2C10
Design for fire and robustness

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List of lessons

1) Introduction to fire safety
2) Fire load
3) Advanced fire models
4) Structural analysis at fire, steel structures at fire
5) Fire resistance of steel structures
6) Fire resistance of composite structures
7) Fire resistance of timber and aluminium structures
8) Fire resistance of concrete structures
9) Fire resistance of timber and aluminium structures
10) Loading at explosion
11) Structural analysis at explosion
12) Robustness
13) Fire tests

Objectives of the lecture

- The state of art in the fire design
- Recent major fire disasters
- Choice of appropriate procedure
- Eurocodes for fire design
- Educational materials on internet

Fire safety in buildings

- **Prescriptive based approach**
  - States how a building is to be constructed
- Performance based approach
  - States how a building is to perform under stated criteria

Set of rules for prescriptive approach

For example :

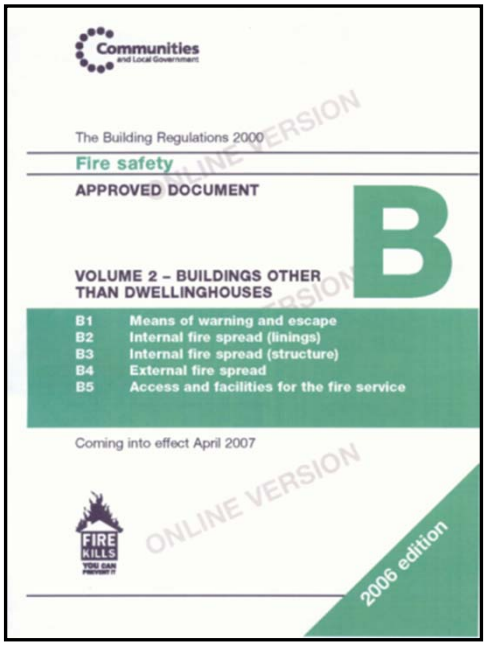
Minimum fire resistance for members

Maximum fire compartment size

Maximum travel distances

Minimum number of exists

Etc.

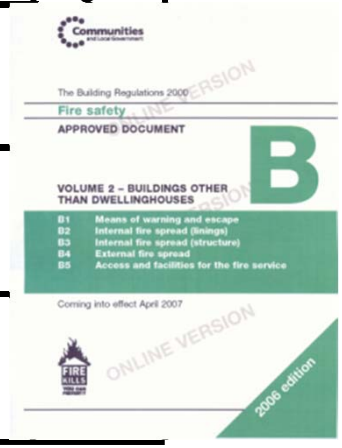


Example of prescriptive approach

- Fire resistance periods

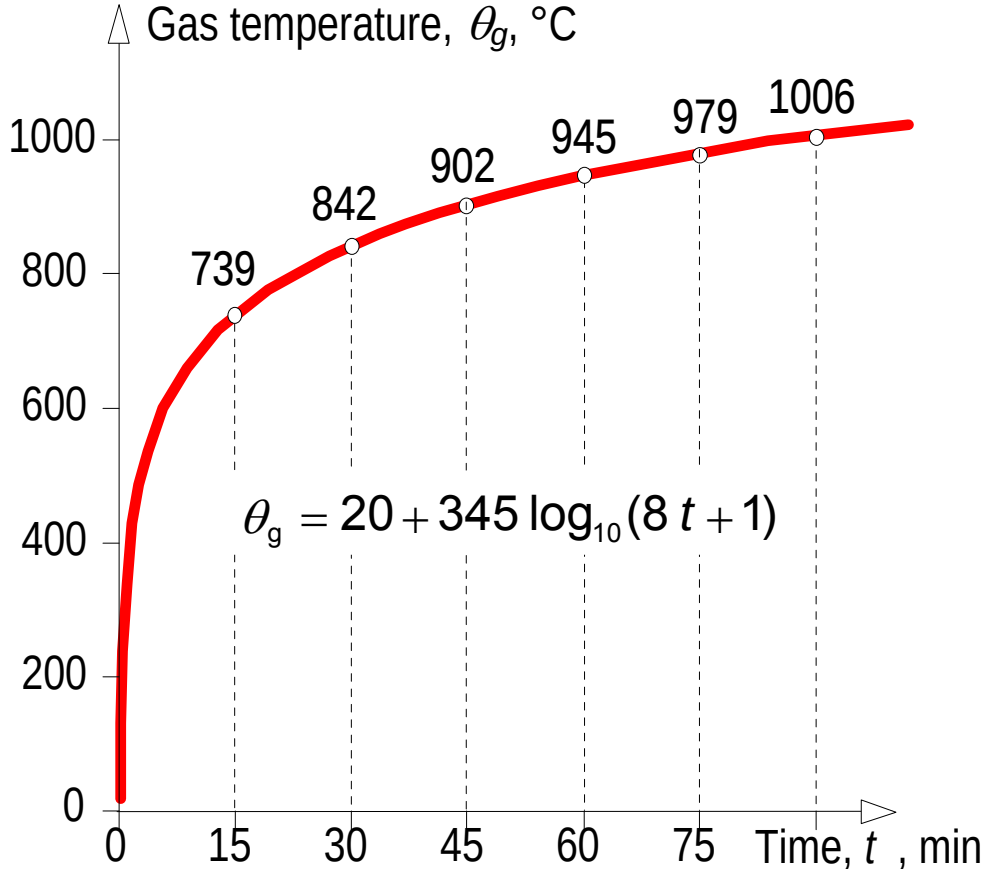
	Height of Building (m)			
	<5	<18	<30	>30
Residential (Non Domestic)	30	60	90	120
Offices	30	60	90	
Shops, Commercial, Assembly	60	60	90	
Industrial & Storage	60	90	120	
Car Parks - Open	15	15	15	

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



Standard fire resistance

Heating according to nominal standard fire curve



Standard fire resistance

Used for

- Load bearing capacity **R**
- Insulation **I**
- Integrity **E**

Marked as

- R15; RE30; REI90

History of the standard fire test

Over 100 years of testing

- **1890's** early attempts at establishing structural fire behaviour at the behest of **insurance companies**

Fire test of intumescent coating

- **1917** First US Standard produced
- **1932** First Edition of BS476 (UK)
- **1933** E119 (US) produced
- **1985** ISO 834
- **2003** EN 1991-1-2

Fire protection

- Unprotected steel for limited fire resistance, eg. R15
- Fire protection:
  - Concrete/brick encasing
  - Board protection
  - Intumescent coating
  - Sprayed protection
  - Composite members



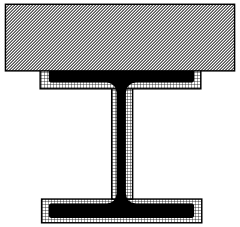
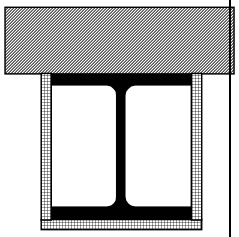
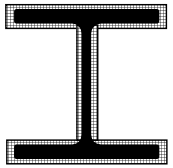
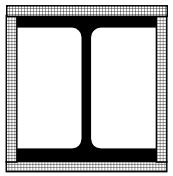

