Title: **Fire Induced Progressive Collapse**

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Fire Induced Progressive Collapse

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ABSTRACT

This paper considers issues related to fire induced progressive collapse of tall buildings in extreme events. It discusses current fire engineering practice, particularly as it relates to tall building design and the issues that need to be considered in the understanding and prevention of progressive collapse. This paper concentrates on the scenario where further to an extreme event active life safety systems are no longer effective. It proposes suggestions, subject to further research, as to what can be done to improve the performance of buildings against fire induced progressive collapse.

The paper recommends that Building Codes introduce some form of simple minimum design requirements that reduces the risk of progressive collapse for all buildings. For high-risk structures the paper recommends that a comprehensive performance based approach should be used to assess and mitigate the risk from extreme fire and impact loading. This approach considers the whole performance of the building under extreme events and includes an assessment of the means of escape, fire fighting, active fire safety systems and passive fire protection, in combination with the performance of the structure and its behavior under extreme conditions.

Background

In commercial tall buildings there is a very small risk of progressive collapse due to a normal accidental fire. There have been very few records of progressive collapse caused by accidental fires. It can be argued, therefore, that existing design methods and procedures are both acceptable and appropriate for conventional fires.

From the authors perspective the immediate public reaction following the September 11th attack however, is such that for commercial purposes, iconic and high-risk structures may now require additional safety measures to limit the potential for fire induced progressive collapse.

However, rather than concentrate on a single fire safety measure to increase tall building robustness in extreme events, such as an increase in passive fire protection thickness as a means to limit progressive collapse in fire, it is instead suggested that a total building design approach with an integrated package of safety measures be developed. The aim being to utilize the beneficial aspects of the performance of whole structure in fire with other passive and active systems, as well as egress and firefighting measures, such that a performance-based design approach is adopted to address building response to an extreme event.

The general public is keenly aware of the issues relating to progressive collapse. It is important that designers take necessary measures to design future buildings to help limit a progressive collapse where the damage potential is disproportionate to the cause, either as a result of fire, blast or impact loading. The aim is that, on a number of fronts, the building fabric and life safety strategy include appropriate levels of inherent redundancy to better address potential extreme events.

The building industry now has at its disposal sophisticated modeling techniques, more extensive research data on how buildings perform under fire conditions and the benefits of advances in new construction materials. The challenge facing the industry is how best to apply this knowledge to ensure that an appropriate level of safety is achieved in a cost effective manner. Clients are potentially likely to invest more if they can prove their building is safer, and therefore improve its marketability. This is already the case for certain key high rise projects.

However it is clearly not appropriate to design all buildings for a damaging impact and multiple fire scenarios similar to that experienced by the WTC. It seems appropriate to have flexible design standards such that if buildings have more risk due to perceived vulnerability, population or usage; then the risk is counteracted by appropriate precautions and mitigation measures.

The authors believe that there is a need for an integrated approach to address real structural response to fire in order to better quantify the appropriate allocation of mitigation measures. Essentially, a performance-based approach to the design of structures in fire conditions is required.

For example:-

- To what extent should the provision of suppression systems influence the fire resistance requirements in extreme events?
- Should passive fire protection requirements be related to the ductility of the structure and its ability to redistribute load?
- In the event that certain elements are deemed critical (or 'key') such that, their 'structural removal' would result in significant collapse, should it then be appropriate to adopt significantly increased fire, blast or impact protection for such members?
- If the structure is of a form in which alternative load paths exist, or in which progressive collapse through the cold zones is restricted, then should this influence the passive fire protection strategy for the building?
- Can a full second - order analysis of fire-structure interaction be a means of addressing design details to limit progressive collapse and further influence the fire suppression and fire resistance strategy?

There is a temptation to increase the requirements on all fronts to improve safety – e.g. increased fire suppression, fire resistance and structural sizing of elements. It is evident however that the resulting cost increases may be prohibitive. But more importantly such increases may not present an increased robust building response to an extreme event. The performance-based approach to fire and structure interaction ensures an effective means of presenting a cost-effective elevation of safety levels.

In order to develop a system that has the appropriate levels of redundancy to deal with unexpected events it is necessary to consider the following factors, which can contribute to or mitigate a fire induced progressive collapse:

- Failure of the active life safety systems
- Failure of passive fire protection materials
- The size of fire, its duration and rate of growth
- Structural materials
- Loading in the Structure

- Ability to redistribute load
- Structural Configuration
- Ductility of the elements
- Ductility of connections

Recent large building frame tests in real fire conditions, and resulting analysis, have shown that detailing of connections and load distribution paths are key to enhanced structural response to fire conditions. Work on passive fire protection materials since 9/11 has shown that it may be possible to specify materials with increased response in extreme events. A combination of these may serve to mitigate the lack of active safety systems in an extreme event.

Existing Fire Engineering Approach to Tall Building Design

Building and fire regulations are becoming performance-based worldwide. With respect to fire, performance based analysis and design is a comprehensive approach to fire engineering which covers all aspects of the design including:

- Fire initiation and development
- Calculation of fire size
- Means of detection and suppression
- Smoke management
- Means of escape
- Fire fighting facilities and response
- Control of fire spread both within the building and to adjacent buildings
- Compartmentation
- Real performance of structures in fire
- Emergency light and power
- Materials and their response to fire – internal linings and finishes

A performance-based approach considers an analysis of fire scenarios to meet specific performance criteria and objectives agreed by all parties. These parties can include amongst others the authorities having jurisdiction, the building owner or occupier. The governing objective for commercial high-rise construction is typically to minimize fire related injuries and prevent undue loss of life. However a performance-based design means concepts such as business continuity and asset protection can also be addressed. (Little,Meacham & Smilowitz 1999;Olsson 2001)

Some comments on Passive Fire Protection

Passive fire protection requirements are formulated based on testing of assemblies in the standard furnace test as per ASTM E119 (ASTM 2000). Traditionally it has been assumed the standard furnace test replicates real structural response to fire conditions. Therefore if a single element or assembly, with or without fire protection, survives a 1 hour or 2 hour furnace test, it has an equivalent ability in a real fire to survive for 1 hour or 2 hours respectively.

