for Flat Safety Glass and Safety Plastics for Use in Buildings, British Standard (BS), British Standards Institution, UK (1981).

BS. BS 476: Parts 20: 1987, Fire tests on building materials and structures, Method for determination of the fire resistance of elements of construction (general principles), British Standards (BS), British Standards Institution, UK (1987a).

BS. BS 476: Parts 21: 1987, Fire tests on building materials and structures, Method for determination of the fire resistance of loadbearing elements of construction, British Standards (BS), British Standards Institution, UK (1987b).

BS. BS 476: Parts 22: 1987, Fire tests on building materials and structures, Method for determination of the fire resistance of non-loadbearing elements of construction, British Standards (BS), British Standards Institution, UK (1987c).

BS. BS 8202, Part 2, Coatings for Fire Protection of Building Elements, Code of Practice for the Use of Intumescent Coating Systems to Metallic Substrates for Providing Fire Resistance. British Standards (BS), British Standards Institution, UK (1992).

BS. BS 6262: Part 4, Code of Practice for Glazing for Buildings - Safety Related to Human Impact, British Standard (BS), British Standards Institution, UK (1994).

BS. BS 952: Part 1, Glass for glazing - Classification, British Standard, British Standards Institution, UK (1995).

BS. BS 5588: Part 0, Fire Precautions in the Design, Construction and Use of Building, Part 0: Guide to Fire Safety Codes of Practice for Particular Premises/ Applications, British Standards (BS), British Standards Institution, UK (1996).

BS. BS ISO/TR 13387-1: 1999, Fire Safety Engineering - Part 1: Application of fire performance concept to design objective, British Standards (BS), British Standards Institution, London, UK (1999a).

BS. BS ISO/TR 13387-2: 1999, Fire Safety Engineering – Part 2: Design fire scenarios and design fires, British Standards (BS), British Standards Institution, London, UK (1999b).

BS. BS 7974, Application of Fire Safety Engineering Principles to the Design of Buildings - Code of Practice, British Standards (BS), British Standards Institution, UK (2001).

BS. BS EN 13501-2, Fire classification of construction products and building elements Part 2: Classification using data from fire resistance tests, excluding ventilation services, British Standards (BS), British Standards Institution, UK (2003).

BS. BS 8800, Occupational health and safety management systems – Guide, British Standards (BS), British Standards Institution, UK (2004).

Building Journal Hong Kong China. HongkongBank headquarters building: An eye-catching “space-scraper” explores the Hong Kong skyline, August 1985, p. 62-86 (1985).

Building Journal Hong Kong China. Bank of China Tower: Accounting to nature through natural forms, June 1990, p. 50-88 (1990).

Bukowski, R.W. P.E. Predicting the fire performance of buildings: establishing appropriate calculation methods for regulatory applications, AsiaFlam ’95, International Conference on Fire Science and Engineering, Hong Kong, March 15-16 (1995).

Butz, J.R., Marmaro, R.W., Tetla, R.R.W. and Grosskopf, K.R. Fine water mists for suppression of Class B fuel fires, Halon Options Technical Working Conference. Proceedings. HOTWC 1994. Sponsored by: University of New Mexico, Halon Alternative Research Corp., National Association of Fire Equipment Distributors, Inc., Fire Suppression Systems Assoc., Hughes Associates, Inc. May 3 5, 1994, Albuquerque, NM, 596 pp (1994).

Button, D and Pye, B. Glass in Building: A Guide to Modern Architectural Glass Performance, Pilkington, Oxford, UK (1993).

Castle, G.K. The nature of various fire environments and the application of modern material approaches for fire protection of exterior structural steel, Journal of Fire and Flammability, Vol. 8 (1974).

Chow, C.L., Chow, W.K., and Lu, Z.A. Assessment of smoke toxicity of building materials. Proceedings of the 6th Asia-Oceania Symposium on Fire Science & Technology, Daegu, Korea, 17-20 March 2004, p. 132-142 (2004).

Chow, W.K. Numerical studies on recent large high-rise building fire, ASCE - Journal of Architectural Engineering, Vol. 4, No. 2, p.65-74 (1998).

Chow, W.K. A preliminary discussion on engineering performance-based fire codes in the Hong Kong Special Administrative Region, International Journal on Engineering Performance-Based Fire Codes, Vol. 1, No. 1, p. 1-10 (1999).

Chow, W.K. Smoke control by air curtain for spaces adjacent to atria, Journal of Environmental Systems, Vol. 27, No. 2, p. 151-162 (1999b).

