Developments and Future Direction of Structural Fire Engineering

Colin Bailey

Why Structural Fire Engineering ?

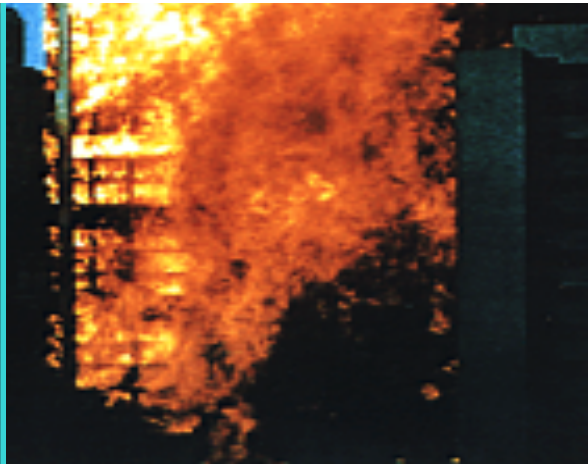
Great Fire of London 1666

The Building Act 1667 was the first piece of legislation

Houses were to be built in brick or stone.
Number of storeys and width of walls carefully specified.
Streets wide enough to act as a fire break.



‘Structural Fire Engineering is the science and art of designing and constructing with economy and elegance, buildings, frameworks and other similar structures to protect people, property and the environment from the destructive effects of fire’

World Fire Statistics – April 2014

Table 2: Adjusted figures for direct fire losses and as average percentage of

millions, except for Japan - billions)

Country	Currency	Direct Losses 2008	2009	2010	Percentage 2008-2010
Hungary	Ft		580	210	0.
Singapore	$S	110	115	115	0.
Slovenia	SIT				0.
Australia [1,2]	$AUS	1,000	955	940	0.
Czech Republic	Kč	3,700	2,450	2,200	0.
Spain [3] *	€	910			0.
Poland *	zl	1,450	1,150		0.
United States	$US	17,500	14,000	13,000	0.
Japan	¥	615	610	565	0.
New Zealand	$NZ	240		210	0.
Germany	€	2,850	2,950	2,700	0.
United Kingdom	£	1,950	1,750	1,750	0.
Netherlands	€	1,050	925	675	0.
Finland	€	305	280	330	0.
Sweden	kr	5,950	5,550	5,650	0.
Denmark	kr				0.
France	€	4,550			0.
Italy	€	3,150	3,750	2,600	0.
Norway	kr				0.

Financial loss !

Fire Safety in Buildin

Occupants, Fire-Fighters, Public in the proximity of the building

Aims:

To limit, to acceptable levels, the probability of death and injury to people, property loss, and damage to the environment.

Loss of business

Limit emissions of gaseous pollutants

Minimum levels of safety covered by legislation

Given in the Building Regulations and seeks to ensure reasonable levels of health and safety for people in and around buildings

The Regulations relating to fire cover:

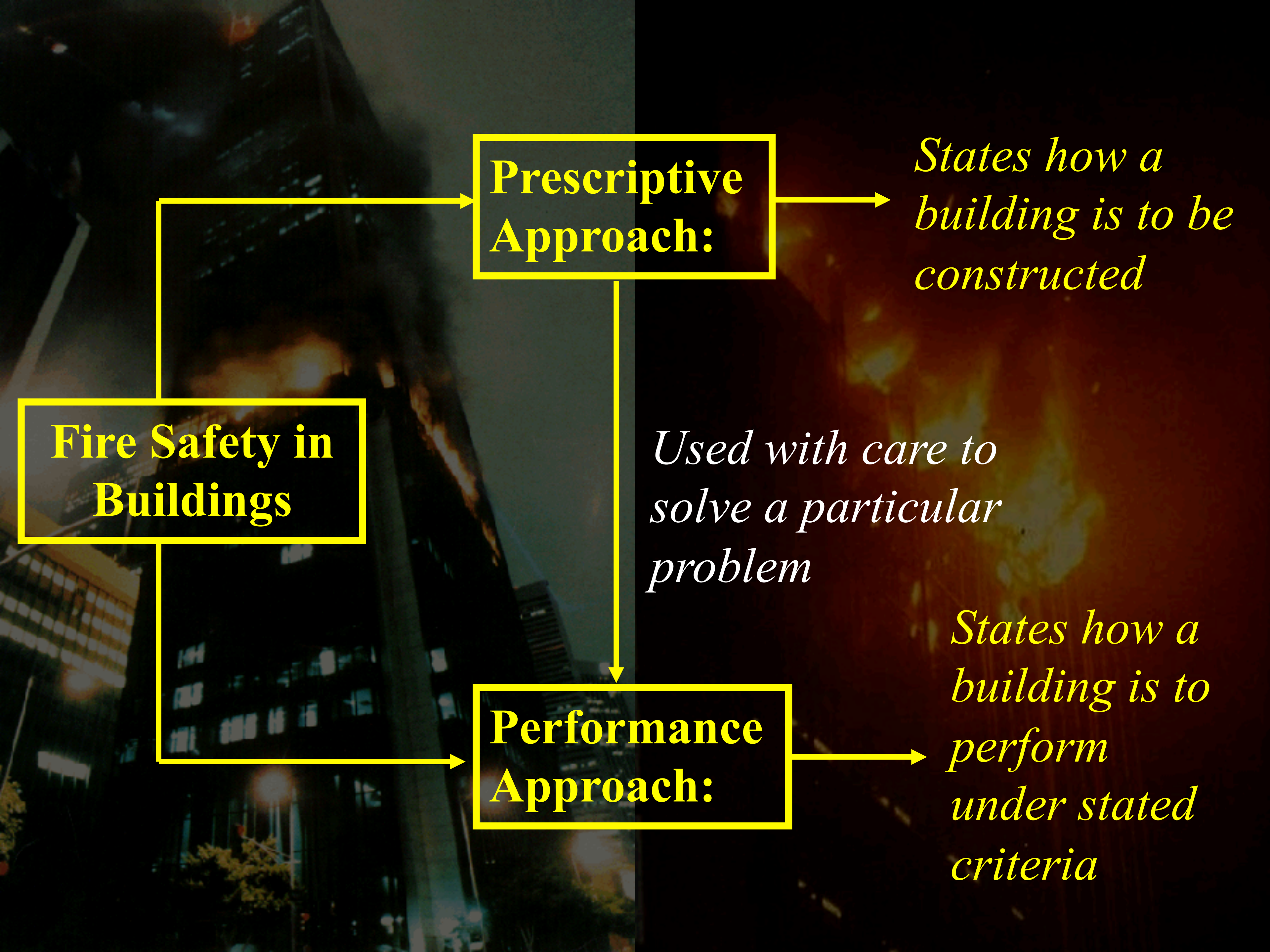
- Means of escape
- Internal fire spread (linings and structure)
- External fire spread
- Access and facilities for the fire service.

Covers life safety only !!!!

B3: Internal fire spread (linings and structure)

‘The building shall be designed and constructed so that, in the event of fire, it’s stability will be maintained for a reasonable period.’

Only relates to life safety


Prescriptive Approach:
States how a building is to be constructed
Fire Safety in Buildings
Used with care to solve a particular problem
Performance Approach:
States how a building is to perform under stated criteria

Prescriptive Approach – *Set of rules*

For Example :

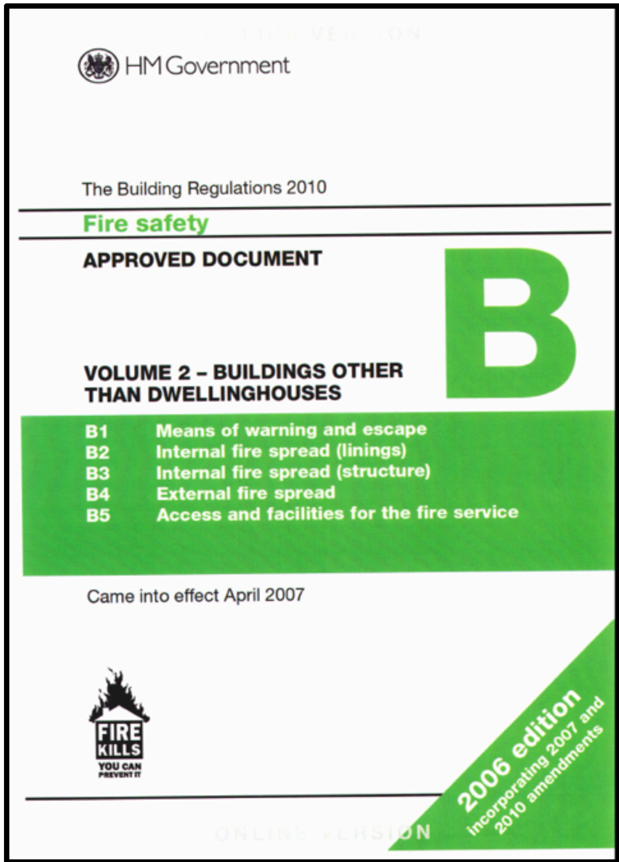
Minimum fire resistance for members

Maximum fire compartment size

Maximum travel distances

Minimum number of exists

Etc..

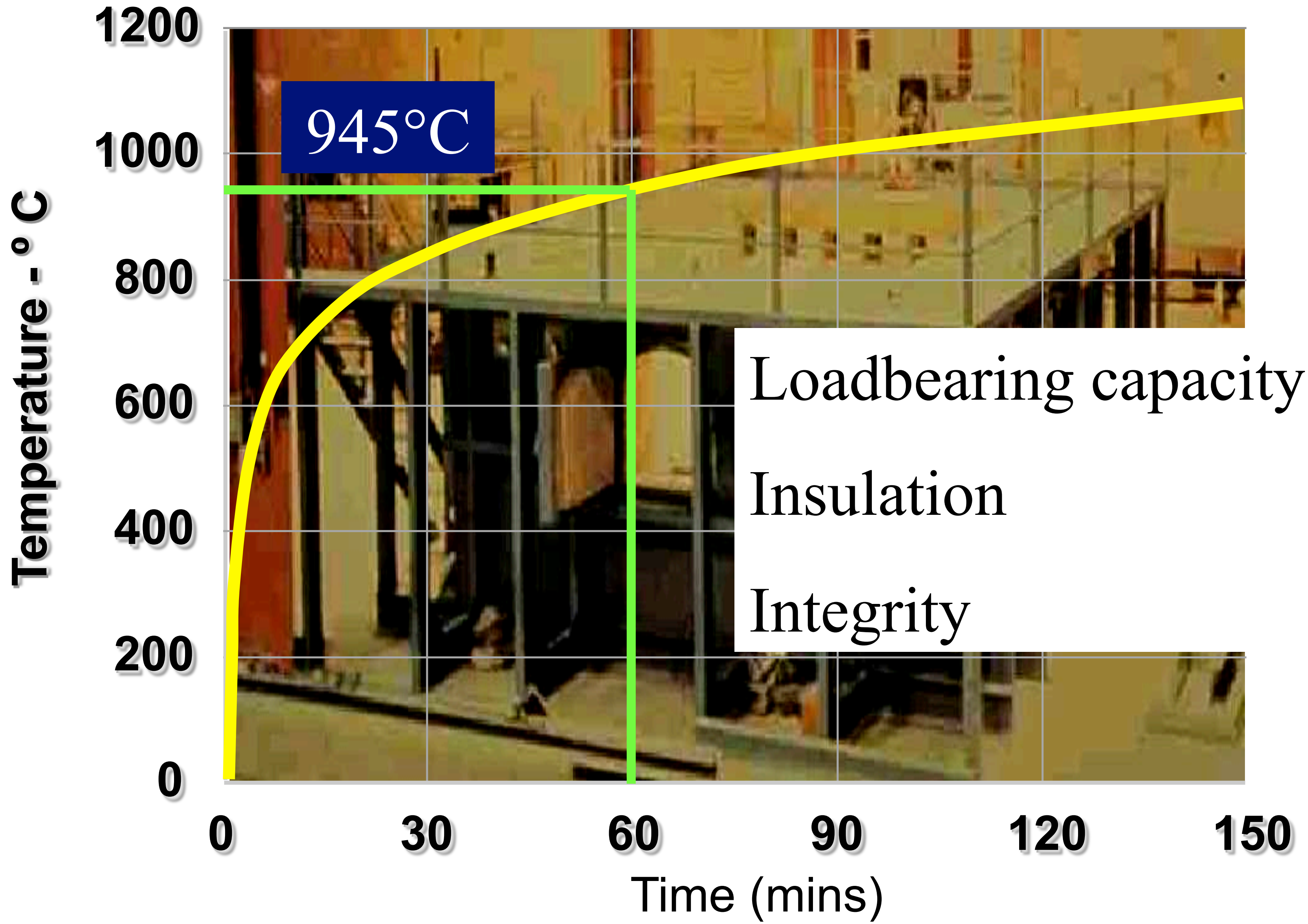


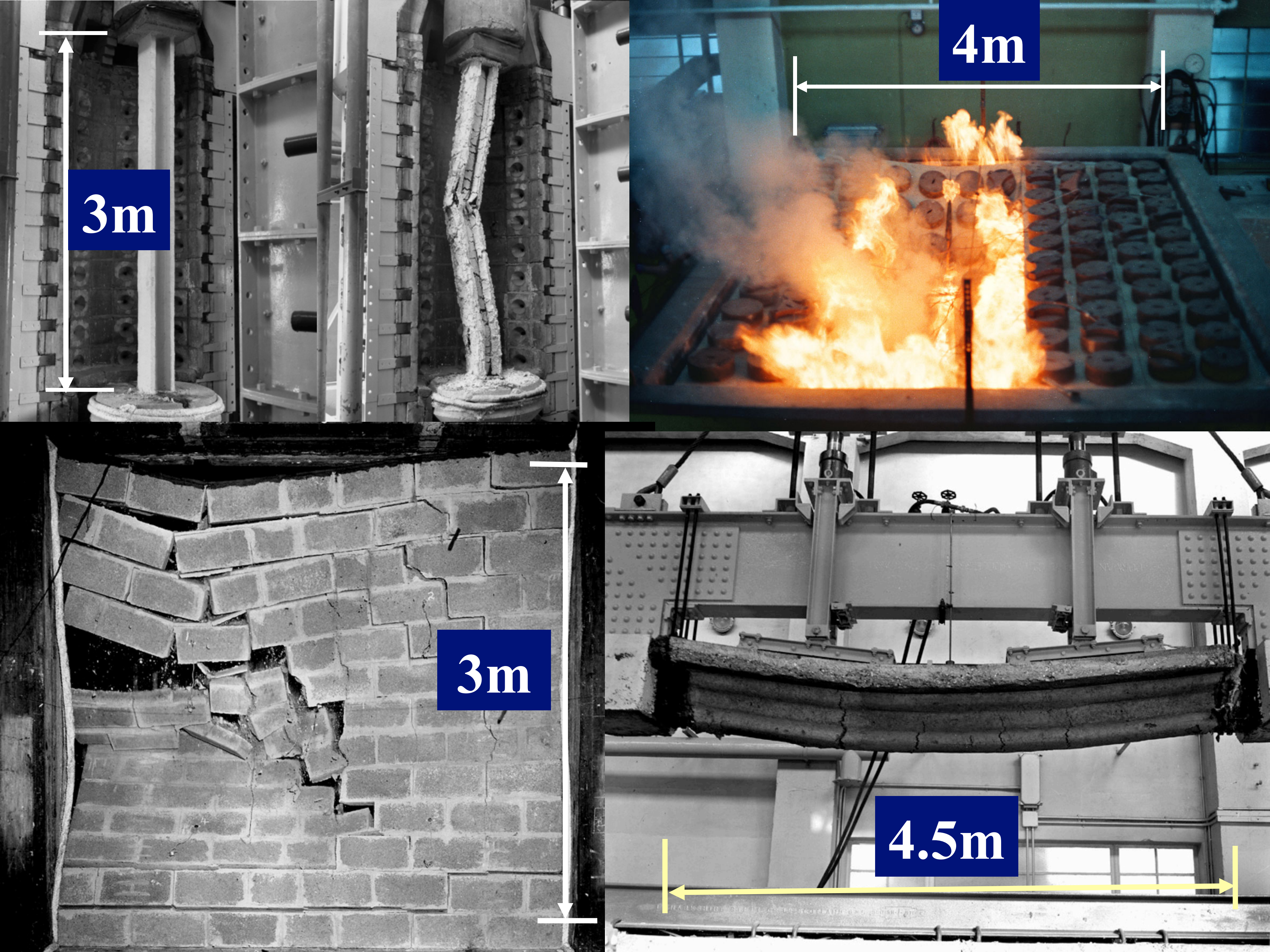
Example of fire resistance periods (Approved Document B Vol. 2)

	Height of Building (m)			
	<5	<18	<30	>30
Residential (Non Domestic)	30	60	90	120
Offices	30	60	90	+ Sprinklers
Shops, Commercial, Assembly	60	60	90	
Industrial & Storage	60	90	120	
Car Parks - Open	15	15	15	15

60 minutes fire resistance means that the elements in the building will survive 60 minutes in a standard fire test

Standard Fire Resistance




3m
4m
3m
4.5m

History of the Standard Fire Test

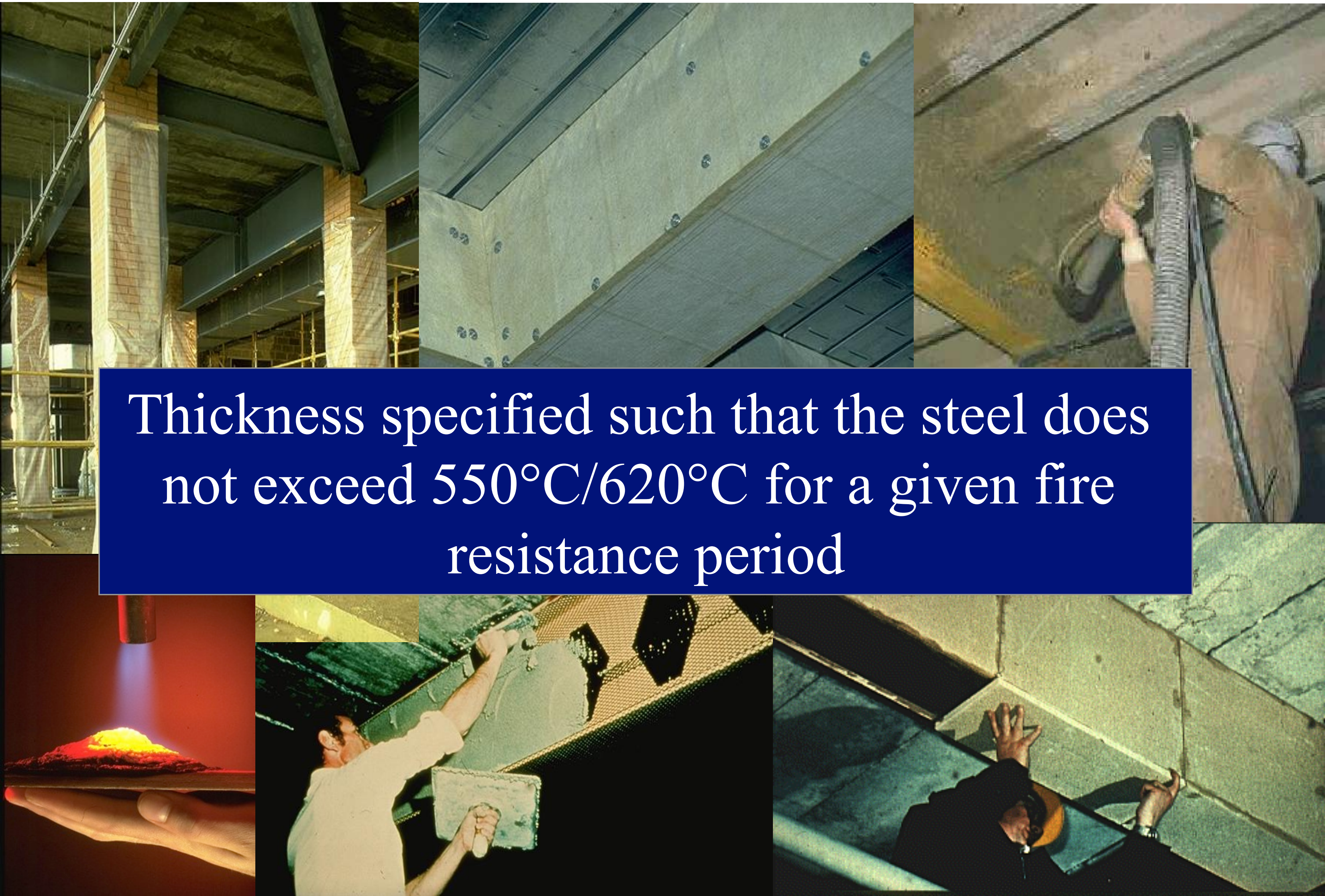
- 1890’s where early attempts at establishing structural fire behaviour were made at the behest of insurance companies
- 1917 First US Standard produced.
- 1932 First Edition of BS476 (UK)
- 1933 E119 (US) produced.
- 1985 ISO 834
- BSEN 1363-1

124 years of testing ! & still going

Minimum fire resistance for members
(Deemed to satisfy rules)

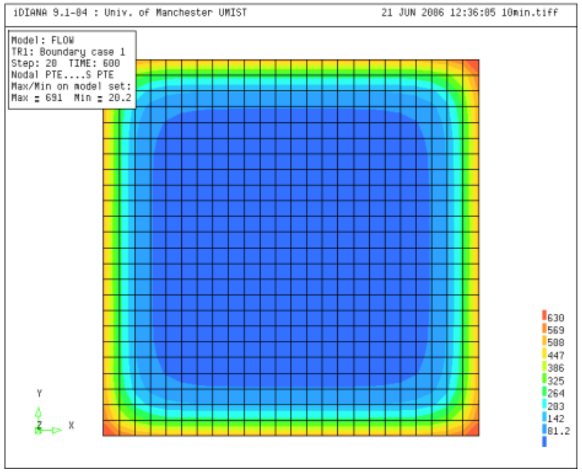
Quality of test v Quality on site

Generic and Proprietary Fire Protection Materials

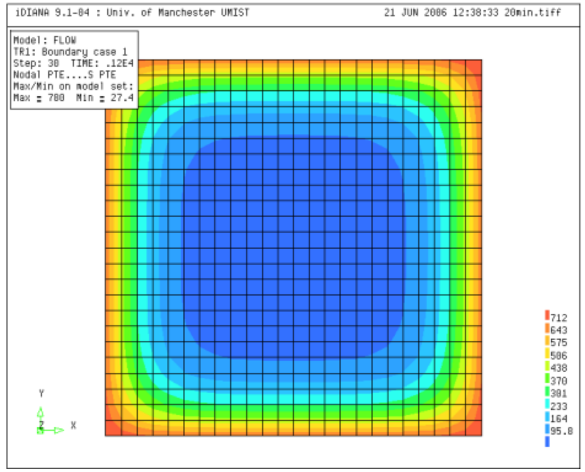


Thickness specified such that the steel does not exceed 550°C/620°C for a given fire resistance period

Strength / Stiffness of concrete members in fire

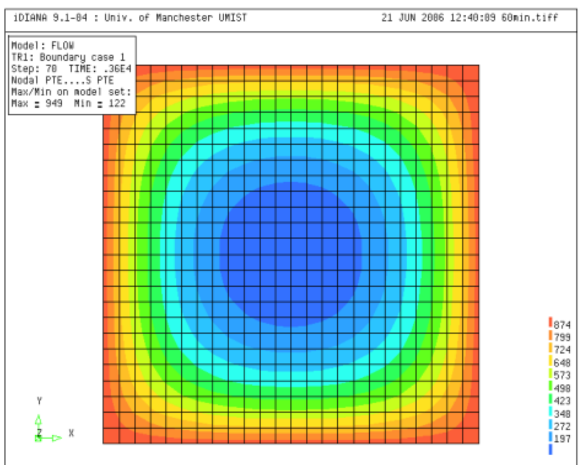


10min of fire

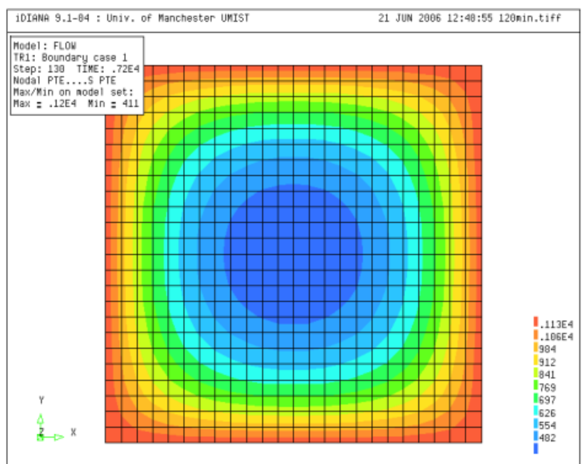


30min of fire

Overall size of column is important to allow for strength loss in concrete.



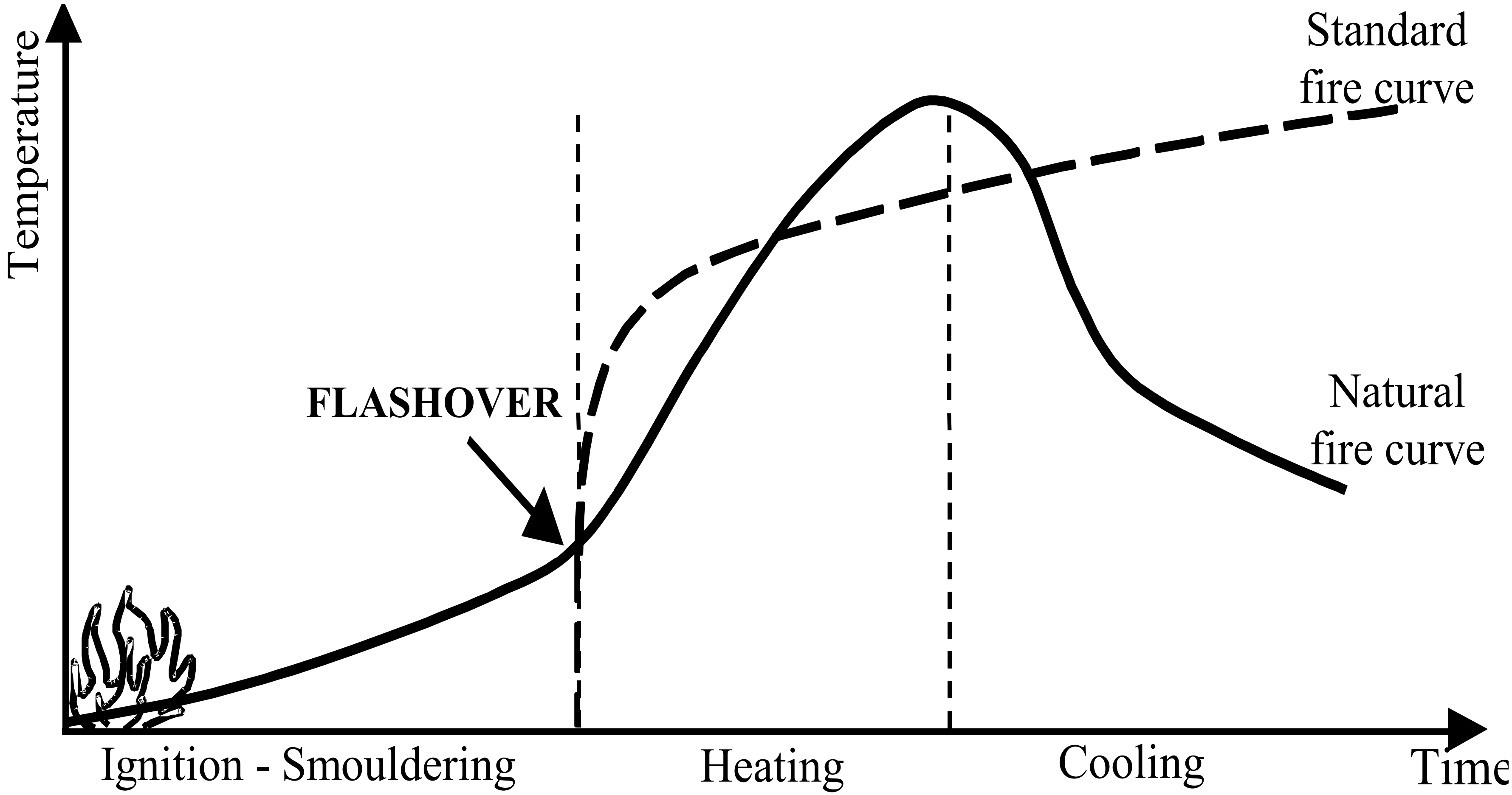
60min of fire



120min of fire

Position of reinforcement is important

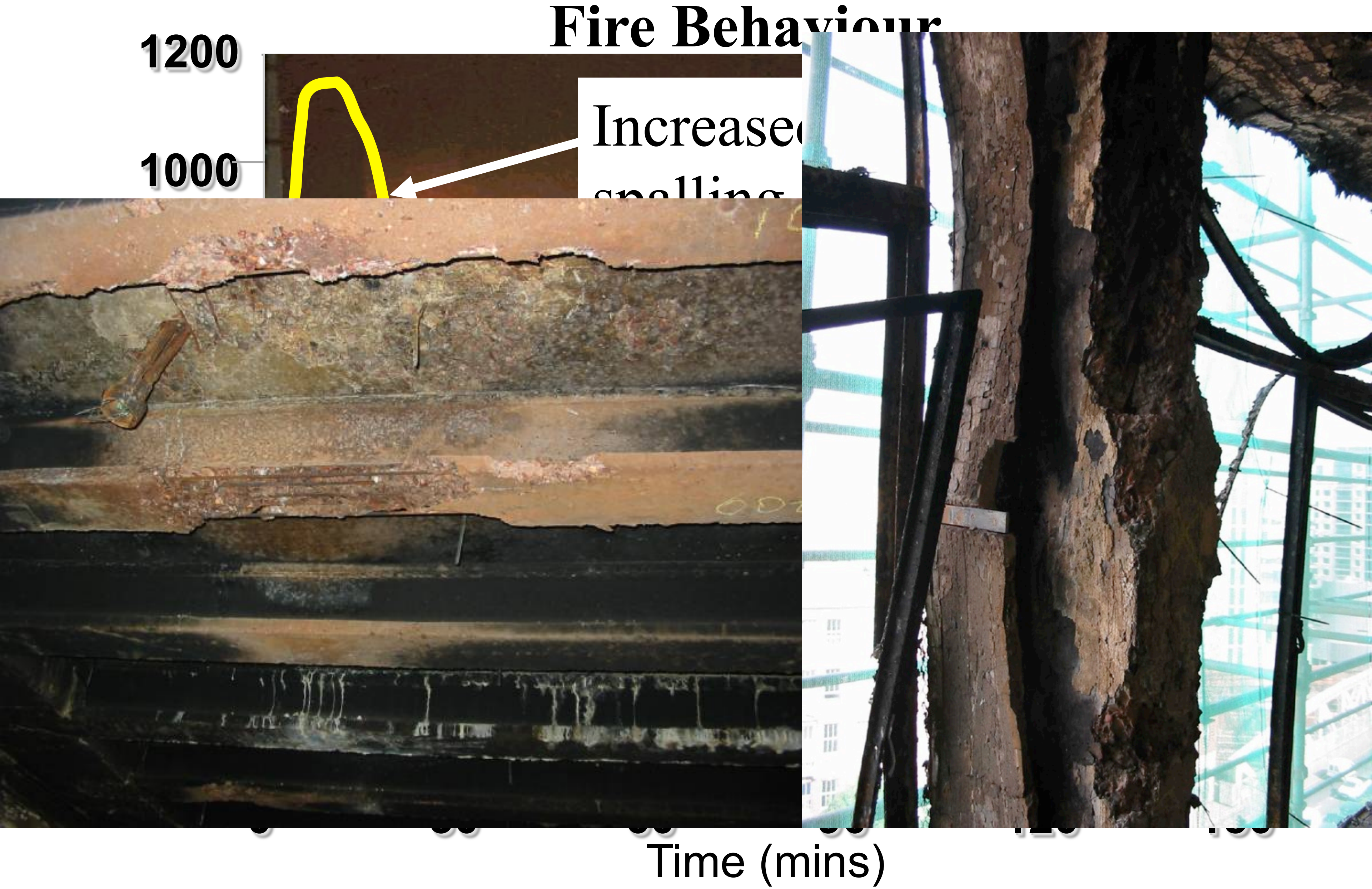
Limitations of the prescriptive approach



