Arup Fire's presentation regarding tall buildings and the events of 9/11

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This document is based upon a talk given at the NCE conference held at the Cavendish Conference Centre, London 12 April 2005.

The talk entitled "Reducing the risk and mitigating the damaging effects of fire in tall buildings" can be found at http://www.nce-fireengineering.co.uk/index.asp.

Where appropriate for this medium we have expanded/modified some of the material presented at the conference.

Introduction

Arup Fire has investigated structural response in fire for many years, so after 9-11 we considered it essential to develop a clear understanding of possible structural collapse modes in severe fires.

We therefore commenced a major program of numerical analysis of the response of tall building structural forms to multiple floor fires. Arup, as well as many other consultancies around the world has a policy of supporting and being part of cutting edge research as we believe it forms the basis of our advancing profession.

Therefore our structural fire research and analysis discussed in this paper was carried out with our main research partner the Centre of Fire Research Excellence, at the University of Edinburgh and the structural fire safety team there led by Professor Jose Torero.

Since 9-11 there has been a greater interest in the safety of tall buildings and how increased safety can be achieved without compromising on aesthetics or unnecessary costs.

We will discuss how both these can be achieved with an increase in life safety compared with prescriptive solutions when fire engineered solutions founded within a risk assessment are used.

Arup is active in this process in the UK, the americas, in Australia and in Asia. We intend to closely monitor and influence the regulatory and design community responses to tall building safety.

It is our view that the National Institute of Standards and Technology's (NIST) report into the events of 9-11 is a critically important document for tall building design worldwide.

Its conclusions will have a major influence on the Regulatory environment, and on clients' expectations for tall building design. We believe it will provide invaluable data for future design validation.

At the specific request of the NCE we will therefore comment on NIST's probable collapse theory issued 5 April 2005.

We do not underestimate the enormous and very difficult task NIST are undertaking. Arup as well as many other interested parties are following NIST's progress with interest. Sometimes however we may disagree with NIST and we therefore currently plan to comment on the draft final report due in June as part of the public consultation process before the final issue in September.

Response to extreme events

The events of 9-11 changed the perceptions of building designers, contractors, owners and occupiers with respect to safety and security issues in buildings. Everybody had a reaction.

Tall building design moved out of the technical domain and now also forms part of the realm of public interest, due to the heightened awareness of building performance since 9-11.

Codes and standards have historically evolved as a result of reactions to major events. It is to be expected that major disasters will provoke knee-jerk reactions. One example of this is the call for much longer periods of fire resistance on tall buildings immediately after 9-11.

This is an understandable emotion driven response but we would propose instead that designing a structure with fire as a design load provides a more robust design solution.

Simply increasing fire proofing thickness without understanding the actual structural response to heat provides no guarantees of increased safety.

The Arup response

So what has the reaction of Arup been since the events of 9-11? Where can we do more to give reassurance to people living and working in tall buildings and how can we help our tall building clients?

Following 9-11 a number of questions were asked by the many stakeholders in the design process. These questions related to people concerns as well as commercial questions relating to insurance and lettable values.

Some examples of these concerns were:

- What are the life safety and insurance issues associated with these extreme events?
- What is the best approach to understanding the buildings real performance in fire or other security events?
- What tools are available to satisfactorily resolve the issues and therefore people's concern?
- Might this type of disaster occur again, even without the extreme cause?

The Extreme Events Mitigation Task Force (EEMTF) was set up in Arup to address our clients' concerns world wide. It was a specially created network of specialists tasked with identifying and solving the design concerns and new issues 9-11 posed.

On 9-12, life went on but people were nervous. Tenants became uneasy about occupying the upper floors of buildings. Some suggested the way forward was building low and only in concrete.

Practical implications for businesses in high rise city centres were therefore high, and it is our view that this remains the case. Therefore, it is important to react to lessons learned, but not to over-react.

An integrated design approach

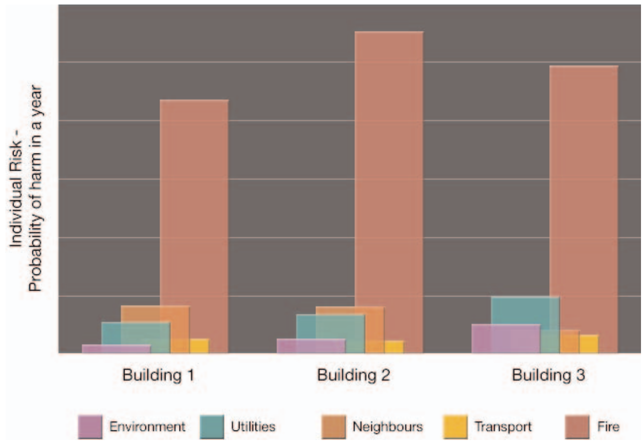
From the EEMTF work, we have found three issues to be of major concern and critical importance for tall building design and we will focus on these for the remainder of this presentation.