Chow, W.K. Support on carrying out full-scale burning tests for karaokes, International Journal on Engineering Performance-Based Fire Codes, Vol. 3, No. 3, p. 104-112 (2001a).

Chow, W.K. Fire safety requirements in karaokes: comments on the new karaoke establishments bill, International Journal on Engineering Performance-Based Fire Codes, Vol. 3, No. 2, p.59-66 (2001b).

Chow, W.K. Numerical studies of air flow induced by mechanical ventilation and air-conditioning (MVAC) systems, Applied Energy, Vol. 68, No. 1, p. 135-159 (2001c).

Chow, W.K. Instant responses – On the attack fire at World Trade Centre, International Journal on Engineering Performance-Based Fire Codes, Vol. 3, No. 3, p. 128-129 (2001d).

Chow, W.K. Speech on ‘Essential fire safety provision for highrise buildings in Hong Kong: Lessons learnt from World Trade Centre incident’, Hong Kong Institute of Construction Managers, 8 January, 2002, Hong Kong (2002a).

Chow, W.K. Proposed fire safety ranking system EB-FSRS for existing high-rise nonresidential buildings in Hong Kong, ASCE – Journal of Architectural Engineering, Vol. 8, No. 4, p. 116-124 (2002b).

Chow, W.K. Review on heat release rate of burning furniture, International Journal on Engineering Performance-Based Fire Codes, Vol. 4, No. 2, p. 54-59 (2002c).

Chow, W.K. Fire safety in green or sustainable buildings: Application of the fire engineering approach in Hong Kong, Architectural Science Review, Vol. 46, No. 3, p. 297-303 (2003a).

Chow, W.K. Preliminary view on urban mass fires research, Forum on Fire Safety Science & Technology, National Key Basic Research Project (973 project), 6 November 2003, Hangzhou, Zhejiang, China – Paper presented (2003b).

Chow, W.K. Fire control safety idea of super building – in Chinese, Safety Bimonthly (An Quan), Vol. 25, No. 3, p. 7-11 (2004).

Chow, W.K. Aspects of fire safety in ultra highrise buildings, International Journal on Engineering Performance-Based Fire Codes, Vol. 6, No. 2, p. 47-52 (2004b).

Chow, W.K. Common problems on engineering performance-based fire codes and education training, Keynote speech to Workshop of the Fire Engineering Designs and Applications, 15-16 April 2004, City University of Hong Kong, Hong Kong (2004c).

Chow, W.K. (Ed.). Proceedings of the Fire Conference 2004 – Total Fire Safety Concept, 6-7 December 2004, Hong Kong, China (2004d).

Chow, W.K., Hung, W.Y., Zuo G., Dong H. and Gao Y. Preliminary experimental study of double-skinned façade, International Journal on Engineering Performance-Based Fire Codes, Vol. 6, No. 3, p.155-167 (2004a).

Chow, W.K., Hung, W.Y., Gao Y., Zuo G. and Dong H. Experimental study on smoke movement in double-skinned façade, Research Report, Areas of Strength: Fire Safety Engineering, The Hong Kong Polytechnic University (2004b).

Chow, W.K., Li, Y.Z., Cui, E. & Huo, R. Natural smoke filling in atrium with liquid pool fires up to 1.6 MW, Building and Environment, Vol. 36, No. 1, p. 121-127 (2001).

Chow, W.K. and Wong, L.T. Fire safety codes for Hong Kong: Inadequacy for atrium design, Building Services Engineering Research and Technology, Vol. 19, No. 2, p. 93-99 (1998).

CIBSE. Guide E, Fire Engineering, The Chartered Institution of Building Services Engineers, London, UK (2003).

CNN news. 16 June (2002).

Corbett, G.P. A case study of fire protection in large stadia: The San Antonio Alamodome, Journal of Applied Fire Science, Vol. 8, No. 2, p. 117-132 (1998-99).

Cuzzillo, B.R. and Pagni, P.J., Thermal breakage of double-pane glazing by fire, Journal of Fire Protection Engineering, Vol. 9, No. 1, p. 1-11 (1998).

Damage Control Information Newsletter. No. 010, Water mist fire suppression system part 1, Military Sealift Command, US Navy, US, 19 September (1997).

DIN 4102: Part 2, Fire behaviour of building materials and building components; building components; definitions, requirements and tests, Deutsches Institut Fur Normung, Germany (1977).

Drysdale, D. An introduction to fire dynamics, 2nd ed., Wiley, Chichester, UK (1999).

Emporis. Official World's 200 Tallest High-rise Buildings, Emporis Building Database, June (2005).

