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Safety in tall buildings

and other buildings with large occupancy

Prepared by an international working group convened by
The Institution of Structural Engineers

John M Roberts, FREng BEng(Hons) PhD CEng FIStructE FICE, Babtie Group, *Chairman*
John Ahern, AADIP RIBA, J Ahern Associates, *representing The Royal Institute of British Architects*
Stuart J Alexander, MA CEng FIStructE FICE MIMgt, WSP Group
W Gene Corley, PhD CEng FIStructE, CTL Group
Keith J Eaton, BSc(Eng) PhD CEng FIStructE MIM, The Institution of Structural Engineers
Paul F Everall, MA(Cantab) CEng MICE Hon RICS HonFIBC Hon FB Eng, Department for Transport, Local Government and the Regions, *Observer*
Max Fordham, OBE FREng MA FCIBSE FConsE Hon FRIBA, Max Fordham LLP, *representing The Chartered Institution of Building Services Engineers*
Craig Gibbons, BEng(Hons) PhD CEng MICE MHKIE, Arup, Hong Kong
Peter R Head, OBE FREng CEng FIStructE FICE, FaberMaunsell
Martin Kealy, BSc(Hons) CEng FIFireE MSFPE MCIBSE, WSP Fire, *representing The Institution of Fire Engineers*
Gordon G T Masterton, BSc BA MSc DIC CEng FIStructE FICE FIES MCIWEM, Babtie Group, *representing The Institution of Civil Engineers*
David McCullogh, FRICS PPIBC, Hartlepool Building Control, *representing The Royal Institution of Chartered Surveyors*
John B Menzies, FREng BSc(Eng) PhD CEng FIStructE Dip CU, Standing Committee on Structural Safety
David B Moore, BTech PhD CEng MIStructE, BRE Ltd
H K Ng, MSc CEng FIStructE, J M K Consulting Engineers Hong Kong
Alan Parnell, FRIBA PPIFireE, Fire Check Consultants, *representing The Royal Institute of British Architects*
Ysrael A Seinuk, PE CEng FACI FICE FASCE, Cantor Seinuk Group Inc
Faith H Wainwright, BA CEng FIStructE, Arup, London

Corresponding members
David I Blockley, FREng BEng PhD DSc CEng FIStructE FICE, University of Bristol
Thomas J P Byrne, BSc MSc, WSP Group
Charles Clifton, BE(Hons) ME(Civil) FIPENZ FNZSEE, HERA
Ian P Firth, BSc MSc DIC CEng FIStructE FICE, Flint & Neill Partnership
Graeme Forrest-Brown, MSc CEng MICE, Maunsell Structural Consultants Ltd
Norman Glover, BSc CE FIStructE, Aegis Institute, Architectural Institute ASCE
Mick G Green, BE CEng MIStructE MICE, Buro Happold
John A Hill, FREng BSc CEng FIStructE FICE, Doran Consulting
Alan P Jeary, PhD DSc CEng FIStructE MIEE FCIOB, University of Western Sydney
Bob A McKittrick, BSc CEng FIStructE FICE, Scott Wilson
Brian S Neale, AGCT CEng FIStructE MICE FIDE, Health and Safety Executive
Graham Owens, MSc PhD CEng FIStructE MICE MWeldI, Steel Construction Institute
Roger J Plank, BSc(Eng) PhD CEng MIStructE MICE, University of Sheffield
Ian Thirwall, CEng FIStructE MICE, Cameron Taylor Bedford
Martin J Wyatt, BSc MSc PhD CEng MIStructE MBCS, BRE Ltd

Secretary
Susan M Doran, BSc(Eng) AKC PhD CEng MICE ACIS, The Institution of Structural Engineers

Contents

Foreword

The reality of threats to the safety of tall and large buildings was starkly demonstrated by the unprecedented events at the World Trade Center in New York on 11 September 2001. Had these events not occurred, the World Trade Center would no doubt have continued to give many years of excellent service. The buildings were not unsafe by any criterion hitherto regarded as being credible in peacetime.

This Report examines what can be learned from the extreme events of 11 September 2001 for the future design of new buildings and the appraisal of existing ones. The purpose is to assist owners and operators of tall/large buildings and their professional advisers to play their part in reacting to the new threats to the safety of building occupants. The Report presents therefore initial recommendations by the Working Group on 'Safety in Tall Buildings' following review of damage by extreme events to tall/large buildings at the World Trade Center and elsewhere world wide.

The Working Group has concentrated initially on gaining an overview of the safety issues arising from the events of 11 September 2001. The aim has been to point to directions for improving future provisions for occupant safety in tall/large buildings. The resulting initial recommendations are in no way a panacea for dealing with threats to the building infrastructure. Rather they indicate possibilities that require consideration and study.

There are many ways to inflict heavy blows of death and destruction in cities. For society as a whole, the most effective measures that can be taken following the events of 11 September 2001 are those related to improving security in cities (especially around high 'profile' tall/large buildings, landmarks and infrastructure), preventing terrorists from gaining control of means to make attacks, and the deeper resolution of conflicts that breed resentment and create the environment in which terrorism flourishes.

The solutions to reducing the probability of a recurrence of extreme events, such as occurred on 11 September 2001, do not lie within the gift of building owners and construction professionals. This Report, nevertheless, seeks to contribute to public safety by providing recommendations to assist building owners and their professional advisers to provide buildings and infrastructure better able to sustain any future malicious attacks with a reduced risk of loss of life. Much further work and international collaboration amongst construction professionals and others is needed to assist building owners and their professional advisers to optimise occupant safety in extreme events.

I would like to thank members of the Working Group and others, around the world, who have collaborated and contributed generously to the preparation of this Report. I would also particularly like to thank John Menzies for preparing drafts of the report for the Working Group.

John Roberts
Chairman
July 2002

Summary

Following the extreme events at the World Trade Center in New York on 11 September 2001, the Institution of Structural Engineers convened a Working Group on 'Safety in Tall Buildings', with the support of fellow professional bodies, industry and the United Kingdom government, to review and report on the safety issues. The objective was to provide guidance and advice on the implications that follow the structural collapses and loss of life at the World Trade Center.

At the outset it was decided the Working Group would not undertake any independent investigation of the extreme events on 11 September 2001. Rather it would consider all relevant available information, in particular the papers submitted to the Group by its members and others and the large number of other papers recently published elsewhere. The scope included buildings of large occupancy generally, since it was anticipated that the guidance produced would also be relevant to them.

The Group considered not only the collapses and damage to buildings at the World Trade Center, but also recent collapses and damage to other tall/large buildings due to extreme events in other parts of the world.

Review of available information on the collapse of the World Trade Center (WTC) towers identified several major safety questions:

- **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?**

Consideration of these questions focussed attention on key safety issues related to vulnerability to progressive collapse, to passive and active fire protection, and to escape, its management and the emergency services. Other safety issues, i.e. security and safety of cladding, security and safety of building services, security against unauthorised entry, and implementation of design and construction, were also found to be relevant. The key issues as a whole are multi-disciplinary and strongly interrelated.

There was recognition that extreme man-made events that may cause a major emergency in a tall/large building can take many different forms. Their nature and scale cannot be predicted precisely. There was consensus that loss of life and damage caused can be limited in many extreme events by the use of broadly-based strategies involving design, construction and management of the building.

Key safety 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. structural elements and particularly the connections between them).
- The retention of structural integrity in fire.

The Working Group concluded that the events of 11 September 2001 have created a new situation in which a reappraisal of provisions for safety is required.

Whilst the events were unprecedented in scale, they were not wholly unique. An aircraft impact into a tall building had occurred previously, although it was not a deliberate act. Indeed, some seven months after the World Trade Center events, an aircraft struck the 32 storey Pirelli building in Milan. **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.** There is, however, no single or precise answer to the safety issues of designing tall/large buildings and their operating and management systems against the wide range of possible extreme man-made events that may occur.

Decisions need to be made by owners, operators, designers and building managers based on an understanding of all the issues. There are strong interactions between the building structure, fire protection, building services systems and the building management and emergency services. Overall strategies involving the design of the building, its management and the relationships with emergency services are required in order to maximise protection of building occupants for a wide range of possible extreme events.

Identification of the key safety issues led the Working Group to develop initial recommendations for consideration by owners, operators, designers, builders, and building and emergency services managers. The recommendations necessarily at this early stage indicate only possible directions for actions relating to the key safety issues. Provisions in these directions would help to improve the safety of occupants when extreme events occur in a new or existing tall/large building. Decisions on their adoption and the standards to use in any particular case would depend on wider considerations. For that purpose in-depth technical and economic studies together with consideration of policies on safety of people in tall/large buildings may be needed. The Report gives a preliminary list of needs for such work.

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.

Passive and active fire protection

- Provide robust, resilient and durable passive fire protection.
- Treat active fire protection, e.g. sprinklers, as an addition to, and not a substitute for, passive fire protection, and do not consider it for extreme events.
- Ensure compartments are gas tight and seals are sound on building completion by inspection, testing and certification.
- Provide protection to compartments and mitigate spread of smoke.
- Design building to survive complete 'burn out' of contents.
- Require independent approval, as a part of licensing and periodic third-party audit of life-safety systems, of modifications to passive and active fire protection.