Life safety

Structural damage – risk of collapse – structural fire engineering only concerned with this phase of the fire

Limitations of the prescriptive approach

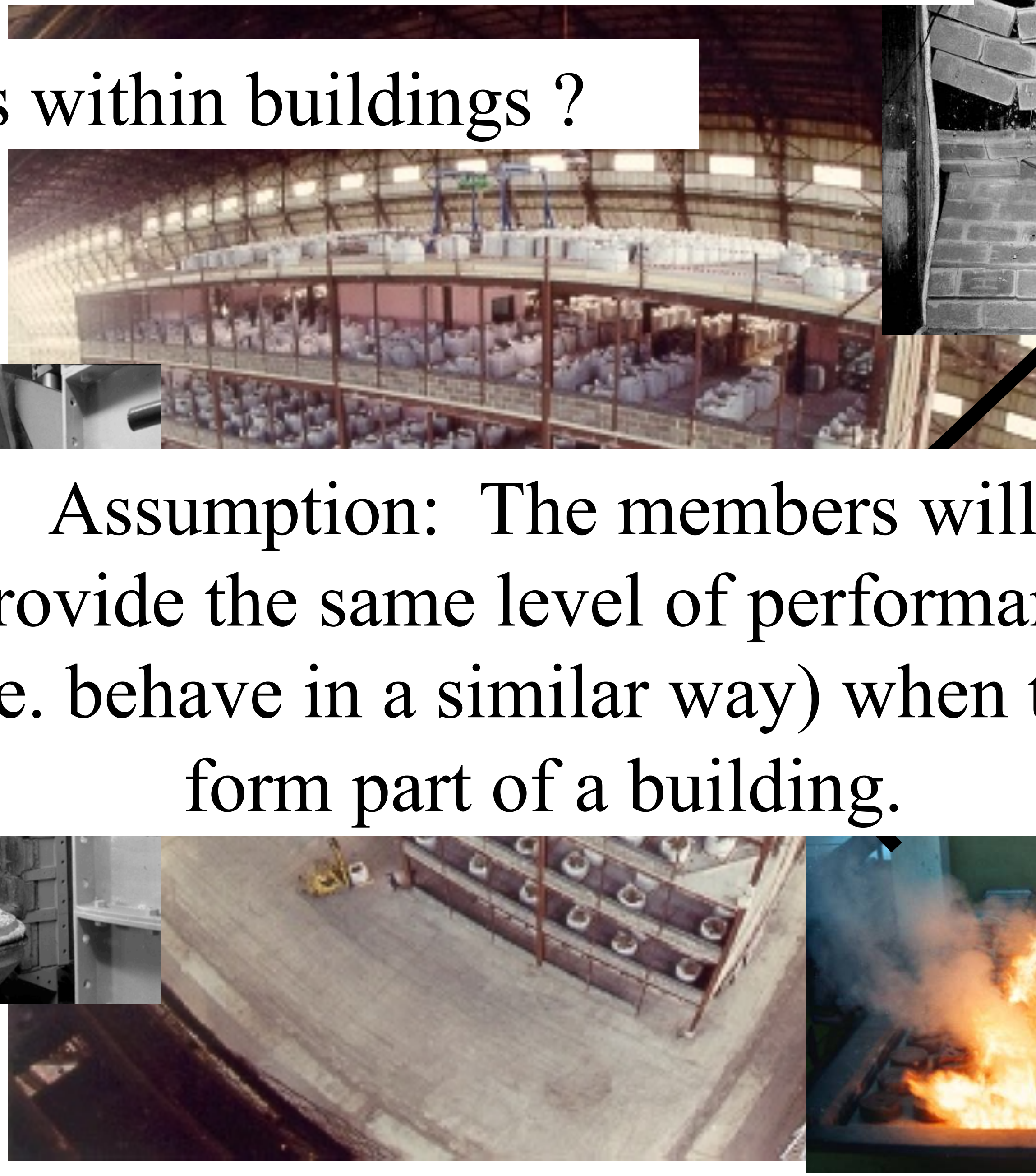


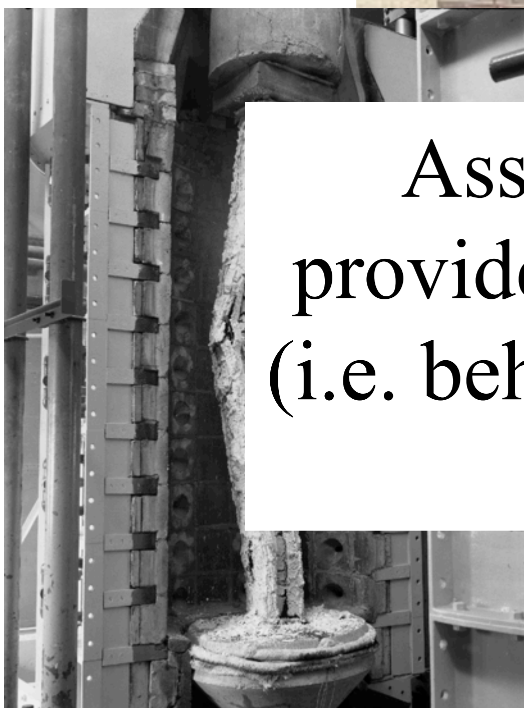
Real buildings; spans up to 15m

Standard fire tests; span = 4.5m

Limitations of the prescriptive approach

Members within buildings ?





Assumption: The members will provide the same level of performance (i.e. behave in a similar way) when they form part of a building.

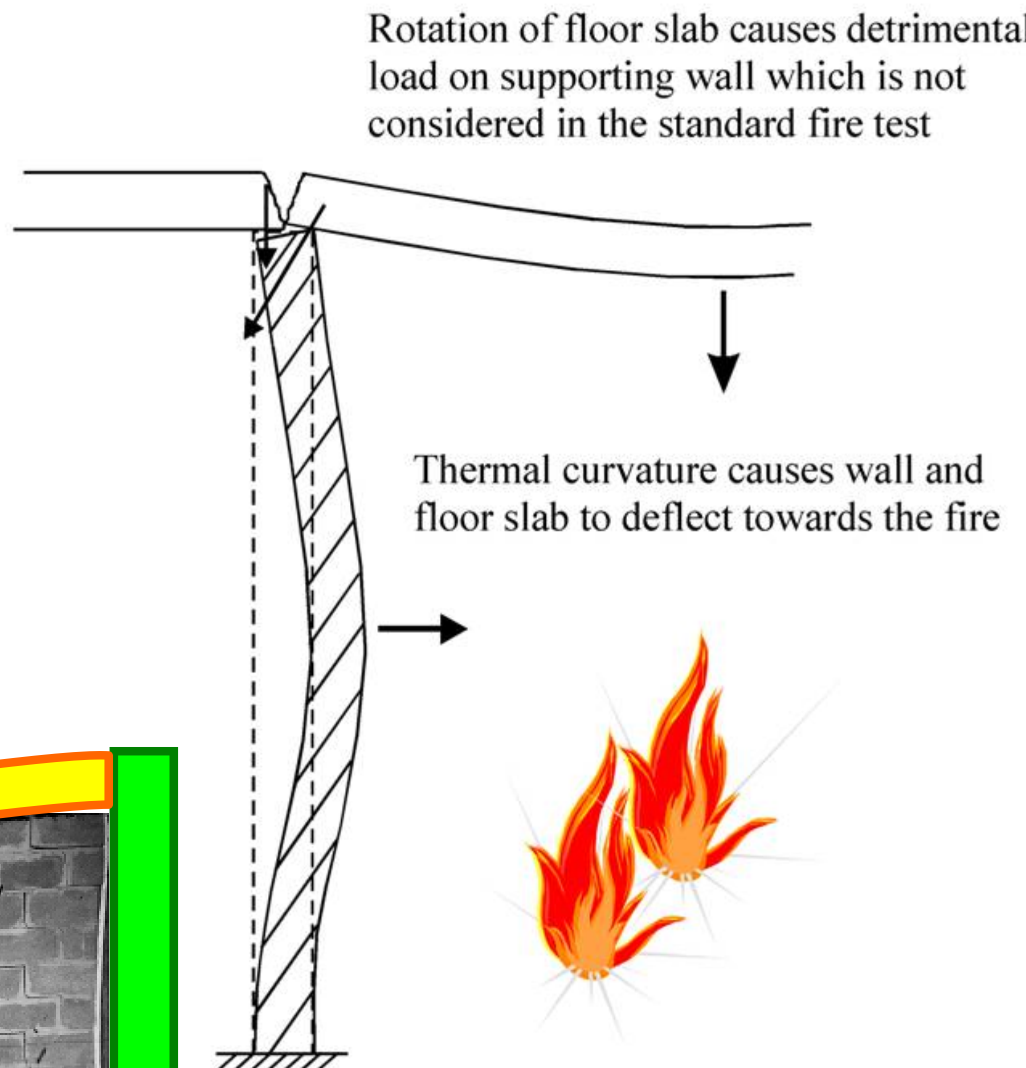
- 8 Storey steel-framed building.
- 7 compartment fire tests of varying size.
- All steel beams left unprotected.
- Max. steel temp 1150°C.

- 7 storey concrete-framed building.
- 1 compartment fire test.
- Max atmospheric temp 950°C

Cardington Fire Tests :
Steel-framed building
Max. steel temperature
1150°C

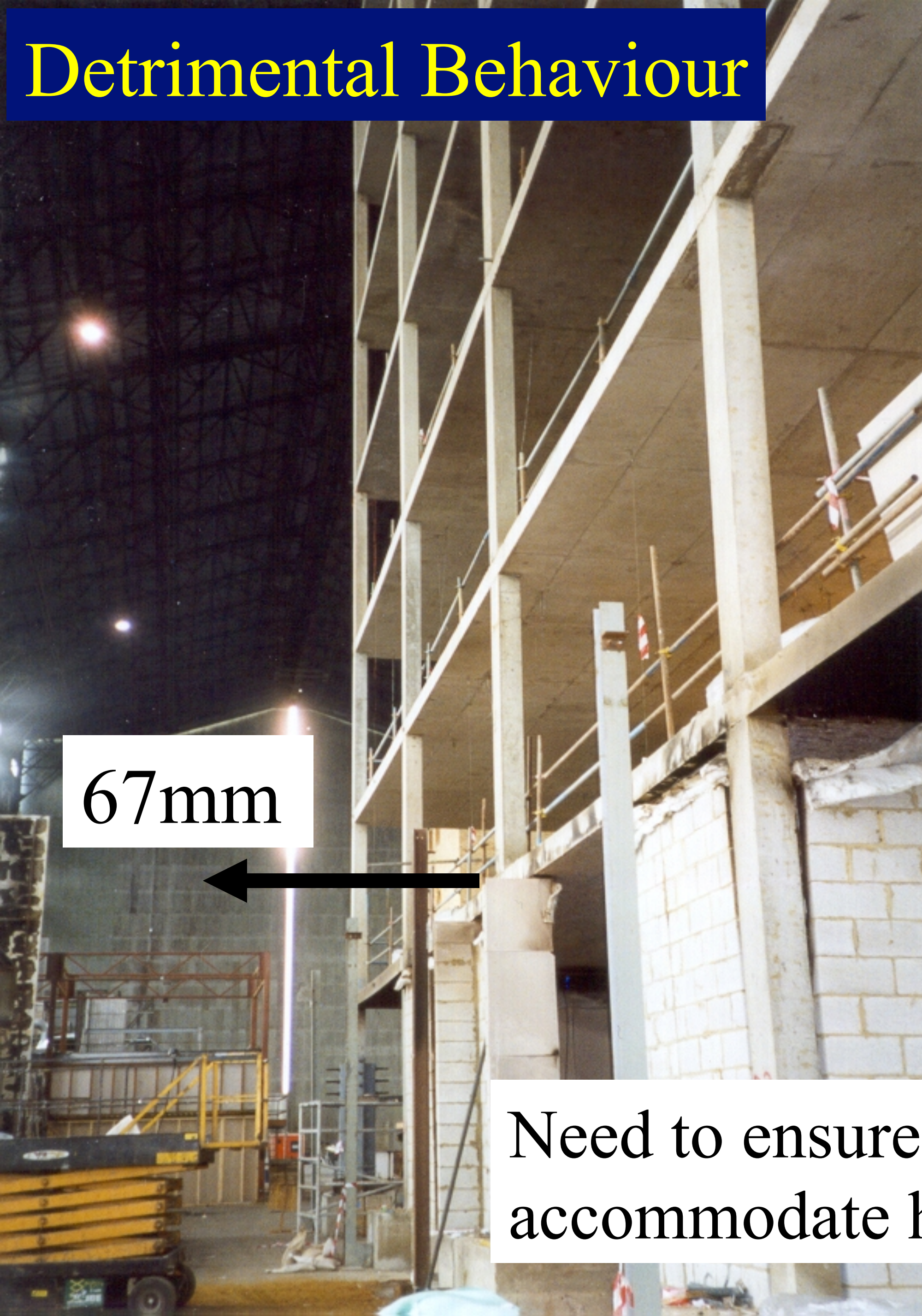
Maximum Atmosphere temperature = 950°C

Detrimental Behaviour





Detrimental Behaviour



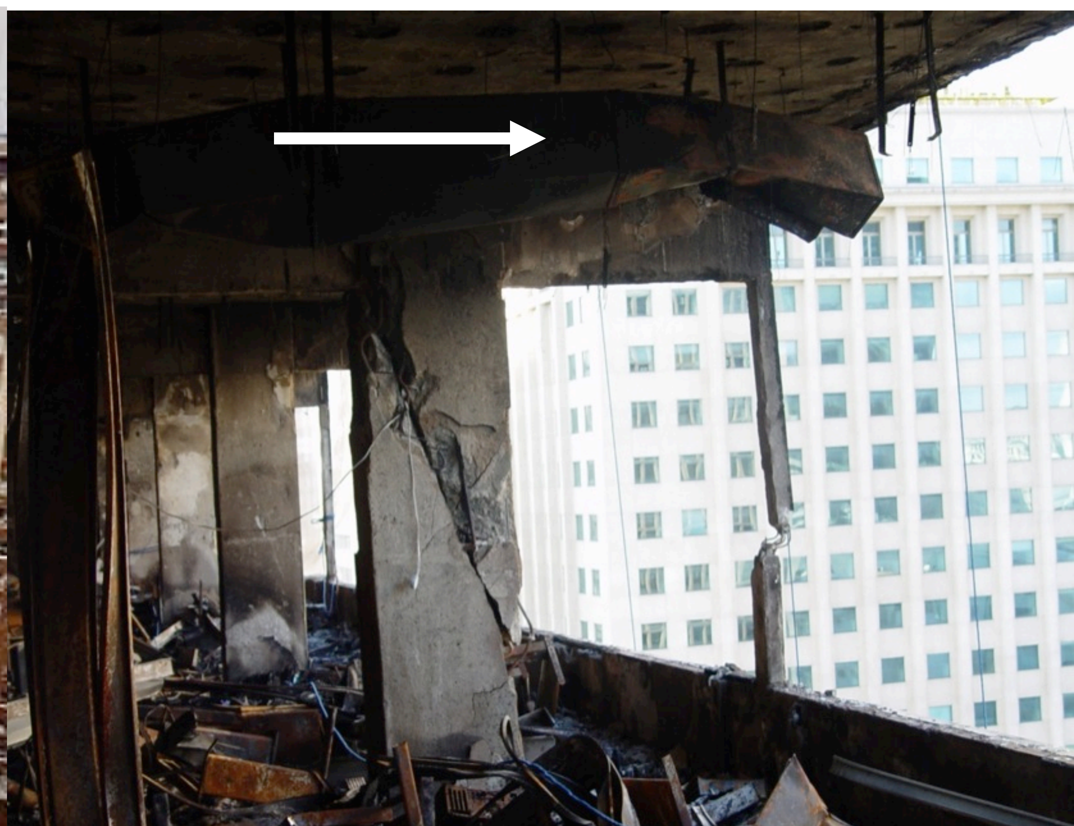
Need to ensure building can resist or accommodate horizontal displacements

Fire in a concrete building with 22 stories

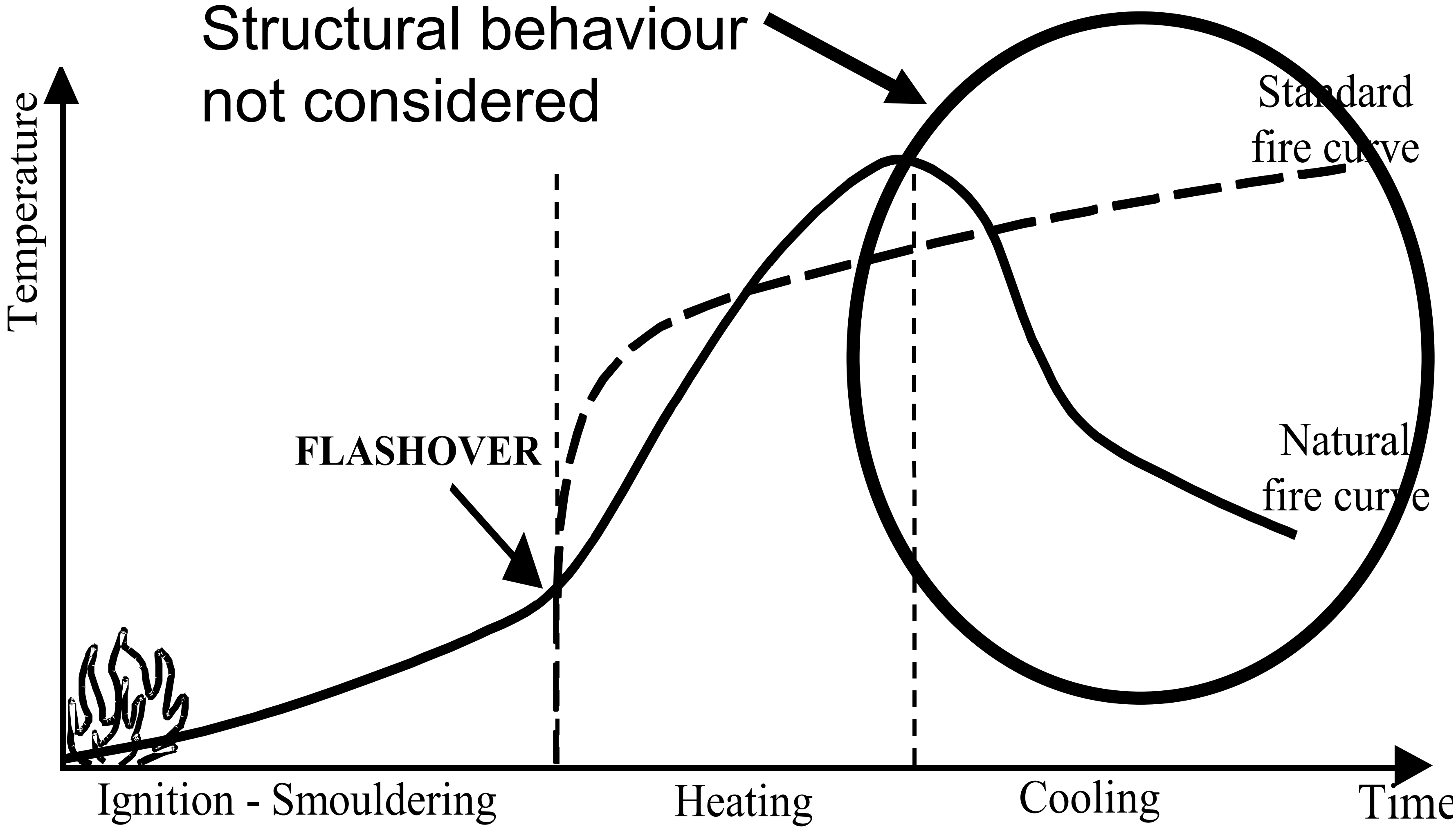
Date: 26-Feb-2004

Helm Stoltz Building– Rio de Janeiro (downtown) – Brazil

Year of construction: 1960



Limitations of the prescriptive approach

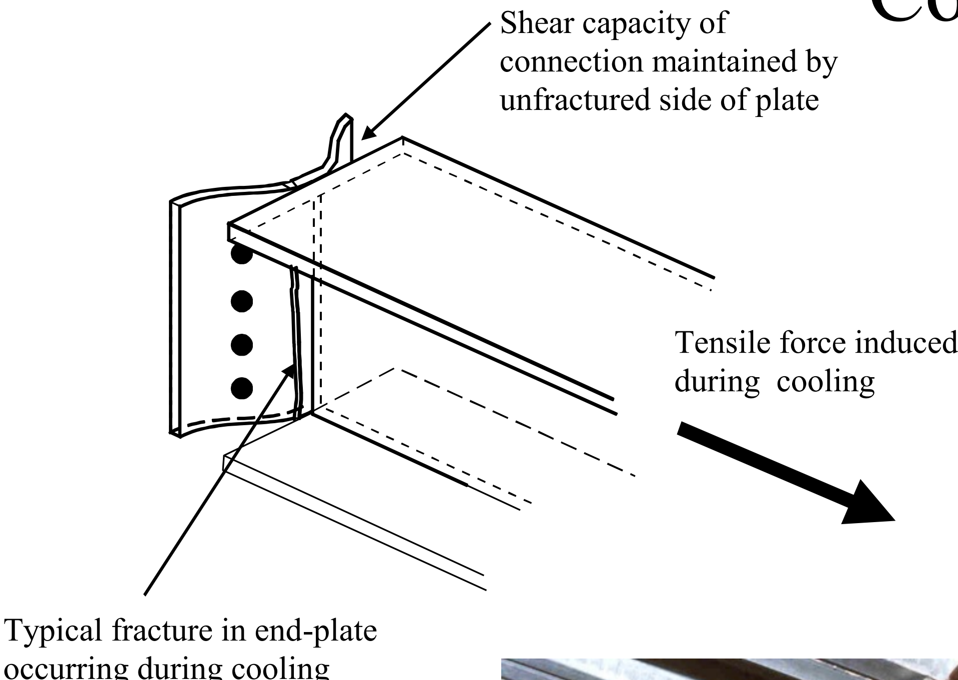


Life safety

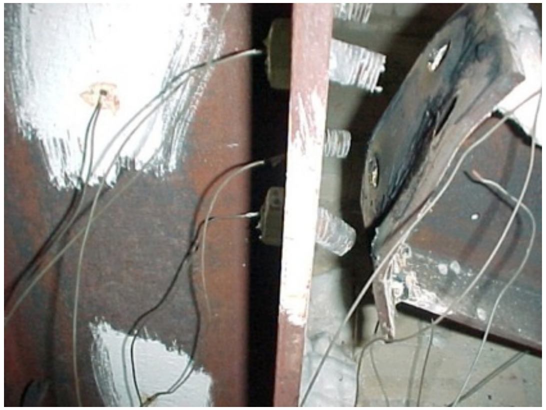
Structural damage – risk of collapse – structural fire engineering only concerned with this phase of the fire

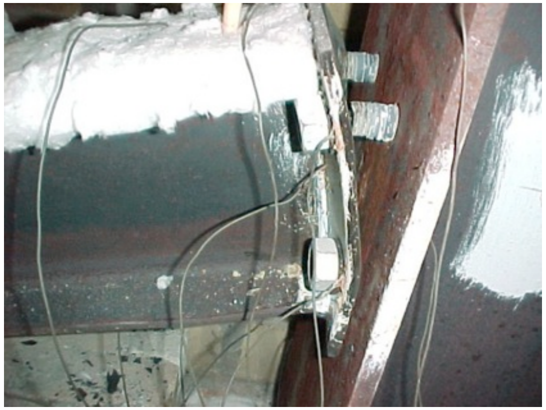
Limitations of the prescriptive approach

Cooling



Connections In Fire

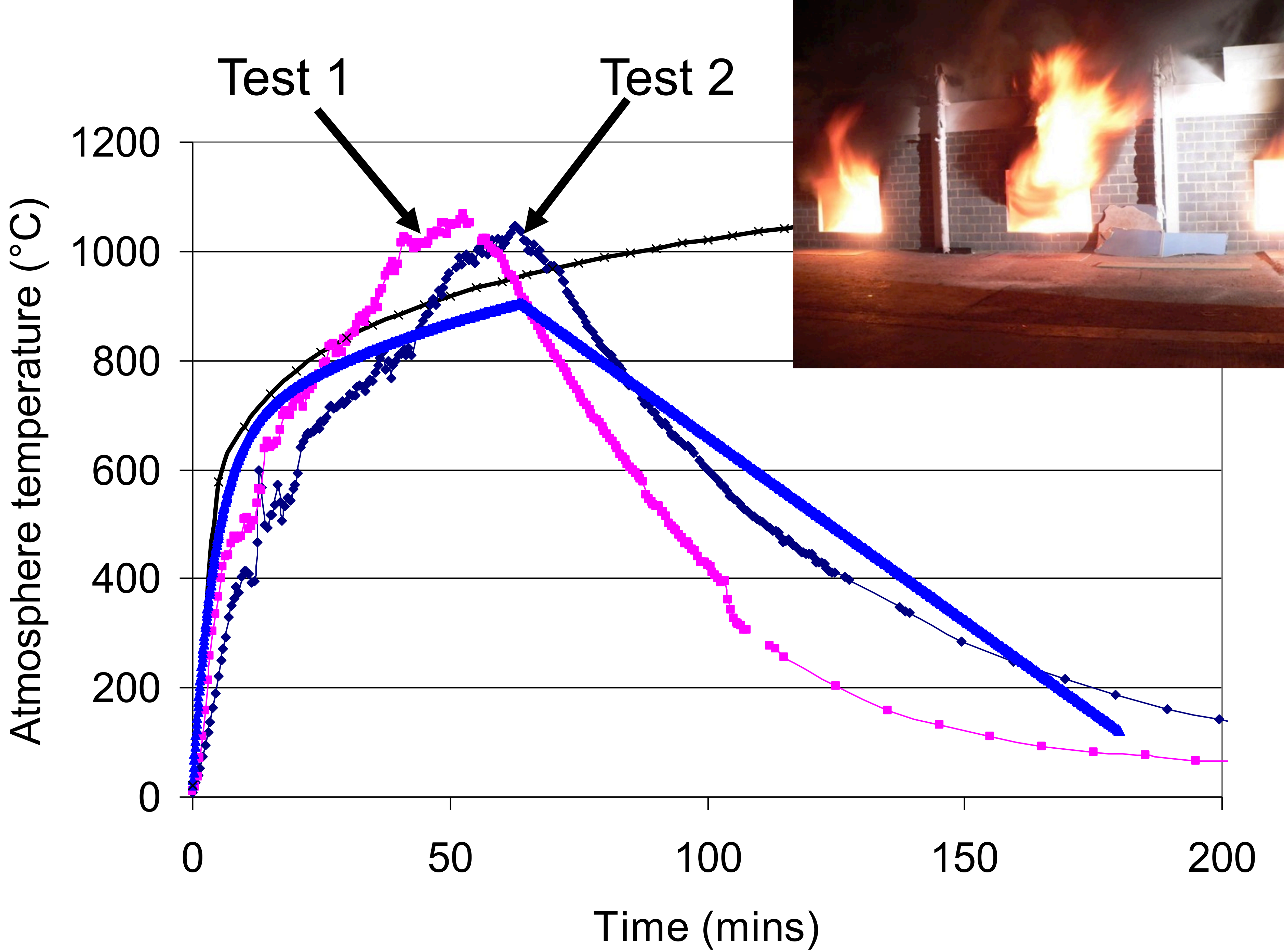




Testing of flush end-plates at Manchester

Full-scale testing on hollowcore slabs

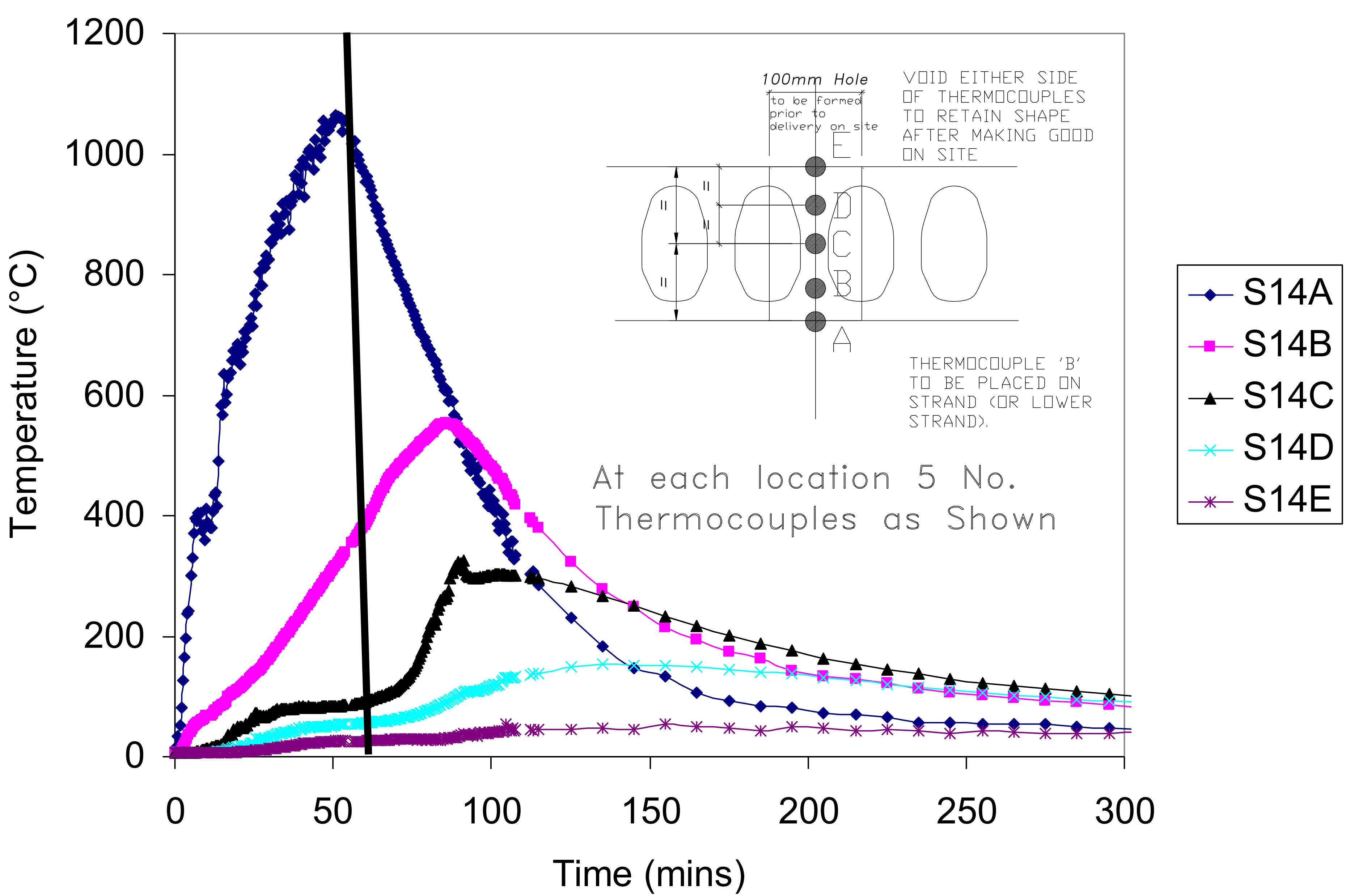
Limitations of the prescriptive approach



