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ISBN 0 901297 24 0

Tall/large building

A building of many storeys or of large size that may be occupied by significant numbers of people.

Hazard

Anything that has potential to cause loss or damage (harm).

Hazard (or emergency) scenario

The total circumstances within or around a tall/large building arising due to an event that may place occupant health and safety in jeopardy.

Risk

The combination of the likelihood of occurrence of a particular hazard and the consequences thereof.

Incident

An abnormal event within or outside a tall/large building that requires investigation by the building management and may give rise to an emergency.

Extreme event

A man-made or naturally-occurring abnormal event that may cause a major emergency in a tall/large building.

Emergency

An incident outside or within a tall/large building that requires investigation or action by emergency services.

Major emergency

An emergency caused by an extreme event outside or within a tall/large building that may place the safety of all occupants in jeopardy either by causing loss of stability of the whole building or by the environment in part or the whole of the building becoming harmful to health and safety due to fire gases or contaminants in the air, water or food supply.

Multi-occupancy

The occupancy of a tall/large building by more than one organisation.

Robustness

The ability of an engineered structure or system that enables it to survive a potentially damaging incident or extreme event without disproportionate loss of function.

Redundant structure

A structure that possesses more load paths than required for equilibrium.

Fire compartment

A part of a building, comprising one or more rooms, spaces or storeys, constructed to prevent the spread of fire to or from another part of the same building.

Ductility

The ability of a structural material or element to deform without fracturing.

Passive and active fire protection

- The real performance of buildings in fire compared to data from standard fire tests on components.
- The robustness of passive fire protection not only in extreme events but also over time in service.
- The effectiveness of compartments to prevent spread of fire and smoke.
- The survivability and functionality of active fire protection systems in extreme events.
- The desirability of a building being able to survive a full burn-out of its contents without collapse.

Escape, its management and the emergency services

- The physical robustness, size and safety of escape routes and the diversity of vertical escape options.
- The use of occupant access/egress lifts and emergency services' lifts for evacuation.
- Timely access for effective fire fighting and rescue, and provision of protected water mains.
- Provision for simultaneous evacuation in addition to phased evacuation.
- Management/emergency response plans for the evacuation of occupants depending on the nature and severity of the extreme event.
- Provision and use of communications and information systems during emergencies.
- Training of building management, emergency services and occupants in emergency management and response.
- Procedures for gathering relevant information when an extreme event occurs and for communication between building management, emergency services and occupants.

Other safety issues

Security and safety of cladding, including glazing

- Propensity to cause injury in the event of explosion, impact or fire outside or within the building.

Security and safety of building services

- Design of services systems for robustness, redundancy, and with isolation provisions.
- Protection and sealing of systems.
- Security against unauthorised access to building services equipment, plant and control rooms.

Security against unauthorised entry

- Prevention of approach and entry with malicious intent.
- Management and emergency services plans for response to potential extreme event scenarios.

Implementation of design and construction

- Assurance of adequacy, including durability, of safety-critical elements.
- Quality of components and workmanship in life-safety installations.

4 The collapses of the World Trade Center towers

4.1 The WTC towers collapsed following, in each case, deliberate impact by a Boeing 767 aircraft. Information on the attack and subsequent events leading to the collapse of the towers is given in detail elsewhere[(2)]. The events are summarised briefly below.

4.2 Each tower remained standing immediately after it was hit. Although the structure was weakened by the impact, the immediate damage to it, it may be said, was not disproportionate in the circumstances. There was however a substantial amount of local damage to the structures and to the passive and active fire protection. On impact, the aviation fuel from the aircraft caught fire and an immediate conflagration of fuel, aircraft and building contents developed in the vicinity. Gas temperatures as high as 900–1100°C locally in some areas and 400–800°C in others have been estimated[(2)]. After about 1 hour and 43 minutes in the case of the north tower (WTC1) and about 56 minutes in the case of the south tower (WTC2), the heat from the widespread fires had penetrated the remaining structure. The increase in temperature of the structure weakened it further in the vicinity of the crash location. As a result, it was unable to continue to support the section of the building above the crash site. This structure then failed allowing the building above to fall under gravity onto the section of building below. The descending section of building gained momentum as potential energy was released and converted to kinetic energy. A progressive collapse of the whole of each building followed, the increasing kinetic energy being sufficient to cause catastrophic damage to propagate downwards through the essentially undamaged lower storeys.

4.3 The aircraft impacted on the WTC1 tower almost centrally on the north face and the vertical axis of the building between the 94th and 98th floor. It caused substantial damage to the north face. For the WTC2 tower, the aircraft impacted on the south face between the 78th and 84th floor to one side of the central axis of the building. In this case substantial damage was apparent to the south face in the zone of impact. The aircraft impact nearer to one corner of the WTC2 tower appeared eventually to result in the upper section of that building tilting over to some extent from the vertical as it collapsed.

4.4 Prior to the collapses, several fire compartments of the buildings in the locality of the impacts had probably been breached. In addition, the lightweight fire protection to the nearby steel external columns, core columns and floor trusses was friable and would not have withstood the impact and subsequent fires in the breached compartments sufficiently to prevent the affected steelwork from heating up to temperatures at which load-bearing capacity was severely reduced. The column failures initiating the progressive collapses may have been somewhat different in the two cases because of differences in the impacts and fire damage. However, the cause, in generic terms, and the end result was the same. Both buildings suffered complete, catastrophic progressive collapse.

4.5 After the aircraft impacts, emergency services despatched to the towers concentrated on evacuating and rescuing people. Instructions to occupants of the towers appear to have differed depending on location. In some cases people were advised to leave the building, in others to remain. The reports of witnesses indicate that there was no expectation that the towers might collapse. As the gravity of the situation became more apparent, more people tried to leave the towers. Most of those below the impact-damaged floors managed to escape. For all but a very few people at or above the point of impact, escape was impossible because the stairs were impassable and the lifts unusable. The other effort of the emergency services was to fight the fires, but with lifts no longer working, access to the fire locations required an arduous climb. The effort was to no avail. In hindsight, it can be concluded that the circumstances made it impossible to put out the fires before the towers collapsed. The task was impossible not only because of the difficulty of access, but also because of the formidable obstacles to providing sufficient water at the fire location. In addition, destruction of the fire protection had greatly increased the vulnerability of the structure to the fire. Sadly many fire fighters were in the towers and also perished when they collapsed. There were more than 3000 fatalities amongst the occupants of the buildings and the aircraft, fire fighters, police and other emergency services personnel.

7.5.3 Security against unauthorised entry

7.5.3.1 The approach needs to focus on measures of deterrence and defence involving both the design and management of the building since detection of many hazardous substances is not practical. Measures that may be justified to reduce the risks of unauthorised entry include:

- Provide no more entry points than are needed to enable efficient use of the building and evacuation in major emergencies.
- Tightly manage and control entries, including goods delivery and basement parking. Sophisticated security equipment and vetting of security and contract staff may be needed.
- Install surveillance and monitoring systems, both outside and within the building, to give immediate warning of any suspicious activity and to deter access attempts and make apprehension and identification likely.

7.5.3.2 Effective security measures against unauthorised entry to tall/large buildings (and also against approaching into close proximity carrying destructive substances on the person or in road vehicles) can do much to reduce risks to occupants from malicious acts. Whilst architectural and engineering design can be made so that possible points of entry are limited in number and able to be controlled effectively, means of escape for occupants should not be prejudiced. Security systems can act as a barrier and deterrent to potential intruders. Constant surveillance may assist by providing early detection and record for subsequent police investigation. Provision of effective security is more difficult for tall/large buildings with multi-occupancy and/or multi-functions. A security policy is needed for each building implemented by a responsible team.