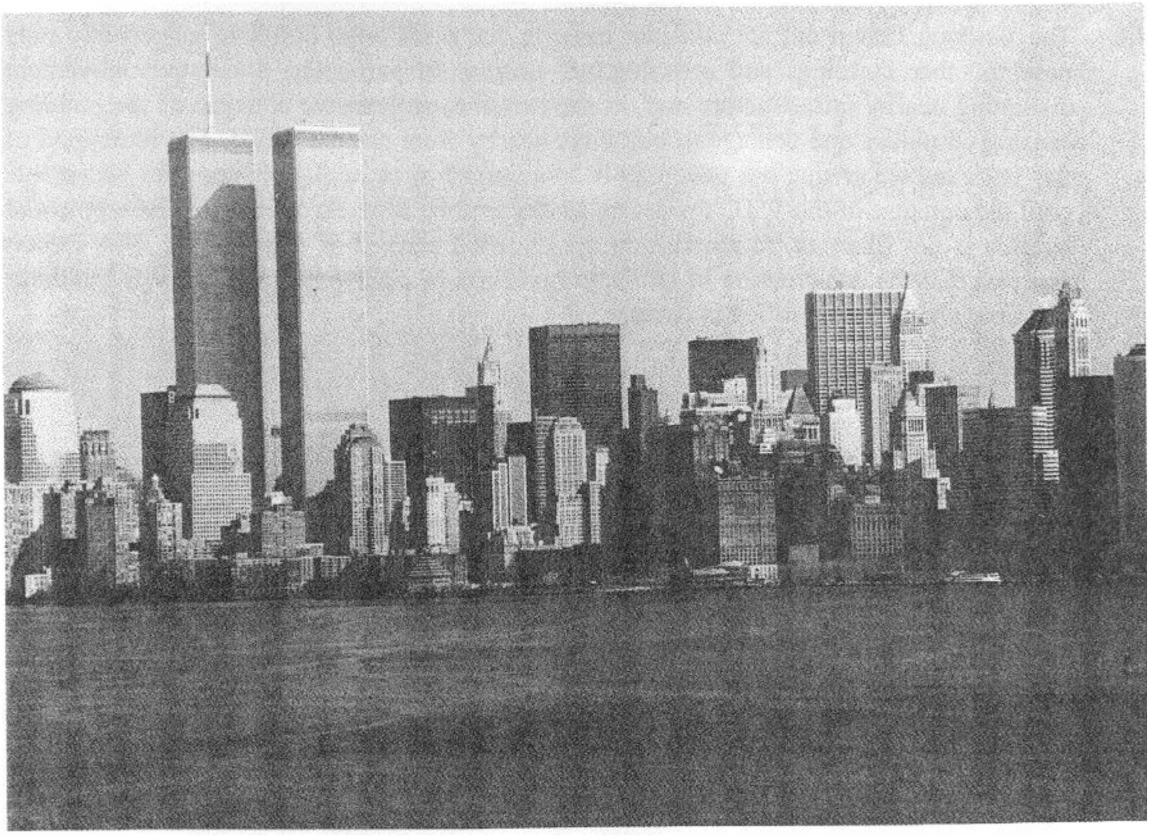
1 Introduction

1.1 The collapse of the World Trade Center (WTC) towers in New York on Tuesday 11 September 2001 resulted in a great loss of life. The WTC towers were designed and built using good practice of the time, in the mid-1960s/early 1970s. They had performed well for three decades and indeed stood for some time following the immediate damage caused by the attack. They had also performed well in a major bomb attack (1993) and a relatively large fire (1975). For construction professionals, e.g. engineers, architects and construction and facilities managers, involved in the design, construction and management of tall buildings and other buildings that house large numbers of people, questions about the safety of such buildings and their occupants came to mind immediately following the collapses. One overall question was at the forefront: Can tall/large buildings be made and managed so that they will be more resistant to damage by extreme events caused by malicious acts and so that occupants are better protected and have more time and opportunity to escape?

1.2 The Institution of Structural Engineers therefore convened the Working Group on 'Safety in Tall Buildings' with the support of fellow professional bodies, industry and the United Kingdom government to review the issues and report. The Working Group was made up of professional engineers and other pro with wide and international experience of safety issues in buildings.

1.3 The solutions to reducing the probability of a recurrence of extreme events such as occurred on 11 September 2001 do not lie within the gift of building owners, operators and construction professionals. However, this Report seeks to assist them to provide safer tall/large buildings, both new and existing, affording better protection to people in extreme events.

1.4 This Report has been prepared by the Working Group taking into account international feedback and practices. Safety issues are outlined in Section 5 and initial recommendations for new and existing tall/large buildings are included in Section 7. At this early stage, the recommendations are for consideration recognising that in-depth studies, development and research will be needed in many cases to determine application. Areas for development and research are therefore also identified.



3 The World Trade Center towers

3.1 Construction of the two 110-storey WTC towers of the World Trade Center began in August 1966. They were officially opened in April 1973. Each tower was 411m high above ground level, 63.5 x 63.5m. square on plan, with a central core, 24 x 42m on plan, containing lifts, staircases and service shafts. Their design and construction are described elsewhere[1, 2, 3], but briefly were as follows.

3.2 The towers were examples of a form of building generally referred to as a tube-tower structure. The whole building façade was used as a structural member, each face comprising a frame made up of 59 box-section steel columns at 1.02m centres connected together by deep spandrel beams. Shear connection between the two faces at each corner of the building was provided so that the frames, together with the floors, formed a torsionally-rigid framed tube fixed to the foundations. This framed tube was designed as a simple free-standing cantilever structure to carry all lateral loads.

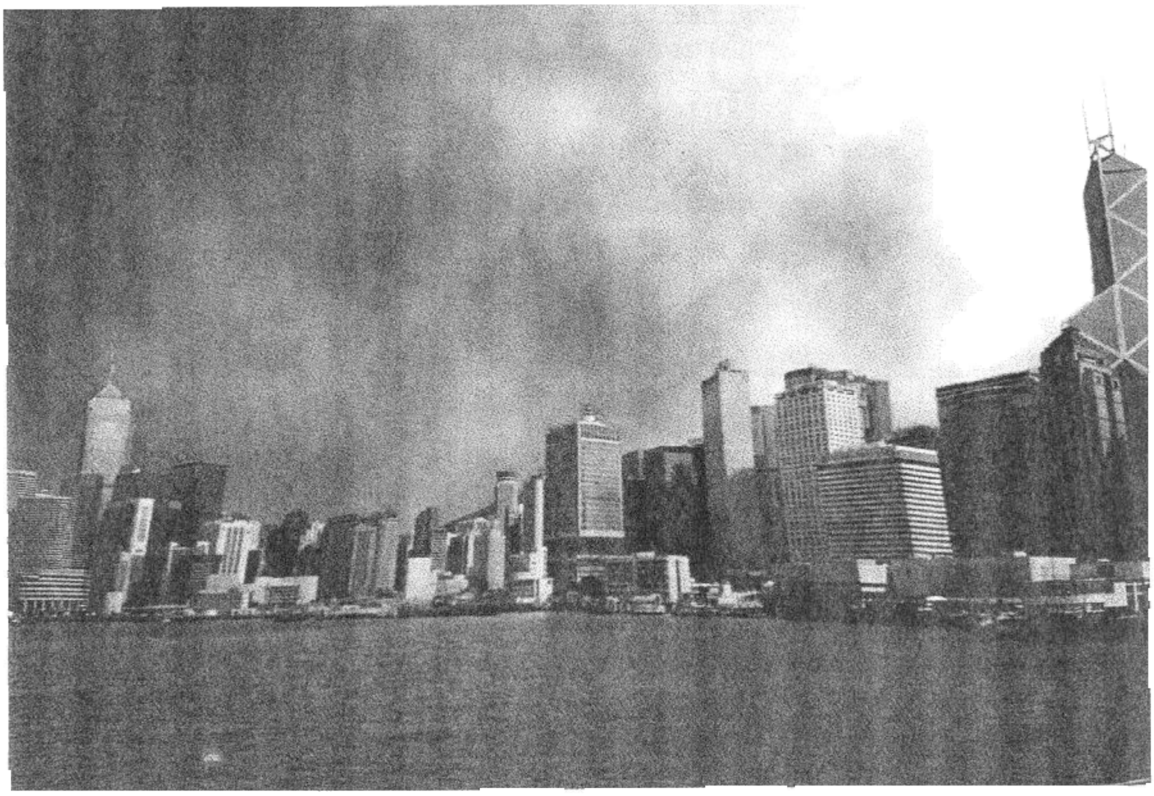
3.3 The core, consisting of 44 steel columns, was designed and detailed to carry vertical load only. The floors spanned, without intermediate columns, from the facade to the core. The floor system comprised 900mm-deep lightweight steel primary trusses at 2.04m centres, braced by secondary trusses and spanning between the perimeter frames and the core. The secondary trusses supported a profiled steel deck with a 100mm lightweight concrete slab on top and connected compositely to the primary trusses. There were three independent emergency fire exit staircases in the core of each building[2]. The staircases did not run in continuous vertical shafts from the top to bottom of each building. Occupants using the stairs had to transfer from one vertical shaft to another via a transfer corridor at several floor levels as they descended. There were also 99 separate passenger lifts in the core of each tower with several serving each floor in two groups operated on different power supplies.

3.4 Passive fire protection was provided to the external box columns by spray-applied mineral fibre of varying thickness, faced with aluminium pre-formed sheet externally. The undersides of the floor systems were not protected by a fire-rated suspended ceiling but the steel trusses were protected by a spray-applied mineral fibre. It has been reported that in the north tower (WTC1), the fire protection to the trusses in the vicinity of the aircraft impact had been upgraded[2]. A series of structural improvements had also been made in this tower that may have helped it to remain standing longer after the aircraft impact. Compartmentation was notionally horizontal by the floor construction, the floor slabs being cast flush against the spandrel beams. At stair and lift shafts, separation was provided by walls constructed of metal studs with two layers of gypsum board on the exterior and one layer on the interior. Vertical separating walls varied, some spanning from slab to slab and others extending only up to the suspended ceiling. The effectiveness of the compartmentation is likely to have been progressively reduced over the years by the installation of IT and communications systems. No pressurisation or other smoke control system was used for the stairways, lift shafts or lift lobbies.

3.5 Active fire protection in the form of sprinklers had been retrofitted in the towers subsequent to their construction. Standpipes supplying water for hose lines were located in each of three stair shafts.

3.6 Overall the WTC towers were light open structures, engineered very efficiently to meet design serviceability and ultimate limit state conditions for normal dead, imposed and wind loads. They were also designed to withstand as a whole the forces caused by the horizontal impact of a large commercial aircraft of the time, a Boeing 707. The overturning effect of this postulated event would not be particularly severe, being of the same order as the wind load effect.

4.6 There was also substantial damage to buildings adjacent to the WTC towers[2]. Seven World Trade Center (WTC7) caught fire and subsequently collapsed, see Appendix A. The Marriott Hotel (WTC3), a building with 22 storeys above grade and 6 storeys below, collapsed under the impact of falling debris from both WTC tower collapses but it did not collapse progressively. In total, partial or complete collapse of 10 major buildings occurred and more than 50 buildings were damaged. Some issues raised by the individual performance of these buildings are incorporated into the discussion in this Report.