Classified fire protection

Thickness of protection depends on

- Fire resistance class
- Section factor

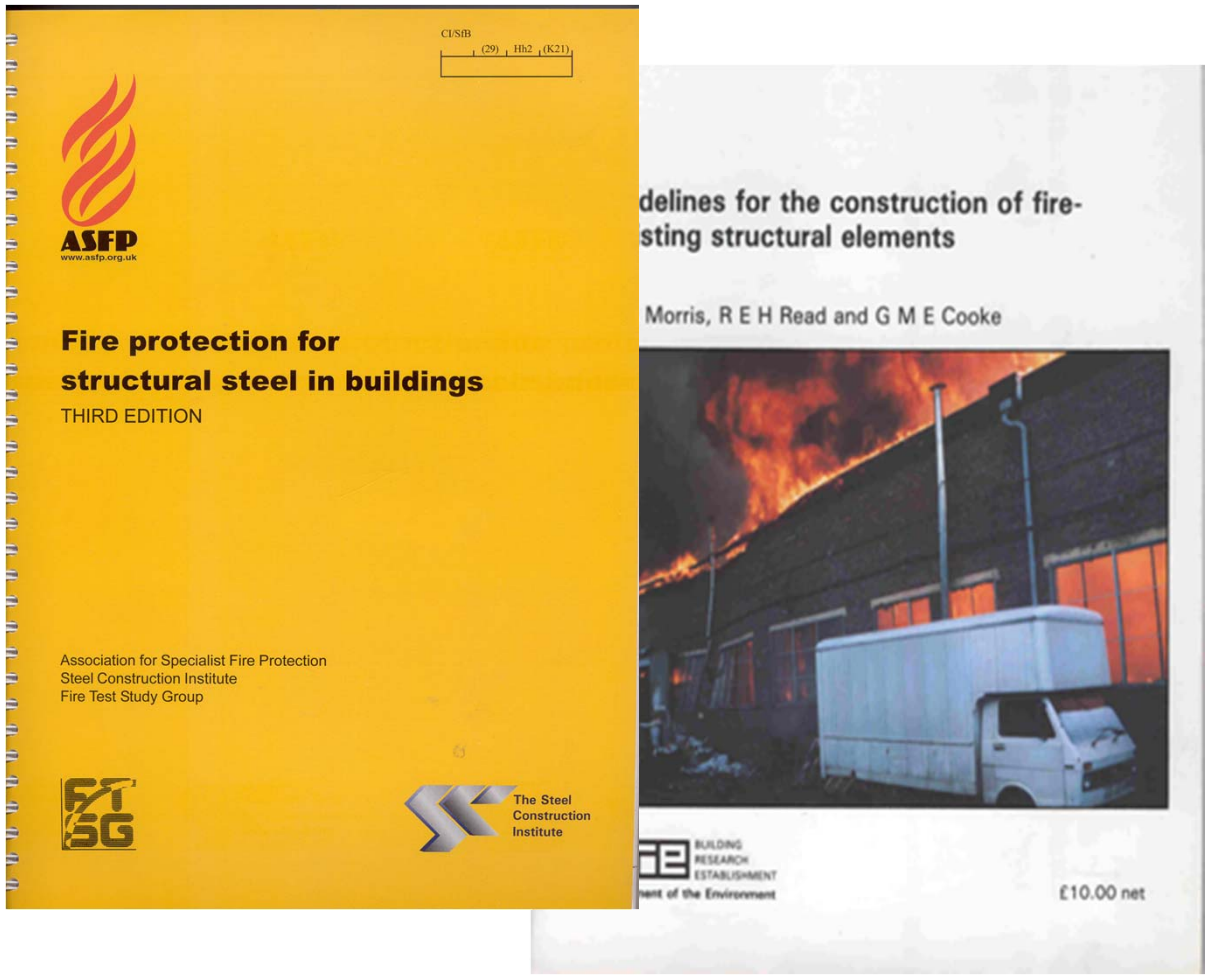
Section factor

$$A_m/V = \frac{\text{the surface area of the member per unit length [m}^2\text{/m]}}{\text{the volume of the member per unit length [m}^3\text{/m]}} \quad [\text{m}^{-1}]$$

Fire exposure	3-sided		All-round	
Type of protection	Contour 	Box 	Contour 	Box 
Section factor A_m / V =	$\frac{\text{Steel perimeter} - b}{A}$	$\frac{2h + b}{A}$	$\frac{\text{Steel perimeter}}{A}$	$\frac{2h + 2b}{A}$

Simple prescriptive rules

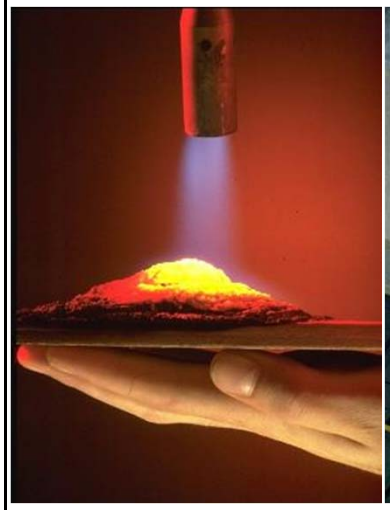
– deemed to satisfy

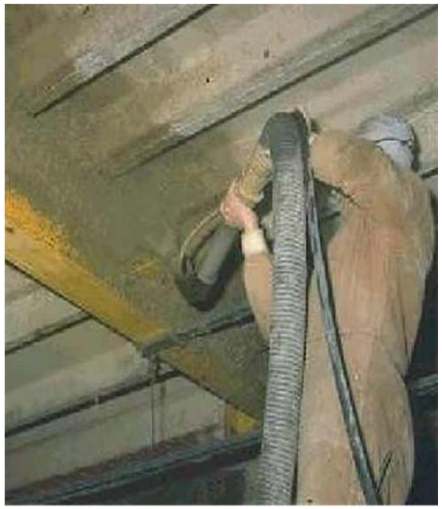


Generic and proprietary fire protection materials

Thickness specified:
the steel does not exceed
for a given fire resistance period

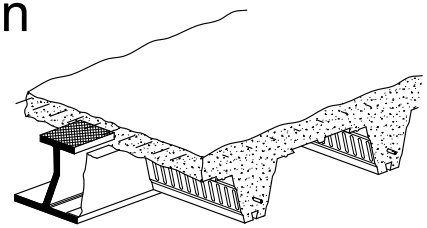
550°C / 620°C (element exposed from three sides only)



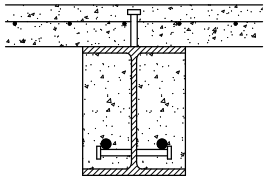


Composite sections

Filled sections till fire resistance 60-90 min
Additional reinforcement 120 min

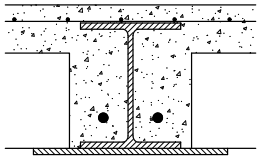


Slab



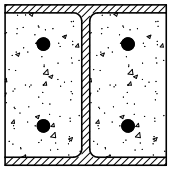
Beams

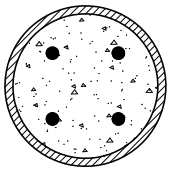
Patially encasses
Slim floor

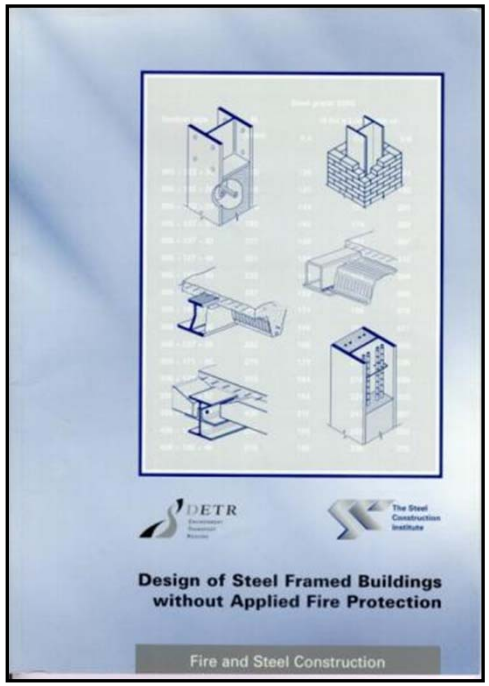


Columns

Partially encassed
Concrete filled







Advantages

- Limited design effort
- Experience has shown that approach works
- Approach is easily understood by all parties
- Based on nominal standard fire tests

