Structures in Fire · from Cardington to 9/11/2001 and beyond

火災時の構造挙動:カーディントン実大火災実験から 9.11WTC 崩壊まで,そして将来

December 14, 2012

Hosted by

Kyoto University Global COE Program
Global Center for Education and Research on
Human Security Engineering for Asian Megacities

Co-hosted by

Kyoto University Inter-Graduate School Program for Sustainable Development and Survivable Societies

Structures in Fire・from Cardington to 9/11/2001 and beyond

Representative: Kazunori Harada
Date: December 14th, 2012
Place: Seminar room, C2-213, Dept. of Architecture and Architectural Engineering, Kyoto University Katsura Campus, Japan

Organized by the Global COE Program "Global Center for Education and Research on Human Security Engineering for Asian Megacities"
Co-organized by Kyoto University Inter-Graduate School Program for Sustainable Development and Survivable Societies (GSS)

Invited Person: Asif Usmani (Prof., The University of Edinburgh, UK)
Number of Participants: 21 persons
Participants: Kazunori Harada (Prof., Dept. of Architecture & Architectural Engineering), 3 students in HSE course, 1 student in GSS course, 16 students in department of Architecture & Architectural Engineering.

Purpose

The purpose of this seminar is to learn about the mechanism of building collapse due to fire action. Referring to the UK's experience on the development of engineering methodology, the concept of structural engineering against fire action is introduced. The history of development based on actual fires, large scale experiments are described, followed by the tragedy of WTC collapse. The needs for rational engineering approach are specified especially for tall and super-tall buildings. The participants learned about the history of battle between fire accidents and engineering approaches to cope with them.

Invited Speaker

Prof. Asif Usmani is the head of the Institute for Infrastructure & Environment, School of Engineering, the University of Edinburgh. His background is computational mechanics and engaged in education and research on structural behavior during normal use as well as during fire accidents. He is well-known as his computational methods for structural behavior and design against fire effect.

Achievement and Results

An overview of the structures in fire, research at the University of Edinburgh over the past 15 years was presented. Lessons learnt from the Cardington fire tests in the middle 90s and their implications on the practice of structural fire engineering in the UK will be presented. The tragic and unprecedented events of September 11, 2001 forced a re-examination of previous understandings and stimulated research on tall buildings. Edinburgh research has been about discovering possible inherent weaknesses in structural design of tall buildings (including WTC towers). The results from this work produced interesting insights on tall building response to multiple floor fires. Much of this and previous work has led to a strong effort towards developing performance based structural engineering methodologies for fire resistance of structures. A brief summary of this and some other major projects at Edinburgh will be presented at the end.

Through this seminar, it was found that computational structural engineering in fire is becoming more and more popular in UK for designing structures especially tall and super-tall buildings. For those buildings, the traditional approach is not always effective. Fire scenarios including multi-story fires should be included for design of important buildings.

Group photo of participants

火災時の構造挙動：
カーディントン実大火災実験から 9.11WTC 崩壊まで，そして将来

代 表 者：　原田　和典
開催日時：　2012 年 12 月 14 日
開催場所：　京都大学桂キャンパス C2 棟ゼミ室 213

主　　催：　京都大学グローバル COE プログラム「アジア・メガシティの人間安全保障工学拠点」
共　　催：　京都大学グローバル生存学大学院連携プログラム

招 聘 者：　アシフ・ウズマーニ教授（エジンバラ大学，社会基盤環境センター長）
参加人数：　21 名
主な参加者：　原田和典（教授，建築学専攻），GCOE コース履修生３名、GSS プログラム履修生１名、工学研究科建築学専攻・建築学科の学生１６名

目的・概要

このセミナーの目的は，火災による建物崩壊のメカニズムとそれを防止するための工学的方法について学ぶことである．セミナーでは、火災に対処する工学的方法論の英国における発展の経過を解説し，火災に対処するための工学的構造設計の概念を示す．歴史的経過としては，注目を集めた火災事故を踏まえた大規模火災実験が行われた．その結果に基づき，工学的設計法が開発され普及してきた．その矢先にＷＴＣ崩壊が起こったため，超高層ビルの耐火設計について方法論の再構築が求められている．セミナー参加者は，火災事故とこれを防ぐための工学的方法の関係を学ぶことができる．

講師について

アシフ・ウズマーニ教授は、英国エジンバラ大学の社会基盤環境センター長である。学術的バックグラウンドは計算力学で、日常時の構造設計に加えて、特に火災時の構造挙動の予測と崩壊防止のための設計法を研究している。火災時の構造予測の数値計算方法に関して著名な研究者である。

セミナーの様子・得られた成果

講師により、英国エジンバラ大学における１５年間の研究成果が示された。１９９０年代中盤にカーディントン実験場における実規模火災実験から学んだこと、その成果が英国内の建築の構造設計に与えた影響が概説された。２００１年９月１１日のＷＴＣ崩壊は、高層および超高層ビルの構造耐火設計の基本的コンセプトの再考を迫られている。

エジンバラ大学における超高層ビルの研究は、ＷＴＣなどの超高層ビル特有の火災に対する脆弱性を明らかにした。研究の結果、多層同時火災における構造体の特異な挙動を明らかにした。これらの研究成果を踏まえ、構造体の性能的な耐火設計を実現する努力が行われている。セミナーの最後の部分では、これに関連する研究内容が紹介された。

本セミナーを通じて、英国での計算力学に基づく構造耐火設計が普及を進めていること、特に超高層ビルに対しては、既存の設計手法では不十分であり、仮想同時火災などの火災シナリオに基づいた合理的方法の必要性を認識できた。

参加者集合写真

京都大学グローバルCOEプログラム
アジア・メガシティの人間安全保障工学拠点
Global Center for Education and Research on Human Security Engineering for Asian Megacities

GCOE seminar on

Structures in Fire・from Cardington to 9/11/2001 and beyond

Date: Fri., 14., Dec., 2012, 14:45-16:00
Venue: Kyoto University Katsura Campus
Building C2, Room 213 (2nd floor)
Invited speaker:
Prof. Asif Usmani, The University of Edinburgh, UK

Prof. Asif Usmani is the head of the Institute for Infrastructure & Environment, School of Engineering, The University of Edinburgh. His background is computational mechanics and engaged in education and research on structural behavior during normal use as well as during fire accidents. He is well-known as his computational methods for structural behavior and design against fire effect.

Abstract of Lecture:

An overview of the structures in fire・research at the University of Edinburgh over the past 15 years will be presented. Lessons learnt from the Cardington fire tests in the mid 90s and their implications on the practice of structural fire engineering in the UK will be presented. The tragic and unprecedented events of September 11, 2001 forced a re-examination of previous understandings and stimulated research on tall buildings. Edinburgh research has been about discovering possible inherent weaknesses in structural design of tall buildings (including WTC towers). The results from this work produced interesting insights on tall building response to multiple floor fires. Much of this and previous work has led to a strong effort towards developing performance based structural engineering methodologies for fire resistance of structures. A brief summary of this and some other major projects at Edinburgh will be presented at the end.

Participation of anyone interested is welcome. This seminar is co-organized by GSS (Global Sustainability and Survivability) interdisciplinary seminar on man-made disaste). Inquiry can be sent to Prof. Kazunori HARADA (Dept. of Architecture and Architectural Eng., harada@archi.kyoto-u.ac.jp)

京都大学グローバルCOEプログラム
アジア・メガシティの人間安全保障工学拠点
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ＧＣＯＥセミナー

火災時の構造挙動：カーディントン実大火災実験から 9.11WTC 崩壊まで，そして将来

日時：12 月 14 日（金）14:45～16:00
場所：京都大学桂キャンパスＣ２棟　２１３ゼミ室
講演者：アシフ・ウズマーニ教授（エジンバラ大学）

講演者は、エジンバラ大学工学部の社会基盤・環境センターの筆頭教授を務められています。ご専門は計算力学で、構造設計全般と火災時の構造体の挙動予測と制御に関する教育・研究にご尽力されております。

講演概要：

このセミナーでは英国エジンバラ大学における１５年間にわたる火災時の構造挙動研究成果を示します。特に１９９０年代中盤にカーディントン実大火災実験での教訓とそれが構造設計実務に与えた影響を解説します。２００１年９月１１日のＷＴＣ崩壊は、超高層建物の既存知見の再検討を余儀なくされました。エジンバラ大学の研究チームは、ＷＴＣのような超高層ビルが必然的に持つ弱点を洗い出し、多層同時火災における興味深い挙動を明らかにしました。これらの研究成果に基づき、性能に基づく耐火設計への努力が続けられています。これに加え、エジンバラ大学での関連研究を交えて紹介します。

・ご関心のある方の来聴を歓迎します。
・このセミナーはグローバル生存学大学院連携プログラム 学際ゼミナール（人為災害・事故）との共同開催となります．
・セミナー問い合わせ先
　原田和典（工学研究科建築学専攻，教授，harada@archi.kyoto-u.ac.jp）

Seminar at Kyoto University, 14 Dec. 2012

'Structures in Fire': from Cardington to 9/11/2001 and beyond

Asif Usmani
BRE Centre for Fire Safety Engineering

Institute for Infrastructure and Environment
School of Engineering
The University of Edinburgh

Where is University of Edinburgh?

City of Edinburgh (Old Town)

Forth rail bridge (site of 3 bridges from 3 centuries)

Scottish Parliament (autonomous)

University of Edinburgh, Old College, 1583

University and the School of Engineering

University of Edinburgh

College of Science & Engineering	College of Humanities & Social Science	College of Medicine & Vet. Medicine

School of Physics

School of Chemistry

School of Mathematics

School of Biological Sciences

School of GeoSciences

School of Informatics

School of Engineering (5 Research Institutes)

Materials & Processes	Digital Signal Processing	Mirco & Nano Systems	Energy systems	Infrastructure & Environment

BRE Centre for Fire Safety Eng

www.see.ed.ac.uk/fire

BRE CENTRE *for* FIRE SAFETY ENGINEERING
UNIVERSITY *of* EDINBURGH

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Fire Safety Engineering

The University of Edinburgh has been an important institution in the field of *Fire Safety Engineering* for over three decades. Many of those who are now leaders in the field came to Edinburgh to study and research under the supervision of the late **Prof David Rasbash**, one of the main pioneers of the discipline, and **Prof Dougal Drysdale**, author of the definitive text book on the subject, *'Introduction to Fire Dynamics'* (Wiley, 2nd edition 1998). Teaching and research in fire safety continues at Edinburgh under the leadership of **Prof Jose Torero**, appointed to the BRE/RAE Chair in Fire Safety Engineering in 2004.

The BRE Centre for Fire Safety Engineering is part of the **Institute for Infrastructure and Environment**, **School of Engineering** at **The University of Edinburgh**.

Edinburgh was recently voted the UK's **'most desirable city to live in.'**

Follow us:

What we do

We are a world-class research fire centre with 40 research members from more than 18 different nationalities.The BRE Centre for Fire Safety Engineering exists to:

- Equip tomorrow's leaders in the field

Seminar at Kyoto University, 14 Dec. 2012

‘Structures in Fire’: from Cardington to 9/11/2001 and beyond

Part 1: Fundamentals

Key references:

Fundamental principles of structural behaviour under thermal effects
***Fire Safety Journal*, 36:721–744, 2001**

Assessment of the fire resistance test with respect to beams in real structures
***Engineering Journal*, American Institute of Steel Construction, Inc., 40(2):63-75, 2003**

Key events in the structural response of a composite steel frame structure in fire
***Fire and Materials*, 28:281–297, 2004**

Behaviour of a small composite steel frame structure in ‘long-cool’ and ‘short-hot’ fires,
***Fire Safety Journal*, 39:327–357, 2004**

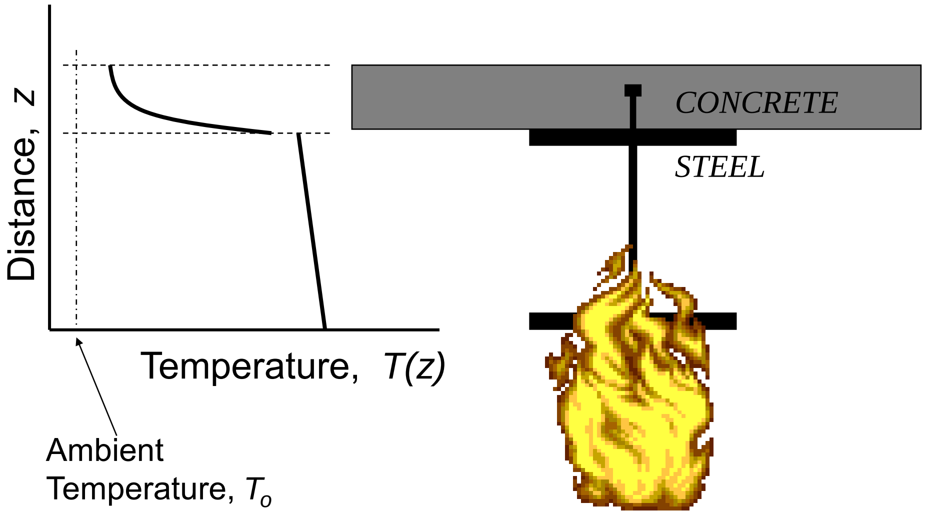
Understanding the Response of Composite Structures to Fire
***Engineering Journal*, American Institute of Steel Construction, Inc., 42(2):83-98, 2005**

A New Design Method to Determine the Membrane Capacity of Laterally Restrained Composite Floor Slabs in Fire, Part 1: Theory and Method, *The Structural Engineer*, 83(19):28–33, 2005

A New Design Method to Determine the Membrane Capacity of Laterally Restrained Composite Floor Slabs in Fire, Part 1: Validation, *The Structural Engineer*, 83(19):34–39, 2005

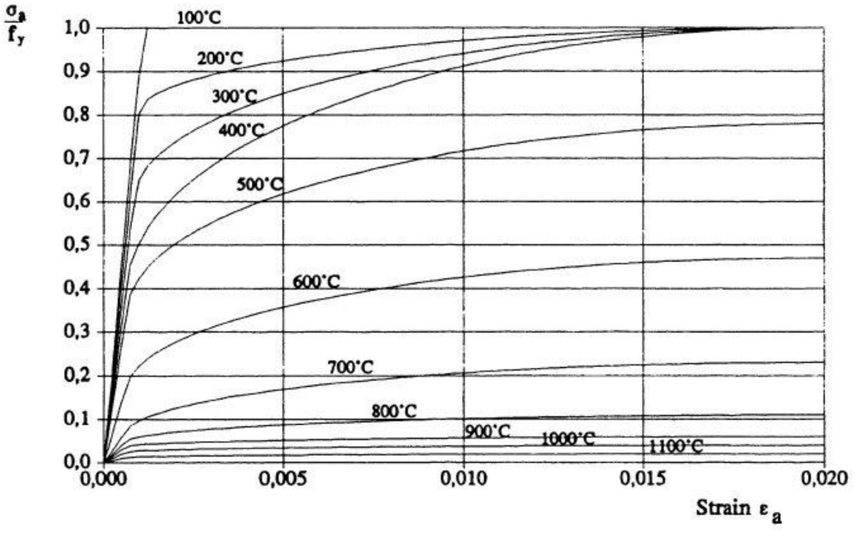
Seminar at Kyoto University, 14 Dec. 2012

Effect of fire on structures



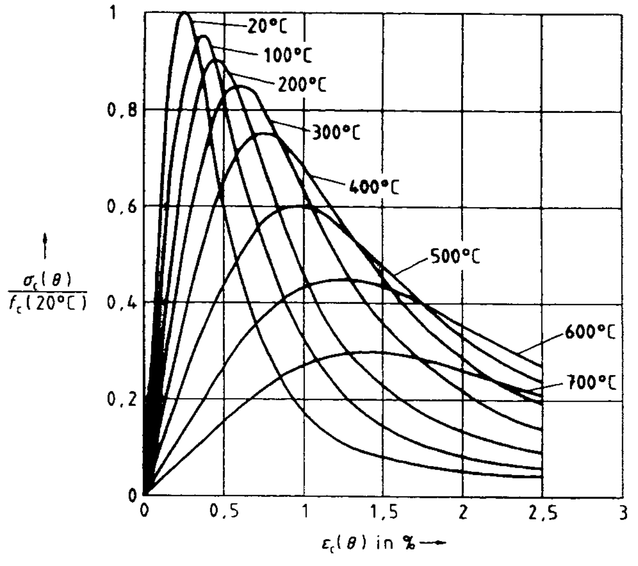
Materials of construction are exposed to high temperatures

Structural steel stress-strain behaviour



Source: ENV 1993-1-2:1995
(S235 steel)

Siliceous concrete stress-strain behaviour



Source: ENV 1992-1-2:1995

Consequence of "material" based thinking

- Concrete is considered a "**good**" material and reinforced concrete structural members/components are considered safe if sufficient cover to steel reinforcement is provided

- Steel structures are thought to need "**protection**" from fire as steel is a good conductor of heat

- Engineers have therefore focussed disproportionately on "protecting" steel structures

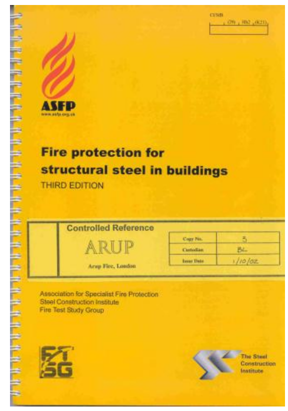
Traditional approach to building fire safety

Fire safety requirements are usually expressed as

- Insulation → **For general building fire safety** — **Compartmentation:** maintaining structural and thermal barriers to prevent spread for a sufficient length of time to enable safe egress of all occupants
- Integrity → (Compartmentation, as above)
- Stability → **For structure/structural members** — **Fire resistance:** length of time for which the member or other component is required to withstand exposure to the fire regime given by the standard fire without the load capacity falling below the fire limit state factored load or loss of integrity and/or insulation

Prescriptive of "fire protection" approach

- Provides protection during the fully developed stages of a fire (post-flashover)
- maintain the elements of construction below a critical temperature (steel <550° C)
- Design based on the fire resistance test BS 476 "yellow book" approach
- Calculate the Hp/A (or Am/V) for the section
- Read Table in Code to find necessary fire resistance rating (0.5, 1, 1.5, or 2 hours) in terms of the building type, height and occupancy
- Decide on protection material
- Look up the fire protection thickness



Section factors

High A

Low V

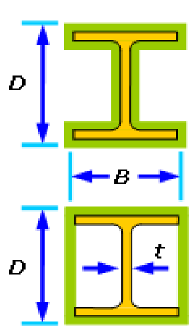
Fast heating

Low A

High V

Slow heating

Determination of section factor A/V:



Profiled protection

$$\frac{4B + 2D - 2t}{\text{steel cross-section al area}}$$

Box protection

$$\frac{2(B + D)}{\text{steel cross-section al area}}$$

Source: www.mace.manchester.ac.uk/project/research/structures/strucfire/default.htm

Code bases fire resistance requirements

Fire resistance required
(from Approved Document B: England and Wales 2000)

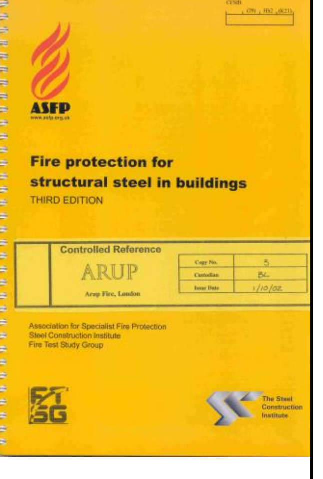
	Height of top storey-metres			
	<5	<20	<30	>30
Approx. no. of storeys	2	5/6	8/9	9+
Residential	30	60	90	120
Offices	30	60*	90*	120 plus sprinklers (floors 90 minutes)
Shops, commercial	60*	60	90*	
Industrial and storage	60*	90*	120*	
Car parks (closed)	30	60	90	
Car parks (open-sided)	15	15	15	60