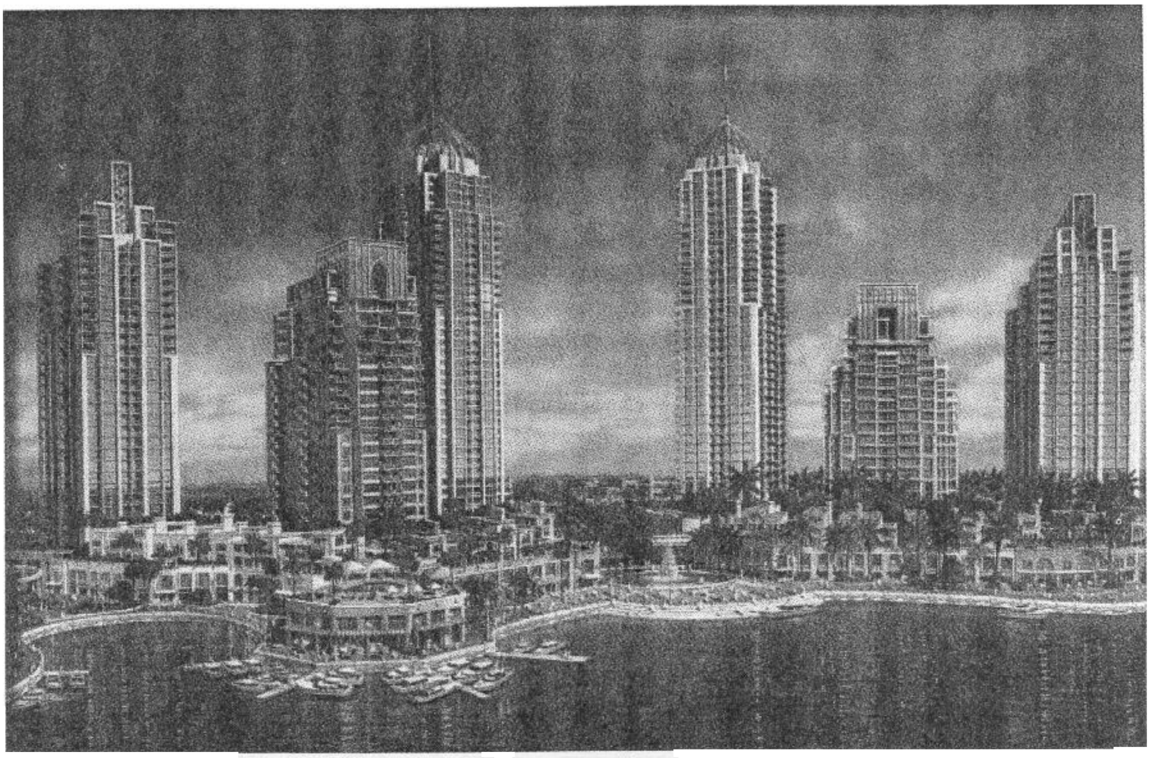


The essential features of the progressive collapse phenomenon in buildings are therefore that it requires a local damage event to 'trigger' it and, for propagation, it requires growth of kinetic energy (usually derived from release of potential energy) to exceed the energy needed to collapse the structure beyond the 'trigger point'. The size of trigger event needed and the vulnerability to collapse propagation depends mainly on the redundancy of the structure, and the strength, ductility and hence the energy-absorption capacity of the structure, that is of the vertical and horizontal structural elements and, most importantly, the connections between them.

In general terms, the more redundant the structure (i.e. the more alternative load paths) and the stronger and more ductile the elements and connections, the bigger the 'trigger' needed to initiate progressive collapse and the less will be the vulnerability to collapse propagation. Reduction of vulnerability requires the structure to be made more robust so that the threshold for initiating progressive collapse is raised. As a result the probability of it occurring due to an extreme event can be made smaller. There is a need to be aware that some potential trigger events, such as explosions, may load the structure, e.g. floors, in opposite directions to the forces due to normal loads.

Structures with high vulnerability to progressive collapse are those where release of potential energy occurs when the initial local damage (the 'primary' damage) is a relatively minor event in the vicinity, such as a local accident or weakening of a critical structural element. In contrast to cases where collapse is driven by external energy (e.g. explosion), gravity-driven progressive collapse, as occurred at the WTC towers, results in damage that is usually perceived as being disproportionate to the original event. Structures that are highly resistant to progressive collapse are generally termed 'robust' structures and are those where a more severe accident or extensive weakening is needed in order to make collapse progressive. In recent times there have been several incidents of partial or complete progressive building collapse, the best known being the partial collapse of Ronan Point in London in 1968. Large losses of life resulted in some cases, see Appendix A.

For each of the WTC towers, the damage to the vertical load-carrying columns and floors from the aircraft impacts was followed by further weakening caused by the ensuing fires. The total weakening was then sufficient to allow the potential energy of the part of the building above to be released and converted to kinetic energy as that part fell under gravity. This kinetic energy was sufficient to commence destruction of the building floors below the



mentation measures will clearly have limited effectiveness in containing a major fire emergency. Compartmentation and control of air has a wider importance arising from possibilities of extreme man-made events that use air contamination as the instrument of damage, see Section 5.5.2.

5.3.1.6 An option that could be considered is the design for survival of the structure until the compartment contents have burned out completely. A fire engineering approach based on a natural fire exposure would be needed if this design criterion were adopted. In recent years two building fires in the United Kingdom, at Broadgate[6] and at Churchill Plaza, Basingstoke, have provided an opportunity to observe how modern buildings perform in fire. In both cases most of the combustible materials were involved in the combustion process. Structural collapse did not occur. Similarly, large-scale experimental fire tests on steel, timber and concrete buildings undertaken by BRE[7] at Cardington and by BHP[8] in Australia led to complete 'burn out' of all the fire load. Such practical evidence suggests that buildings, if suitably designed, may be able to survive complete 'burn out' without collapse.

5.3.2 Active fire protection

5.3.2.1 The partial effectiveness of passive protection to keep occupants safe when fires occur in buildings has led to the increasing use of active fire protection in addition to passive protection. Active protection is usually provided in tall/large buildings by sprinklers that operate automatically as a fire develops, dousing the fire with water. Their role is to catch a fire when it is still small and put it out or inhibit its spread. For the WTC towers, the active fire protection by sprinklers was effective in dousing small accidental fires that occurred prior to 11 September 2001. On 11 September 2001, the sprinkler system would have been overwhelmed by the fires, even supposing the sprinkler and water supply systems were still operative. Active fire protection using sprinklers is not able to stop fully developed fires and also is vulnerable separately to loss of water pressure due to extreme event damage. Design for fire needs to consider the likelihood and consequences of failure of the sprinkler system.

5.3.2.2 Fire fighting, of course, is an important means of active fire protection through the use by occupants of equipment provided in the building to fight small fires and the use by fire fighting services of their more powerful equipment. However, in tall/large buildings, there are limits to the size of fire that a team of fire fighters can bring under control. The limits can be severely reduced, as was seen at the WTC towers, by the phased evacuation is planned, a protected lobby to each stair or a smoke control system is required. For buildings over 30m high, the building also requires protection by an automatic sprinkler system, which makes serious smoke contamination of escape routes less likely, at least for 'conventional' fires.

5.4.1.5 Tall/large buildings in the United Kingdom are generally designed with a limited phased evacuation, e.g. evacuating the 'fire floor' and the floor above, as the main response to an emergency. Post 11 September 2001, large numbers of building occupants are likely to wish to evacuate over short periods in response to real or perceived emergencies. Effective communications between building management and occupants is clearly an important factor in maintaining the safety of occupants during emergencies.

5.4.1.6 Similarly, issues need to be examined relating to the use of lifts for evacuation (and for access by emergency services' personnel). In a major emergency a proportion of occupants are likely to try to use the lifts to escape whatever warnings are given about not doing so. Evacuation by the lifts used by occupants for normal access/egress may be possible safely in some emergencies. Where there is a warning of an event, the use of lifts for evacuation will minimise evacuation time. It may be possible also to use dedicated fire fighting lifts for evacuation, perhaps of disabled occupants, in some emergency circumstances. However their use could inhibit emergency services operations. Evacuation by lift is an established strategy in a few special structures.

5.4.1.7 The use of lifts is more likely to be safe if the shaft is of robust construction and the lift system and its power supply is robust and protected. An important factor in determining whether use of a lift in an emergency will be safe is the state of knowledge at the time of functionality of the shaft and the lift system. Monitoring of the power system and the air condition is needed to enable the building management to decide whether there is low(acceptable) risk to occupants, given the emergency in hand, in allowing use of particular lifts for evacuation. However, a major risk to occupants is that they may be overwhelmed by smoke as they wait for the lift. Consideration also needs to be given to providing emergency 'break-out' arrangements so that passengers in a lift can be rapidly rescued (or can rescue themselves) if the lift stops functioning during use.

5.4.1.8 In some countries, including the United Kingdom, the provision of dedicated fire fighting shafts is required. Such shafts include stairs, lift and lobby in a protected enclosure. They can be an effective facility for enabling emergency services personnel to reach the incident location quickly. A further advantage is that escape stairs are kept free for use by occupants evacuating the building. Dedicated fire fighting shafts can also provide protection for water mains and communications links.

5.4.1.9 Diversity in vertical escape options by lifts or stairs is likely to increase the chance of successful evacuations. Options might be increased by placing stair entrances on different sides of a central core. Options might also be increased by dispersing stairs and lifts in separate shafts instead of placing them in a central core. The balance of advantage and disadvantage for the safety of occupants is not clear. A central core is usually large and can be built of robust construction to give good protection. Separate cores would individually be smaller and placed nearer to the outside of the building where they would tend to be more vulnerable to extreme events. Whatever the arrangement, the stairways need to be independently robust so that damage affecting one stair is less likely to affect nearby stairways.

5.4.2 Management of escape

5.4.2.1 Occupants of tall/large buildings have tended to feel secure in normal circumstances and to be intent on pursuing their usual day-to-day activities. They have tended not to be particularly receptive to fire drills and to be reluctant to evacuate. The logistics and expense of completely evacuating a tall/large building and the hazards involved are considerable even as a fire drill in non-emergency circumstances. For most emergencies, simultaneous evacuation may be considered inappropriate.

5.4.2.2 The safety of occupants in major emergencies can usefully be distinguished from their stairs. Situations where there is an acceptable risk to using lifts to evacuate disabled or large numbers of able-bodied occupants need to be identified in escape strategies. The communications systems provided for delivering advice to occupants are crucial.

5.4.2.9 Escape depends on the arrangements for managing the evacuation, including advice to occupants on when and how to evacuate the building, the routes to take, and the assistance by emergency services. Simultaneous complete evacuation of a building by all occupants without use of lifts may not be a practical possibility in existing tall/large buildings if this was not a design criterion. Provisions for phased evacuation only, as at the WTC towers, are usually included in designs. However, the experience of 11 September 2001 indicates that simultaneous evacuation of a substantial proportion of all floors, is a key requirement in certain major emergencies and should be planned for. Even where existing tall/large buildings have been designed only for phased evacuation, there is need to plan for simultaneous evacuation.