However the standard furnace test has always been criticized due the well-referenced fact that the heating regime does not represent most real fires. Real fires are a function of fuel load, compartment dimensions, thermal properties of the compartment boundaries, and the quantity of unprotected openings that allow ventilation in a post flashover fire. They can therefore be more severe or less severe than the standard furnace.

However more importantly the standard furnace test does not assess real structural response in fire conditions because single elements/assemblies are tested in a furnace even though they form component parts of complex 3 dimensional frames in real buildings.

Performance-based design approaches assess overall structural response to real fires. Real fires are used as a basis of design, and frame responses can be determined using simple analytical techniques or Finite Element analyses.

Since the WTC collapse this is even more relevant, as by using explicitly defined design basis fires designers can also assess extreme event effects on overall structural response. This allows designers to develop structural assemblies, which may minimize detrimental structural responses.

Fire protection periods for structural elements are generally codified outside of the performance codes and structural elements typically range from 30minutes to 240minutes. In the US the standard requirement for fire protection on commercial buildings with a sprinkler system are 3hrs for vertical structure and 2 hrs for floors or separation. In Europe a similar structure would require 2 hours throughout.

Until September 11th most designs did not consider the potential of terrorist attack. Performance based scenarios did not normally consider extreme events such as terrorist attacks, except for embassies and similar secure buildings. However the Performance Based design method is particularly suited to looking at any form of design scenario, including such attacks. In considering extreme scenarios it is possible to estimate the extreme consequences of similar events. Following the Sept 11th attack, several studies have been carried out on high-rise buildings that are currently being designed, to assess the effects of a similar event and other extreme scenarios.(Arup, 2002)

Fire protection on structural steelwork is typically provided by either a cementitious spray, reinforced concrete, mineral fiber, Gypsum board, or an intumescent coating. In concrete structures it is provided by the cover to main reinforcement.

Hydrocarbon fires (ASTM 1993), or conventional fires ignited by significant accelerants, differ in that the heat gain is very rapid – significantly quicker than that assumed for the standard time-temperature profiles upon which fire protection materials are tested (see Fig 1 which compares the time temperature profiles for a hydrocarbon fire, a standard fire and a natural fire curve with high fuel content and minimal ventilation within a compartment.)

This rapid gain of temperature can have a devastating effect on concrete and cementitious spray, the two most common forms of fire protection. The temperature of the moisture vapor entrapped in the concrete rises rapidly and turns to steam at 100°C. Unable to dissipate quickly through the microstructure of the concrete the pressure builds up causing an explosive spalling or "pop-corn cracking" of the concrete. Higher strength concretes are particularly prone to this effect.

It shall be noted that Norwegian codes, specific for use in the offshore industry, offer a sacrificial design of 4-8mm per minute to account for spalling under hydrocarbon fire conditions. (Danialsen et al 1988; Hammer 1990). This offers some food for thought in the design and detailing of reinforced concrete columns in which the main reinforcement is located 30-40mm from the face of the column.

The concrete pop-corn effect has been documented in several tunnel fires such as the that in the Channel Tunnel in 1996 (see Fig 2). Many studies were performed to look at repair solutions, which limited the effect. These included trials incorporating steel fibers as well as trials using polypropylene fibers. It was evident that the latter performed significantly better. The chosen solution adopted a dosage of 5kg/m^3 of polypropylene fibers within the mix.

In the event of a fire, these fibers tend to melt, increasing the porosity of the concrete that increases the porosity of the concrete and thereby dissipate the pressure build-up, which would otherwise occur.

It should be noted that these improved fire resistance concretes, incorporating polypropylene fibers, are presently being constructed into a number of buildings around the world including underground station developments in Hong Kong.

Intumescents have been tested using the standard hydrocarbon fire curves, for off shore applications also. Intumescents have a more robust reputation against normal building fit-out wear and tear. Further investigation into their performance under impact and other extreme events is proposed as a useful next step to developing robust passive fire protection materials.

It is evident that in situations where key stability elements are identified, such improved materials could be used, reasonably cost effectively, to provide an elevated resistance to accelerated temperature rise conditions. This in conjunction with structural redundancy could go some way to mitigate effects of fire on structures and so limit progressive collapse mechanisms.

Design For Progressive Collapse

The investigation into the 1995 Oklahoma City bombing, Fig 3, (FEMA/ASCE 1996; Prendergast 1995,) found that the progressive collapse of the banded beam system, which had little or no redundancy caused most of the fatalities. Although the investigation did not result in changes to building codes there is now increasing pressure to do so.

Certain codes around the world require specific consideration of the issues of robustness of floor plate systems and of buildings as a whole. One such example is the requirement in the UK, where by floors, and their connection to the perimeter structure are designed to resist prescribed tying forces. This requirement was prompted by the collapse of Ronan Point in 1968 (see figure 3). The building was constructed from pre-cast concrete elements. A gas explosion occurred on the 18th floor, blew out the perimeter structural panels, resulting in the collapse of the floors above in that quadrant of the building. The falling debris impacted the floors below, resulting in the failure of the majority of floors below. The incident was identified as a progressive collapse, the extent of which was disproportionate to the cause.

The subsequent requirement for tying forces is intended to prevent the blowing out of perimeter structural panels in such a similar situation. When applied to framed structures, the prescribed tying forces were also considered to offer a ‘catenary resistance’ to floors in the event of key element removal. Figure 4 shows a photograph of a blast damaged building which, whilst obviously having suffered a significant traumatic event, did not collapse disproportionately, and highlights the need benefits of tying action within the floor diaphragms.

The requirements in such codes in terms of tying force requirements is relatively simplistic in that a static load is derived and applied to the connection design. The key issue is that the requirements are not complimented by any ductility, or rotational capacity requirement. As can also be seen from Figure 4, it is evident that rotational capacity of connections at the supports is also required, in addition to the tying requirement, in order to allow the floors to act in this manner. All too often, the detailing necessary to satisfy the tying requirement results in connections with reduced rotational capacity. Clearly this is an aspect which needs to be reviewed and is discussed in detail in a later section of this paper.