* Reduced by 30 mins when sprinklered

"Look up" tables

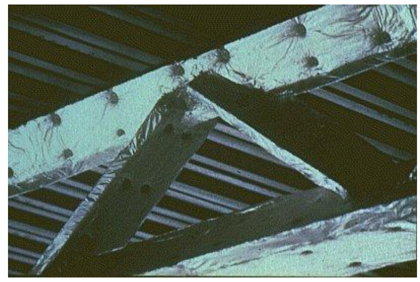
changed to **Am/V** to be consistent with Eurocode

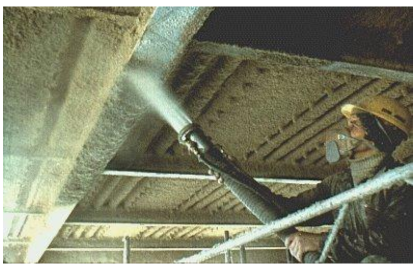
Hp/A Up to	Dry Thickness in mm to provide fire resistance of 1/2 hr	1 hr	1.5 hr	2 hr	3 hr	4 hr
30	10	10	14	18	26	35
50	10	12	17	22	33	43
70	10	13	19	25	37	48
90	10	14	21	27	39	52
110	10	15	22	28	41	54
130	10	16	22	29	42	56
150	10	16	23	30	44	57
170	10	16	23		44	

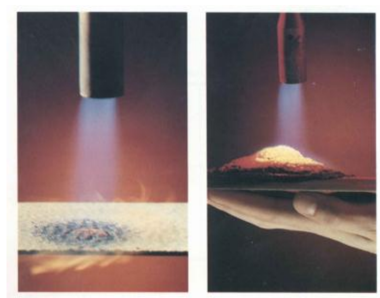


Download latest version from:
www.mace.manchester.ac.uk/project/research/structures/strucfire/DataBase/References/defaultSteel.htm

Fire protection







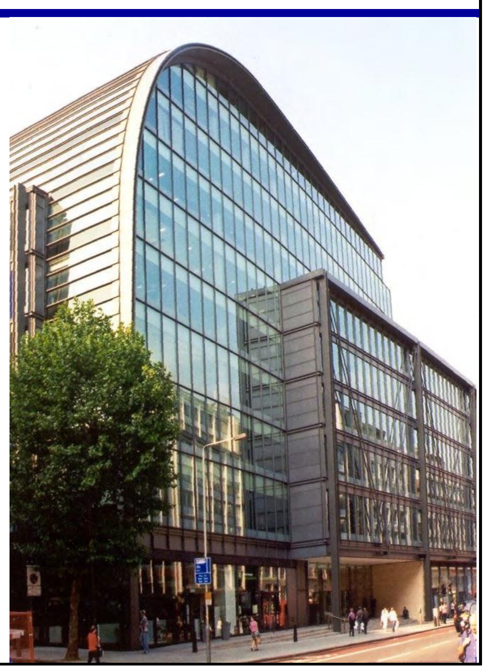
Comparative costs of steel frame buildings

Cost of the structure is approximately 10% of the cost of the building

Cost of fire protection can be between 10% to 30% of the cost of structure (depending upon, usage & height)

Therefore 1-3% of the total cost of a steel frame building can just go on "fire protection"

Source: *Comparative Structure Cost of Modern Commercial Buildings* (SCI report)



Broadgate Phase 8 fire (23 June'90)

14 storey building under-construction

Fire duration 4.5 hrs
Temp > 1000° C for 2 hrs
Fire protection incomplete, steel temperatures estimated to be under 600° C

13.5m span/1m deep trusses and floors had over 500mm permanent deflections and buckled members and unprotected columns had shortened by upto 100mm, but there was no overall collapse

Total losses ~ £25 M,
struct. repair ~ £2 m (1500 m^2)
completed in 30 days



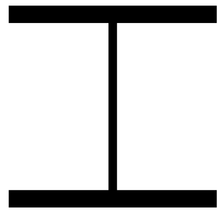

Source: *Stuctural fire Investigation of Broadgate Phase 8 fire* (SCI report), available from www.steelbiz.org

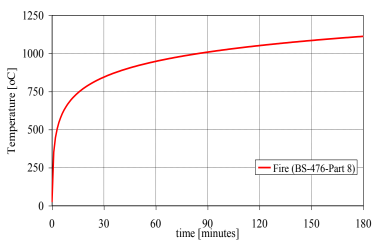
Aftermath of Broadgate fire

- Structural behaviour in fire was found to be much better than expected (especially so, because a lot of the steel was unprotected)
- Steel industry with EU funding constructed an 8-storey steel frame building in Cardington (UK) and carried out 6 full scale fire tests
- The results showed that the structural behaviour was much more complex and was not explainable only by "material" stress-strain behaviour at high temperature
- The other key effect ignored in traditional practice, *i.e.* change of member dimensions as a result of *thermally induced deformation* and the *restraint* to it was found to have a considerable role to play in the overall structural response

Traditional practice against reality

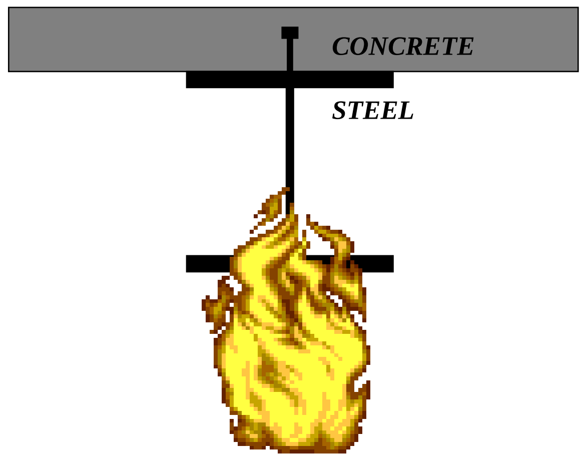
Isolated single structural member with simple boundary conditions (such as in a furnace)





subjected to "standard" fire

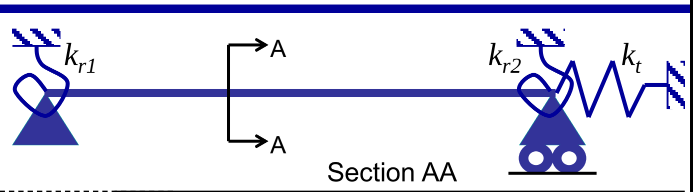
composite structural members with finite restraints against rotation/translation at boundaries

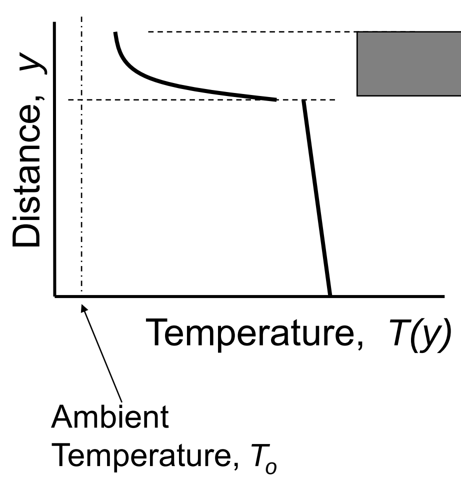


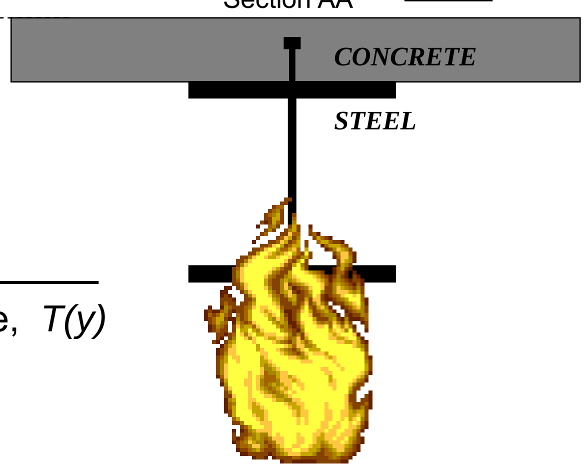
subjected to "real" fire

Simplest "realistic" model of composite beam

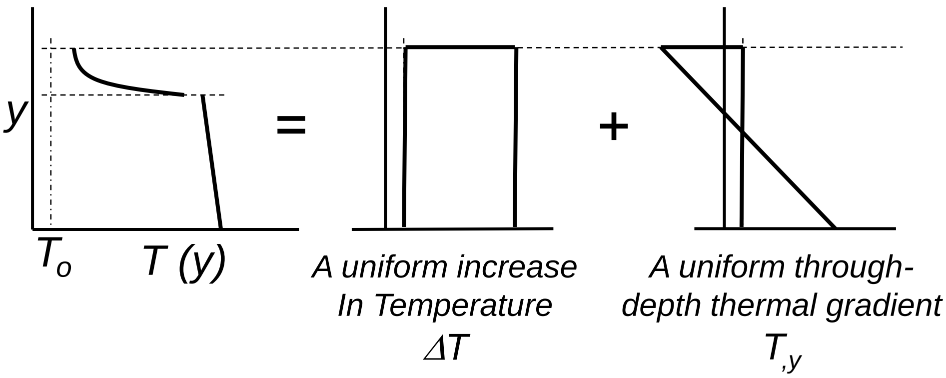
Structure subjected to the illustrated temperature distribution







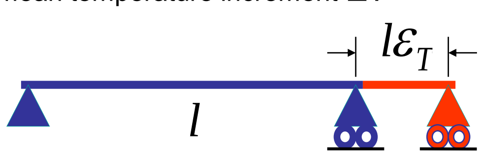
Decompose temperature into simpler effects



Governing parameters

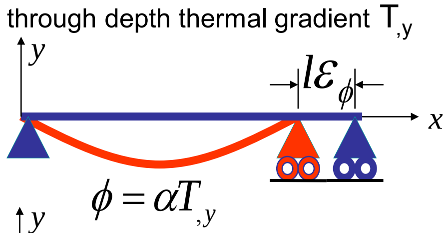
Thermal expansion induced by mean temperature increment ΔT

$$\varepsilon_T = \alpha \Delta T$$

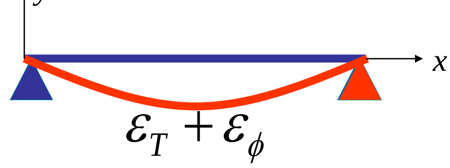


Thermal curvature f induced by through depth thermal gradient $T_{,y}$

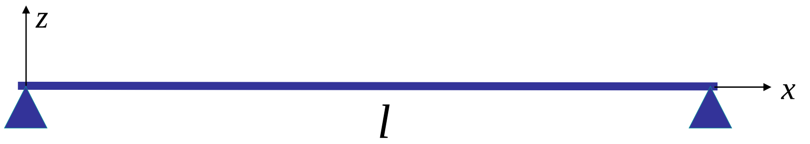
$$\varepsilon_\phi = 1 - \frac{\sin {}^{l\phi}\!/_2}{{}^{l\phi}\!/_2}$$



Combination of the two effects leads to large deflections and often very low stresses (internal forces)



Beam with restrained ends



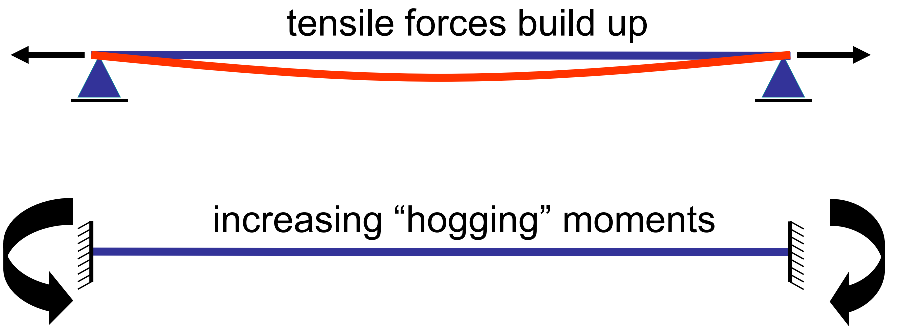
free to rotate at ends

Uniform temperature increase in restrained beam

The beam material must ***yield***
or it should ***buckle***
as the temperature increases

At what temperature increment a rigidly restrained steel beam (σ_y = 275 MPa) yield?

Uniform thermal gradient in restrained beam



Combined behaviour (assuming slender beam)

$$\varepsilon_T = \alpha \Delta T$$

$$\varepsilon_\phi = 1 - \frac{\sin {}^{l\phi}/_{2}}{{}^{l\phi}/_{2}}$$

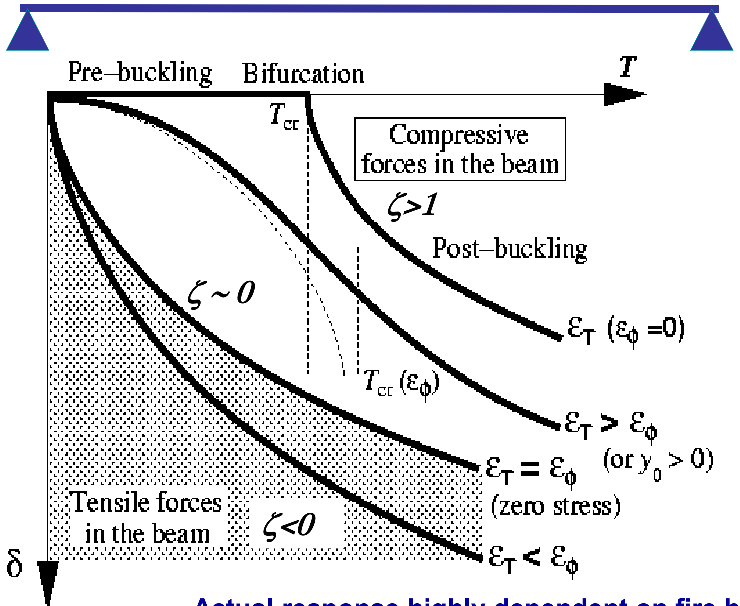
$$\varepsilon_{buckling} = {}^{\pi^2}/_{\lambda^2}$$

λ is slenderness ratio

$$\zeta = \frac{\varepsilon_T - \varepsilon_\phi}{{}^{\pi^2}/_{\lambda^2}}$$

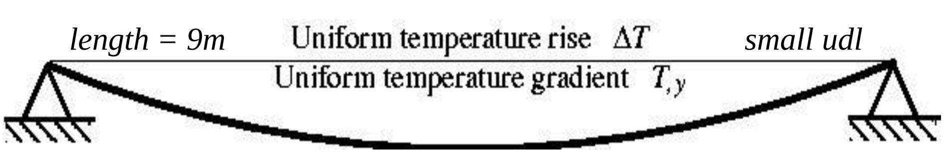
dimensionless parameter

Temperature-deflection of a restrained beam



Actual response highly dependent on fire history!

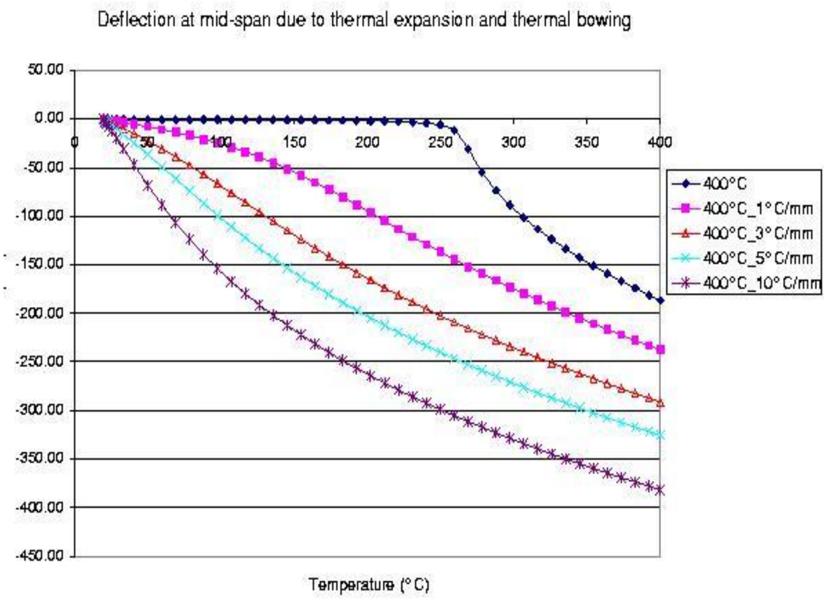
Verification of theory using an FE model



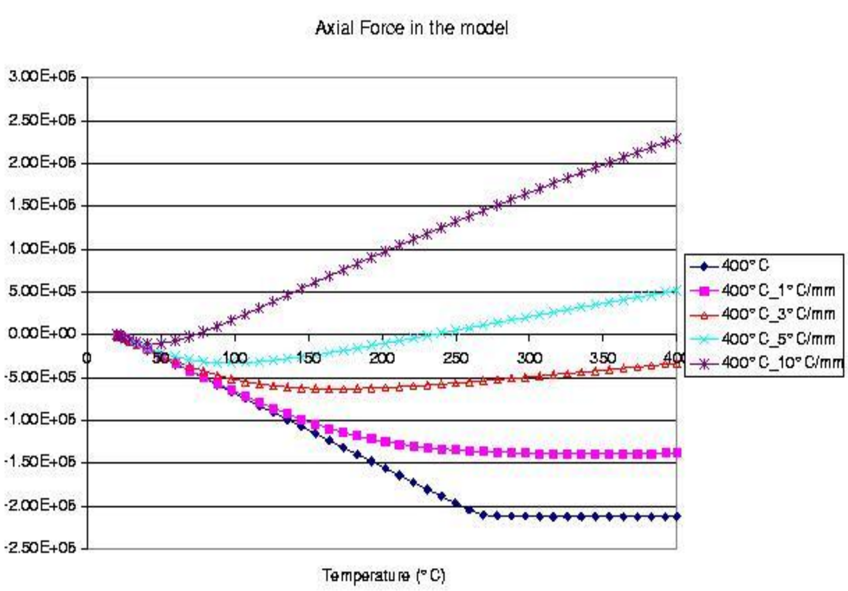
Subjected to the following five temperature and thermal gradient combinations

	ΔT °C	$T_{,y}$ °C/mm
1	400	0
2	400	1
3	400	3
4	400	5
5	400	10

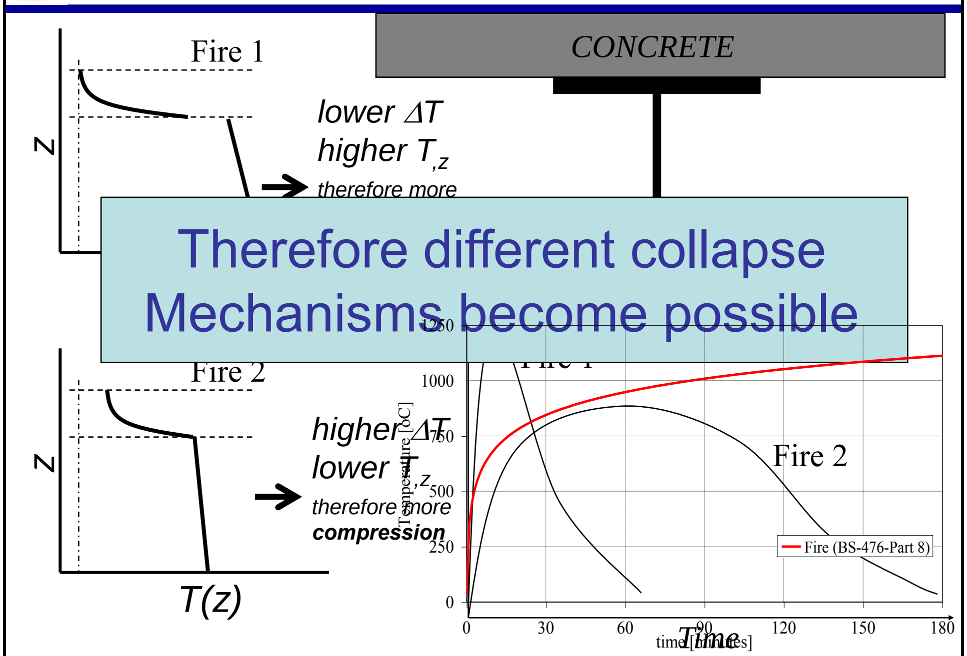
Deflection at midspan of beam



Axial forces in the beam



Implication: Effect of fire history on response



Seminar at Kyoto University, 14 Dec. 2012

'Structures in Fire': from Cardington to 9/11/2001 and beyond

Part 2: Whole structure behaviour of real buildings

Key references:

A structural analysis of the first Cardington test, *Journal of Constructional Steel Research*, 57(6):581–601, 2001

A structural analysis of the Cardington British Steel Corner Test, *Journal of Constructional Steel Research*, 58(4):427–442, 2002

How did the WTC Towers Collapse? A New Theory, *Fire Safety Journal*, 38:501–533, 2003

Effect of Fire on Composite Long span Truss Floor Systems, *Journal of Constructional Steel Research*, 62:303–315, 2006

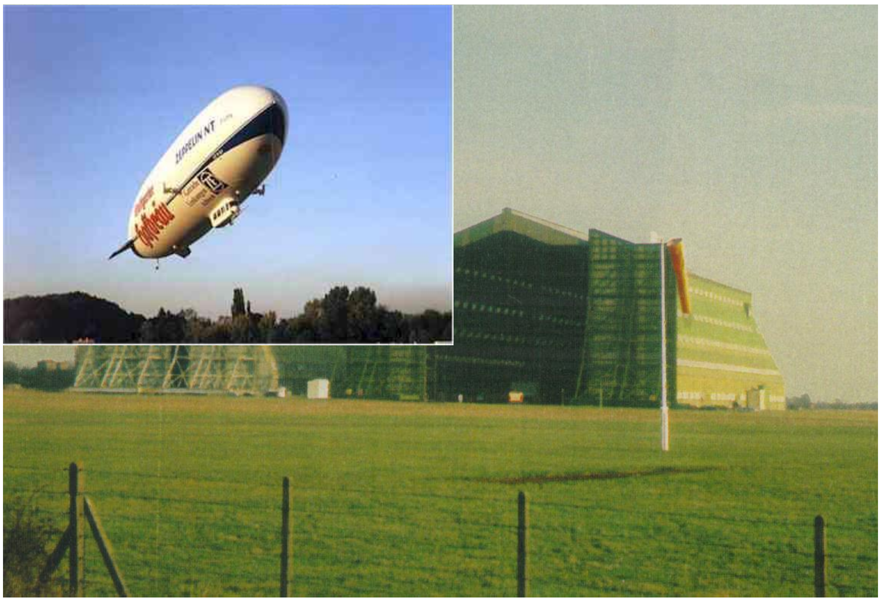
Behaviour of small composite steel frame structures with protected and unprotected edge beams, Journal of Constructional Steel Research, 63:1138–1150, 2007

Structural response of tall buildings to multiple floor fires, *Journal of Structural Engineering*, ASCE, 133(12):1719–1732, 2007

A very simple method for assessing tall building safety in major fires, *International Journal of Steel Structures*, 9:17–28, 2009

Tall building collapse mechanisms initiated by fire: Mechanisms and design methodology, *Engineering Structures*, 36:90–103, 2012

BRE Large BuildingTest Facility

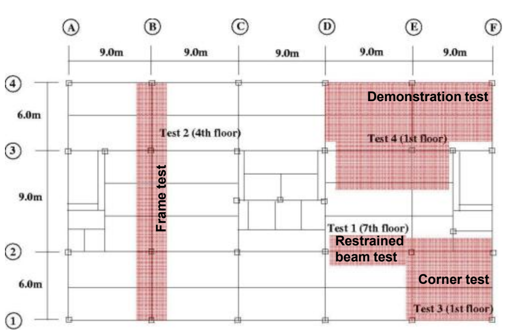


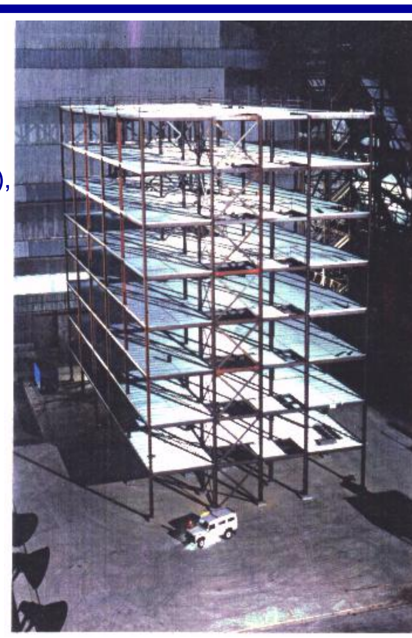
Cardington frame

8 Storey steel frame composite structure

2 tests by BRE

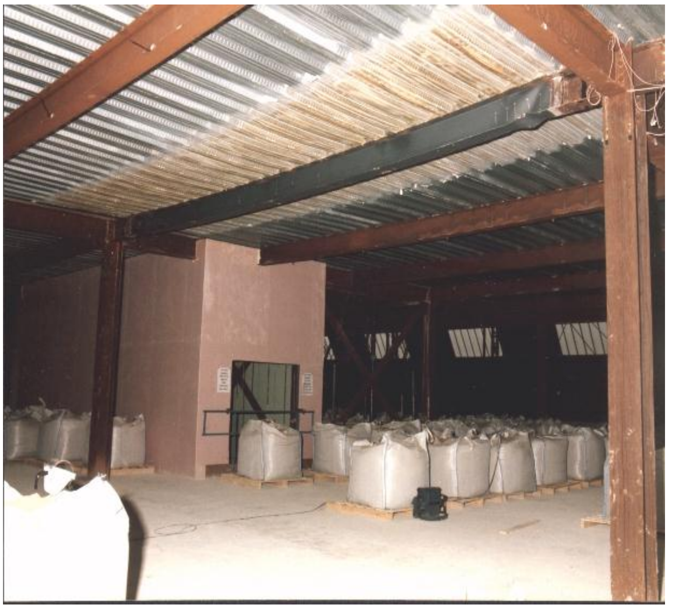
4 tests carried out by “British Steel” (Corus), shown on building plan below



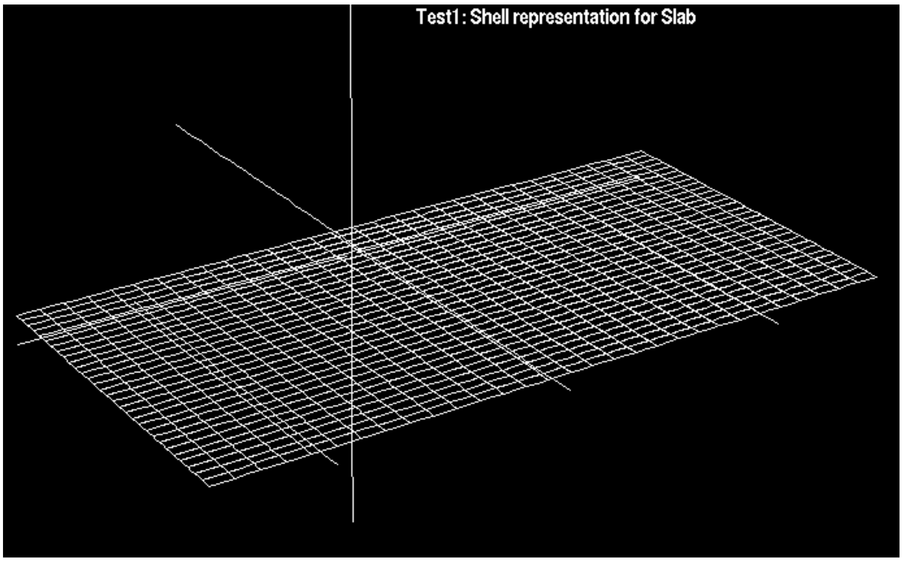


Download report from:
www.mace.manchester.ac.uk/project/research/structures/strucfire/DataBase/References/MultistoreySteelFramedBuildings.pdf

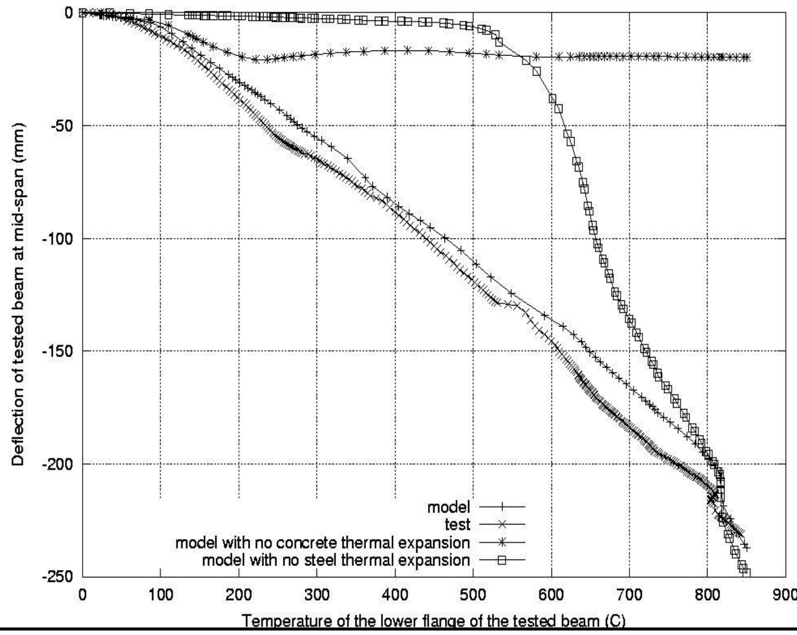
Restrained beam test (columns protected)



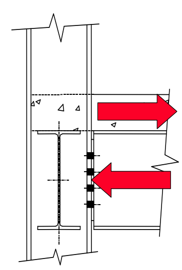
FE model of restrained beam test



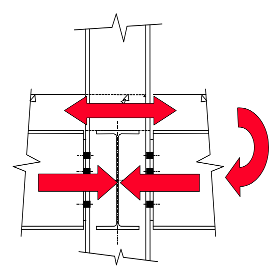
Deflections with/without thermal expansion



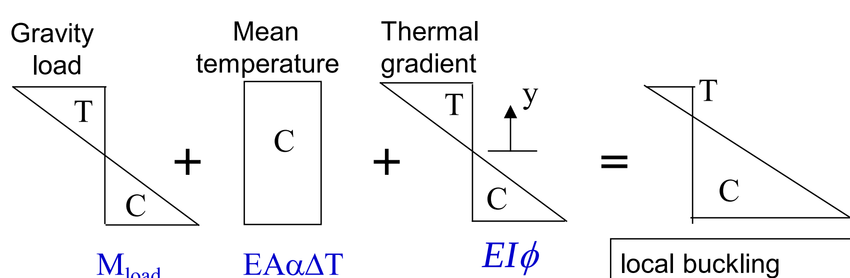
Beam bottom flange “buckling” phenomenon



End panels



Interior panels



local buckling
beam bottom flange?

Bottom flange stress in steel beam at 150°C

$$\frac{M_w z}{(I)_x} + E_{\max}\alpha\Delta T + E_{\max}\alpha T_{,z} z$$

w = 16.5 kN/m ΔT = 80 °C $T_{,z}$= 0.5 °C/mm

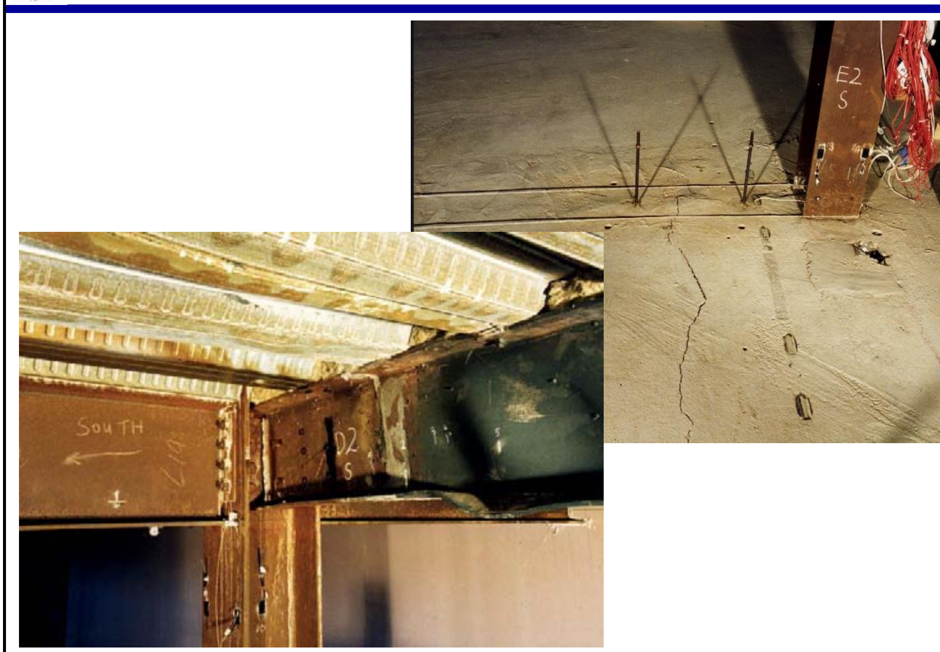
127 Mpa   160 Mpa   286 Mpa ➡ 573 Mpa >> 318 Mpa

$$\sigma_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{0.425}{\left(b_f / t_f\right)^2}$$

➡ 524 Mpa

=> Plastic yielding!

Restrained beam test "buckling" and cracking

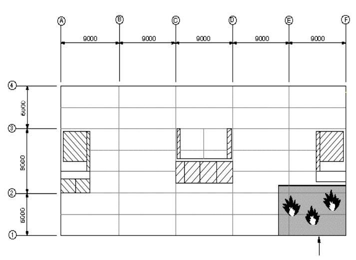


Local buckling (BS Corner Test)

Local buckling (BS Demonstr. Test)

Tensile rupture of connections in cooling

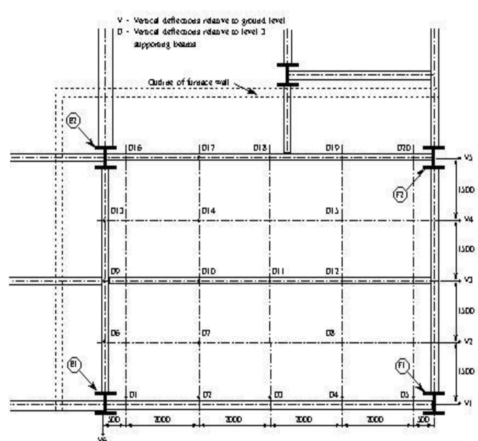
British Steel Corner Test



TEST 3 : CORNER COMPARTMENT TEST

Location

Structural details



Test 3 - Transducer Positions for Measuring Vertical Deflections

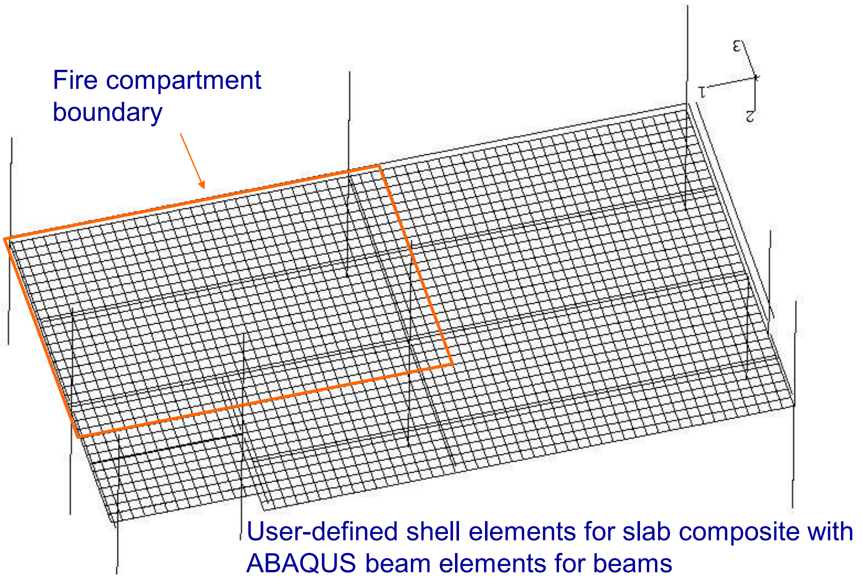
BS Corner Test Fire Compartment

Max Compartment temperatures ~ 1100 °C

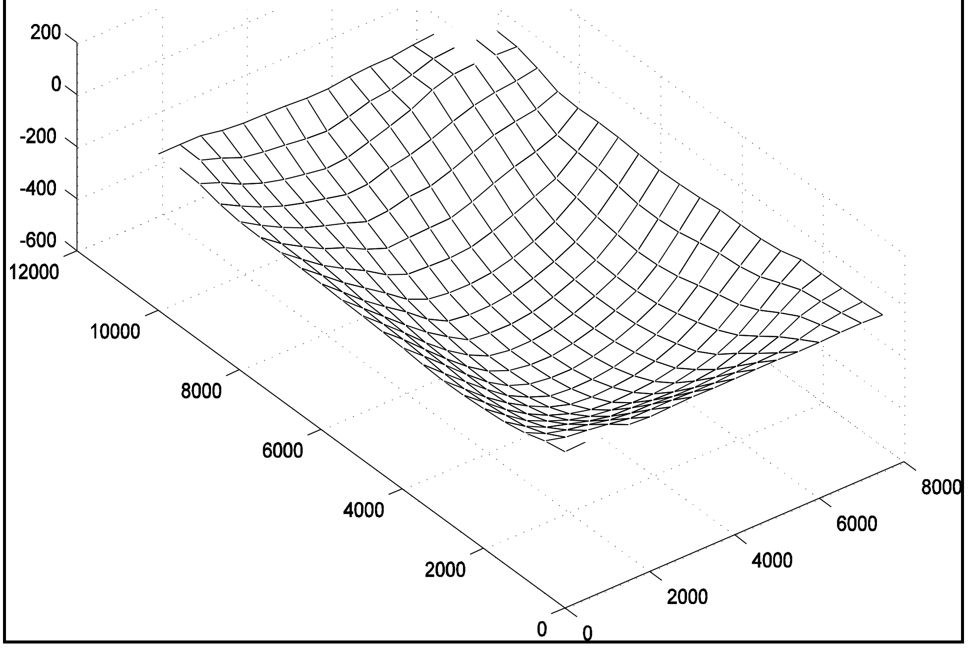
Max Uprotected Steel temperatures ~ 1000 °C