Disadvantages

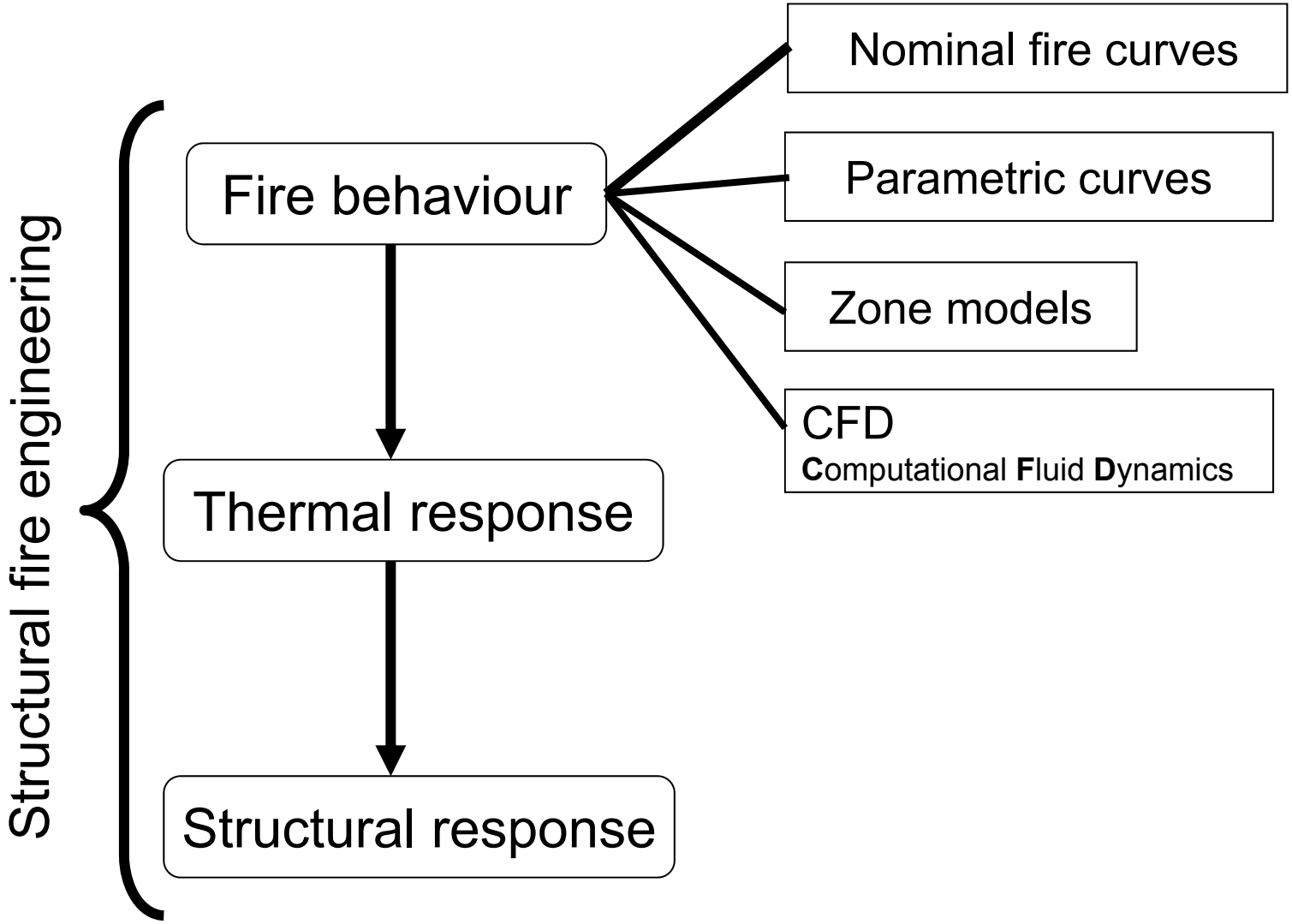
- Actual structural behaviour ignored
- Effect of real fires ignored
- Levels-of-safety and robustness unknown
- Optimum solution in terms of
  - life safety unknown
  - economical impact unknown
  - environmental damage unknown

Fire safety in buildings

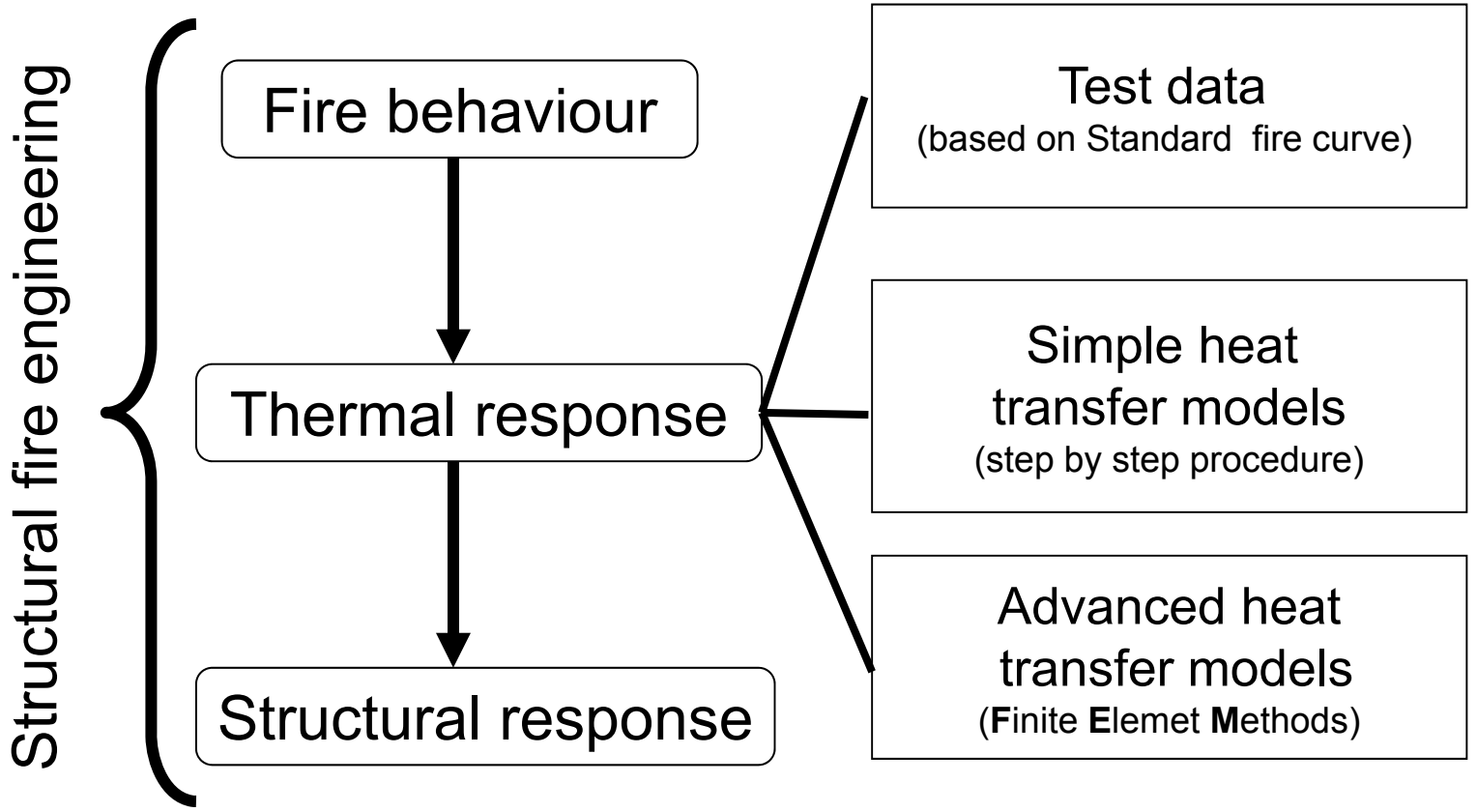
- Prescriptive based approach
  - States how a building is to be constructed

- **Performance based approach**
  - States how a building is to perform under stated criteria

