Insights into the behavior of structures in fire and the implication on practice

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Opening Minds • Shaping the Future

Fire safety requirements are usually expressed as

- ♦ Insulation →
- ♦ Integrity →
- ♦ Stability →

For general building fire safety

Compartmentation:
maintaining structural and thermal barriers to prevent spread for a sufficient length of time to enable safe exit of all occupants

For structure/structural members

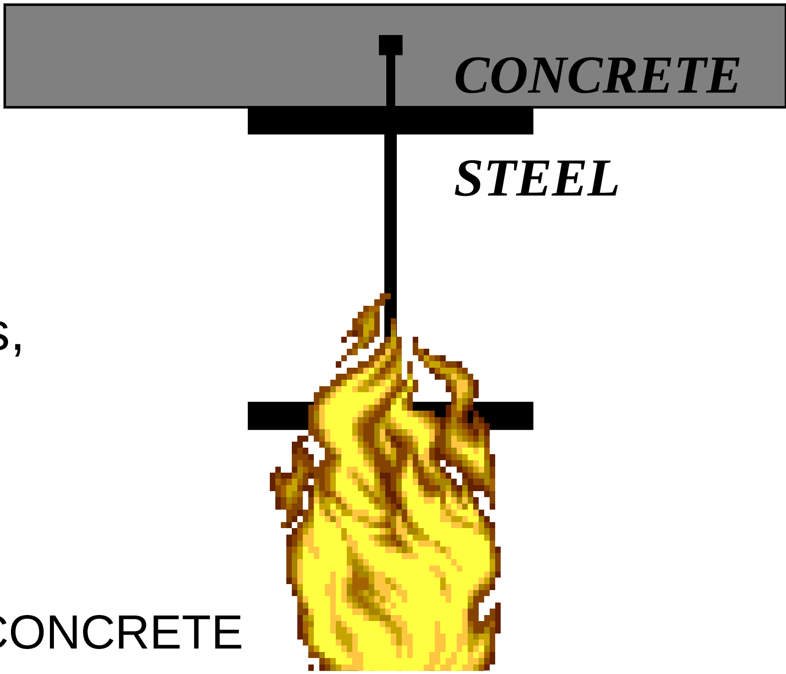
Fire resistance:
length of time a structural component withstands exposure to a "***standard fire***" while retaining adequate capacity to resist fire limit state load

The basis for traditional approaches

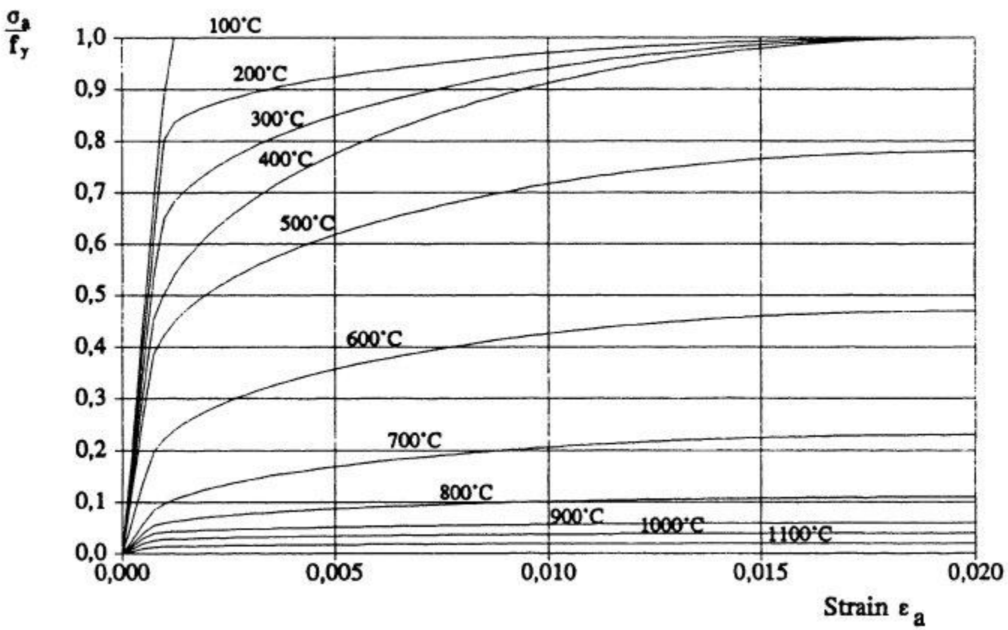
Observations

Fire heats steel, steel rapidly loses stiffness & strength at temperatures above 400ºC with only half the strength remaining at 550ºC

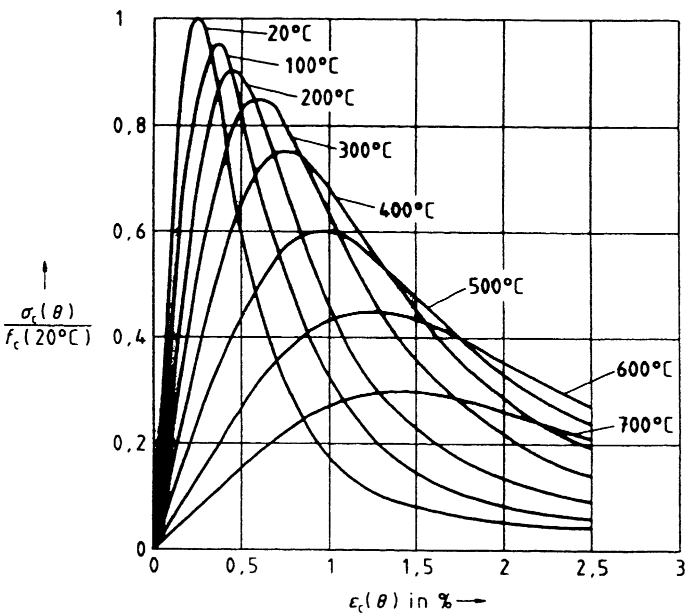
While concrete also loses strength and stiffness, its low thermal conductivity means that fire only affects the surface layers



STEEL



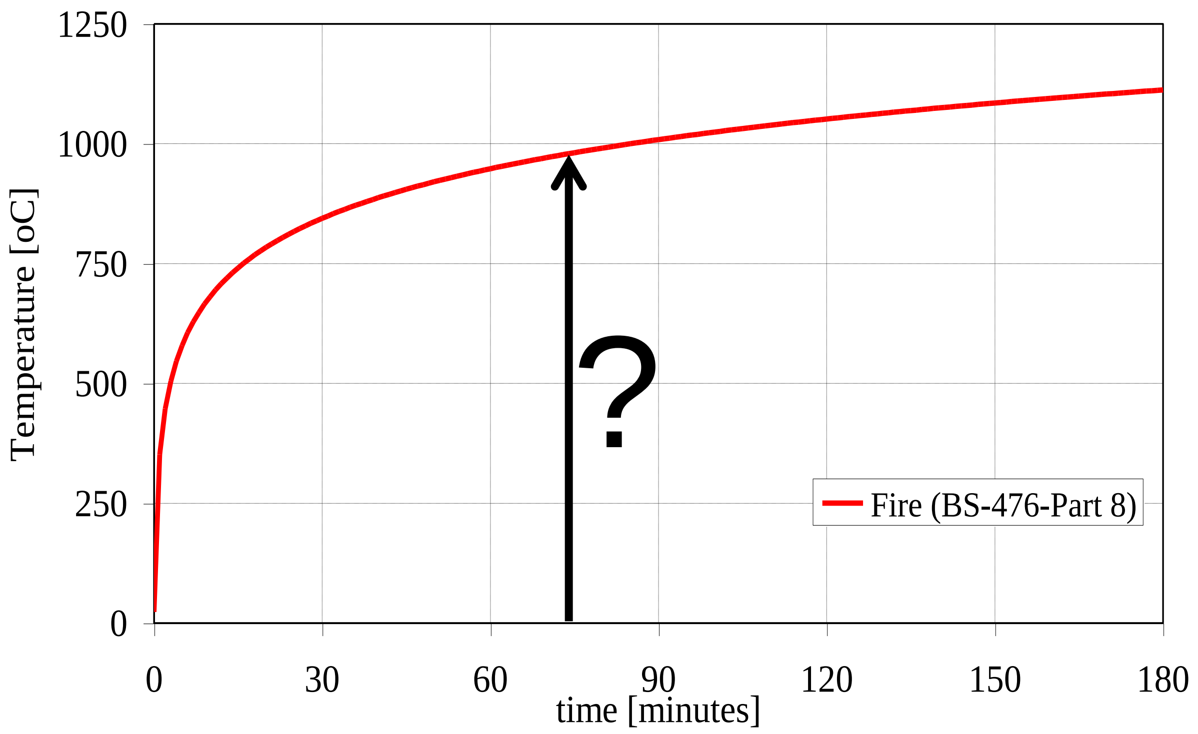
CONCRETE



Proposed (traditional) solution

Protect ***ALL*** steel for a *long enough* period

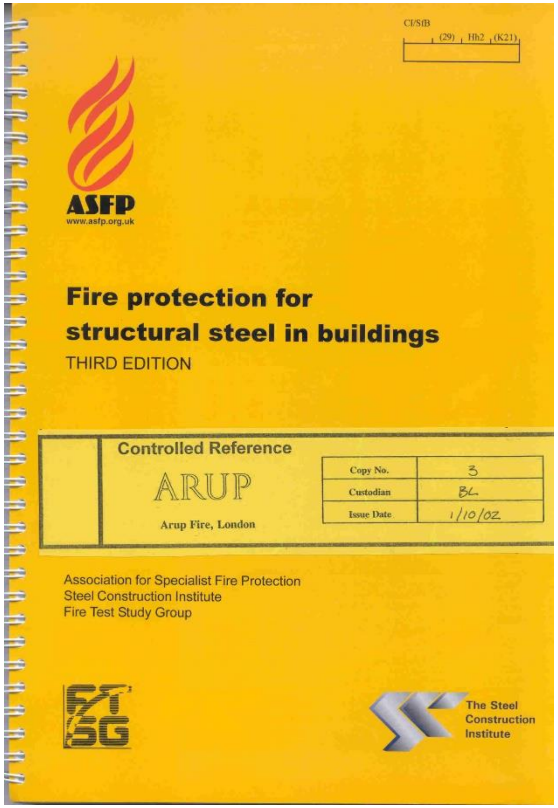
Provide *sufficient cover* to reinforcing bars based on *duration of exposure*



Standard fires specify a fixed temperature-time curve (originally developed over 100 years ago in USA in a 2.9mx2.9mx4.4m compartment to reach 926 Celcius in 30 mins).

Prescriptive “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

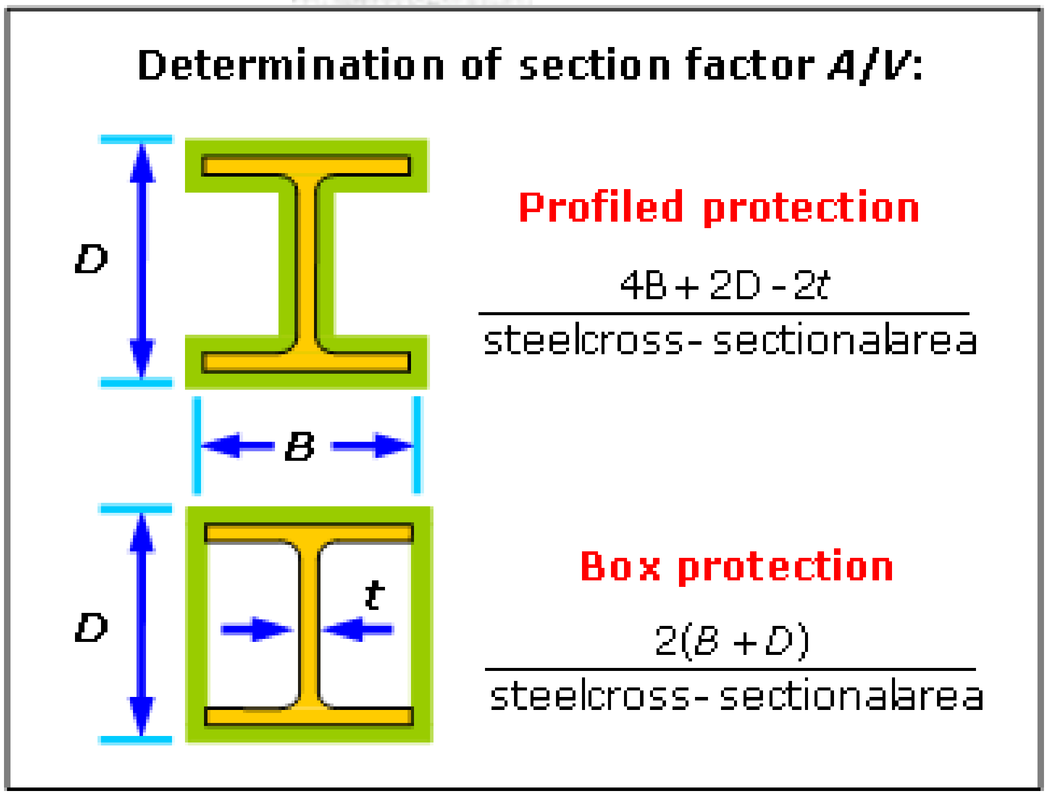
Low V

Fast heating

Low A

High V

Slow heating



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

Code bases fire resistance requirements

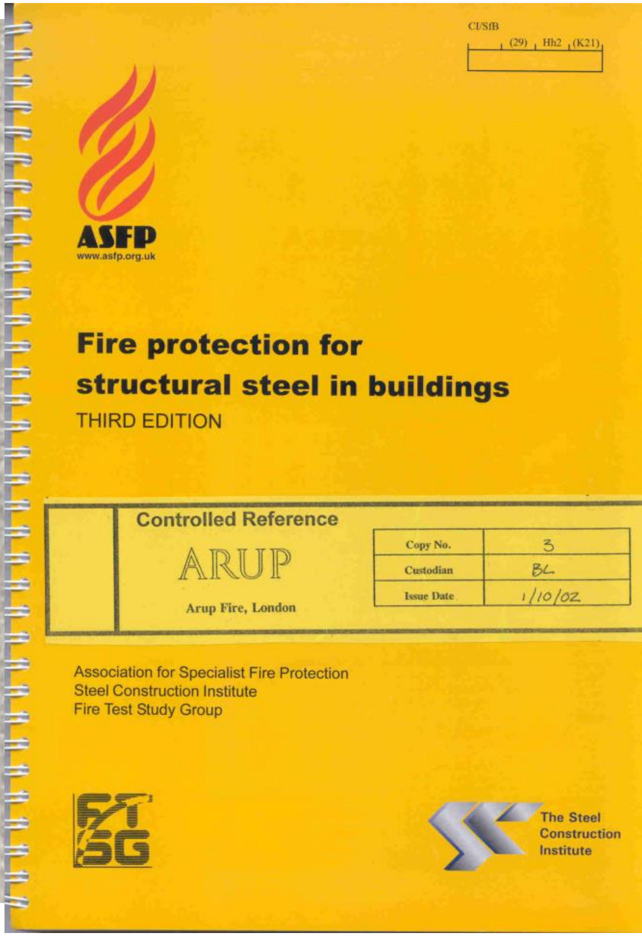
Fire resistance required
(from Approved Document B: England and Wales 2000)

	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

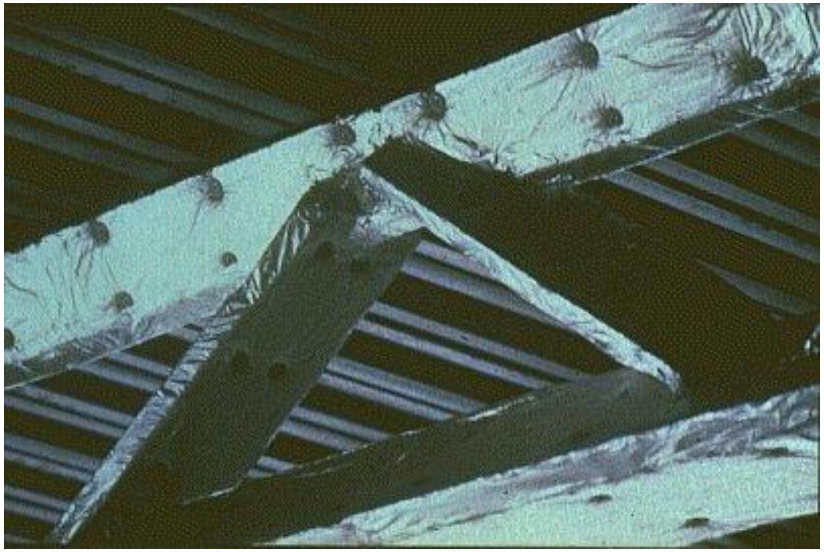
changed to **Am/V** to be consistent with Eurocode

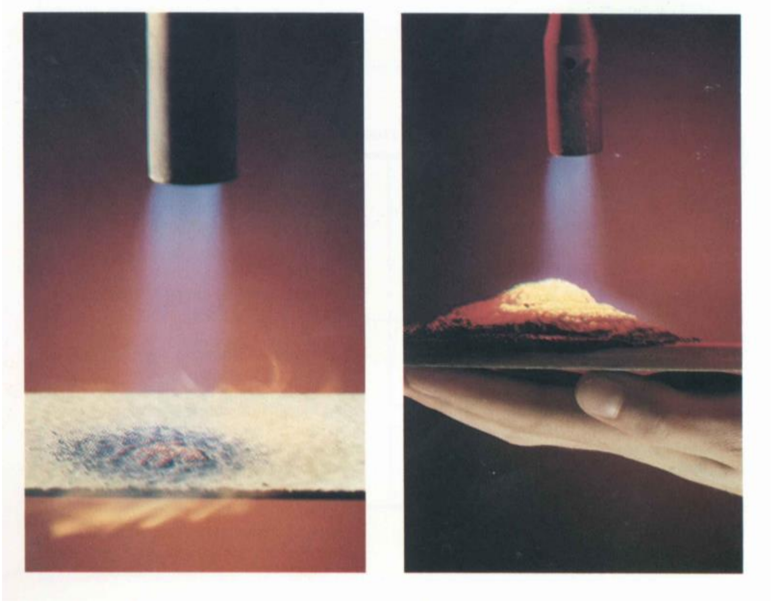
Hp/A Up to	Dry Thickness in mm to provide fire resistance of 1/2 hr	1 hr	1.5 hr	2 hr	3 hr	4 hr
30	10	10	14	18	26	35
50	10	12	17	22	33	43
70	10	13	19	25	37	48
90	10	14	21	27	39	52
110	10	15	22	28	41	54
130	10	16	22	29	42	56
150	10	16	23	30	44	57
170	10	16	23		44	



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

Fire protection





Consequence of design based on material behaviour

Reinforced concrete structures are considered to possess inherent resistance to fire

Steel framed structures are considered to require protection against fire


Delft University Architecture
Faculty Building, May 2008
Concrete structures do fail in fire!
Gretzenbach, Switzerland (Nov, 2004)

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)

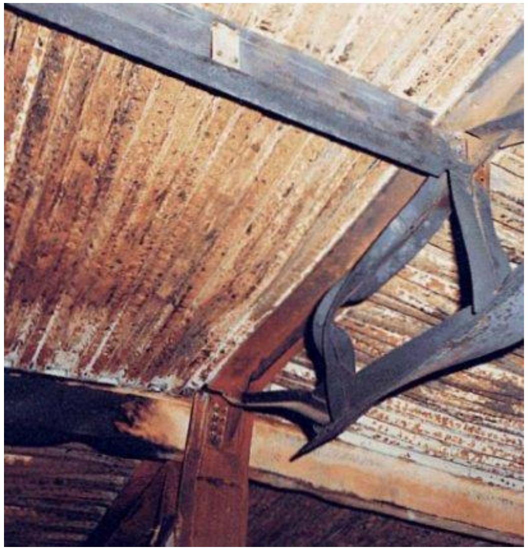
Broadgate Phase 8 fire (23 June'90)