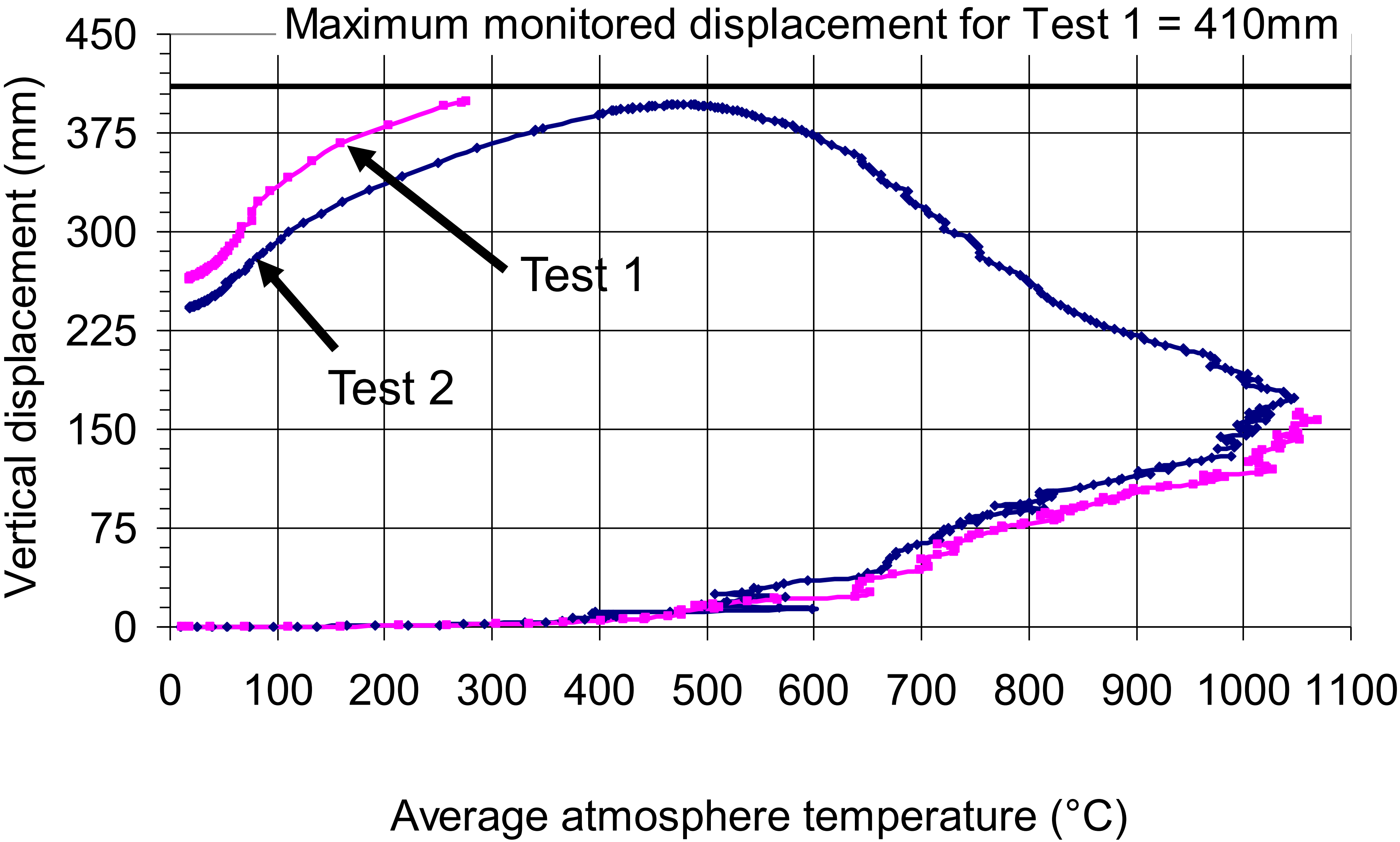
Test 1
Test 2
1200
1000
800
600
400
200
0
Atmosphere temperature (°C)
0
50
100
150
200
Time (mins)


MKM
BUILDING SUPPLIES
"My Kind of Merchant"

Fire protection fell off at 60 mins !



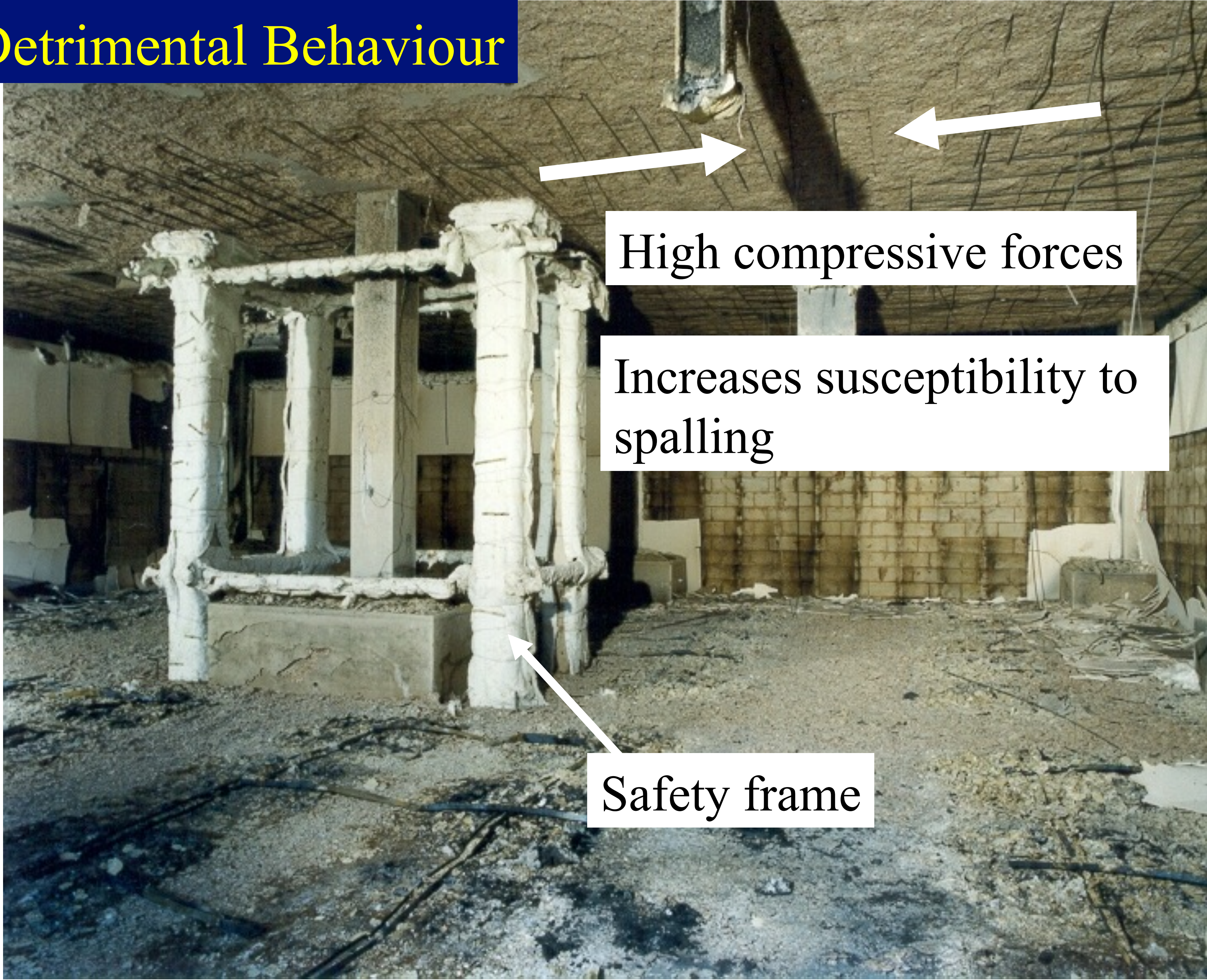
Temperature (°C)
Time (mins)
0
200
400
600
800
1000
1200
0
50
100
150
200
250
300
100mm Hole
to be formed prior to delivery on site
VOID EITHER SIDE OF THERMOCOUPLES TO RETAIN SHAPE AFTER MAKING GOOD ON SITE
E
D
C
B
A
THERMOCOUPLE 'B' TO BE PLACED ON STRAND (OR LOWER STRAND).
At each location 5 No. Thermocouples as Shown
S14A
S14B
S14C
S14D
S14E



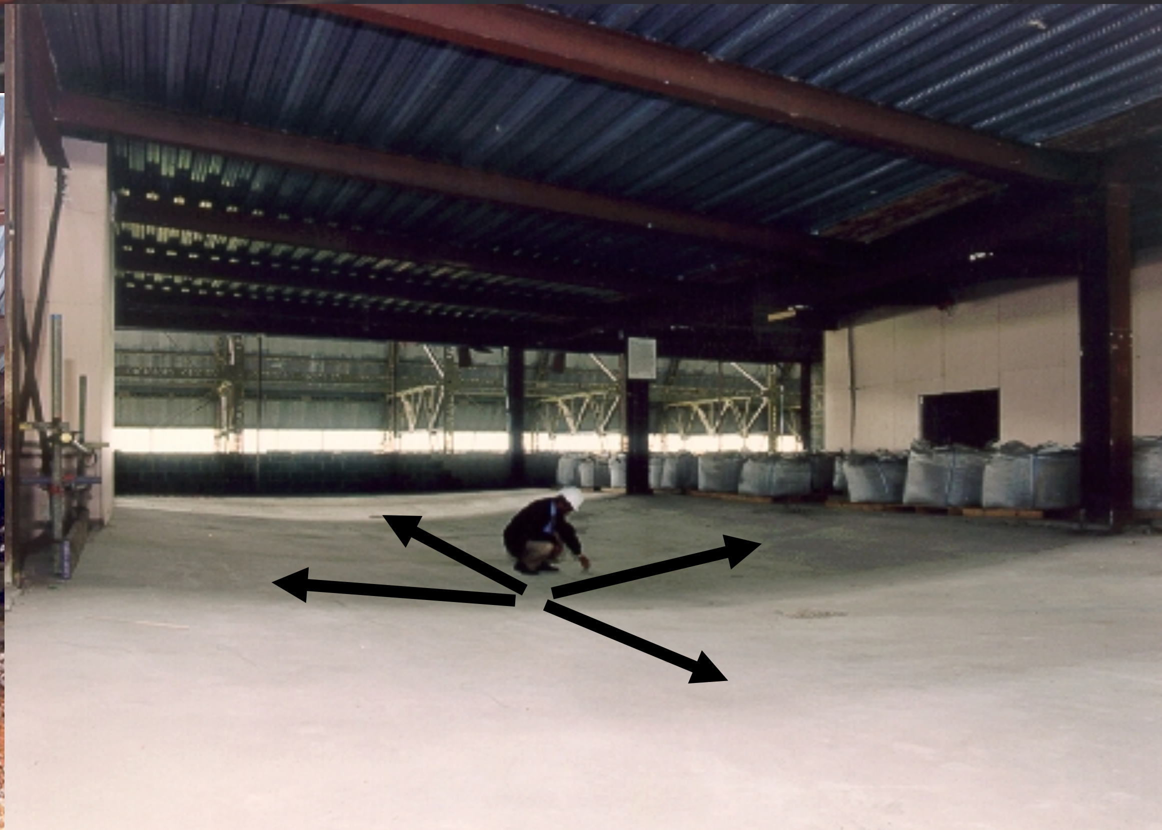
Maximum monitored displacement for Test 1 = 410mm
Test 1
Test 2
Vertical displacement (mm)
450
375
300
225
150
75
0
0
100
200
300
400
500
600
700
800
900
1000
1100
Average atmosphere temperature (°C)

Detrimental Behaviour

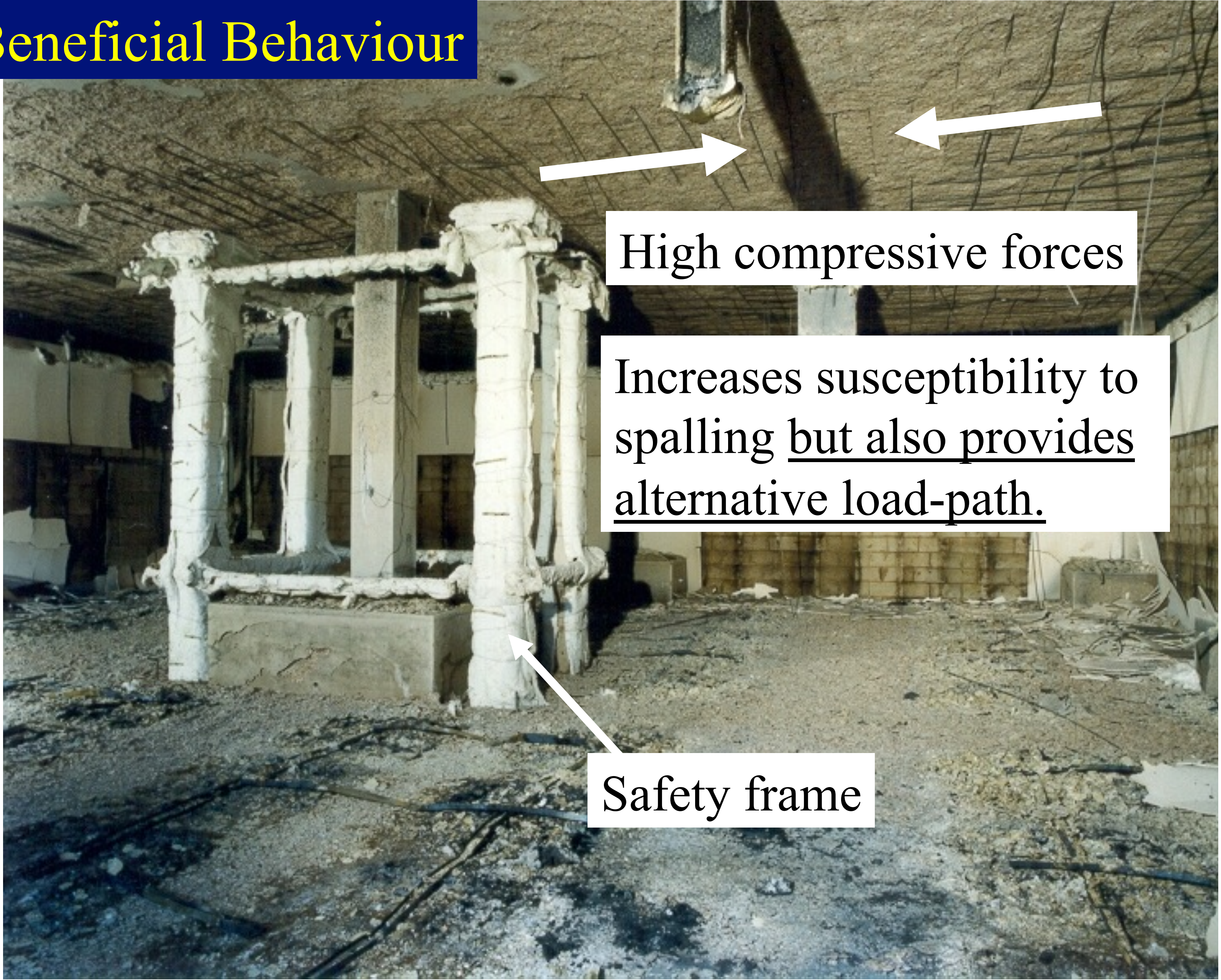
Detrimental Behaviour



Beneficial Behaviour

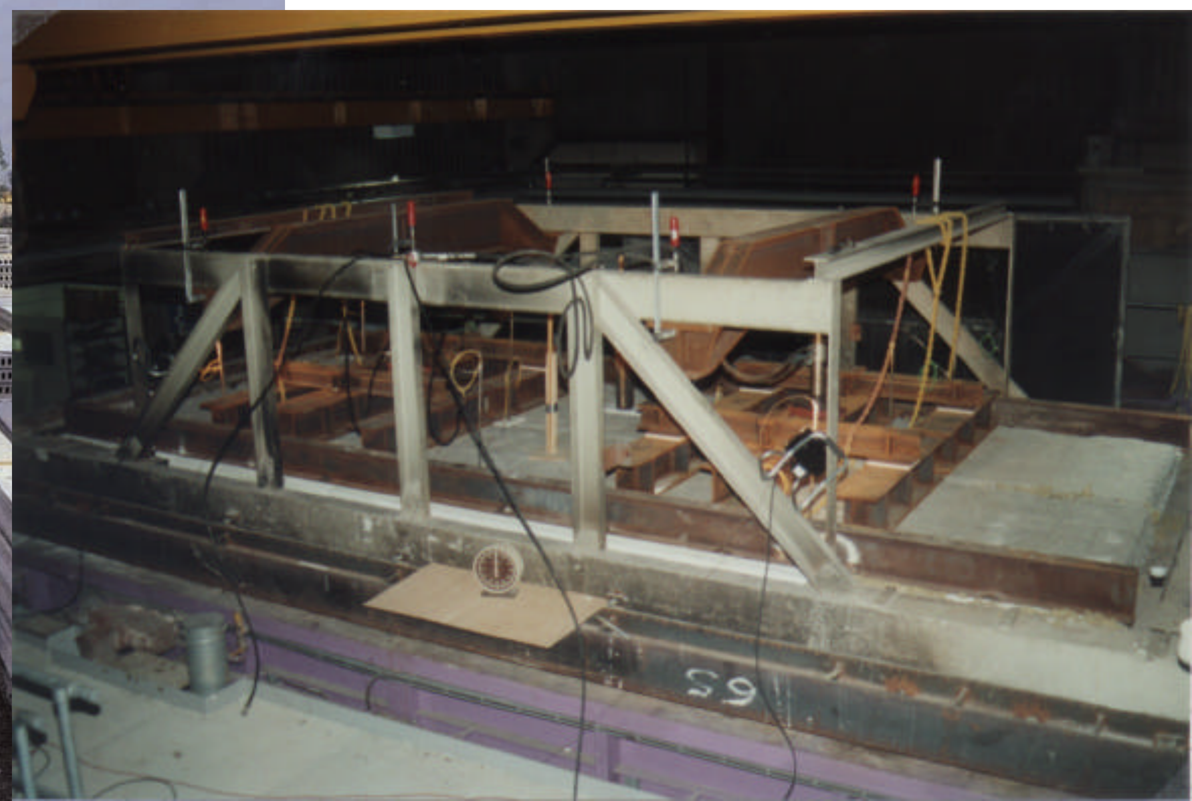


Beneficial Behaviour



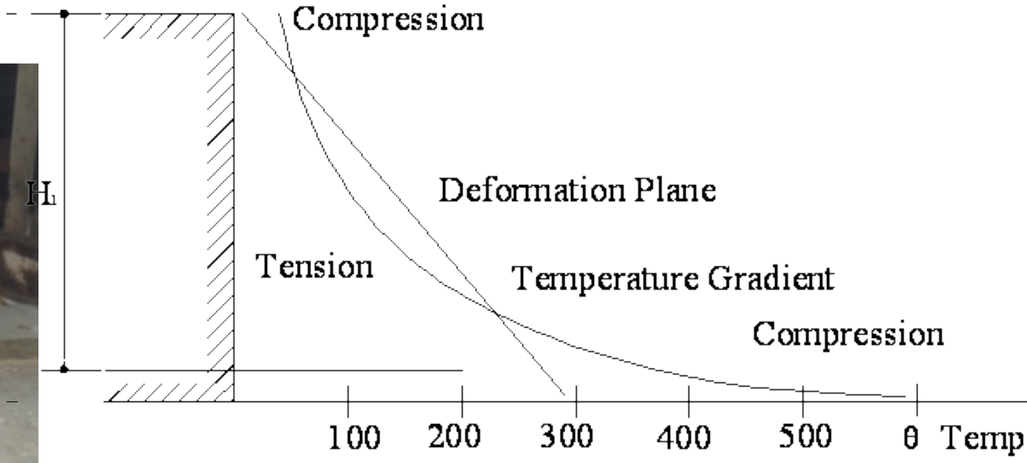
Pre-cast Hollowcore Floors

Beneficial effects of whole building behaviour



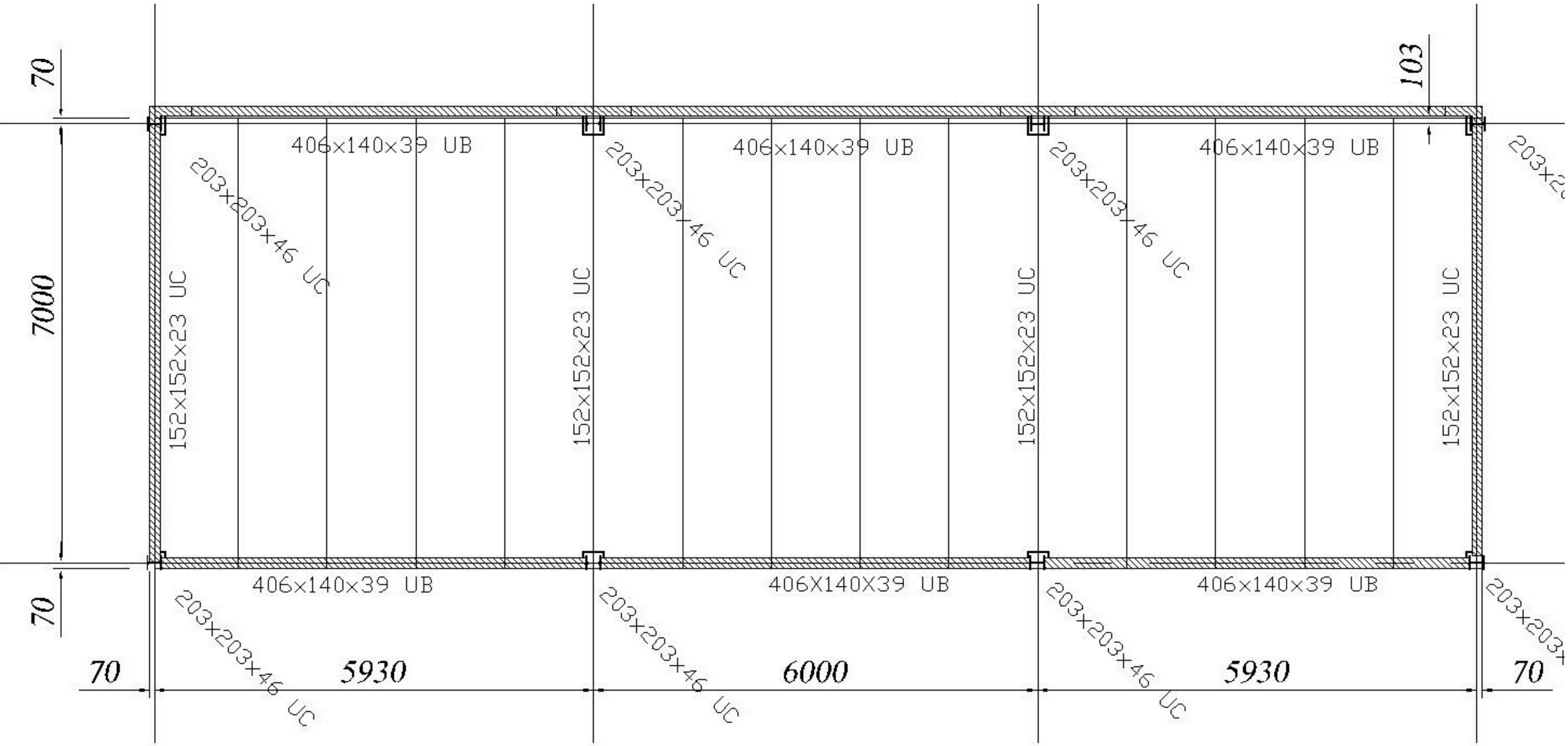
60 mins Fire Resistance

Lasted 21 mins in a standard fire test.



Test Structure: 7.02m×17.76m (internal plan dimensions) ×3.6m height

15 units 1.2m wide×200mm deep



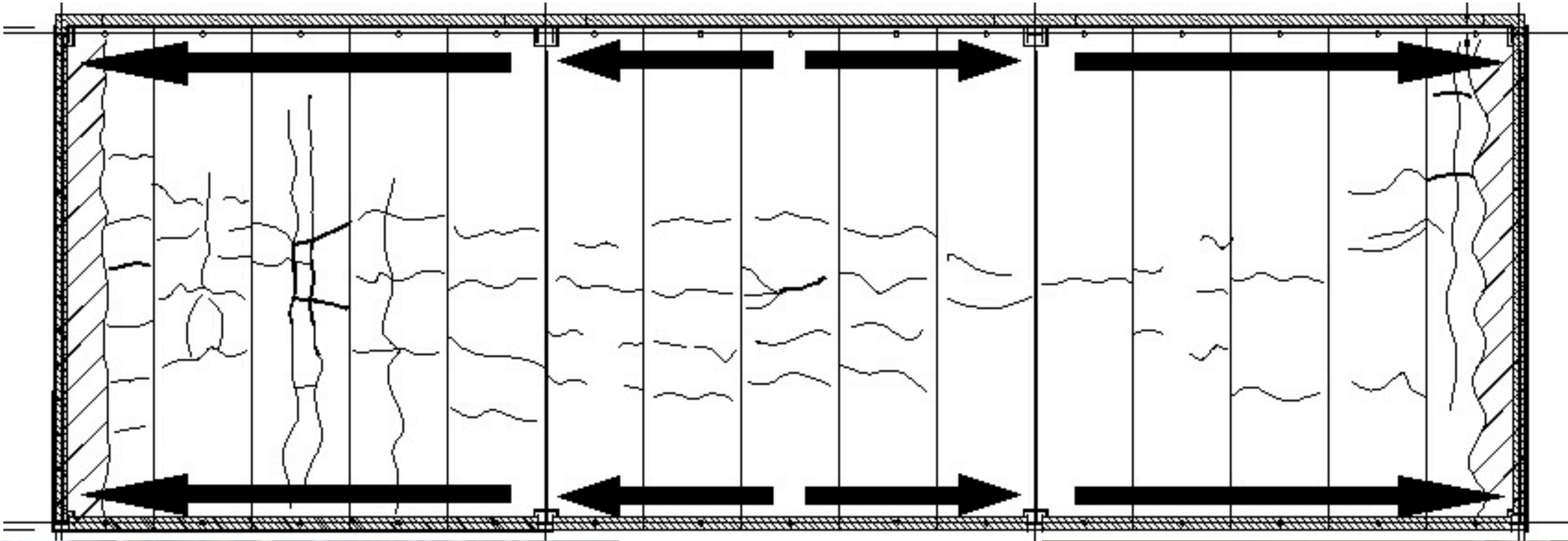

570MJ/m^2
(32.5kg wood/m^2)

Design to BSEN1992-1-2

Maximum strand temp = 553ºC

Flexural capacity = 39.7kNm

Applied load = 54.8kNm



Evidence of a lateral compressive strip forming enhancing flexural and shear capacity

Prescriptive approach

Prescriptive approach

(Based on Standard Fire Tests)

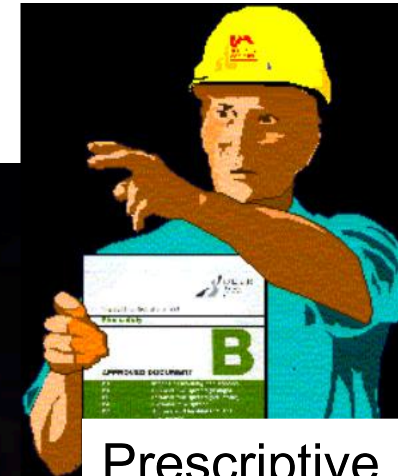
Advantages:

- Limited design effort
- Experience has shown that approach works (to date!)
- Approach is easily understood by all parties

Prescriptive approach

Disadvantages:

- Actual structural behaviour is ignored
- Effect of real fires ignored.
- Levels-of-safety and robustness are unknown.
- Optimum solution in terms of life safety, economical impact and environmental damage is unknown.