Favro, P.C. In consideration of elevators as part of a building evacuation scheme, The 2nd Symposium on Elevators, Fire, and Accessibility, The American Society of Mechanical Engineers, Baltimore, Maryland, 19-21 April (1995).

FEMA. World Trade Center Building Performance Study, Federal Emergency Management Agency, FEMA, US, May (2002).

Fire. Scientists recreate World Trade Center collapse. (News Extra), Fire, October (2003).

Fire Code Reform Research Program. Fire Code Reform, Fire safety in shopping centres, Final Research Report: Project 6, Sydney, Australia, July (1998).

Firetherm. Firetherm Firesteel Classic catalog, England (1998).

FIREWIND version 3,3, Fire Modelling and Computing Systems, Australia (2000).

Fordham, M. Natural ventilation, Renewable Energy, Vol. 19, p. 17-37 (2000).

Fortune, J.W. Mega-High-Rise elevatoring, Elevator World, December. (1997).

FSD. Codes of practice for minimum fire service installations and equipment and inspection and testing of installations and equipment, Fire Services Department (FSD), Hong Kong (1998).

GB 50045-95. Code for fire protection design of tall buildings, 2001 Ed., National Standard of The People’s Republic of China (2001) - In Chinese.

GBTool. Green Building Tool, Green Building Challenge (2005).

Geronsin, R. Job hazard assessment: a comprehensive approach, Professional Safety, American Society of Safety Engineers, p. 23-30, December (2001).

GIC. Effective building management & fire safety rest with owners, Daily Information Bulletin, Government Information Centre (GIC), Hong Kong Special Administrative Region, 26 June (1998).

Gratia, E. and Herde, A.D. Design of low energy office buildings, Energy and Buildings, Vol. 35, p. 473-391 (2003).

Greater London Council (GLC). London Building Acts, 1930-39, London Building (Constructional) By-laws, 1972, London (1972).

Grimwood, P. WTC fire and collapse, Fire, November (2001).

Hansell, G.O. Smoke control in atrium buildings, Building Control, No. 22, p. 40-51 (1987).

Harmathy T.Z. and Oleszkiewicz I. Fire drainage system, Fire Technology, Vol. 23, No. 1, p. 26, February (1987).

HKIA Journal. HKIA annual awards and exhibitions 97, PACE Publishing: Hong Kong (1998).

HKO. Summary of meteorological observations in Hong Kong 2002, The Year's Weather-2002, Hong Kong Observatory (HKO), Hong Kong (2002).

Hong Kong Standard (HKS). 11 January, Hong Kong (1994).

Hong Kong Standard (HKS). 21 November, Hong Kong (1996).

Hong Kong Standard (HKS). 26 January, Hong Kong (1997).

HKSAR Government. Chief Executive's Policy Address 2001, Hong Kong Special Administrative Region (2001).

HMSO. Post-war Building Studies No. 20, Fire Grading of Buildings Part I General Principles and Structural Precautions, Her Majesty's Stationary Office, London, UK (1946).

HMSO. Post-war Building Studies No. 29, Fire Grading of Buildings Part II Fire Fighting Equipment in Buildings, Her Majesty's Stationary Office, London, UK (1952).

HMSO. The Building Act 1984, Her Majesty's Stationary Office, London, UK (1984).

HMSO. The Fire Safety and Safety of Places of Sport Act 1987, Her Majesty's Stationary Office, London, UK (1987a).

HMSO. Statutory Instrument 1987 no. 286, The Nightwear (Safety) (Amendment) Regulations, Her Majesty's Stationary Office, London, UK (1987b).

HMSO. Fire precautions act 1971: guide to fire precautions in existing places of work that require a fire certificate: factories, offices, shops, and railway premises, Her Majesty's Stationary Office, London, UK (1989a).

HMSO. The Fire Precautions (Factories, Offices, Shops and Railway Premises) Order 1989, Her Majesty's Stationary Office, London, UK (1989b).

HMSO. The Building Regulations 2000, Her Majesty's Stationary Office, London, UK (2000).

Ho, D. Climatic responsive atrium design in Europe, ARQ: Architectural Research Quarterly, Vol. 1, Part 3, p. 64-75 (1996).

Hong Kong Christian Council. The missiological implication of the 2001 population census of Hong Kong (2004).

Hultquist, H. and Karlsson, B. Evaluation of a Fire Risk Index Method for Multi-storey Apartment Buildings, Department of Fire Safety Engineering, Lund University, Sweden (2000).