Both Canada and the UK have simple but explicit guidance for progressive collapse design, which mitigate the effects of accidental key element or column removal on buildings more than 5 stories. The

US also has clear guidance and recommendations to prevent progressive collapse, contained in the ASCE 1999. (ASCE 1999) These however, are not explicit and deal with design principles and objectives rather than clear design methodologies. The requirements of ASCE are also not reflected in many city codes, nor are they reflected in design codes, such as ACI 318-99. (ACI 318-99). The overall result is that the vast majority of buildings in non-seismic areas are designed without any provision against progressive collapse. This situation is clearly unacceptable. It is important that designers design buildings to prevent the failure of a single element causing a disproportionate amount of damage.

US seismic codes provide recommendations for tying forces and joint ductility, which will help to resist progressive collapse, although the codes do not explicitly check for column failure. It is suggested here that such recommendations be investigated for the progressive collapse situation.

The Analysis of Non-Linear Behavior of Structures in Fire

In the last 10 years, full scale testing of partial or complete floor plates has shown that the standard furnace test does not represent the heat regime in most real fires or the non-linear structural response (Kirby 200). Figure 5&6 show some details from a series of fire tests at Cardington, UK. (Bailey and Moore, 1999; Allam, Burgess and Plank, 1999).

The standard furnace test does not assess real structural response in fire conditions because single elements of structure are tested in a furnace whereas the real behavior is determined by a complex 4 dimensional interaction of the 3-D behavior of beams, columns and diaphragm subject to large non-linear displacements against heat and time.

The only reliable method, at present, of predicting the complex structural behavior observed in any whole frame structure in fire is to model the frame using a finite element code incorporating non-linear geometry, non-linear material constitutive properties with increasing temperature and suitable thermal expansion coefficients. This allows designers to develop structures that perform well in a fire.

These techniques are already being used around the world to justify the non-linear behavior of structures to agreed performance standards, thereby, in particular circumstances, allowing fire protection to be reduced or omitted completely. The reverse is also true. When designing for an extreme event such modeling will allow designers to develop sufficiently robust connection and structural configurations, which also incorporate the benefits of enhanced passive fire protection. After all, there may be more assurance about the actual behavior of a floor in a fire when it is modeled explicitly rather than if it is protected by a series of arbitrary rules without any understanding of its actual behavior in a fire.

Non-linear finite element analysis of composite structures has been used to assess the performance of structures in fire and have been correlated against full-scale tests. The results of these tests (Edinburgh 2000; Lamont 2002) and analyses typically conclude:

- Unprotected steel and composite floors can survive for considerable periods without failure
- Redundancy is effective and load paths change in redundant structures as elements fail.
- The composite slabs are effective in acting as tension and compression membranes when large deformations occur, contributing significantly to the ultimate behavior of the structure.
- Thermal expansion and thermal bowing effects dominate the structural behavior.
- Imposed loading with loss of material stiffness and strength at increasing temperatures are important but secondary issues.
- Large downward deflections are good for the structure under fire conditions because they absorb horizontal expansions relieving stresses as a result of restrained thermal expansion.

- Connections can be modeled explicitly and need to be able to accommodate substantial rotations without brittle failure.
- Deflections are not a measure of the stress state of the building at high temperatures.
- In fixed-ended members with a through depth temperature gradient, curvature causes moment.
- In pin-ended restrained members curvature leads to tension.
- Higher restraint to horizontal movement leads to greater deflections.

Although non-linear analysis gives the most accurate understanding of actual behavior, there are many sensitive parameters that can affect results. More research and debate is needed to agree design methods and assumptions. However these techniques are being actively used (Usmani 2001).

The following behaviors now associated with composite structural response to fire are important:

- Combinations of thermal expansion and bowing with various restraint conditions can produce a large range of deflection and internal force patterns
- In slabs and other 2D members compatibility of displacements in the two directions may govern internal forces and displacements.
- Recent research (Lamont, 2002) has shown that the most detrimental fire in terms of the structural response is likely to be a ``short-hot" fire, where large deflections develop in a very short time. The slab experiences high mechanical tensile strains at reinforcement level because of the high temperature gradient in the composite slab.
- Modeling of edge constraints and protection assumptions are key. Protected edge beams allow the slab to be anchored on all four sides of the frame throughout the heating regime. When the edge beams were unprotected the slab would tend towards 1D catenary action, which is a much weaker load carrying mechanism than 2D tensile membrane action.

Non-linear analysis is an effective tool to obtain an understanding of how structures behave in extreme fire conditions. Parametric studies are required to see how sensitive designs are to assumptions. However these techniques are already influencing the way major structures are being designed for fire loading because it offer the only reasonable tool to predict actual structural response to fire.

Ductility

The seismic performance of buildings is governed by ductility of the elements and connections. Similarly the performance of structures under high temperatures, after failure of fire protection, is also strongly influenced by the ductility of the connections and the ability of elements to form ductile hinges, thus allowing gross deflections prior to failure. Whereas seismic design concentrates on the lateral load system, fire design needs to consider all elements.

As stated above, significant ductility of the connection is required such that under fire conditions, a reliable deformation of the floor can be achieved such that it is not pre-empted by ‘brittle type’ failure. Depending on the profile of temperature across the floor, it may be necessary for the connections to exhibit ductile behavior under ‘non-elevated temperature conditions’. The presently adopted tying force methods in other parts of the world may not be sufficient to address this issue.

Arup have undertaken studies of the behavior of floor plates under normal ‘non-fire’ conditions using second-order finite element analysis techniques incorporating non-linear material properties. The basis of the study was to examine the energy absorption capability of the floor plate assuming the impact from the floor above falling. The floor plate in question was that involving a conventional long span office composite floor system connected to a conventional reinforced concrete core. The studies showed that the weak link in the ability to absorb energy was the secondary beam to core wall connection despite it being designed to resist prescribed tying forces. The lack of ductility (rotational capacity) of the connection effectively limited the plastic (i.e. energy absorbing) deformation of members elsewhere in the floor (see Figure 7).