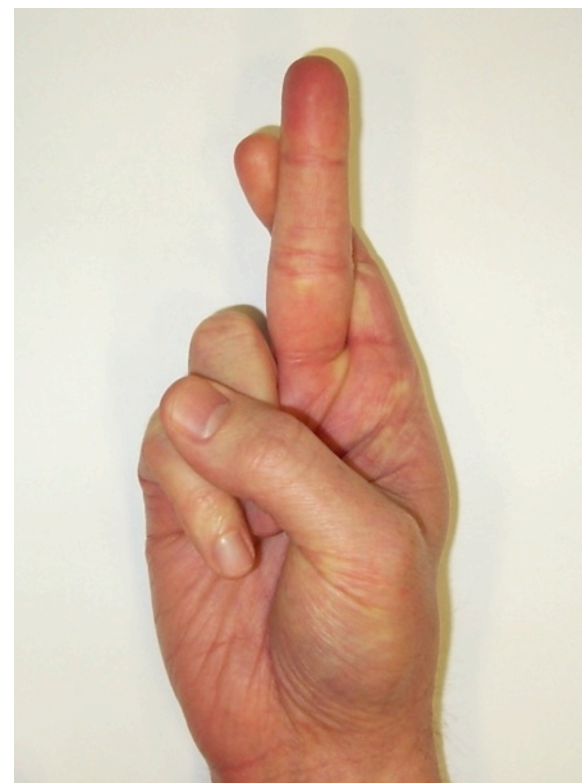


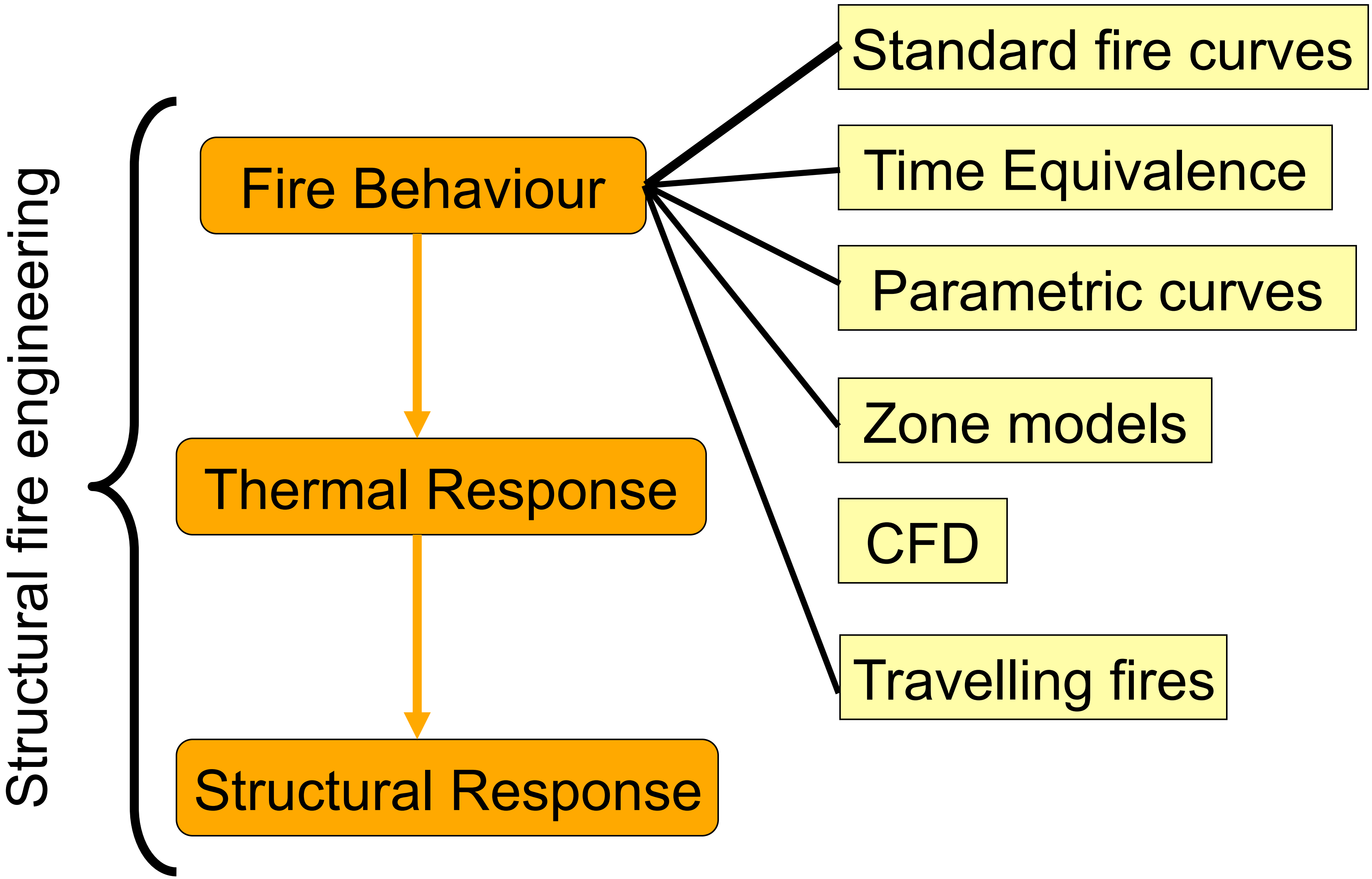
Prescriptive approach

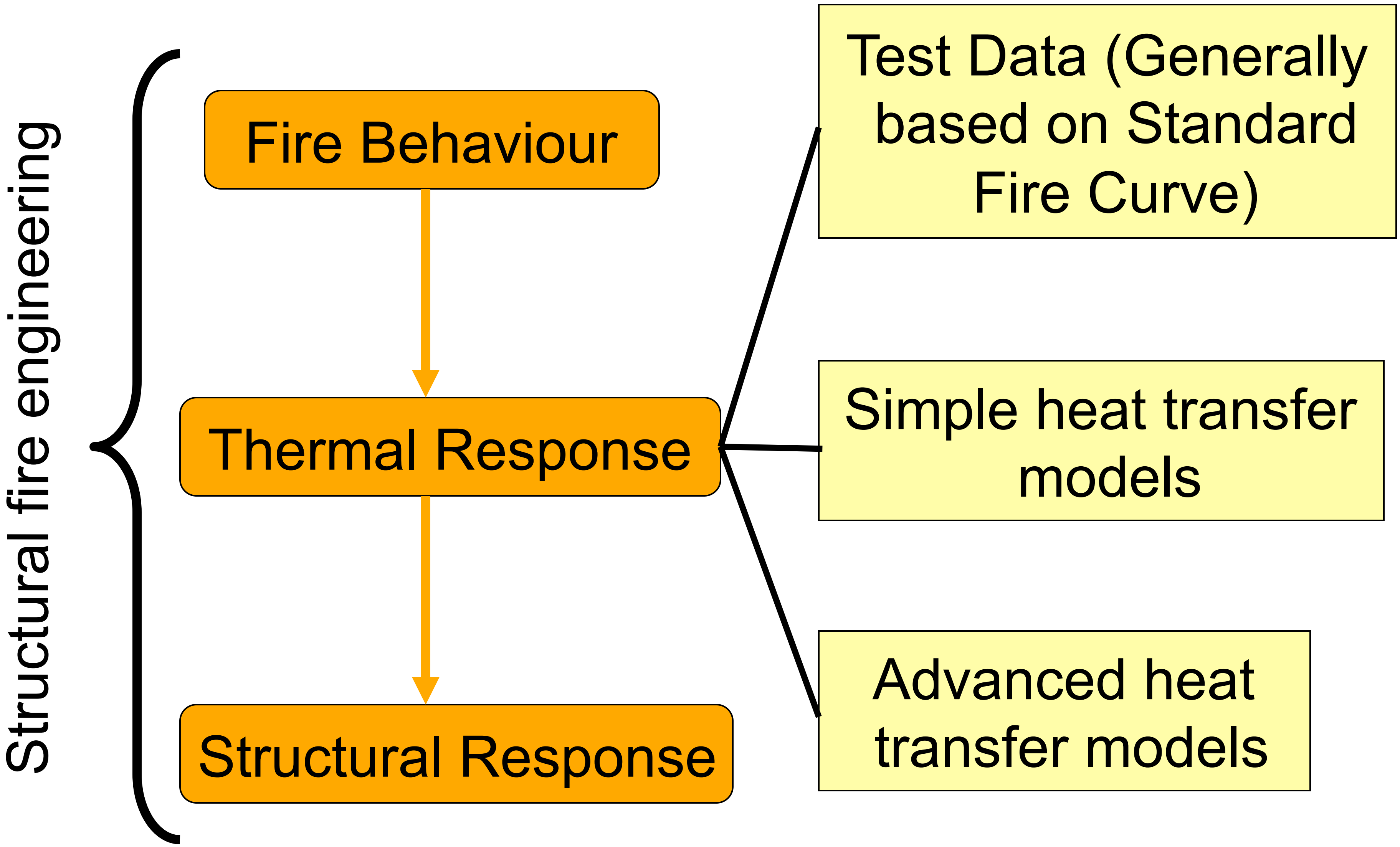
Structural fire engineering – prescriptive approach

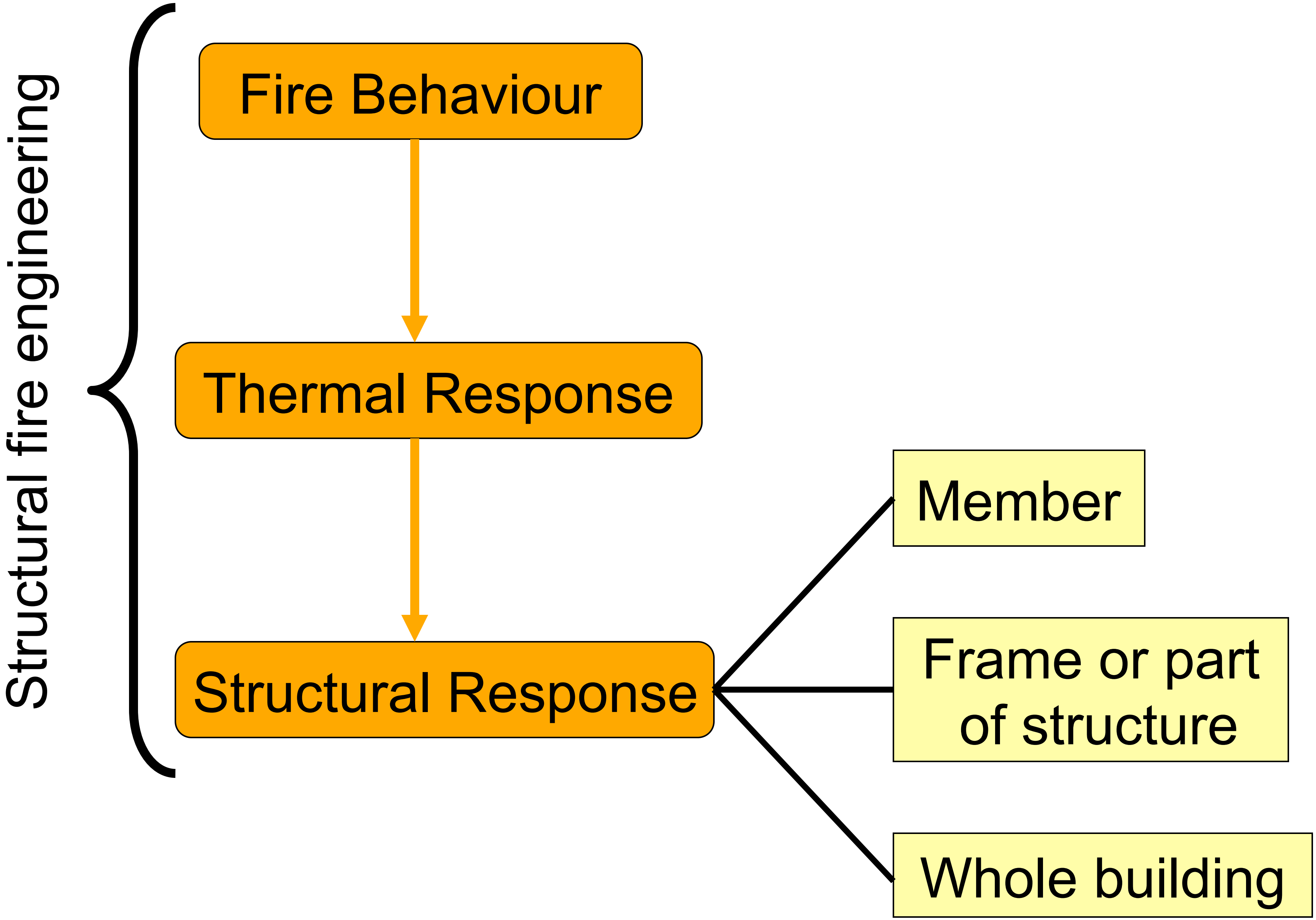
- Actual structural behaviour is ignored
- Effect of real fires ignored.

Compensating errors ???




Structural fire engineering
Fire Behaviour
Thermal Response
Structural Response
Standard fire curves
Time Equivalence
Parametric curves
Zone models
CFD
Travelling fires


Structural fire engineering
Fire Behaviour
Thermal Response
Structural Response
Test Data (Generally based on Standard Fire Curve)
Simple heat transfer models
Advanced heat transfer models


Structural fire engineering
Fire Behaviour
Thermal Response
Structural Response
Member
Frame or part of structure
Whole building

Performance-based structural fire engineering

Advantages

- Allows actual behaviour and robustness of the building to be assessed.
- Allows optimum design to be determined taking into account life safety, financial impact and environmental issues.
- Can be used as part of an assessment of multiple risks (e.g. explosions followed by a fire)

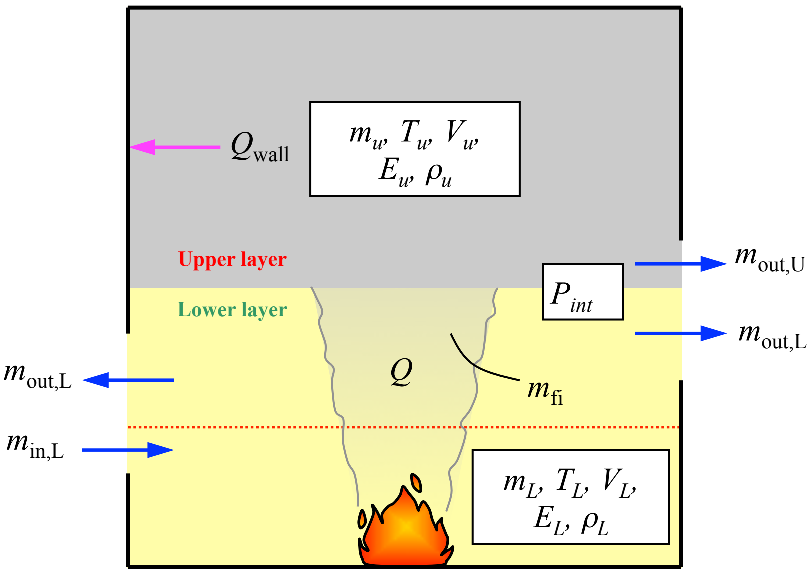
Performance-based structural fire engineering

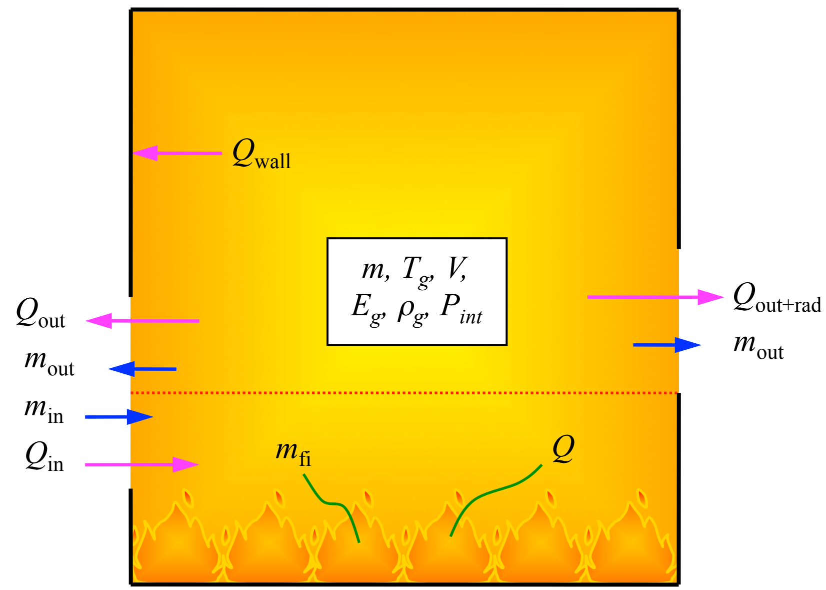
Disadvantages

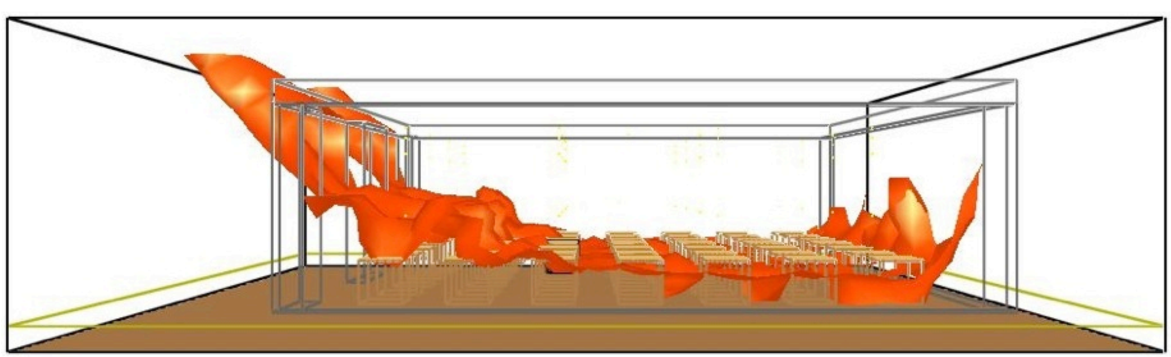
- Design effort increased compared to other methods (client may not understand added-value).
- Requires multi-discipline skills.
- Design can be complicated.
- Change of building use may make the fire design invalid.

Use of Advanced Models

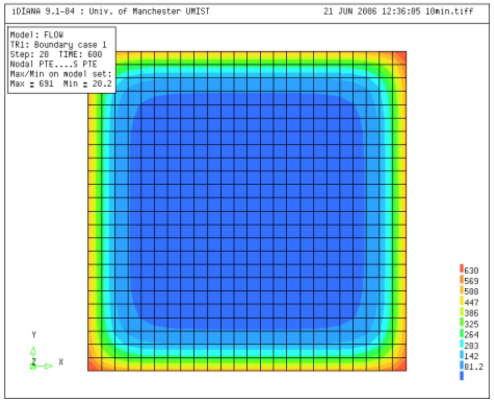
To predict fire, thermal and structural behaviour.



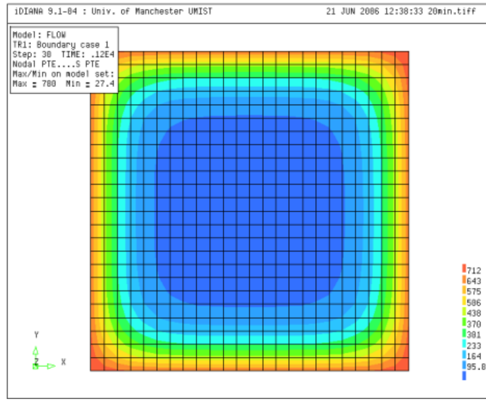




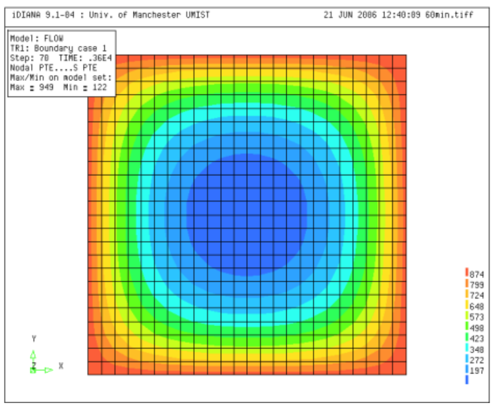
Use of Advanced Models



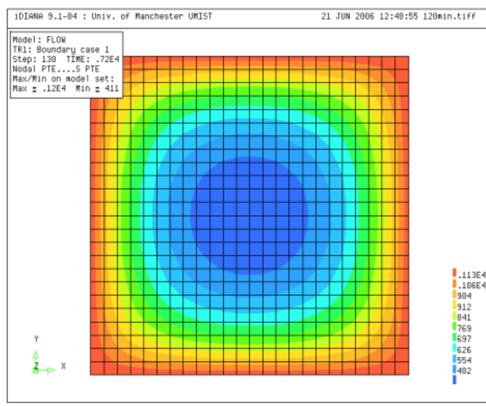
10min of fire



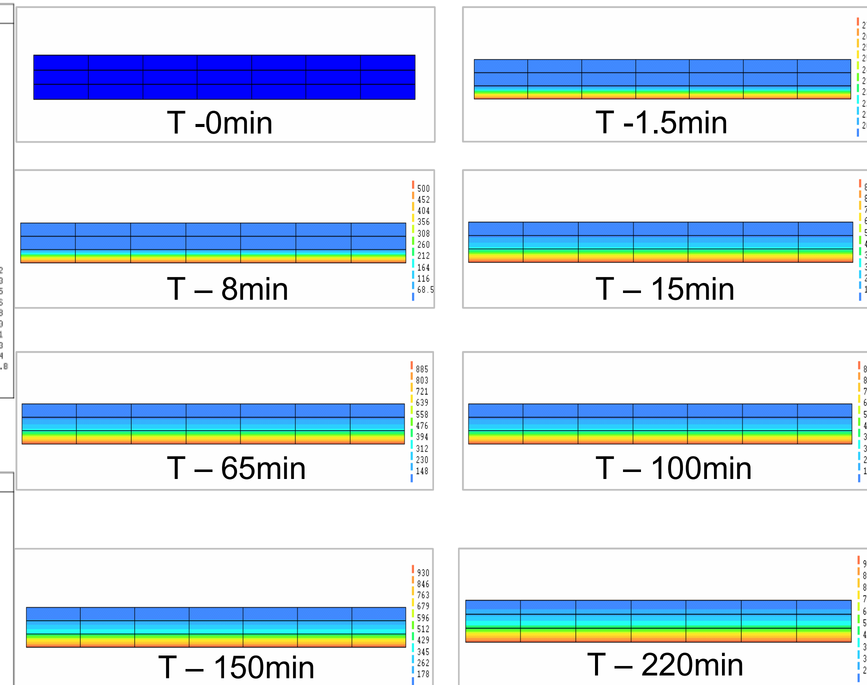
30min of fire

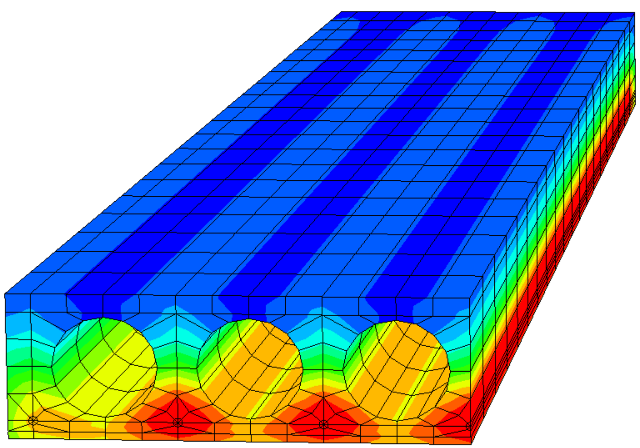


60min of fire

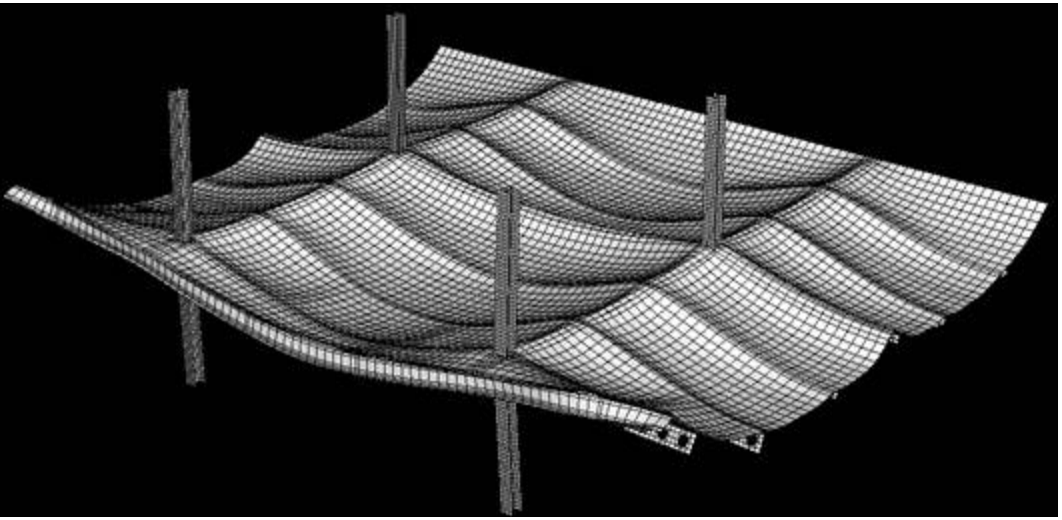


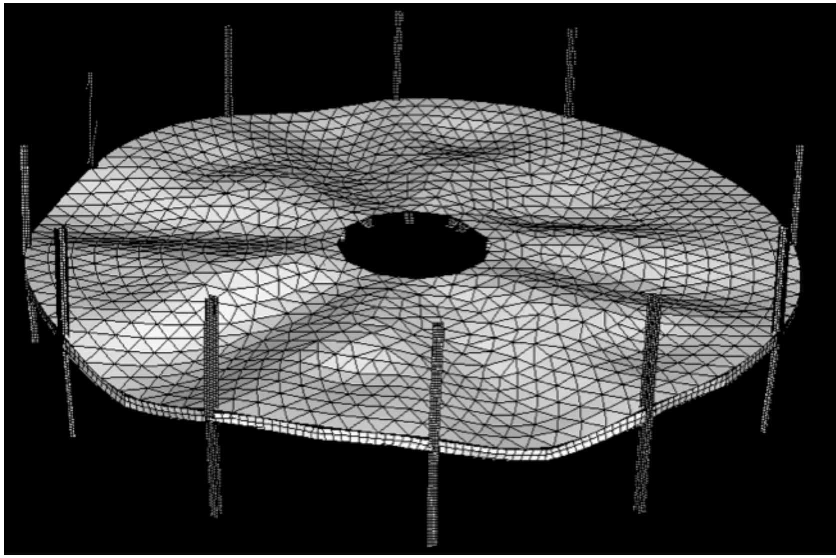
120min of fire

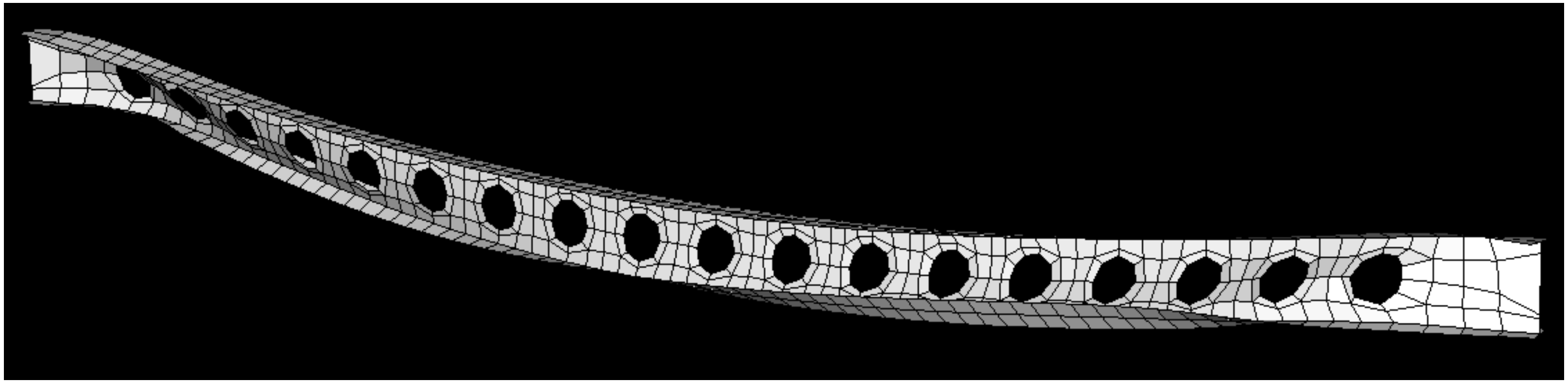




Use of Advanced Models



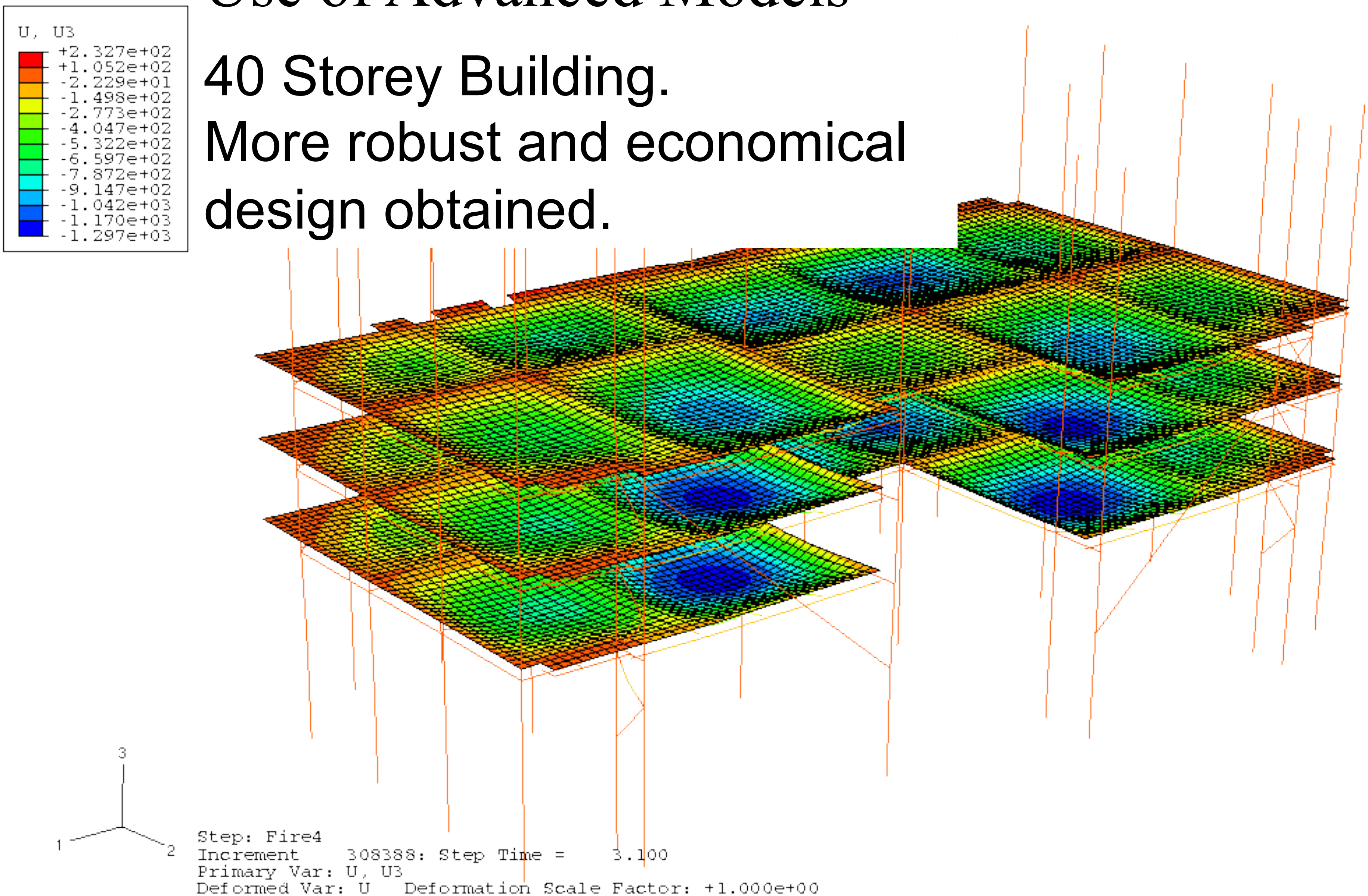




(images courtesy Arup Fire)