Hung, W.Y. and Chow, W.K. Review on fire regulations for new high-rise commercial buildings in Hong Kong and a brief comparison with those in overseas, International Journal on Engineering performance-based Fire Codes, Vol. 3, No. 1. p. 25-51 (2001).

Hung, W.Y. and Chow, W.K. Review on the requirements on fire resisting construction, International Journal on Engineering Performance-Based Fire Codes, Vol. 4, No. 3, p. 68-83 (2002a).

Hung, W.Y. and Chow, W.K. Architectural features for the environmental friendly century, Sustainable Building 2002: 3rd International Conference on Sustainable Building, 23-25 September 2002, Oslo, Norway – Paper 011 presented in the Session on New Symbiotic Building and Environmental Technology – The Future Scope in Subtropical Region (2002b).

Hung, W.Y. and Chow, W.K. Fire safety in new architectural design associated with the extensive use of glass, Proceedings of 2003 International Symposium on Fire Science and Fire-protection Engineering, China Fire Protection Association, p.389-396 (2003).

Hung, W.Y. and Chow, W.K. Review on fire protective coatings for structural steel elements, International Seminar on Recent Developments of Fire Protection in Structures, Fire Group of The Hong Kong Institute of Steel Construction, Hong Kong, 19 February (2004a).

Hung, W.Y. and Chow, W.K. Possible collapse scenarios of World Trade Center twin towers, Proceedings of the Subgroup 4: Smoke Movement and Toxic Harmful Gases Transfer in Fire of the National 973 Project "Fire Dynamics and Fundamentals of Fire Safety", Hefei, China, 26 May 2004, p. 16-24 (2004b).

ICC. International Building Code 2000, International Code Council, US (2000).

ISO. International Standard ISO 9705:1993(E), Fire tests: Full - scale room test for surface products, International Organization for Standardization (ISO) (1997).

ISO. ISO 3233, Paints and Varnishes – Determination of percentage volume of non-volatile matter by measuring the density of a dried coating. International Standards, The International Organization for Standardization (ISO) (1998).

ISO. ISO 834-1:1999, Fire-resistance tests - Elements of building construction - Part 1: General requirements, International Organization for Standardization (ISO) (1999).

Jackson, A. et al. Atrium buildings, Canadian Architect, Vol. 42, Part 4, p. 22-36 (1997).

JIS. JIS A 1304, Method of fire resistance test for structural parts of buildings, Japanese Industrial Standard (JIS), Japanese Standards Association, Japan (1994).

Jones, J., Messadi, T. and Li, S.S. Experimental study of the cooling season performance of ventilated double-glass envelope cavities, International Building Physics Conference, Tools for Design and Engineering of Buildings, September 18-21, 2000, Eindhoven, The Netherlands, p. 357-365 (2000).

Kent, C. Inside the livable city: The atrium, Inland Architect, Vol. 33, No. 1, p. 36-43 (1989).

Kitipornchai, S. Are tall buildings in Hong Kong safe from terrorist plane crashes?, Hong Kong Engineer, Vol. 29, No. 11, p. 23, November (2001).

Klote J.H. & Milke, J.A. Design of smoke management systems, American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), Atlanta, Georgia, USA (1992).

Kragh, M. Mechanically ventilated double skin facades, Advances in Building Technology: Proceedings of the International Conference on Advances in

Building Technology, December 4-6, 2002, Hong Kong, China, Volume 2, p.1233-1240 (2002).

Lam, J.C. An analysis of residential sector energy use in Hong Kong, Energy – The International Journal, Vol. 21, No. 1, p. 1-8 (1996).

Lam, J.C. and Li, D.H.W. An analysis of daylighting and solar heat for cooling-dominated office buildings, Solar Energy, Vol. 65, No. 4, p. 251-262 (1999).

Law, M. Prediction of fire resistance, Symposium No. 5, Fire Research Station, HMSO, London, UK (1971).

Laws of Hong Kong. Chapter 123F, Building (Planning) Regulations, Building Ordinance, Hong Kong (1997a).

Laws of Hong Kong. Chapter 123B, Building (Construction) Regulations, Building Ordinance, Hong Kong (1997b).

Laws of Hong Kong. Chapter 502, Fire Safety (Commercial Premises) Ordinance, Hong Kong (1998).

Laws of Hong Kong. Chapter 572, Fire Safety (Buildings) Ordinance, Hong Kong (2003).

Laws of Hong Kong. Chapter 573A, Karaoke Establishments (Licensing) Regulation, Hong Kong (2003b).

Lechner, N. Heating, Cooling, Lighting: Design Methods for Architects, 2nd ed., John Wiley, New York (2001).