1. It must be stressed that it is not possible to design for every conceivable or inconceivable event. Therefore a threat and risk assessment can be used to quantify real risks, in order to develop suitable mitigation measures, on a project by project basis.
2. The evacuation of buildings and the ability of new and existing buildings designed for a phased evacuation to now accommodate a total evacuation in a non-fire event is a practical reality in tall building design now.
3. Understanding the role of structure and its real response to fire along with the performance of fire proofing materials in real events is also key - even more so as events such as the Madrid fire enhance our understanding of real structural performance.

Threat and risk assessment

The design process can be summarised here in an integrated design approach: establishing the real risks, analysing their impact on the building performance using the tools available to us, and developing designs to accommodate this.

Beneficial mitigating options to clearly defined scenarios are the goal. There is no point in spending large sums of money on a protection system that may offer little extra benefit.



Case study: Threat and risk assesment

Example of a risk profile approach

The above graph is an example of threat and risk assessment or risk profiling work of a tall building in London for a major commercial bank. It was used to help the client select a building to occupy or to assess various new building designs.

In this case the client occupied building 2 but was due to move to building 1. He wanted to understand the risk of a fire or other event in building 2 and how it compared to their new proposed building (building 1) and another selected tall building in London (building 3).

Semi-quantified risk techniques were used to look at various life safety and business hazards. Results were used as a choice indicator for establishing design solutions and system selection. They could also be used to help determine insurance loss predictions. This is an example of a risk-informed decision.

Lifts for evacuation, already in use by the fire brigade, and greatly enhances evacuation times

Building Evacuation Issues

The ability to evacuate tall buildings in an imminent catastrophic event was highlighted by the Arup Task Force as a key lesson.

Key considerations are:

- Evacuating whole buildings via stairs that are designed to evacuate only two or three floors in a fire event.
- The interaction of fire fighters and escapees.
- The possibility of using lifts for evacuation.

Many people are now unwilling to stay in a building on fire even if it is remote from their location and want to be reassured that they can evacuate in a timely fashion. Therefore a new approach to designing for evacuation must be considered.

It is becoming a key tenant requirement, in the UK for example, that tall buildings are designed to have the capacity for a total evacuation.

This has resulted in whole building evacuation studies using tools such as STEPS (evacuation software) and ELEVATE (lift software) to understand real evacuation times and therefore the real capacity of the core design in a building.

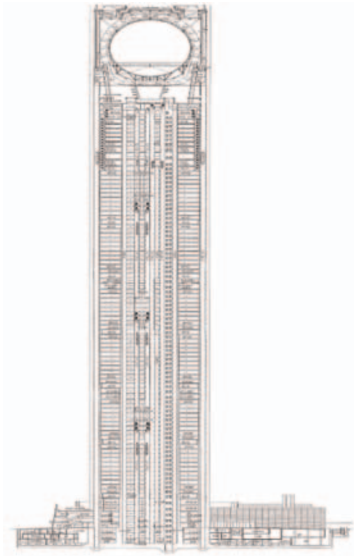
We are increasingly proposing the use of lifts as part of evacuation in fire and non-fire events and we continue to work with other interested parties in developing an acceptable design standard to allow this to become a reality in fire design.

Currently the Arup approach is to protect the lifts for evacuation to the same standard as fire fighting lifts. There is lots of interest in this use of lifts. Approximately 15% of people may have a problem walking down protected staircases of any height. In a tall building, where physical conditioning may become an issue that percentage rises considerably.

Enhanced lifts are a potential option and can result in a 40% decrease in overall evacuation times

It is estimated that it takes 20–30 seconds per floor by foot on stairs. A standard high-rise has lifts capable of moving about 15% of the population in five minutes.

Firefighters use lifts during 'high-rise' fires at a much later stage in the fire than those evacuating so using the lifts for occupant evacuation has minimal impact. We have found that they are most efficient in shuttle mode eg. between a refuge floor and ground.



Kowloon Station Mega Tower and Shanghai World Financial Centre, China: samples of projects where lifts have been proposed as a key means of escape

The Mega Tower in Hong Kong and the Shanghai Tower are both in excess of 100 storeys high and lift evacuation has been proposed by Arup Fire on these projects.