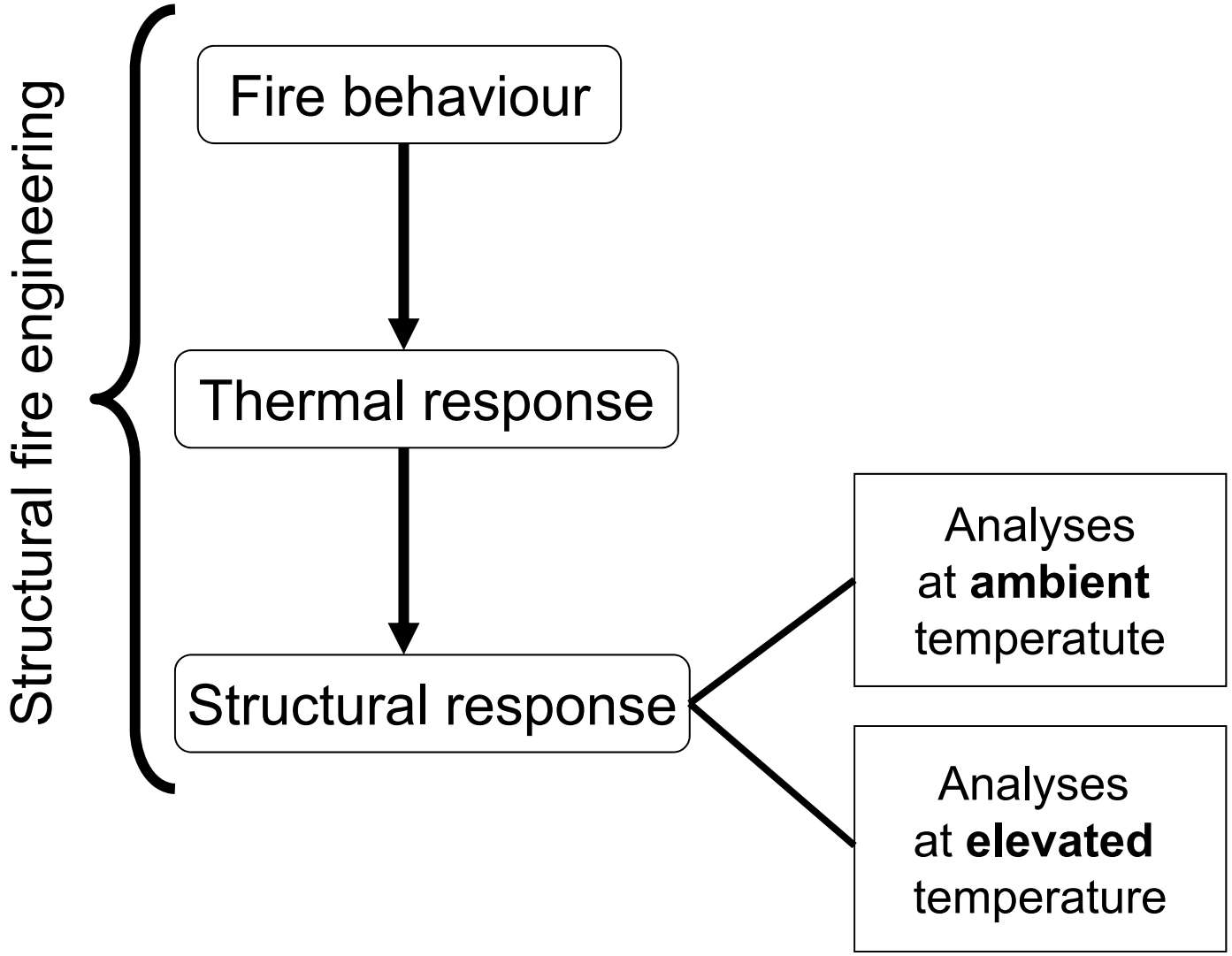
Fire behaviour



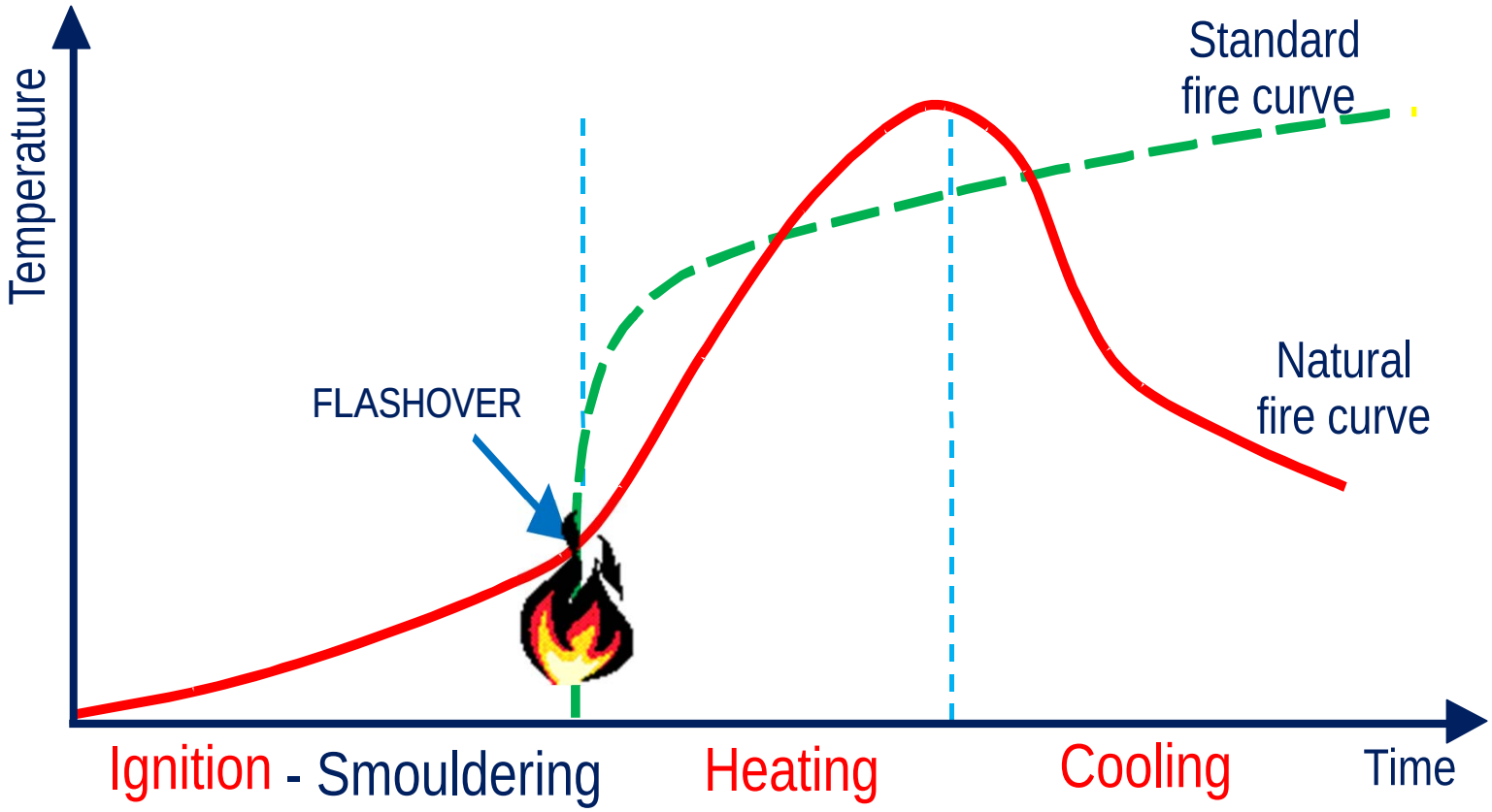
Thermal response



Structural response

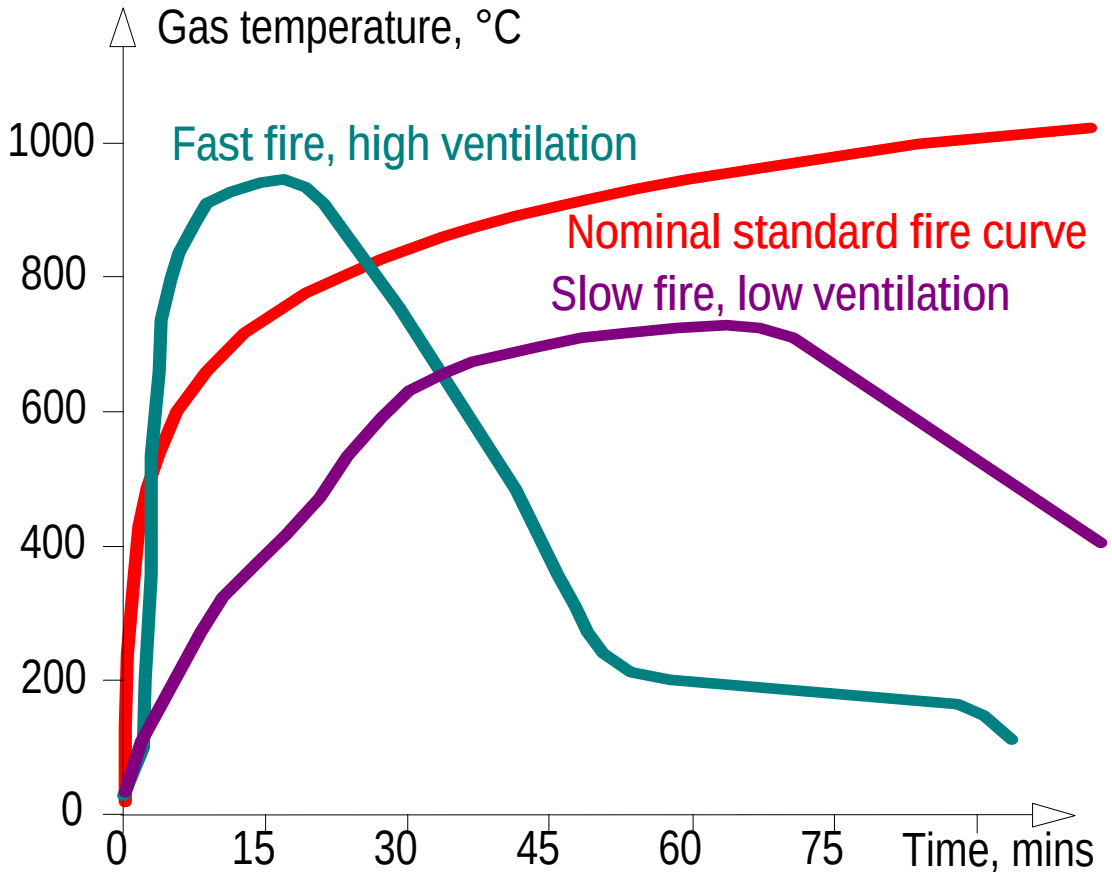


Fire modelling



Three phase of natural fire

Ventilation and fire load

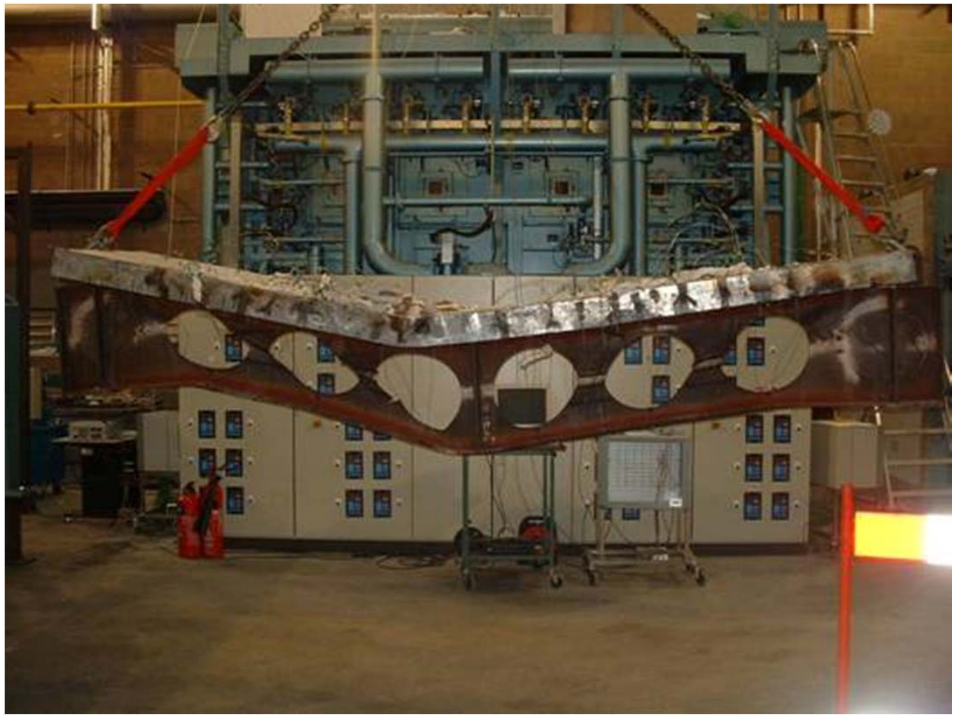


Standard fire curve is inaccurate

Fire modelling

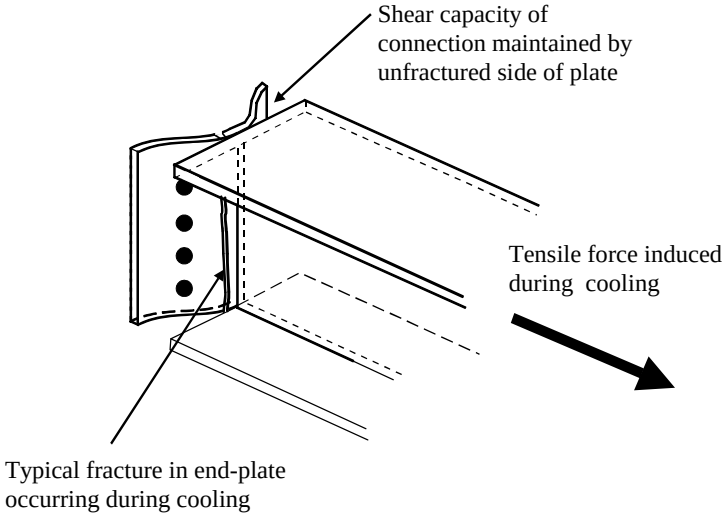
- Compartment fire
  - Nominal standard fire curve
  - Parametric fire curve
    - Reached accuracy in case of the Cardington fire test (a widen MS PowerPoint presentation)
  - Zone models
  - **C**omputational **F**luid **D**ynamics CFD
- Localized fire
  - Nominal standard fire curve, very conservative
  - Parametric fires
    - Reached accuracy in case of the Ostrava fire test (a widen MS PowerPoint presentation)
  - **C**omputational **F**luid **D**ynamics CFD

Real structures



- Today buildings are complex
  - Large spans
  - Mixed building technology
  - New materials

Overall behaviour