7.5.3.3 Preventing road vehicles from coming into close proximity of a tall/large building is an important mitigation measure for protecting occupants against malicious acts involving explosives. Physical barriers such as ditches, bollards, large planters and fountains can be designed and placed to keep unauthorised vehicles at a distance from the building. On the other hand, the design needs to allow access by emergency vehicles.

7.5.3.4 For security, performance monitoring and post-event analysis, the use of a 'black box' – analogous to those used in aircraft – could be considered. Technology associated with 'intelligent' buildings could be used to record useful data about the 'health' and status of the structure, the building systems, and occupant activity in and around the building.

7.5.4 Implementation of design and construction

7.5.4.1 The best intentions to provide for the safety of occupants can be undermined during the processes of design, construction, maintenance, repair and building management by:

- Errors in design.
- Defective construction (below-standard components and installation) not in accordance with the design and specifications.
- Shortfalls in the maintenance and repair of the building fabric and its systems.
- Shortfalls in the management of the building that allow management system failures to remain uncorrected and preparedness plans to lapse.

7.5.4.2 The large potential consequences in tall/large buildings caused by extreme events make it necessary for higher standards of risk control to be adopted in these processes.

7.5.4.3 To control the risks, independent third-party inspection and certification of the safety-critical aspects of design, construction and maintenance is needed to give adequate assurance of safety[15]. In particular, stricter and tighter on-site construction control is necessary, especially for safety-critical parts.

7.5.4.4 For tall/large buildings especially, independent third-party inspection and certification of fitness for use of products and installations should be required. The costs of the

8 Development and research needs

8.1 Development and research work on the following topics, many of which are interrelated, are needed to assist consideration of the initial recommendations for enhancing the safety of occupants in extreme events. In some cases, original study and testing is not needed. Rather development work is needed to bring together existing knowledge and understanding in order to develop practical guidance.

8.2 Vulnerability to progressive collapse

(1) Robust structures for tall/large buildings – the provision of ductility, energy absorption capacity and redundancy, and the design and protection of structural elements fundamental to safety.

(2) Provision of robustness and protection for stairwells and lift shafts.

(3) Analytical tools to support performance-based engineering design of buildings for extreme events, and in particular for combinations of events.

(4) Guidance on design of robust structures based on parametric studies of ductility in different construction systems, building types and details.

8.3 Passive and active fire protection

(5) The durability in a tall/large building environment of passive fire protection and its resilience to extreme events and to distortion of the base material.

(6) The behaviour of whole building structures in real fires using fire modelling.

(7) Compartmentation:

(a) Ability of compartments to prevent the spread of smoke or contaminated air.

(b) Diversity and robustness of escape routes.

(8) Standards of fire load and fire size for use in building design.

8.4 Escape, its management and emergency services

(9) Escape route flow and number, location and occupancy capacities of stairs in emergency situations where many occupants may wish to evacuate over a short period of time.

(10) Protection of escape routes from smoke or contaminated air for extended periods.

(11) Decision support and information/communication systems for implementation of response strategies and management of emergencies, including the escape of occupants and the protection of key personnel.

(12) Guidance on operational planning, including major emergency planning and management, based on emergency response strategies and protocols for the wide range of extreme event scenarios that can be foreseen as significant risks.

(13) Enhancement of the linkages between building management and the emergency services within emergency response strategies.

(14) Making communication between building management and occupants in a major emergency more effective.

(15) Occupant evacuation models for engineering design relating to fire and other extreme event scenarios. Modelling of incident development and occupant movement in order to inform response strategies, including testing of models.

(16) Detection systems for providing building management with real-time information on the conditions within and around the building and the status of building services and security systems.

(17) Use of lifts for evacuation and other use in emergencies.

7.2.3 Whilst extreme events are largely unpredictable, the occurrence of many amongst the large number of possibilities can be foreseen, e.g. severe earthquake in some parts of the world, accidental or deliberate road vehicle/aircraft impact, explosion, fire, or impact followed by fire. Generally designers have considered single extreme events and not combined events, such as occurred at the WTC towers where impact was followed by fire. Given a generally robust structure, the protection provided against extreme events can usually be made more effective by using an implicit or explicit risk identification process to determine the extreme events and combinations of circumstances most likely to occur. It may then be possible for the design to be adjusted to provide reduction of specific risks using risk management approaches as discussed in Appendix C. Such reductions may be identified in particular for combinations of potential impact, explosion and fire events.

Recommendations for consideration: Vulnerability to progressive collapse

- Raise the 'trigger' threshold, i.e. increase the capability of the structure to limit damage and to bridge over damaged parts by provision of alternative load paths. For this purpose, use structural elements with robust, ductile and energy absorbing properties and tie them together with strong ductile connections, recognising the directions of potential extreme event forces.
- Give specific consideration to elements that are fundamental to the survival of the structure.

7.3 Passive and active fire protection

7.3.1 Passive fire protection, including compartmentation

7.3.1.1 To be effective in extreme events, passive fire resistance materials require greater capability for resisting removal by impact, explosion, fire, or by degradation over time due to vibration or 'wear and tear' by occupants and maintenance. A greater capability for protecting structures in fires than provided for by current standards is also needed. The use of hydrocarbon-grade fire protection that has capability for withstanding rapid temperature rise and temperatures up to 1200^{O}C, might be considered. Practical research is needed on the resilience of passive fire protection materials to blast, impact and large deformations of the structure underneath, and the associated robustness criteria for these materials.

7.3.1.2 Modern tall/large buildings tend to contain considerable amounts of combustibles that can also cause relatively high temperature fires, especially if there is a through draught. Given these circumstances and the potential range of extreme events, it is suggested fire compartmentation should be more effectively provided and maintained in tall/large buildings. Pressurisation and smoke control should be a part of the design. Design fires should perhaps be assumed to last to 'burn out' with design based on the performance of the whole structure in real fires, as opposed to using the indications from standard comparative tests on building elements. The protection and compartmentation around key sources of fuel energy, such as oil storage, should be made to a high standard. Compromises to the integrity and effectiveness of compartmentation, for example as a result of installation of new IT and communications systems during building use, should be controlled by appropriate approval processes.

7.3.2 Active fire protection

7.3.2.1 Incidents of fire in buildings generally, and in tall/large buildings in particular, suggest that sprinklers, which commence in operation when the fire is small, are very effective in limiting the scale of fire losses, see Appendix A. However, sprinklers are usually not capable of extinguishing a large or fully developed fire as may arise nearly instantaneously from some man-made extreme events. Sprinklers remain a valuable protection in cases where relatively small fires are the initiating event. It is desirable to increase the effectiveness of sprinkler operation by providing redundancy in water supply systems and protection of water supply routes.

and capable of responding effectively to potential risks to safety. Consideration should be given to adopting a licensing system for tall/large buildings akin to the systems used for sports stadia in the United Kingdom.