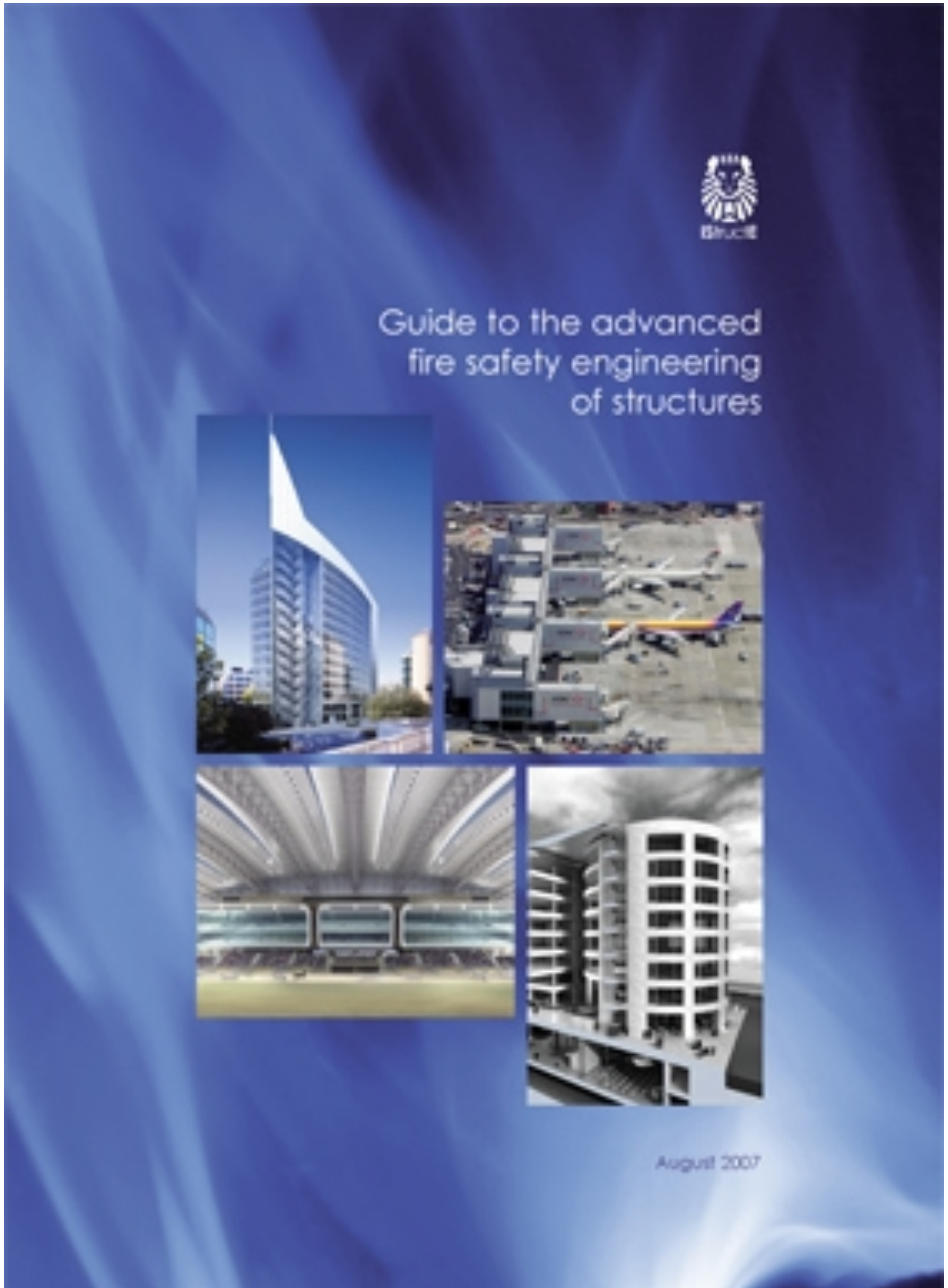
Use of Advanced Models

40 Storey Building.
More robust and economical design obtained.



(images courtesy Arup Fire) ARUP

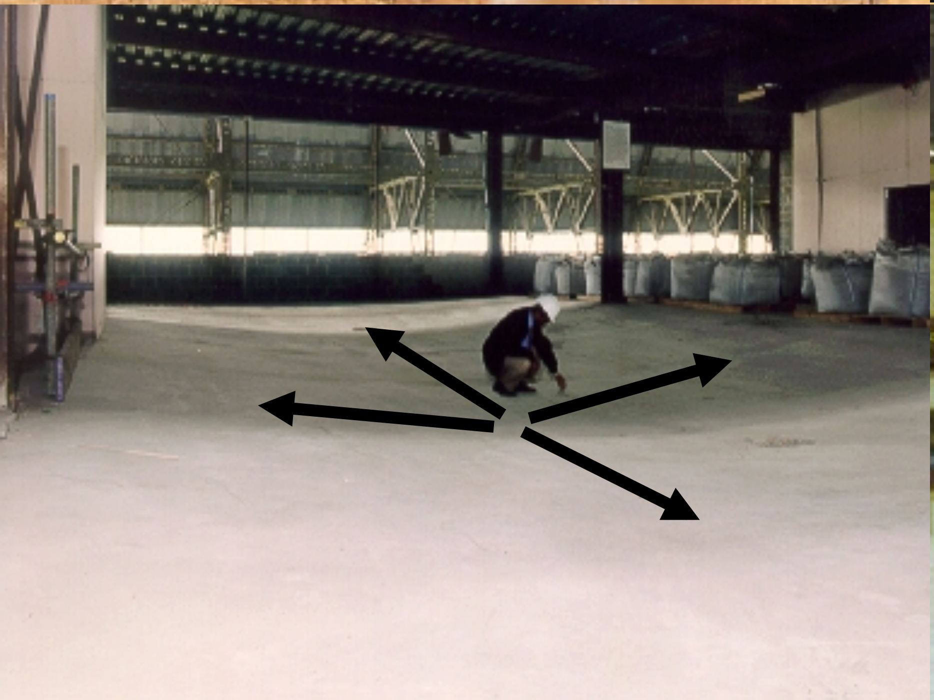


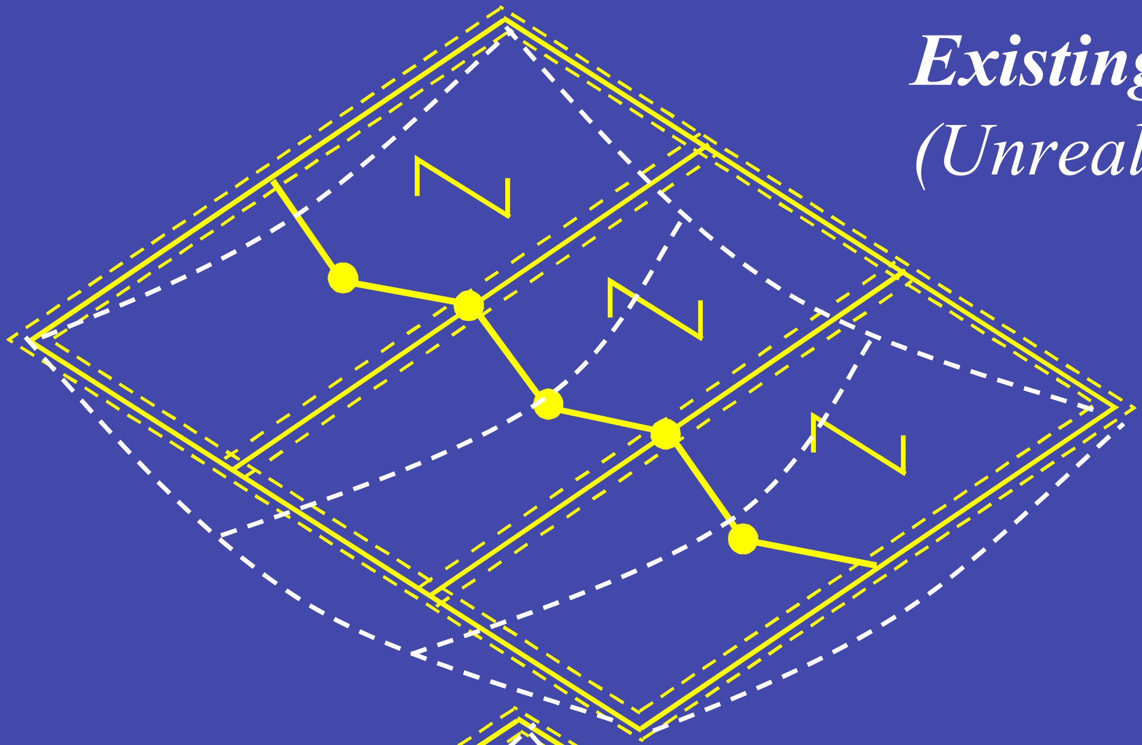



Presents a framework for carrying out advanced Structural Fire Engineering.

Guidance on Validation, Verification & Review

Membrane Action



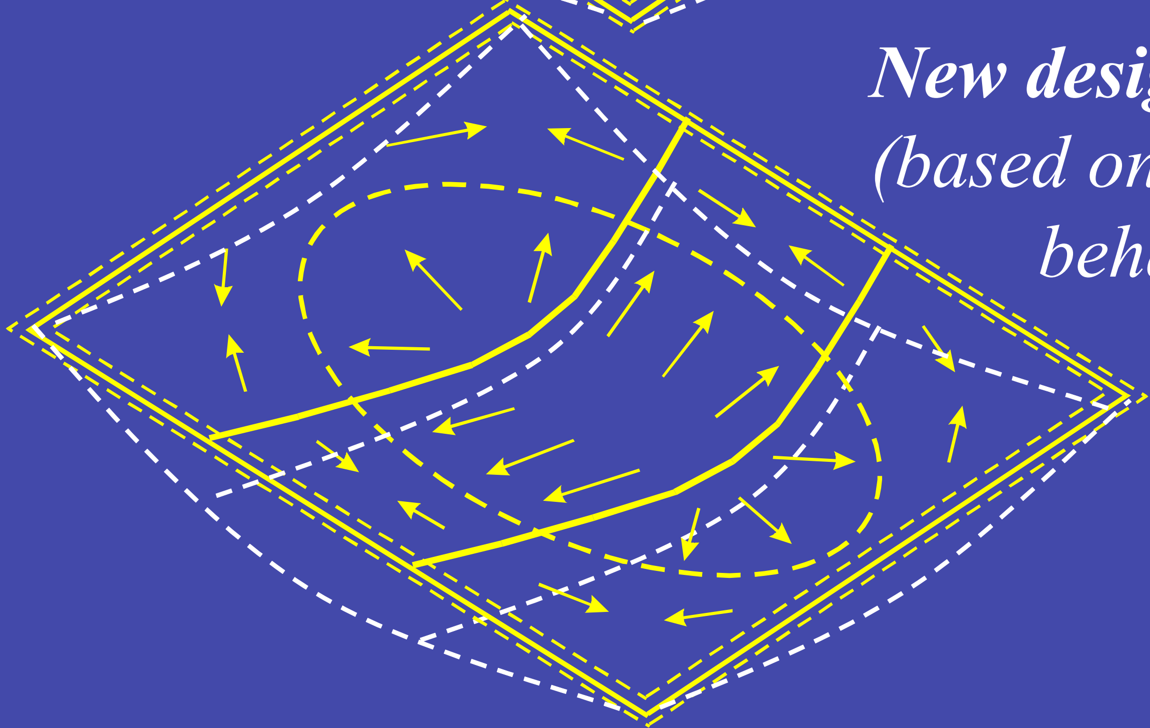


Existing design method

(Unrealistic member behaviour)

Composite slabs based on flexural behaviour

Steel beams typically protected

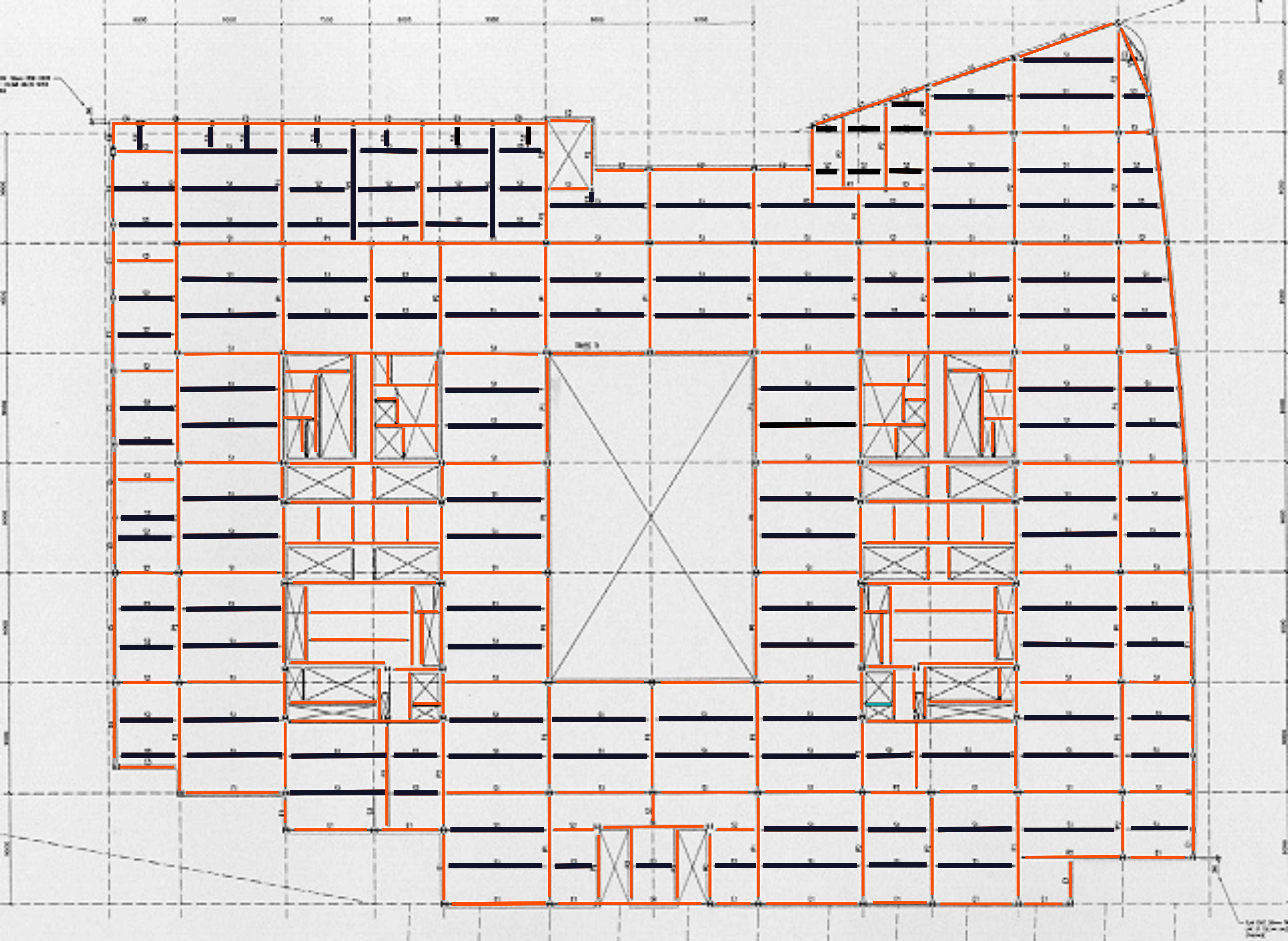


New design method

(based on research into realistic behaviour)

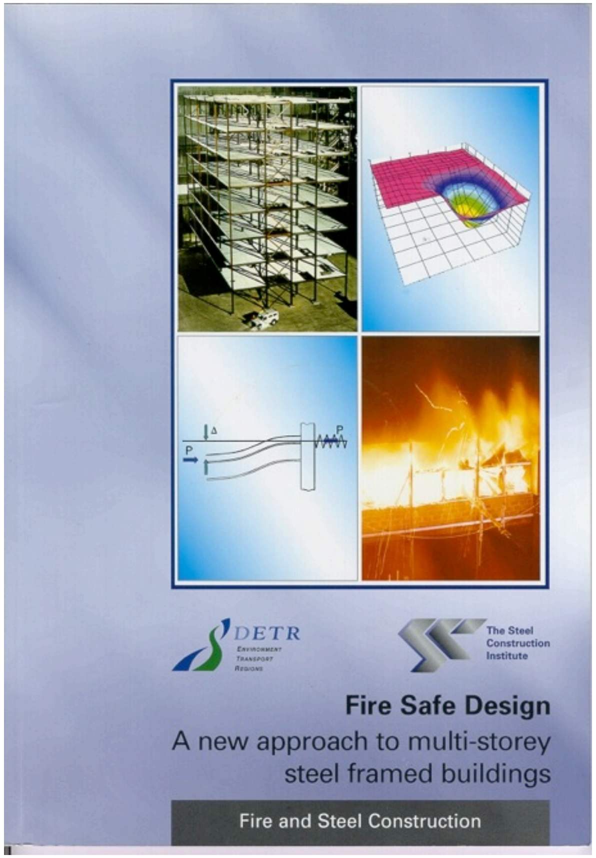
Composite slabs based on membrane action

Some steel beams unprotected



Unprotected beams

40 to 55% of beams can be left unprotected.




digest
CI/SfB Hh2 (K2)
Digest 462

Steel structures supporting composite floor slabs: design for fire

Colin Bailey
BRE Centre for Structural Engineering

Test results and observations from real fires in real buildings have continually shown that steel framed structures comprising composite floor slabs and downstand steel beams perform far better than current fire design methods suggest.

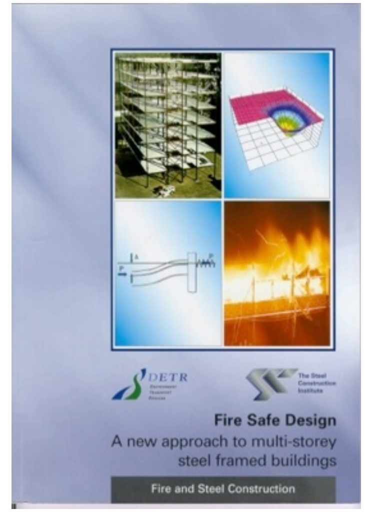
This Digest shows how the true structural behaviour of these types of buildings can be calculated in fire, allowing a reduction in the amount of passive fire protection currently used.

Designers commonly perceive that steel structures will perform badly in a fire, resulting in the general practice of protecting or partially protecting exposed parts of a steel frame. Steel, as with all materials, loses strength and stiffness as its temperature rises and if the building structure is considered on an element by element basis, the perception of bad performance of exposed steel members in fire is reasonable. However, tests (Figure 1) and observations from real fires in real steel structures, which incorporate a composite flooring system with downstand steel beams, have shown that these types of structures perform far better than current design methods suggest. It is possible, by considering the true inherent fire performance of these structures, that a significant amount of passive fire protection that is currently specified for the steel beams is unnecessary. Analysis of test results [1] has shown that the load path mechanisms of a steel structure, supporting a composite slab, during a fire are different from those assumed during the normal use of the building. In particular, membrane action of the composite slab at large displacements is the predominate behaviour in a fire (fire-limit state). This Digest shows how the membrane action of the composite slab can be incorporated into the structural fire design and how passive fire protection is required only on specific supporting downstand steel beams.

Figure 1 Fire test on a steel framed structure with a composite floor

BRE
constructing the future

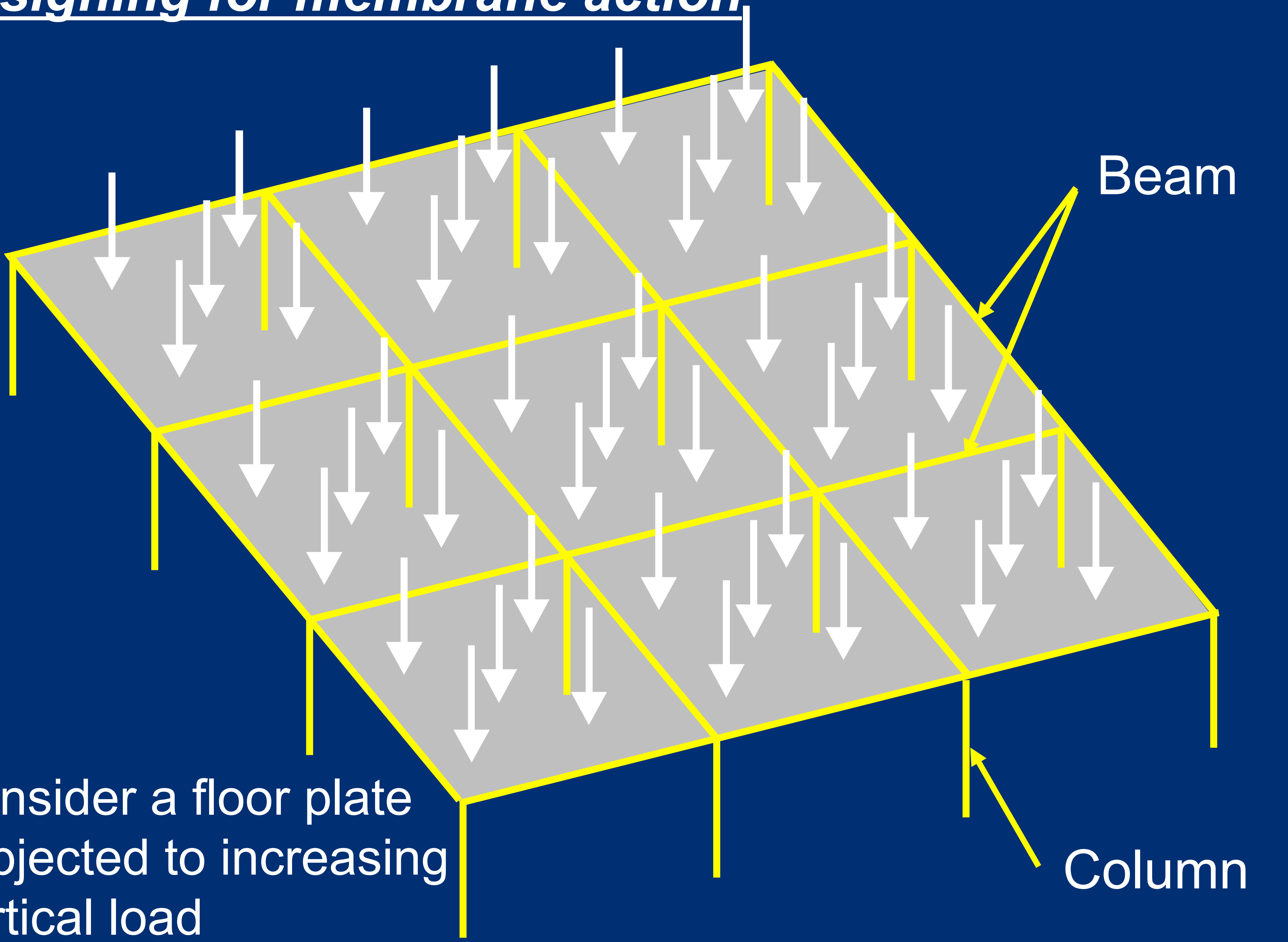
Simple design guides



ArcelorMittal MACS+ design software

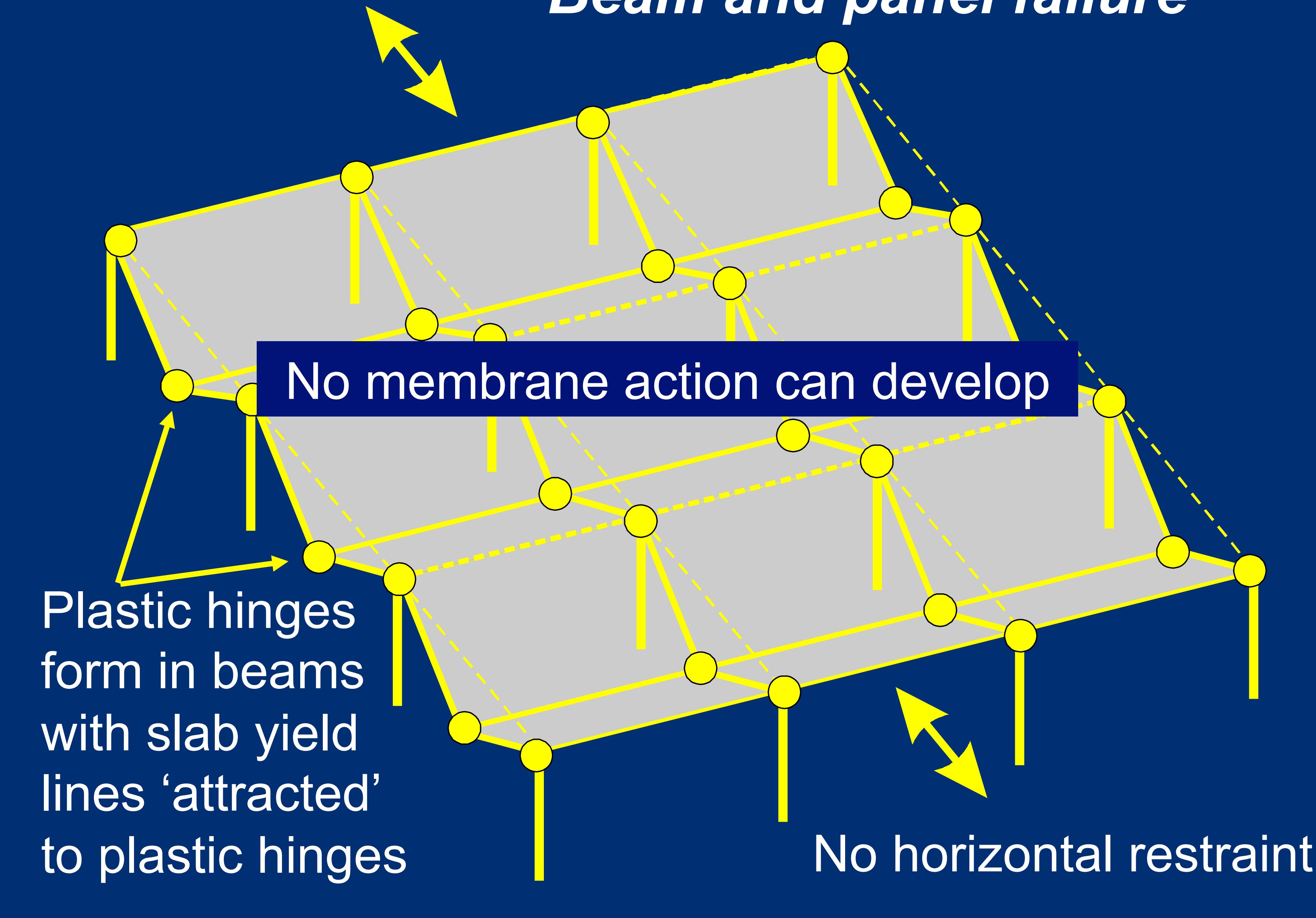
- BOBST building (Switzerland)
- ArcelorMittal Steel Centre (Belgium)
- EVS Building (Belgium),
- Geric Commercial Ccentre (France)
- BNP Bank Tower (France)
- BP Sloar Office building (Spain)
- Noho Square Office Building
- Victoria Circle office buildings in London
- West Cheshire College – Ellesmere Port
- Aquinas College – Stockport
- Derby Riverlights (mixed use building)
- Bristol Broadmead (mixed use building)
- Hayman Primary – Nottingham
- The Heath Academy – Runcorn.
- 55 Basinghall Street, London
- 35 Basinghall Street London,
- Exchange Place, Edinburgh (Hanover Cube)
- East Ayrshire Schools, Scotland
- Charles Street, Leicester (Akeler) – Commercial Office
- Kingsgate Shopping Centre, Scotland
- Park House, London (Land Securities) – Mixed Use (Commercial, Retail & residential)
- St. Davids, Cardiff (Bovis Lend Lease) – Shopping Centre
- Kirkcaldy "Victoria" Hospital, Scotland - Healthcare
- Osnaburgh Street "Regents Place", London – Commercial office
- Abbey Mill House "The Blade", Reading – Commercial office
- T-Mobile UK Headquarters Hatfield Business Park, Hertfordshire, UK
- Diener Building Novartis in Basel Switzerland;