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



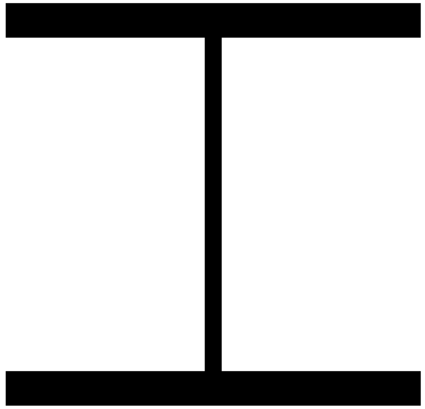
Source: *Stuctural fire Investigation of Broadgate Phase 8 fire* (SCI report), available from www.steelbiz.org

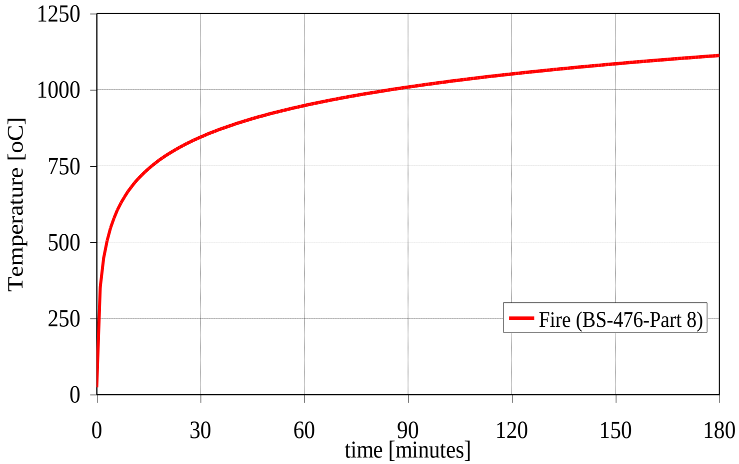
Aftermath of Broadgate fire

- 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

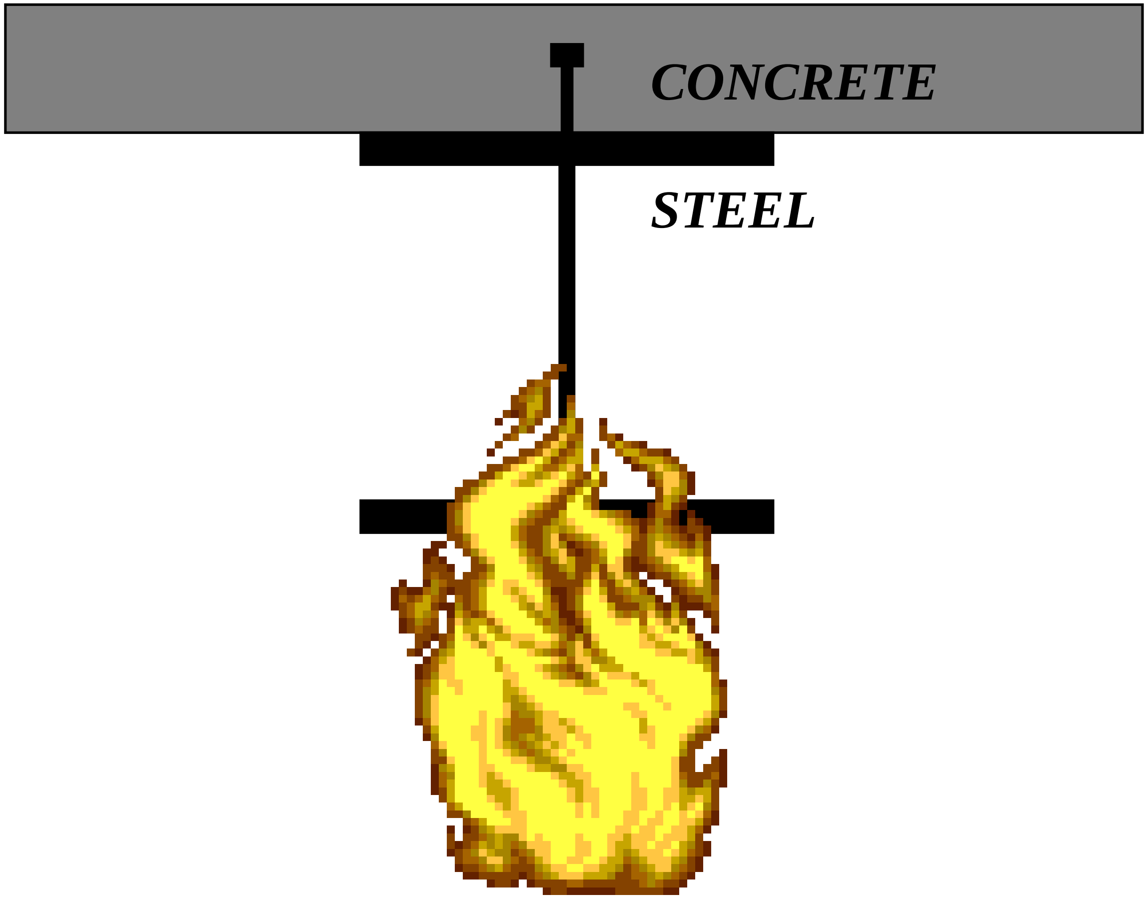
Isolated single structural member with simple boundary conditions (such as in a furnace)





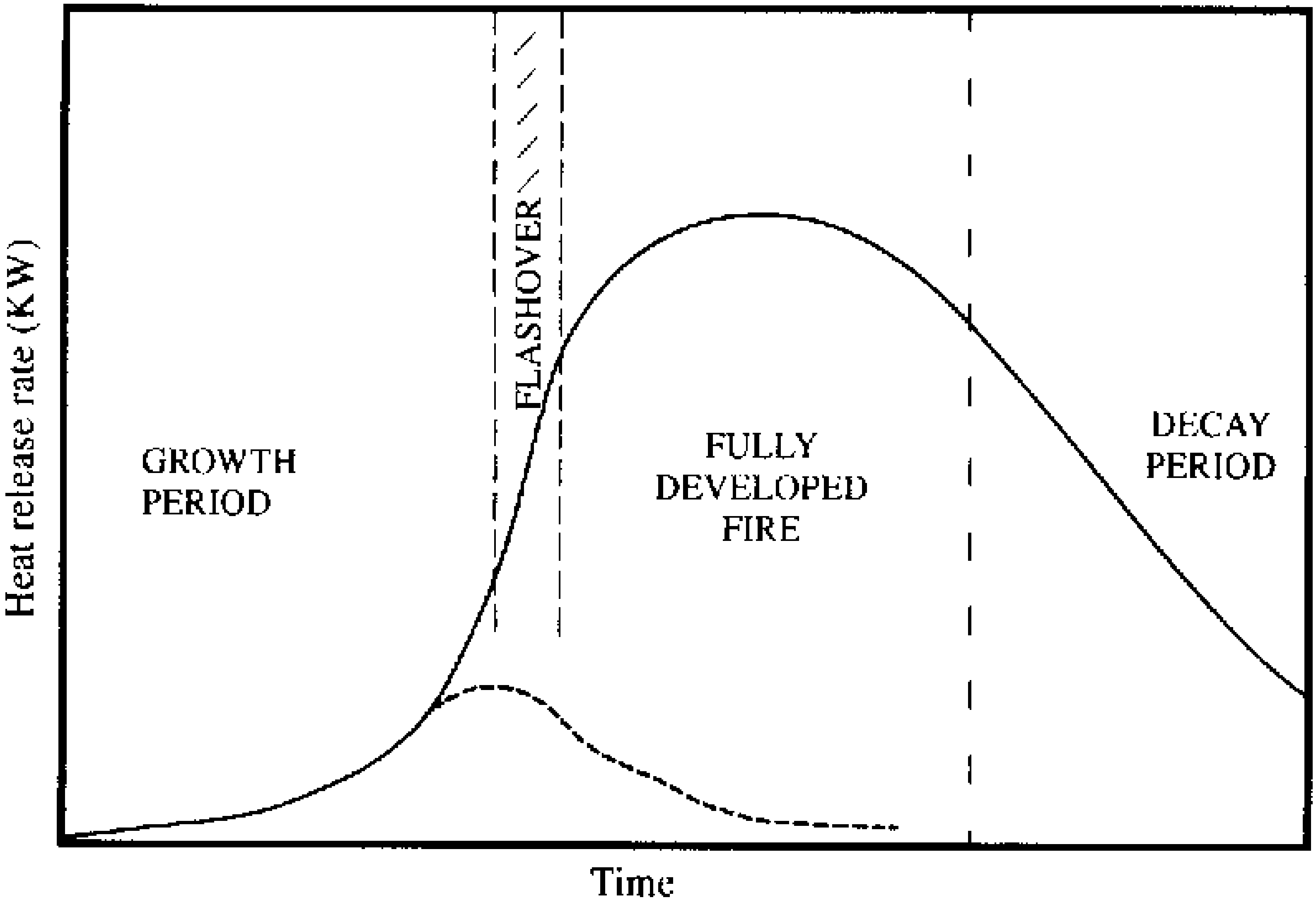
subjected to “standard” fire

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



subjected to “real” fire

Compartment fire behaviour



Play 3min flashover video

The Fully Developed Compartment Fires

Ventilation controlled fire. Fuel load, fibre insulation board, 7.5 kg/m^2

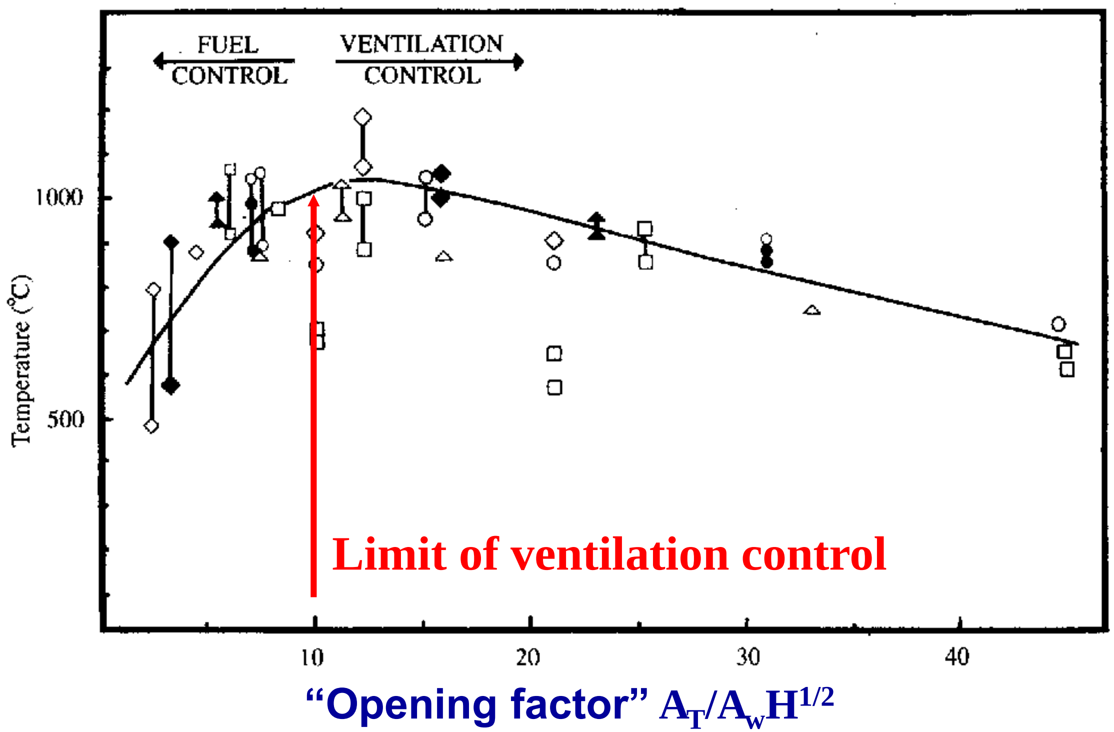
Fuel controlled fire. Fuel load, wood cribs, 15 kg/m^2

As the "burning" of 1 kg air releases 3 MJ of energy, in the post-flashover fire, the rate of heat release (RHR) in the compartment is:

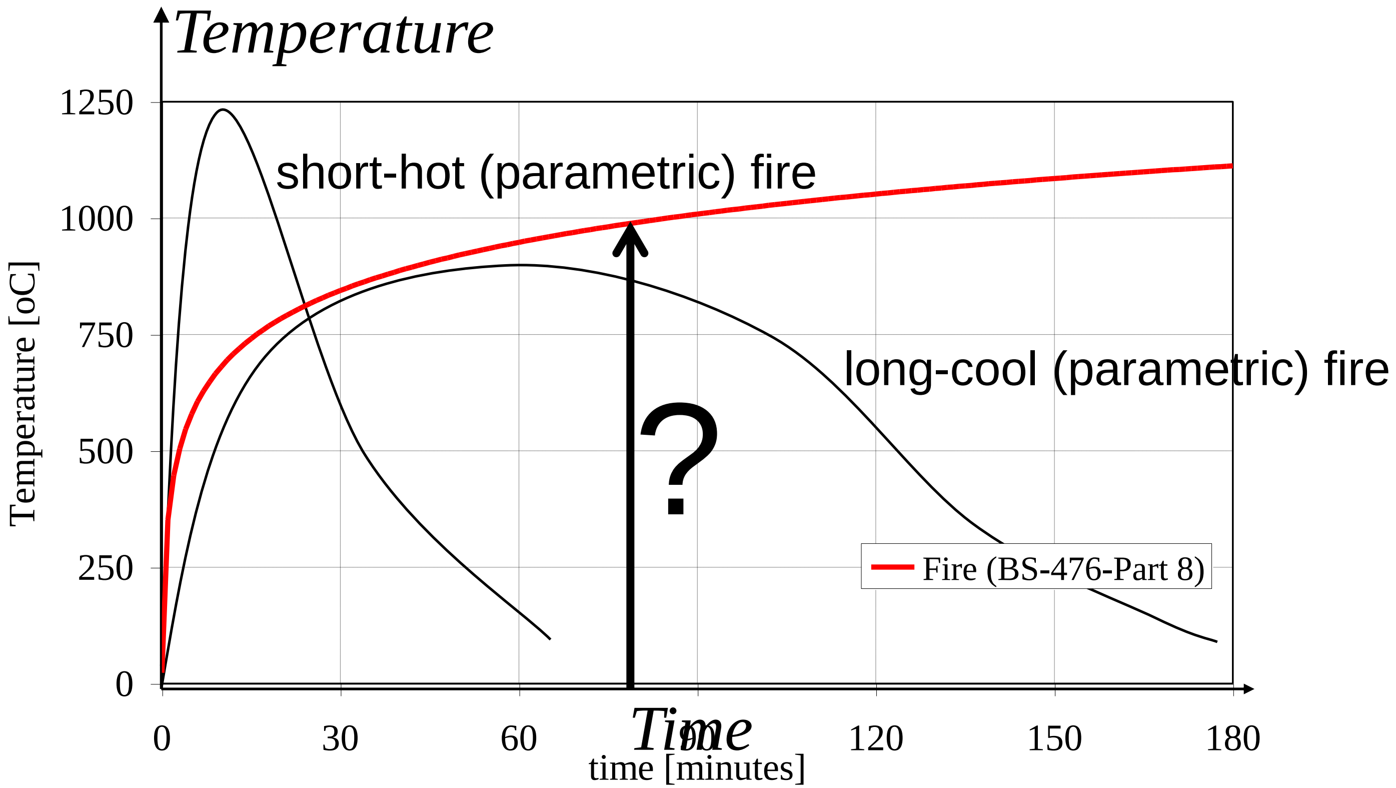
$$\mathrm{RHR} \approx 3 \times 0.52 A_w \sqrt{H} \ \ \mathrm{MW}$$

The Fully Developed Fire

Experimental data shows that the ventilation controlled fire is the most "severe" if judged by the maximum temperatures