Max Deflections ~ 300 mm

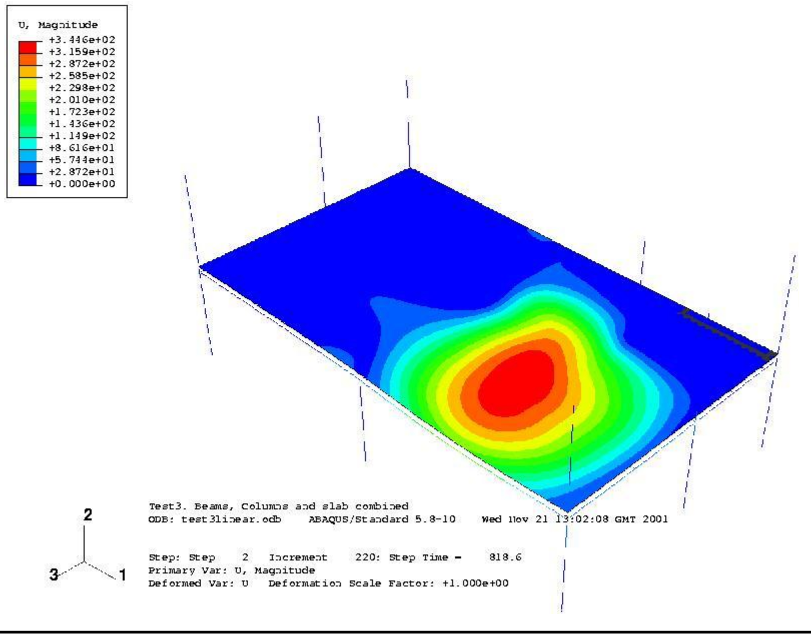
FE model for BS Corner test



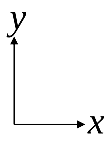
Actual Corner test deflected shape

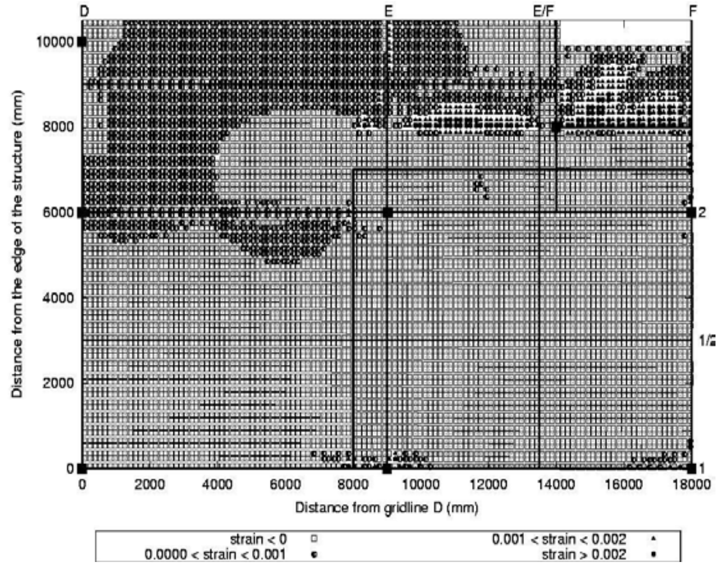


Deflection



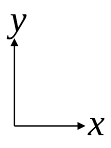
Slab ε_x strains at reinforcement level

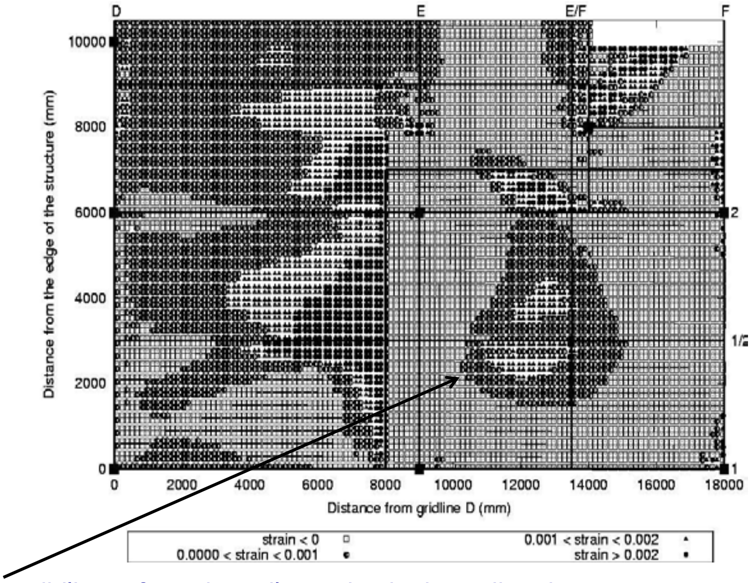




All of the slab in the fire compartment in under compression

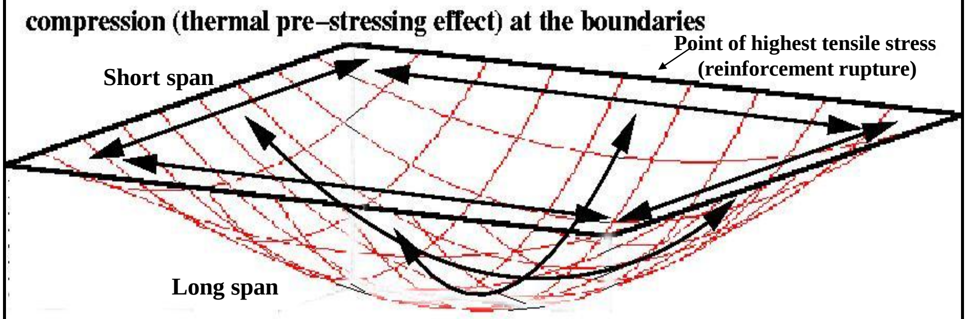
Slab ε_y strains at reinforcement level



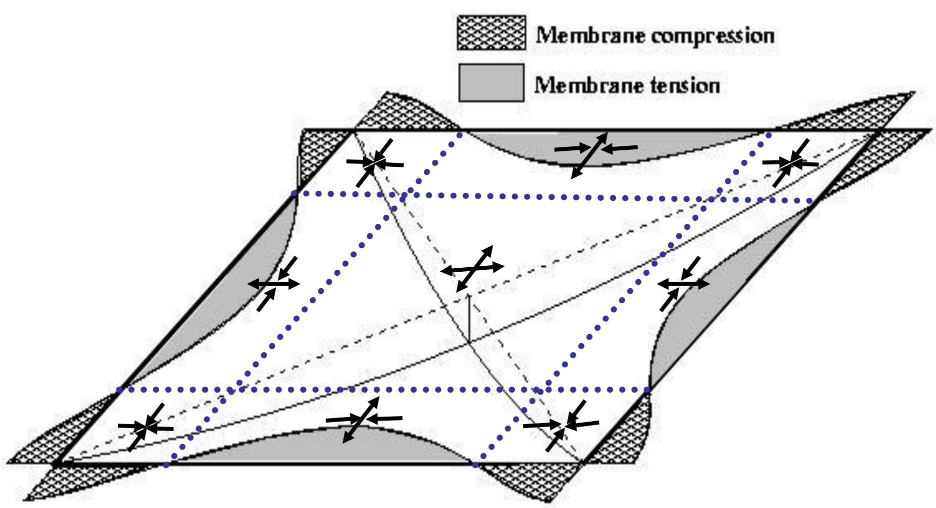


Compatibility enforced tensile strains in the *y* direction

Tensile membrane action in slabs



Typical membrane stress distribution at restrained boundary



Lessons (horizontal structural members only)

Tensile membrane action (TMA) in the spans and compressive membrane action (CMA) near perimeter observed

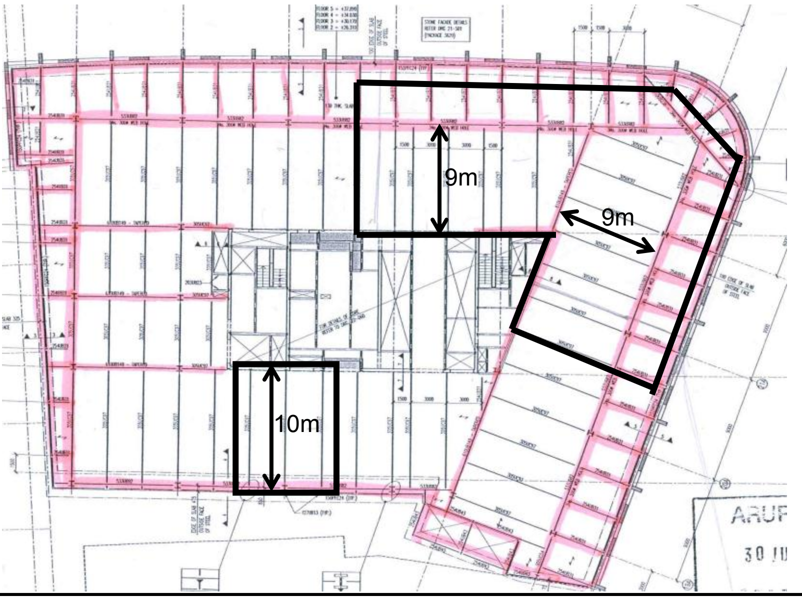
This load carrying mechanism more reliable in fire, thermal strains help produce the "right shape"

Capacity further enhanced by thermal pre-stressing (CMA)

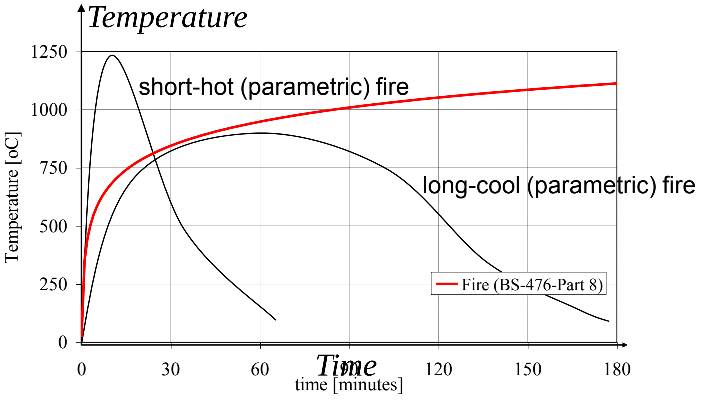
Local effects such as local buckling of lower flange not important

Plantation Place (Arup Fire)

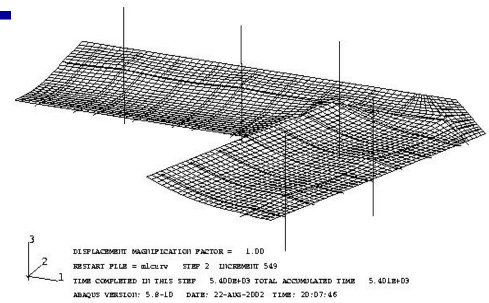
Two sub-structure models

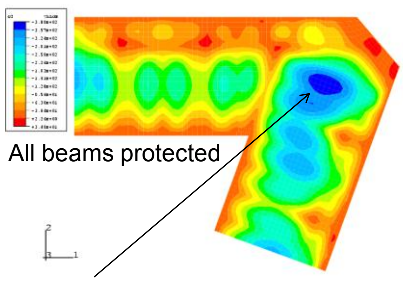


Fire scenarios



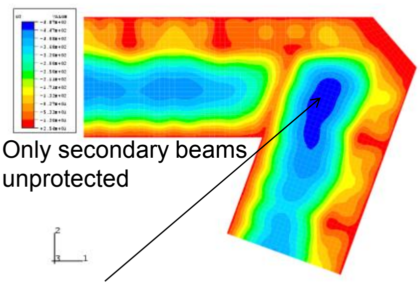
Results from model 1





All beams protected

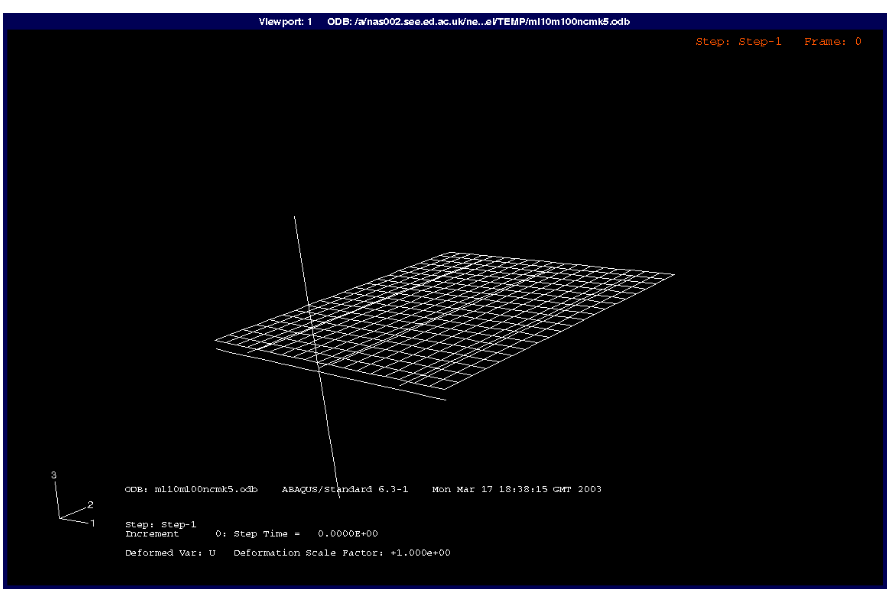
380mm max deflection



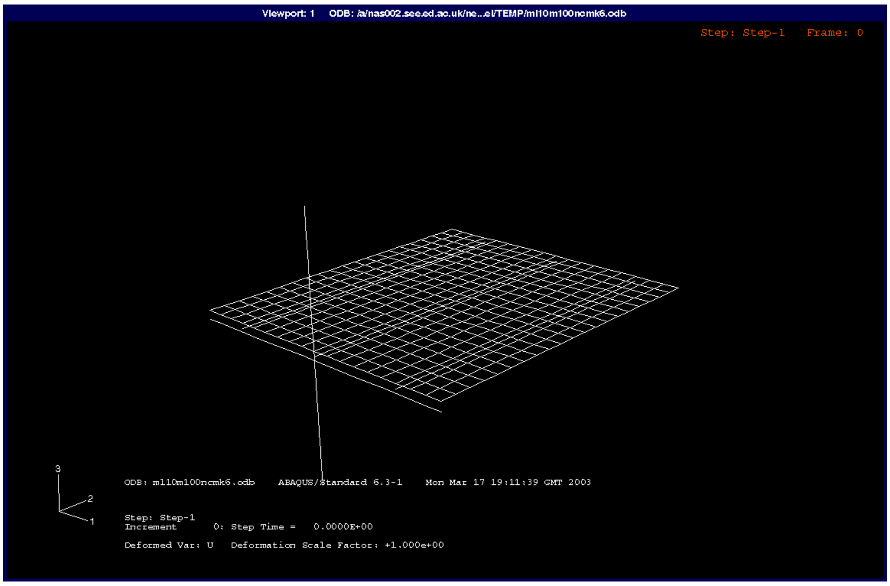
Only secondary beams unprotected

470mm max deflection

Unprotected 10m panel

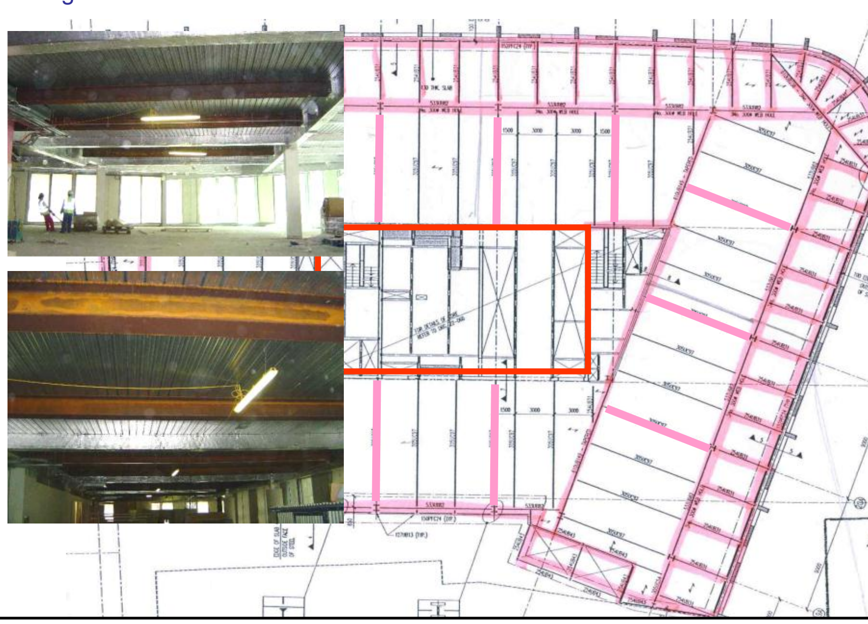


Protected 10m panel



Final Proposal (accepted)

Saving of £250K on Plantation Place



Fires in tall buildings

Mandarin hotel and CCTV building, Beijing

Fires in Tall buildings

- The risk of multiple floor fires is ignored in design – *even single whole floor fires not considered*
- Fires in tall buildings often involve multiple floors
- Designers still mainly rely simply on "*protecting*" - to keep temperatures below ~550°C
- The real "*protection*" (risk reduction) obtained is unquantified (no calculations on system behaviour)
- The probability is low, the consequence of collapse is high -therefore the risk can be very high, for instance………

Collapse of World Trade Centre 7 (11/9/01)

The WTC Collapses

Report from the official US investigation (available at *wtc.nist.gov*) provides a detailed description of the probable causes of the collapse of the twin towers

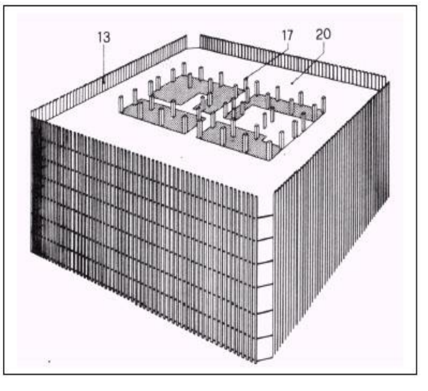
The key factor in the collapse was the post-impact fire, as both buildings Had remained stable after impact

University of Edinburgh team studied the effect of multiple floor fires (ignoring impact damage) on the structure of the towers (before NIST investigation was completed) and highlighted many of the Issues picked up by NIST

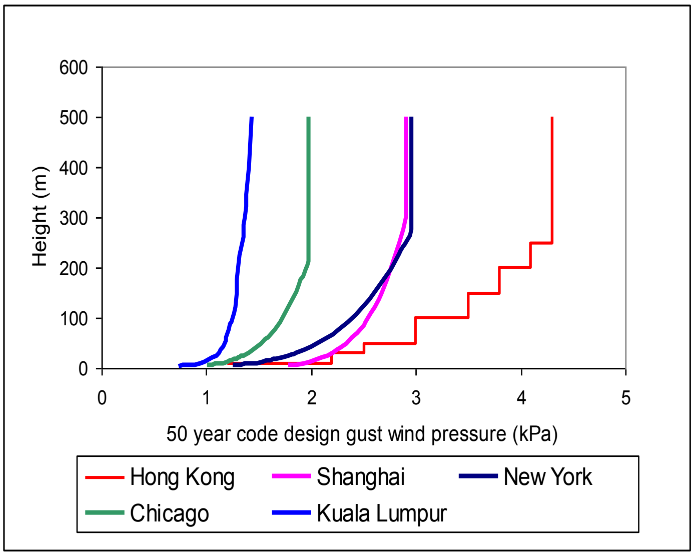
Some of the key findings from this work are presented