The study showed that by reducing the thickness of the cast –in end-plate connector from 16mm to 10mm, the total energy absorption for the floor plate, in term of resisting debris impact from the floor above, increased by 20%. This is quite compelling in that the cost of the connection is effectively reduced. Further rotation enhancing measures (which also reduce cost) are illustrated diagrammatically in Figure 8.

- Larger gaps between beam ends and the face of the connection.
- Omitting shear studs at the ends of the beam to permit improved straining of continuity reinforcement.

More testing and research is required to understand and develop cost effective standard details that perform well in extreme fire conditions.

Special Moment Resisting Frames designed for seismic loading would perform well in extreme fire conditions. They have sufficient ductility to generate hinge action in beams and have continuity requirements that would allow catenary action. Similarly welded steel frames will perform well; a good example was seen at No 7 World Trade Center, which was subject to some form of fire load for 7 hours prior to collapse. Looking at the debris field the connections remained intact, and there was substantial energy absorbed by yielding of steel. The cost and benefit (in terms of safety) of ductile connections should be compared with alternative measures of progressive collapse prevention, such as design for column removal or providing key elements.

Structural Configuration

The ability of a building to redistribute loads is determined by the structural system as well as the ductility of components.

Rigid Tubes Rigid Tubes such as a fully braced tube or a dense moment frame, e.g. World Trade Center can readily redistribute loads and can easily accommodate the removal of one, or several columns elements on any facade. Because the tubes are rigid they are effective at redistributing load and substantial damage can be usually done to the frame without any major sign of distress to the total structure.

The frame of the World Trade Center was extremely stiff and a simple analysis of Tower 2, (see Fig 8), indicated that it was very effective at redistributing load prior to failure. With a large opening on two adjacent sides the floor deflection was only about 6-9in, explaining why there was no obvious warning prior to collapse.

The lack of warning of failure was clearly a major cause of casualties and was due to a lack of understanding and awareness from designers, users and firefighters.

However the rigidity and strength of the tube at WTC was what made it so effective at redistributing load under extreme fire. A more flexible frame would have more difficulty redistributing load and would be more susceptible to progressive collapse from more concentrated damage

Flexible Tubes. A flexible tube would be a conventional frame system, such as a braced core with a vertical load resisting perimeter frame or an outrigger and band beam system. The frame could be either a ductile system or a non-ductile system.

With the loss of a single column the non-ductile system would have a tendency to progressive collapse, losing a vertical strip of building. Tubes with ductility or those designed for progressive collapse will deform substantially before collapse. This is beneficial as the building shows distress before failure. However it should be remembered that a system designed for the accidental removal of one column would have a limited ability to withstand say, the accidental removal of 4 columns.

Collapse Strengthening. On special buildings it may be appropriate to introduce key columns to inhibit progressive collapse. For instance every 4th column could be designed as a robust element whose purpose was to act as an alternative vertical load path in the event of impact and fire. These elements could be reinforced against impact loads and protected by a different fire protection system, such as polypropylene concrete. The dual combination of mixed structural systems with mixed fire protection systems provides an effective and redundant system, which may be appropriate for high-risk buildings in extreme events. Figure 9 shows failure configurations for rigid and flexible tubes and the concept of key elements.

Structural Redundancy and Removal of Key Elements

The main difficulty with non-linear analysis is defining the extreme load conditions to be analyzed; such as what size plane, how much fuel, what impact level, what wind load etc. However a simple yet effective approach to assess the performance of the building is to remove key elements and assess the resulting structural response, without necessarily giving too much consideration as to the cause of the removal.

It is possible to use simple static analyses to observe effects of removing key elements in high-rise buildings.

This approach consists of a simple static analysis of a badly damaged structure, which gives a good indication of how the building could perform with major elements damaged or unable to take load. The designer simply removes a variety of key elements to determine how the building elements need to be designed to redistribute load. The elements removed represent the result of damage that is to be considered due to an extreme event or could cover a variety of scenarios. The designer then has the option to examine a variety of scenarios.

In Fig 10, 11 & 12, work carried out by Arup for a high-rise building is presented. These figures describe the process and some of the damage scenarios examined for a tall building. These show that redundant structures with ductile detailing can be very effective at redistributing loads when badly damaged.

Irrespective of the choice of structural system, such studies could be a valuable aid to the Fire Department to educate them on how buildings have been designed to perform and to show them how the building would perform when several critical elements were damaged.

This type of analysis is now being used to help owners build confidence for themselves and for their tenants that tall buildings can be designed to withstand extreme damage without collapse.

Conclusions and Recommendations

The NIST seminars and research are focused on building a consensus among building professionals on how best to deal with progressive collapse. The authors are firmly of the view that it is unacceptable for the deliberate or accidental removal of a single structural element to cause a progressive collapse. It is recommended that Building Codes introduce some simple minimum design requirements for progressive collapse that cover all buildings. In their simplest form these could be easily derived from ASCE 1999 or from the best practice in Canadian, European or British codes.

Special requirements need to be developed for high-risk buildings. Owners and design professionals are already considering many techniques to make buildings safer than before September 11th. These could be developed into a Performance Based design approach for high-risk structures that would result in prevention measures appropriate for the risk.

Initially some form of design guidance note should be produced that outline techniques that are being used to enhance building performance under extreme events.

The techniques that could reduce the risk of progressive collapse are:

- Removal of Key Elements Assessment
- Non linear impact analysis and design
    - Design of key elements for impact
    - Analysis of floors for heat loading
- Provision of collapse strengthening elements
- Enhanced passive fire protection of key elements
- Detailing for Ductility

The need for more research has been discussed within the paper and include:

- Development of ductile standard details for extreme fire conditions
- Correlation of fire protection with fire performance so that appropriate levels are recommended in Building Codes.
- Documentation and agreement of non-linear analysis techniques.
- Development of fire protection that will avoid "pop-corn" effects for concrete elements and passive fire protection materials.
- Progressive collapse on a large scale is not well understood and needs to be better documented. Many buildings in the US are currently demolished using explosive and progressive collapse and could provide excellent opportunities for further investigation and research.