Recommendations for consideration: Escape, its management and the emergency services

- Provide protection to escape routes from ingress of smoke.
- Protect vulnerable parts of building services systems and incorporate redundancy.
- Provide separate stand-by power for vital building services and for lighting of escape routes.
- Provide robust adequately-sized escape routes and diverse locations for them and provide protection for final exit routes.
- In addition to phased evacuation for emergencies, plan for timely simultaneous evacuation of a large proportion of floors in major emergencies, including use of lifts as well as staircases.
- Be prepared for extreme event emergencies through development and trial use of emergency response strategies that guide decisions on evacuation, communication with occupants and the emergency services
- As part of preparedness, make sure that: plans of the building are deposited in a remote accessible location; engineering advice can be obtained quickly during an extreme event; communication systems with floors, stairwells and lifts are in place and functioning; training for the management team, emergency services and occupants is given; and evacuation procedures are practised at regular intervals.
- Require independent approval, as a part of licensing and periodic audit of life-safety systems, of modifications to escape routes.

7.5 Other issues

7.5.1 Security and safety of cladding, including glazing

7.5.1.1 It is possible through appropriate selection of materials and design of glazing systems to reduce injuries to people caused by fragments of glass when explosion or fire occurs within or outside of the building. Levels of protection in existing buildings can be improved by the use of anti-shatter film. For new buildings, a higher level of protection can be obtained, for example by using laminated glass with an interlayer together with suitably designed window frames and fixings. A combination of laminated and toughened glass can be used in particularly vulnerable locations.

7.5.2 Security and safety of building services

7.5.2.1 The probability of occurrence of extreme events in create a hazard to occupants can be reduced a broadly-based strategy. The and its management. Measure

- Minimise the risk of hazardc 7.5.3.
- Make the air and water distri points (e.g. air intakes, air h mechanical equipment roo monitored with vision syste
- Reduce the vulnerability of systems by designing for and incorporating r in routes and provisions for isolating contaminated zones. that contamination released in

5.5.4.2 Buildings generally, including tall/large buildings, invariably have defects at the time they are handed over after construction. Current experience in the United Kingdom, for example, indicates that 'zero defects' at handover rarely occurs. Defects are often present in life safety installations such as security and fire alarms, passive fire protection and active fire fighting systems, e.g. sprinklers. Commercial pressures can result in sub-standard building products being on the market. Many products in use now have not undergone third party evaluation and a large proportion fail to meet fitness for purpose standards on first testing. The quality of installed sprinkler systems is not always ensured by installation inspections. Installed life-safety systems are not always commissioned and tested, or subsequently maintained in working condition.

5.5.4.3 An important feature of protective products and systems is that they are durable over time in service. They should not degrade significantly and undermine the protective capabilities of the systems. New installations or upgrades of existing installations should be made with long-term robustness in mind.

Key issues: Other issues

Security and safety of cladding, including glazing

- Propensity to cause injury in the event of explosion, impact or fire outside or within the building.

Security and safety of building services

- Design of services systems for robustness, redundancy, and with isolation provisions.
- Protection and sealing of systems.
- Security against unauthorised access to building services equipment, plant and control rooms.

Security against unauthorised entry

- Prevention of approach and entry with malicious intent.
- Management and emergency services plans for response to potential extreme event scenarios.

Implementation of design and construction

- Assurance of adequacy, including durability, of safety-critical elements.
- Quality of components and workmanship in life-safety installations.

2 Objectives of the Working Group

The Working Group, known as the 'Working Group on Safety in Tall Buildings', was set up by the Institution of Structural Engineers in October 2001. The Working Group operated in a collaborative way and included representatives from across the disciplines concerned with design, construction and management of tall/large buildings. It had the backing of the Construction Industry Council (CIC) and invited members included representatives of the Institution of Civil Engineers (ICE), the Royal Institution of Chartered Surveyors (RICS), the Chartered Institution of Building Services Engineers (CIBSE), the Royal Institution of British Architects (RIBA) and the Institution of Fire Engineers (IFE). Members also included professional engineers from New York and Hong Kong as well as from the United Kingdom experienced in the design of tall/large buildings and in safety and risk management. A number of other experts provided assistance to the Working Group by correspondence. The UK Department of Transport, Local Government and the Regions (DTLR) nominated an observer.

The objective of the Working Group was to provide guidance and advice on the implications that follow the collapses and the subsequent loss of life at the World Trade Center in New York on 11 September 2001.

At the outset it was decided the Working Group would not undertake any independent investigation of what happened at the World Trade Center. It would, however, consider all relevant available information, in particular the papers submitted to the Group by its members and others and the large number of papers published elsewhere since 11 September 2001. The aim has been to develop thinking so that the Group could provide guidance on safety issues in tall buildings. It was anticipated that the guidance produced would also be relevant to other buildings and structures that may be occupied by large numbers of people. The Group considered not only the collapses of the WTC towers but also collapses and damage to other tall/large buildings nearby and to other tall/large buildings in other parts of the world due to extreme events in recent years.

The activities of the Working Group have focussed primarily on the safety of people (occupiers/users/workers) in and around tall/large buildings rather than the safety or protection of the building itself.

The Working Group did not consider hazards that a tall/large building conceivably may pose to other buildings and infrastructure nearby. In particular, foundation movement disrupting nearby infrastructure and, in the extreme, progressive collapse of the building causing casualties and damage to buildings nearby were not examined. The likelihood of this latter hazard arising has generally been assumed to be negligible and thus acceptable until the collapse of the WTC towers on 11 September 2001. Avoidance of these potential hazards is not likely to be possible in the crowded centres of major cities. This Report assumes that the construction of tall/large buildings in close proximity to other buildings will continue to be permitted in cities.

response and safety of emergency services personnel (fire service, ambulance service, police and those who are required to disable and remove dangerous devices and substances) in major emergencies. As for building occupants, the steps taken by emergency services should be based on an assessment of the nature and effects of the emergency, including judgment of the likelihood that part or all of the building may become structurally unsafe. For this purpose, informed assessment from the local Building Control authority or structural engineers is essential. Its provision needs to be included in the preparations for major emergencies. Informed assessment is also needed to identify areas within the building that are already or may become dangerous or harmful to the health and safety of occupants. Finally contingency plans are needed for situations where a significant number of emergency services personnel are injured or otherwise made unable to operate.

5.4.3.2 Preparations for major emergencies should automatically include plans for attendance in the shortest possible time, for access to the building, and for the location of emergency services vehicles. They will also include the setting up, in association with the building management, of command and control procedures so that the response can be managed efficiently. Up-to-date information on the building and the incident should be to hand. Communication systems are very important in achieving an effective response. Reported shortfalls in communications in some tall/large building emergencies need to be avoided by initial planning, provision of effective equipment and training.

5.4.3.3 Emergency services teams cannot be effective in all possible emergency situations. For example, there are limits to what a team of fire fighters can do. For some major emergencies, there are some circumstances where no benefit would be gained by allowing emergency services personnel to enter the building, e.g. if dedicated fire fighting lifts are inoperable. Such considerations need to be taken into account in emergency response plans.

5.4.3.4 Optimum judgements on deployment of emergency services personnel are only likely to be made if emergency services managers have relevant knowledge of their capabilities and good information on the event. These managers need to be informed by the building management about the building itself and about the nature of the event, its location and scale, and the possible implications for the safety of the building and the health and safety of its occupants. Such information is crucial to decisions on whether emergency services should enter the building, the equipment they should carry, and their purpose. These requirements need to be met through the development of emergency management strategies and response plans for each tall/large building.