- Cooling phase of fire
  - Connection behaviour
  - Mostly collapse of structures

Advantages

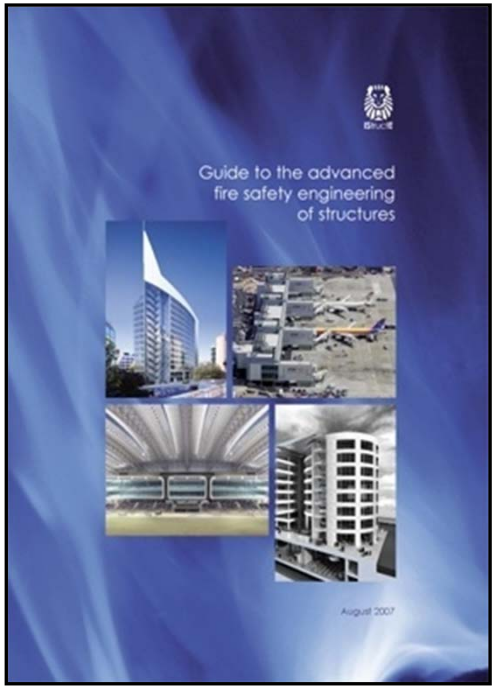
- Actual behaviour and robustness of the building
- Optimum design taking into account
  - Life safety
  - Financial impact
  - Environmental issues
- Part of an assessment of multiple risks
  - Earthquake followed by a fire
  - Explosion followed by a fire

Disadvantages

- More design effort
- Requires multi-discipline skills
- Design can be complicated
- Change of building use
  may make the fire design invalid

Design methodology

- Simple models
- Based on test of elements
- Advanced structural fire engineering
  - Guidance
  - Modelling
  - Validation
  - Verification
  - Review



Formative assessment question 1

- What are the advantages of prescriptive based approach for fire safety of buildings?
- How is defined section factor?
- What are the advantages of fire engineering?
- Explain major steps of fire engineering?
- How are divided the models of fire?