Lee, B.E. and Wills, J. Vulnerability of fully glazed high-rise buildings in tropical cyclones, Journal of Architectural Engineering, /vol. 8, No. 2, p. 42-48 (2002).

LEED. Leadership in Energy and Environmental Design (LEED) Green Building Rating System for New Construction and Major Renovations (LEED-NC) Version 2.1 (2002).

LPS. LPS 1107, Issue 1, Requirements, Tests and Methods of Assessment of Passive Fire Protection Systems for Structural Steelwork, Loss Prevention Standard (LPS), Loss Prevention Certification Board Limited, Borehamwood, England (1987).

LPS. LPS 1124, Issue 2, Requirements, Tests and Methods of Assessment for LPCB Certification of Active Fire Protection Systems (Intumescent) for Structural Steelwork, Loss Prevention Standard (LPS), Loss Prevention Certification Board Limited, Borehamwood, England (1989).

Lui, G.C.H. and Chow, W.K. A preliminary proposal on fire safety management for karaoke establishments, System Safety Society: Proceedings of the 18th International System Safety Conference on System Safety on the Frontier of Technology, Fort Worth, Texas, U.S.A., 11-16 September, 2000, p. 76-84 (2000).

Ma, H. Illustrative description to the GB50045-95, Code for fire protection design tall buildings- In Chinese, Public Co. China (1995).

Magnago Lampugnani, V. Hong Kong architecture: the aesthetics of density, edited by Magnago Lampugnani, V., Prestel Verlag: New York (1993).

Malhotra, H.L. Fire resistance and fire behavior, CIB symposium on systems approach to fire safety, Tskuba, Japan (1979).

Malhotra, H.L. Design of fire-resisting structures, Surrey University Press, New York, USA (1982).

Malhotra, H.L., Fire safety in buildings, Building Research Establishment report, Department of the Environment, Building Research Establishment, Fire Research Station, Borehamwood, Herts, WD6 2BL, UK (1987).

Military Standard. MIL-STD-882C, Department of Defense System Safety Program Requirements, US, January (1993).

Milke, J. Study of building performance in the WTC disaster, Fire Protection Engineering, No. 18, p. 6-16 (2003).

Miller, E. Textiles properties and behavior in clothing use, B T Batsford Ltd, London (1992).

Morgan, H.P. and Hansell, G.O. Fire sizes and sprinkler effectiveness in offices – Implications for smoke control design, Fire Safety Journal, Vol. 8, p. 187-198 (1984/85).

Morris, W.A., Read, R.E.H. and Cooke, G.M.E. Guidelines for the construction of fire-resisting structural elements, Building Research Establishment, UK (1988).

Munro, J.R. A history of fire prevention in buildings I, The Architect and Surveyor, May/June (1970a).

Munro, J.R. A history of fire prevention in buildings II, The Architect and Surveyor, July/August (1970b).

Murrell, J. Multi-layer paint surfaces – a hidden fire hazard, Fire, p.19-20, March (1998).

Nash, P. & Young, R.A. Sprinklers in high-rise buildings, Fire Research Station, Building Research Establishment (1978).

NFPA. NFPA 101, Life Safety Code, National Fire Protection Association (NFPA), Quincy, MA (1994).

NFPA. The SFPE Handbook of Fire Protection Engineering, 2nd Ed., Society of Fire Protection Engineers, National Fire Protection Association (NFPA), USA (1995).

NFPA. NFPA 101, Life Safety Code 2000 Edition, National Fire Protection Association (NFPA), Quincy, MA, USA (2000a).

NFPA. NFPA 92B, Guide for smoke management systems in malls, atria and large areas, National Fire Protection Association (NFPA), Quincy, MA, USA (2000b).

NFPA. NFPA 601, Standard for Security Services in Fire Loss Prevention, Chapter 1 Introduction, National Fire Protection Association (NFPA), Quincy, MA, USA (2000c).

NFPA. NFPA 2001, Standard on clean agent fire extinguishing system, National Fire Protection Association (NFPA), Quincy, MA, USA (2000d).

NFPA. NFPA 101A, Guide on Alternative Approaches to Life Safety, National Fire Protection Association (NFPA), Quincy, MA (2001).

NFPA. NFPA 550, Guide to the Fire Safety Concepts Tree, Chapter 3 Definitions, National Fire Protection Association (NFPA), Quincy, Mass. (2002).

NFPA. Fire Protection Handbook, 19th ed., National Fire Protection Association (NFPA), Quincy, MA, USA (2003).