Key issues: Escape, its management and the emergency services

- The physical robustness, size and safety of escape routes and diversity of vertical escape options.
- The use of occupant access/egress lifts and emergency services' lifts for evacuation.
- Timely access for effective fire fighting and rescue, and provision of protected water mains.
- Provision for simultaneous evacuation in addition to phased evacuation.
- Management/emergency response plans for the evacuation of occupants depending on the nature and severity of the extreme event.
- Provision and use of communication and information systems during emergencies.
- Training of building management, emergency services and occupants in emergency management and response.
- Procedures for gathering relevant information when an extreme event occurs and for communication between building management, emergency services and occupants.

impracticability of timely access to the fire when it is at height and lifts are inoperable. Dedicated lift shafts for emergency services use can preserve access for fire fighting. However, extreme event damage can lead to loss of fire fighting lifts thereby preventing ready access by the emergency services to fire at height. Loss of water supply due to extreme event damage can also render fire fighting impractical. The provision of robust shafts and water supplies increases the possibility of effective fire fighting.

5.3.2.3 The heating, ventilation and air conditioning (HVAC) systems can play an important role in preventing the spread of smoke in tall buildings. However, such capabilities are not required in UK codes (except Section 20 buildings in inner London). Pressurisation of staircases (or natural ventilation) is only intended to keep escape and fire access stairs reasonably clear of smoke – it is not intended to keep floors clear. For tall buildings compartmentation is intended to reduce smoke spread from floor to floor. The effectiveness of còmpartmentation can be undermined by services penetrations, lift shafts and poor construction. HVAC systems can be designed to depressurise the fire floor and positively pressurise the adjacent floors, further reducing the spread of smoke – this is commoly referred to as 'sandwich pressurisation' or 'opposed airflow'. These systems are commmonly used in the United States and design methods are given in CIBSE Guide E[9] and NFPA 92A[10].

Key issues: Passive and active fire protection

- The real performance of buildings in fire compared to data from standard fire tests on components.
- The robustness of passive fire protection not only in extreme events but also over time in service.
- The effectiveness of compartments to prevent spread of fire and smoke.
- The survivability of effective active fire protection systems in extreme events.
- The desirability of a building being able to survive a full burn-out of its contents without collapse.

5.4 Escape, its management and the emergency services

5.4.1 Escape routes and emergency services access

5.4.1.1 The possibility of escape by people from a building in an emergency depends on whether safe evacuation routes are available. Questions arise on the size of escape routes and safe areas, on the dependability of services to escape routes and protected areas, in particular clean air supply and light, and on the extent to which escape routes and protected areas can be made resistant to extreme event damage.

5.4.1.2 Protected areas can be within or outside of the building. It is necessary for escape routes to protected areas and finally to places of safety to be adequate in size and negotiable safely by occupants. Where practical, designated 'safe refuge' areas within the building can be provided for some eventualities.

5.4.1.3 In some modern buildings, cores, escape routes and protected areas may be sealed and pressurised by air conditioning equipment, e.g. Petronas Towers in Kuala Lumpur. These systems need to be made robust so that they are unlikely to be made ineffective by physical damage or contamination in extreme events that are likely to occur. Smoke contamination of escape stairs has been reported in a number of major fire incidents in the United Kingdom, United States and Canada, sometimes with fatal consequences. Contamination may arise due to failure of containment barriers – doors being left open or inadequate sealing – or from lack of ventilation, pressurisation or purging provision for contaminated air.

5.4.1.4 In the United Kingdom, increased levels of protection for escape stairs with building height are required by codes relating to fires. For buildings over 18m high or when

5 Safety issues raised by the collapses of the World Trade Center towers

5.1 Major safety issues

5.1.1 Tall/large buildings should provide a safe environment for people within them and in their vicinity, and they should enable people to escape to safety as far as is practicable following an extreme man-made or naturally-occurring event. The provisions made have been tested in recent years not only at the World Trade Center but also elsewhere in the world, see Appendix A.

5.1.2 The aim of consideration of an extreme event in the design of a tall/large building is to accept that some damage to the building is likely to be inevitable and to design so that the damage is localised and still allows occupants the best chance of escape. Prevention of extreme man-made events through national and international security is a priority. **However, for the future, it has to be assumed that there may be more severe and different extreme events in tall/large buildings than have occurred to date. Limitation of damage for all eventualities to that which is tolerable or practicable has to be the working aim.**

5.1.3 In this context, several key questions arise from the experience of the WTC tower collapses:

- **What can be done to reduce the vulnerability of a tall/large building to collapsing progressively and totally?**
- **Should provisions for the protection of occupants and the building itself in the event of fire be set at a higher standard?**
- **Could escape routes and evacuation of building occupants and the linkage with the emergency services be better provided and managed to help save lives?**

5.1.4 The above questions and others lead to the need to review how designers and owners/operators determine an appropriate level of protection against extreme events which have remote probabilities of occurrence but which potentially have very severe consequences. The questions focus attention on safety issues that are multi-disciplinary and strongly interrelated. They are discussed below.

5.2 Vulnerability to progressive collapse

5.2.1 The concept of disproportionate damage relates to the cause of the damage. It is generally expected and required that 'small' events that may damage man-made artefacts and organisations should only cause relatively 'small' damage. Similarly 'large' events (in comparison to the artefact's size and purpose or to the organisation) causing 'large' damage may be accepted, particularly if the event is rare or totally unforeseen. There is an expectation that damage will be resisted to a practical extent in the operating environment. This expectation applies to all artefacts, including tall/large buildings. In the case of the damage on 11 September 2001 to the WTC towers, the initial impact damage caused by the aircraft was not disproportionate in the circumstances. The subsequent situation where many fatalities resulted from inability of occupants to escape from locations above the points of impact and from the eventual fire-induced progressive collapses may be less acceptable if it could be prevented by practicable means. The challenge now is to determine if and how such situations can be avoided in the future.

5.2.2 Progressive collapse is a term well understood by structural engineers to refer to a spreading of collapse through a considerable part or the whole of a structure following local damage to a relatively small structural part. The event causing the initial local damage does not generally provide the energy required to cause collapse to propagate progressively. In most cases of progressive collapse in building and civil engineering structures, the energy is derived from potential energy released as parts of the structure fall under gravity. Depending on the form of the structure, progressive collapse may progress vertically or horizontally. For tall buildings, vertical progression is usually the main concern[4].

fire locations. These floors then began to add to the kinetic energy of the falling construction, adding more 'fuel' to the destruction of the building and bringing the rate of collapse similar to that of free fall.

Key issues: Vulnerability to progressive collapse

- The redundancy of the structure and available alternative load paths.
- The strength, ductility and hence the energy absorption capacity of the structure (i.e. the structural elements and particularly the connections between them).
- The retention of structural integrity in fire.

5.3 Passive and active fire protection

5.3.1 Passive fire protection, including compartmentation

5.3.1.1 The purpose of passive fire protection of structural elements in buildings is to prevent or delay temperature rise in the elements so that they are not weakened to the extent that they can no longer fulfil their load-carrying role before people have left the building and surrounding areas and, if possible, the fire is brought under control or burns out. For steel-framed buildings, the fire protection of columns is particularly critical. Protection is by means of a non-combustible material encasing and in contact with the element and/or of an insulating casing that prevents fire gases reaching the element directly. For this purpose the protection needs to have strength and stability in fire conditions as well as heat insulating properties and a surface finish with low spread of flame properties.

5.3.1.2 Passive fire protection is usually given a time rating over which it will remain effective, based on standard laboratory tests, i.e. the BS 476 test in the United Kingdom and the ASTM E119 test in the United States[5]. Laboratory furnaces are relatively small and therefore cannot mimic the real behaviour of a structure in fire, only the performance of an individual element. The time rating does not bear any relation to the time the building will survive in a 'real' fire. The standard laboratory tests are comparative and not intended to be predictive of behaviour in fire in a building.