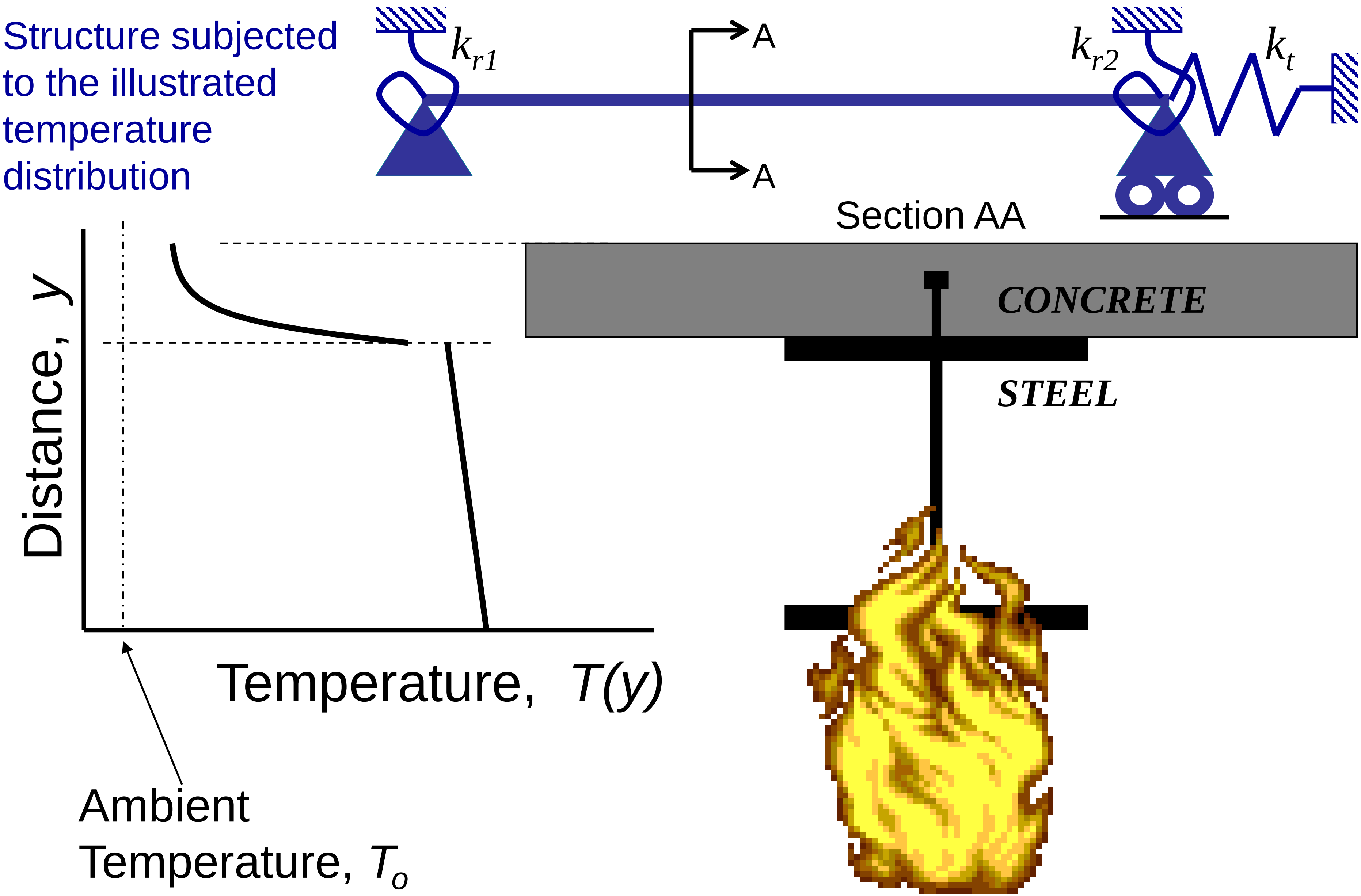


Natural fires in a compartment

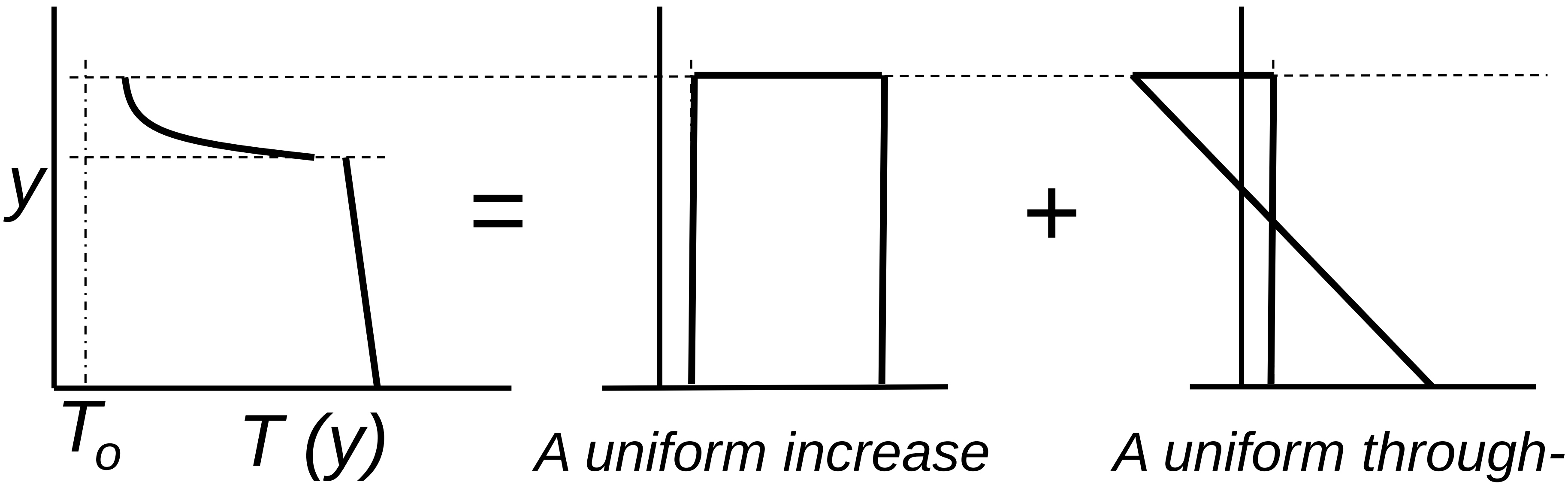


Simplest "realistic" model of composite beam

Structure subjected to the illustrated temperature distribution



Decompose temperature into simpler effects



A uniform increase In Temperature ΔT

A uniform through-depth thermal gradient $T_{,y}$

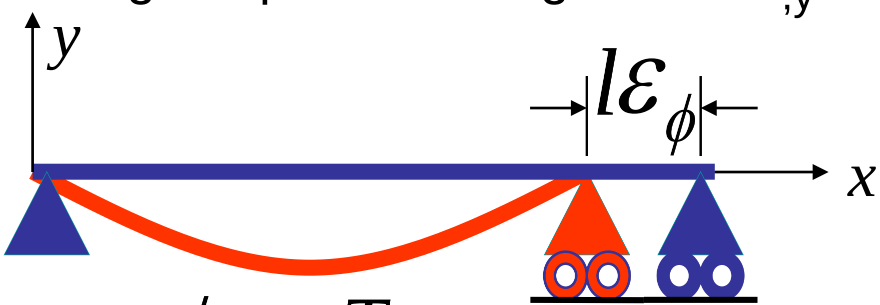
Governing parameters

Thermal expansion induced by mean temperature increment ΔT

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

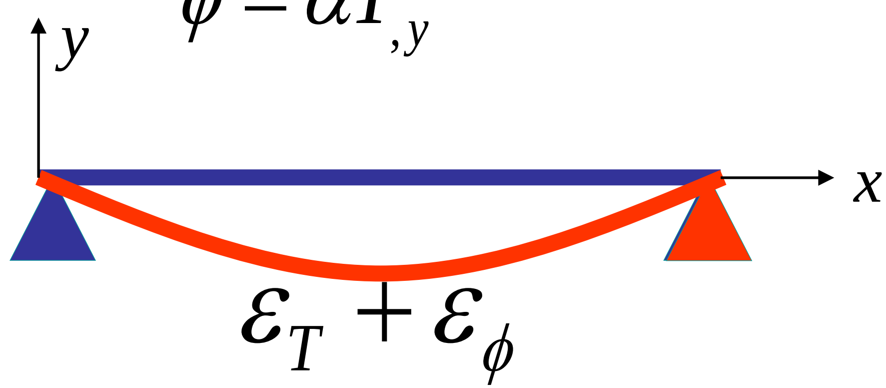
Thermal curvature f induced by through depth thermal gradient $T_{,y}$

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

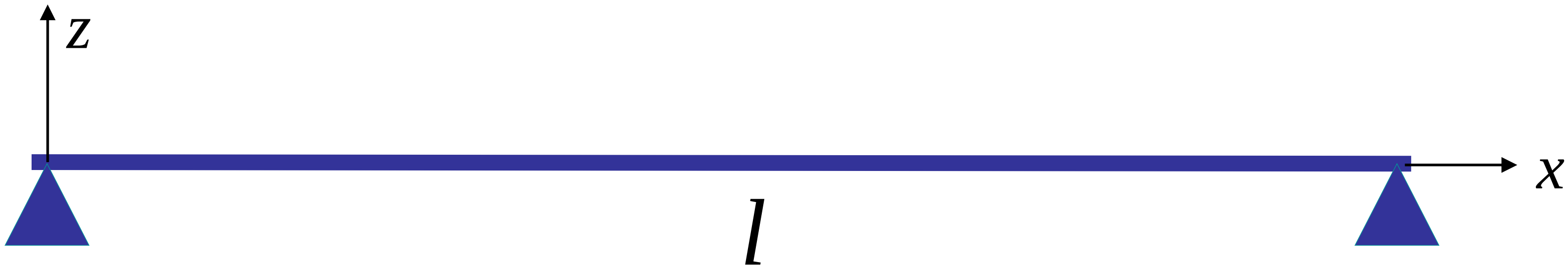


$$\phi = \alpha T_{,y}$$

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

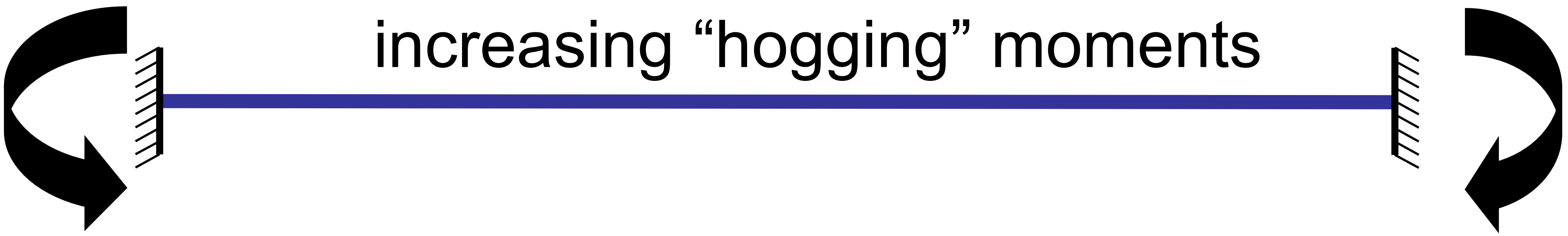
Uniform temperature increase in restrained beam

Compressive forces build up

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)

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

$$\varepsilon_\phi = 1 - \frac{\sin \left. l\phi \middle/ 2 \right.}{\left. l\phi \middle/ 2 \right.}$$

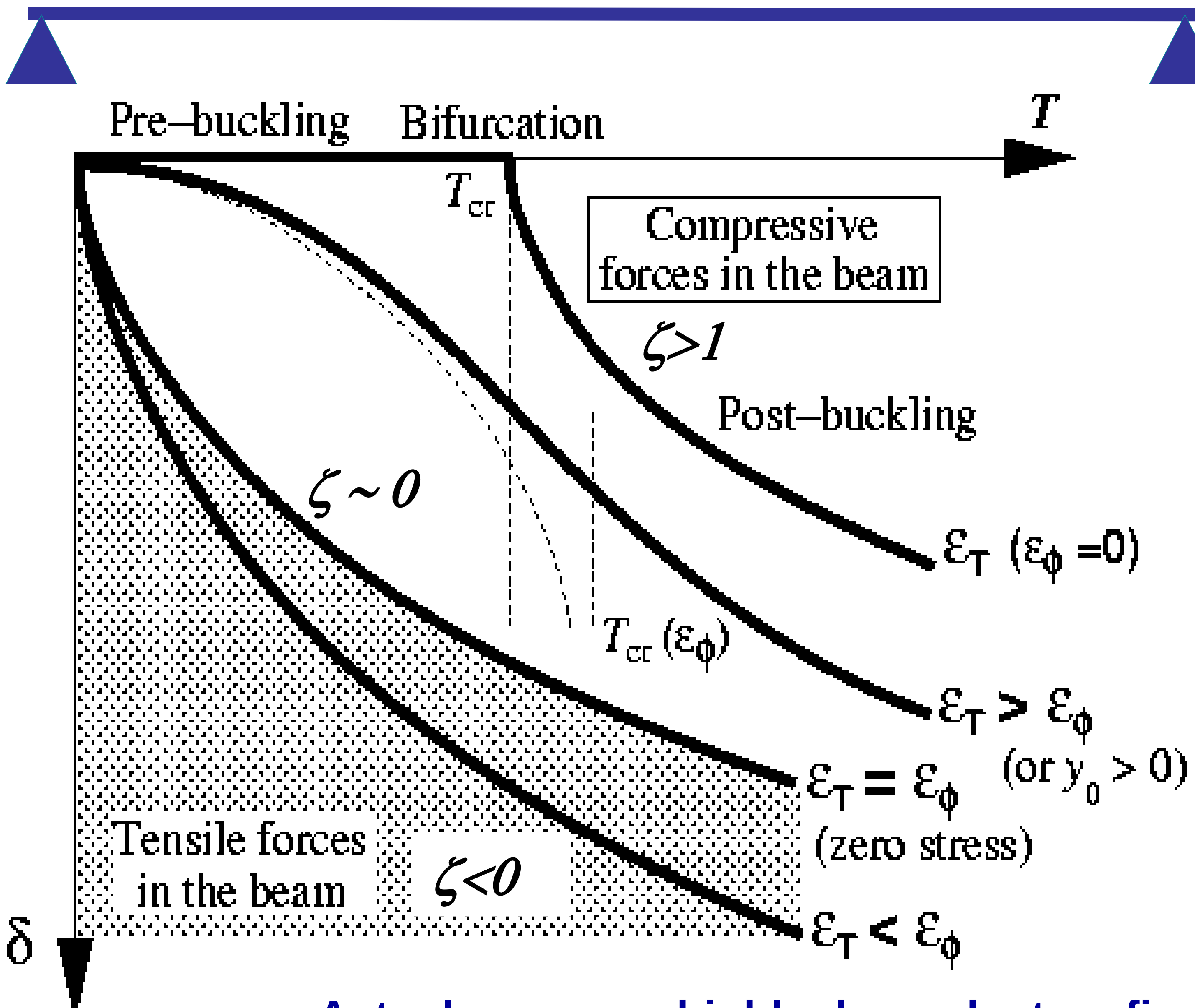
$$\varepsilon_{buckling} = \left. \pi^2 \middle/ \lambda^2 \right.$$

λ is slenderness ratio

$$\zeta = \frac{\varepsilon_T - \varepsilon_\phi}{\left. \pi^2 \middle/ \lambda^2 \right.}$$

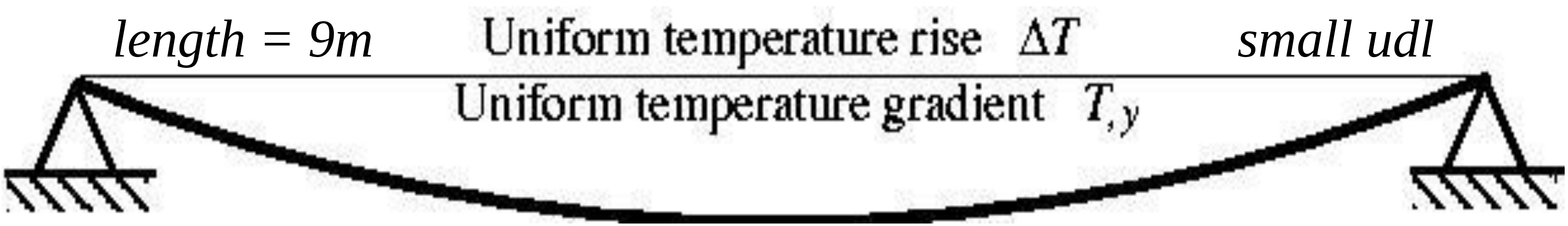
dimensionless parameter

Temperature-deflection of a restrained beam



Actual response highly dependent on fire history!

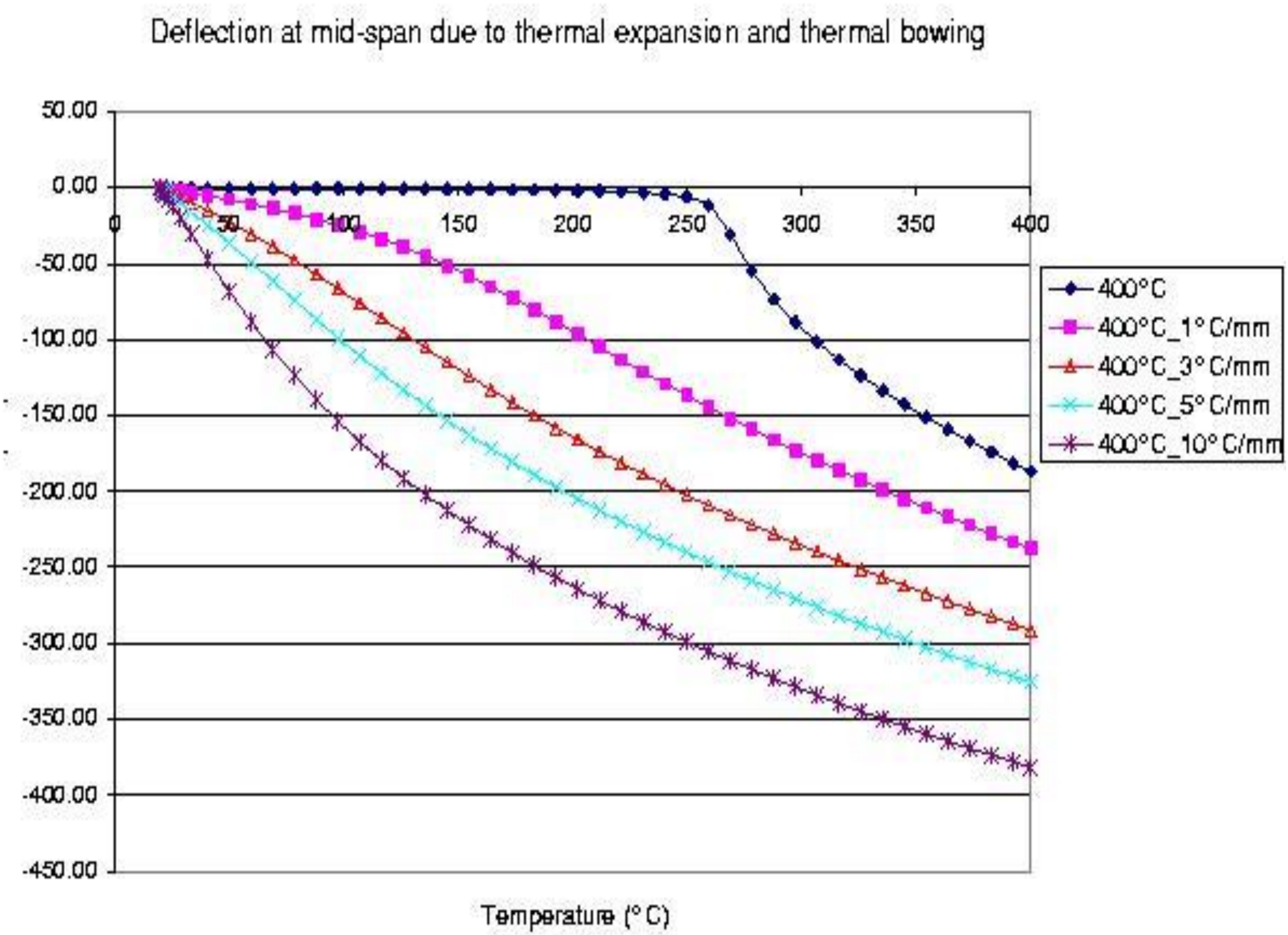
Verification of theory using an FE model



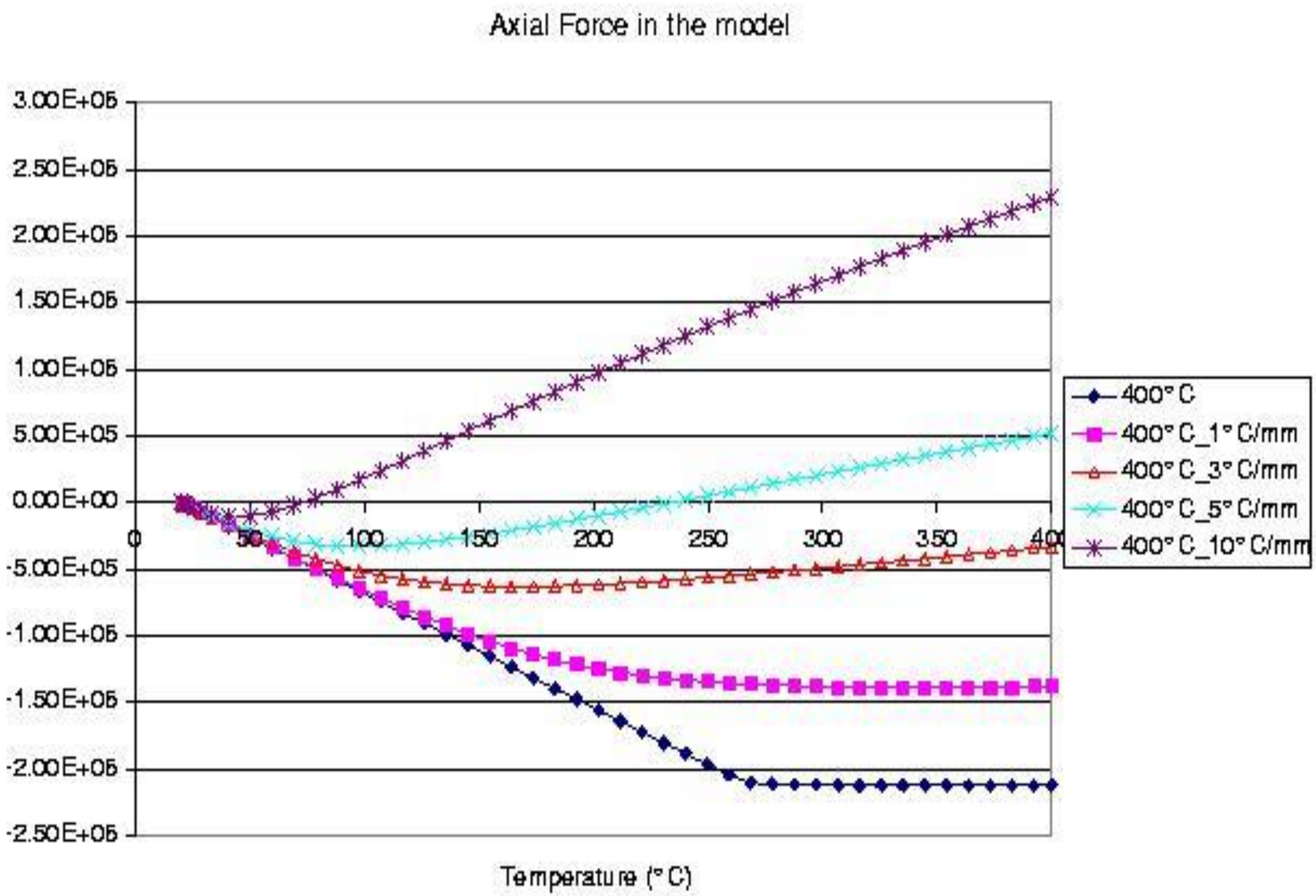
Subjected to the following five temperature and thermal gradient combinations