Lecture from major disasters

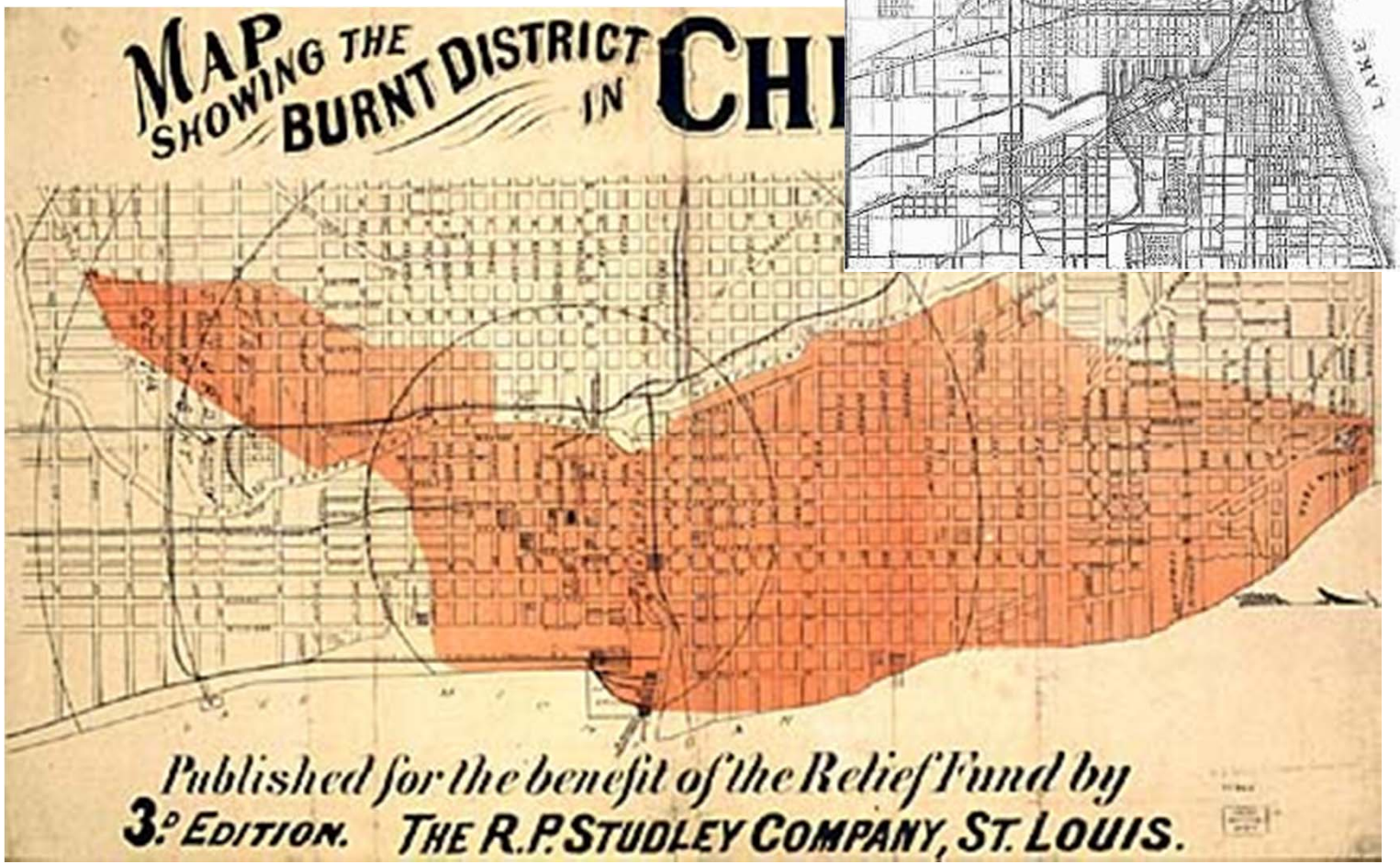
Lecture from major disasters

Lecture from major disasters

Lecture from major disasters

Lecture from major disasters

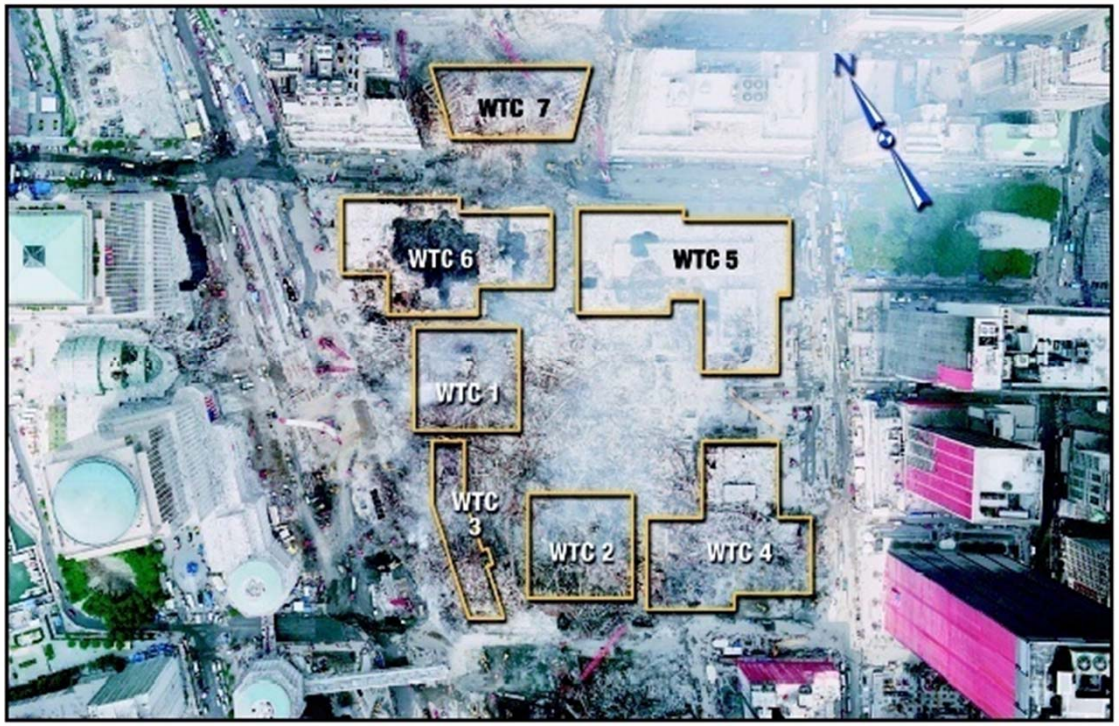
Great Chicago Fire, 8-10 October 1871



World Trade Center 11.09.2001

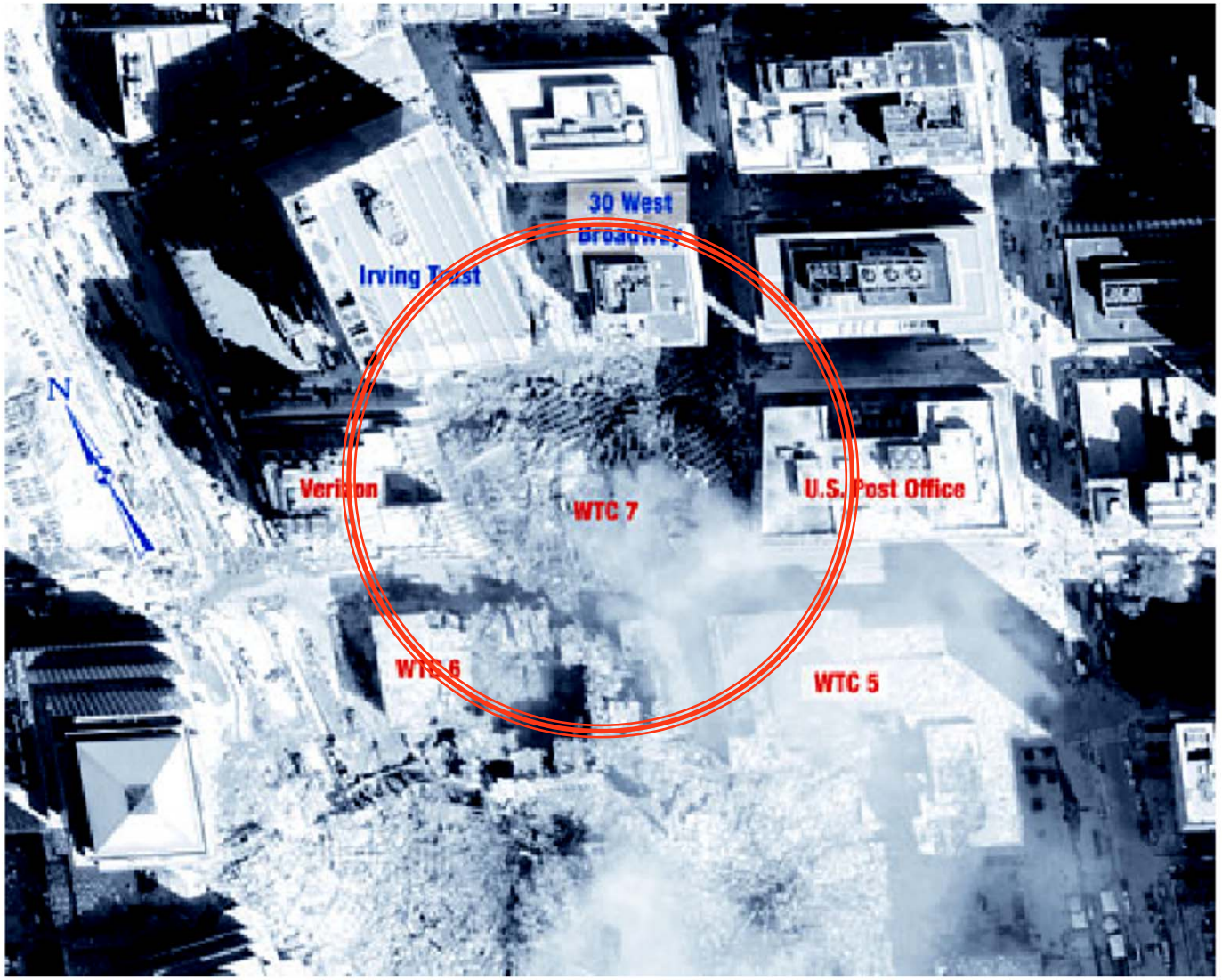
Other WTC buildings

- 50 buildings were hit by twins
- 17 buildings were demaged
- Source of knowledge