In a high-rise building currently under design in London, there is a large number of occupants expected in viewing galleries, restaurants and retail on the higher floors. The prescriptive solution would be four protected stairs for a phased evacuation. The proposed solution is two protected stairs plus double deck lifts (protected to fire fighting standard) and dedicated refuge floors.

The aim is for people to be guided by marshals to either use the stairs to the ground or to travel via the stairs to protected refuge zones and then queue for a lift. This will result in evacuating the origional floors as quickly as current designs, but a much quicker total evacuation of the building.

There is currently no guidance on acceptable waiting times in refuge floors. On these projects, Arup has proposed eight minutes based on evacuation times from stadia as per UK guidance. It is assumed this will meet the patience levels of the occupants.

This solution provides for faster means of escape times in a total evacuation and also reduces the area required for stair cores which increases the potential lettable area.

The state of structural fire engineering

What is structural fire engineering?

Finally, the third key issue identified since 9-11 is structural fire engineering. As part of this topic, we will also relay some preliminary views on NIST's 5 April 2005 probable collapse theory for World Trade Center (WTC) 1 and 2.

The picture above showing spray applied protection is the extent of structural fire engineering on most buildings, tall or otherwise. Structural engineers do not traditionally consider fire as an actual load on the structural frame.

What are we doing as an industry to allow this to happen?

Seismic design relies on modelling, risk analysis and changes to the structural stiffness. Wind design relies on additional structural members and wind tunnel tests. Current fire design relies on very simple, single element tests and adding insulating material to the frame. Thermal induced forces are not calculated or designed for.

So what is structural fire engineering?

It is the ability to determine credible fire scenarios and then calculate the thermal and mechanical response of the structure to fire. In other words the fire becomes a design load on the structure.

After a major program of research and development in the UK by Edinburgh University, Sheffield University, BRE, CORUS, Imperial College, Arup Fire, FEDRA, et al, designers have the ability to analyse real structural response to fire.

Plantation Place, London

So what does this really mean on a project?

At Plantation Place South in London, based on the specific structural performance to fire, we could demonstrate no fire proofing was required on the secondary steelwork.

Plantation Place: structural fire engineering used to provide an alternative fire resistance design

How did we do this?

We used computer modelling to predict the whole frame load carrying mechanisms in fire. These were catenary action in the beams and tensile membrane action in the slab supported by cooler edge beams and columns.

This lower reliance on passive fire protection is in contrast to the NIST work where the amount
of fire protection on the truss elements is believed to be a significant factor in defining the time to collapse.

However there is no evidence in NIST's preliminary report that this is backed up by structural modelling in response to fire. It appears that only heat transfer modelling considering different levels of fire protection have been carried out and the failure of the individual elements has been related to loss in strength and stiffness only.

Thermal expansion and the response of the whole frame to this effect has not been described as yet.

Some recent multiple floors in high-rise structures

Analysis of high-rise structures in multiple floor fires

But what about tall buildings which are treated as a higher risk for fire, as opposed to a building the size of Plantation Place?

More specifically what structural fire behaviours can be beneficial or in fact create intrinsic weak response to fire?

Tall building fires are not limited to the events of the WTC which makes it even more important to learn from these events.

We have therefore spent several years analysing structural response to fire in order to develop new design techniques for structures in real single floor or multiple floor fires fires.

This work was then expanded after 9-11 to try and understand the structural responses observed during the events of that day.

As part of these studies, we have analysed WTC type structural designs in various severe fire scenarios. In addition we have been investigating the behaviour of long span cellular beams in fire – the most popular form of construction in London at this time.

More recently the Madrid fire in 2005 showed that concrete frames appear to be very robust in multiple floor fires but is this true of all concrete frames?

The Madrid and also the recent Paddington office fire highlighted the risk of fire spread floor to floor via breaches in compartmentation and via the facade. This resulted in the structure having to cope with multiple floor fires even though this is not assumed as a basis for design in prescriptive regulations.

The tall building studies presented here must not be viewed as a forensic investigation of the WTC buildings. Nor is that what we want to achieve – for we must be able to translate any new understanding to all different forms of construction. And so we are therefore carrying out a series of parametric studies to understand structural response to fire. Using real events to confirm or validate model assumptions is a critical way to determine confidence in the model.

Our aim is to be in a position where we can understand if there are any specific progressive collapse mechanisms in tall structures that are not known or not understood in the fire limit state.