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

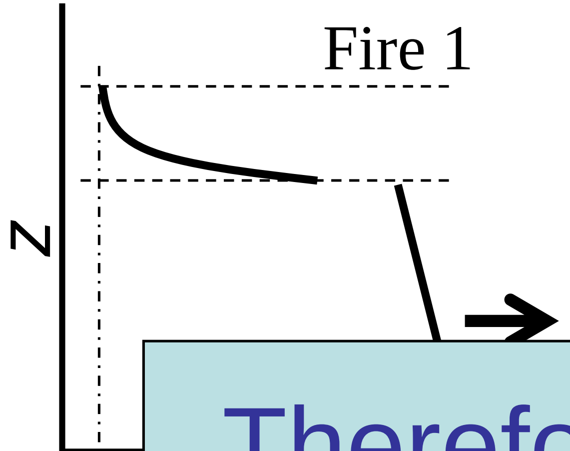
Deflection at midspan of beam



Axial forces in the beam



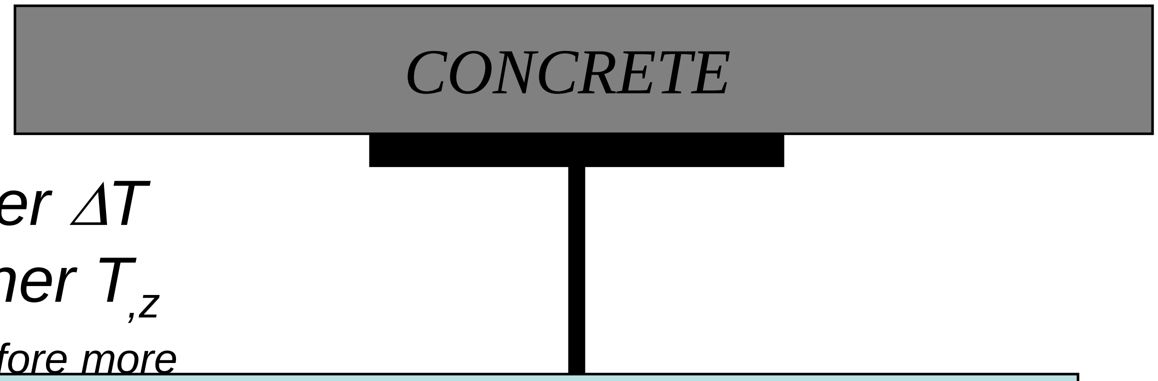
Effect of fire history on response



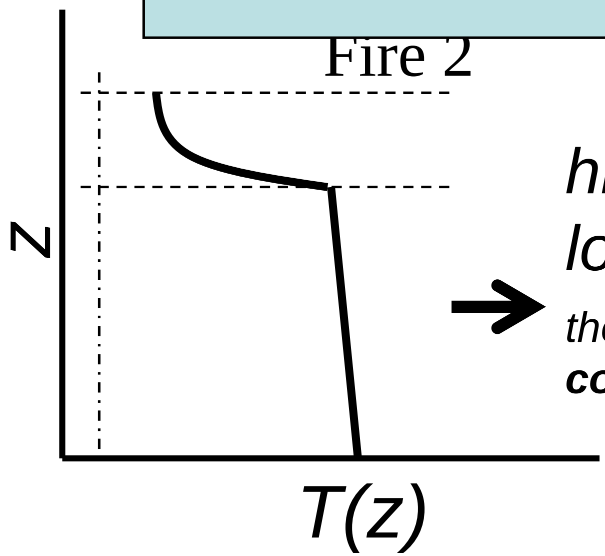
lower ΔT

higher $T_{,z}$

→ *therefore more*



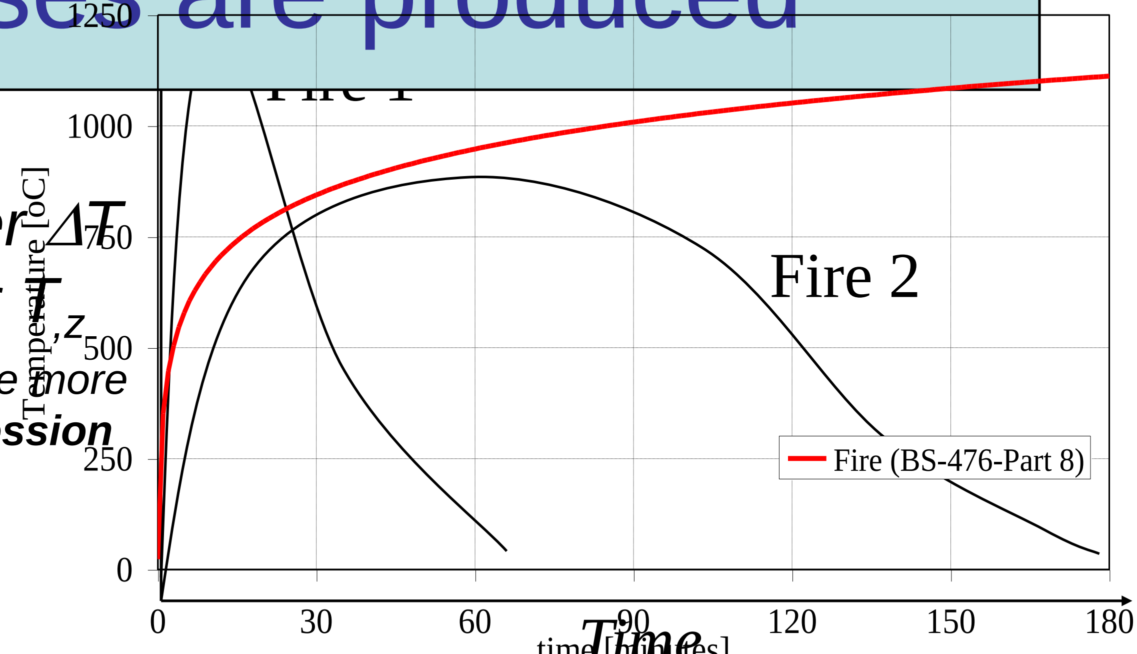
Therefore different mechanical responses are produced



higher ΔT

lower $T_{,z}$

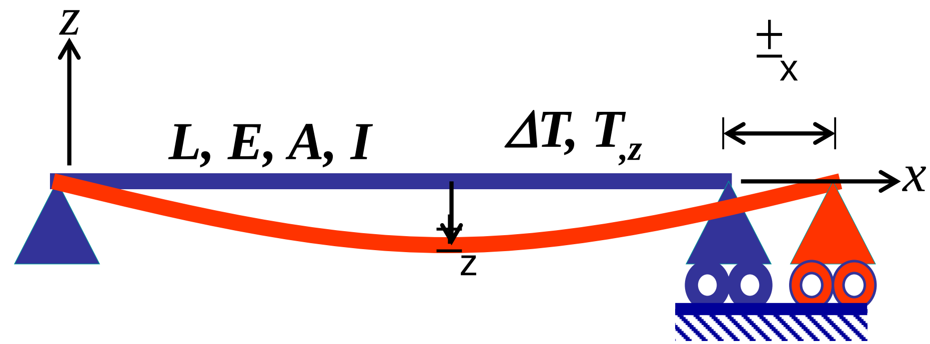
→ *therefore more* ***compression***



Analytical solutions for simple cases

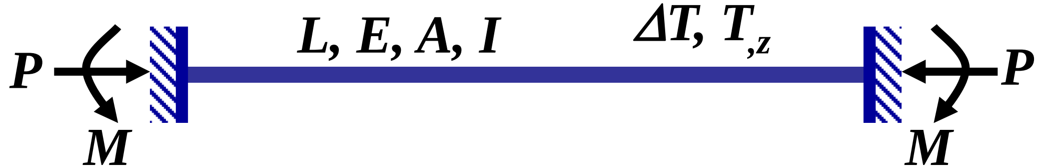
$$\pm_z = \pm_{circ}(^2{}_Á) \; ¼ \; \pm_{sin}(^2{}_Á)$$

$$\pm_x = (^2{}_T \; ¡ \; ^2{}_Á)l$$

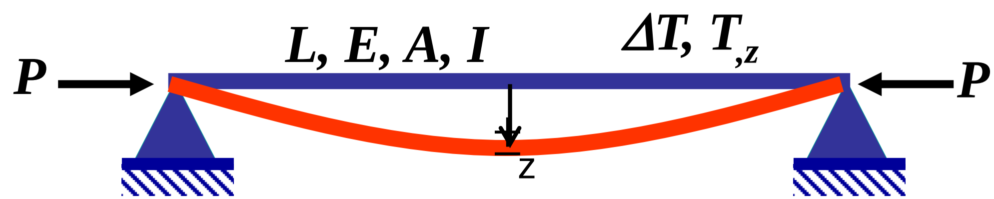


$$P = EA(^2{}_T \; ¡ \; ^2{}_Á)$$

$$M = EI Á$$



$$P = EA(^2{}_T \; ¡ \; ^2{}_Á)$$



Deflections assuming $^2{}_T > ^2{}_Á$

Pre-buckling deflections

$$\pm_z = \pm_{circ}(^2{}_Á) + \frac{C \pm_{circ}(^2{}_Á)}{1 \; ¡ \; C}$$ where, $$C = \frac{0{:}3183 l^2 A}{¼}(^2{}_T \; ¡ \; ^2{}_Á)$$

from thermal bowing   from P-δ moments

Post-buckling deflections

add to $\pm_z$ above a $\pm_{sin}(^2{}_p)$ calculation where, $$^2{}_p = ^2{}_T \; ¡ \; ^2{}_Á \; ¡ \; \frac{½}{_3 2}$$