5.4.2.10 Irrespective of whether evacuation is phased or simultaneous, there clearly needs to be good communication with the building occupants on when to leave and the routes to take. The experience at the WTC towers raises a range of issues about occupant response and management of evacuation in tall/large buildings.

5.4.2.11 Consideration is needed concerning what information and requests/instructions should be relayed to occupants for different emergency scenarios and also concerning how the information is relayed. Several issues arise:

- Following the World Trade Center events, very large numbers of occupants may decide to evacuate during the early stages of an incident in a tall/large building. Crowding of escape routes may then occur, possibly preventing occupants from evacuating affected floors. Depending upon the effectiveness of compartmentation and ventilation or control of contaminated air, various parts of escape routes may become contaminated. Occupants attempting to evacuate the building may then be in more danger than those remaining *in situ*. On the other hand, if the emergency is serious, occupants delaying evacuation may become trapped and compromise their own survival.
- The information and requests/instructions given to occupants are therefore crucial. Occupants need to have a confident understanding of the situation and the evacuation strategy being used. Information and requests/instructions should be based on accurate knowledge by the building management of the conditions in all areas of the building and of the likely changes in each area as the emergency develops. A position often taken is that occupants should be given as little information as possible. More considered opinion is that occupants should be kept fully informed. They will then be in a position to make rational decisions on the action they should take. It may also be argued that occupants have a right to expect to be kept fully informed. It is generally agreed that people do not 'panic' when an emergency first comes to notice. They tend to try to assess the situation and, as a result, may delay their escape. A common procedure is to reassure occupants that they are not in danger but, following the extreme events at the World Trade Center, occupants of tall/large buildings may not accept such reassurance without tangible evidence.
- Good communication systems are needed to enable the effective management of emergencies. The nature and type of communication and alarm systems have a major influence on the response of occupants. Current guidance, e.g. the CIBSE Guide in the United Kingdom[9], assumes 'conventional' fire emergencies but can be used to model the effects of extreme events.

5.4.2.12 Occupant familiarisation and 'training' for possible emergencies can assist them to remain calm and respond optimally to standby or evacuation requests. Training of occupants can greatly increase their ability to escape quickly and provide valuable reassurance about how quickly they can get out.

5.4.3 Interaction with emergency services

5.4.3.1 The collapses of the WTC towers have raised new concerns relating to the operational

5.5 Other issues

5.5.1 Security and safety of cladding, including glazing

5.5.1.1 Cladding, especially glazing, can become a hazard when certain extreme events occur within or outside of a building, e.g. explosion or fire. For example, glass fell onto fire fighters at the First Interstate Bank Building fire in Los Angeles from the 12th to 16th floor levels and spread out up to 100 feet from the building, see Appendix A.

5.5.1.2 People in the vicinity at ground level near to a tall/large building can also be at risk from falling glazing when an explosion occurs nearby. Another well-recognised hazard to people in the vicinity of tall/large buildings is the detachment of cladding panels. The explosion in the centre of Manchester in 1996, although it caused no fatalities, led to over 800 injuries almost all of which were due to falling cladding debris, mostly glass, see Appendix A.

5.5.2 Security and safety of building services

5.5.2.1 Although not demonstrated in the attacks on the WTC towers, a wide range of extreme events could place occupant health and safety in jeopardy by interfering with building services (ventilation, air conditioning, water supply, heating/cooling and electricity supplies, waste disposal and catering services). In some cases, but not all, similar measures are needed to protect occupants to those measures that are used for protection from the hazard of smoke.

5.5.2.2 Physical damage to services systems can cause loss of functionality or make them unsafe. Contamination by chemical, radioactive or biological substances can have rapid and widespread harmful effects on occupants. Such hazardous substances may be delivered by airborne release outside the building at high or low level, or by airborne release within the building. They may also be delivered by contamination of water supplies, by spreading contamination around inside the building through people or materials that are moved around or by contamination of food or catering equipment.

5.5.3 Security against unauthorised entry

5.5.3.1 Tall/large buildings usually have a high 'profile'. They are likely to attract the curious and those with malicious intent because they are landmarks, often occupied by high profile organisations. They represent a concentration of commercial value. They contain large numbers of people and are often multi-functional and have multi-occupancy.

5.5.3.2 Threats may arise from commonly-occurring criminal acts, or from malicious actions that pose a widespread hazard to the building and its occupants as a whole. Conceivably they may also arise from the use of sophisticated devices, based on widely available electronic and information technology, placed in a building, possibly connected to the buildings' systems and activated when placed, or automatically, or remotely at a later time. In addition, the latter type of threat may be through contamination using chemical, radioactive or biological agents. Whilst the risks of commonly-occurring criminal acts can be reduced through currently-available entrance design and security systems, malicious acts causing widespread hazards require decisions based on a thorough appraisal of the design and management of the building that establishes how vulnerability can be reduced and controlled.

5.5.4 Implementation of design and construction

5.5.4.1 The safety of a tall /large building may be compromised by active and/or latent errors by those involved in design, construction and management in use, including responses to emergencies. The underdesign found after the construction of the Citicorp Center provides a salutary lesson[11]. The human error subsequently found in the design of a tall building in Rio de Janeiro after its progressive collapse in 1998 causing 8 fatalities provides another example[12]. There have also been cases of defective construction or maintenance leading to serious damage, e.g. façade failures[13]. Actions to minimise these risks to tall/large buildings in the past have followed current practice for buildings generally, although frequently to a higher standard of attainment on the basis of the perceived importance of the building in question.

6 The new situation post 11 September 2001

6.1 The extreme events that destroyed the WTC towers on 11 September 2001 were unprecedented in scale, but they were not wholly unique. Aircraft impacts into tall buildings had occurred previously, although not as a deliberate act. Indeed, a further landmark building, the 130m high Pirelli building in Milan, was hit by a relatively light aircraft at the 26th floor level on 18 April 2002[14]. Several accidents have also occurred where an aircraft has crashed in a built-up area of a city. In addition, damage to other tall/large buildings caused by accidental or malicious acts, particularly explosions and fire, has occurred over recent years, see Appendix A.

6.2 The explosion damage events referred to in Appendix A are those causing most loss of life and damage to tall/large buildings in recent years (excluding war zones). Other less serious events have occurred. In general, reinforced concrete and steel-framed buildings with well-detailed connections are usually able to withstand nearby explosions without sustaining extensive permanent damage. Structural damage is likely to be confined to a zone close to the seat of the explosion. Collapse of an entire building is rare. However, building communication and services systems are often rendered inoperable. Most injuries and fatalities are caused by falling glass, blast-propelled debris, or by smoke inhalation. World wide, the incidence of substantial damage to tall/large buildings by explosions, accidental or deliberate, is infrequent but possibly increasing. Given the potential large consequences, explosion damage from small or large devices remains a major hazard to the occupants of tall/large buildings.

6.3 The fire damage incidents referred to in Appendix A are those that have caused substantial losses of life and damage to tall/large buildings in recent years. World wide, substantial fire damage, whether by accident or arson, causing large losses of life is quite rare although fire incidents in high-rise buildings are common, with the numbers of fatalities usually being relatively low. However the potential for large life losses exists and fire is one of the greatest risks for tall/large buildings. Fire must therefore continue to be considered a major hazard to the safety of occupants of tall/large buildings.

6.4 Extreme event damage to tall/large buildings caused by malicious acts is not therefore a new problem. However, the events of 11 September 2001 have challenged perceptions of the safety of tall/large buildings. They have shown that malicious acts can cause the total destruction of a tall/large building and result in large loss of life. A new situation has been created in which a reappraisal of provisions for safety is required.

6.5 Further incidents of extreme damage caused by malicious acts can be expected in the future. Whilst the risk of such events for most cities and buildings is very low, an ongoing risk exists of large explosions, fire or other form of extreme man-made event aimed at harming occupants and causing damage to tall/large buildings. Other extreme events that can be expected arising from malicious acts are those that may make building services (ventilation, air conditioning, water supply, heating and electricity supplies and catering services) unsafe.

6.6 Natural disasters, such as earthquakes and hurricanes, may also threaten the safety of occupants of tall/large buildings and the buildings themselves. Such extreme events are prevalent in some regions of the world. Tall/large buildings in these regions are designed to a practical extent to resist these events and protect occupants. Examples of such events are not given here. Design philosophy and practice are well developed in many regions of the world relating to common natural disasters. Most buildings that are properly 'engineered' survive well and generally do not collapse during these events. Design routines continue to be improved as learning from events occurs. The design and management provisions made for the survival and safety of occupants in buildings in such disasters provide a basis for learning in order to improve the safety of buildings in extreme man-made events such as explosions, fire and impact.

6.7 It is clear that there is no single or precise answer to the issues of designing tall/large buildings and their operating and management systems against the wide range of

7.1 Introduction

7.1.1 The extreme events of 11 September 2002 raise the question of what improvements in the design of new tall/large buildings, or the appraisal of existing ones, can practically be made for the protection of people when a major emergency occurs. Extreme events that may cause a major emergency take many different forms. Although many can be foreseen, some cannot and, in any event, their nature cannot be predicted precisely. Nevertheless the risks to occupants and the damage they cause can be decreased by the provision of more robust structures, services systems, fire and other protection, and means of escape, and by the use of emergency response plans. Enhanced provisions in these areas can give more effective protection against many potential extreme events.

7.1.2 The design of buildings, and especially tall/large buildings, is a complex process of evaluating uncertainties and balancing risks and costs. For extreme events, risk management techniques are available that can assist identification and evaluation of potential hazard scenarios and choices of design and management provisions, see Appendix C. The design of fire protection systems, means of escape, emergency access and management is every bit as important as the design of suitably robust structures and building services systems. There are strong interactions between all of these elements and the management of a major emergency that have a marked influence on the safety of building occupants.

7.1.3 The Working Group has reviewed therefore the issues identified in Section 5 and makes the following initial recommendations of matters for consideration by owners, operators, designers, and building and emergency services managers of tall/large buildings. To assist consideration, in-depth technical and economic studies together with review of policies on the safety of people in tall/large buildings are needed. Recommendations are also given therefore on needs for supporting development and research, see Section 8.