Designing for membrane action

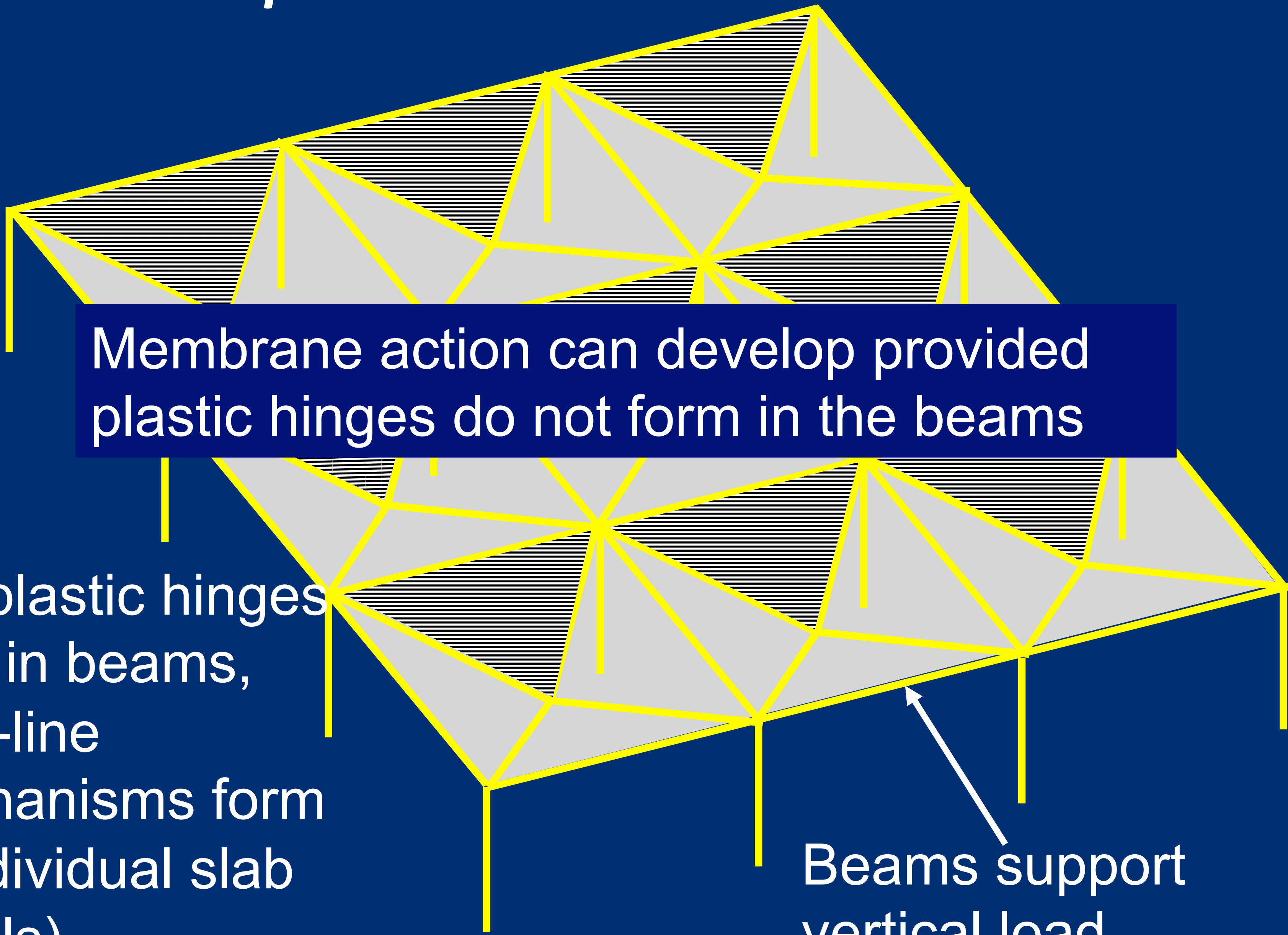


Consider a floor plate subjected to increasing vertical load

Beam and panel failure



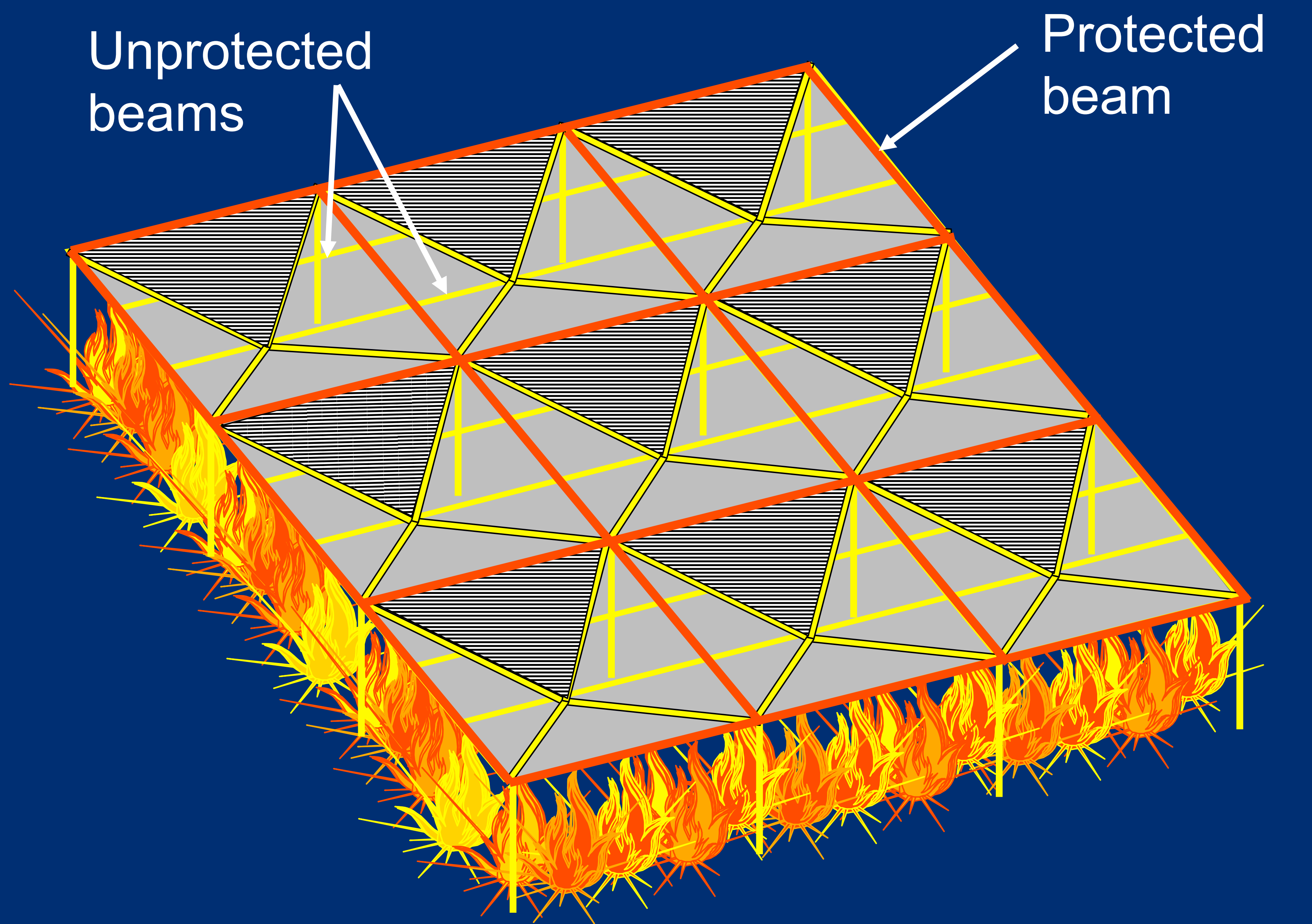
Slab panel failure



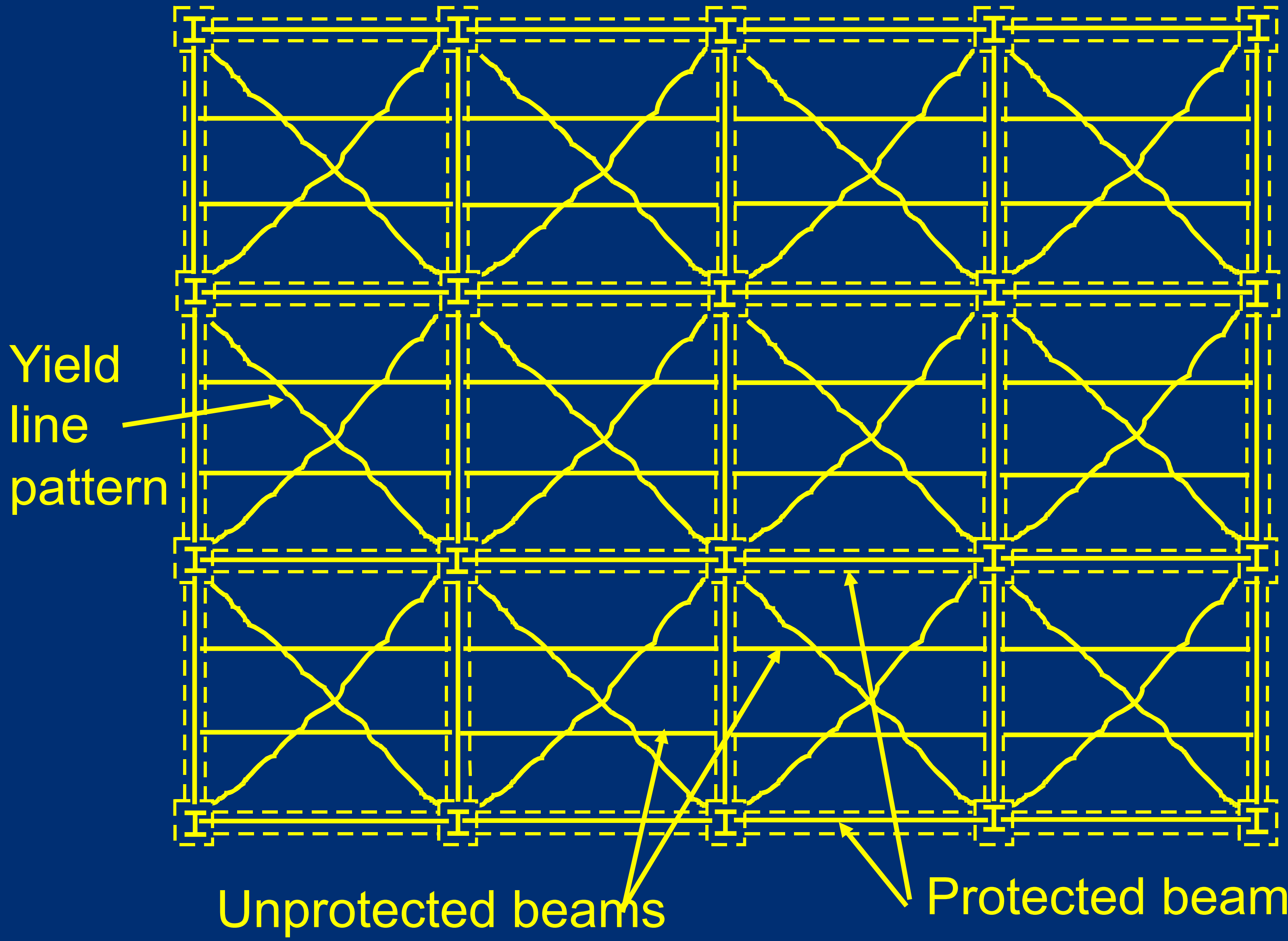
Membrane action can develop provided plastic hinges do not form in the beams

(No plastic hinges form in beams, yield-line mechanisms form in individual slab panels)

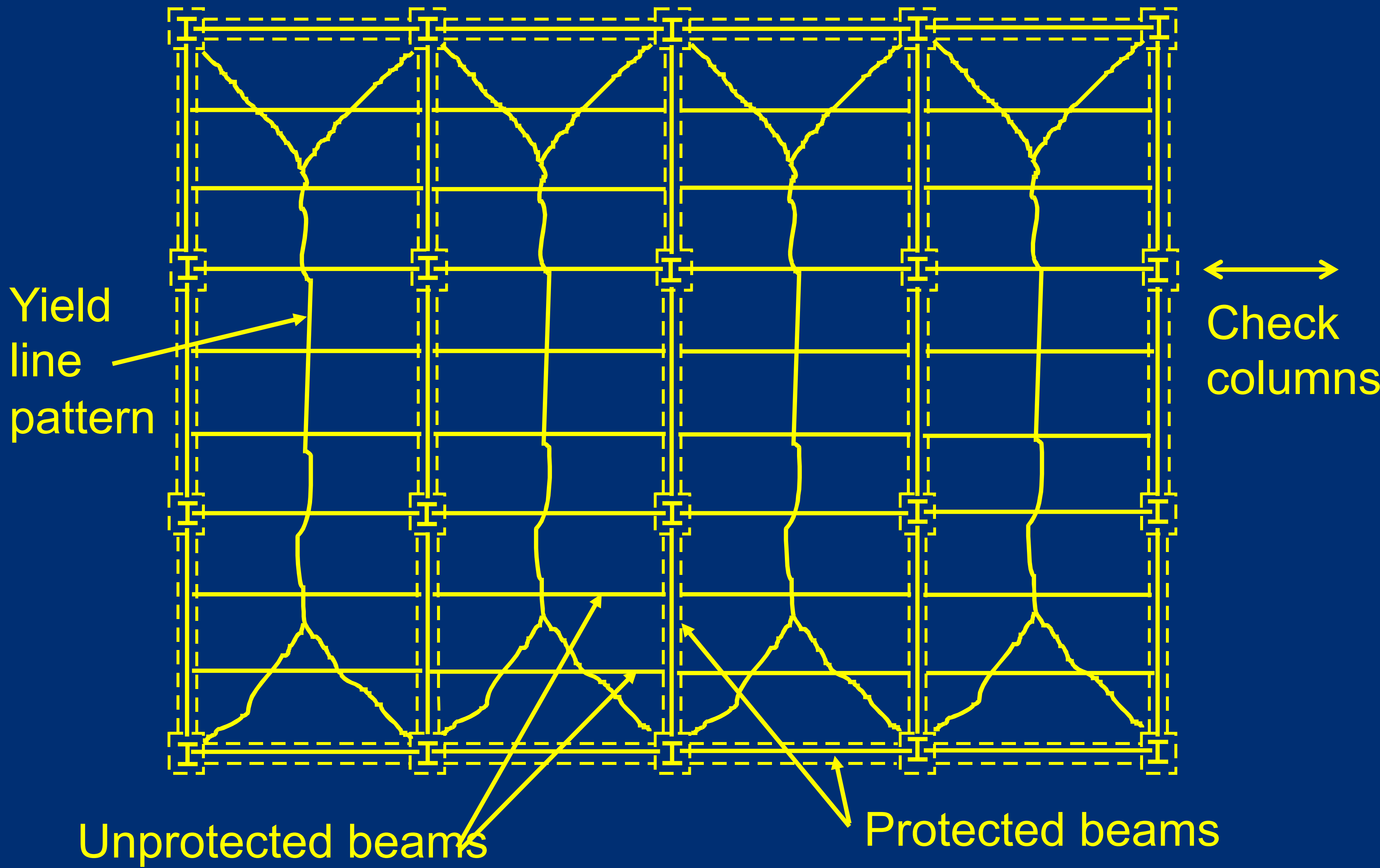
Beams support vertical load


Unprotected
beams
Protected
beam

Designing for membrane action in fire

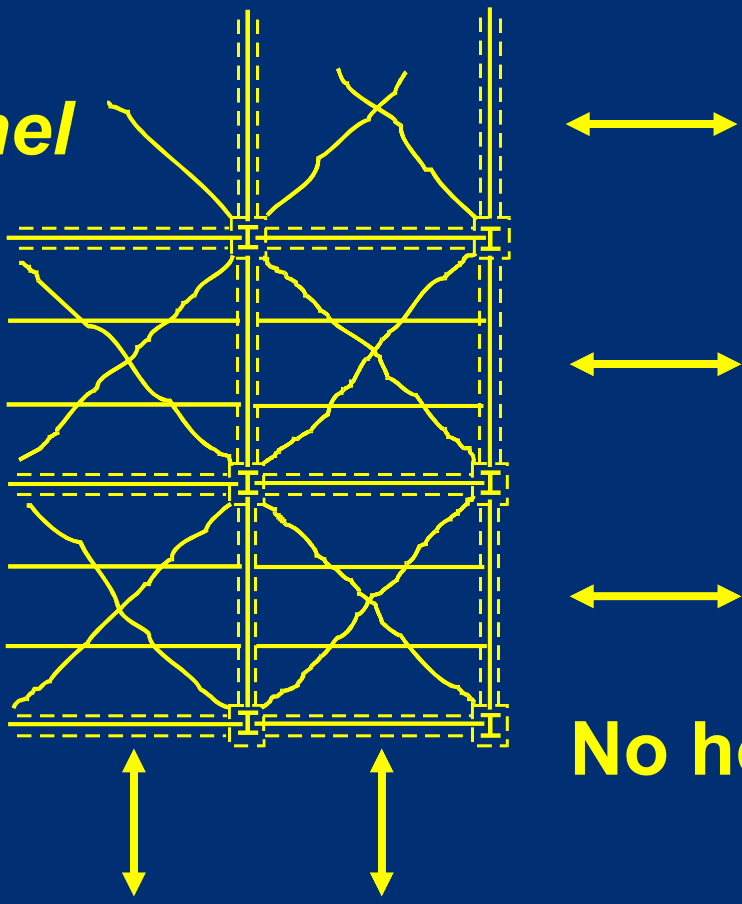


Designing for membrane action in fire



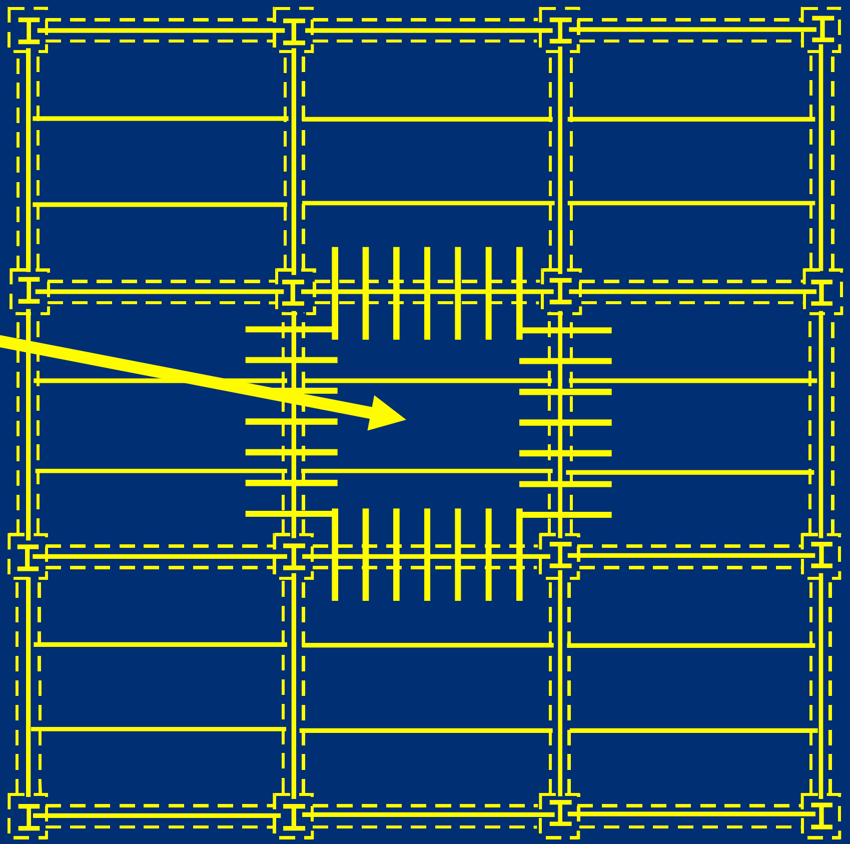
Are the heated panels unrestrained or restrained against horizontal movement ?

Edge panel



No horizontal restraint

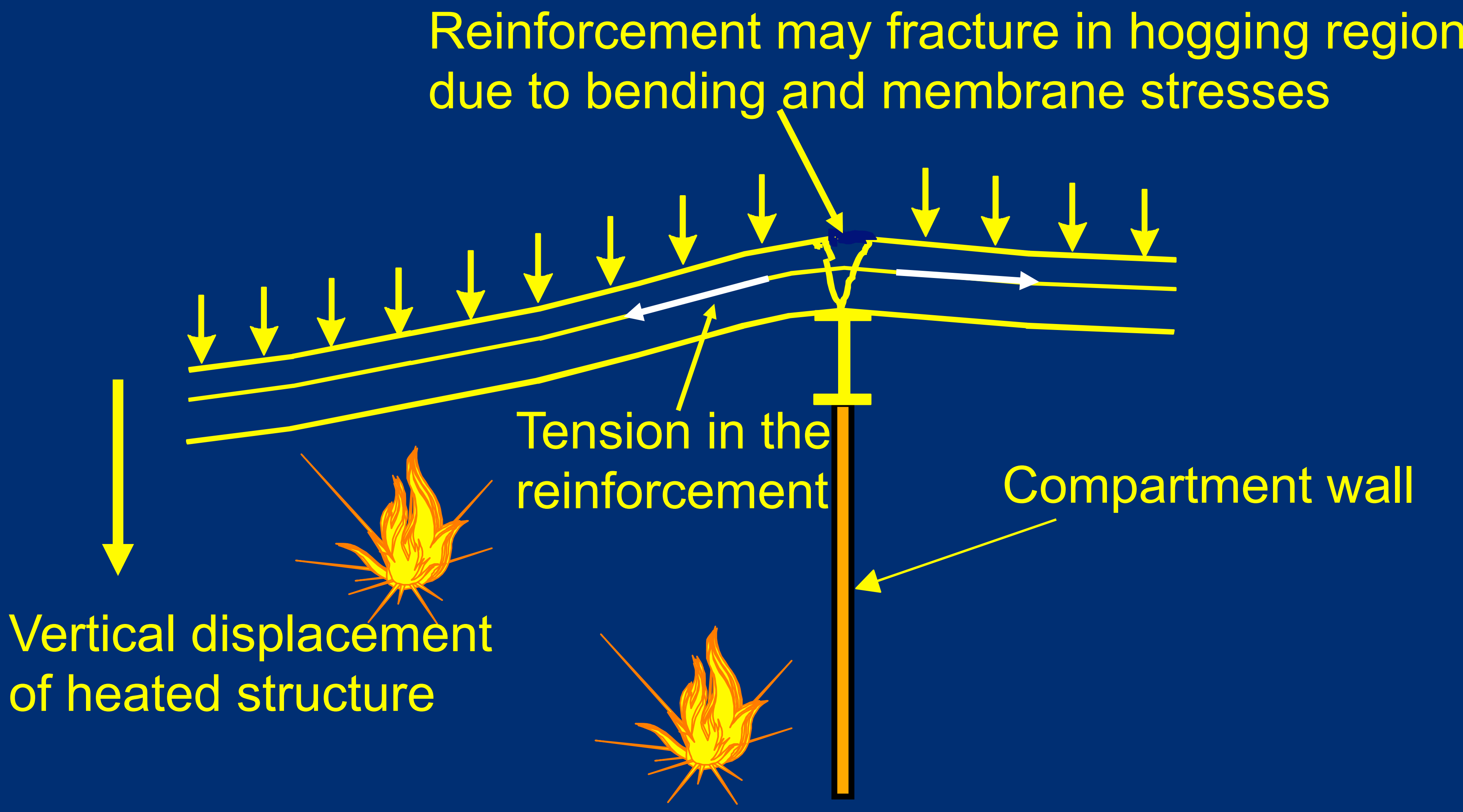
Internal
panel ?



Internal panel : reinforcement is continuous

∴ is horizontal restraint provided ?