Understanding real behaviour

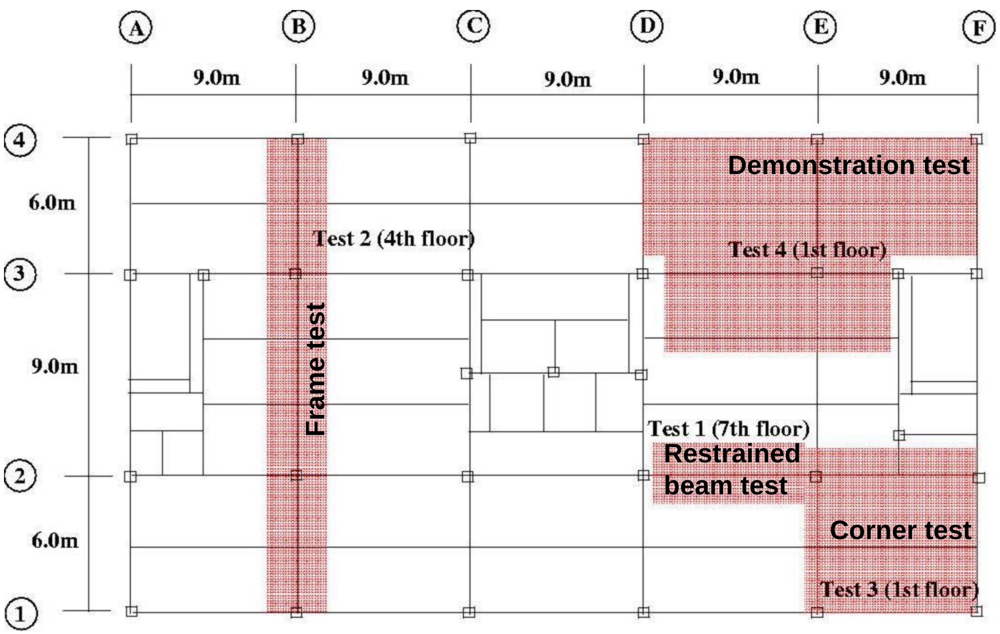
based on mechanics

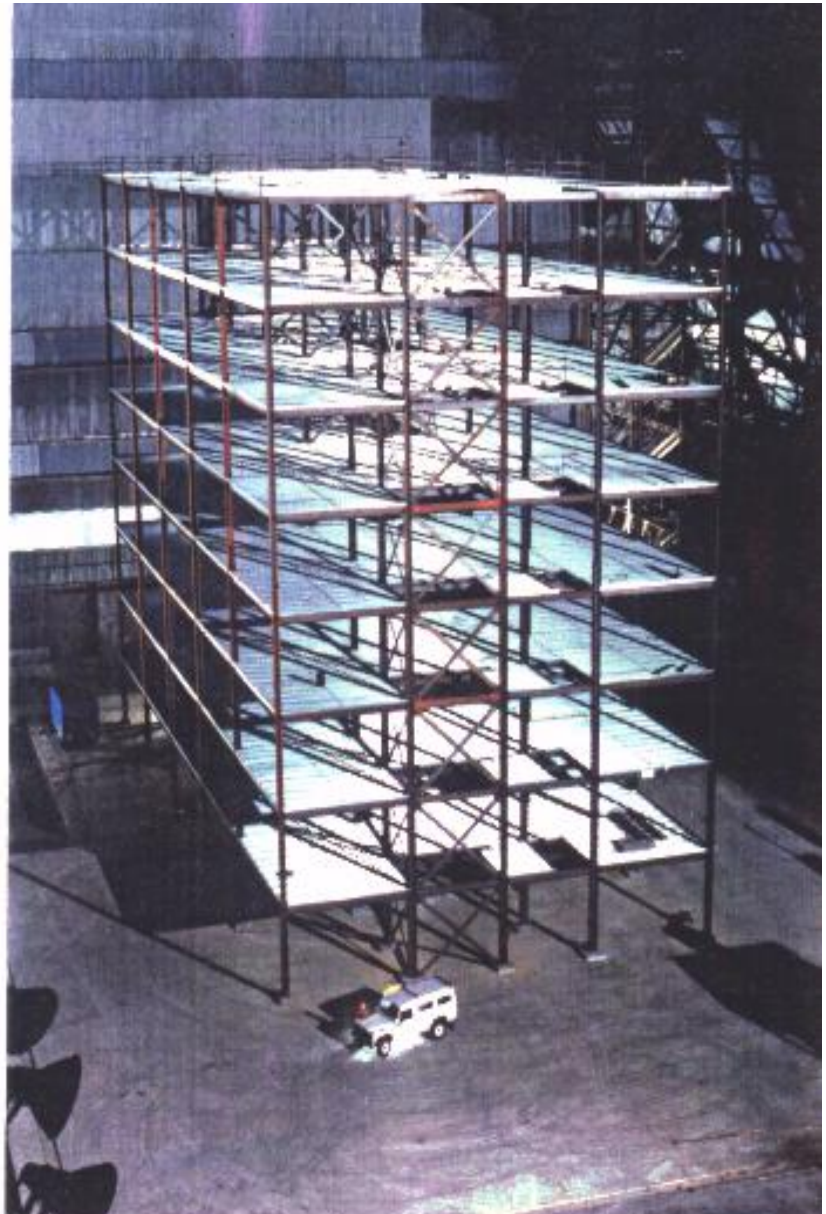
Cardington frame

8 Storey steel frame composite structure

2 tests by **BRE**

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

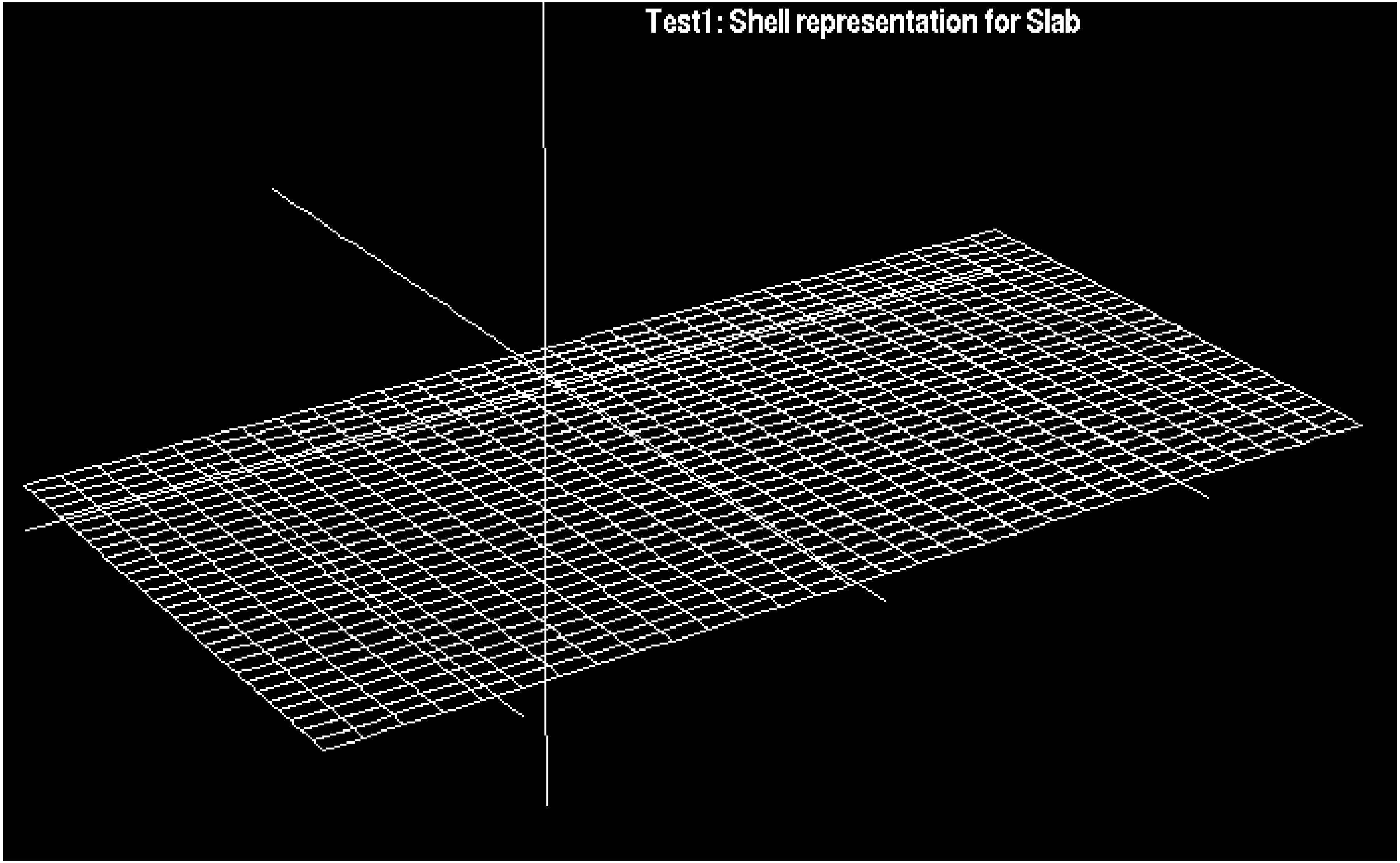




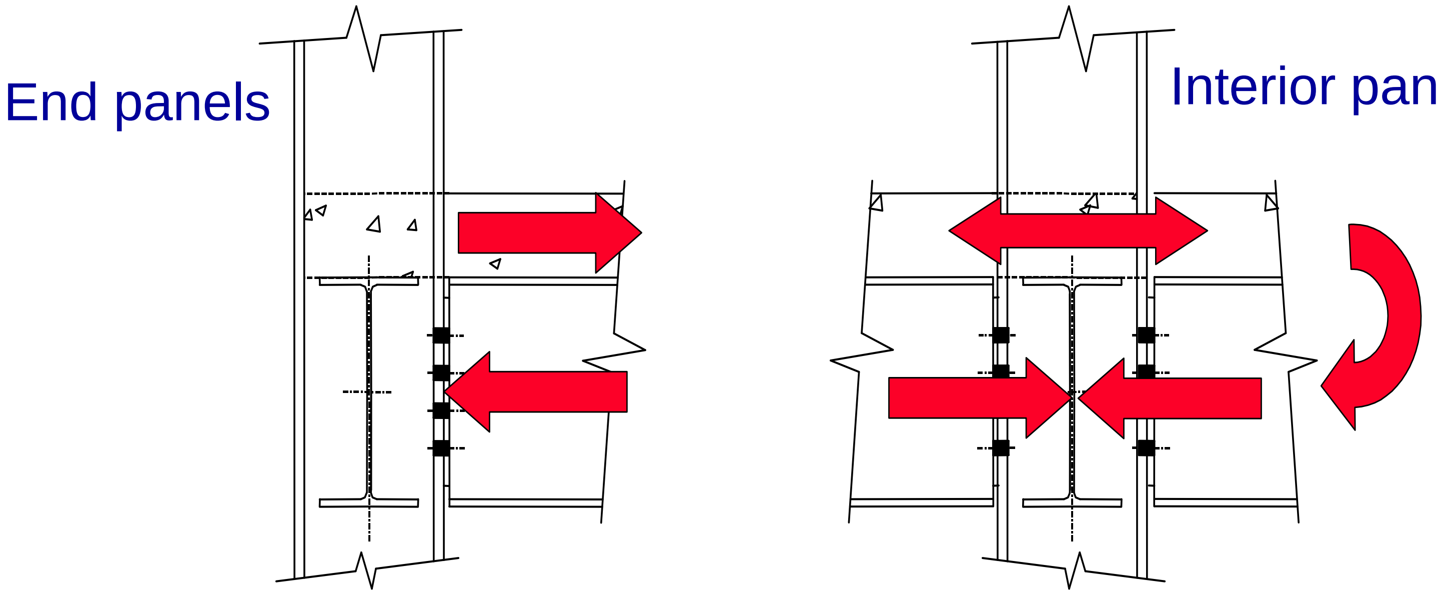
Download report from:
www.mace.manchester.ac.uk/project/research/structures/strucfire/DataBase/References/MultistoreySteelFramedBuildings.pdf

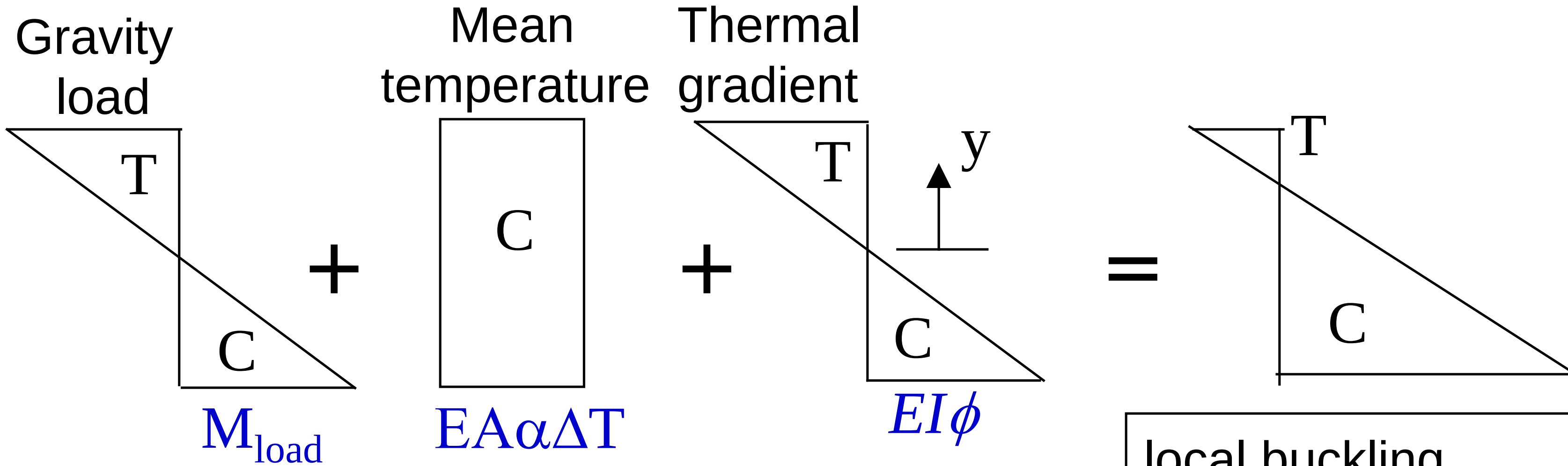
Cardington restrained beam test

FE model of restrained beam test



Composite beam end-restraint conditions

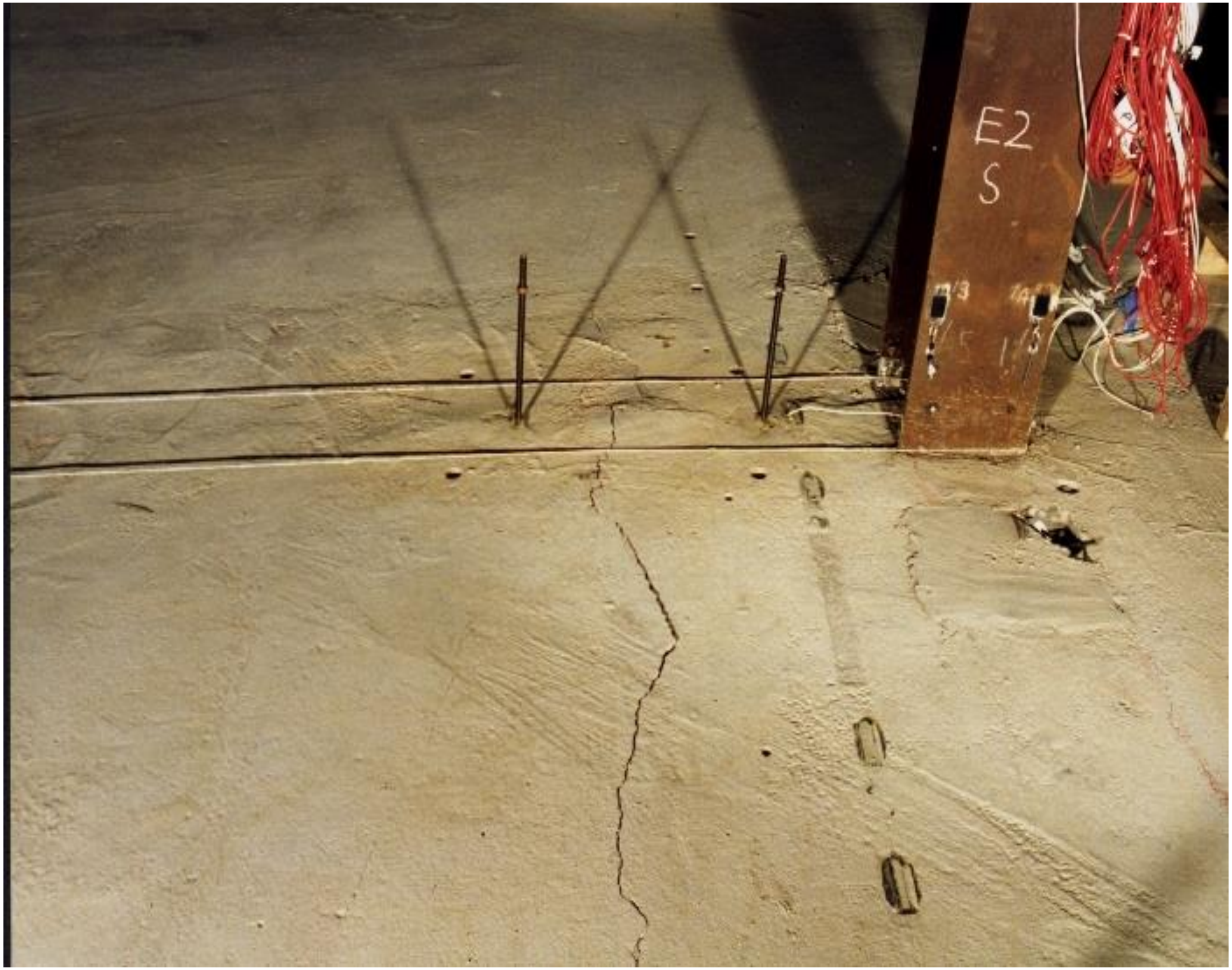




local buckling
beam bottom flange?

Local “buckling” in restrained beam test

Tension crack (restrained beam test)

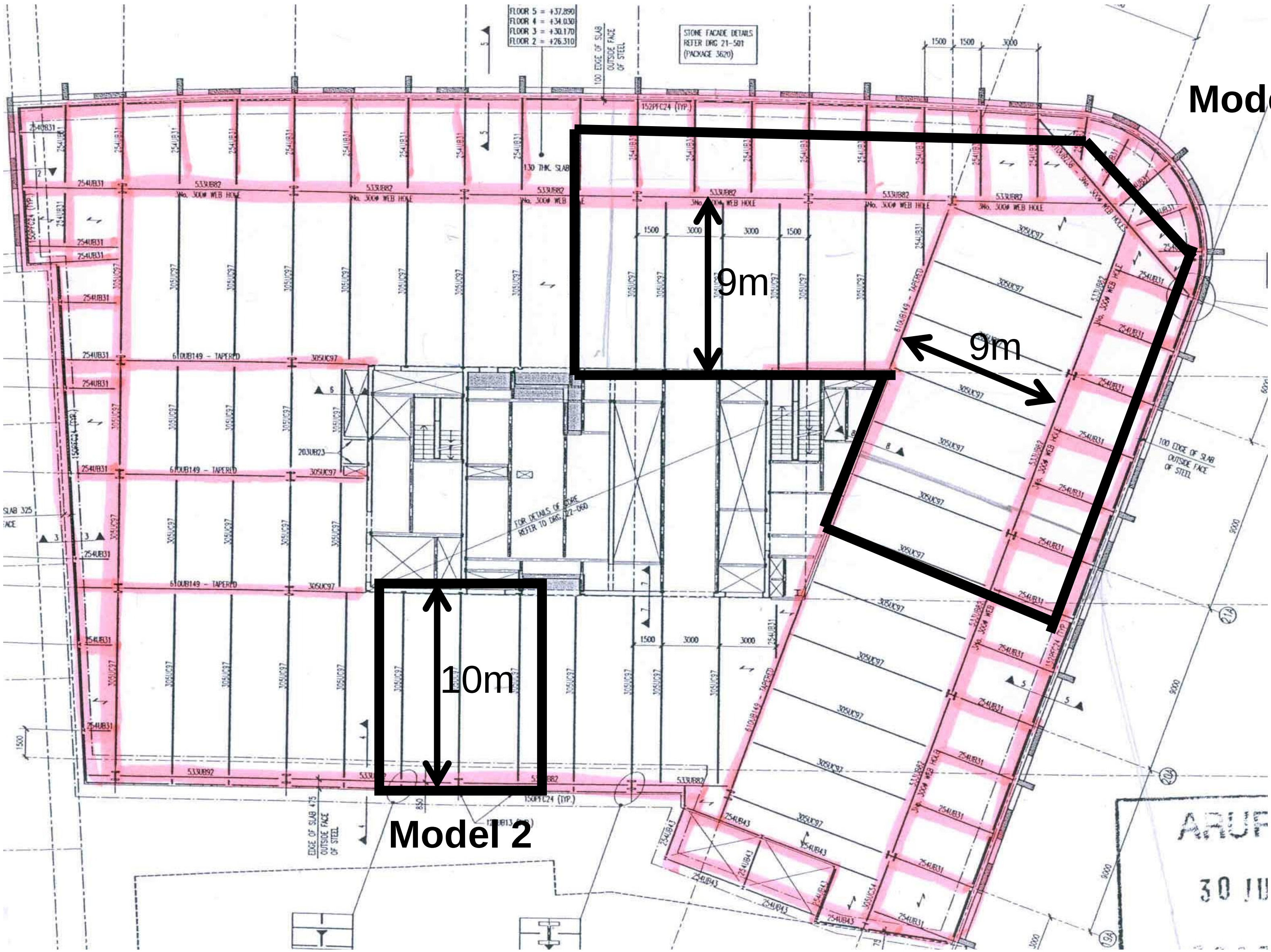


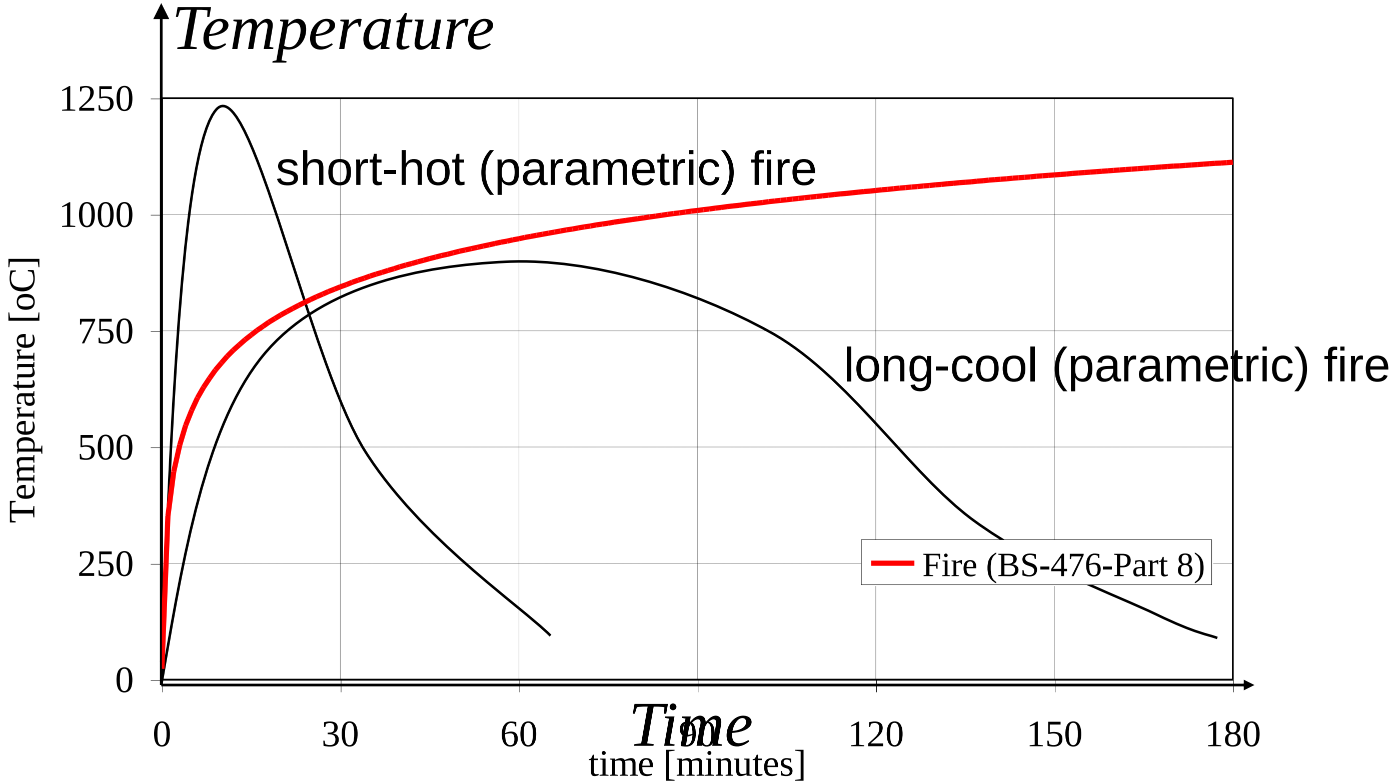
Local buckling (Corner Test)

Tensile rupture of connections in cooling

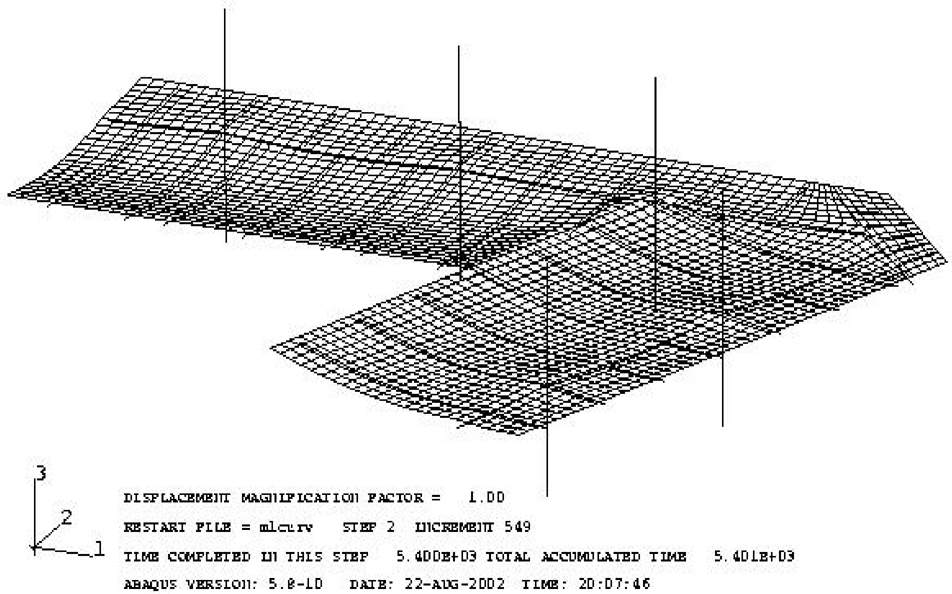
Plantation Place (Arup Fire)