7.2 Vulnerability to progressive collapse

7.2.1 The location, direction and magnitude of the forces that extreme events may exert on a tall/large building cannot usually be predicted accurately. In these circumstances, the main protection against them initiating progressive collapse is to provide a robust structure that will remain stable even if a number of structural elements are damaged, i.e. suffer 'primary' damage. Robustness is achieved by use of structural redundancy and structural elements that are strong and ductile and capable of absorbing a high amount of energy as they deform under extreme loads. The elements need to be joined by connections with similarly adequate strength and ductility properties so that alternative load paths are present in the structure. It is insufficient merely to tie structural elements together. Tying alone does not inherently provide a ductile structure or one with good energy absorption capability. Fully tied structures made up of strong elements and connections with good ductility (to maximise their ability to deform under load before they break) have inherent residual strength and therefore low vulnerability to progressive collapse. Provision of strength and ductility needs to recognise that the potential directions of extreme event forces may be opposite to the forces due to normal loads, e.g. uplift due to explosions. In addition, there are some structural situations where weak tying or no connection between parts of a structure can protect against the whole structure becoming involved in a progressive collapse. Knowledge of vulnerability of building structures to progressive collapse is incomplete and research is needed to improve understanding of the phenomenon.

7.2.2 Redundant structures have alternative load paths for carrying the loads around parts where local structural damage may occur. Where a structural element is fundamental to the survival of the whole structure, its design clearly should be given specific consideration. Such elements need to be robust in themselves and, if possible, protected from potential exposure to hazards, e.g. where they are necessarily located near fuel storage that in some extreme event scenarios might catch fire.

7.3.2.2 Heating, ventilating and air conditioning (HVAC) systems may be helpful in the control of fire and occupant survival if linked to fire detection equipment or informed manual control. For this purpose, control of ventilation fans needs to include, for example, the ability to shut them down quickly in a fire-affected zone, and to pressurise adjacent compartments and escape routes appropriately.

Recommendations for consideration: Passive and active fire protection

- Provide robust, resilient and durable passive fire protection.
- Treat active fire protection, e.g. sprinklers, as an addition to, and not a substitute for, passive fire protection, and do not consider it for extreme events.
- Ensure compartments are gas tight and seals are sound on building completion by inspection, testing and certification.
- Provide protection to compartments and mitigate the spread of smoke.
- Design building to survive complete 'burn out' of contents.
- Require independent approval, as a part of licensing and periodic audit of life-safety systems, of modifications to passive and active fire protection.

7.4 Escape, its management and the emergency services

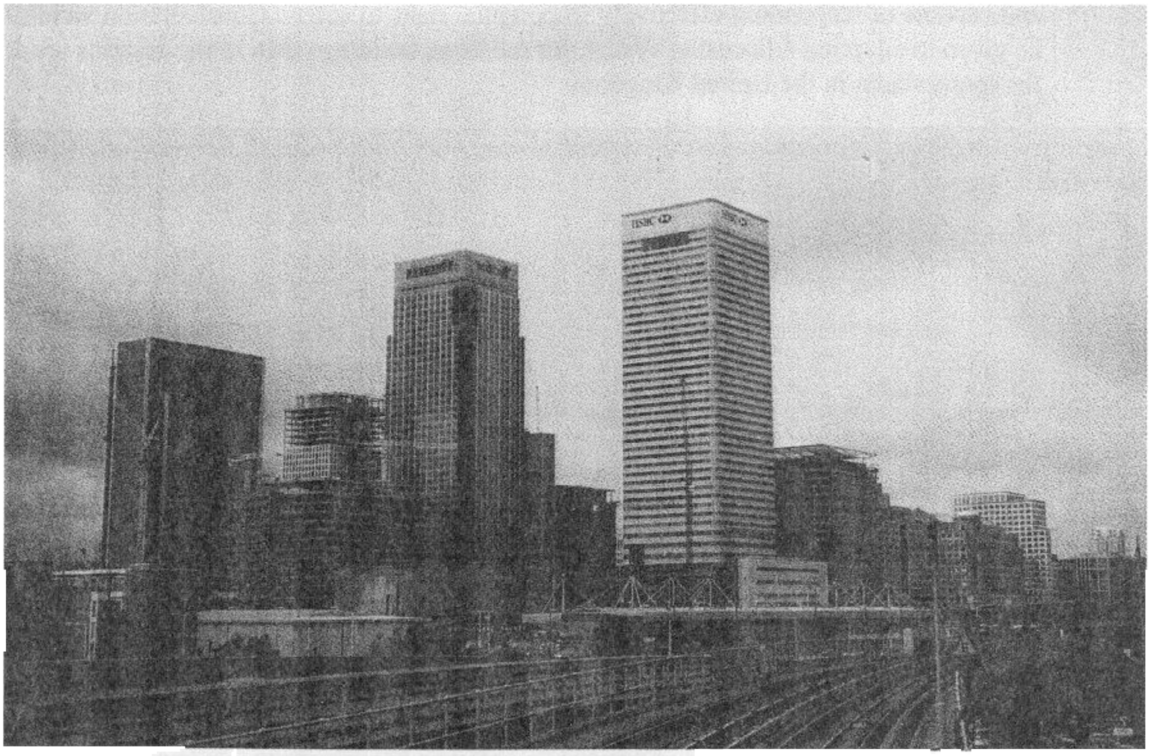
7.4.1 Escape routes and emergency services access

7.4.1.1 For tall/large buildings, a high level of physical protection of escape routes appears desirable, for example by requiring robust shaft construction and stairwell protection by ventilation, pressurisation or smoke lobbies. Further examination is needed of the processes by which smoke may spread during major emergencies and of methods of providing improved protection of occupants over extended periods in the building and during evacuation.

7.4.1.2 Shafts containing escape routes need to have sufficient structural robustness and integrity so that there is only a small risk of them becoming impassable by occupants during an extreme event. Routes should be separated or separately protected even if placed together in the same shafts. They also need to provide a secure environment so that occupants, who may be on the route for an extended period, are safe. For this purpose, shaft pressurisation and blast-resistant doors to lobbies might be considered. Diversity of numbers and location of escape routes and exits is desirable to provide occupants with more options for escape. This would reduce the likelihood that all routes become impassable in an extreme event. Placing entrances to stairs on opposite sides of a central core to give alternative exits from each floor may be a way of increasing diversity. Alternatively, the use of more than one core might be considered.

7.4.1.3 The physical size of escape routes, e.g. stair widths, should also be such that they have sufficient capacity to allow simultaneous evacuation from a number of adjacent floors and possibly the whole building. The dimensions of staircases need to be sufficient so that congestion and delays in evacuating affected floors are avoided in most circumstances. Escape routes also need to be usable by occupants with a wide range of physical capabilities. It may be that properly designed and protected lifts can be used for evacuation generally. The development of design requirements and operating protocols for the use of lifts for evacuation is needed. In 'fire' emergencies, escape by lift needs to be restricted to floors not affected by the fire as the risk of waiting for a lift on the 'fire floor' is too high. Lift control systems should be designed so that signals from the fire alarm system prevent lifts from stopping at 'fire floors'. Provisions should be made for escape from 'stopped' lifts.

7.4.1.4 Escape route provision should allow all occupants to evacuate the building without becoming distressed by congestion or delay. Support systems, e.g. ventilation/air conditioning of shafts, electricity supply and communications systems need to have



7.4.3.3 Strategies need to be defined for each of the main types of major emergency that may arise. Necessarily they involve control of HVAC and other services, management of occupants and the emergency services. There is justification for preparations for major emergencies in tall/large buildings including exercises involving all emergency services and local hospitals as are carried out for other hazard scenarios, such as train crashes.

7.4.3.4 For any emergency, rapid identification of the nature and location of the emergency is required so that the optimum management response is selected. Communication systems that work in a major emergency are vital to the survival and safety of occupants. A further critical feature is the location and protection of the building management communication and control system. As far as is practical it should be protected from becoming inoperable in extreme events.

7.4.3.5 A performance approach based on time to escape is usually employed in modern fire safety design of large, complicated and heavily populated buildings, although these times are normally based on phased evacuation, and may not be valid for simultaneous evacuation. This is a more rational approach for such buildings compared to the traditional prescriptions given in codes that use distance as the escape criteria. Code requirements for maximum travel distances in tall buildings vary significantly around the world. A performance approach is likely to be more suitable for major emergencies, including those that are not fire-related. It can be used for existing as well as new buildings.

7.4.3.6 In many aspects of life safety in major emergencies, time is of the essence. Time to detection of incident, to action by building management to control the incident, to movement of occupants to a place of safety, and to intervention by emergency services can all be critical factors in the survival of occupants. Further work is needed to improve predictive modelling of incident development, of movement and evacuation of people in relation to areas where the air is contaminated by the event, and of protective actions by management and emergency services[9]. These tools may then be used to identify harmful areas in the building and suggest design solutions and/or management strategies.

7.4.3.7 In relation to building maintenance and management more generally, periodic third-party audit and certification is recommended during building use to make sure that life safety installations are maintained as intended. In addition, the management of the operation of the buildings' systems, including emergency response strategies and plans, should be subject to independent audit and certification to make sure they remain alert

purged quickly or contained as appropriate, and more generally so that they can respond flexibly to a range of scenarios. Provide redundancy in the siting of plant.

- Make entrances to the building, e.g. lobbies, mail rooms and utilities entries, separate air distribution zones with separate air supply and extract.
- Locate building air inlets so as to minimise risk of externally released substances being drawn into them.
- Filter or treat inlet air. These measures are desirable and may be appropriate in some cases. They are not sufficient alone to reduce risks to occupants from airborne contaminants. In addition, a flexible capability for pressurisation or depressurisation of compartment volumes relative to those nearby and to the outdoors, and good airtightness are desirable to enable control of contaminated air. Such measures involve large consumption of energy. Provision for natural ventilation may be more suitable since a higher rate of air change is possible compared to that achieved by mechanical systems.

  Seal air distribution systems, including preventing bypass around filters. Make compartment boundaries good physical barriers by sealing unnecessary penetrations.
- Include redundancy and isolation capability in water supply systems. Dedicated risers for fire fighting purposes may not be the only water supply redundancy that is justified. Ability to isolate parts of services supply can be especially beneficial in preventing growth of an emergency, e.g. ability to stop oil being pumped through pipes adjacent to a fire.
- Control and vet food and catering services.

7.5.2.2 Surveillance and security measures used in the management of the building can also contribute to reducing risks to occupants from malicious acts against building services systems, see Section 7.5.3. Access to vulnerable points around and within the building can be made as difficult as possible and, in addition, fences, grilles and locks can contribute to security. Access attempts can be deterred by the use of CCTV and other surveillance methods that make apprehension and identification likely. Detectors may also be used within services systems to detect some types of harmful substances.

7.5.2.3 In addition to strategies of deterrence and protection described above, methodologies for clean-up and recommissioning after incidents need to be in place.

increase in quality and certainty of system effectiveness would probably be no more than the costs of reworking faulty installations. Inspection should focus on the quality and soundness of those parts of the structure and building systems that are critical to life safety in extreme events, e.g. structural system, cladding, fire protection systems, services supply facilities, and alarm and security systems.