The Structure

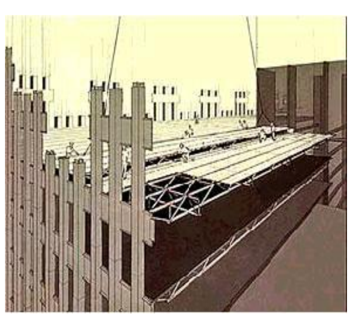
- 417m (WTC 1) and 415m (WTC 2)
- Innovative design for a light economical structure and column free office space
- Very closely spaced columns: 1m centres connected by 1.3 m deep spandrel beams
- Formed a perforated tube for wind loads
- No requirement to transfer lateral load allowed the floor system to be very light (900 mm light steel struss composite with 100 mm concrete slab)
- Floor acted as diaphragm to provide lateral restraint to all columns



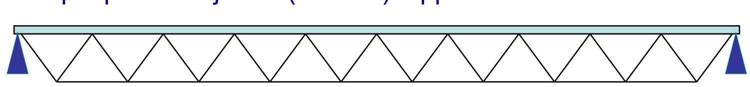
Wind Pressures around the World



WTC twin towers' key structural details



900mm deep 'open-web joists' (trusses) topped with 100mm concrete deck

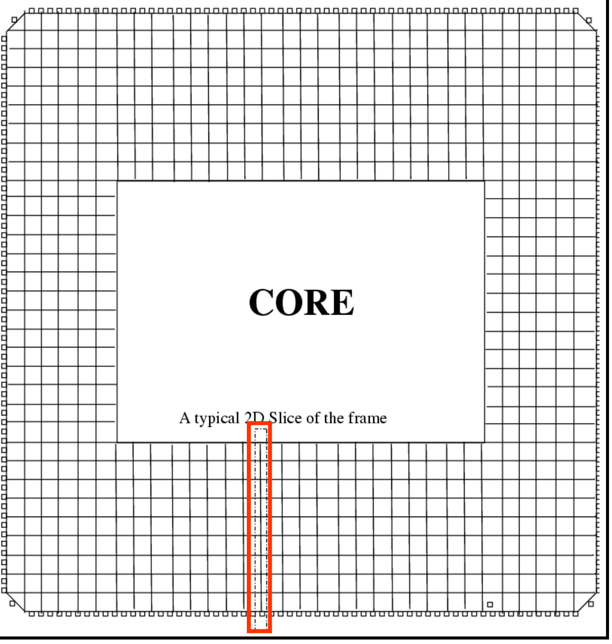


Deforming thermally against strong lateral restraint (expansion and bowing)

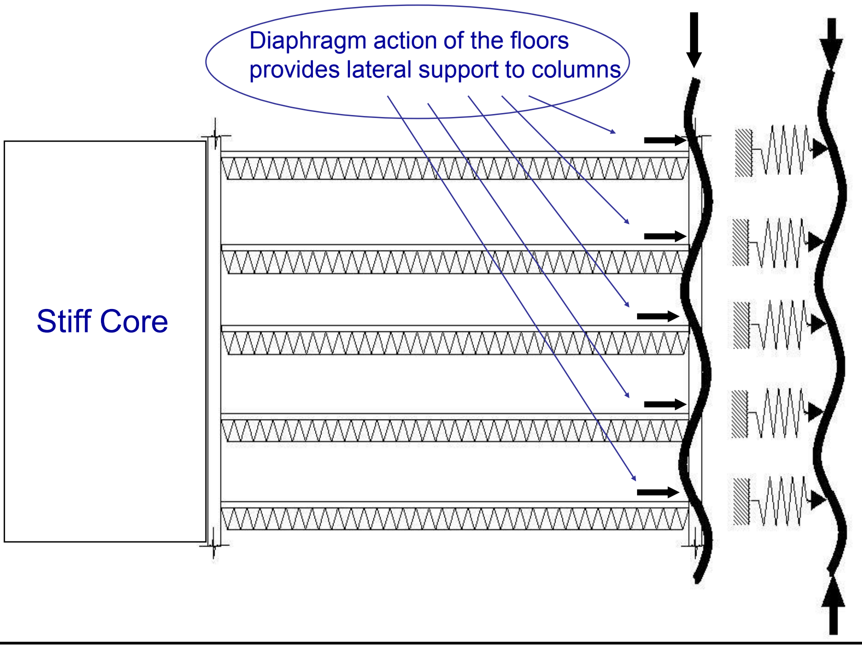
Expansion at 500 ^{o}C = 90mm => midspan deflection of 0.9m (assuming rigid restraints)

First model

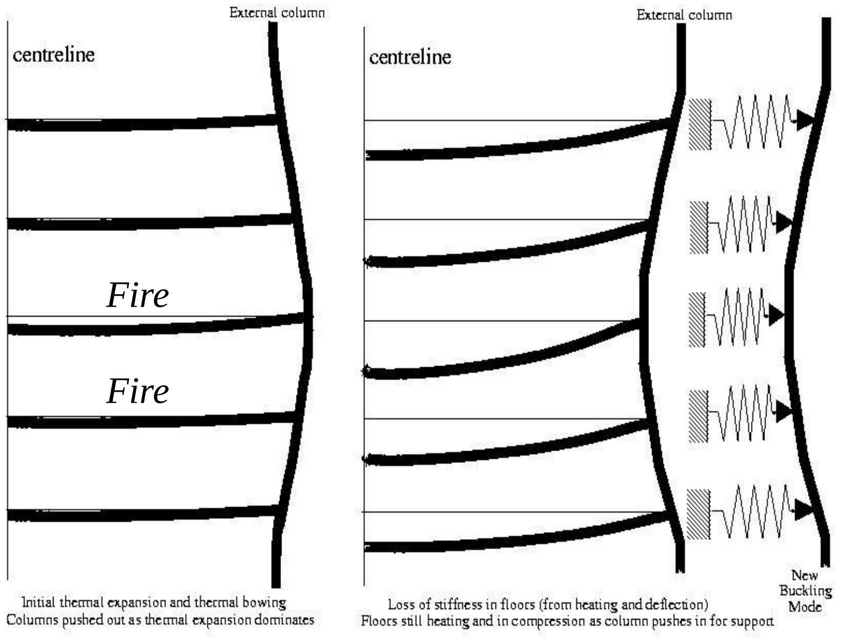
Analysing one long-span (18m) representative frame



Design column buckling mode

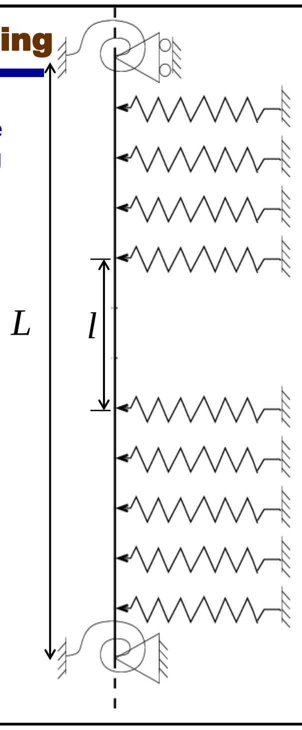


Initial hypothesis



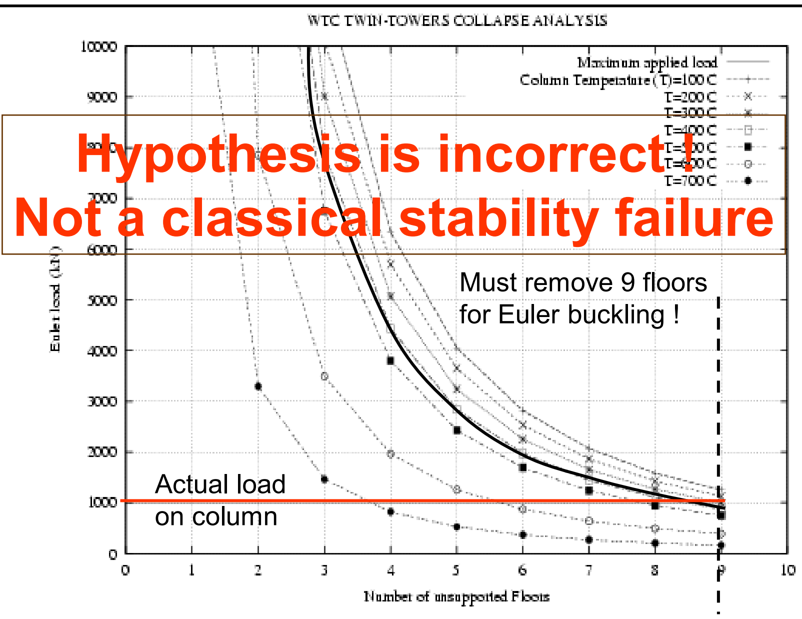
Buckling

Check to see if the how many missing floors are needed for the perimeter column to buckle?



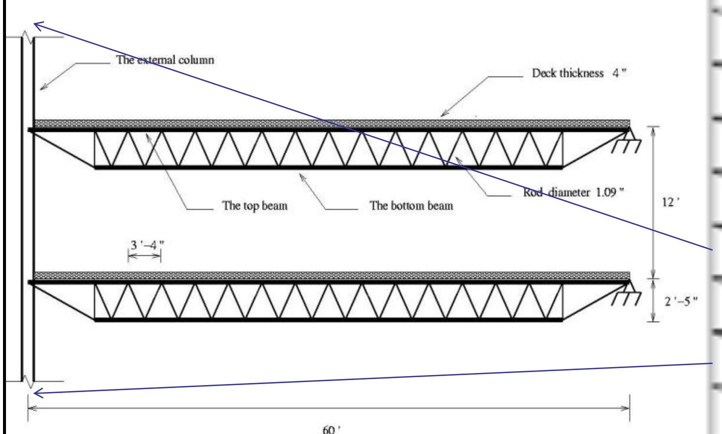
$$P_{cr} \approx \frac{2\pi^2 EI}{L^2} \quad \text{for} \quad \frac{L}{l} \approx 1$$

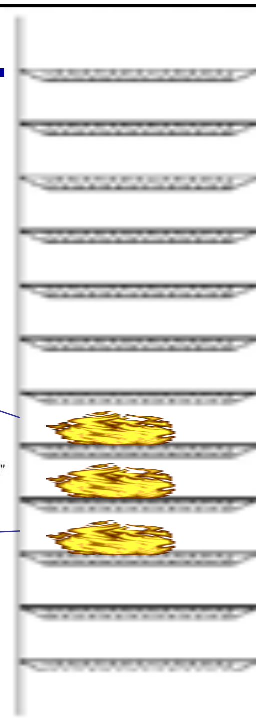
$$P_{cr} \approx \frac{4\pi^2 EI}{L^2} \quad \text{for} \quad \frac{L}{l} \approx \infty$$



Number of unsupported floors for Euler buckling

First finite element model





Actual dimensions (FEMA report) and BCs

Fire definition

Floors

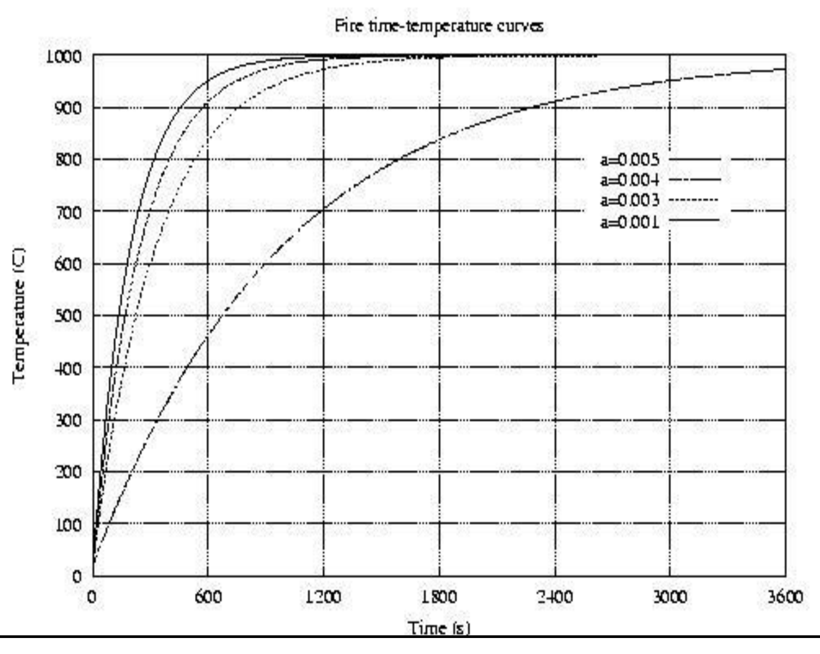
$$T(t) = T_0 + (T_{max} - T_0)(1 - e^{-at})$$

Columns

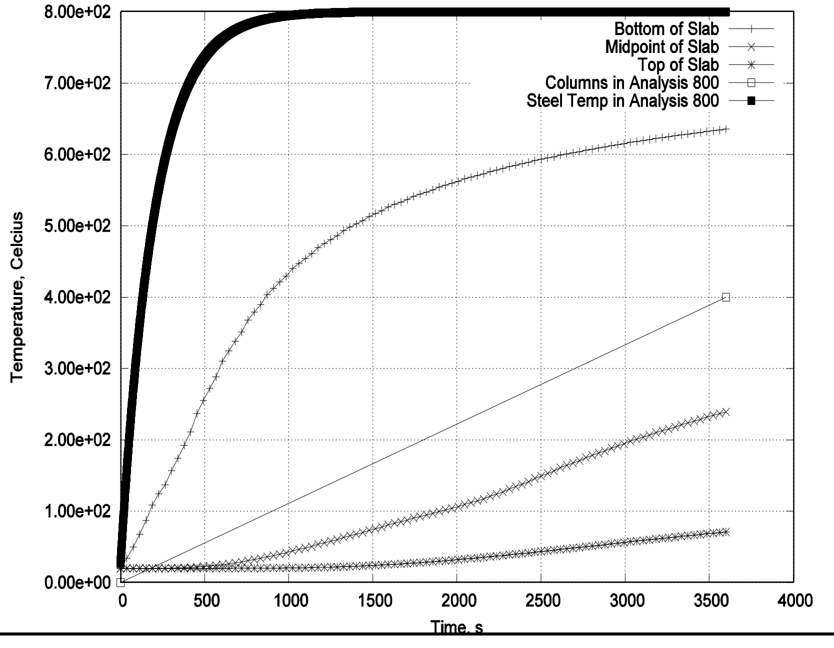
$$T(t) = T_0 + \frac{(400 - T_0)}{t_{max}} t$$

Column Temperature always < 400°c

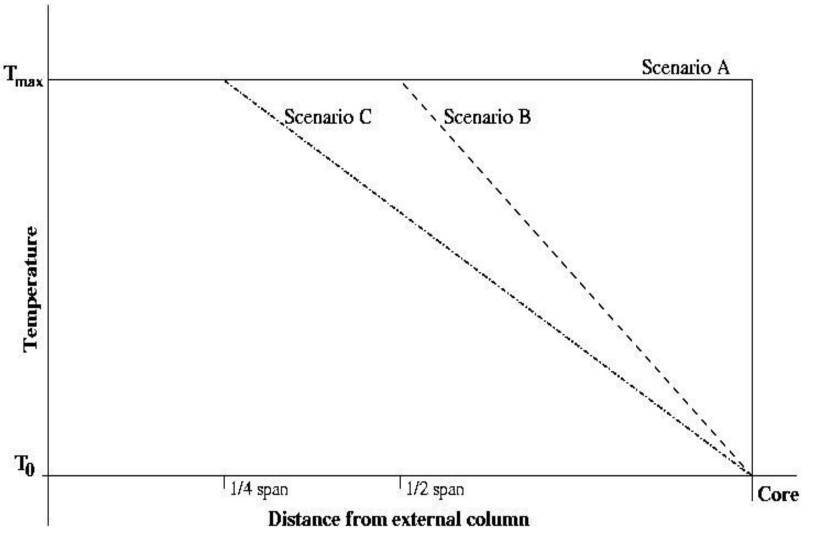
1000°C fire for different values of '*a*'



Sample temperature profiles for 800°C 'fire'



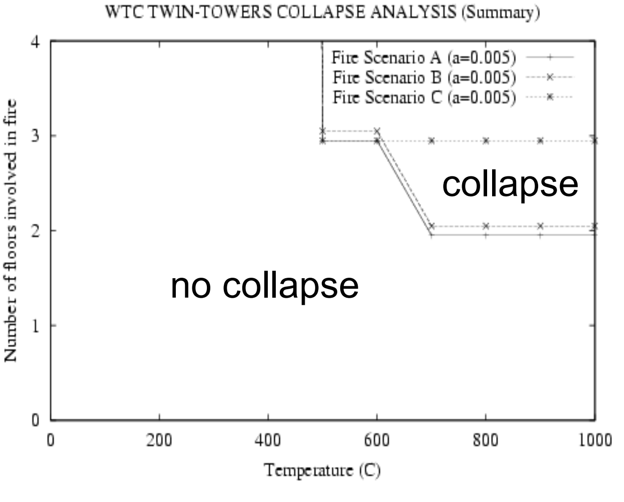
Fire Scenarios



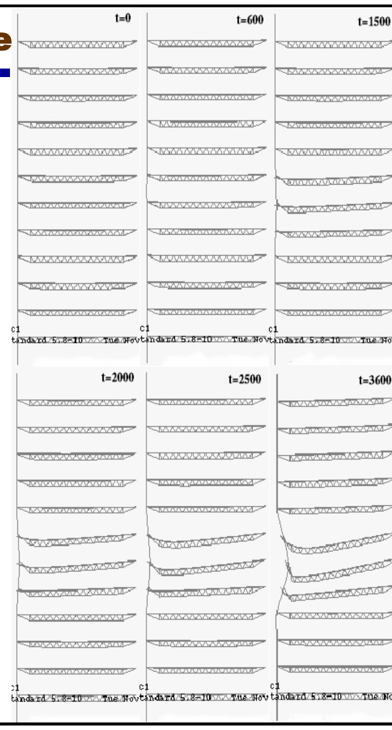
All fire scenarios analysed

Fire Scenario		Number of floors under fire and range of Maximum temperatures		
Tempr. distr.	a	1	2	3
A	0.005	400°C-1000°C	400°C-1000°C	1000°C
B	0.005	400°C-1000°C	400°C-1000°C	-
C	0.005	400°C-1000°C	400°C-1000°C	-
C	0.004	400°C-1000°C	400°C-1000°C	-
C	0.003	400°C-1000°C	400°C-1000°C	-
C	0.001	400°C-1000°C	400°C-1000°C	400°C-1000°C