REFERENCES

Allam A., Burgess I. And Plank R., 1999, *"The Large-Deflection Behavior of Steel and Composite Frames in Fire"*

American Concrete Institute. (1999) "*Building Code Requirements for Reinforced Concrete and Commentary"* ACI318-99 and ACI318R-99, Detroit, Mich

American Society of Civil Engineers (1998) "*Minimum Design Loads for Buildings and Other Structure*" ASCE 7-98, Reston , VA

Arup: March 2002. *"Life Safety – A New Perception, March 07, 2002"* Internet publication 3.2Mb http://www.arup.com/WTC_06_03_02.doc

Bailey C.G. and Moore D.B. The behavior of full-scale steel framed buildings subject to compartment fires. *The Structural Engineer*. 77(8):15-21, 1999.

Danialsen, U; Hammer, T A; Justnes H; Smeplass S: "*Marine concrete structures exposed to hydrocarbon fires",* SINTEF Report STF25 A 88064, December 1988.

FEMA Building Performance Analysis Team (Corley W.G.et al). "*The Oklahoma City Bombing: Improving Building Performance through Multi-Hazard Mitigation (FEMA 277)"* FEMA/ASCE, Washington, D.C.; 1996

Hammer T A, "*Marine concrete structures exposed to hydrocarbon fire. Spalling resistance of LWA Concrete"*. SINTEF Report STF25 A90009, March 1990.

Kirby B.R. British Steel data on the Cardington fire tests. Technical report, British Steel, 2000.

Lamont S. "*The behavior of multi-storey composite steel framed structures in response to compartment fires*" PhD thesis The University of Edinburgh 2002. www.civ.ed.ac.uk/research/fire/project/thesis.html

Little R., Meacham B. and Smilowitz R. "*A Performance-based Multi-objective Framework for Security and Natural Hazard Mitigation*

Olsson, P. (2001) Proceedings from the conference "*Building for the 21st Century*", Queen Elizabeth II Conference Centre, London, UK on 9-11 December 2001. Published by Council on Tall Buildings and Urban Habitat, Lehigh University, Pennsylvania, US (2002)

Prendergast J. "*Oklahoma City Aftermath*" Civil Engineering – ASCE, Vol. 65, No. 10, October 1995, pp. 40-45

The University of Edinburgh. Final report of the DETR-PIT project: Behavior of steel framed structures under fire conditions. Technical report, The University of Edinburgh, 2000. www.civ.ed.ac.uk/research/fire/project/main.html

Usmani A.S., Rotter J.M., Lamont S., Sanad A.M. and M.Gillie "*Fundamental principles of structural behavior under thermal effects"*. Fire Safety Journal Vol. 36 No. 8 2001.

SFPE Engineering "*Guide to Performance-Based Fire Protection Analysis and Design of Buildings*" SFPE Task Group on Performance-Based Analysis and Design, 2000.

ASTM E119-00 Standard Test methods for Fire Tests of Building Construction and Materials, ASTM 2000

ASTM E1529 – 93, Standard Test Methods for Determining Effects of Large Hydrocarbon Pool Fires on Structural Members and Assemblies, ASTM 1993.

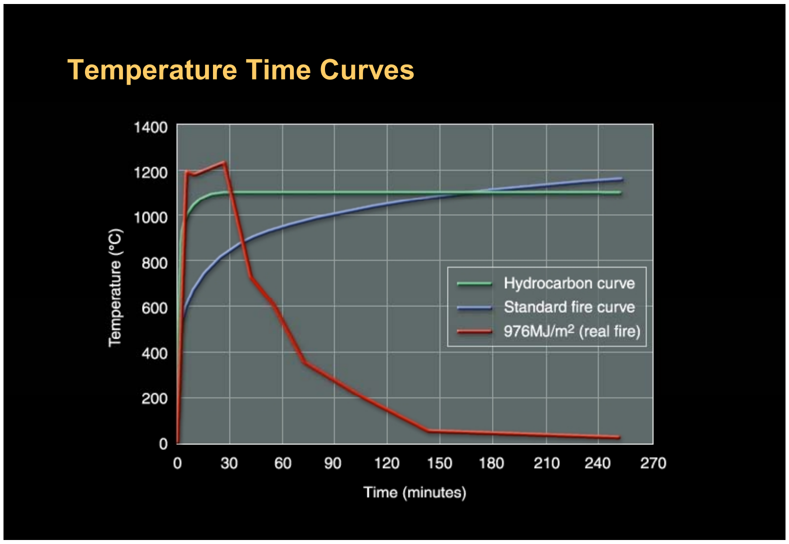


Figure 1: Comparison of standard temperature time curve, standard hydrocarbon curve and natural fire curve with room containing high fire load and minimal ventilation.

Figure 2: Comparison of concrete in fire, with and without polypropylene fibers

Figure 3—Progressive Collapse - Ronan Point 1968, Oklahoma City 1995

Figure 4—Ductile Failure of Floors showing hinges and tying action.