Recommendations for consideration: Other issues

Safety of cladding, including glazing

- Use laminated and/or toughened glass with fixings designed taking account of potential explosion loading.

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.

8.5 Other issues

8.5.1 Security and safety of cladding, including glazing

(18) Cladding and glazing systems with minimum propensity to cause injuries following impact, fire or explosion.

8.5.2 Security and safety of building services

(19) Robust and protected building services systems, their performance and control.

(20) The location and protection of plant rooms, water and oil storage.

(21) The means of protecting against dispersion of airborne contaminants in and around tall/large buildings in major emergencies.

(22) The siting and number of air inlets for tall/large buildings.

8.5.3 General

(23) Risk management processes.

(24) Strategies for risk avoidance, reduction and acceptance.

(1) Hart, F. *et al.: Multi-storey buildings in steel,* 2nd edition. London, Collins, 1985

(2) Federal Emergency Management Agency. *World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations.* FEMA 403, May 2002

(3) *11th September 2001*, Supplement to High-rise Buildings, Munich Reinsurance Company, 2001

(4) Standing Committee on Structural Safety. *Structural Safety 1996-99.* Twelfth Report, London, SETO, 1999

(5) American Society for Testing and Materials. *Standard Test Methods for Fire Tests of Building Construction and Materials.* ASTM E119-00. West Conshohocken, Pa, ASTM, 2000

(6) Steel Construction Industry Forum. *Investigation of Broadgate Phase 8 Fire.* Ascot, Steel Construction Institute, 1991

(7) Bailey, C. G., Lennon, T. and Moore, D. B.: 'The behaviour of full-scale steel-framed buildings subjected to compartment fires'. *The Structural Engineer,* volume 77, no 8, pp 15-21, 20th April 1999

(8) Thomas, I. R. *et al.: Fire Tests of the 140 William Street Office Building.* BHPR/ENG/R/92/043/SG2C. Melbourne, Australia, BHP Research, 1992

(9) Chartered Institute of Building Services Engineers. *Fire Engineering,* CIBSE Guide E. London, CIBSE, 1998

(10) National Fire Protection Association. *Recommended Practice for Smoke Control Systems.* NFPA 92A. Quincy, Mass., 1996

(11) Katzman, G. M. *et al.*: 'Risk Assessment of Citicorp Center Original Design'. In: *Safety, Risk and Reliability – Trends in Engineering,* International Conference, Malta, 2001, p303-308. Zurich, IABSE, 2001

(12) Do Valle, G.: 'Failure of a building in Rio de Janeiro'. In: *Safety, Risk and Reliability – Trends in Engineering,* International Conference, Malta, 2001, p699-704. Zurich, IABSE, 2001

(13) Nugent, W. J. and Schmidt, M. K.: 'Failures of Modern High-Rise Building Facades and Components'. In: *Safety, Risk and Reliability – Trends in Engineering,* International Conference, Malta, 2001, p711-716. Zurich, IABSE, 2001

(14) 'Pirelli floor beams sag after Milan plane crash explosion'. *New Civil Engineer,* 25 April 2002, pp 6-7

(15) Standing Committee on Structural Safety. *Structural Safety 2000-01.* Thirteenth Report. London, SETO, 2001

strength, and orientation. Nearly all windows on the upwind faces were shattered. Large annealed glass windows were blown in and glass shards were projected well into adjacent offices. Where blinds were drawn on windows, the projectile hazard was reduced noticeably. It was also evident that blast effects of the explosion on the interior were of low intensity. The only windows to survive on the upwind face of the building were double-glazed in toughened, 10mm-thick glass. These windows were found to be crazed. The 33mm-thick laminated glass windows at street level survived without crazing.

Manchester City Centre 1996

A1.10 A large bomb was detonated in the central shopping district of Manchester, England causing extensive damage[A2]. There were no fatalities but many injuries were caused by flying glass. Structural assessments found that the damage caused by the explosion was mainly to glazing and cladding panels. Although glazing damage was extensive, it appeared to be randomly distributed. Ground-floor windows relatively close to the blast remained intact, whilst windows much further away and at high elevation were shattered. The worst case of structural damage occurred near to the heart of the explosion where the structural frame of a 200 tonne pedestrian bridge was twisted and lifted off its bearings. A retail store immediately adjacent to the site of the explosion was subsequently demolished.

London Docklands 1996

A1.11 There were two fatalities and office buildings and nearby homes were damaged extensively when a home-made vehicle bomb was detonated in London Docklands[A2]. There was little structural damage to nearby buildings. However glazing and cladding damage was extensive. No glazing within 50m of the blast survived.

A2 Damage caused by fire

Seven World Trade Center 2001

A2.1 The 47-storey building known as Seven World Trade Center (WTC7) was set on fire by debris from the WTC towers (WTC1 and WTC2) when they collapsed on 11 September 2001. WTC7 collapsed totally about seven hours later. The collapse appears to have been due primarily to the effects of fire, and not to impact damage from the collapsing WTC towers[2]. The collapse may have been associated with the burning of a large quantity of diesel fuel stored in tanks on the 5th, 7th and 8th floors, and with nearby steel trusses used to bridge the building structure over electricity substations. No other case of a fire-protected steel-framed building collapsing totally in fire is believed to have occurred in spite of there having been several cases world wide of large uncontrolled fires in tall buildings, even where the fire has burnt out all combustible materials inside. The mechanisms causing the total collapse of WTC7 have not yet been confirmed. Loss of structural integrity in one of the load transfer systems caused by fire has been suggested as the 'trigger' event.

Andraus Building, Sao Paulo 1972

A2.2 The fire developed on four floors of the 31-storey department store and office building. It then spread externally up the side of the building involving another 24 floors. Wind and combustible interior finishes and contents contributed to the fire spread. The building was constructed of reinforced concrete. Its façade had extensive floor to ceiling glazed areas, with a spandrel of only 350mm in height and projecting 305mm from the face of the building. After the fire broke through the windows, three to four floors above the department store floors were exposed to a flame front. The front increased in height as more floors became involved. At its peak the mass of flame over the external façade was 40m wide and 100m high and projecting at least 15m over the street. There were 16 fatalities.

Joelma Building, Sao Paulo 1974

A2.3 Fire started on the 12th floor near to a window of this 25-storey office building of reinforced concrete construction. The *in situ* concrete floor slabs projected 900mm on the north wall and 600mm on the south wall. The exterior facade was made of hollow tiles rendered with cement floor cabling. Window and spandrel glass shattered. The fire spread up three floors to level ten. There were three fatalities.

A3 References

(A1) Ministry of Housing & Local Government. *Report of the inquiry into the collapse of flats at Ronan Point, Canning Town,* London. HMSO, 1968

(A2) Yandzio, E., and Gough, M.: *Protection of buildings against explosions.* SCI Publication 244, Steel Construction Institute, 1999

(A3) Federal Emergency Management Agency. *The Oklahoma City Bombing: Improving building performance through multi-hazard mitigation.* FEMA 277. Reston, Pa., ASCE, 1996

such as New York and Florida feel their specific needs are best met by a locally-developed code. Some cities, such as New York, Chicago and Los Angeles, also have unique codes that do not entirely conform to the local state codes. Many codes in the United States, e.g. New York City, provide exceptions/exemptions for government agencies and public utilities. The New York City Building Code did not require detailing for seismic events when the WTC towers were designed and built. Requirements for fire (covering compartmentation, fire resistance and escape routes) are quite detailed.

B1.9 The National Fire Protection Association in the United States has produced a 'Life Safety Code' that is specific to fire[B3]. An NFPA task group has developed guidance on performance-based design.

B1.10 Many codes for design are largely prescriptive. The relationship to life safety is not always clear. However, performance-based guidance is becoming more widely established.

B1.11 This very brief review of some of the regulations that relate to the safety issues in tall/large buildings indicates that requirements are not consistent around the world. The differences are due largely to independent development of regulations in each country and local experience and conditions. Even where regulations are the same, important differences in the detailed code rules for implementation exist that may substantially influence the levels of safety achieved.

B1.12 Development work is needed in many areas of performance-based design covering the main safety issues. Performance-based fire safety engineering design is perhaps the area where development is already well advanced and can be speeded up. The approach has already been used in the design of tall/large buildings and other facilities with unique design features, e.g. airport buildings, railway stations and tunnels. Generally time, e.g. time to escape, is likely to be the performance parameter of greatest relevance in many aspects of building design, operation and management for extreme events.

B1.13 The discussion below briefly describes some of the main requirements and provisions of Regulations and codes of practice in the United Kingdom, United States, Australia, Hong Kong and some other countries. The discussion is not intended to be exhaustive but rather to illustrate the large number and different scope of regulations and code requirements that exist around the world relating to safety issues in tall/large buildings.

B2 Vulnerability to progressive collapse

B2.1 Some regulations and codes of practice explicitly recognise the design principle for buildings that damage should not be disproportionate to the cause. Currently, regulations and codes of practice for buildings in the United Kingdom, United States and elsewhere have different requirements for design against progressive collapse. In the United Kingdom, there is a regulatory requirement, originally introduced following the progressive collapse of Ronan Point in 1968, to provide (in buildings over 5 storeys tall) structural resistance with the aim of limiting damage caused by an accident so that it is not disproportionate to the cause. *Building Regulations Approved Document A* and British Standard codes of practice give advice on meeting the requirement. During 2001 the UK Department of Transport, Local Government and the Regions (DTLR) consulted on proposals to amend the Regulations to bring all buildings within the compass of the requirement. The associated British Standard codes of practice provide guidance on designing the form and detail of structures for ductility and robustness. Structural elements fundamental to the survival of the structure are recognised. Effective vertical and horizontal tying forms the main thrust of the approved design rules.

B2.2 The Eurocode EN1990: *Basis of design*[B4] adopts, as a fundamental requirement, the principle that a structure shall be designed in such a way that it will not be damaged by events like fire, explosion, impact or consequences of human errors, to an extent disproportionate to the cause. It gives strategies for avoiding or limiting damage along the lines of the recommendations in Section 7.2. Essentially, avoid or reduce hazards, select a redundant structural form with a low sensitivity to the hazards considered, and design and connect the structure together with strong ductile elements and connections so that it can absorb energy and survive removal of parts in an extreme event.

BS 476 standard test used in the United Kingdom, the test is not intended to predict actual behaviour of the component in a building during a real fire. A handbook of fire protection engineering has been published by the Society for Fire Protection Engineering[B7].