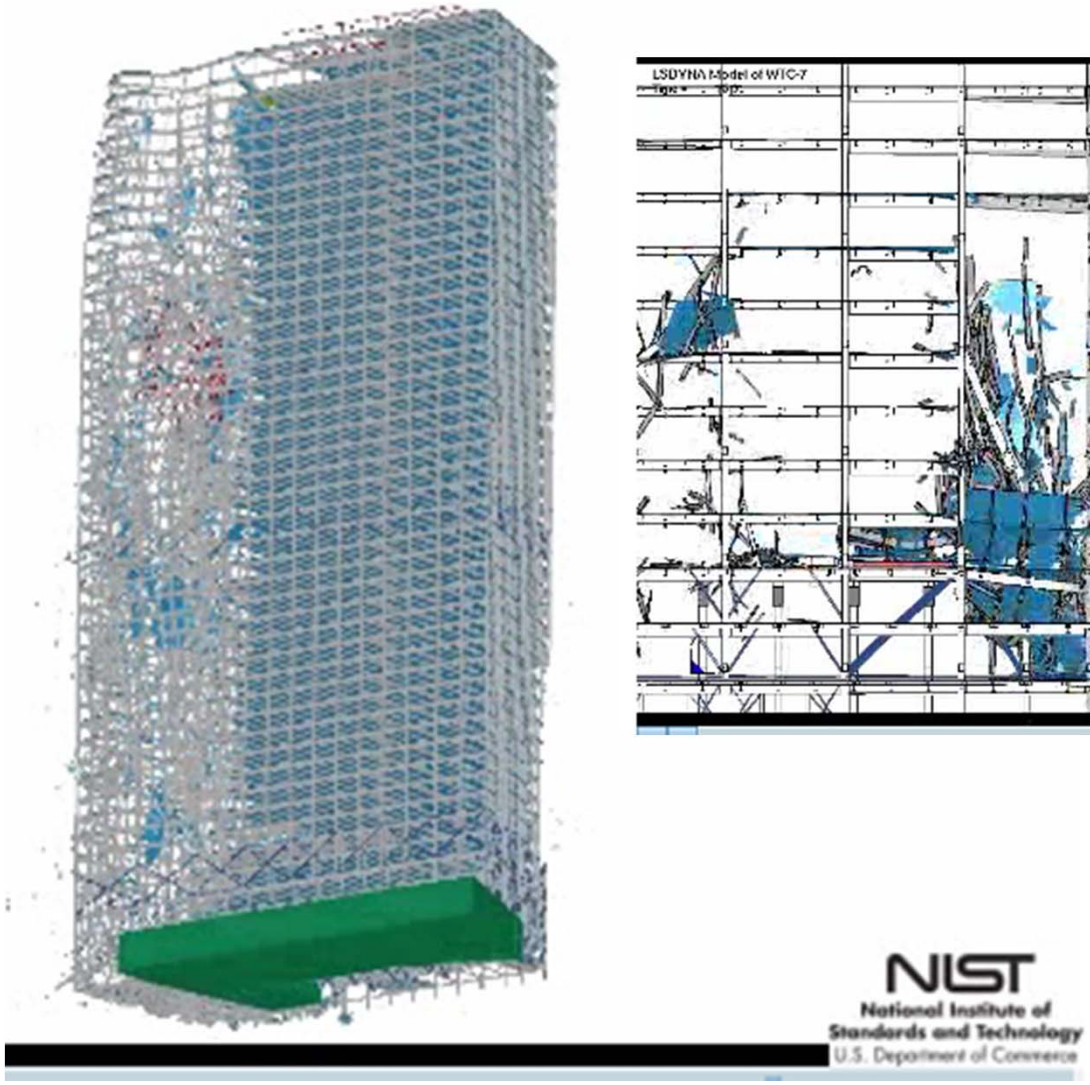


Progresive collapse

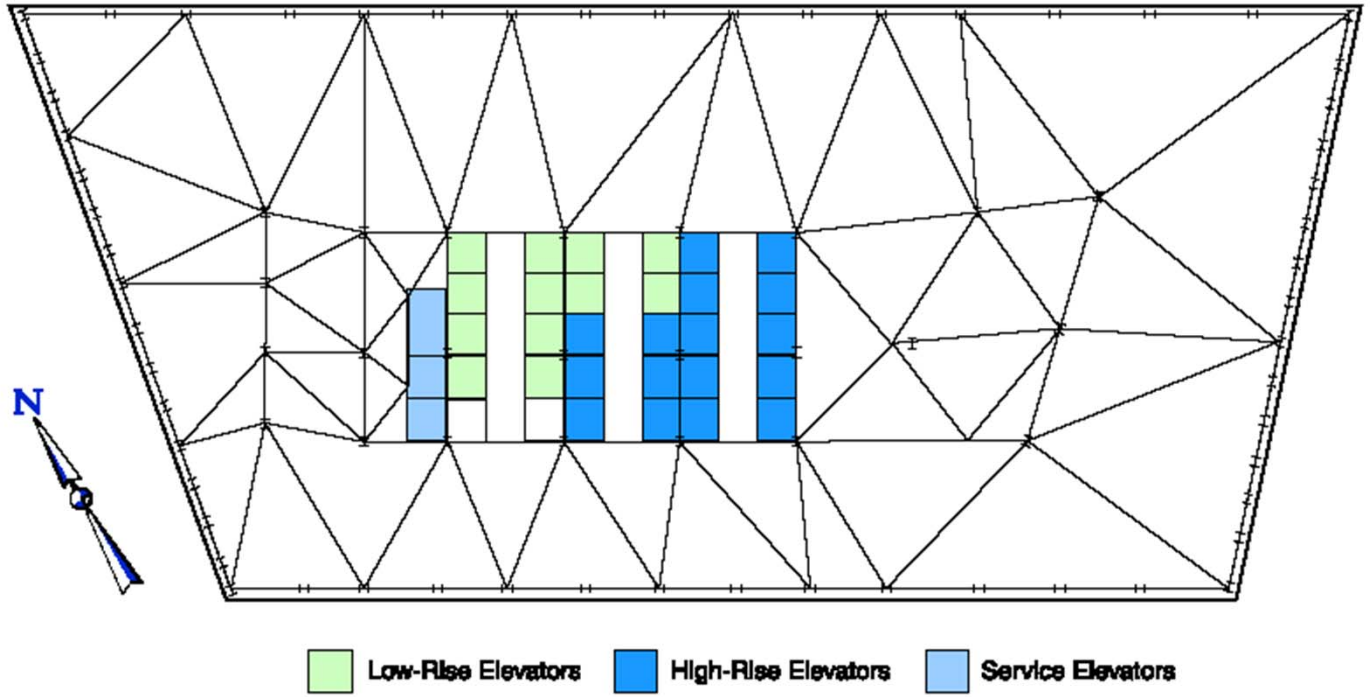
WTC building 7 only



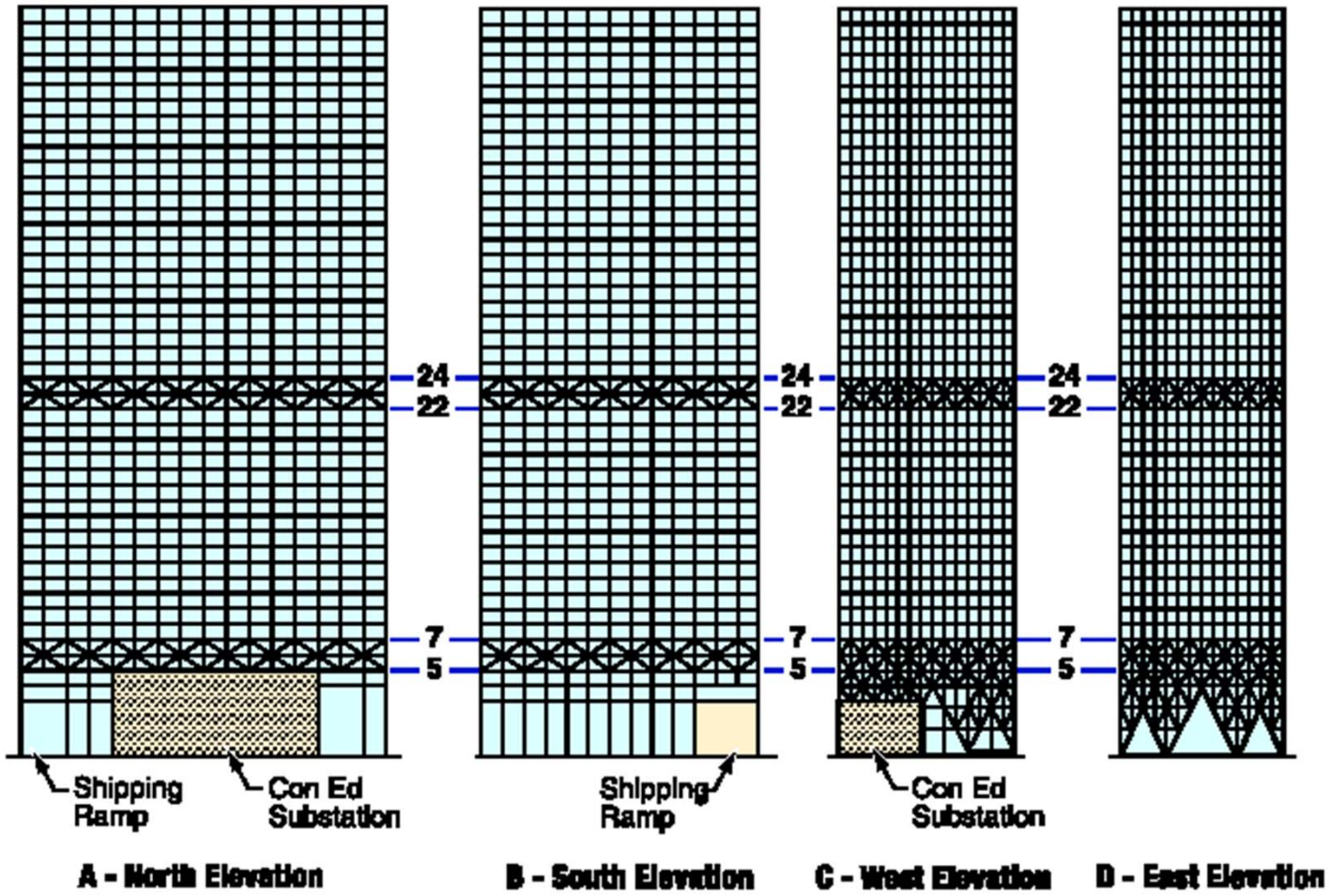
WTC7 – modelling