5.3.1.3 The aircraft impacts and fires were very onerous challenges to the fire resistance provisions in the WTC towers. Gas temperatures as high as 900–1100°C have been estimated to have developed locally in the fires[2]. Much of the passive fire protection would have been destroyed in the vicinity of the aircraft impacts by the impacts themselves and the fire of aviation fuel, followed by ignition and burning of the aircraft and building contents. Additionally, there is the possibility that the overall integrity of the passive fire protection systems was weak prior to the damage on 11 September 2001. Passive fire protection should be the correct thickness, durable and remain firmly in place during the life of the building. It should not flake or fall off. It should also be resistant to removal by building movement and vibration and by 'wear and tear' by occupants and building maintenance personnel.

5.3.1.4 Compartmentation is used as a passive protection in buildings to prevent (or at least delay) the spread of fire and smoke from its initial location. Separate compartments may be created from a floor, part of a floor, escape staircase or lift shaft so that people outside the compartment on fire are safe until rescued, or have a safe escape route. Compartment effectiveness may be reduced over time by poorly managed building operations, for example installations of IT and communications systems. Inadequately supervised cabling installations often leave holes where fire and smoke can pass through.

5.3.1.5 Generally passive fire protection and compartmentation have protected people to a considerable degree from conventional fires in buildings, i.e. fires involving the burning of the contents generally found in offices, residential buildings and the like. Flame damage is usually concentrated close to the origin of the fire indicating the effectiveness of compartmentation. However, compartmentation is often less effective at controlling smoke spread. When extreme damage is inflicted, such as in the WTC towers, compartsafety in emergencies, i.e. what might be considered to be 'conventional' accidental events, e.g. a local fire. In the latter case, there is generally no need for early complete evacuation of the building, although phased evacuation of several floors may be needed. Normal practice would involve a pre-alarm whereby only security personnel would be informed of the early stages of an incident. An alarm or evacuation request would be relayed to occupants by the building management after the incident has been investigated and only if it is considered to be sufficiently serious to merit a partial or complete evacuation. This approach reduces the risk of false alarm but inevitably results in delay in starting evacuation. However, where a fire can be seen, heard or felt, evacuation is likely to begin earlier. For all incidents, the building management (and at a later stage the emergency services) need access to sufficient accurate information to formulate an appropriate emergency response. Given the wide range of possible emergencies, reliable systems are required to enable management to obtain the relevant information about the incident and resulting conditions in the building so that an appropriate response can be determined. Likewise, reliable systems are needed to enable implementation of the response.

5.4.2.3 The preliminary incident alarm to occupants may be followed by some form of partial evacuation in which occupants are moved away from the affected area. The remainder of the occupants are not disturbed or, perhaps more usually, are informed of the situation, placed on standby, and requested to continue normal activities unless otherwise instructed as the incident progresses.

5.4.2.4 Such procedures of phased evacuation may be considered adequate for most normal hazard scenarios, particularly accidental fires associated with the specific occupancy. Such fires usually have small beginnings and can be confined to an area or to one floor of a building, for an extended period. The challenge for building management in such situations is usually to ensure a timely and calm response by the occupants, with a rapid and efficient evacuation of the affected area or floor.

5.4.2.5 The management of a major emergency in a tall/large building arising from an extreme event can be crucial to the safe escape of the building occupants. The right decisions are not easily determined, since any major emergency will be a unique event. Decisions have to be made quickly bearing in mind the whole building and not just the location of the incident.

5.4.2.6 There have been a number of recent incidents in tall/large buildings of sufficient magnitude to involve several floors at once, to threaten the whole building structure and to alarm the building occupants as a whole, e.g. the aircraft strikes on the WTC towers, and the bomb explosions at St Mary Axe, The Murrah building and the WTC1 tower, see Appendix A. Dealing with such major emergencies requires integration of building design and emergency management strategies. The incidents have highlighted inefficiencies and difficulties of ensuring efficient, rapid and well-managed evacuation of tall/large buildings. Current prescriptive design has been developed with fire emergencies primarily in mind and emphasises the provision of horizontal and vertical means of escape. However, reports of occupant behaviour during the recent incidents show that these provisions are often inappropriately or inefficiently used. In some cases evacuation times have been long because occupants have been slow to respond to requests to evacuate and have then tended to crowd some routes whilst others are underused. In other cases, occupants have all tried to leave at once, clogging escape routes designed even for simultaneous evacuation, let alone those designed for phased evacuation. Efficient evacuation depends upon the implementation of an effective emergency management strategy, making the best use of warning systems, security staff and escape routes.

5.4.2.7 Where it is decided in a major emergency that the best strategy is to maintain occupants in place with progressive phased evacuation of affected parts of the building, then particular consideration needs to be given to the advice to occupants to remain or leave as required.

5.4.2.8 Where it is decided that complete evacuation, or evacuation of large numbers of people from a number of floors simultaneously, is required, then escape routes must have sufficient capacity and be a practical option for the majority of occupants. Not all occupants with the normal range of physical capabilities are likely to be able to walk down 50–100 storeys of built-in redundancy. Effective live communications between the building management and occupants, easy-to-follow signs, and reliable lighting of routes, e.g. using battery back-up power, are important provisions.

7.4.2 Management of escape

7.4.2.1 The primary aim in management of emergencies in tall/large buildings is to maintain a safe environment where occupants are located in the building, especially in normal circulation areas and escape routes. A second aim is to manage the occupant population and ensure the optimal means of getting people safely to a place of safety, away from danger and out of the building if necessary.

7.4.2.2 Maintenance of a safe environment depends firstly upon the continuing structural stability and integrity of the building. Continuing structural stability is required for at least sufficient time for occupants to receive warning and evacuate to a place of safety within the building, or if the overall stability of the structure is in doubt, to a safe distance from it. Continuing stability is also important to enable emergency services personnel to retreat clear of the building.

7.4.2.3 Secondly, keeping the environment safe usually also depends upon prevention of the spread of smoke and other airborne hazardous substances. Prevention of their spread can be achieved by compartmentation, assisted by HVAC systems that control air circulation and ventilation, pressurise compartments, e.g. stairs, and contain or purge contaminated air as appropriate.

7.4.2.4 Meeting the second aim depends mainly on:

- Implementation of an emergency response strategy appropriate to the emergency scenario.
- Provision of adequate means of detecting, locating and assessing the hazards and providing appropriate information and requests/instructions to occupants. Sensors are not available or are not reliable for many possible contaminants. As a result, strategies that do not rely on feedback have to be used.
- Provision and protection of safe areas in the building and of emergency means of escape that have adequate capacity to enable occupants to reach a place of safety, when necessary, without being exposed to hazardous conditions.

7.4.2.5 The development of better management, training and information systems is needed to enable effective management of major emergencies as well as those emergencies that can be considered as more conventional. Building managers need to have a wide range of extreme event scenarios in mind.

7.4.3 Interaction with emergency services

7.4.3.1 New emergency response strategies and protocols need to be developed for the management of occupants applicable to the different scenarios that may arise. The nature of the extreme event and its location will have an important bearing on the risk to occupants and how their safety is best protected. For the wide range of potential hazard scenarios, it is necessary to consider how building management will be able to obtain sufficient reliable information during an incident to enable them to decide on an appropriate plan of action and how they will communicate with occupants and emergency services.