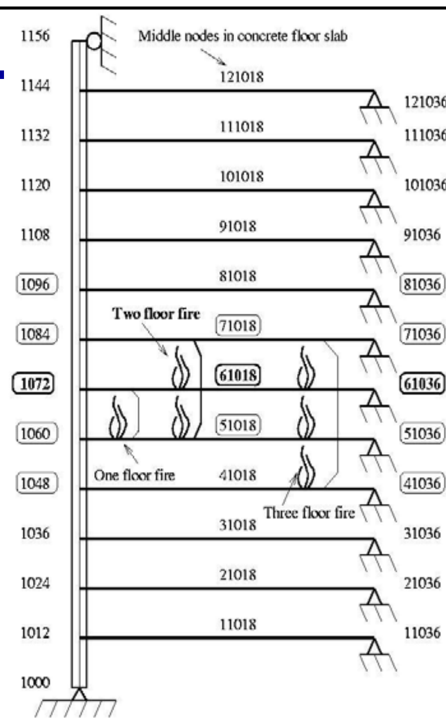
Summary of results



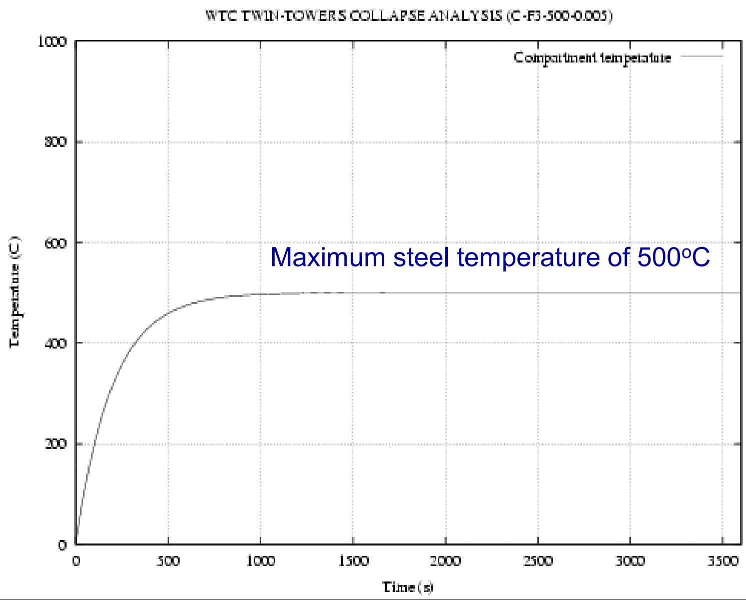
Typical failure mode

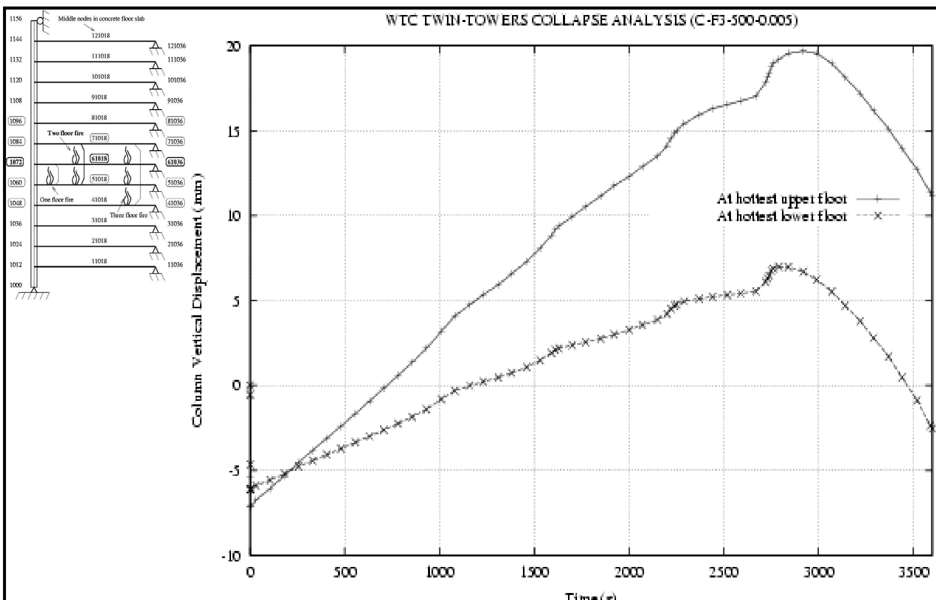


Node location key



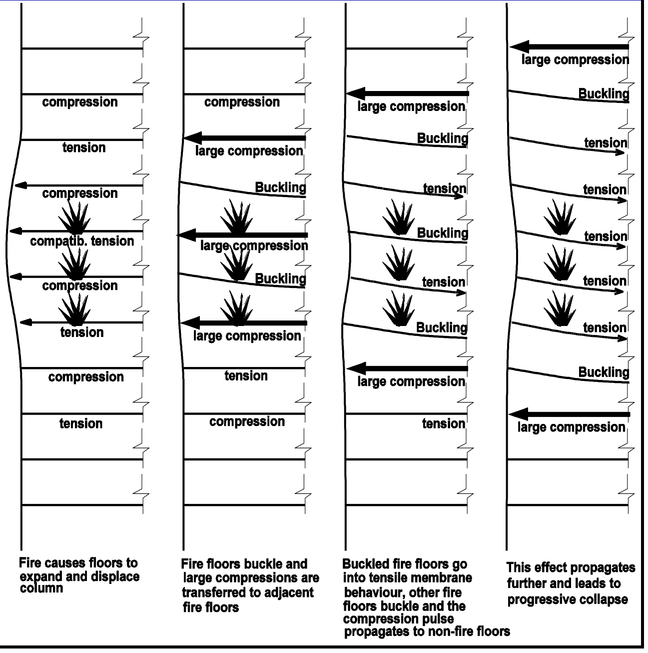
Detailed analysis of C-F3-500-0.005



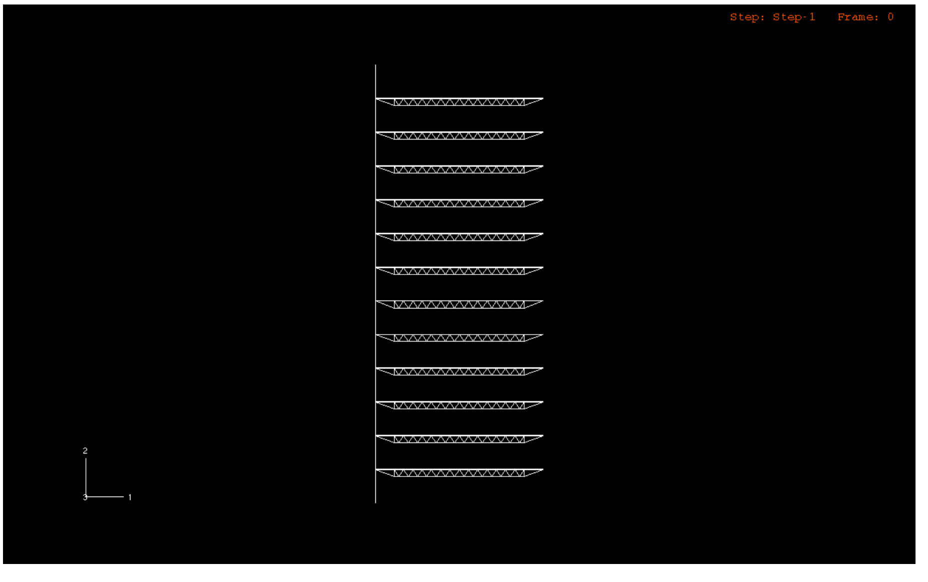


Column vertical displacements

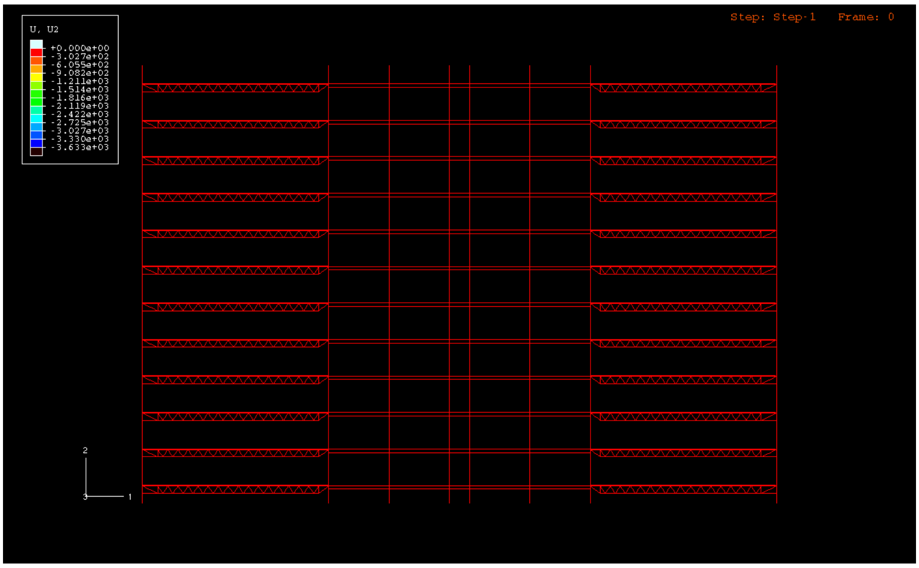
Sequence of progressive collapse



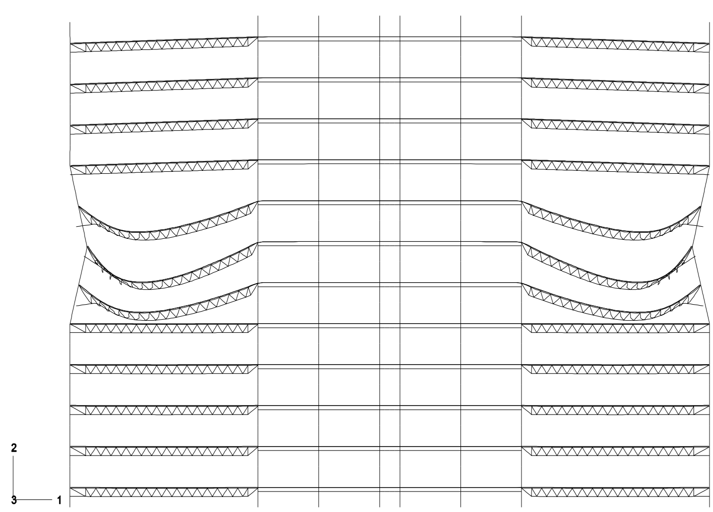
Animation



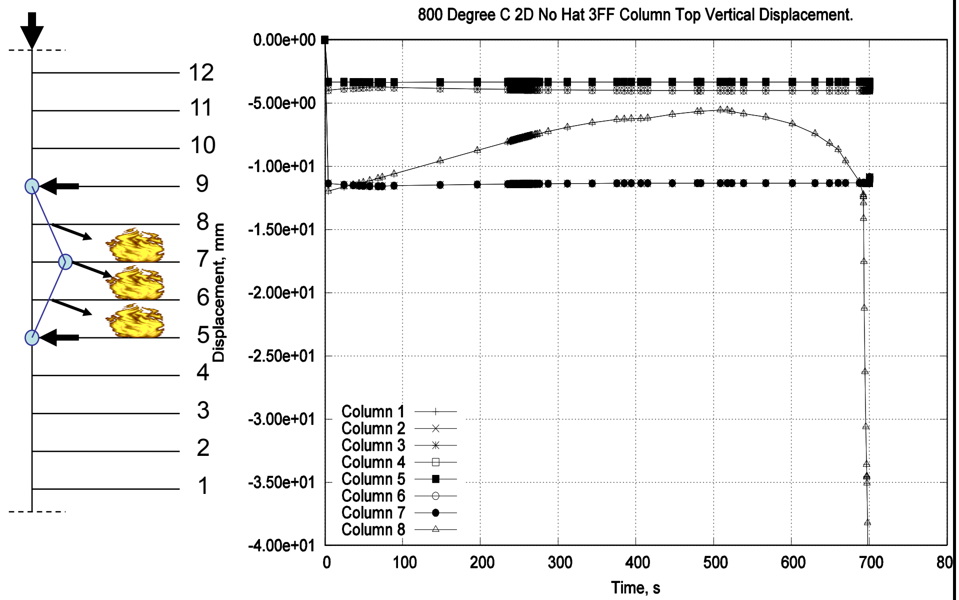
Larger 2D model with 3 floors on fire



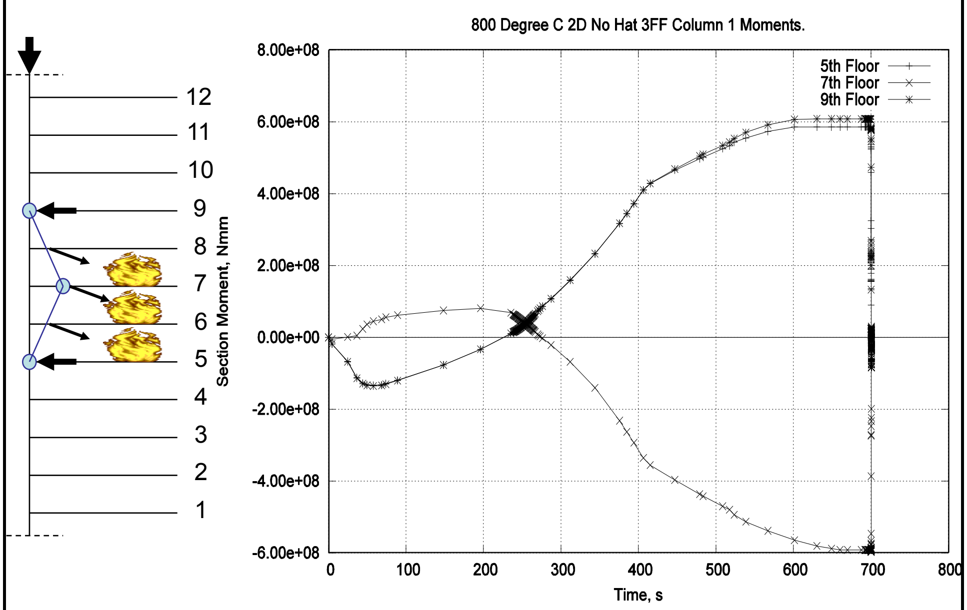
Final failure mechanism (plastic hinges)



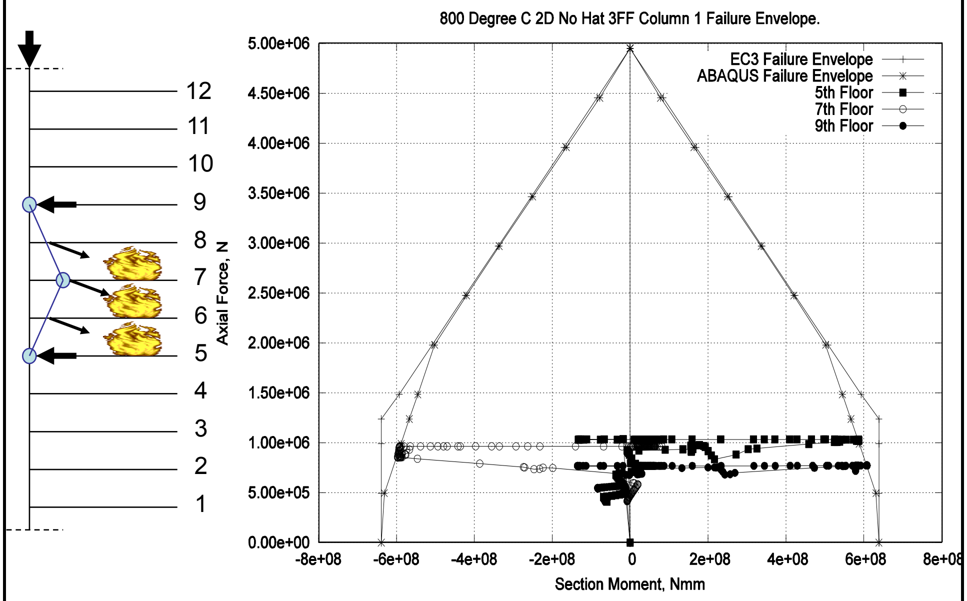
Column vertical displacement



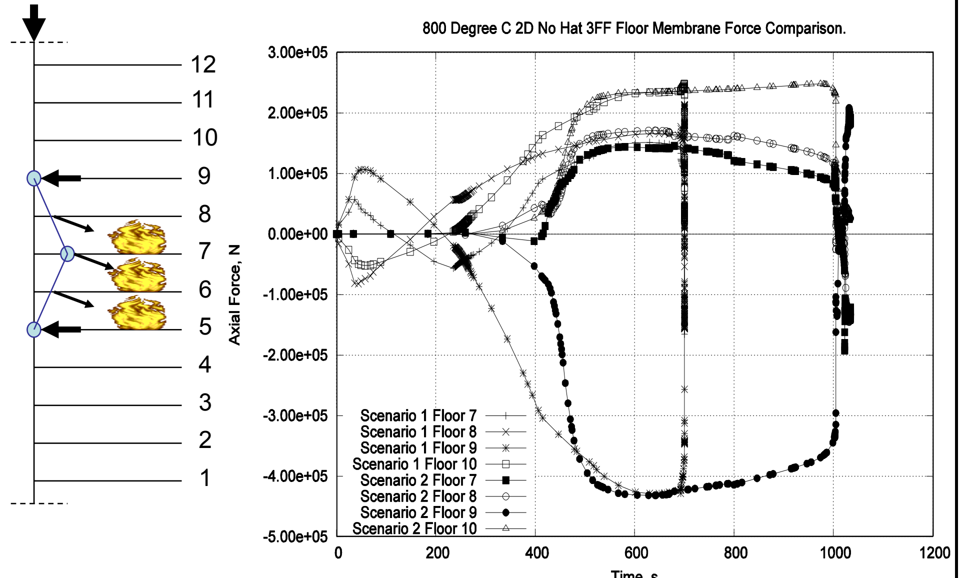
Column moments at hinges



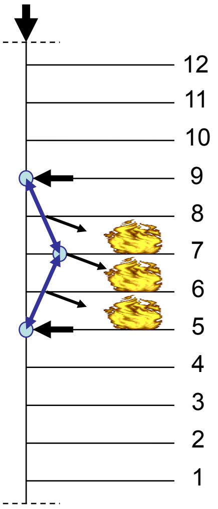
Axial force – moment interaction



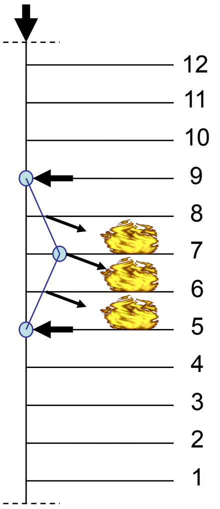
Runs with and without thermal expansion



Possible explanation

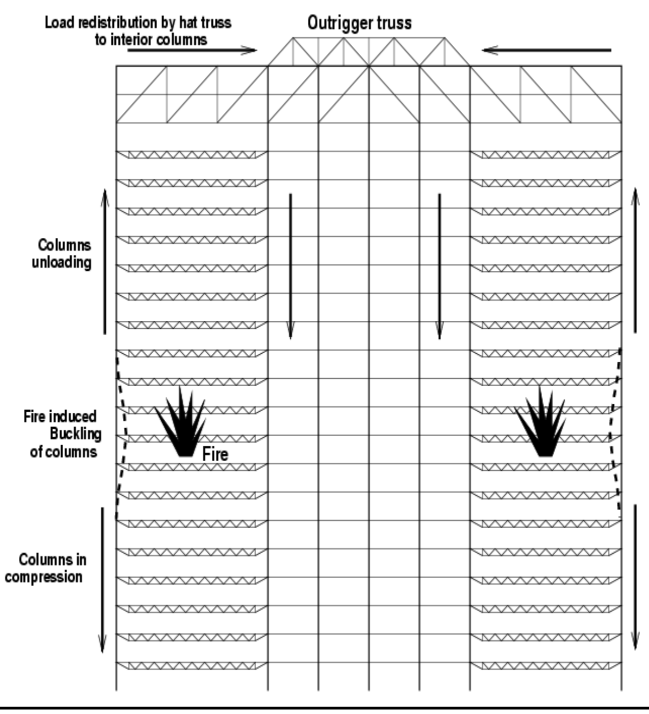


Thermal expansion included

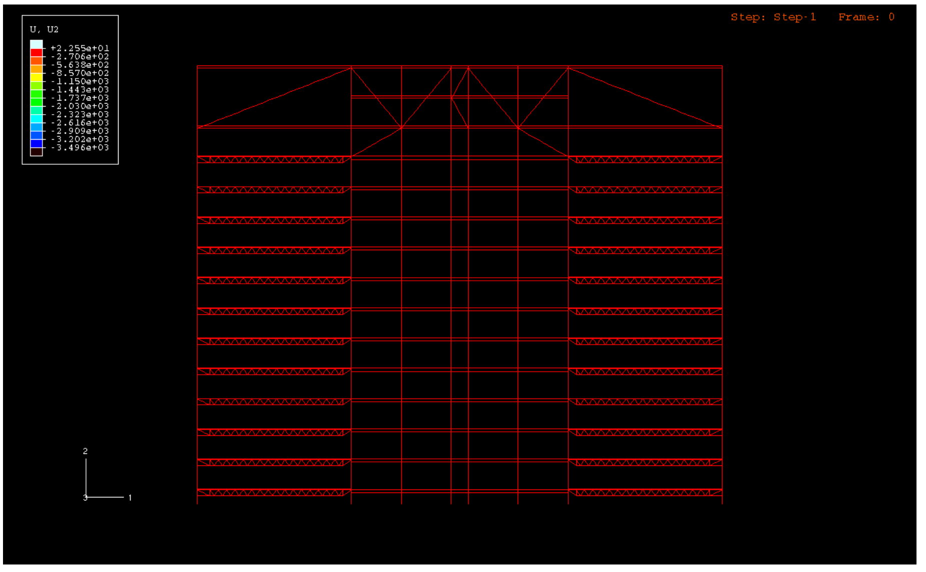


Thermal expansion excluded

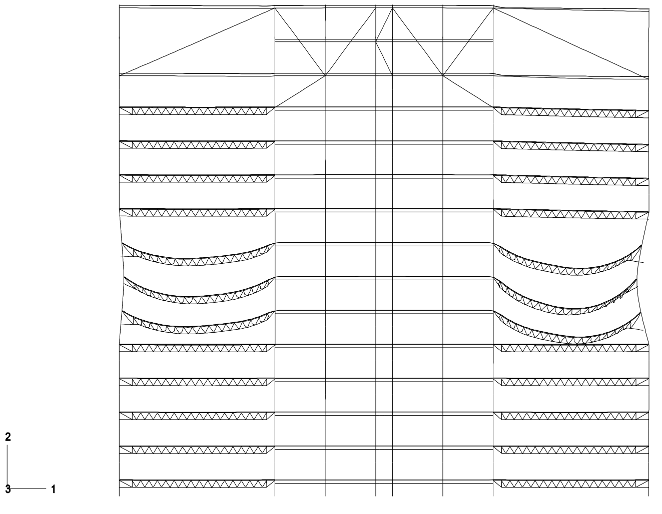
Hat-truss influence on load redistrib-ution