The goal is to develop better solutions for fire, without total reliance on passive fire protection, or on single element behaviour. That way we can take advantage of intrinsic design strengths, and attempt to design out any intrinsic design weakness, in the future.

This is not an easy goal, and we consider the impetus from NIST's work to be a major stepping stone along the road to the profession achieving this.

Our views presented here will be amended based on our own work progress and when NIST publishes its thermo-mechanical response analyses which are not currently in the public domain.

The specific aim of our structural fire research is to understand

- whole frame response to multiple floor fires
- whether fire protection is effective
- the collapse mechanism in WTC 1, 2 and 7 style construction
- If there is achievable strengthening measures that could limit such collapses in buildings in the future
- if there are intrinsic weaknesses in specific construction forms or geometries
- what NIST's final recommendations are, what are they based on, how do they impact design

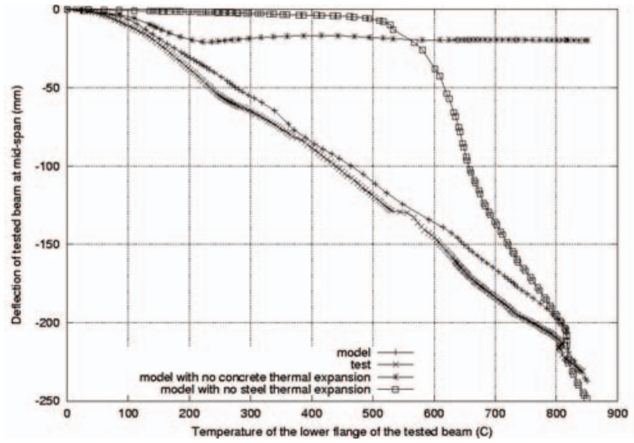
In particular we want to understand if there are any specific progressive collapse mechanisms in tall structures not known or understood as a result of fire.

The WTC towers behaved very well following impact and in response to multiple floor fires indicating that it was a robust system.

The draft NIST report appears to rely on dislodged fire protection.

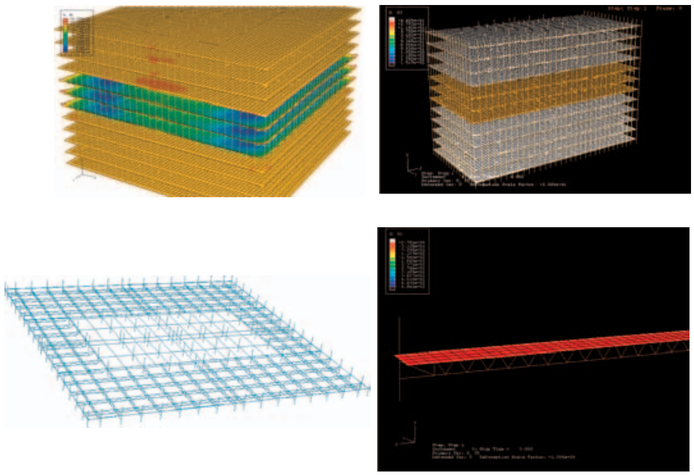
Our main concern with this conclusion is that thermal expansion can swamp all other behaviours and this is not discussed in the NIST report yet. We believe it should be included in a thermo-mechanical analysis to predict the response of any structure to fire, particularly when determining a probable collapse mechanism.

Protected structures - especially slender elements like truss diagonals - heat and deform in a fire. Fire protection is not a shield, it only delays heating.So in a global structural system it is our view that fire proofing to structural steelwork does not imply collapse cannot occur.



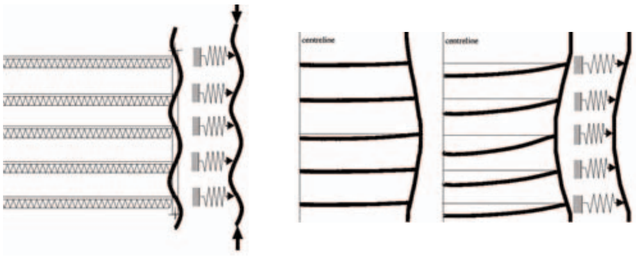
Graph of beam response with and without thermal expansion included in the thermo-mechanical model

This graph shows the mid-span deflection response of a beam analysed by a non-linear finite element analysis. The deflected shape is very different if the thermal expansion is omitted from the analysis.