B3.4 Australian building codes require fire-resisting construction according to building size, building over 5 storeys being the highest category. Load-bearing elements are required to maintain integrity and insulation for specified times. Lightweight non-combustible materials, specified for protecting structure from heat, are required to meet prescribed mechanical tests. Requirements for compartmentation are specified in terms of floor area and volume. Fire stopping of services penetrations is required.

B3.5 In Hong Kong, the Building Code[B8] for fire resisting construction has been derived mainly from earlier British counterparts. A barrier is required at openings in floors to prevent the spread of fire and smoke. Curtain walls extending beyond one storey must be of non-combustible materials and have fire stops in any void between the wall and the building perimeter.

B3.6 Pressurisation methods required for the control of smoke from fire and prevention of its spread through a tall/large building differ across the world. In the United Kingdom, positive pressurisation of stair wells and negative pressures on fire floors are required. In Hong Kong, the fire floor does not have to be depressurised, whilst in Australia additionally the floors above and below the fire floor have to be positively pressurised.

B3.7 Overall, the requirements for the fire protection of building structures and smoke control vary significantly around the world. In many countries, e.g. United Kingdom, United States, Australia, Hong Kong, Sweden and Singapore, the requirements for fire protection are obtained from tabulated data of the performance of structural elements in standard laboratory tests. There are anomalies in the ratings that are derived. Other methods are available for deriving requirements, e.g. the Eurocode method[B9]. These methods are based on 'real' fire scenarios and provide more realistic gas-temperature/time curves that can then be used to input into structural fire analyses to give predictions of the behaviour of the load-bearing system as it is heated by the fire. Proposals being considered by the ISO/TC92 Committee for a framework for long-term standardisation of fire safety in support of performance-based fire engineering design may provide an effective international forum.

B4 Escape, its management and the emergency services

B4.1 *The Building Regulations* of the United Kingdom have requirements in Regulation B1 for means of escape in case of fire[B10]. Provisions for early warning of fire and for means of escape to a place of safety outside the building are required. The requirements for escape routes depend on the use, size and height of the building. They cover number and capacity of routes, distance of travel, protection, lighting, signing and facilities to limit ingress of smoke or to restrict the fire and remove smoke. There are also requirements for fire precautions that require a fire certificate for a tall/large building[B11]. The precautions required, in addition to means of escape, include the provision of fire alarms and fire fighting equipment. As a whole, the requirements for fire safety are designed to ensure the provision of adequate general fire safety, means of escape and related fire precautions.

B4.2 Phased evacuation is recognised in several countries, e.g. United Kingdom[B10], United States[B3] and Australia[B6], as an appropriate way of evacuating tall buildings. The Australian building code provisions for escape require at least two exits for tall buildings and they must be fire-isolated and exit within a certain distance to an open space. There are limits to distances in the building from exits. The size of the exits is related to the number of people accommodated in the building. Barriers must be provided to prevent vehicles blocking exits.

B4.3 In Hong Kong, the Building Code is also prescriptive but well developed on the basis of the long history of tall buildings there. Prescriptive measures include stair pressurisation of fire fighting lift and stair shafts, and provision of refuge floors. Means of escape are defined using total evacuation as the escape strategy. Escape stairs must lead directly to a street and exit doors must be easily operated from within. The width of staircases depends on the number of occupants. Refuge floors are required every 20 storeys, except for residential buildings where

provision of means of escape in case of fire, 1996; Minimum fire services installations and equipment, and inspection, testing and maintenance of installations and equipment. Hong Kong, Fire Services Department, 1998

(B9) Draft prEN 1991-1-2, 2000. *Actions on structures exposed to fire,* CEN 2000

(B10) *The Building Regulations 2000:* Approved Document B: fire safety. London, TSO, 2000

(B11) *Fire Precautions Act 1971,* London, HMSO, 1971

(B12) BS 5588 *Fire precautions in the design, construction and use of buildings,* Series, BSI, London

(B13) BS 5839: Part 8: 1995. *Code of practice for the design, installation and servicing of voice alarm systems, Fire detection and alarm systems for buildings,* BSI, London

(B14) Standards Australia. *Emergency warning and intercommunication systems in buildings.* Australian Standard 2220, Sydney, 1989

(B15) National Fire Protection Association. *National Fire Alarm Code Handbook.* Quincy, Mass., NFPA, 1999

tall/large buildings necessarily embraces consideration of the building as a whole, its design and construction, its protective systems, operation, management, and links to the emergency services. The process typically includes identification of potential events/threats/hazards, assessment of the risks judged against acceptability criteria, and choices and decisions about how the risks will be managed. A range of techniques is available to assist, see for example, reference (C6). Although there is no certain way of identifying all potential hazards and the judgment of what is acceptable is subjective, the process of thinking through different scenarios can be helpful in identifying those measures – whether simple or complex – that have the greatest potential within the constraints of the project to improve life safety.

C9 Specific consideration of risk in extreme event scenarios can play an important role in determining what 'enhancements' should be considered, for example, relating to provisions for fire:

- The use of phased and simultaneous evacuation.
- Use of lifts for evacuation.
- Target time for building evacuation.
- Evacuation management regimes.
- Selection and training of fire marshalls.
- Increasing robustness of escape stairs.
- Robustness of fire protection.

More explicit risk management processes along the above lines could become a wider part of the routine of the creation of tall/large buildings with potential benefit for occupant safety. Development work is needed to transfer and develop the relevant risk management processes used in related industries for tall/large buildings.

C11 References

(C1) Standing Committee on Structural Safety. *Thirteenth Report, 2000-01.* London, SETO, 2001

(C2) Schneider, J.: *Introduction to safety and reliability of structures.* IABSE Structural Engineering Document 5. Zurich, International Association for Bridge and Structural Engineering, 1997

prEN1990, *Basis of design.* CEN, July 2001

BS7974. *Application of fire safety engineering principles to the design of buildings. Code of practice.* London, BSI, 2001

(C5) Draft prEN 1991-1-7. *Accidental actions due to impact and explosions.* CEN, March 2002

(C6) *Managing safety risk.* Guidance Note RT/LS/G/001. Railtrack plc, June 2000

Responding with strength

The industry is attempting to deliver the more robust buildings being demanded. Dave Parker reports.

It is likely to be years before any structural design codes are significantly amended following last year's World Trade Center disaster.

More research into this type of extreme event will be needed before decisions are made. In the meantime, lacking official guidance, the profession must use its judgement in designing buildings for clients who feel at risk. Certain trends are beginning to emerge.

"Designers really have only two options," says Arup Fire International director Peter Bressington. "We can design the building to respond to specific events, such as plane impact or a truck bomb, increasing blast resistance and fire protection, or armouring the cores.

"Or we can lay down simple performance parameters: the building must be able to lose one floor without progressive collapse starting, for example, or all occupants must be able to evacuate the building within a specified time; passive fire protection must resist specified impact and flexure loads, no vehicle must be able to get closer than a certain distance (to a building) without passing a security check."

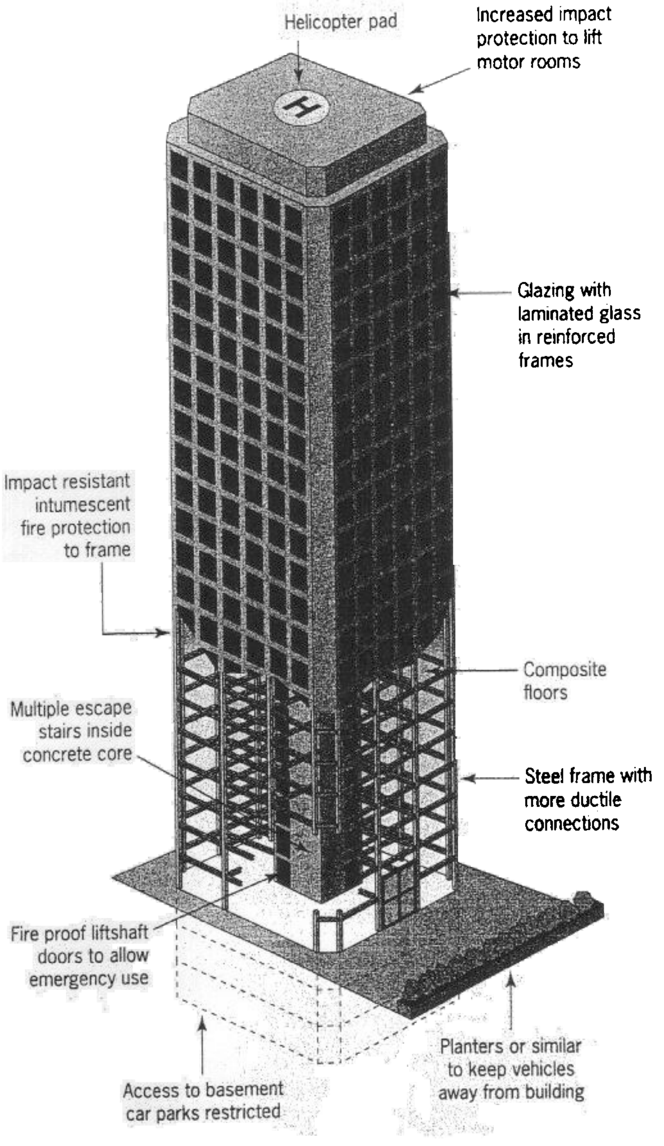
Meeting such parameters could be easier than agreeing what they should be. There is little debate, however, over the need for more robust fire protection to structural steelwork (see box). And few would argue that sprinklers are capable of coping with major events, despite their success in Milan's Pirelli Building (*NCE* 25 April).

On one buzzword there is no disagreement – ductility. Increasing the ductility of the building frame, especially its connections, would give it the capacity to absorb more kinetic energy and remain standing even after massive local deformation or loss of major structural elements.

Connections that rotated rather than sheared would carry loads longer and allow alternative load paths to develop. A floor that sags is preferable to one that stays rigid until it suddenly fails, possibly triggering progressive collapse.

But Babtie Group director Dr John Roberts points out that ductility is not an inherent property of any current frame designs,

Options for increased robustness



Fire protection focus

Twelve months on, the UK passive fire protection (pfp) industry has a measured response to most of the doubts raised about the performance of its protective coatings in extreme events. It turns to the petrochemical and offshore oil industries for inspiration and validation.

"We have materials available that would have performed much better in a World Trade Center scenario," says Association for Specialist Fire Protection (ASFP) chief executive Graham Ellicott. "These were developed for use in hydrocarbon environments and have to be blast resistant.

"A modern high performance cementitous based system would have more than eight times as much adhesion as the gypsum based material used on the WTC development, while an epoxy intumescent coating would be several orders higher again."