Figure 5—Full Scale Fire Tests at Cardington, Connection Failure

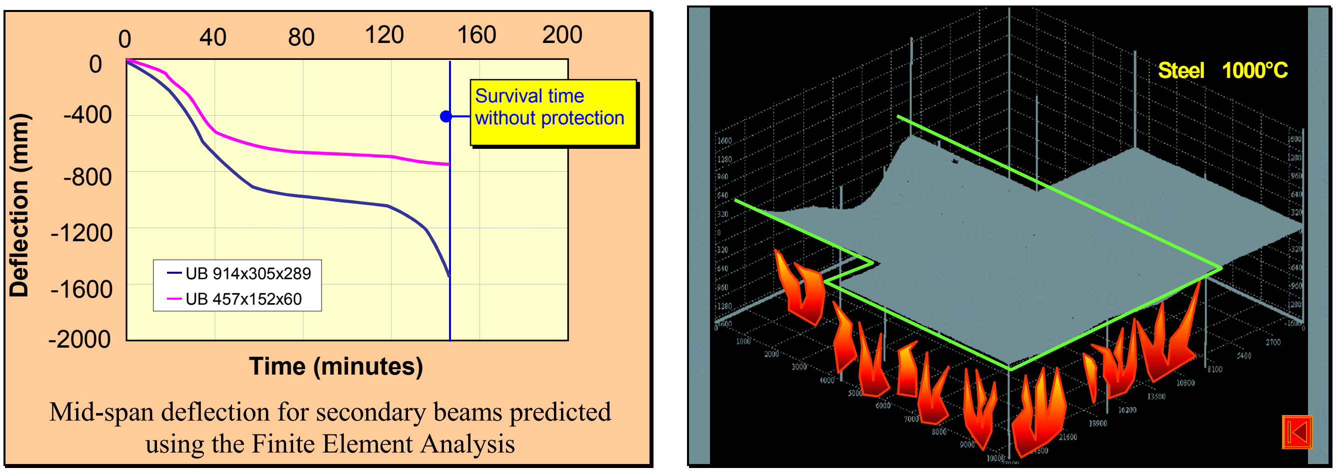
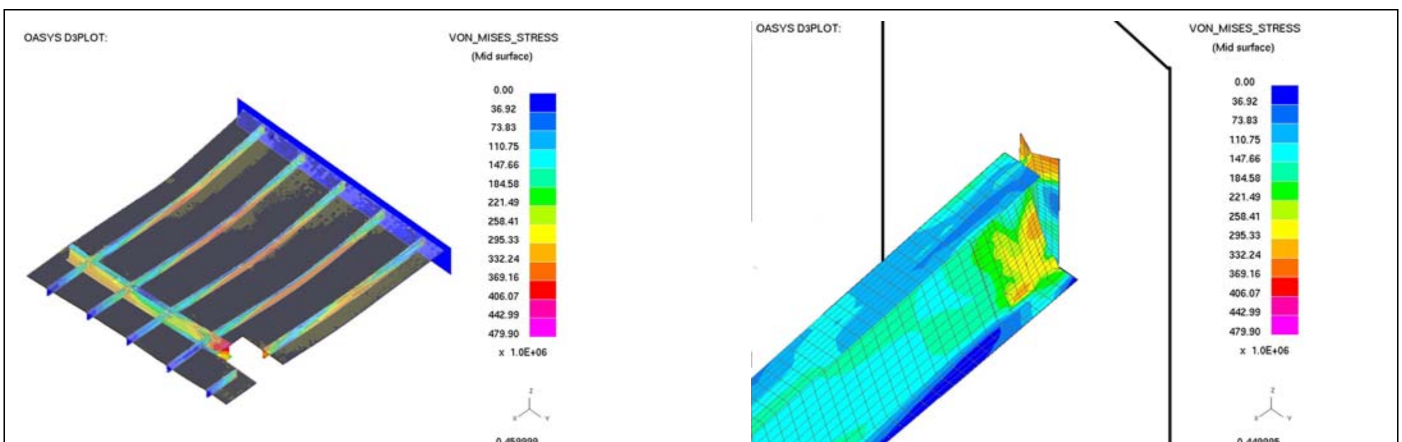