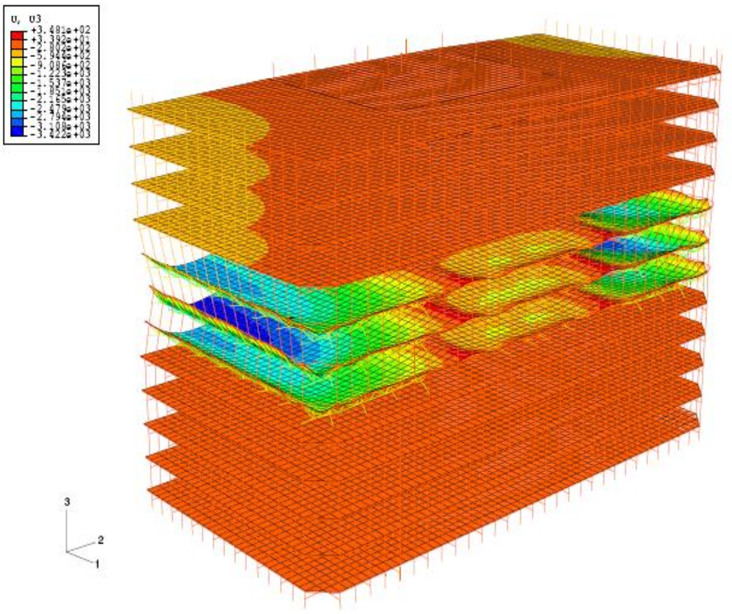
2D hat-truss model - 3 Floor Fire to 800°C



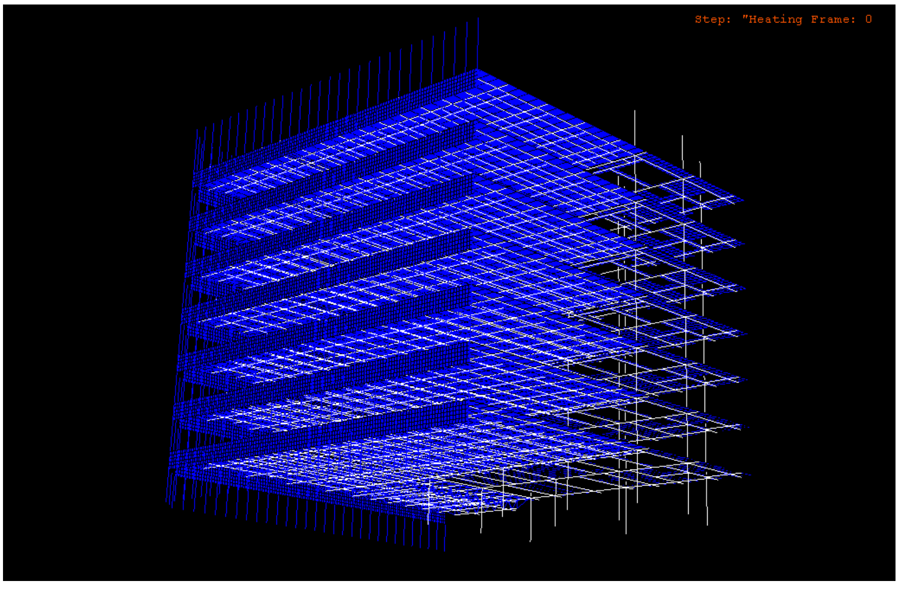
Failure mechanism (plastic hinges in column)



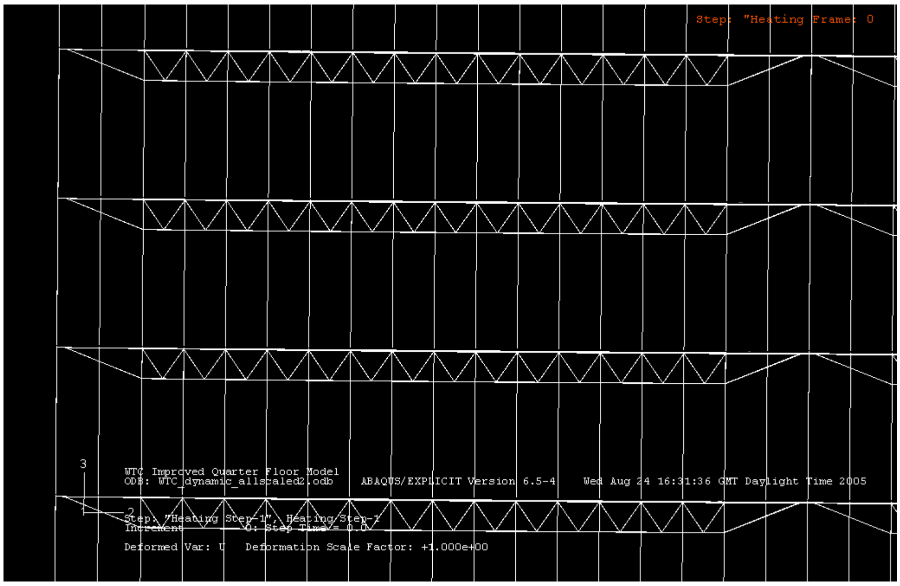
3D Multi-storey model



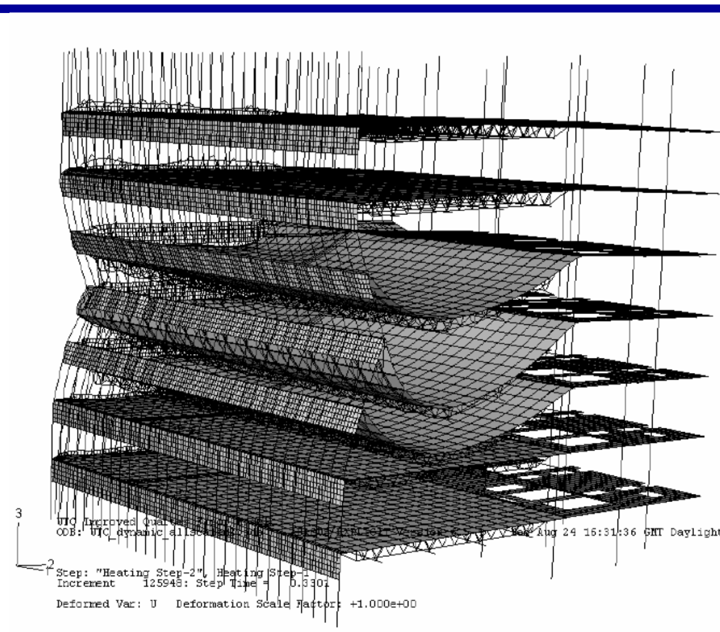
3D Multi-storey model – 3FF, 800°C



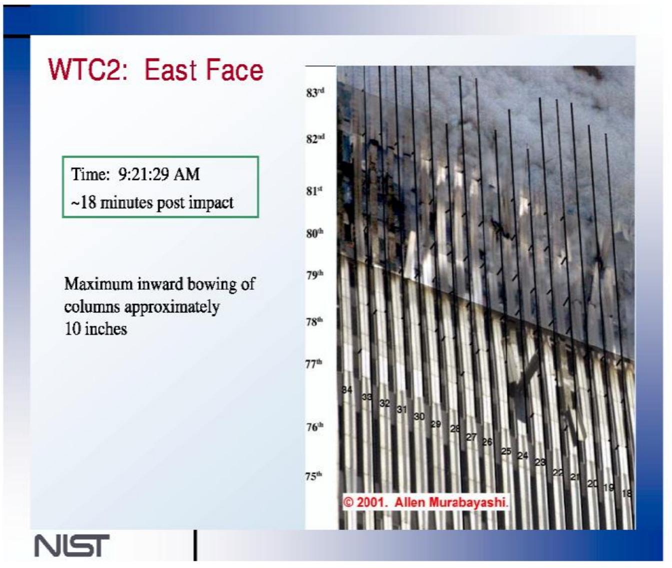
3D model: Truss deformations



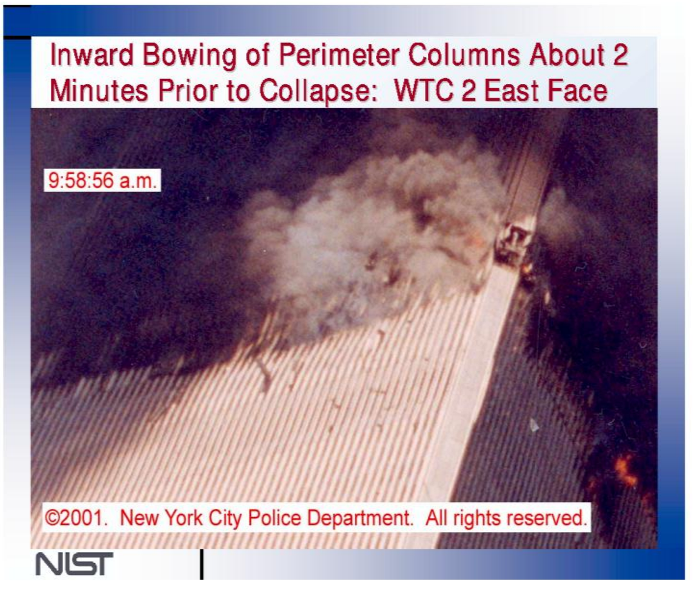
Collapse mechanism from 3D model



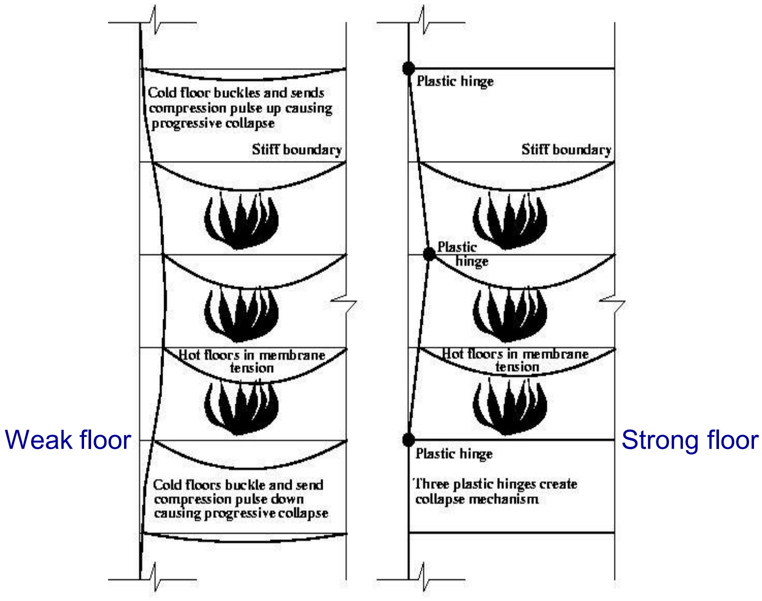
Photograph from NIST report



Photograph from NIST report



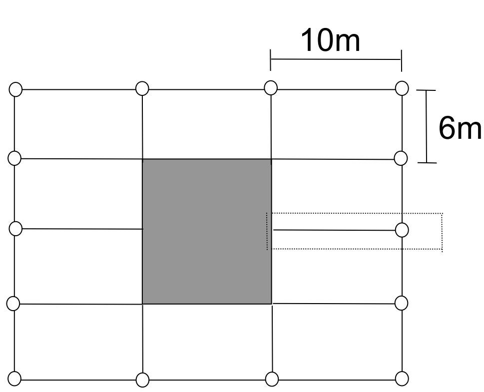
Are there generic collapse mechanisms?

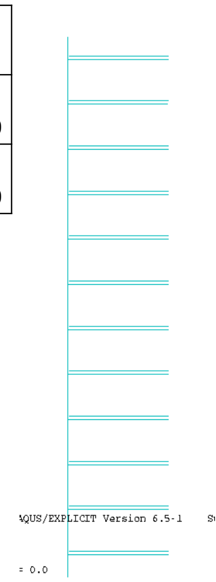


(a) Stiff column weak floor mechanism (b) Stiff floor weak column mechanism

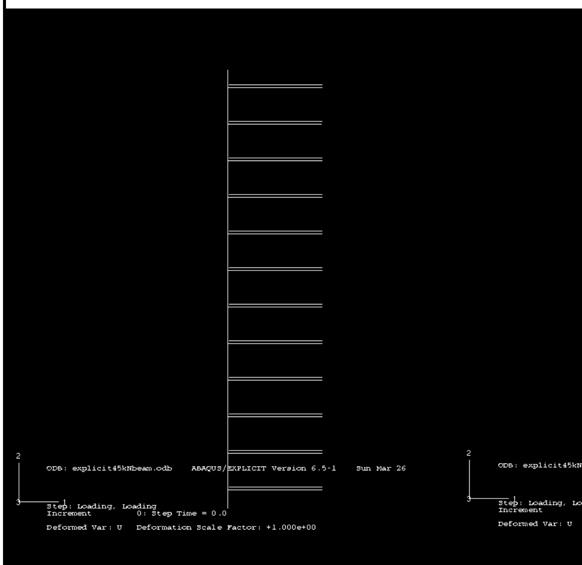
Model to test generic mechanisms

	Universal Beam	Universal Column	Beam udl (N/mm)	Column load (N)	Floor span
Strong beam	533x210x92	305x305x198	45	6000	10
Weak beam	305x102x28	305x305x198	45	6000	10





Model results



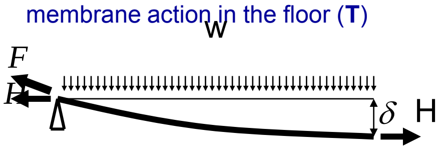
Weak floor mechanism

Strong floor mechanism

Experimental validation of failure mechanisms

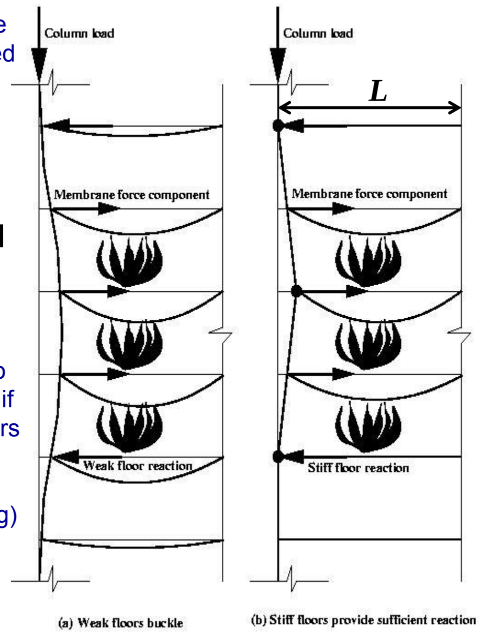
Simple method to assess collapse propensity

0. Start with an adequate model structure & assume number of fire floors involved
1. Assume an appropriate deflection to carry to all the load (udl) by tensile membrane action in the floor (**T**)

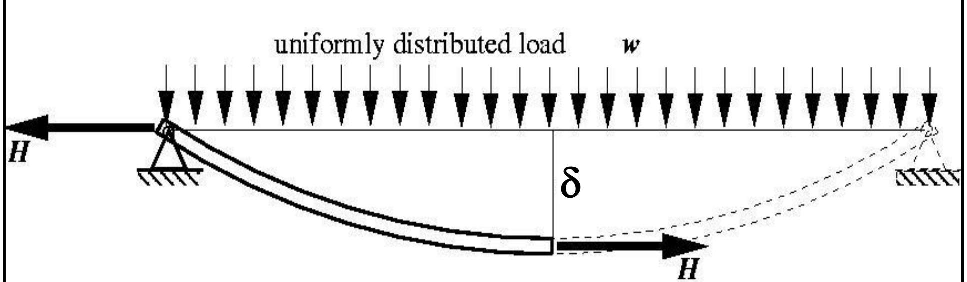


$$H\delta = wL^2/8$$

2. Determine if adjacent floors are able to sustain the reaction without instability, if not - WEAK FLOOR COLLAPSE occurs
3. If adjacent floors remain stable, check columns using an axial force-moment interaction diagram (function of heating) if the maximum moments and forces remain inside the yeild boundaries, if not - STRONG FLOOR COLLAPSE