(A restrained panel will support greater load)



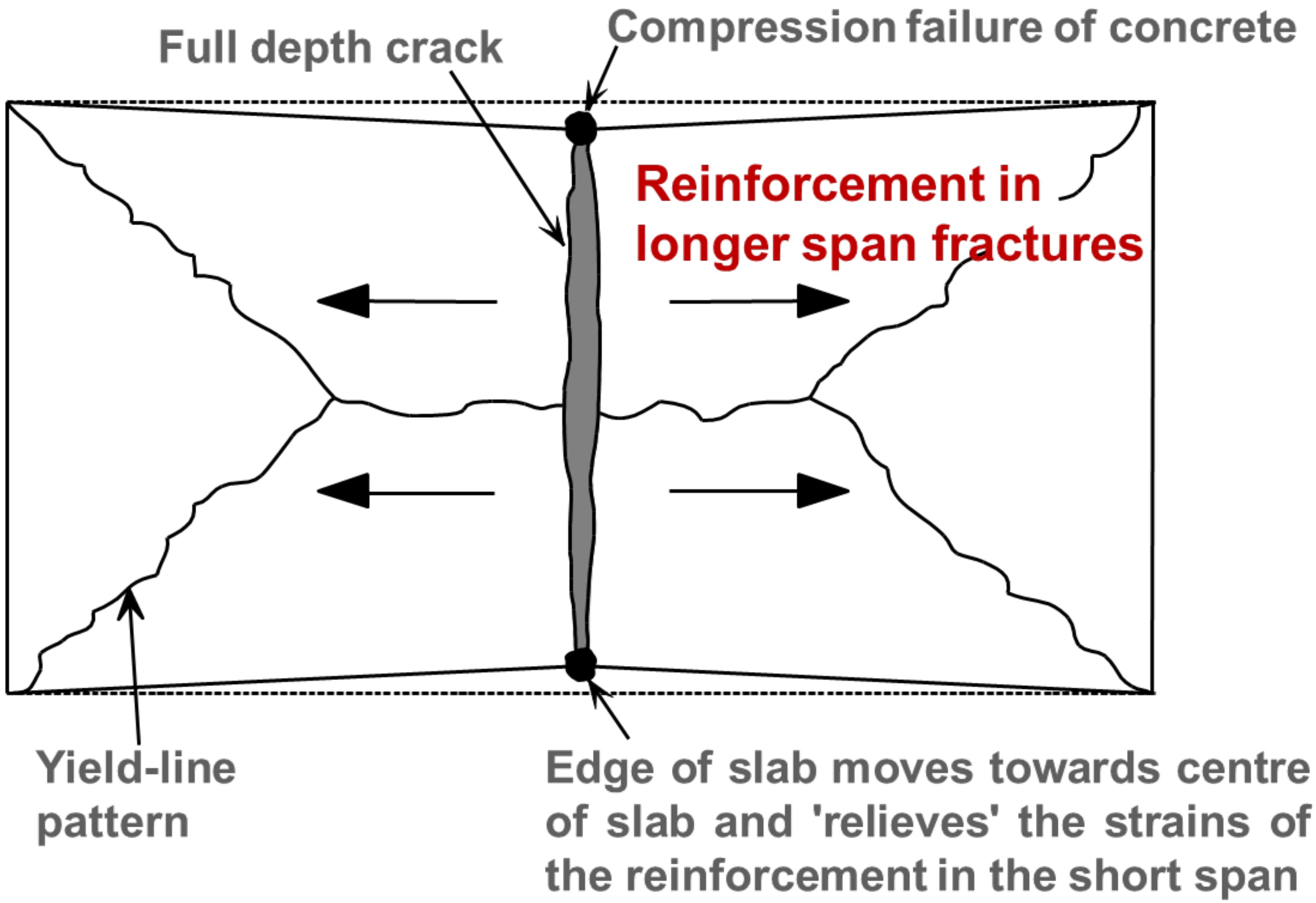
Reinforcement behaviour at location of vertical suppor

Cannot rely on continuity

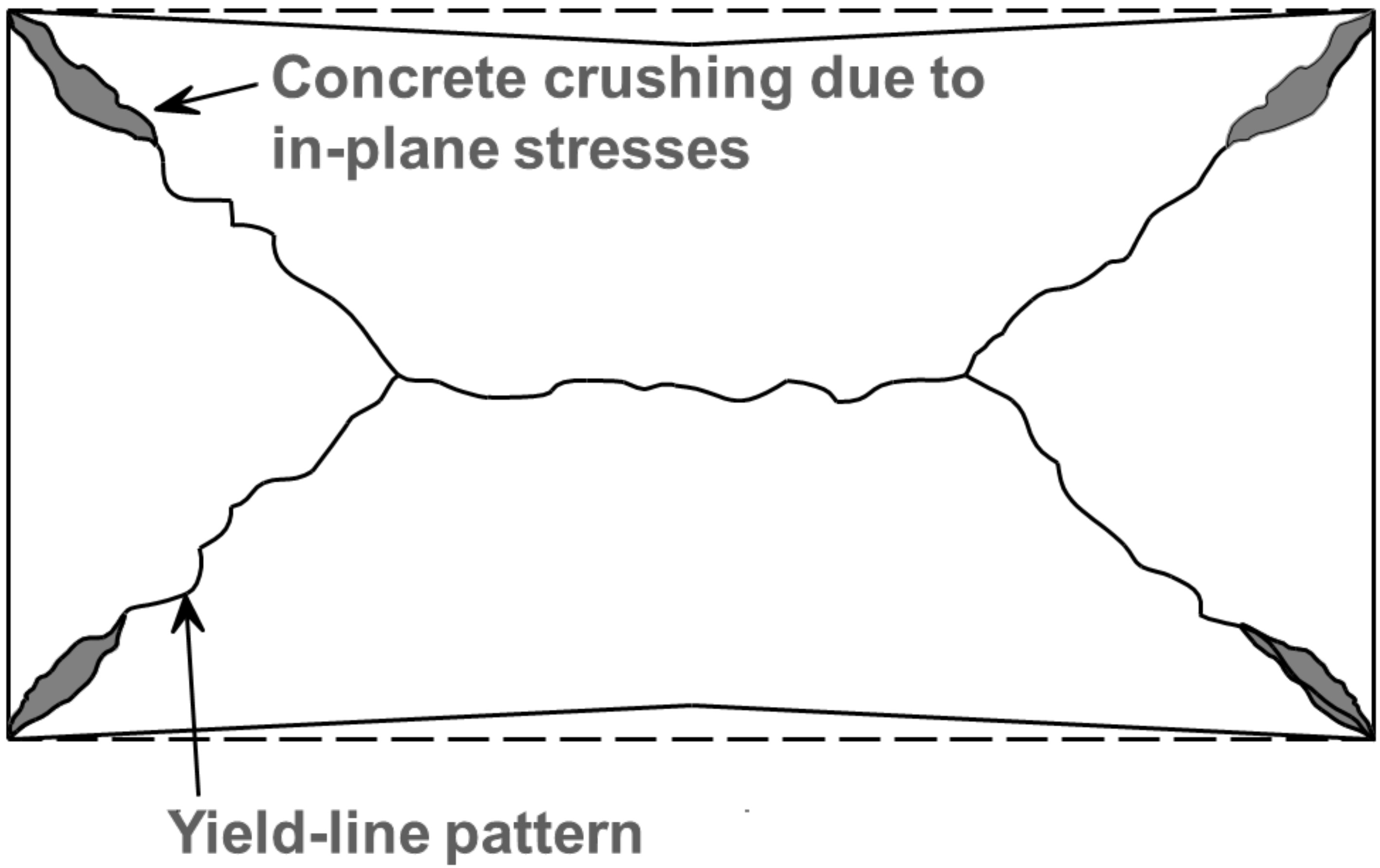
Assume slab panels are simply-supported

Conservative & Flexible

- **Failure modes** (tensile failure of reinforcement)



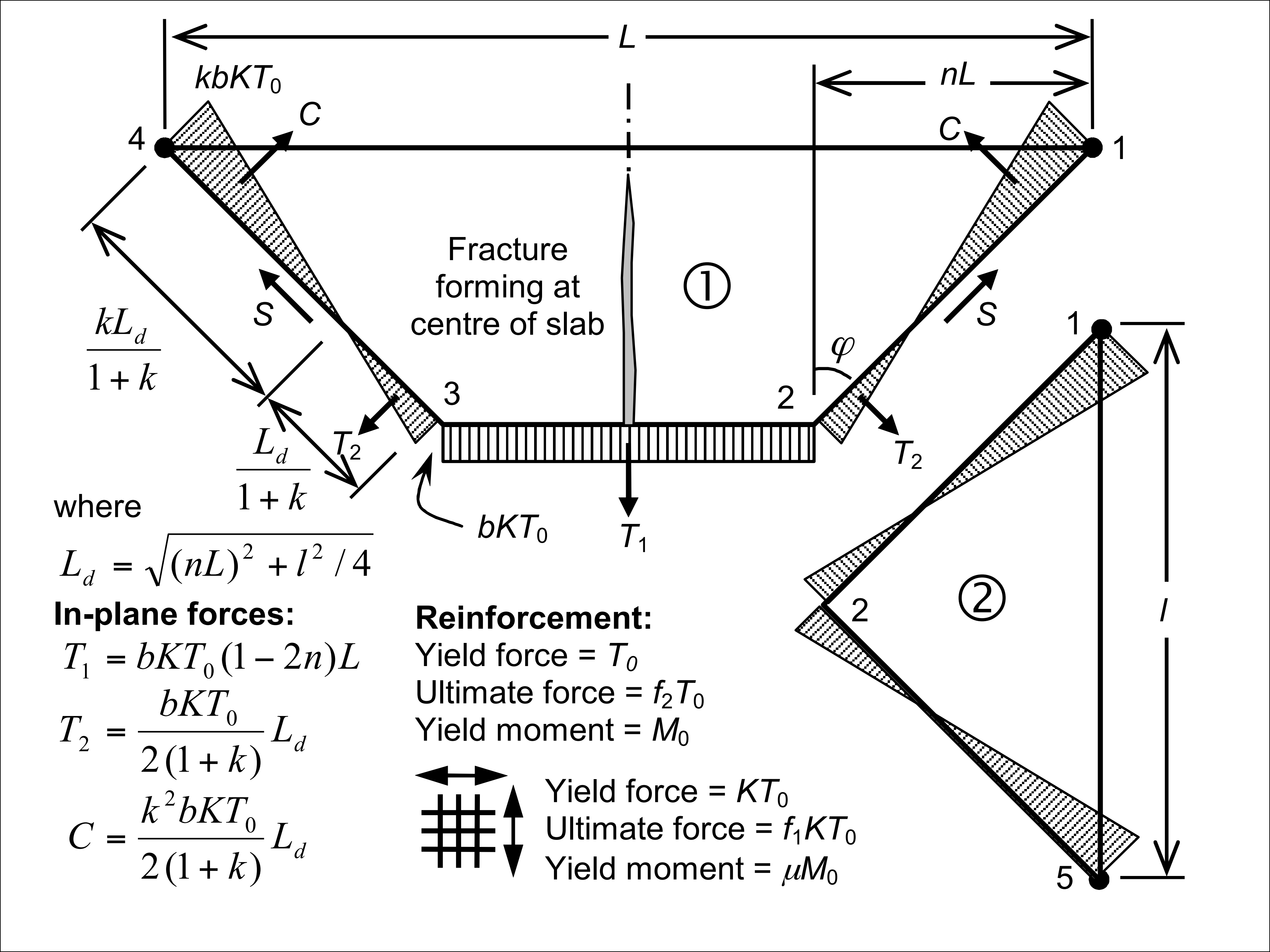
- **Failure modes** (compressive failure of concrete)
  - More likely to occur in case of strong reinforcement mesh



- **Failure modes** (experimental evidence)

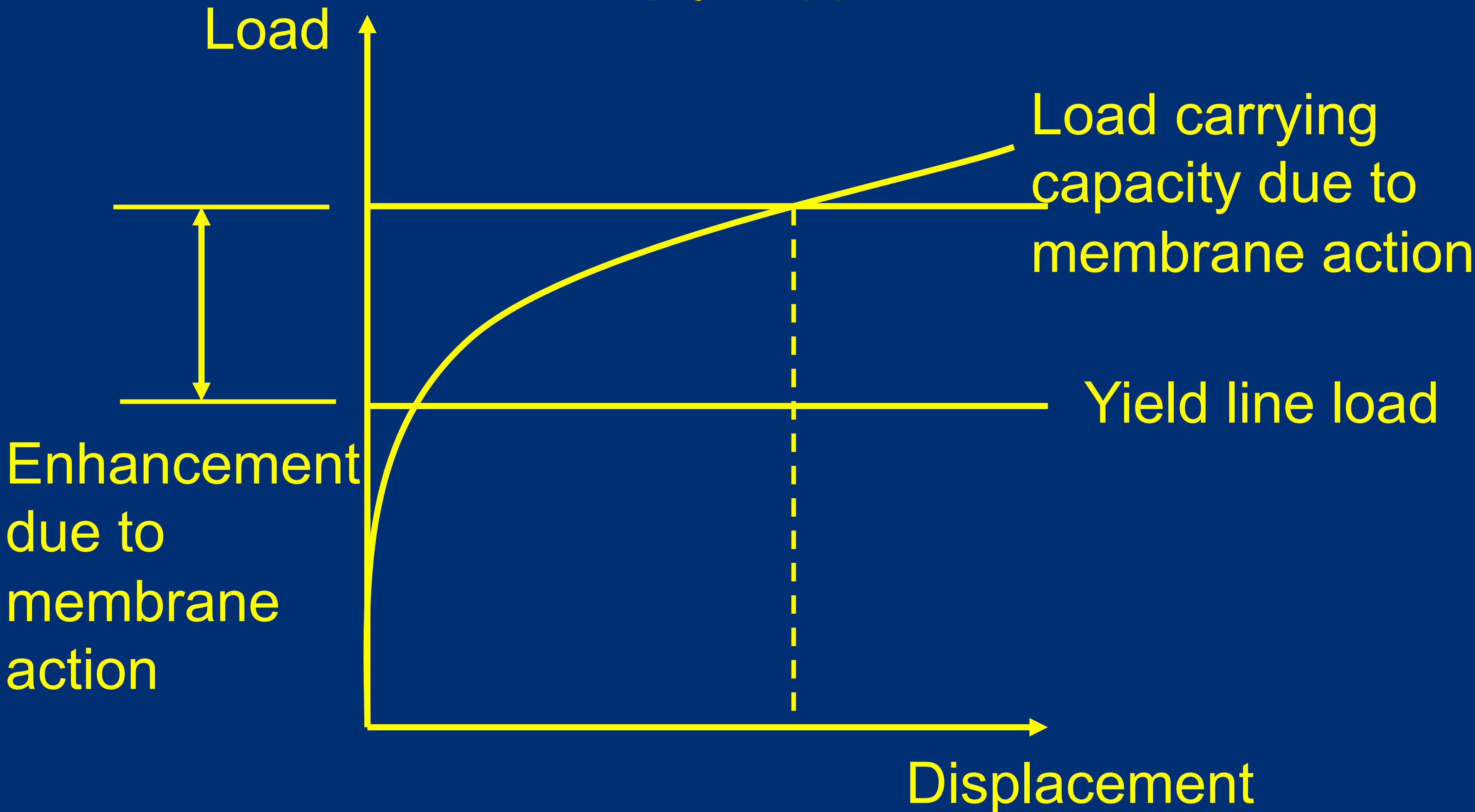
Tensile failure of reinforcement

Compressive failure of concrete



L
nL
$kbKT_0$
C
C
4
1
Fracture forming at centre of slab
①
S
S
$\frac{kL_d}{1+k}$
φ
3
2
T_2
T_2
$\frac{L_d}{1+k}$
bKT_0
T_1
where
$L_d = \sqrt{(nL)^2 + l^2/4}$
In-plane forces:
$T_1 = bKT_0(1-2n)L$
$T_2 = \frac{bKT_0}{2(1+k)} L_d$
$C = \frac{k^2 bKT_0}{2(1+k)} L_d$
Reinforcement:
Yield force = T_0
Ultimate force = $f_2 T_0$
Yield moment = M_0
Yield force = KT_0
Ultimate force = $f_1 KT_0$
Yield moment = μM_0
1
2
②
l
5

Load - displacement relationship of simply-supported concrete slabs

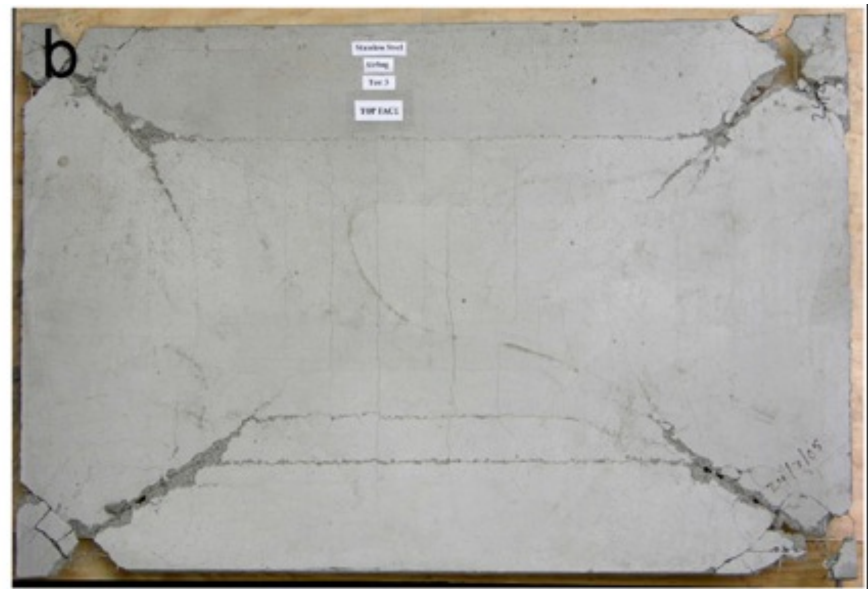


Basic Strength (Energy) Calculation.

Load Capacity at the Fire Limit State =

$$e\left[\frac{\textit{Internal work done by the slab}}{\textit{External work per unit load}}\right] + \frac{\textit{Internal work done by the beam(s)}}{\textit{External work per unit load}}$$

- **Failure modes**



Tensile failure of reinforcement

Compressive failure of concrete

Criteria defined to cover both modes of failure (Maximum displacement and limit on concrete strength)

Validation against test data

7 Full-scale Cardington Tests

1 large-scale BRE test (cold but simulated for fire)

10 Cold tests carried out in the 1960/1970s

15 small –scale tests conducted by Sheffield University in 2004

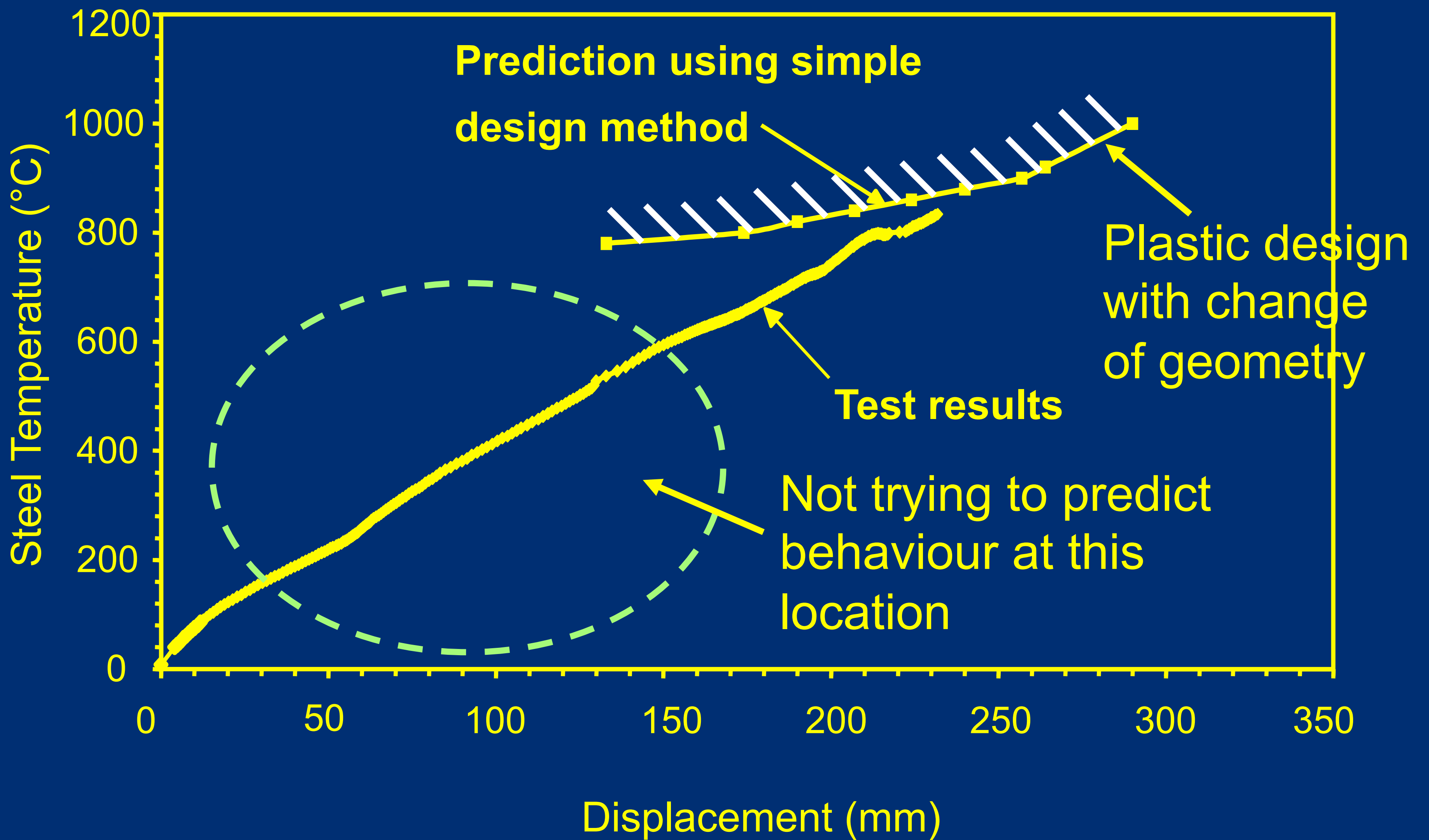
44 small-scale cold and fire tests carried out by the University of Manchester

Full-scale test carried out by Ulster University 2010.

Plus more……

Validation against Cardington fire tests

Test 1 (Cardington)



Small – Scale Experimental Behaviour and Design of Concrete Floor Slabs

22 Cold Tests and 22 Identical Hot tests (Both MS and SS mesh reinforcement)

Test 2 : Mild Steel:

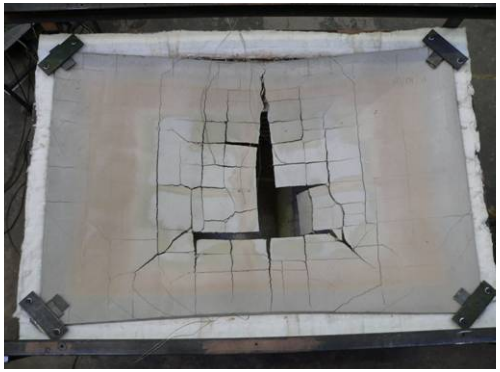
Cold

Compressive failure

Hot

Tensile Failure

No Compressive failure observed in fire tests



MF1

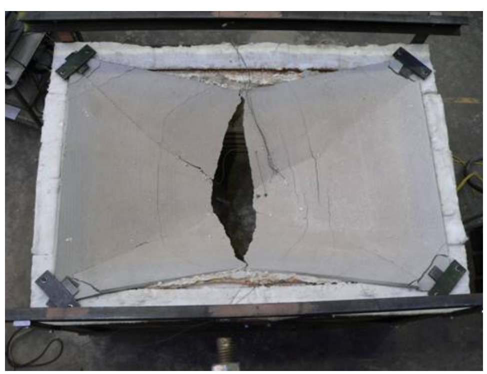
MF2

MF3

MF4

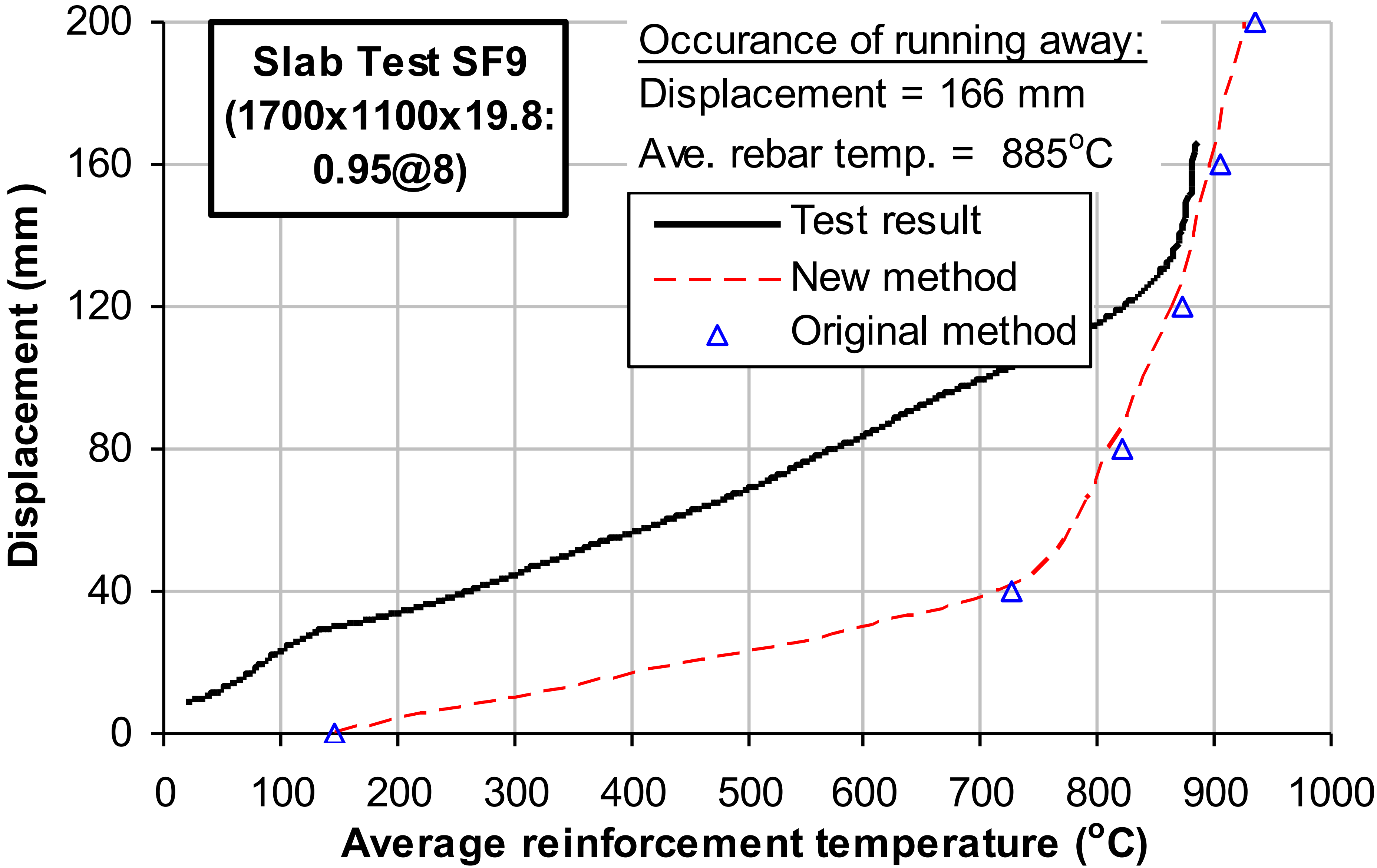
MF5

MF6

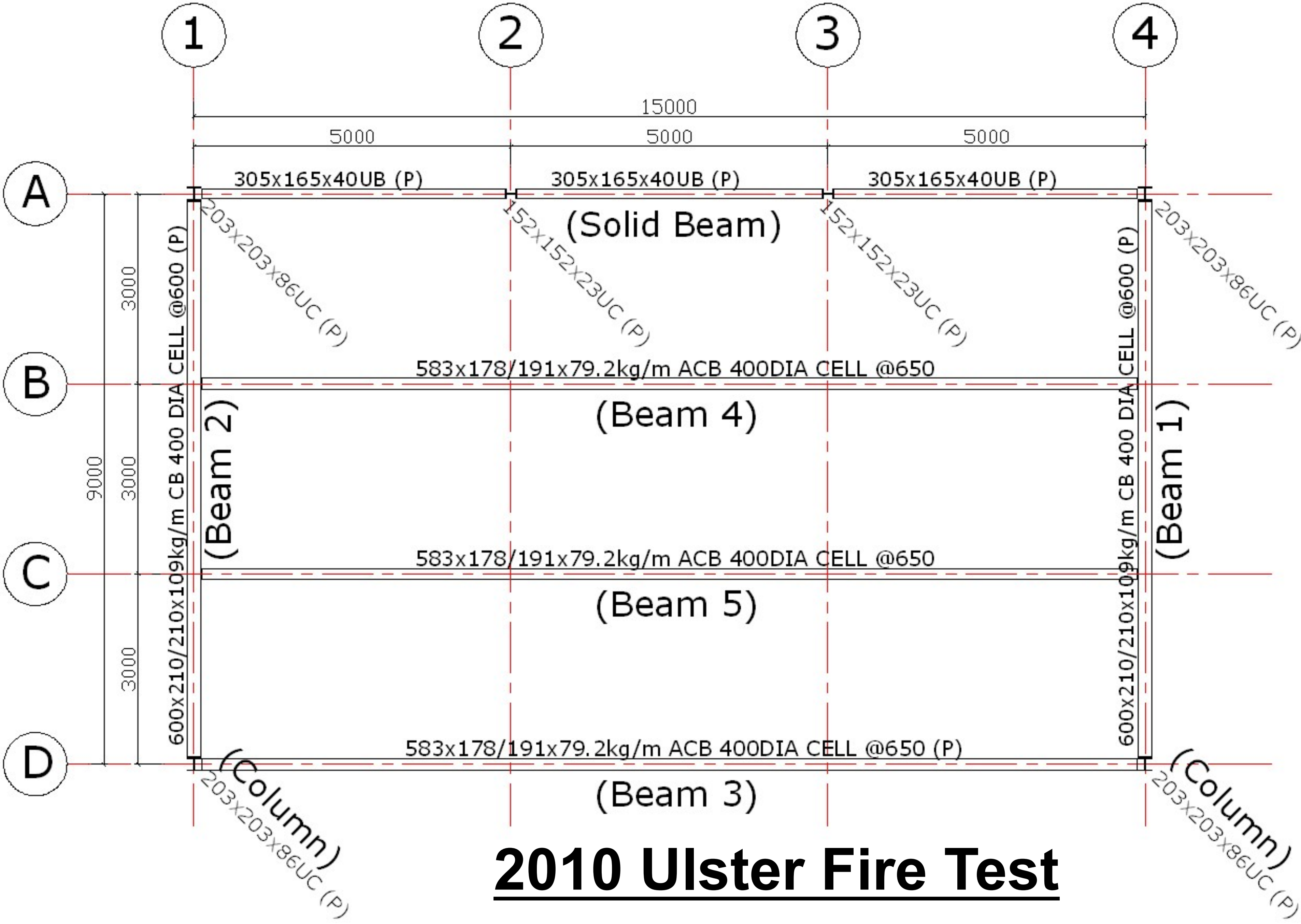


MF7

MF8



Slab Test SF9
(1700x1100x19.8:
0.95@8)
Occurance of running away:
Displacement = 166 mm
Ave. rebar temp. = 885°C
Test result
New method
Original method
Displacement (mm)
Average reinforcement temperature (°C)
200
160
120
80
40
0
0
100
200
300
400
500
600
700
800
900
1000