Figure 6—Analysis of Fire Tests at Cardington



Ductile Failure of Primary Beam **Non-Ductile Failure of Secondary Beam**

Figure 7—Non-Linear Time History Analysis of Floor Plate – Dead Load + Fire

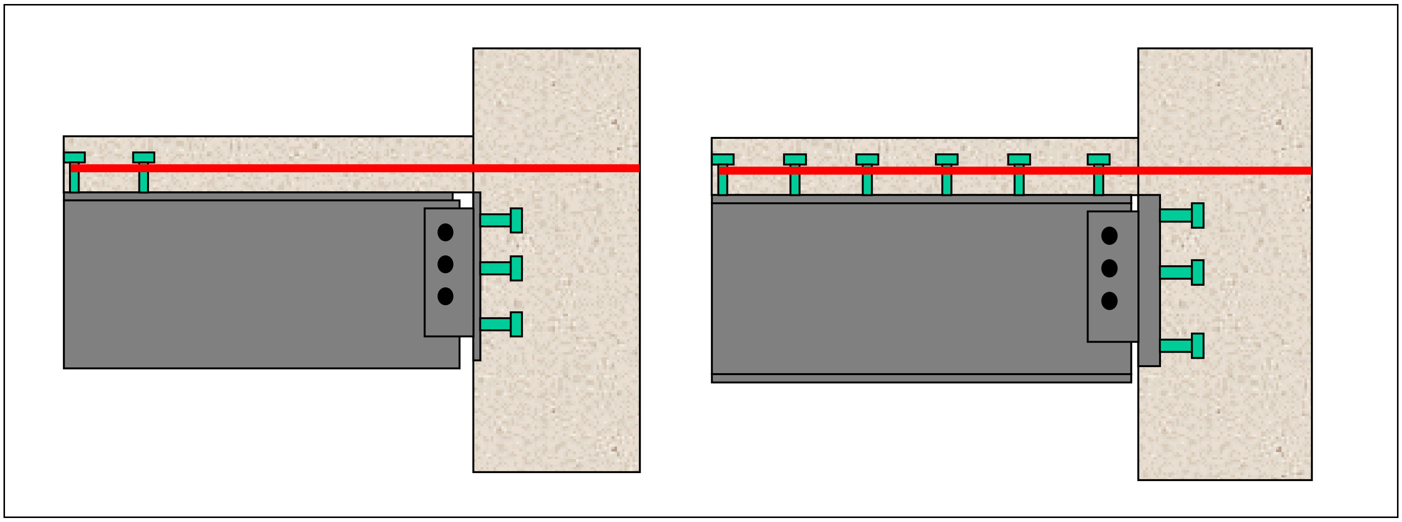


Figure 8—Increasing Ductility of Beam to Wall connection

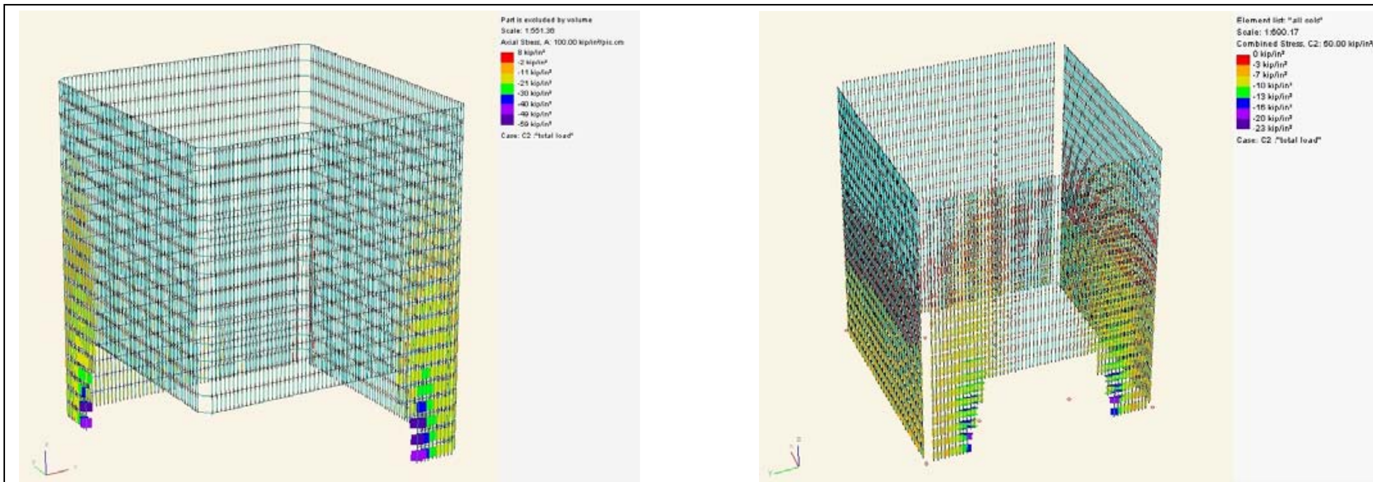
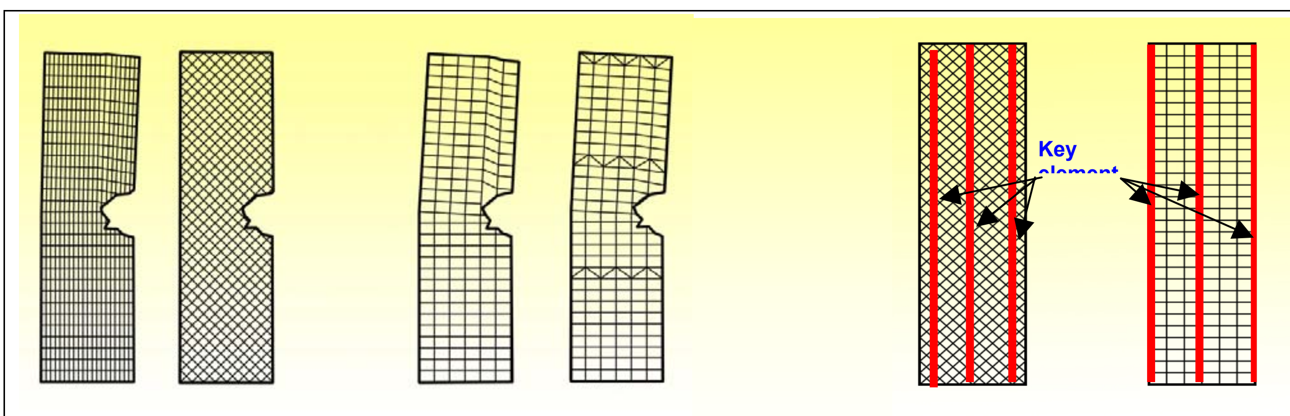
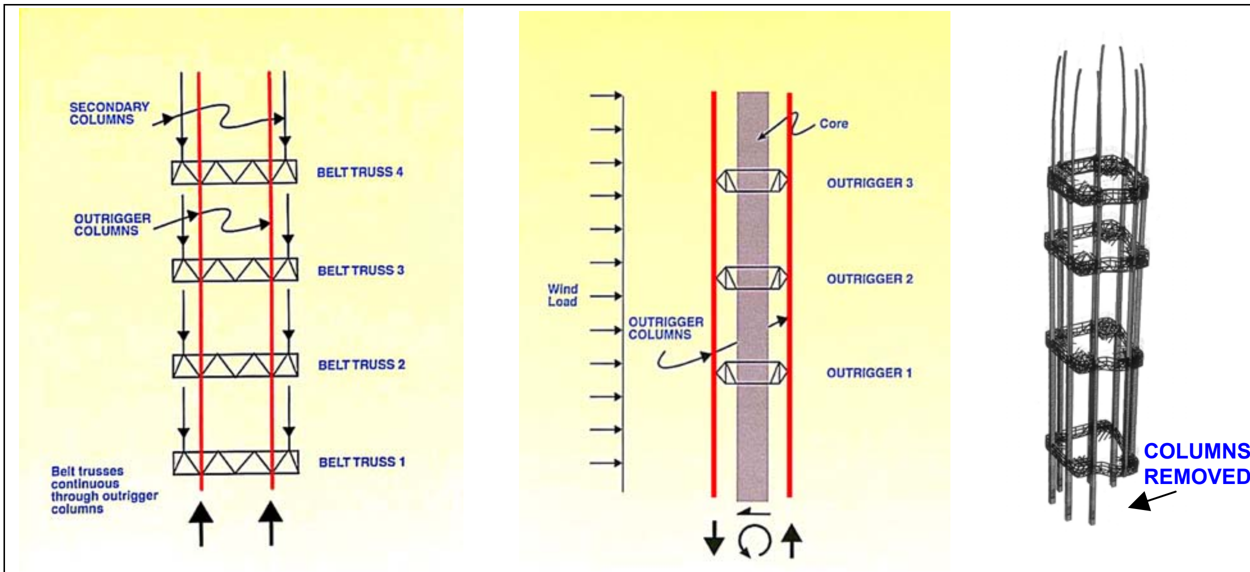


Figure 9—Removal of Key Elements of Rigid Frame (WTC Failure Analysis)