NIST. Documentary information received by NIST, News and Events, NIST and the World Trade Center, National Institute of Standards and Technology (NIST), US (2004a).

NIST. Project 6 – Structural Fire Response and Collapse Analysis, Federal Building and Fire Safety Investigation of the World Trade Center Disaster, NIST and the World Trade Center, National Institute of Standards and Technology (NIST), US (2004b).

NIST. Latest findings from NIST World Trade Center investigation released; Leading collapse sequence for each WTC tower defined, NIST and the World Trade Center, National Institute of Standards and Technology (NIST), US (2004c).

NIST. Shyam Sunder, S. and Gross, J.L., Fire resistance testing of WTC floor system, Federal Building and Fire Safety Investigation of the World Trade Center Disaster, NIST and the World Trade Center, National Institute of Standards and Technology (NIST), US (2004d).

NIST. Project 2 –Baseline structural performance and aircraft impact damage analysis, Federal Building and Fire Safety Investigation of the World Trade Center Disaster, NIST and the World Trade Center, National Institute of Standards and Technology (NIST), US (2004e).

NIST. Key findings of NIST's June 2004 progress report on the federal building and fire safety investigation of the World Trade Center disaster, NIST and the World Trade Center, National Institute of Standards and Technology (NIST), US (2004f).

NIST. NIST tests provide fire resistance data on World Trade Centre floor systems, NIST and the World Trade Center, National Institute of Standards and Technology, US (2004g).

ODPM. Approved Document B - Fire safety - 2000 edition consolidated with 2000 and 2002 amendments, The Office of the Deputy Prime Minister (ODPM), UK (2004).

Oriental Daily News. 19 November, Hong Kong (2002).

Parks, L.L., Kushler, B.D., Serapiglia, L.A., McKenna, L.A. Jr., Budnick, E.K. and Watts, J.M. Jr. Fire risk assessment for telecommunications central offices, Fire Technology, Vol. 34, No. 2, p.156- 176 (1998).

Pasadena Fire Department. Flammable fabrics, USA, http://www.ci.pasadena.ca.us/fire/flammable.asp (2001).

PHOENICS. Version 3.1, CHAM, UK (2000).

Pothorn, H. A Guide to Architectural Styles, Phaidon Press, Oxford (1983).

Process Architecture. Amenity space for interaction: Yamashita Sekkei: Recent works, Tokyo, p. 16-37 (1989).

Quintiere, J.G. Opportunities to learn from 9/11, Fire Protection Engineering, No. 21, p. 27-30 (2004a).

Quintiere, J.G. Review of NIST WTC investigation, Skyscraper Safety Campaign, p. 17-31, Sep (2004b).

Quintiere, J.G. A predicted timeline of failure for the WTC towers (2005).

Quintiere, J.G., Marzo, M. di, Becker, R., A suggested cause of the fire-induced collapse of the World Trade Towers, Fire Safety Journal, Vol. 37, p. 707-716 (2002).

Read, R.E.H. and Morris, W.A. Aspects of fire precautions in buildings, Fire Research Station, Building Research Establishment, Borehamwood, Hert, WD6 2BL, UK (1993).

Real News 24/7. http://www.realnews247.com/wtc_collapse_01.jpg (2005).

Redmill, F. Risk analysis – a subjective process, Journal of Engineering Management, Vol. 12, No. 2, April (2002).

Rehm, R. G.; Pitts, W. M.; Baum, H. R.; Evans, D. D.; Prasad, K.; McGrattan, K. B.; Forney, G. P., Initial Model for Fires in the World Trade Center Towers, Fire Safety Science. Proceedings. Seventh (7th) International Symposium, International Association for Fire Safety Science (IAFSS), June 16-21, 2003, Boston, MA, Evans, D. D., Editor(s), p. 25-40 (2003).

Saxe, T.J., Behr, R.A., Minor, J.E., Kremer, P.A. and Dharani, L.R. Effects of missile size and glass type on impact resistance of 'Sacrificial Ply' laminated glass, Journal of Architectural Engineering, Vol. 8, No. 1 (2002).

Saxon, R. Atrium buildings development and design, second edition, The Architectural Press: London (1986).

SCI. Structural Fire Safety: A Handbook for Architects and Engineers, Steel Construction Institute, Ascot, England (1999).

SCI. Steel Designers' Manual 6th ed., The Steel Construction Institute, Blackwell Science, Oxford, UK (2003).

South China Morning Post (SCMP). 21 November, Hong Kong (1996).

South China Morning Post (SCMP). 9 April, Hong Kong (1997).

South China Morning Post (SCMP). 6 January, Hong Kong (2004).