7.4.3.2 A key member of the building management team needs to be made responsible for the preparation of emergency response strategies. Appropriate structures for devolution of responsibility are required. Training of the building management team in the handling of emergencies is crucial. They need to be familiar before a major emergency occurs with the hazard scenarios that may arise so that they can identify them and decide quickly on an optimum response in any particular case. Knowledge, experience and training are perhaps the best safeguards against human error in the handling of emergencies. This consideration is also relevant to building occupants: they need to be familiar through training with what could happen and how they could escape.

possible extreme man-made events that may occur. There may be many options for enhancing provisions for the safety of building occupants. Decisions need to be made by owners, operators, designers and building managers based on an understanding of all the issues. They need to be based on rational consideration of the 'profile' of the building and the risks to safety during its intended life. There are strong links relating to safety between the building structure, fire protection, services systems and the building management and emergency services. Multi-disciplinary effort is essential to optimise safety. Overall strategies involving the design and construction of the building, its management and the relationships with emergency services are required in order to maximise protection of building occupants.

9 Concluding remarks

9.1 Current world wide social and political conditions suggest that it is now necessary explicitly to take account of risks arising from a wider range of extreme events than has been traditionally considered in the design, operation and management of tall/large buildings. Consideration by the Working Group of recent extreme events causing danger to occupants and damage to tall/large buildings has identified a number of multi-disciplinary and interrelated safety issues.

9.2 The safety of occupants in new and existing tall/large buildings can be enhanced in many extreme event scenarios by reductions in vulnerability to disproportionate damage and more effective protection through design, construction and building management measures. The Working Group believes the key to minimising risks to occupants in extreme man-made events is to use overall strategies involving design, construction, maintenance, operation and management of the building. The initial recommendations made in this Report indicate the main directions for reducing risks to occupants.

9.3 The Working Group recognises that implementation of the recommendations in these directions will depend on the 'profile' of the building and the extreme man-made events considered in any particular case. Development and research are required to provide the necessary tools and standards. In this way the safety of occupants in new and existing tall/large buildings and the safety of the buildings themselves can be enhanced in the future.

9.4 The Working Group benefited from drawing on a wide range of expertise across disciplines and from world-wide locations. In itself this collaboration has proved fruitful and may serve as a model for future investigations/reports into other building/construction issues.

9.5 The salutary reminders of the scale of loss of life and human tragedy at the World Trade Center have been at the forefront in discussions of the implications. The Working Group acknowledges that 11 September 2001 will remain a defining moment in the history of building performance in the face of a malicious attack on civilised life.

Escape, its management and the emergency services

- Provide protection to escape routes from ingress of smoke.
- Protect vulnerable parts of building services systems and incorporate redundancy.
- Provide separate stand-by power for vital building services and for lighting of escape routes.
- Provide robust adequately-sized escape routes and diverse locations for them and provide protection for final exit routes.
- In addition to phased evacuation for emergencies, plan for timely simultaneous evacuation of a large proportion of floors in major emergencies, including use of lifts as well as staircases.
- Be prepared for extreme event emergencies through development and trial use of emergency response strategies that guide decisions on evacuation, communication with occupants and the emergency services.
- As part of preparedness, make sure that: plans of the building are deposited in a remote accessible location; engineering advice can be obtained quickly during an extreme event; communication systems with floors, stairwells and lifts are in place and functioning; training for the management team, emergency services and occupants is given; and evacuation procedures are practised at regular intervals.
- Require independent approval, as a part of licensing and periodic audit of life-safety systems, of modifications to escape routes.

Other issues

Safety of cladding, including glazing

- Use laminated and/or toughened glass with fixings designed to take account of potential explosion loading/impact/fire.

Security and safety of building services

- Use a broadly-based strategy involving design and building management to reduce the risks.

Security against unauthorised entry

- Reduce the probability of occurrence of extreme man-made events with potential to cause progressive collapse, where practicable. For this purpose, use incident prevention or limitation measures, e.g. provide barriers to protect the base of the building from vehicle impact or explosion, and provide security against unauthorised entry.
- Use both design and management provisions to deter and protect against extreme man-made events taking place in or near the building.

Inspection of design and construction

- Reduce the risk of the building performance being compromised during the design and construction processes by appropriate use of independent third-party inspection, testing and certification of safety-related structure and systems.

A1 Damage caused by explosions

Ronan Point, London 1968

A1.1 In the United Kingdom, the progressive collapse of part of the 22-storey Ronan Point flats following a gas explosion on the eighteenth floor is well known[A1]. There were four fatalities. Subsequently the phenomenon of progressive collapse was demonstrated in the laboratories of the Building Research Establishment in the United Kingdom.

A1.2 Following the Ronan Point collapse, the UK Building Regulations were revised to include a requirement for buildings of 5 or more storeys to be designed with the aim that damage caused by an extreme event is not disproportionate to that event, see Appendix B.

World Trade Center, New York 1993

A1.3 A large car bomb was detonated against the south wall of the 110-storey north tower (WTC1) of the World Trade Center in an underground garage two levels below ground[A2]. There were only six fatalities but over 1000 people were injured. Electrical and water supplies were cut and sprinklers and standpipes were made inoperable. The most severe structural damage occurred in the basement levels, creating extensive bomb craters on some of the levels. A shock wave propagated throughout the basement structure, causing the slabs at parking levels to shear free from their supporting columns and other restraint locations. In certain positions, the steel columns that were once braced at the parking levels had unbraced lengths as large as 21m after the explosion.

A1.4 The structural integrity of the tower was not threatened due to the ductility of the framed tube of structural steel and the provisions made in the design of the tower. It was designed to resist a 240km/h wind storm, the loss of perimeter columns by sabotage, and the impact of a fully-loaded Boeing 707 aircraft at any height. Although lateral horizontal pressures during the explosion were severe, the tower did not collapse because the magnitude was insufficient to cause the columns to fail in shear or in combined axial load and bending.

A1.5 Buildings adjacent to the WTC1 tower were designed to less onerous requirements and suffered extensive damage that threatened their structural integrity.

Murrah Federal Building, Oklahoma City 1995

A1.6 A large vehicle bomb was detonated approximately 5m from the north face of the Murrah Building[A3]. The explosion and resulting collapse caused 168 fatalities and substantial damage to the Murrah Building and to other buildings in the vicinity of the blast. The nine-storey Murrah Building of reinforced concrete slab and column construction was damaged severely at the north face where three of the four external columns and an internal column were destroyed causing a 3rd floor spandrel to give way. As a result, eight of the ten bays along the northern half of the building collapsed progressively, together with two bays on the south side. Surveys of the damaged building found that progressive collapse extended the damage beyond that caused directly by the blast.

St Mary Axe and Bishopsgate, London 1992/3

A1.7 Two separate incidents of detonation of relatively large bombs occurred in London[A2]. Only one building suffered complete collapse, a 14th century church, but many suffered considerable damage to cladding and internal fixtures and fittings. Only four buildings immediately adjacent to the explosions suffered severe local structural damage.

A1.8 The European Bank for Reconstruction and Development, approximately 150m from the bomb in St Mary Axe, suffered extensive glass damage. The building was shielded from the blast by an adjacent building and so did not suffer structural damage.

A1.9 The glass damage to the European Bank building illustrated the influence of glass type, size, plaster on both sides and aluminium-framed windows. The fire spread externally up 13 storeys on two of the facades to the top of the building, readily igniting combustible finishes inside the windows of the floors above, enabling the vertical spread of the fire to continue. There were 179 fatalities.