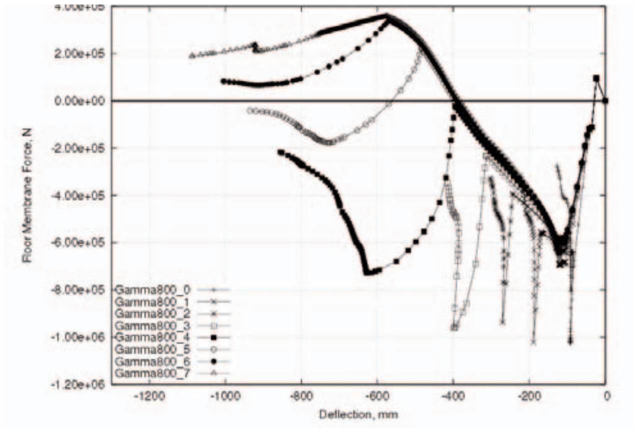


Single truss, single floor, multiple floor thermo-mechancial models

These images are examples of the modelling work we have carried out looking at the response of long span truss floors in fire.



Column buckling mode at ambient and a potential column in the event of multiple floor fires



Predicted floor membrane force available at different steel truss temperatures to support the columns

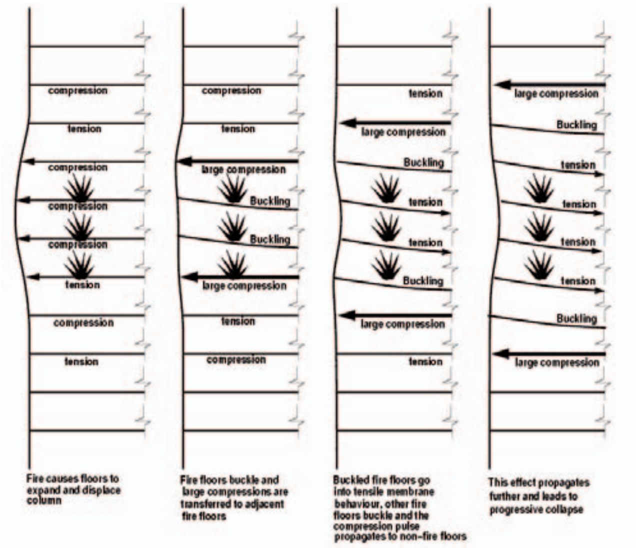
We are analysing the results of our models and arriving at collapse mechanisms which can be caused by thermal expansion.

In ambient design the column has a particular buckling mode based on an effective length between each floor.

In a multiple floor fire scenario that buckling mode can be changed.

The columns are initially pushed out as the floors expand in response to the fires. As the floors increase in length and buckle as a result of expansion they provide less support to the columns.

In addition the floor stiffness decreases as a result of material degradation. There is then potential for the external columns to buckle over their increased length.



Possible tall building collapse mechanism

The figure above is an extension of the work described and is one possible progressive collapse mechanism.

As the fire floors buckle and provide less support to the columns, the columns look for this support from the cold floors immediately above and below the fire floors.

The cold floors in turn become over loaded and buckle, resulting in a mechanism that could propagate and could lead to collapse of the whole structure.

This graph is an example of the data output from our thermo-mechancial analyses and shows the support available to the columns from truss floors at different steel truss temperatures. It forms one part of the basis of our understanding of restraint to columns in fire.

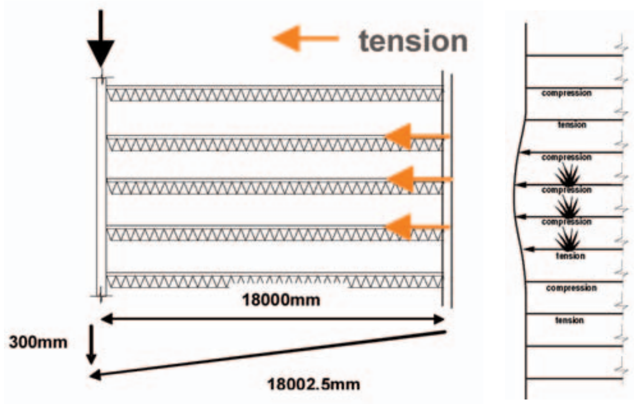
It demonstrates that even at very high temperatures the truss floors can provide restraint.

This could explain the time gap between the column inward bowing shown in the NIST presentation on 5 April at approx 18mins and the structural survival in that state to collapse several minutes later.

However this requires some detailed forensic examination and quantification before a formal statement could be made.

The point of all this work is to one day provide advice to structural engineers about secondary systems that can be introduced to a tall building design to support columns over multiple floors in a fire.