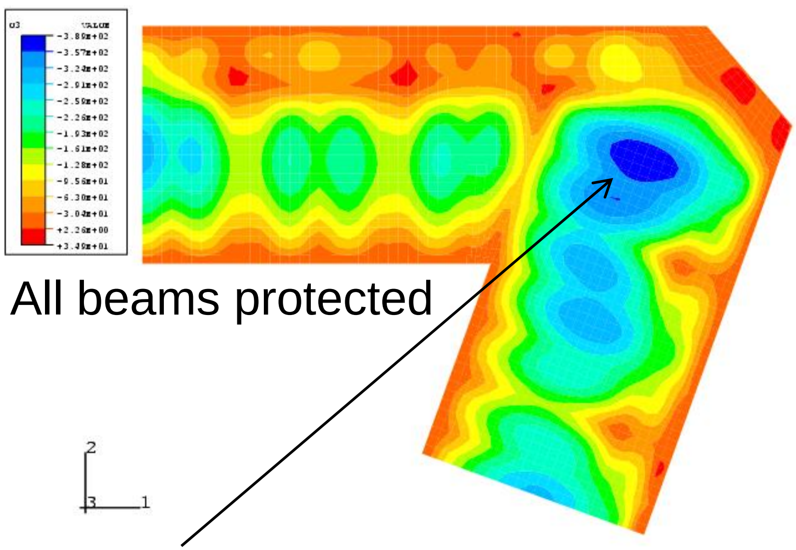
Two sub-structure models




Temperature
1250
1000
750
500
250
0
short-hot (parametric) fire
long-cool (parametric) fire
Fire (BS-476-Part 8)
Temperature [oC]
0
30
60
90
120
150
180
Time
time [minutes]

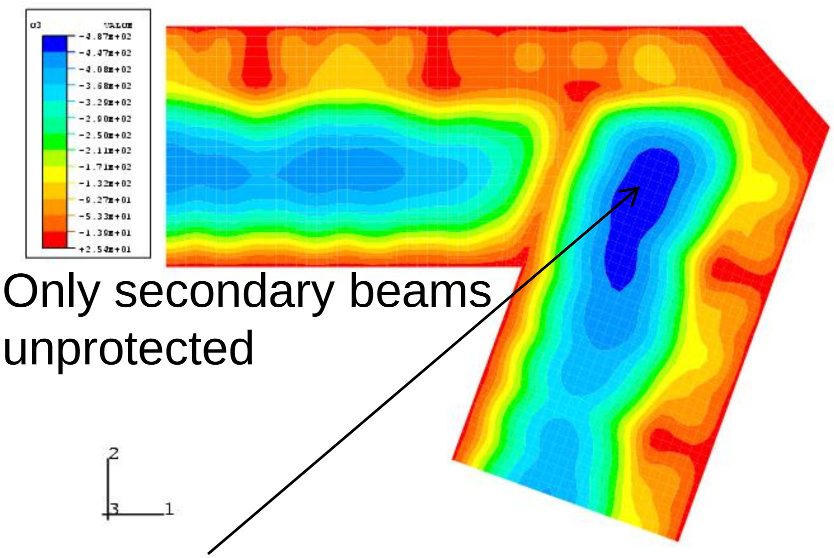
Results from Model 1





All beams protected

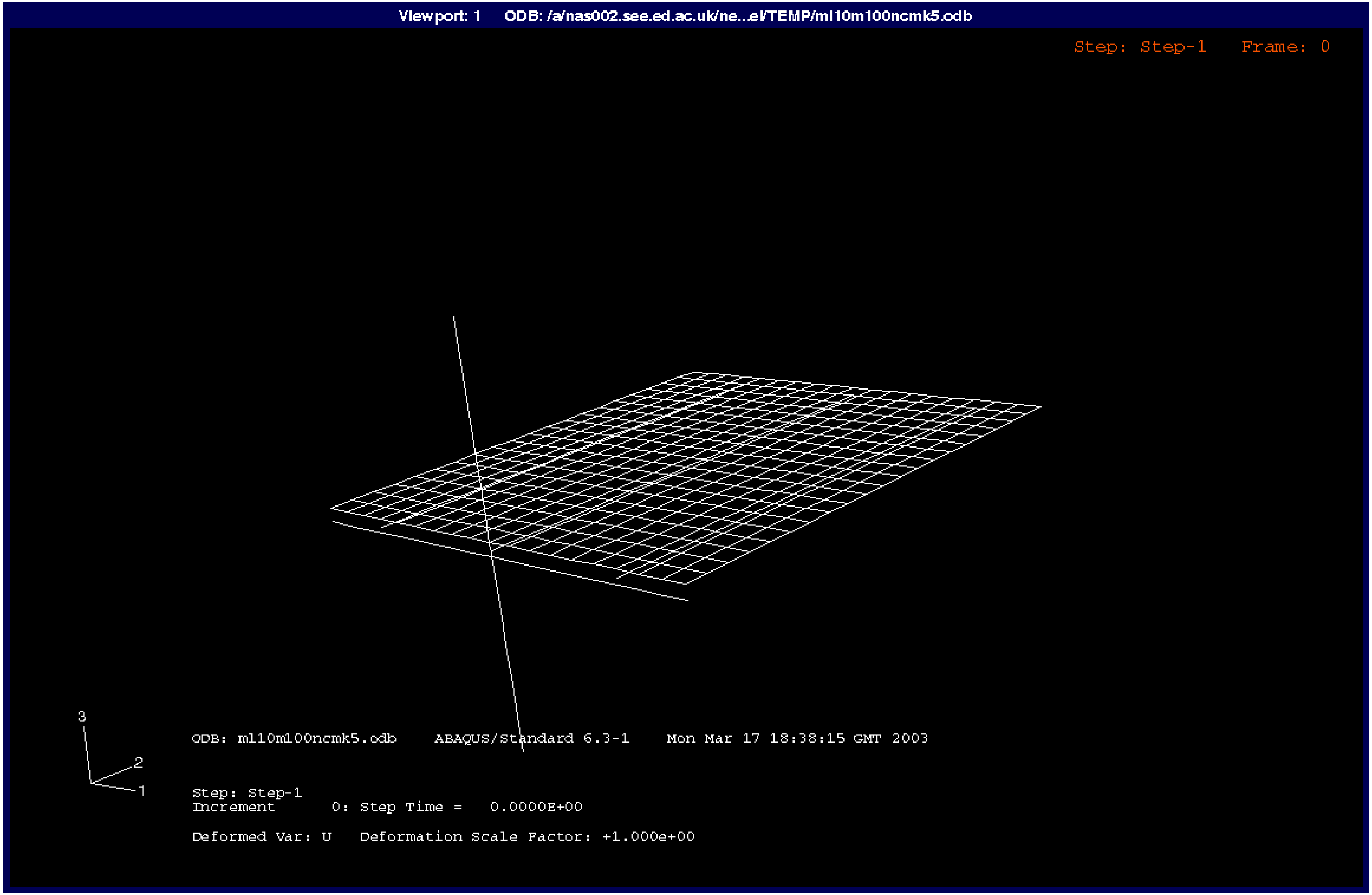
380mm max deflection



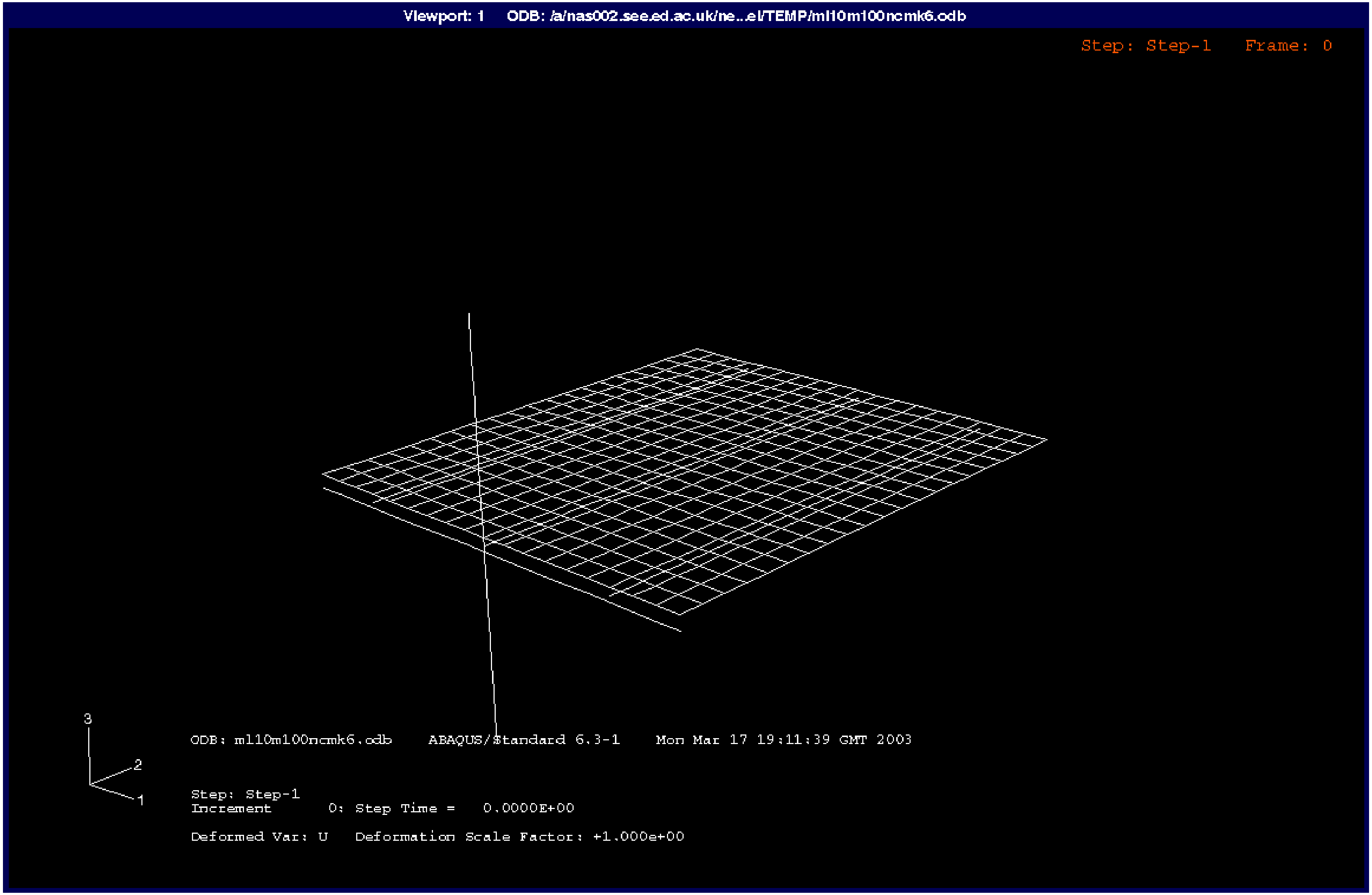
Only secondary beams unprotected

470mm max deflection

Unprotected 10m panel (Model 2)

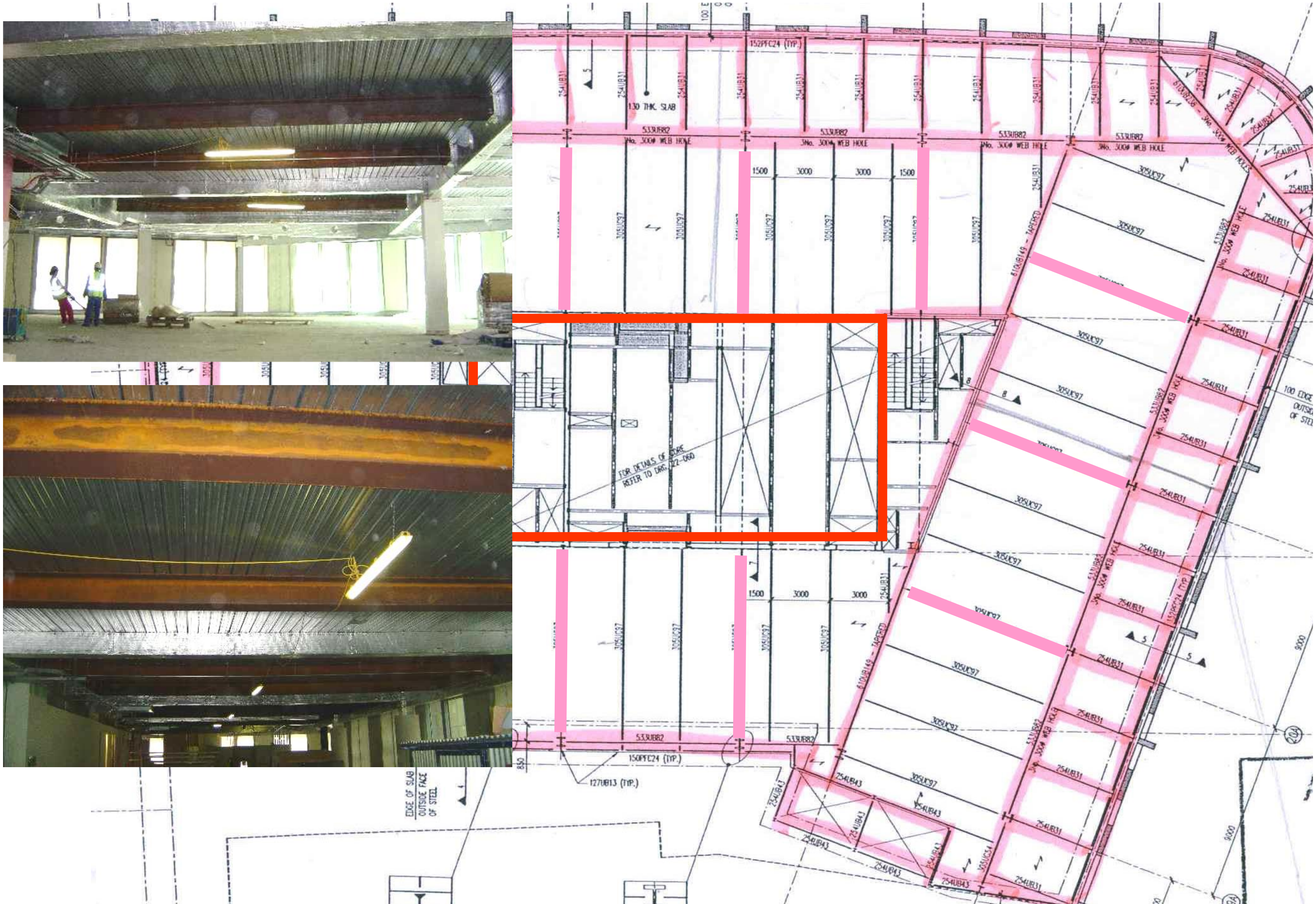


Protected 10m panel (Model 2)



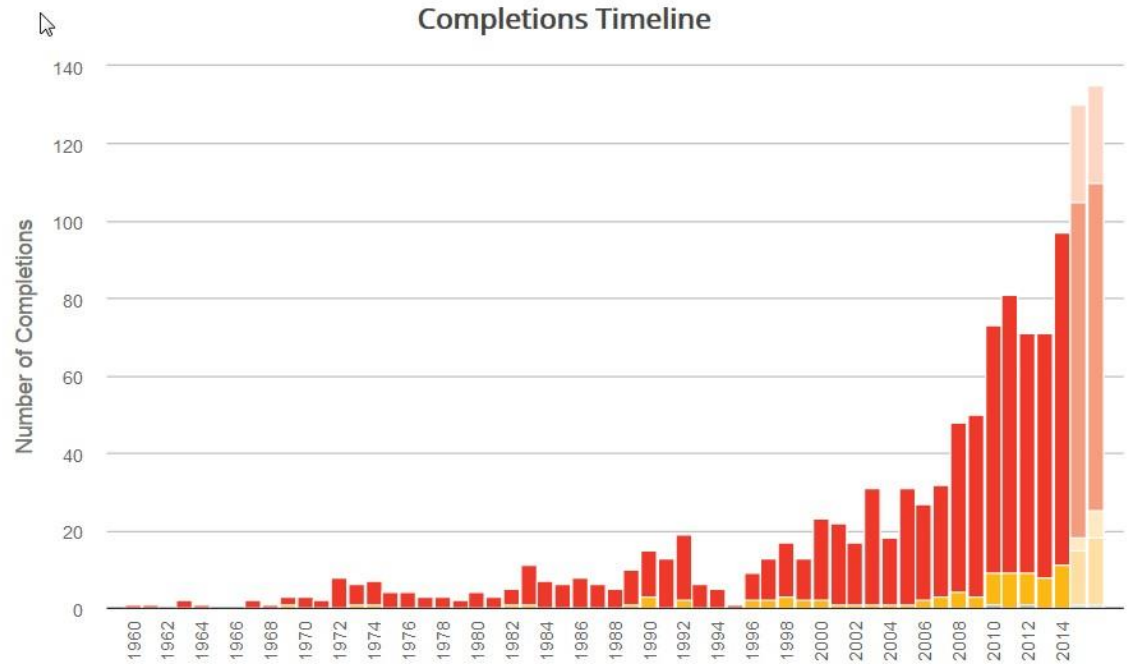
Final Proposal (accepted)

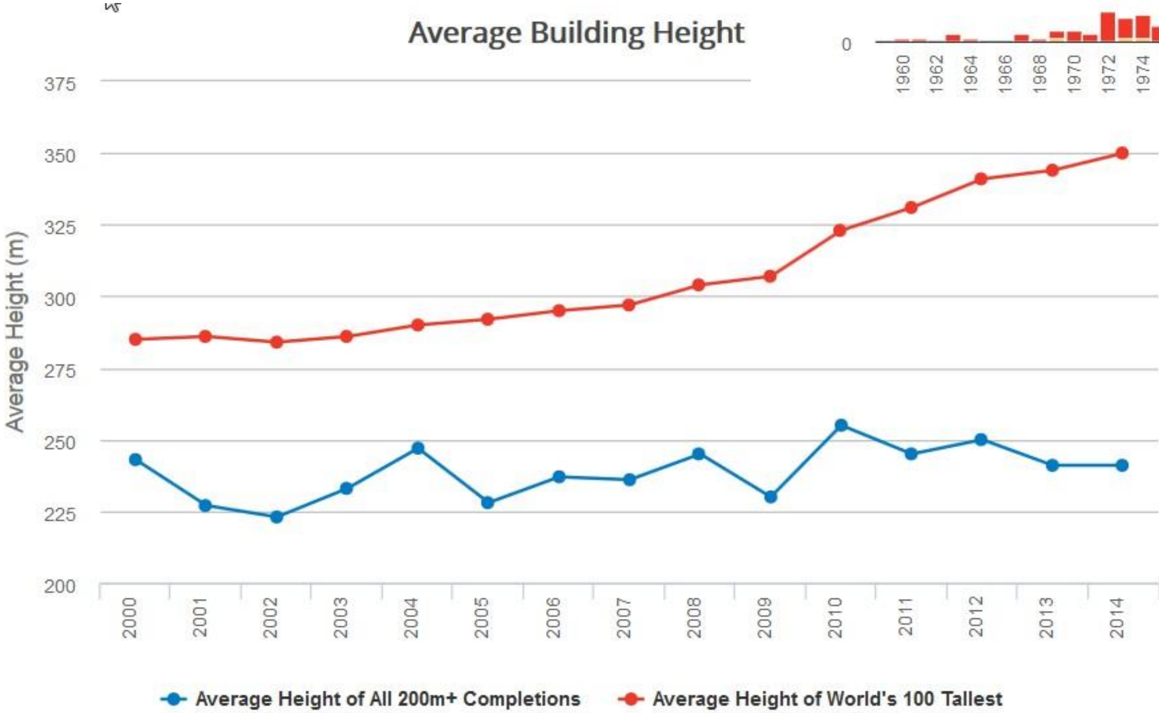
Saving of £250K on Plantation Place



Further complexity: buildings getting taller

All time record of 97 buildings of height > 200m completed in 2014



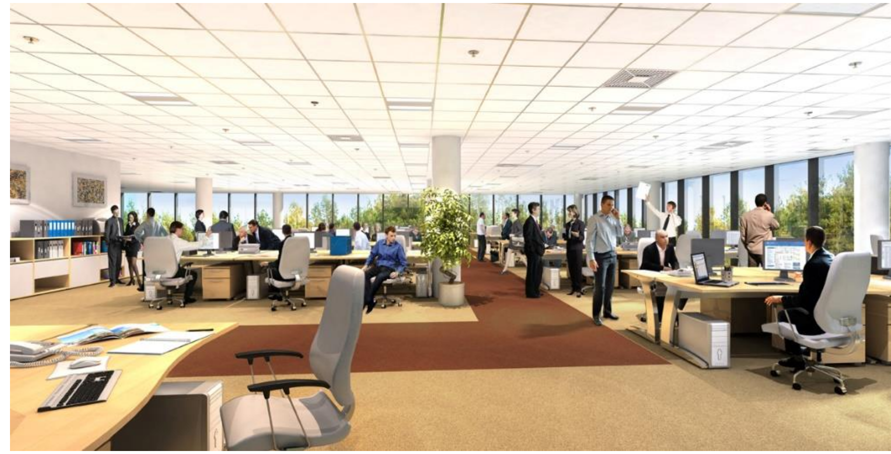


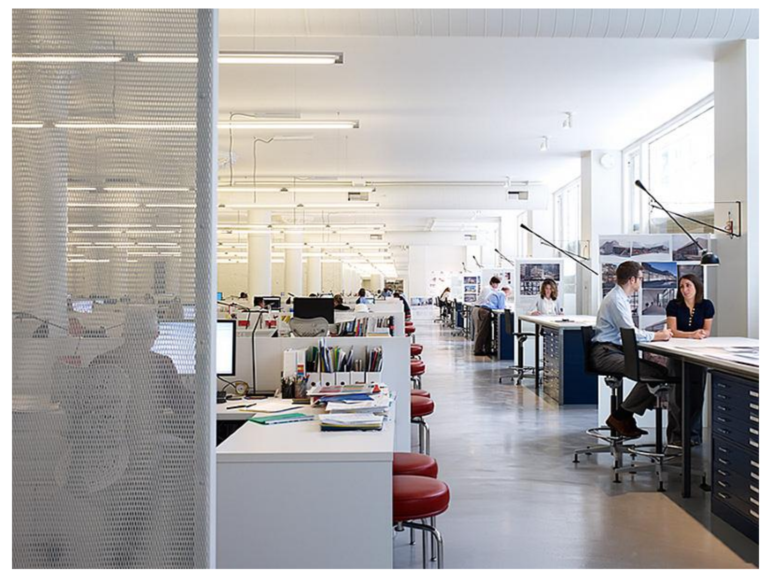
Since 2010, 46 supertalls have been completed, representing 54% of the supertalls that currently exist (85).