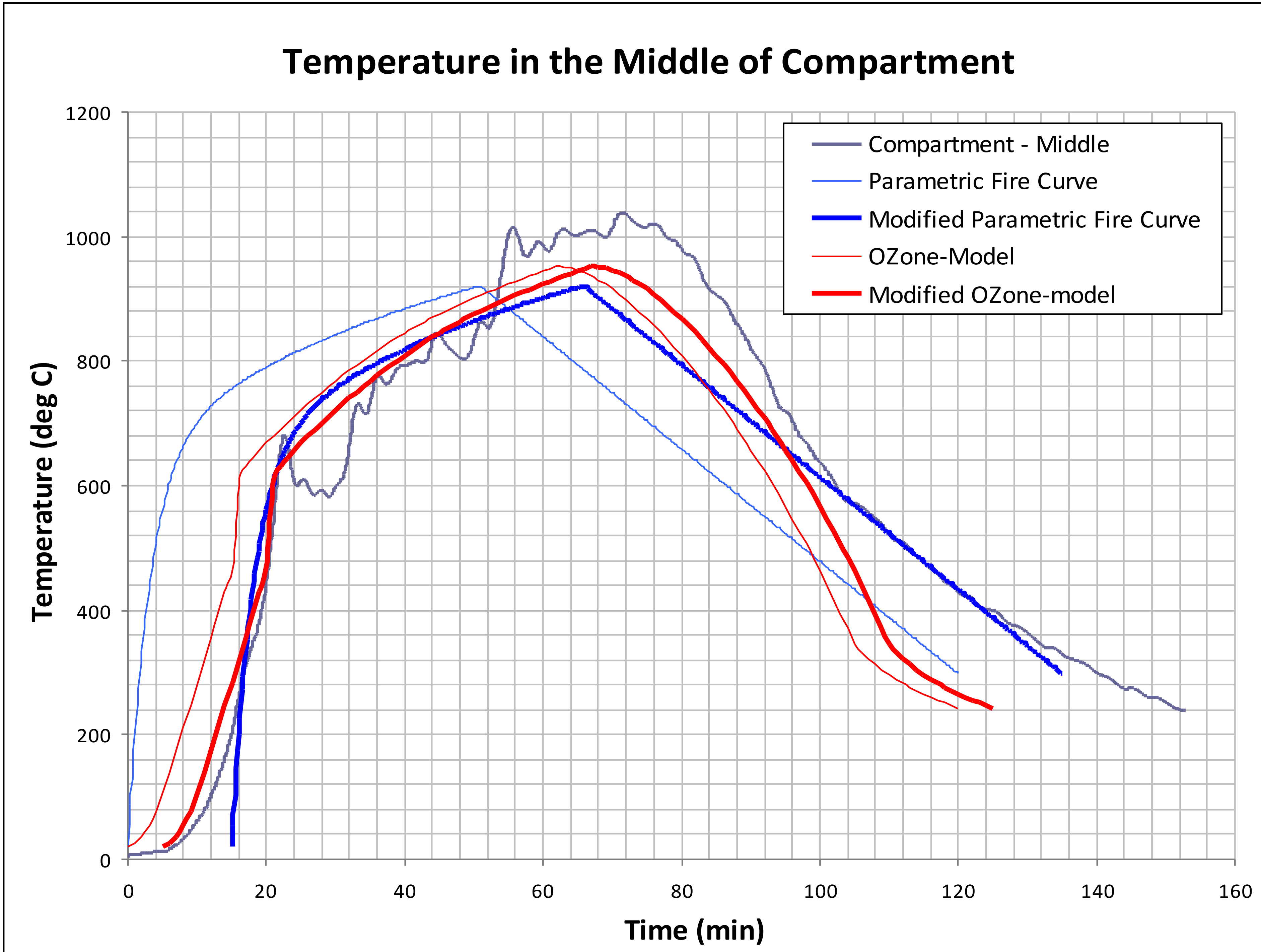


2010 Ulster Fire Test

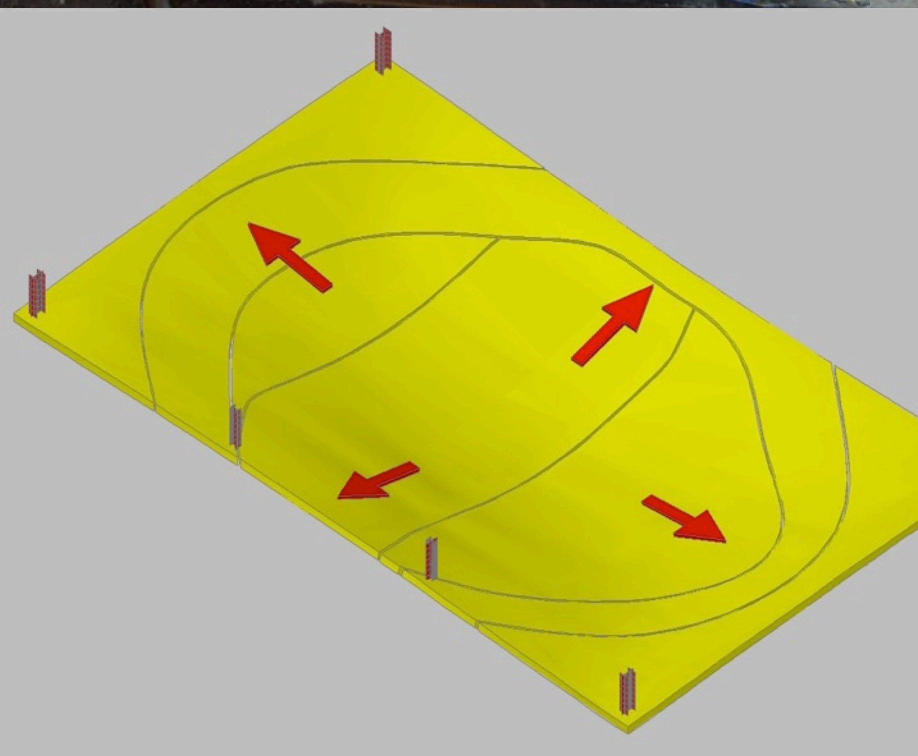
Fire Load = 587MJ/m^2
45 No. 1m x1mx0.5m wooden cribs

Applied load = 3.25kN/m^2
Total load = 6.15kN/m^2

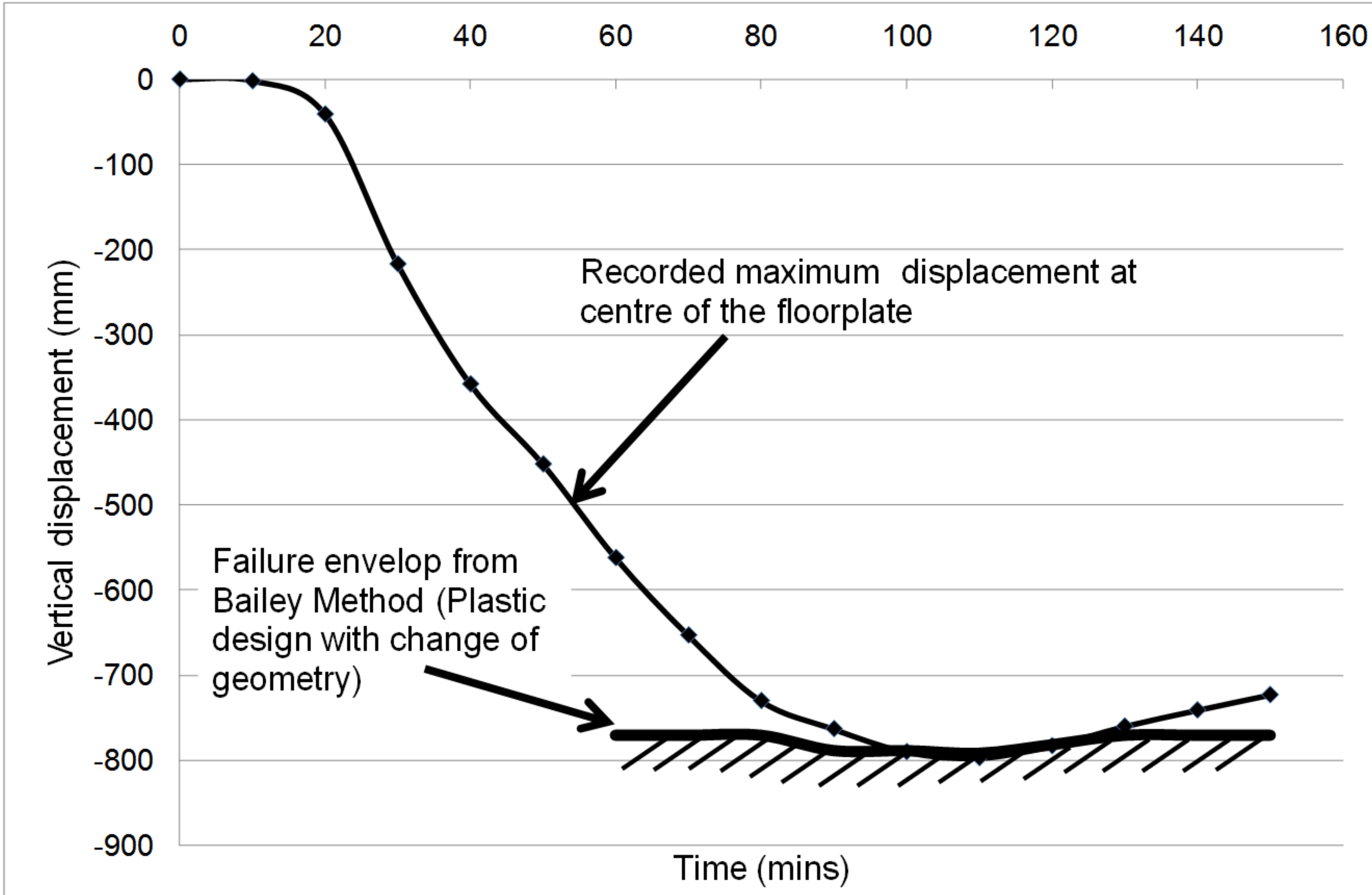

DANGER
Construction Site
KEEP OUT



Temperature in the Middle of Compartment
Compartment - Middle
Parametric Fire Curve
Modified Parametric Fire Curve
OZone-Model
Modified OZone-model
Temperature (deg C)
Time (min)
0
200
400
600
800
1000
1200
0
20
40
60
80
100
120
140
160

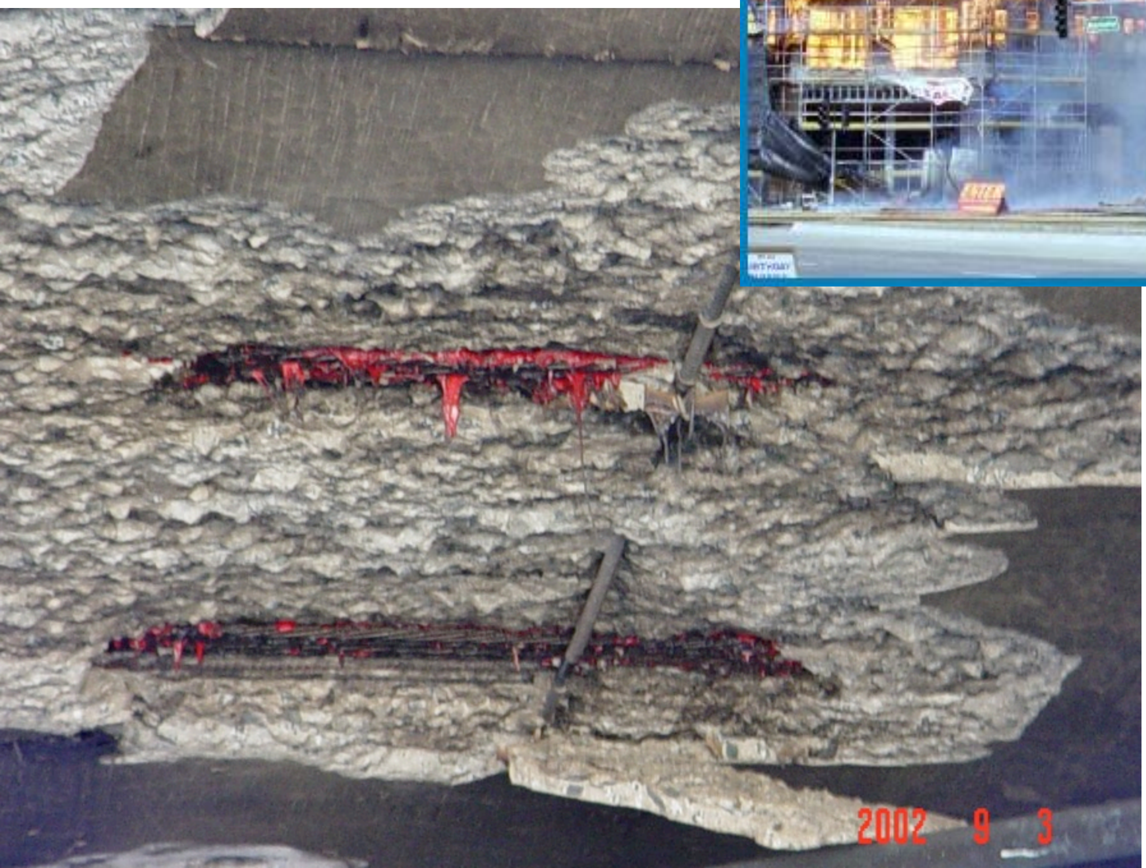



28 10:06



0
20
40
60
80
100
120
140
160
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
Vertical displacement (mm)
Time (mins)
Recorded maximum displacement at centre of the floorplate
Failure envelop from Bailey Method (Plastic design with change of geometry)

Limited testing on PT slabs



Post-tensioned Slabs in Fire

Unbonded System

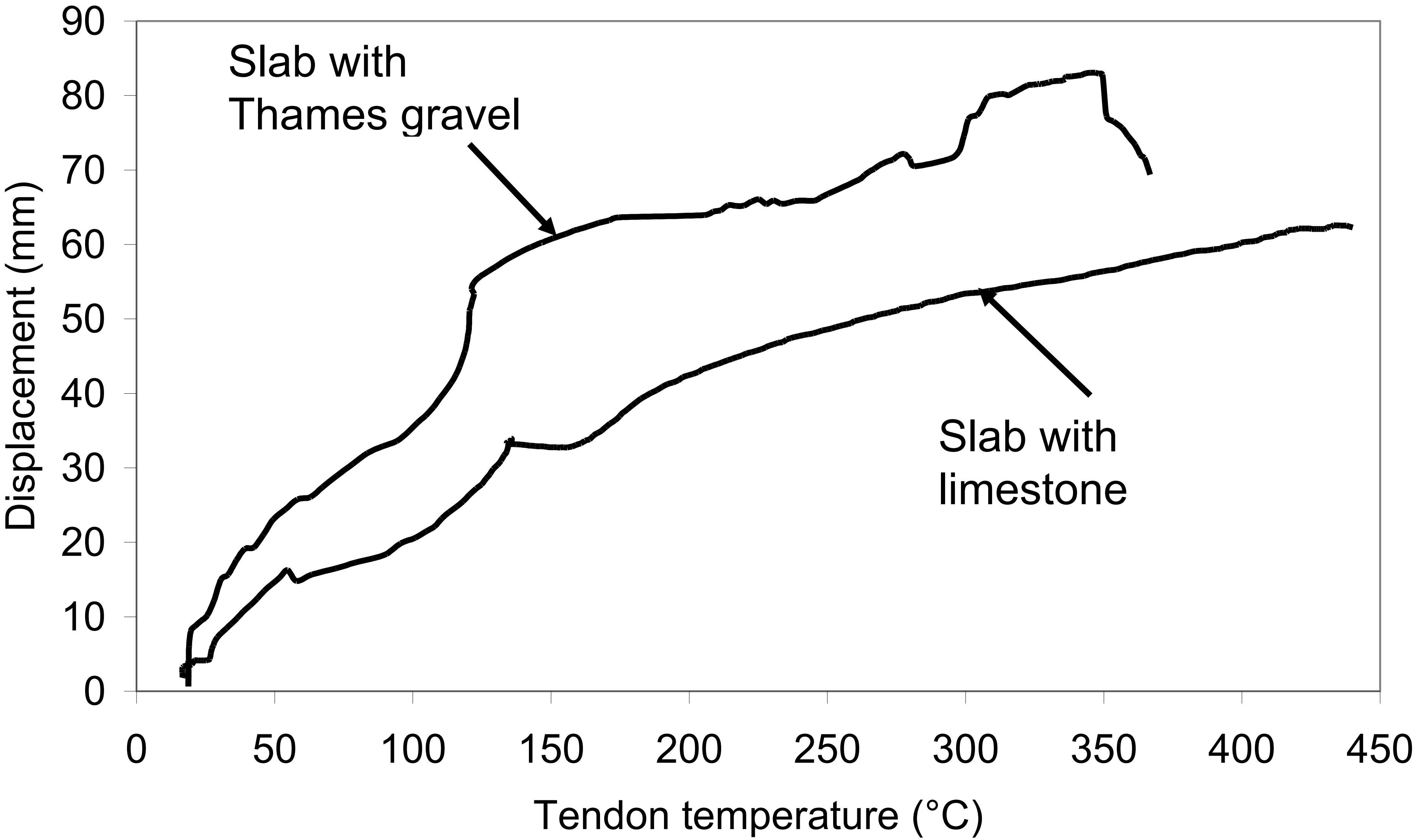
Bonded System

Main post-tensioning systems investigated

Post-tensioned slab fire tests

Completed experimental programme

Test specimen	Slab age (Days)	Concrete Strength (MPa)	Moisture content (%)	Fire	Long. Exp.		Duct		Coarse Agg.	
					Free	Rest.	Plastic	Metallic	LS	TG
T1	79	44.4	---		X				X	
T2	79	48.2	---		X					X
T3	169	48.0	2.54	X	X				X	
T4	213	41.0	2.15	X		X			X	
T5	149	40.0	2.34	X	X					X
T6	205	39.7	1.70	X		X				X
TB1	149	41.2	---		X		X		X	
TB2	170	30.3	---		X			X	X	
TB3	260	36.6	1.19	X	X		X		X	
TB4	258	40.9	1.93	X		X	X		X	
TB5	251	35.5	1.07	X	X		X			X
TB6	244	38.6	2.50	X		X	X			X
TB7	202	40.4	2.43	X	X			X	X	
TB8	195	42.3	1.84	X		X		X	X	
TB9	188	36.9	2.27	X	X			X		X
TB10	180	39.3	2.18	X		X		X		X



Slab with Thames gravel
Slab with limestone
Displacement (mm)
Tendon temperature (°C)
0
10
20
30
40
50
60
70
80
90
0
50
100
150
200
250
300
350
400
450

Findings:

1) Slabs with Thames gravel aggregates have a much higher vertical and horizontal displacements compared to slabs with limestone aggregates.

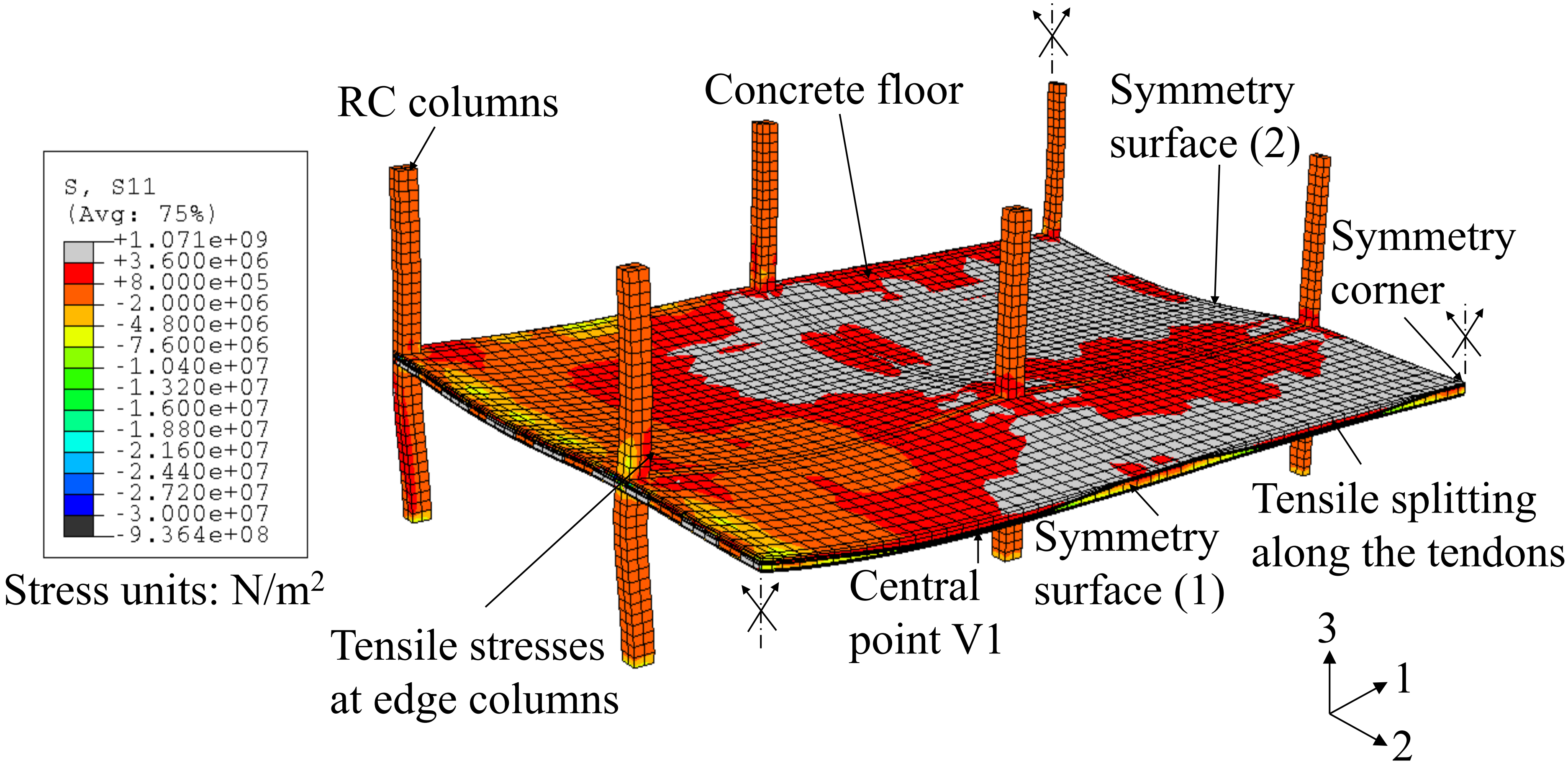
2) The unbonded slabs failed in a brittle (sudden) manner

3) BS code was unconservative for unbonded slabs but OK for bonded slabs. Eurocode was generally conservative.

4) Tendon temperature in the bonded slabs with plastic ducts were slightly greater than the bonded slabs with metallic ducts, due to the ease at which moisture escaped from the grout surrounding the tendon once the plastic ducts melted at 230°C.

5) FE models have been validated and are being used to extend the experimental results.

Whole building behaviour



Maximum principal stresses in F4 (scale 5:1)

(a) (b) (c) (d)

Fig.6: Spalled columns before repairing (a-b) after repairing with epoxy resin mortar© and GFRP (d)

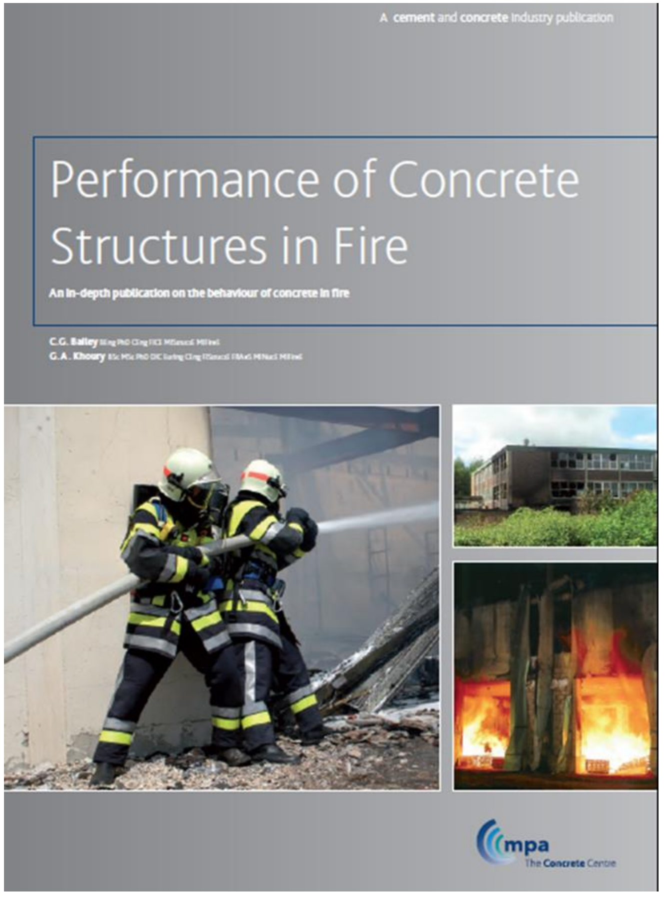
Fig.4: Electric furnace set up and columns before going in to furnace

Fig.5: Columns before heating

Fig.6: Columns after heating

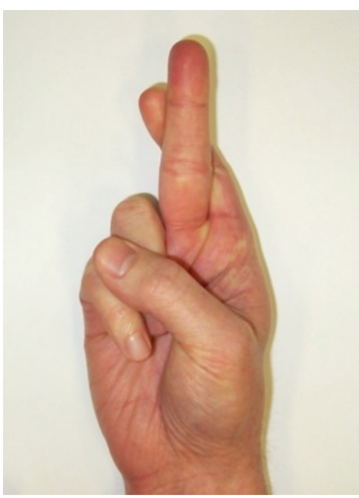
- permeability
- moisture content
- age of concrete
- strength of concrete
- compressive stress and restraint
- type of aggregate
- aggregate size
- cracking
- reinforcement
- cover to reinforcement
- supplementary reinforcement
- steel fibres
- polypropylene microfibres
- air entrainment
- fire severity.

Factors influencing explosive spalling – discussed in the book.



Structural Fire Engineering

Prescriptive Approach:



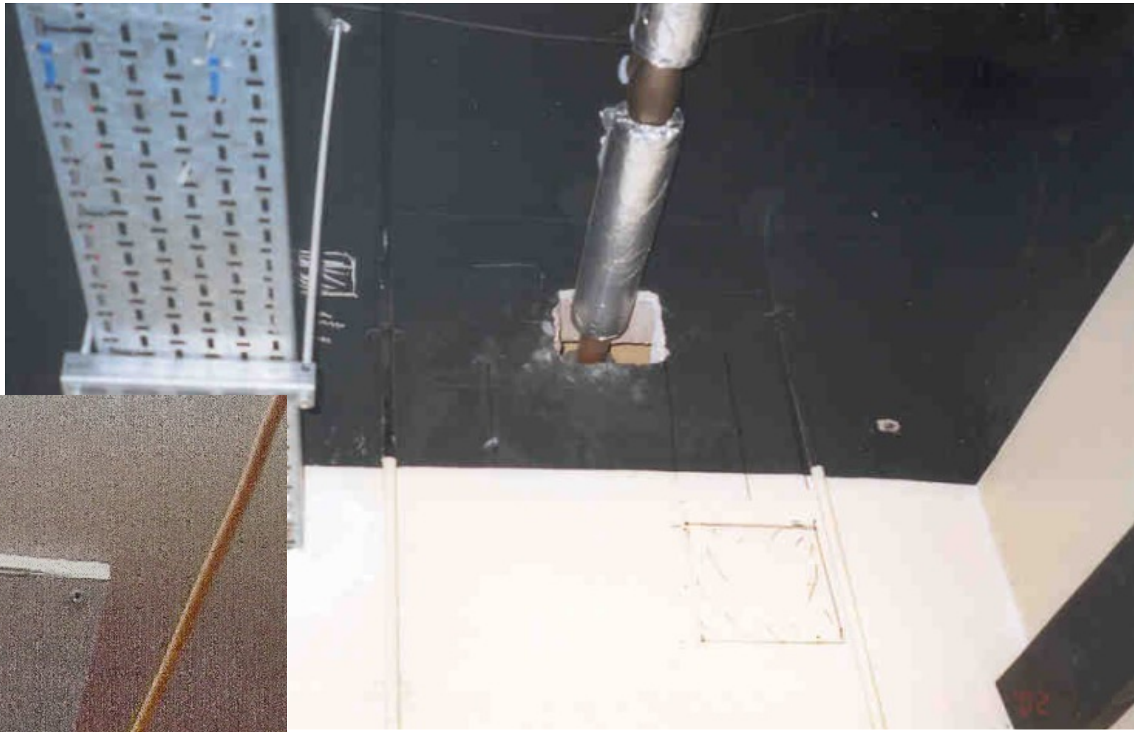
Performance Based Approach:

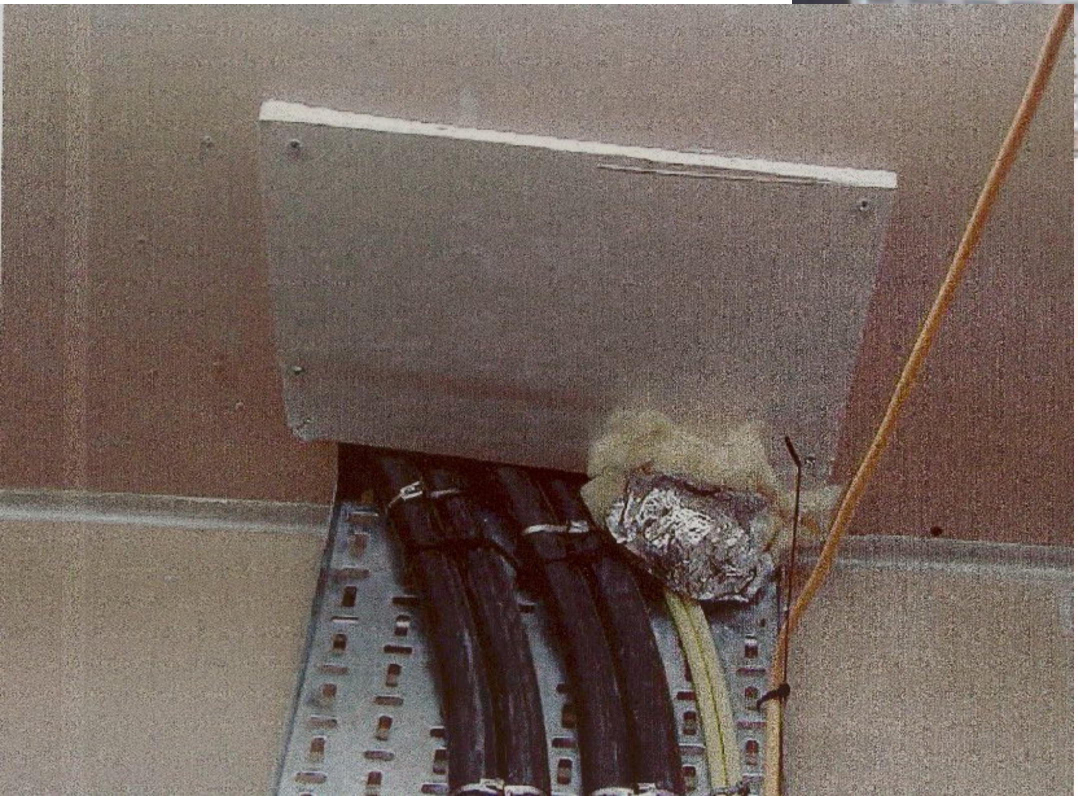
Greater understanding of how buildings behave in fire.

More robust designs

More economical designs

Whatever Design Approach is Followed
- if the simple things MUST be done correctly !!!





We must continue to promote a performance-based approach – otherwise rely on luck.

Education, Research, New Materials


The End
Thank you