Las Vegas Hilton Hotel 1981

A2.4 This 30-storey hotel of reinforced concrete construction had windows between floors separated vertically by a prefabricated spandrel of masonry, plaster and plasterboard on steel studs. The fire started on the 8th floor of the east tower lift lobby involving curtains, carpeting on the walls, ceiling and floor, and furniture. An exterior plate glass window shattered allowing a flame front to extend upwards outside the building. The fire spread from the 8th floor up 22 storeys to the top of the building in about 20 minutes.

A2.5 The vertical fire spread was facilitated mainly by two mechanisms. Flames outside the upper windows radiated heat through the windows and ignited curtains and timber benches with polyurethane foam padding which then ignited carpeting on room surfaces. The second mechanism involved the flames contacting the plate glass windows. It is believed the triangular shape of the spandrels and recessed plate glass caused additional turbulence which rolled the flames onto the windows causing their early failure.

A2.6 There were 9 fatalities. The doors to the hotel rooms where four fatalities occurred were open or had been opened by the fire. There were no fatalities in rooms where the doors had been kept closed.

First Interstate Bank Building, Los Angeles 1988

A2.7 This 62-storey building had sprinkler protection only in the basement, garage and underground pedestrian tunnel. The building had a structural steel frame with sprayed fire protection and steel floor pans and lightweight concrete decking. The exterior curtain walls were glass and aluminium with a 100mm gap between the curtain wall and the floor slab, fire stopped with 15mm gypsum board and fibreglass caulking.

A2.8 The fire started on the 12th floor and extended to the floors above primarily via the outer walls of the building. Flames also penetrated behind the spandrel panels around the ends of the floor slab where there was sufficient deformation of the aluminium mullions to weaken the fire stopping allowing the flames to pass through, even before the windows and mullions had failed. Flames were estimated to be lapping 10m up the face of the building. The curtain walls including windows, spandrel panels and mullions were almost completely destroyed by the fire. However, the building structure as a whole did not collapse. There was one fatality.

One Meridian Plaza, Philadelphia 1991

A2.9 The construction of this 38-storey bank building used structural steel with concrete floors on metal decking and protected with spray-on fire protection. The exterior of the building was covered by granite curtain wall panels with glass windows attached to perimeter floor girders and spandrels. Only the below-ground services floors were fitted with sprinklers at the time of construction. Subsequently sprinklers had been installed on the 30th, 31st, 34th, and 35th floors and to parts of the 11th to 15th floors. Fire broke out on the 22nd floor, penetrated through the windows and heat exposure from the fire plumes ignited materials on the seven floors above. The fire was stopped as it approached the 30th floor which had sprinklers. Although the fire burned for 19 hours, the structure did not collapse. Three firemen lost their lives.

President Tower, Bangkok 1997

A2.10 This 37-storey retail, commercial office and hotel development was under construction. Interior fit-out was not fully completed and the sprinkler system was not yet operational. An explosion and fire on level seven caused the destruction of the aluminium framed curtain walling. The effectiveness of fire stopping at the floor edges was compromised by floor to

Appendix B: Regulations and codes of practice

B1 General

B1.1 The regulations and directives governing the construction of tall/large buildings generally cover a similar, but not always the same, scope in each country. National and/or local regulations require application for permission, often in the form of a licence, to construct buildings. Other regulations govern the form and detail of the building itself. The latter are usually intended primarily to ensure personal safety and, as a requirement of lower importance, to protect the building against damage and defects. There do not appear to be regulations in any country requiring a licence to operate and use a tall/large building once built, although there are controls on some aspects of buildings such as emergency exits and fire escapes, e.g. in hotels. In comparison, licences to operate some other types of facility where large numbers of people are accommodated, e.g. sports grounds, are required in some countries. These licence systems are generally for the control of safety-related aspects of the facility and its operation.

B1.2 Regulations governing protection against natural hazards, such as wind and earthquake, are usually related to requirements for structural stability of the building. The severity of the natural hazard that must be resisted is usually specified, sometimes via associated standards and codes. These requirements usually also serve to protect people in the vicinity from falling parts of the building, especially parts of the façade. In some cases regulations give specific requirements for the structure to be resistant to progressive collapse in the event of an accident. Generally, man-made hazards to the structure are known as accidents, e.g. impact and explosions. Malicious acts are specifically excluded or are not specifically referred to. Guidance on the magnitude of accidents to take into account in design is sometimes given in codes of practice.

B1.3 Regulations generally recognise fire as a major risk to buildings and require provisions for fire protection that cover fire resistance, compartmentation, sprinklers and escape routes. The requirements may be more onerous for tall buildings than others. The differences reflect the higher risk in tall/large buildings of spread of fire and smoke and the greater limitations in such buildings on escape and on the ability of emergency services to rescue people at height and to fight fires within the building.

B1.4 Regulatory requirements for operational security usually include the safety of lifts, stairs, guard rails and parapets, emergency lighting and non-slip floor coverings.

B1.5 In England and Wales, approved documents together with codes provide guidance on meeting the performance requirements of the *Building Regulations*[B1]. They relate to performance on completion of construction. Similar requirements apply in other parts of the United Kingdom. National standards and codes in the United Kingdom are increasingly influenced by developing European codes that are expected to supersede the national standards in due course.

B1.6 In the United States, there is no national Building Code and most of the states have their own code. Each community determines its own building code requirements[B2]. There are, however, model building codes:

- Uniform Building Code by the International Conference of Building Officials.
- National Basic Building Code by the Building Officials and Code Administrators.
- Standard Building Code by the Southern Building Code Congress.
- Codes relating to fire by the National Fire Protection Association.

B1.7 An International Building Code by the International Codes Council (applicable in United States only) also exists. It is essentially a conventional prescriptive code obtained by merging the three United States model codes. An alternative, the International Codes Council Performance Code, has recently become available.

B1.8 None of these codes is mandatory but many states adopt one of them, at least in part. Others, B2.3 In the United States, whilst there is no explicit provision aimed at prevention of progressive collapse, current design guidance of cast *in situ* reinforced concrete structures and structural steel frames (with properly designed and constructed connections) generally produces structures with substantial ductility. For zones of high seismicity, the model codes in the United States have detailing provisions that are intended to increase structural ductility and toughness, thereby reducing the risk of progressive collapse during earthquakes. Following the explosion at the Murrah building in 1995, see Section A1.6, the potential of failure of key elements to trigger progressive collapse has been recognised[B5].

B2.4 Australian requirements are given first as a functional statement of capability of the building to withstand combinations of loads and other actions to which a building may reasonably be subjected[B6]. Associated performance requirements include resistance at an acceptable level of safety to the most adverse combinations of loads that might result in potential for progressive collapse.

The Hong Kong Building Authority uses locally-developed codes of practice for the structural use of steel and concrete. The approach to structural robustness, accidental damage and disproportionate collapse essentially follows the principles and methods adopted in the United Kingdom, although there is little specific reference to robustness in the *Hong Kong Building (Construction) Regulations* and Hong Kong codes of practice for structural design. The code: *Structural Use of Steel 1978* issued by the Building Authority gives no guidance on the issue, either in principle or prescriptive. The code: *The Structural Use of Concrete 1987* does however state the principle – 'The structure should be designed to support loads caused by normal function, but there should be a reasonable probability that it will not collapse catastrophically under the effect of misuse or accident. No structure can be expected to resist excessive loads or forces that could arise due to an extreme cause, but it should not be damaged to an extent disproportionate to the original cause.' From time to time Practice Notes for Authorised Persons and Registered Structural Engineers (PNAPs) are issued by the Building Authority. PNAP 140 gives a list of standards that are considered to satisfy the technical requirements of the Building Regulations. This list includes British Standards BS 8110 and BS 5950. It is through these two particular codes that the conventional provisions for tying, localisation of damage, and key elements, as used in design in the United Kingdom, are applied.