Source: CTBUH Database



What do they look like inside ?





Fires in tall buildings are not a rare a event

Building Name	Location	Floors	Pressurisation / Extraction	Smoke in Stair	Vertical Fire Spread	Structural Damage
Alexis Nihon Plaza	Montreal, Canada	15	No	Yes	Yes	Localised
Schomberg Plaza	New York, USA	35	Unknown	No	Yes	No
One Meridian Plaza	Philadelphia, USA	38	No	Yes	Yes	Localised
Interstate Bank Building	L.A., USA	62	Yes	Yes	Yes	Localised
New York City Bank Building	New York, USA	42	Yes	Yes	Yes	Localised
High Rise Office	Atlanta, USA	10	No	Yes	No	No
Clearwater Condominium	Clearwater, USA	11	No	Yes	No	No
Beach Channel Drive	New York, USA	13	Unknown	Unknown	No	No
Moshulu Parkway	New York, USA	41	Unknown	Unknown	Yes	No
Bedford Avenue	New York, USA	25	Unknown	Unknown	No	No
Grand Avenue	New York, USA	26	Unknown	Unknown	No	No
Shutter Avenue	New York, USA	22	Unknown	Unknown	No	No
WTC 1	New York, USA	110	No	N/A	No	Complete collapse
WTC 2	New York, USA	110	No	N/A	No	Complete collapse
WTC 7	New York, USA	47	Unknown	Unknown	No	Complete collapse

MGM Grand Hotel	Las Vegas, USA	21	Yes	Yes	No	Localised
Garley Office Building	Honk Kong	16	Unknown	No	Yes	No
Royal Jomtien Resort	Thailand	17	No	Yes	No	No
Windsor Tower	Madrid, Spain	32	Unknown	Yes	Yes	Partial Collapse
Parque Central East Tower	Caracas, Venezuela	56	No	Unknown	Yes	Localised
TVCC Tower	Beijing, China	44	Unknown	Unknown	Yes	Unknown
Four Leaf Tower Condominium	Houston, USA	41	Yes	Yes	Yes	No
Westin Hotel	Boston, USA	38	Yes	Yes	No	No
Apartment Block	Missouri, USA	27	Unknown	Unknown	No	No
Great Thornton St	Hull, UK	15	Unknown	Unknown	No	No
Montrose Avenue	New York, USA	16	Unknown	Unknown	No	No
La Frak City Apartments	New York, USA	16	Unknown	Unknown	No	No
Park Avenue, Bronx	New York, USA	20	Unknown	Unknown	No	No
Beach Channel Drive	New York, USA	13	Unknown	Unknown	No	No
Lincoln Place	New York, USA	42	Unknown	Unknown	No	No

50 tall building fires surveyed

Oldest completed in 1924

Majority of the fires occurred in the last 20 years

Cowlard, Bittern, Abecassis-Empis and Torero, Procedia Engineering (2013)


鑫兴快餐
鑫兴快餐

@中国网络资讯台

Shanghai 28 storey building fire (2010) – 58 killed!

"Shanghai jiaozhou road fire" by monkeyking (Peijin Chen).

Collapse of WTC 7

Why are tall building fires different?

Taller buildings	→	Multiple-floor fires
More adventurous architecture	→	Complex structural response
Open plans offices	→	Non-uniform “travelling” fires
Larger number of occupants	→	Extended evacuation times
City centre locations	→	Delays in emergency response

↓

Significantly increased risk
(probability x consequence)

NO CURRENT REQUIREMENT FOR TREATING TALL BUILDINGS DIFFERENTLY

Except that usually higher fire resistance times are specified

or

the recommendation to use

PERFORMANCE-BASED DESIGN (or P-B ENGINEERING)

Fire tends to travel in large spaces

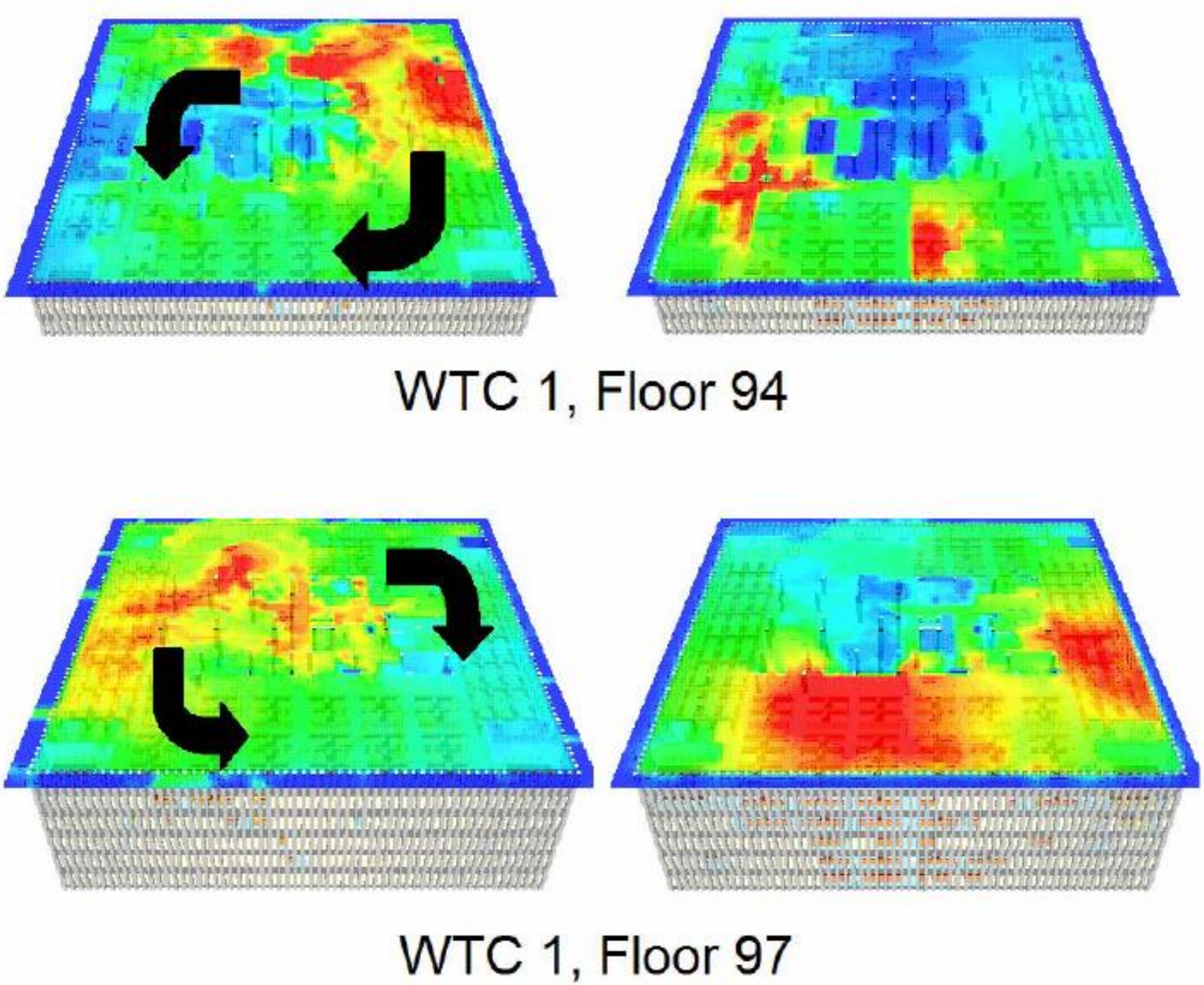


Figure 6–29. Direction of simulated fire movement on floors 94 and 97 of WTC 1.

Source:
NIST NCSTAR 1-5

NIST recommendation in WTC investigation reports

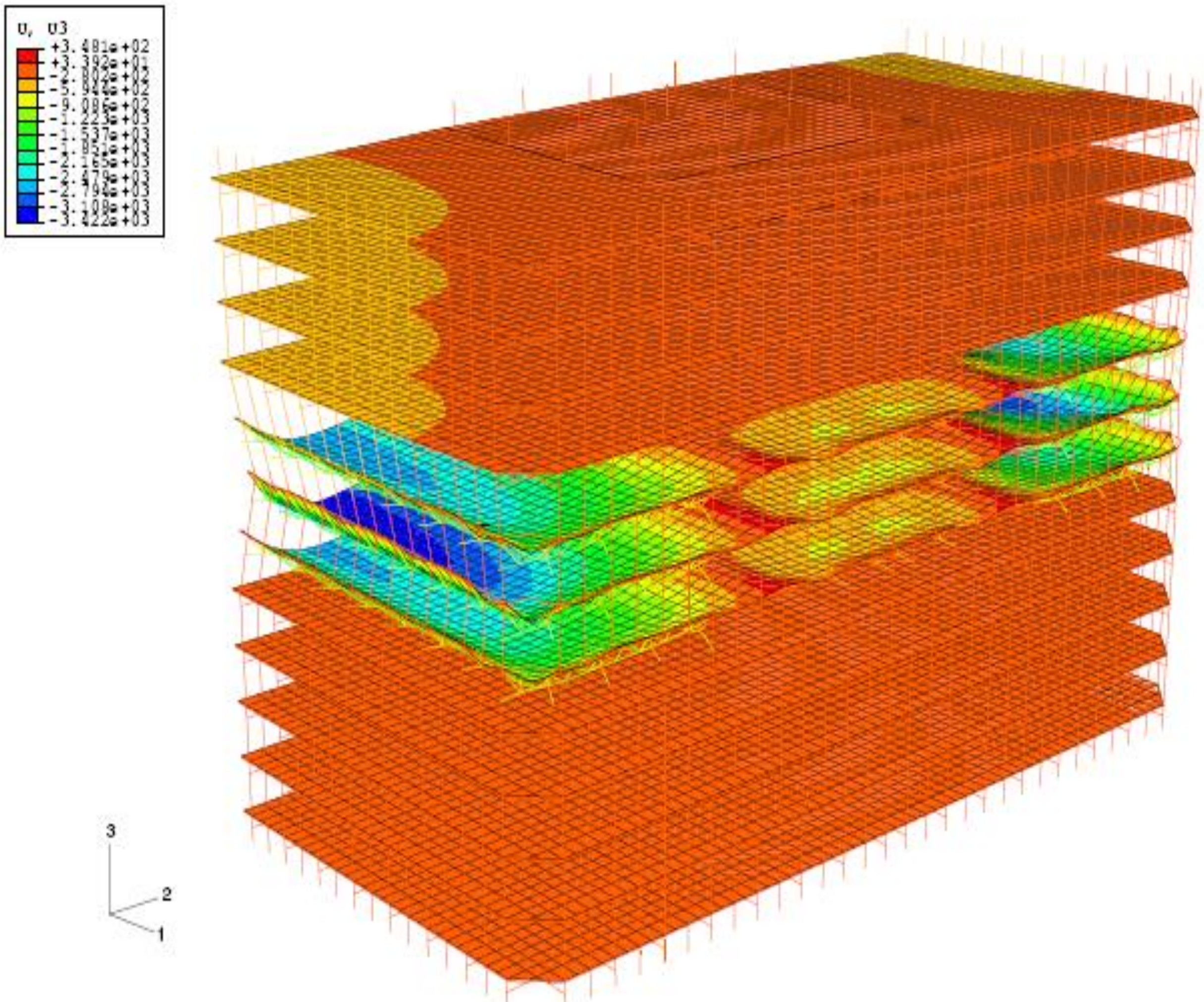
Code recommendations starting from Approved Document B (UK, 1991) and followed by many other international codes including Eurocodes ask for Performance-based Design, where building and fire compartments are outside the limits of prescriptive design

No coherent guidance provided

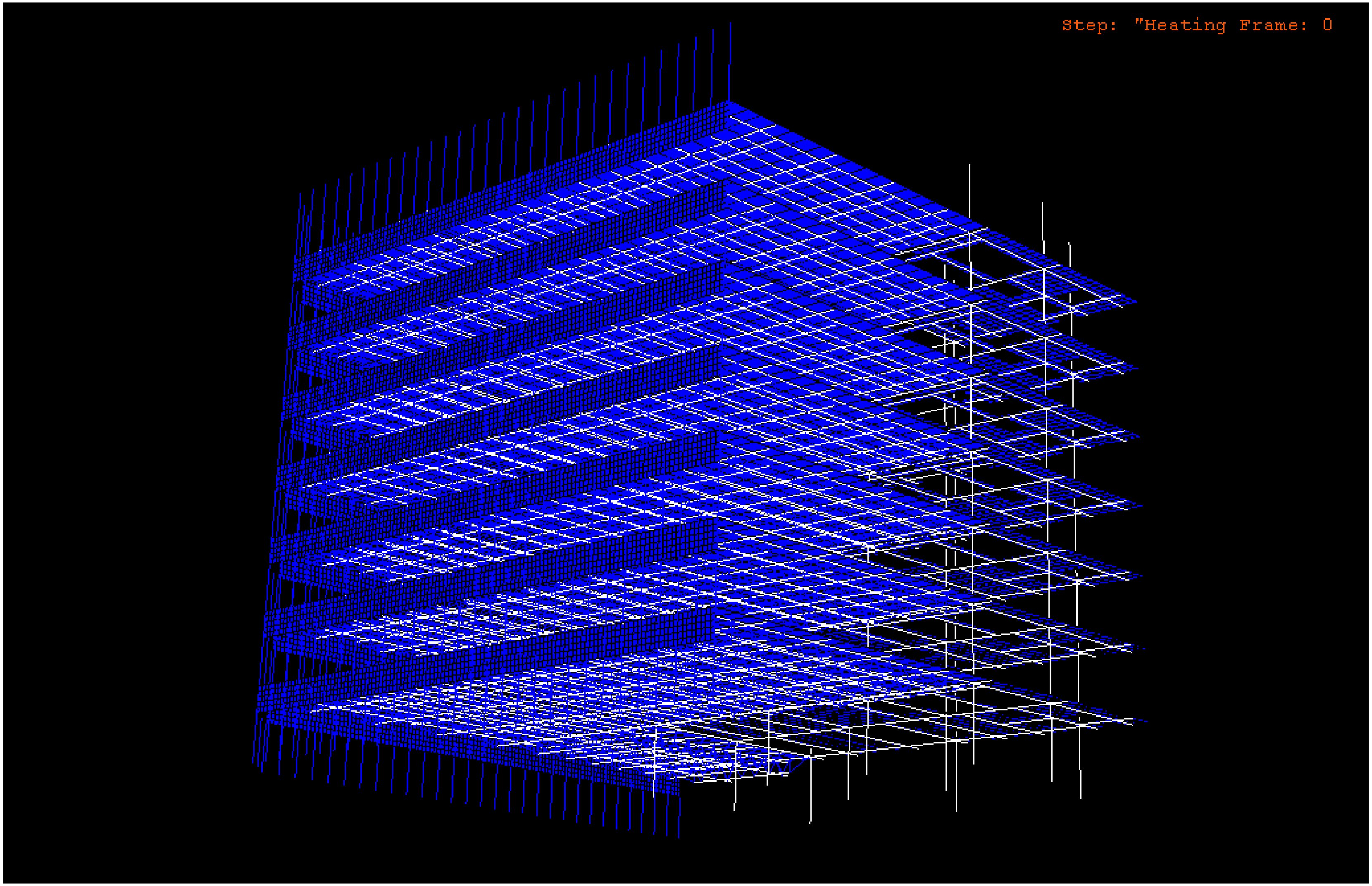
Engineers left to own devices

ADHOCISM RULES!