Rigid Tubes **Flexible Tubes** **Tubes with Key Elements**

Figure 10 – Rigid and Flexible Tubes, with Key Elements



Vertical Load System **Wind Load System** **Collapse Ananlysis**

Figure 11—Ductile Systems – Analysis of 80 Story Bulding with Structural Vaporization

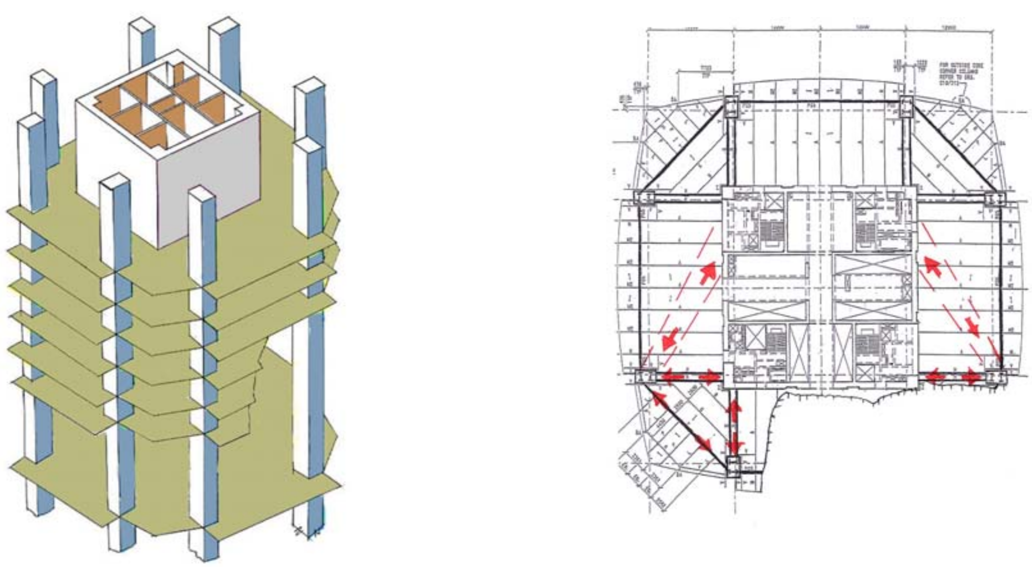


Figure 12—Structural Removal of Floor Diaphragms

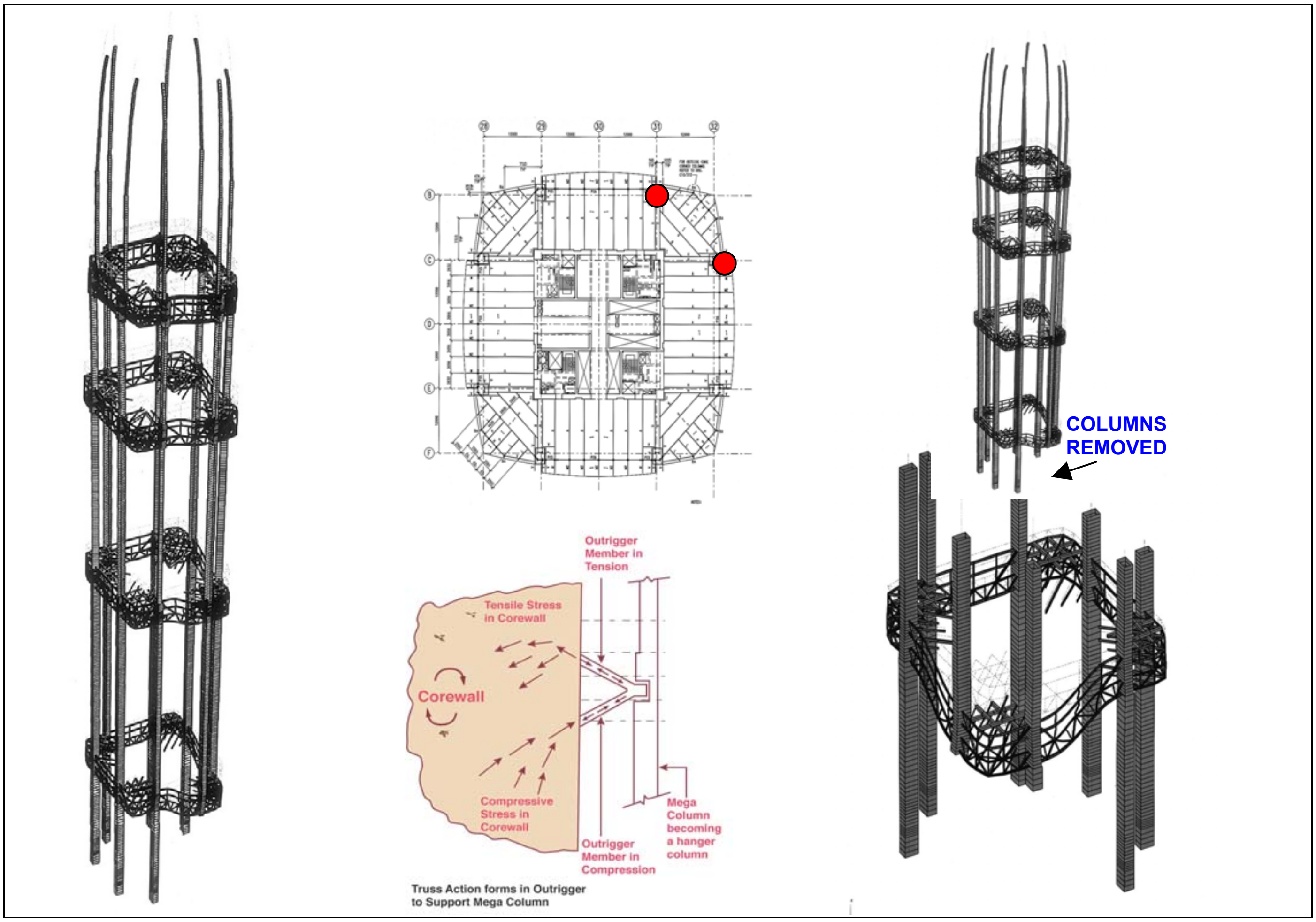


Figure 13—Structural Removal of Columns at Base of High Rise