Overall therefore, regulatory and code requirements across the world differ in the extent to which they recognise vulnerability to progressive collapse. There appear to be none that deal explicitly with the issues of weakening from impact or explosion combined with further weakening from a major fire.

B3 Passive and active fire resistance

B3.1 There are regulatory requirements in the United Kingdom for inhibiting the spread of fire within a building through the use of linings that resist the spread of flame, and through fire-resisting construction that sub-divides the building into fire compartments. Overall, these requirements seek to prevent the premature failure of the building structure in a fire. There are also requirements to restrict fire spread over external walls and roofs and from one building to another.

B3.2 Sprinklers are recommended in all buildings (except those for residential use) where they exceed 30m in height to the highest floor. Under the *Building Regulations*, the sprinklers need to be designed to a higher specification of 'life safety standard'. The higher specification includes additional measures that reduce the likelihood of sprinkler failure. The regulations relating to fire work together as a package. Compartmentation is required to contain the spread of a fire, sprinklers to stop the fire developing sufficiently to breach the compartmentation, and protected shafts to enable people to escape safely when, by necessity, they have to escape passed the fire.

B3.3 In the United States, many states and cities have fire codes that give building requirements. Building code requirements for structural fire protection are based on laboratory tests, the ASTM E119 standard fire test on building components[5]. This standard test provides comparisons between component behaviour under controlled conditions. Similarly to the

the requirement is relaxed to 40 storeys. In Germany, concrete shafts are required for escape stairs.

B4.4 The use of lifts for evacuation in emergencies in airport control towers is allowed in the American code NFPA 101(B3) and, in the United Kingdom, Part 5 of BS 5588(B12) allows their use in buildings.

B4.5 Code requirements for fire detection systems vary significantly around the world. For example, in Australia, both smoke detectors and sprinklers are required in tall office buildings whilst, in Hong Kong, only sprinklers are required for the detection and suppression of fire.

B4.6 Various standards exist for informative warning systems, including BS 5839: Part 8(B13), AS 2200(B14), and NFPA 72(B15). In many countries, only relatively simple alarm systems are required, e.g. a bell.

B4.7 The provision of access and facilities for emergency fire services are required in the United Kingdom. Designated fire fighting shafts (lift and stairs) are required that have additional fire protection measures to protect 'emergency services' personnel and to facilitate their fire fighting work, i.e. the shafts may be pressurised or ventilated. Similar requirements apply in Hong Kong. Other countries, e.g. Australia, do not have this requirement.

B4.8 Overall current regulations and codes are focussed on emergencies and means of escape in case of fire. Further research is needed not only on systems for escape and emergency services access in case of fire, but also on life safety in non-fire types of extreme event where different evacuation and rescue strategies may be needed.

B5 Other issues

B5.1 Security and safety of cladding, including glazing

B5.1.1 In the United Kingdom, cladding, including glazing, is considered in the *Building Regulations* to be 'structure'. The regulatory requirements for safety of the structure and resistance against disproportionate collapse therefore apply. Approved documents give guidance on design of cladding and fixings to meet the requirements. Enhanced glazing is only required at locations where occupants may accidentally impact against it.

B5.2 Security and safety of building services

B5.2.1 There are no regulations in the United Kingdom specifically covering the security and safety of services in buildings. However there are regulations and standards controlling the supply of electricity and clean potable water

B5.3 Security against unauthorised entry

B5.3.1 The introduction of regulatory requirements for entrance security of buildings is being considered in the United Kingdom.

B6 References

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(B6) Australian Building Codes Board. *Building Code of Australia, 1996* – Canberra. ABCB, 1996

(B7) Society for Fire Protection Engineers. *Handbook of Fire Protection Engineering,* 3rd edition. Quincy, Mass., NFPA, 2002

(B8) Building Department, Hong Kong. *Hong Kong Building Code: Code of practice for the*

Appendix C: Use of risk management processes

C1 Virtually all human activity involves risk. Owners and occupiers should therefore appreciate that absolute safety in tall/large buildings is not achievable. Design, operation and management can only seek to keep risks to occupants and the building itself at an acceptably low level.

C2 A practical overall aim of design of a tall/large building against extreme events with a low probability of occurrence is to make provisions, both in the building and in its operation and management, such that the damage caused is not disproportionate to the event. The 'damage' of primary concern relates to the safety of people. The physical damage to the building itself is also of concern, particularly since damage to the building usually places people at risk. Minimising the damage to the building fabric and its services systems can minimise the 'damage' to people in many, but not all, cases.

Codes and standards have evolved to enable provision of safe buildings. They provide reasonable protection for the occupants of a building in 'normal' hazard events, e.g. 'conventional' fire scenarios. As a result, modern tall/large buildings designed using current good practice to resist normal loading conditions and recognised extreme events such as extreme winds, earthquakes, and road vehicle impacts, have performed well. This success can be attributed to the provision of generally robust structures and systems, and of protective measures within and around buildings to protect the buildings and their occupants from such events. Tragic incidents with loss of life often stimulate a re-evaluation of codes and standards and lead to changes in practice which improve levels of safety.

C4 Safety and the protection of occupants provided by design and by building management for normal circumstances may be strengthened and made more effective in extreme events by specifically identifying possible hazard scenarios, assessing the risks and improving robustness and/or protective measures and emergency response plans accordingly. A rational structured consideration of the hazards and risks of extreme events that may occur during the life of a tall/large building can assist designers and building management to enhance protection and advise building owners and operators.

Explicit processes for identifying potential hazard scenarios and for managing risks due to extreme events have not yet been generally adopted world wide in current regulations and codes relating to building design and management. There is, however, a trend in this direction. Use of explicit risk management processes in structural engineering has been advocated elsewhere(C1, C2, C3). Their use has been encouraged in some other industries, e.g. offshore oil and railways, following reports on incidents of extreme event damage. The reports on, for example, Flixborough oil refinery (1974), Seveso chemical plant (1976), Piper Alpha off-shore oil platform (1988), and King's Cross Underground station (1987) strengthened the trend away from prescriptive design methods towards probabilistic analyses and performance-based design.

In the United Kingdom, the use of risk-based scenarios as the basis of design of structures is becoming established practice. Some relevant standards have been produced, e.g. BS 7974(C4). This fire engineering standard recommends an initial qualitative design review by several experts to decide what are the realistic scenarios and the fire safety objectives. The draft European standard for structural design against accidental impact and explosions(C5) uses the concept that some damage is acceptable and gives design guidance on measures for reducing the probability of the event and the consequences. In other industries in the United Kingdom and elsewhere, e.g. offshore oil, railway and nuclear power, explicit risk management processes are required by regulations and supported by codes.

Well-developed techniques of hazard identification and risk assessment exist to inform risk management processes. Their use can aid judgments by designers and building managers on the risks of man-made hazard scenarios for which it is appropriate to make provisions or enhanced provisions.

Such processes usually begin during the early stages of feasibility and development of the clients' requirements and brief. They can enable more consistent implementation of the principle in design that damage should not be disproportionate to the cause. Application of these processes to