Catenary action (TMA) and flexural resistance

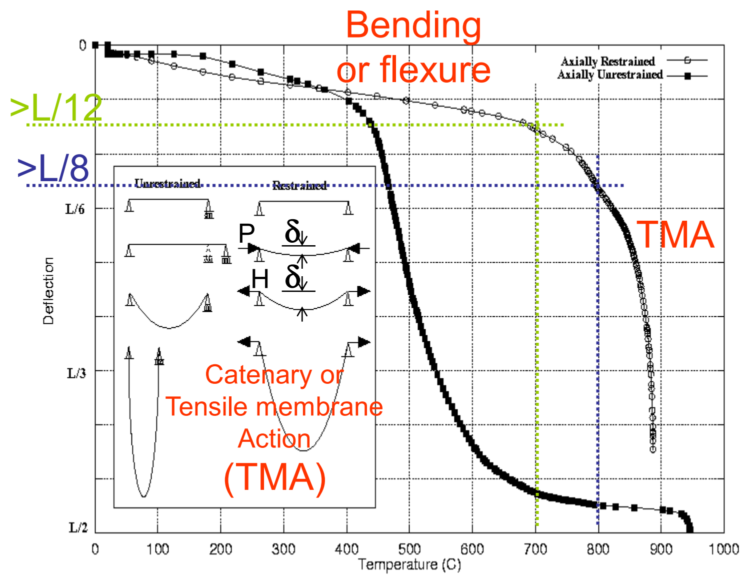


Applied moment = $wL^2/8$

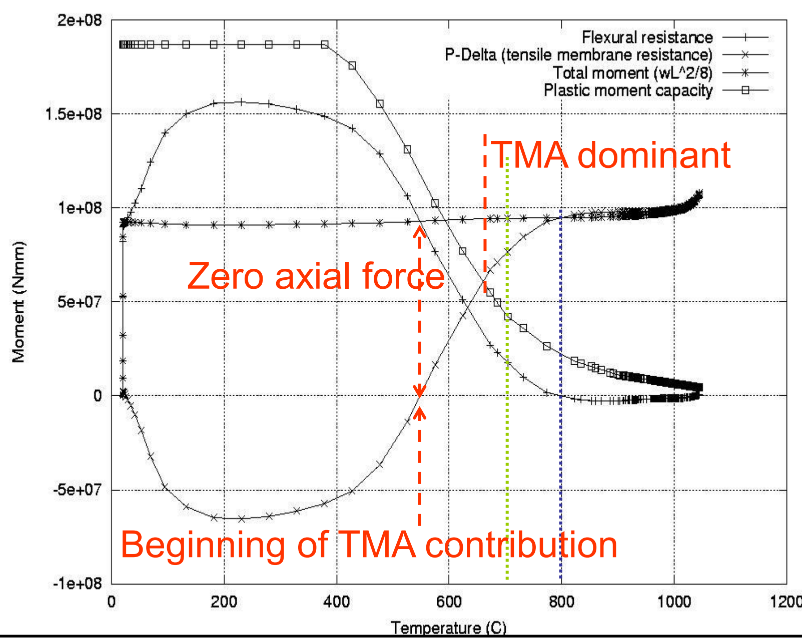
Tensile membrane or catenary resistance = $H\delta$

Residual moment capacity = $Mp(T,H)$

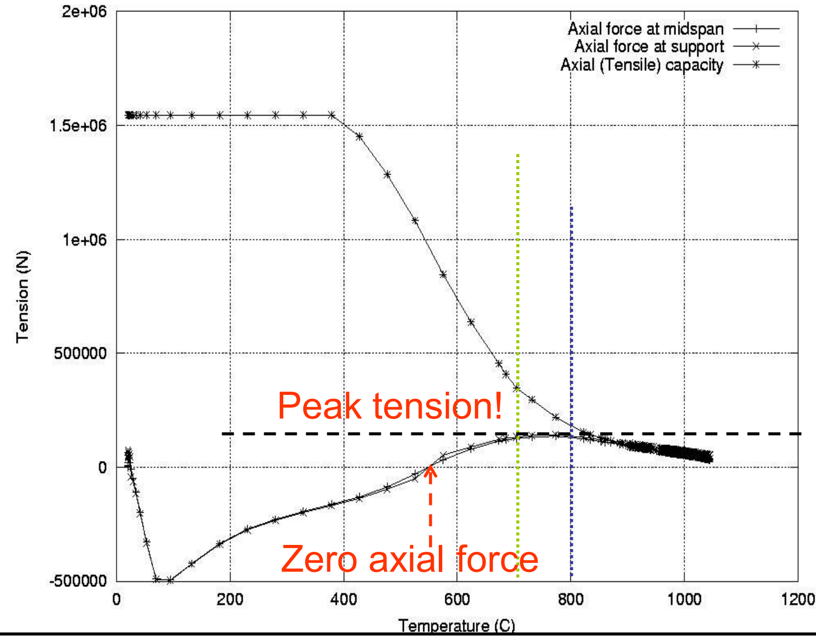
Runaway in beams



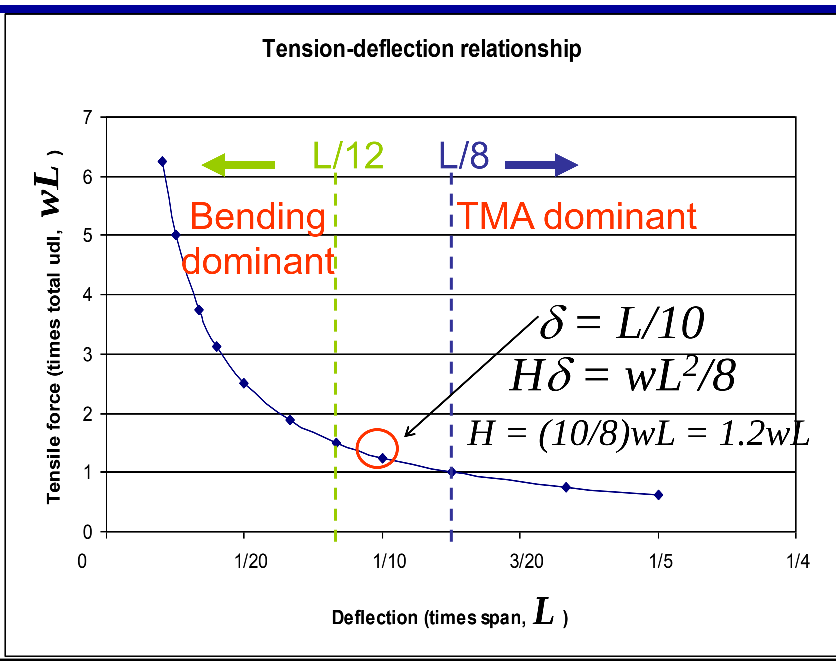
Moment (flexure) evolution



Axial force evolution

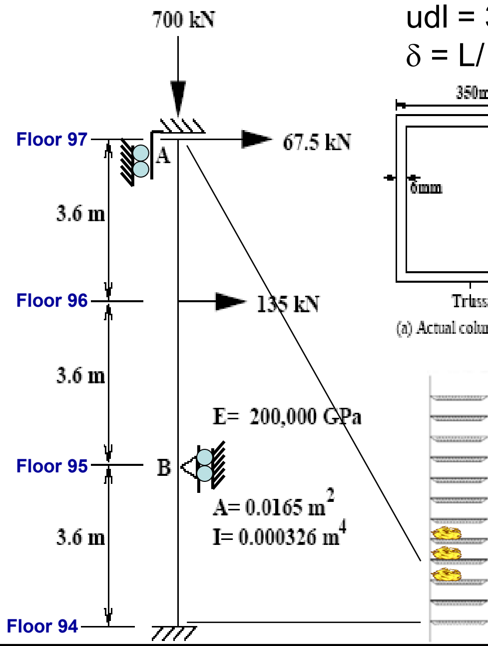


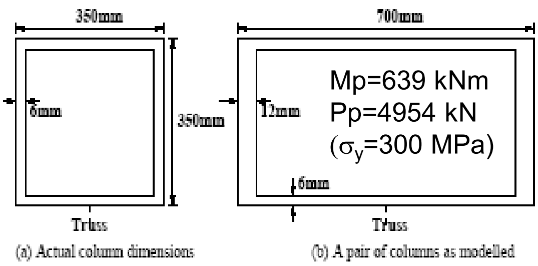
How much deflection (δ) ?

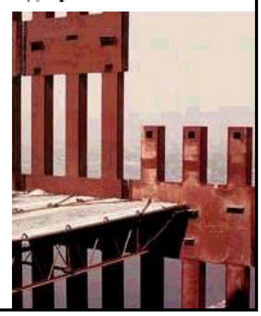


Check North Tower design!

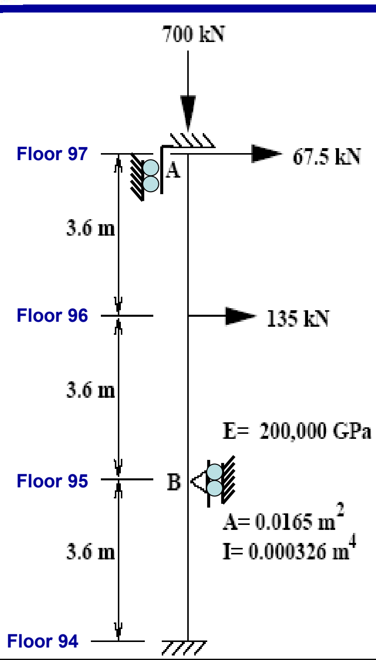
udl = 3 kN/m
$\delta = L/10$







Result



Moment at A = 463 kNm
Moment at B = 570 kNm

Simple interaction check

$M/M_p+P/P_p<1$

$570/639+700/4954=1.03>1$

Therefore first hinge forms at floor 95, then at floor 97, and finally on floor 99, leading to a mechanism.

'Structures in Fire': from Cardington to 9/11/2001 and beyond

Part 3: Development of simulation tools and future vision

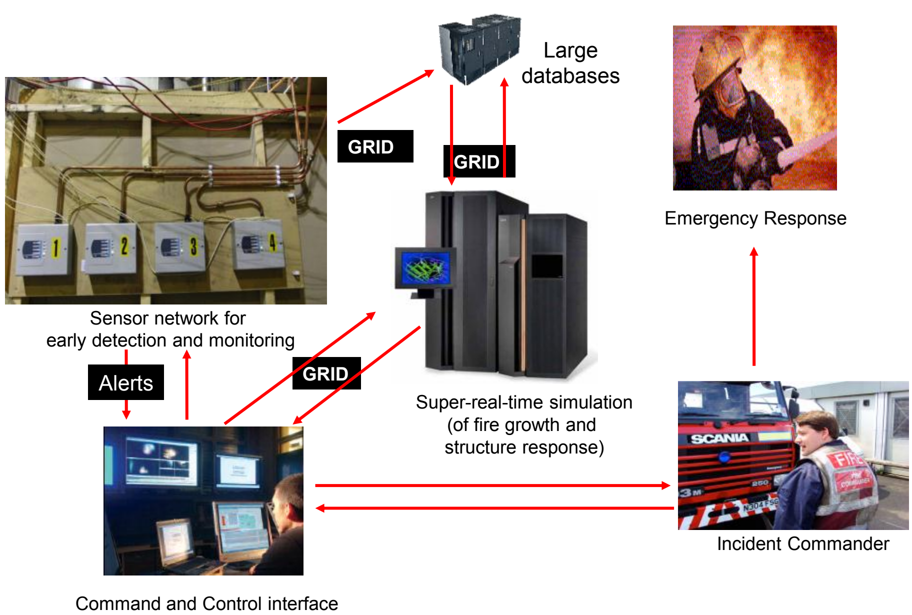
Key references:

FireGrid: An e-infrastructure for next-generation emergency response support, *Journal of Parallel and Distributed Computing*, 70:1128–1141, 2010

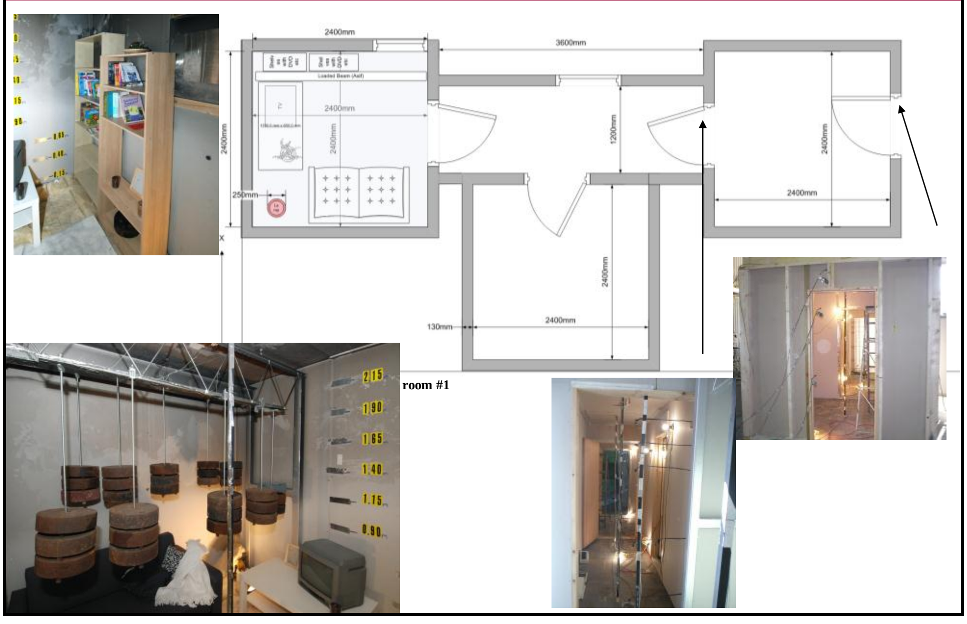
Testing a damaged RC frame in fire, Proceedings of the ICE - *Structures and Buildings*, 165(7):335–346, 2012

Using OpenSees for structures in fire, *Journal of Structural Fire Engineering*, 3(1):57–70, 2012.

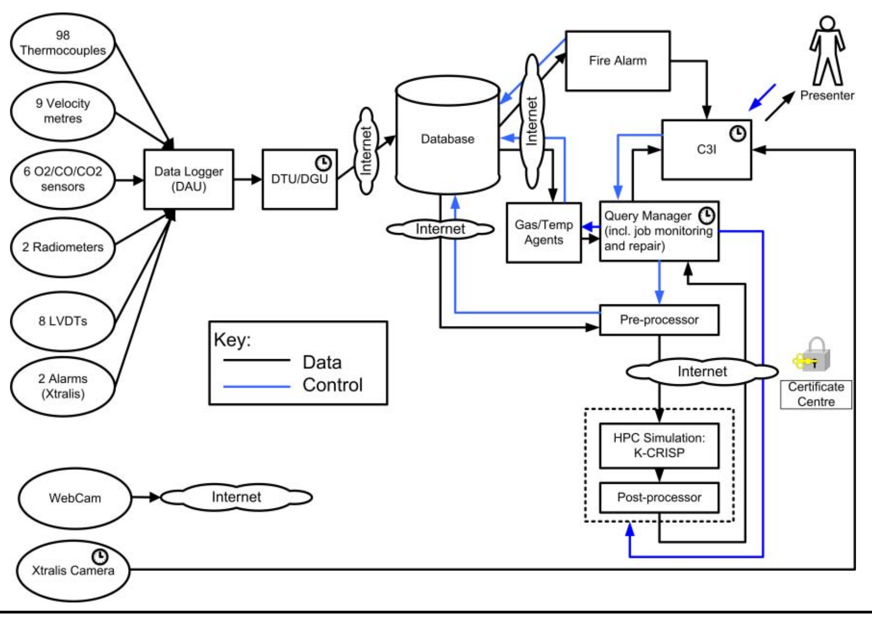
Future Vision: FireGrid Project (2006 – 2009)



Demo in an full-scale apartment mock-up



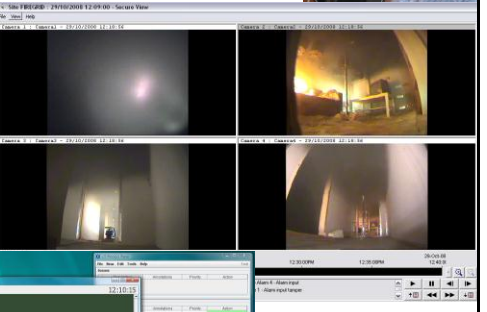
Demo architecture

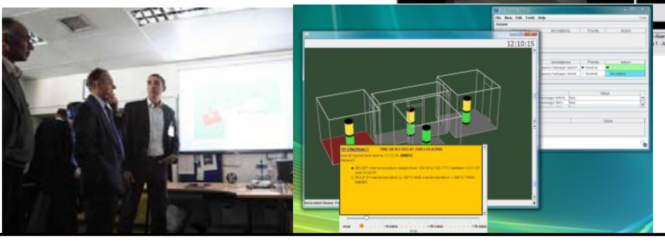


The demo experiment

- Demonstrator designed for live presentation:
  - Jose Torero provided commentary from Viewing Room.
  - Operator in Control Room interacted with C3I.

- Fire tracked by FireGrid system:
  - Delivering real-time status info for incident, along with predictions of impending hazards
  - based on HPC model output,
  - in form amenable to fire incident commander.



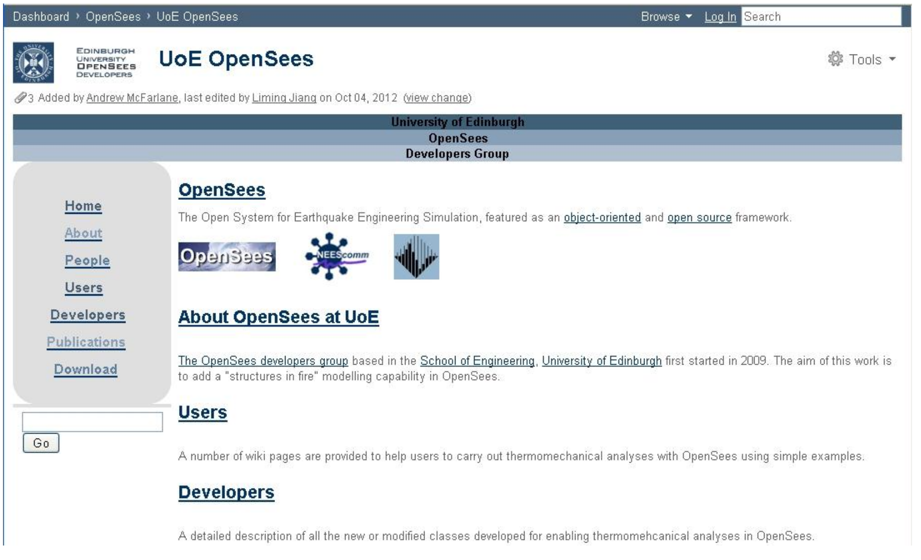


Results

Simulation tool development

http://opensees.berkeley.edu/

Simulation tool development



https://www.wiki.ed.ac.uk/display/opensees/UoE+OpenSees

Current activities and key aims

- Adapting OpenSees for modelling structure in fire

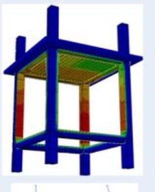
Fire models → (Middleware 1) → Heat transfer → (Middleware 2) → Structural response

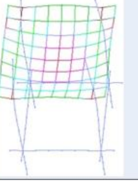
- Performance based structural engineering
  - Analysis and design of structures with explicit treatment of uncertainty
  - PEER framework
  - Need for powerful and flexible simulation tools

- Hybrid testing with OpenSees as the main analysis tool as in Nees

Future simulation tool for full fire and structural response

CFD model **FireFOAM**	Compartment fire simulation to determine time dependent heat flux boundary conditions on compartment surfaces (including surfaces of structural members)
CFD-HT middleware	Mapping heat fluxes obtained from CFD onto the boundaries of the 3D solid FEM heat transfer model of structural members (or vice-versa, for modelling conjugate heat transfer indicated by double arrow)
Heat Transfer model **OpenSees**	Heat transfer analysis of structural members to determine detailed time dependent thermal history of the structural member (this could be uncoupled or coupled to CFD based on the desired level of rigour)
HT-TM middleware	Mapping of temperatures from 3D solid FEM model to structural models made up of a combination of 2D/3D beam-column elements and plate and shell elements for thermo-mechanical analysis (structural damage from this could also be used to modify parameters governing heat transfer)
Thermo-Mechanical model **OpenSees**	Fully nonlinear thermo-mechanical analysis of the structural frame based on the thermal history determined from the previous steps of the analysis, and establishing the full structural response to fire





Thank you

Merry Christmas and a happy New Year

Kyoto University HSE Technical Report Series 236

English title Structures in Fire・from Cardington to 9/11/2001 and beyond
火災時の構造挙動：カーディントン実験から 9.11WTC 崩壊，そして将来

Date: September 5, 2008

Co-hosted by Kyoto University Global COE Program “Global Center for Education and Research on Human Security Engineering for Asian Megacities”

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