Shell Canada Limited. Shell aviation fuels, Aviation Products (2004).

Shields, T.J., Silcock, G.W.H. and Flood, M.F. Performance of a single glazing assembly exposed to enclosure corner fires of increasing severity, Fire and Materials, Vol. 25, p. 123-152 (2001).

Shields, T.J., Silcock, G.W.H., and Flood, M.F. Performance of a single glazing assembly exposed to a fire in the centre of an enclosure, Fire and Materials, Vol. 26, p. 61-75 (2002).

Shields, T.J., Silcock, G.W.H., and Hassani, S.K.S. The behavior of double glazing in an enclosure fire, Journal of Applied Fire Science, Vol. 7, No. 3, p. 267-286 (1997/98).

SSS. System Safety Analysis Handbook, 2nd Edition, System Safety Society (SSS), US, July (1997).

Stec, W.J. and Paassen, van A.H.C. Validation of the simulation models of the double skin façade, Advances in Building Technology, Vol. 2, p.1181-1188 (2002).

The Architectural Press. Building control in Inner London: the London Building Acts and Bylaws and their interpretation, London (1983).

Tamura, G.T. Smoke movement and control in high-rise buildings, National Fire Protection Association, Quincy, Massachusetts, USA (1994).

The Engineer. Protective “bubble” plan to shield terror targets, 1 November (2001).

The Textile Institute. Textile Flammability: current and future issues, Papers presented at the Textile Flammability: current and future issues conference 30-31 March 1999, UK (1999).

The World Bank Group. Module 5: Inequality measures, http://www.worldbank.org/wbi/attackingpoverty/events/Hungary_0603/Module5 MeasuringInequality.pdf (2004).

Thomas, P.H. Testing products and materials for their contribution to flashover in rooms, Fire and Materials, Vol. 5, p. 103-111 (1981).

Thomas. P.H. and Heselden, A.J.M. Fully-developed fires in single compartment – a co-operative research programme of the Conseil International du Batiment, CIB Report No. 20, Fire Research Station, UK, FR Note NO. 923, Aug (1972).

Tsui, S.C. and Chow, W.K. Legislation aspects of fire safety management in Hong Kong, Facilities, Vol. 22, No. 5/6, p. 149-164 (2004).

TVB. Television Broadcasts Limited (TVB) morning news, Hong Kong, 24 April (2003).

TVB Pearl. Television Broadcasts Limited (TVB), Innovation Life, Inspired (2004).

Walters, M. and Hastings, E. M. Fire safety legislation in Hong Kong, Facilities, Vol. 16, No. 9/10, p. 246-253, 1998.

Warrington. European Harmonised Testing, Warrington Fire Research Centre, http://www. wfrc.co.uk/testing_european_harmonization.htm (2002).

Watts, Jr. J.M. Fire risk assessment using multiattribute evaluation, In: Hasemi, Y., Editor, Fire Safety Science: Proceedings of the Fifth International Symposium, Internal Association for the Fire Safety Science, Elsevier, London, p.679-690 (1997).

Watts, Jr. J.M. Fire Risk Indexing, SFPE Handbook of Fire Protection Engineering, Third edition, National Fire Protection Association, Quincy, MA (2002).

Watts, Jr. J.M. and Kaplan, Marilyn E. Fire risk index for historic buildings, Fire Technology, Vol. 37, p. 167-180 (2001).

Wearne, P., Collapse: why buildings fall down, Channel 4 Books, London (1999).

Wood, A. McGrail, D. and Chow, W.K. Immediate action in providing fire safety in cities with dense highrise buildings: The possibility of incorporating skybridges, Symposium on Healthy Building in Urban Environment, Mainland – Hong Kong Joint Symposium 2004, ASHRAE-HKC/ CIBSE-HKB/ HKIE-BSD/ SHENYANG HVAC Committee, to be held in Shenyang, China, 28 & 29 July 2004 – Accepted to publish, June (2004).

US Coast Guard. Chapter 12, Preliminary Hazard Analysis (PrHA), Volumne 3, Risk Assessment Tools Reference, Risk-based Decision-making Guidelines (2005).

Usmani, A. S., Chung, Y. C., and Torero, J. L., How did the WTC towers collapse: a new theory, Fire Safety Journal, Vol. 38, p.501-533 (2003).

Zalosh, R.G. Explosion protection, SFPE Handbook of Fire Protection Engineering, 2nd Ed., Society of Fire Protection Engineers, National Fire Protection Association, Quincy, MA, US (1995).