This extra performance comes at a price, of course. Ellicott says: "Typically, the steel frame represents about 10% of the construction cost of a high rise building. A standard pfp would come in at about 15% of frame cost, a 'hydrocarbon' pfp would be around double that.

"So specifying a much more robust pfp means overall construction costs would be up 1.5%, everything else being equal."

However, Jeremy Hodges, managing director of the fire and risk sciences division at building research body BRE, is less convinced that such materials can simply be substituted for standard building pfps. "The tests the industry quote are less standardised, more ad hoc than the standard furnace tests used for building products," he says.

steel or concrete. "Careful detailing is essential," he says. "This is particularly true where large transfer structures are involved, as on WTC7."

"We are looking at a medium rise project in London that will sit on a transfer structure supported by just a few large columns," says Roberts. "Analysis of what would happen if one of those columns was lost has so far showed no significant advantage for either steel or concrete."

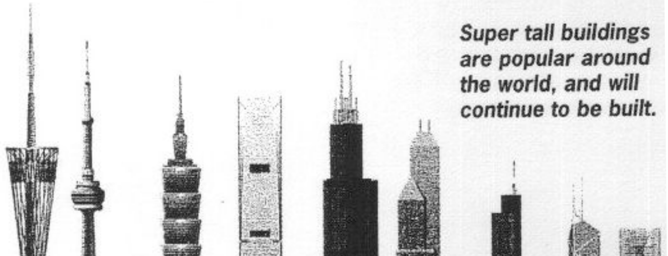
According to Steel Construction Institute director Graham Owens, most buildings of up to 50 storeys, in the UK at least, will continue to have concrete cores and steel gravity frames. "This will still be the most economic option," he maintains. "And UK design codes already produce pretty robust frames.

"But it may be necessary to modify connection design to give more capacity for energy absorption and rotation. I'm confident that we can get a lot of extra ductility just by tweaking current designs."

Determining what levels of improvement may be needed will be the task of the steel industry's Connections Group (*NCE* 25 July). Owens admits current codes and guidance documents focus on static performance and can produce "not very ductile" connections which ultimately fail at the bolts. Final recommendations are likely to take two years to appear – provided someone is willing to supply the essential research funding.

Few designers are likely to adopt a "Pirelli solution" to the problem of providing secure escape routes after a major event.

Three widely separated cores would be hard to fit economically into a standard medium to high rise project. But, says Roberts, even with a single core, it would make sense to position the escape stairs as far apart as possible.

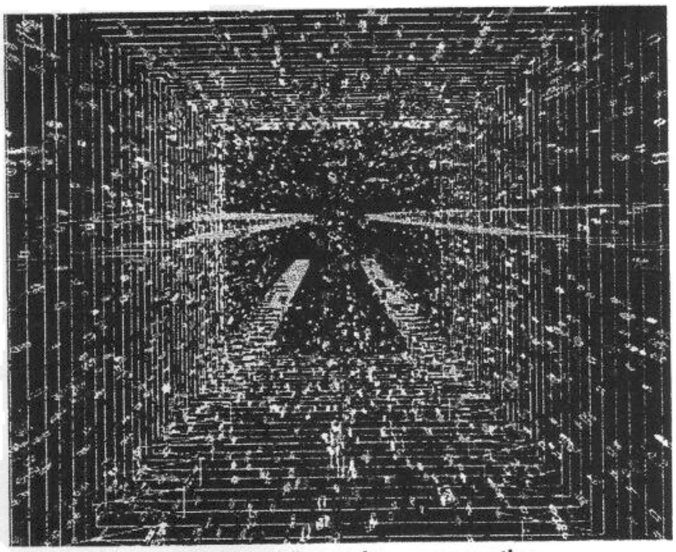


Super tall buildings are popular around the world, and will continue to be built.

"And the structures these high performance materials are designed for are very different, with much larger elements and thicker steel with different thermal properties. Above all, these structures receive much more frequent inspection and maintenance than any building ever will."

But Arup Fire International director Peter Bressington is more sanguine. He believes that a "WTC fire", in which an initial hydrocarbon blaze rapidly evolves into a more familiar office fire, is not properly simulated by any of the standard furnace tests.

"Theoretical modelling using Edinburgh University's ABAQUS programme suggests that a standard intumescent rated at one hour fire resistance could resist a real WTC-type combined fire for at least one hour," he says. "What we need now is another series of full scale fire tests to get hard data on this type of fire."



Computer image of tall building staircase evacuation.

Users demand more safety provisions

Clients and tenants are driving calls for better evacuation and fire resistance provision in high rise, reports Alan Sparks.

Initial fears that clients would shy away from tall buildings appear unfounded. But as London gears up for its next wave of skyscrapers, more questions are being asked of designers.

"Now our clients want to know exactly what emergency evacuation has been considered," explains Richard Thiemann, director at tall building structural engineer Yolles.

"Once an explanation of the level of code requirements has been made, the client has generally felt assured. But this is definitely of greater concern to tenants than in the past. They are also seeking greater reassurance over robustness," he adds.

Arup Fire International director Peter Bressington adds: "Trying to say that the lesson of September 11 is 'It's not a building problem it's a security problem' is just not relieving client anxieties.

"Tenants of tall buildings are demanding to know exactly how long it would take them to get out of the building if anything happens."

Following the events of last year, Canary Wharf undertook a fire drill to see just how quickly it could complete a total evacuation. Timed at just 18 minutes, the effect on the tenants was no doubt reassuring, although lifts were used.

The use of lifts as emergency escapes has been suggested in the joint ICE/IStructE and ASCE/FEMA reports as a way of improving evacuation times. But this is forbidden in fires according to current regulations. Firefighter access lift shafts can be used, but these have a higher fire protection, increased water tightness and have protected or back-up power supplies.

To retrofit a public lift shaft would be very costly and disruptive, according to Thiemann. But there are simple and comparatively inexpensive options open to building owners that will reduce total evacuation times by 30%.

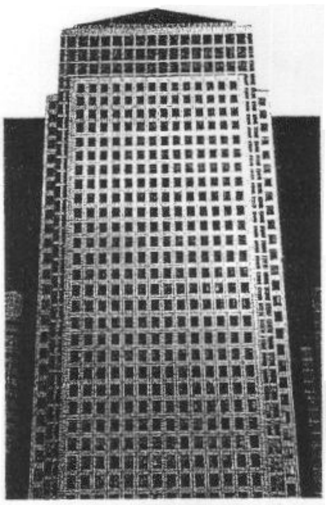
"By improving lighting, ventilation, handrails and most importantly training and information, buildings can very quickly become much safer," states US building use and safety consultant Jake Pauls.

Pauls calculated the evacuation time for the WTC at 100 minutes. But in 1993 when there was a bomb in the lower section of the building, it took eight hours for people to evacuate, mainly due to the lack of information available to them.

"Practising these drills allows tenants to know what to expect. It is normal to have a period of queuing on the stairwells, but unless you expect that some people will panic."

Bressington reports that many tall building owners are now requesting discreet computer simulations of post traumatic event evacuations. "We recently studied a 50 storey office block in New York – and discovered a problem.

"Simulations showed that the



Canary Wharf's main tower can be evacuated in 18 minutes, but using lifts.

final exit was fractionally too narrow and people would jam up there. Simply widening this door transformed the evacuation into a potentially smooth and rapid exercise."

Significant increases in the ability of the building to absorb blast or impact are more difficult and expensive to achieve. British codes demand that any structure over five storeys must remain standing after the removal of a single column. This is more than is demanded in the US but some designers and clients feel it is still inadequate.

"I know of one steel framed building under construction in London which has significantly increased its degree of redundancy following the events of September 11," adds Thiemann.

Popular in Asia is the inclusion of refuge areas in megatowers. The compartments, often lobby areas, have added fire protection to allow tenants to gather in the event of a fire.

Client pressure can also yield changes later in the procurement process. A London office tower under construction will have more robust fire protection to its steel frame than originally specified. A higher performance Portland cement based coating will be used rather than gypsum-based material – at a higher cost.

But making buildings more robust and more fire resistant can never eliminate the risk of a major catastrophe caused by terrorists, says ICE structural board chairman Gordon Masterton.

"No matter how impregnable a building is designed to be, terrorists can always build a bigger bomb," he says.

"As engineers, we must instead ensure that clients understand what is realistic. We do not want to end up chasing our own tails."

Eyewitness

Dan Cuoco, president of consultant Thornton Tomasetti Group, the first engineering consultant contacted by the City of New York after the disaster.

"We could see it from the roof of our offices so saw it live. I remember thinking it was remarkable the towers stood up after the impact but then I didn't feel there was a risk of collapse. I was just thinking that somehow they'd put the fires out. The building was sprinklered, the Fire Department was there.

"We mobilised around 35 engineers to site next morning, when already there were more than 1,000 working on the site with people climbing over the pile. There was a lot of overhanging glass, buildings requiring temporary stabilisation. It was initially really a case of cordoning off anything which was ready to come down.

"It was engineering 'on the fly' – designs and drawings by hand. We'd be told 'a crane must go here', so we used our most experienced people to do quick calculations and sketches which would be sent to steel fabricators, certainly no Autocad drawings.

"Our teams worked 14 hours a day, and the media began to recognise the role played by the engineering profession which went up a few notches in the public eye."

Eyewitness

George Tamaro, principal, Mueser Rutledge geotechnical engineers, worked for the Port Authority on the design and construction of the WTC "bathtub" foundations. His firm designed a system of anchors to support the foundation walls and prevent collapse which would have caused inundation of the site from the nearby Hudson river.

"I was called by Dick Tomasetti to meet with Commissioner Burton from the Department of Design & Construction. I had kept detailed records during the construction with photos, so I loaded up the car with safety gear, and headed down. I had projected in my mind what the actual site problems could be, but was horrified when I got there.

"Everyone was looking up, nobody was looking down. I know that site very well, I could probably go through it blindfold. I told them some of my concerns and of water coming into the site. Everyone was focusing on rescue, but I was afraid they'd move a crane causing some of the walls to collapse, or that a crane would topple over and kill more people. I saw them trying to move a 200t crane out over a piece of decking inside the slurry wall which would have gone straight through – and then decided to do some "cartoon" drawings showing them the problems below grade.

"We couldn't do positive work to start supporting the walls until mid October when the wall started to move at Liberty Street. One wall moved 1.4m – walls had gone into the ultimate moment range of capacity. Our work was nothing to do with geotechnical engineering – it was structural, construction and demolition work – the only geotechnics was that the soil was pushing the wall in. The closeness to water was significant, the river was only 50, 60m away. There was always a risk of inundation – our job was to make sure it never happened."