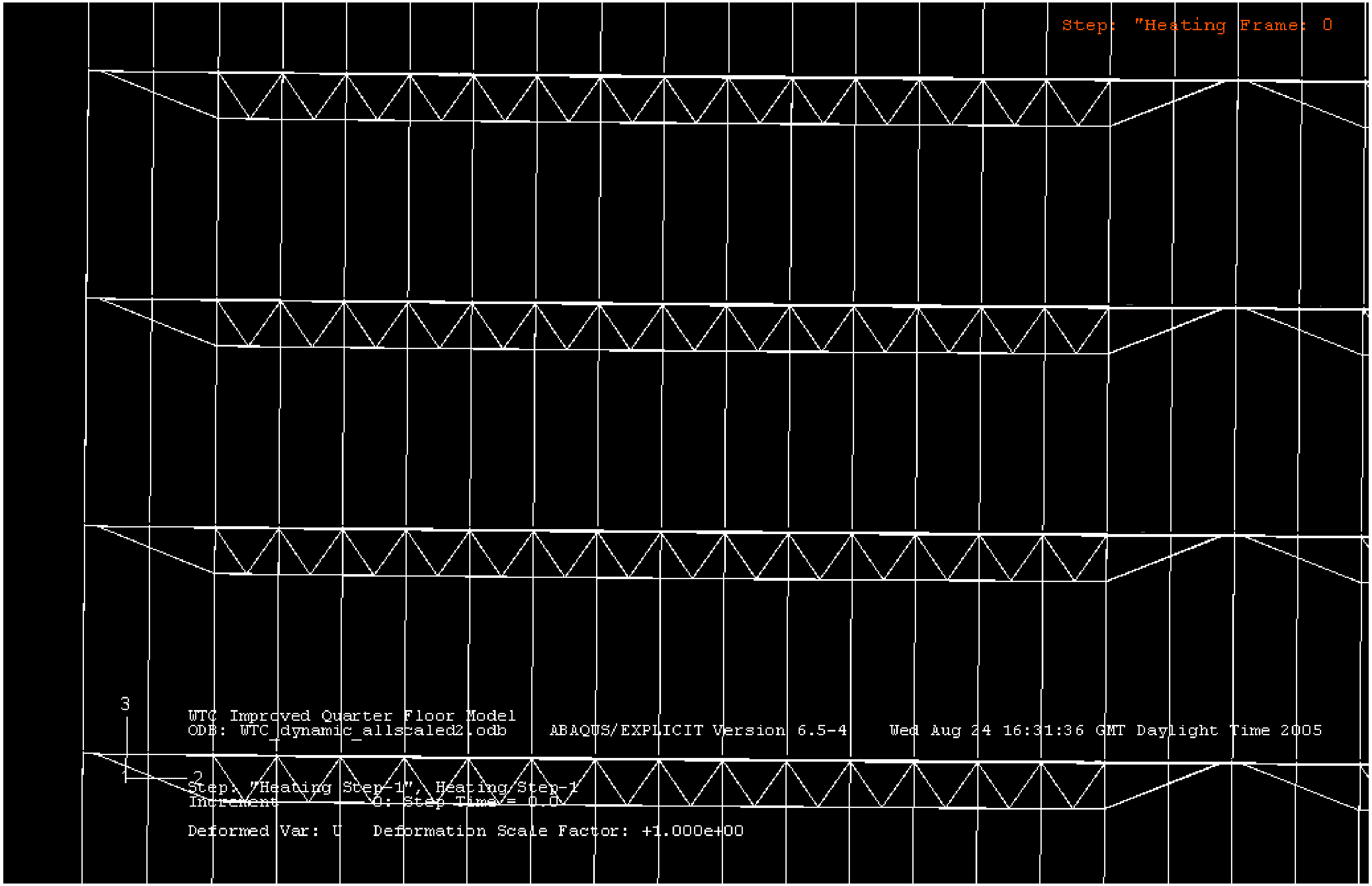
WTC Towers Collapse models (3 Floor Fire – no damage)



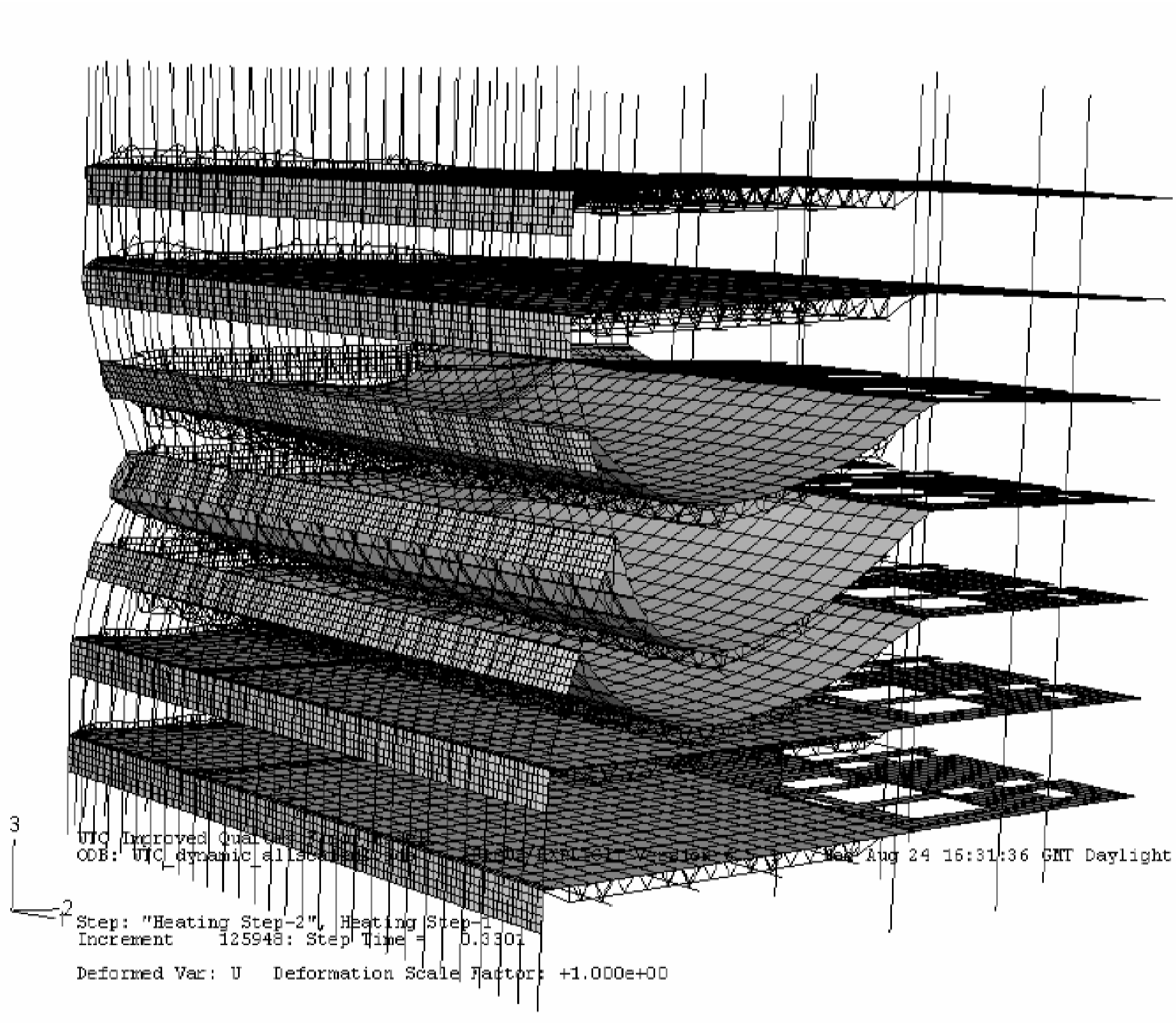
WTC Towers Collapse models (3 Floor Fire – no damage)



3D model: Truss deformations



Collapse mechanism from 3D model



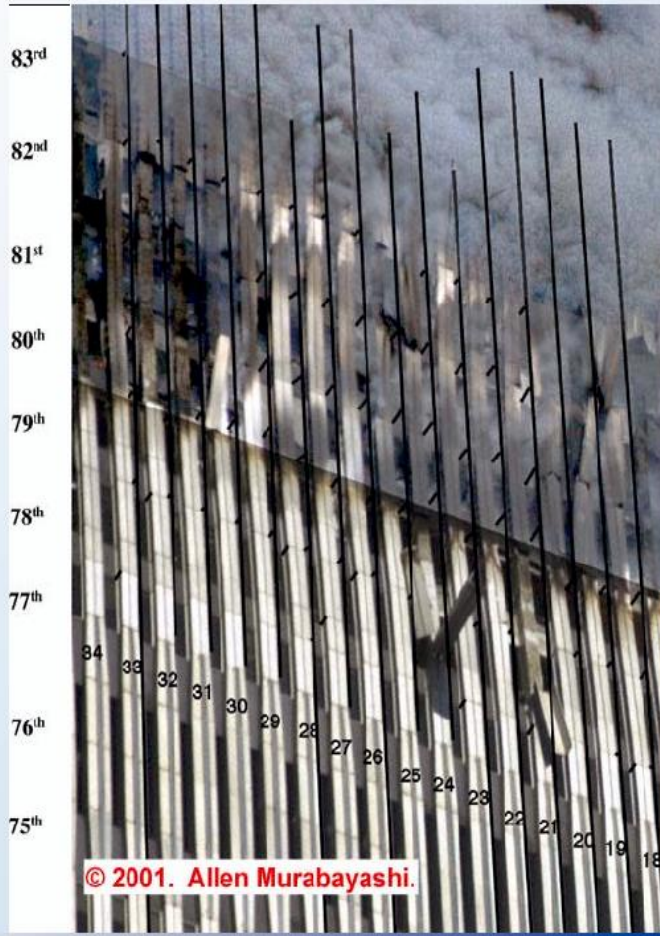
Photograph from NIST report

WTC2: East Face

Time: 9:21:29 AM

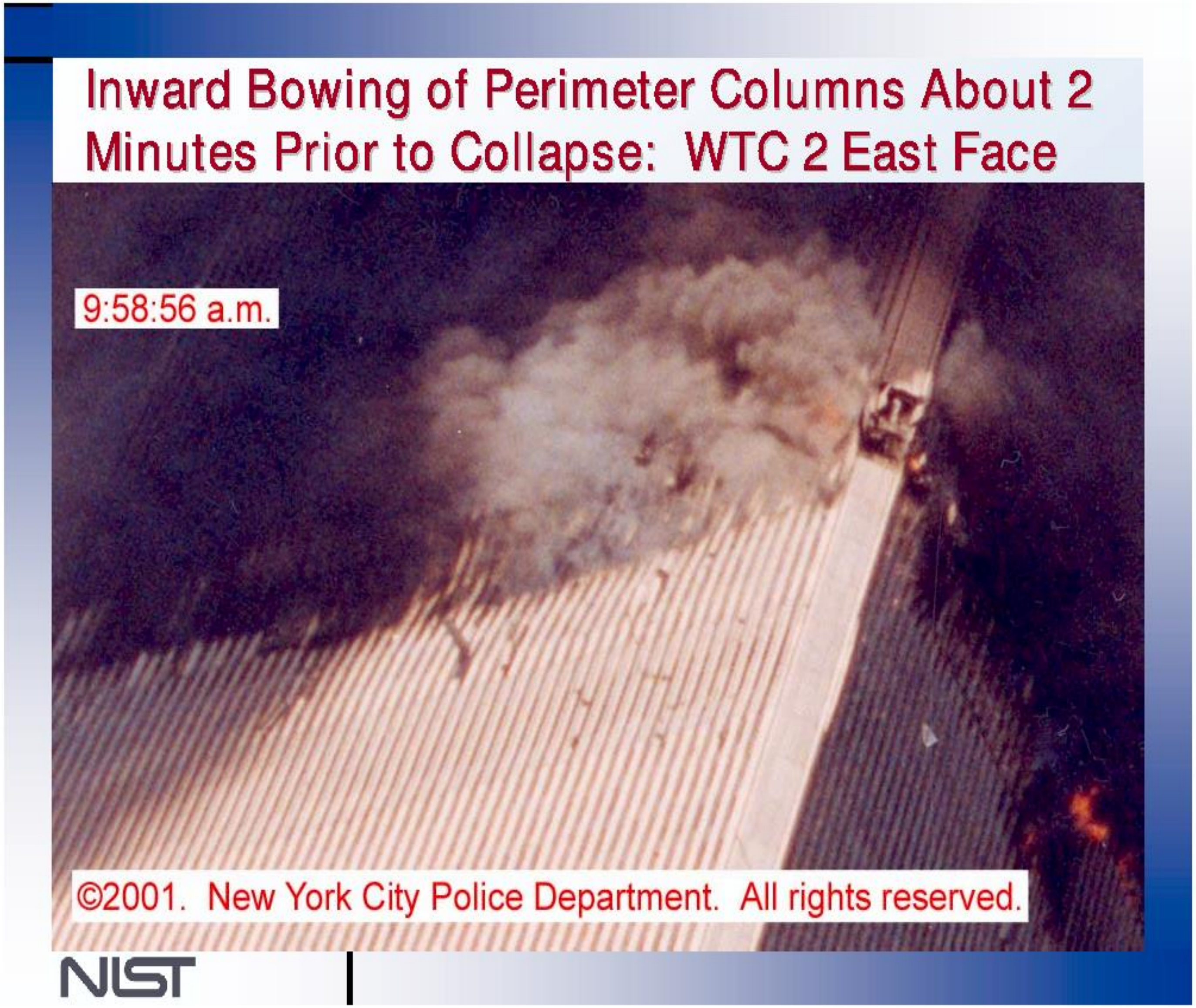
~18 minutes post impact

Maximum inward bowing of columns approximately 10 inches



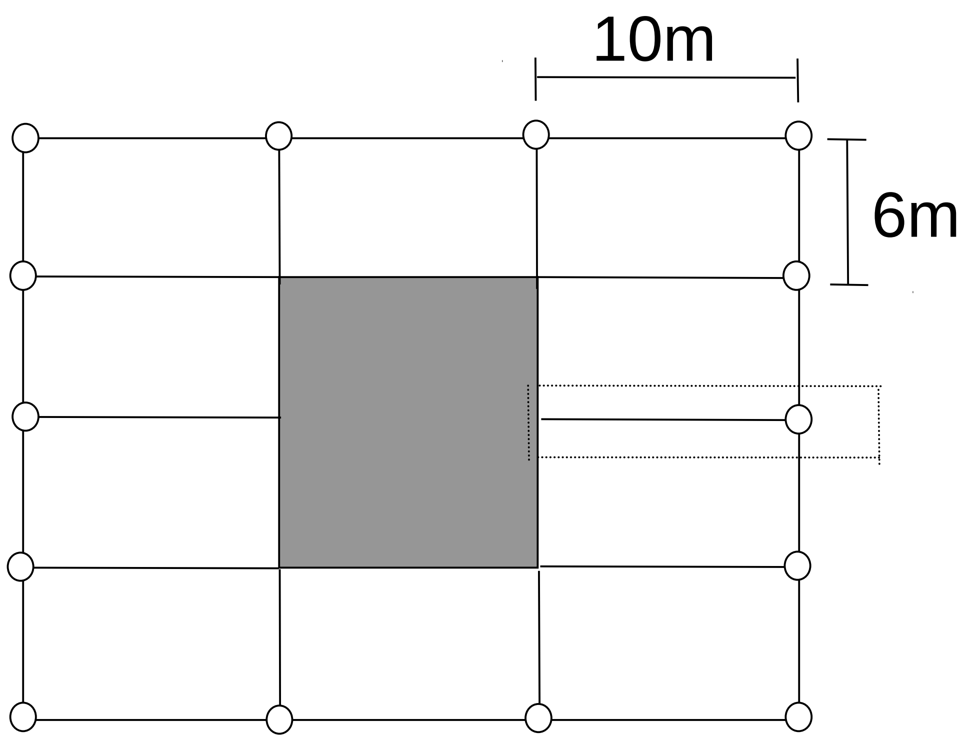
NIST

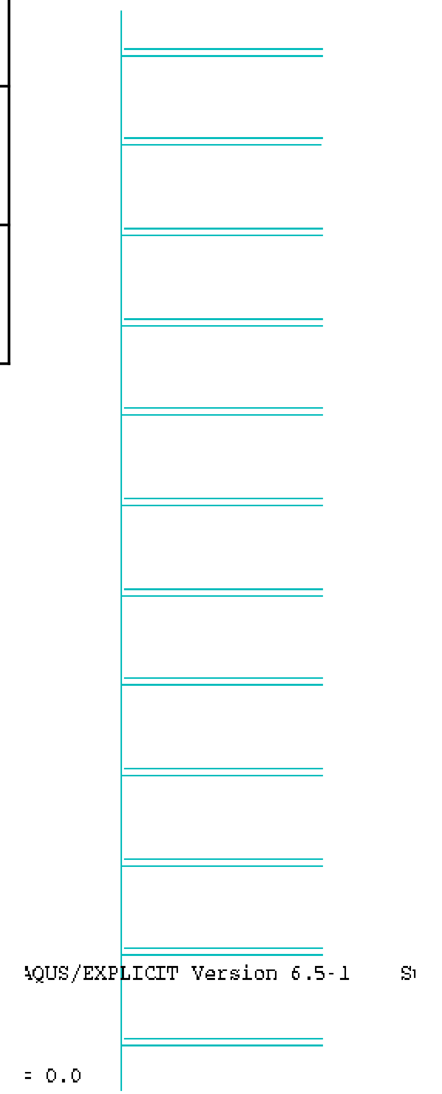
Photograph from NIST report



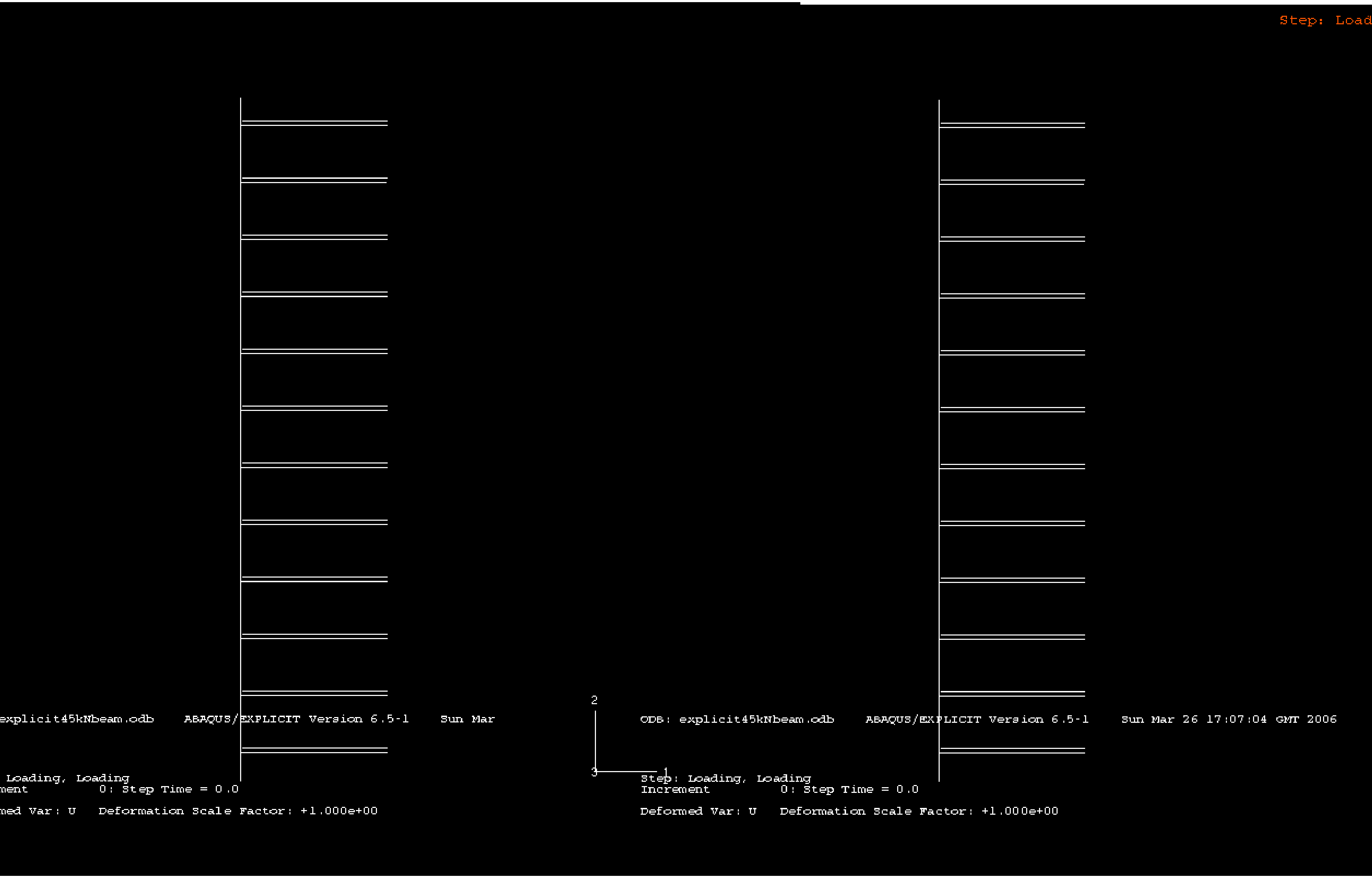
Generic collapse mechanisms for tall buildings

	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

Thank you