PUBLICATIONS ARISING FROM THIS THESIS

Journal Papers

J1 Hung, W.Y. and Chow, W.K.

A review on architectural aspects of atrium buildings.

Architectural Science Review, Vol. 44, No. 3, p. 285-295, September (2001).

J2 Hung, W.Y. and Chow, W.K.

Review on fire regulations for new high-rise commercial buildings in Hong Kong and a brief comparison with those in overseas.

International Journal on Engineering Performance-Based Fire Codes, Vol. 3, No. 1, p. 25-51 (2001).

J3 Hung, W.Y. and Chow, W.K.

Review on the requirements on fire resisting construction.

International Journal on Engineering Performance-Based Fire Codes, Vol. 4, No. 3, p. 68-83 (2002).

J4 Chow, W.K. and Hung, W.Y.

On the fire safety for internal voids in high-rise buildings.

Building and Environment, Vol. 38, No. 11, p.1317-1325 (2003).

J5 Hung, W.Y.

Review on the World Trade Centre terrorist attack fires.

International Journal on Engineering Performance-Based Fire Codes, Vol. 5, No. 2, p.45-49 (2003).

J6 Hung, W.Y.

Architectural aspects of atrium, Special Issue: Advanced fire research and necessity on modeling fire and smoke management as part of the National 973 Project, Fire dynamics and fundamentals of fire safety.

International Journal on Engineering Performance-Based Fire Codes, Vol. 5, No. 4, p. 131-137 (2003).

J7 Chow, W.K., Hung, W.Y., Zuo, G., Dong, H. and Gao, Y.

Preliminary experimental study of double-skinned façade.

International Journal on Engineering Performance-Based Fire Codes, Vol. 6, No. 3, p.155-167 (2004).

J8 Hung, W.Y.

Provision of natural ventilation in Hong Kong premises and their associated fire safety problems.

International Journal on Engineering Performance-Based Fire Codes, Vol. 6, No. 4, p. 255-257 (2004).

J9 Hung, W.Y. and Chow, W.K.

Fire safety provisions for ultra highrise buildings consequent to the World Trade Center incident.

Journal of Applied Fire Science, Vol. 12, No. 1, p. 35-52 (2003-2004).

J10 Chow, W.K. and Hung, W.Y.

Possible collapse scenarios of the World Trade Center Twin Towers.

Asian Fire Fighting, Vol. 24, p.24-37 (2005).

J11 Chow, W.K., Hung, W.Y., Gao, Y., Zou, G. and Dong, H.

Experimental study on smoke movement leading to glass damages in double-skinned façade.

Construction and Building Materials, Accepted to publish, November (2005).

J12 Chow, W.K. and Hung, W.Y.

Effect of cavity depth on smoke spreading of double-skin façade.

Building and Environment, Vol. 41, No. 7, p. 970-979, July (2006).

Conference Papers

C1 Hung, W.Y. and Chow, W.K.

Several points of concern on fire resisting construction.

Symposium on System Design and Operation for Enhancing Sustainability of Buildings, 8-10 July 2002, Chongqing, China, p. A72-A79 (2002).

C2 Hung, W.Y. and Chow, W.K.

Architectural features for the environmental friendly century.

Sustainable Building 2002: 3rd International Conference on Sustainable Building, 23-25 September 2002, Oslo, Norway – Paper 011 presented in the Session on New Symbiotic Building and Environmental Technology – The Future Scope in Subtropical Region (2002).

C3 Hung, W.Y. and Chow, W.K.

Fire safety in new architectural design associated with the extensive use of glass.

2003 International Symposium on Fire Science and Fire-protection Engineering Proceedings, China Fire Protection Association, Beijing, China, p. 389-396 (2003).

C4 Hung, W.Y. and Chow, W.K.

Review on fire protective coatings for structural steel elements.

International Seminar on Recent Developments of Fire Protection in Structures, Fire Group of The Hong Kong Institute of Steel Construction, Hong Kong, 19 February (2004).

C5 Hung, W.Y. and Chow, W.K.

Possible collapse scenarios of World Trade Center twin towers.

Proceedings of the Subgroup 4: Smoke Movement and Toxic Harmful Gases Transfer in Fire, of the National 973 Project, Fire Dynamics and Fundamentals of Fire Safety, Hefei, China, 26 May 2004, p. 16-24 (2004).

C6 Hung, W.Y. and Chow, W.K.

Necessity of a fire risk assessment scheme for existing and new buildings.

Proceedings of the Fire Conference 2004 – Total Fire Safety Concept, 6-7 December 2004, Hong Kong, Vol. 1, p. 94-99 (2004).