This is a structural solution to a fire problem which we consider to be more robust than solely applying passive fire protection.



Geometry of collapse mechanism proposed by NIST in current Draft report

Collapse mechanism proposed by NIST in April 5 Presentation Report

The basis of NIST's collapse theory is also column behaviour in fire.

However, we believe that a considerable difference in downward displacement between the core and perimeter columns, much greater than the 300mm proposed, is required for the collapse theory to hold true.

Why upward expansion of the column would act against the mechanical shortening.

Crude initial calculations indicate that the elastic downward deflection at half the modulus (say at approx. 500C) will be roughly 38mm.

Assuming plastic strains, a maximum yielding of approximately 190mm is possible.

If the downward displacement is 300mm as assumed, the rotation at the perimeter connection would be 300mm vertical over an 18000mm span - extremely small.

The floor elongation must be less than 2.5mm to generate tensile pulling forces on the exterior columns as a result of the column shortening in the core.

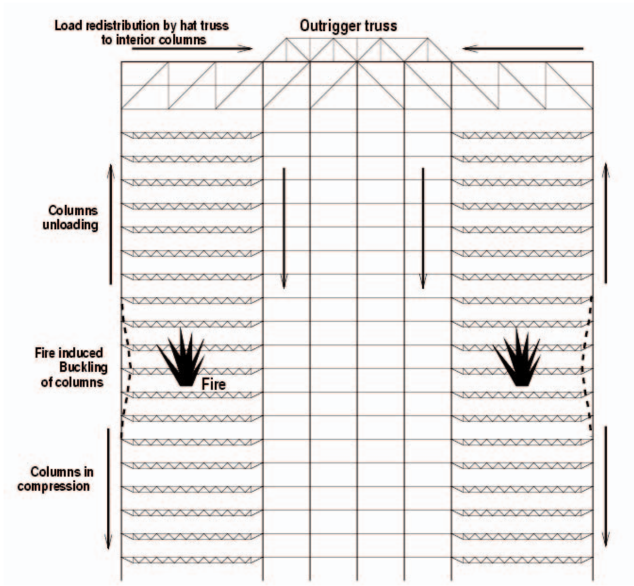
Thermal expansion of the floor truss would be 65mm at 300°C over a length of 18000mm.

Therefore the 2.5mm is swamped by thermal expansion and the core columns cannot pull the exterior columns in via the floor simply as a result of column shortening.

The NIST collapse theory also states that "floors weakened and sagged from the fires, pulling inward on the perimeter columns. Floor sagging and exposure to high temperatures caused the perimeter columns to bow inward and buckle—a process that spread across the faces of the buildings. Collapse then ensued".

This is similar to some of our collapse proposals but no mention of thermal expansion is made, the floor buckling and lack of support to the columns seems to be entirely due to loss in strength and stiffness in their view which we would consider to be only part of the story.

However we await the publication of the final NIST report in this regard.



Possible load transfer via the hat truss at the top of one the tall building studies

Influence of the hat truss on the buildlings performance

We have analysed models with and without a hat truss at the top of a tall-building and found that - a hat truss significantly improves stability in multiple floor fires.

In the image above, the Hat Truss shows clear redistribution from outer columns to the core (primarily the outer core columns). NIST have also observed load transfer via the hat truss. Such issues could become the basis for future fire-related structural design guidance.

Continuing research and development

Arup will continue this study as it is important to our understanding of how buildings work. We will also continue to follow NIST's work on the collapse of the WTC because of our interest in tall building response to fire and tall building design.

We are committed to the belief that building design needs to address thermal expansion effects and the treatment of fire as a load on the structure.

Our aim now and the reason for our continuing research and development in this field is to introduce quantified secondary structural systems to help the structure cope with the loads induced in fire.

Conclusion

On a final note structural fire engineering continues to be important.

We have noticed an interesting step change in the approvals process with specific requests now, even for fully code compliant buildings in terms of structural fire proofing, for global structural responses be quantified and justified, in order to obtain structural design approval..

The CCTV structure was fully protected to code but the approving authority requested that the structural behaviour in fire be calculated

Events will happen and we have to address concerns but we need to make sure that our response is measured and beneficial in many ways.

Our goal is to deliver the design vision for our architects and clients and all the key stakeholders in a project, safely.

Therefore we are recommending threat and risk assessments to determine design solutions, innovative evacuation strategies that address real human response and imminent catastrophic events, and whole frame structural analysis to be employed, as required, on tall buildings in the future.