finished 2008 by NIST



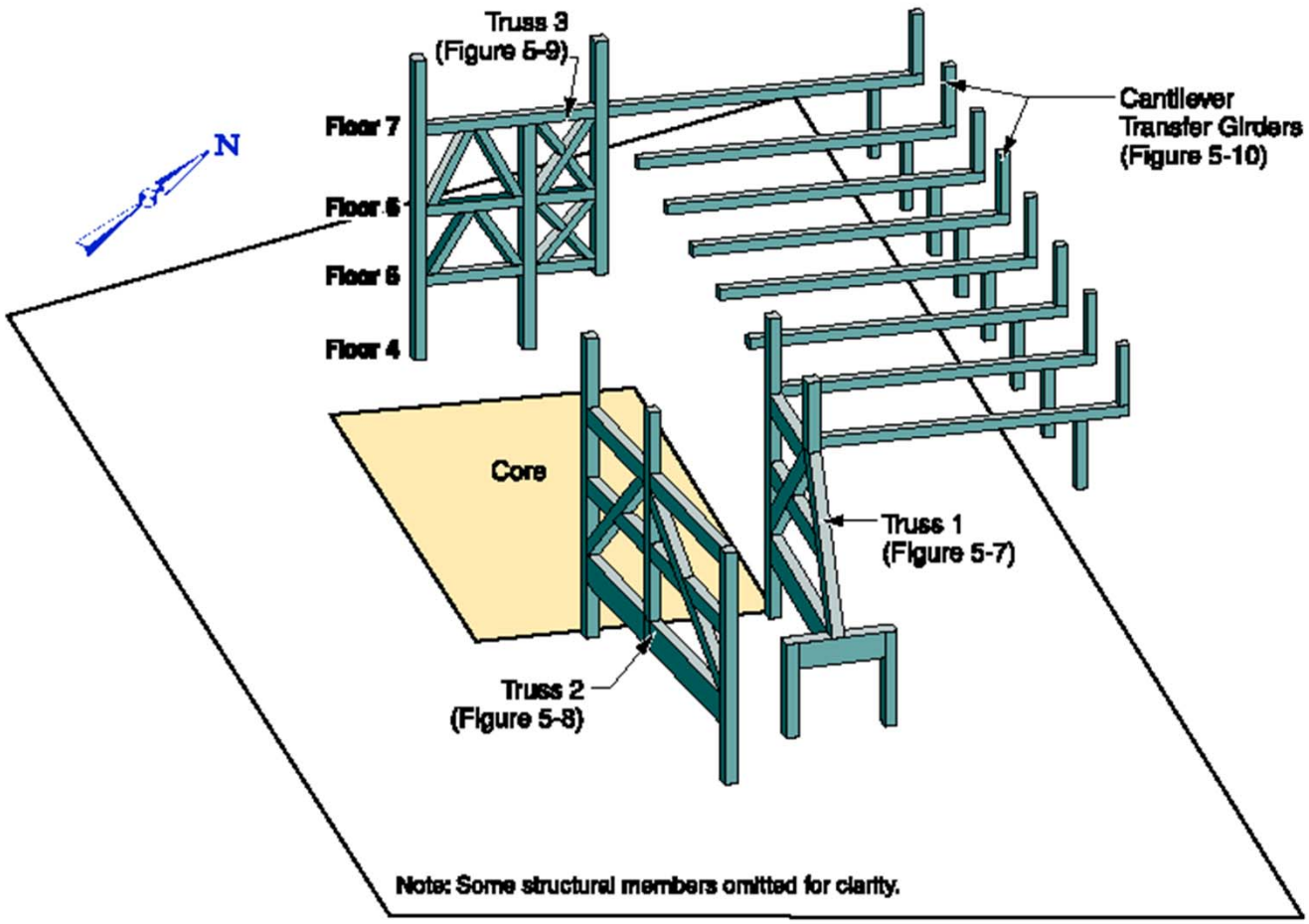
WTC7 plan



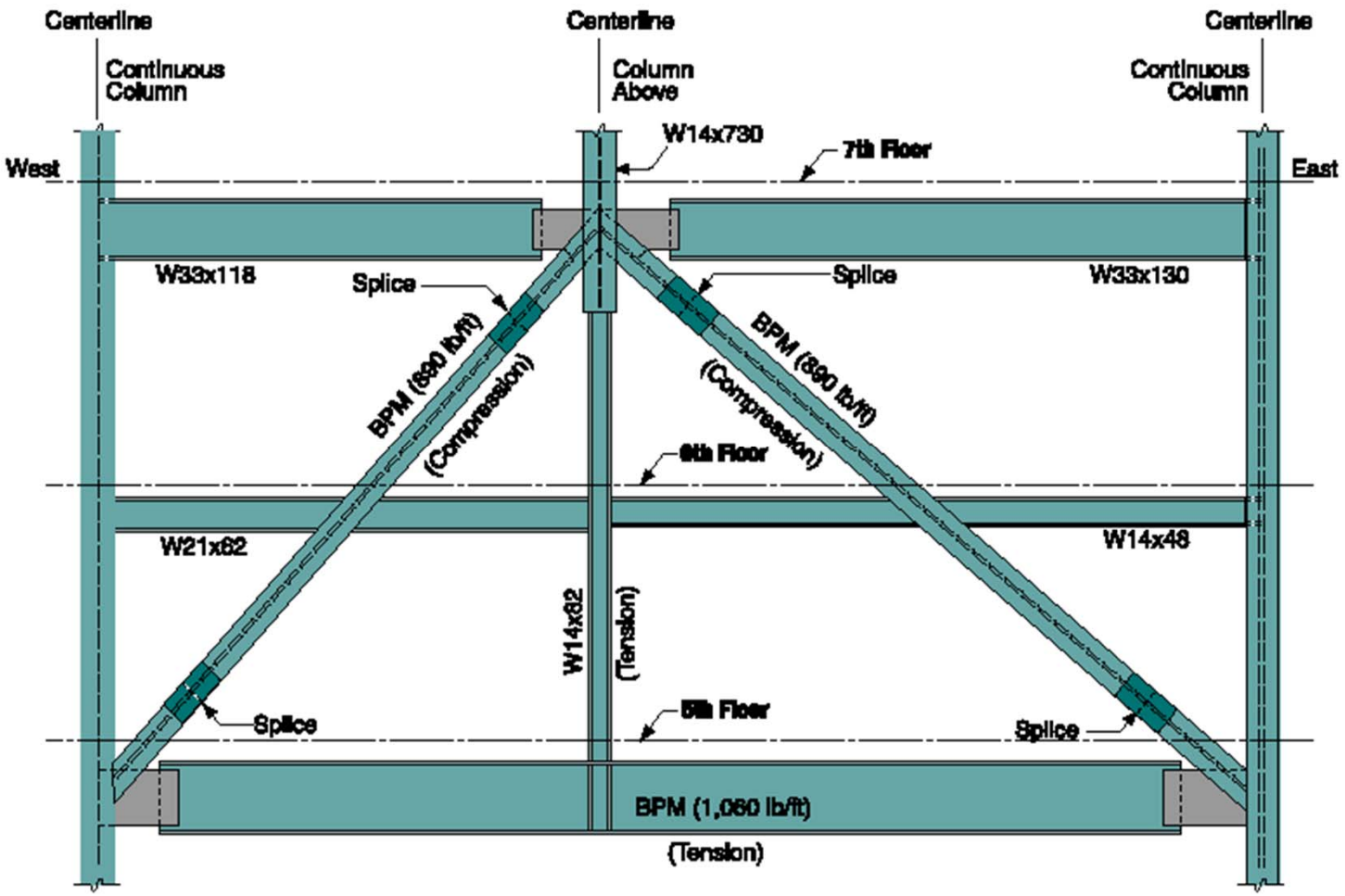
WTC7 view



WTC7 bracing in first floor



WTC7 truss bracing



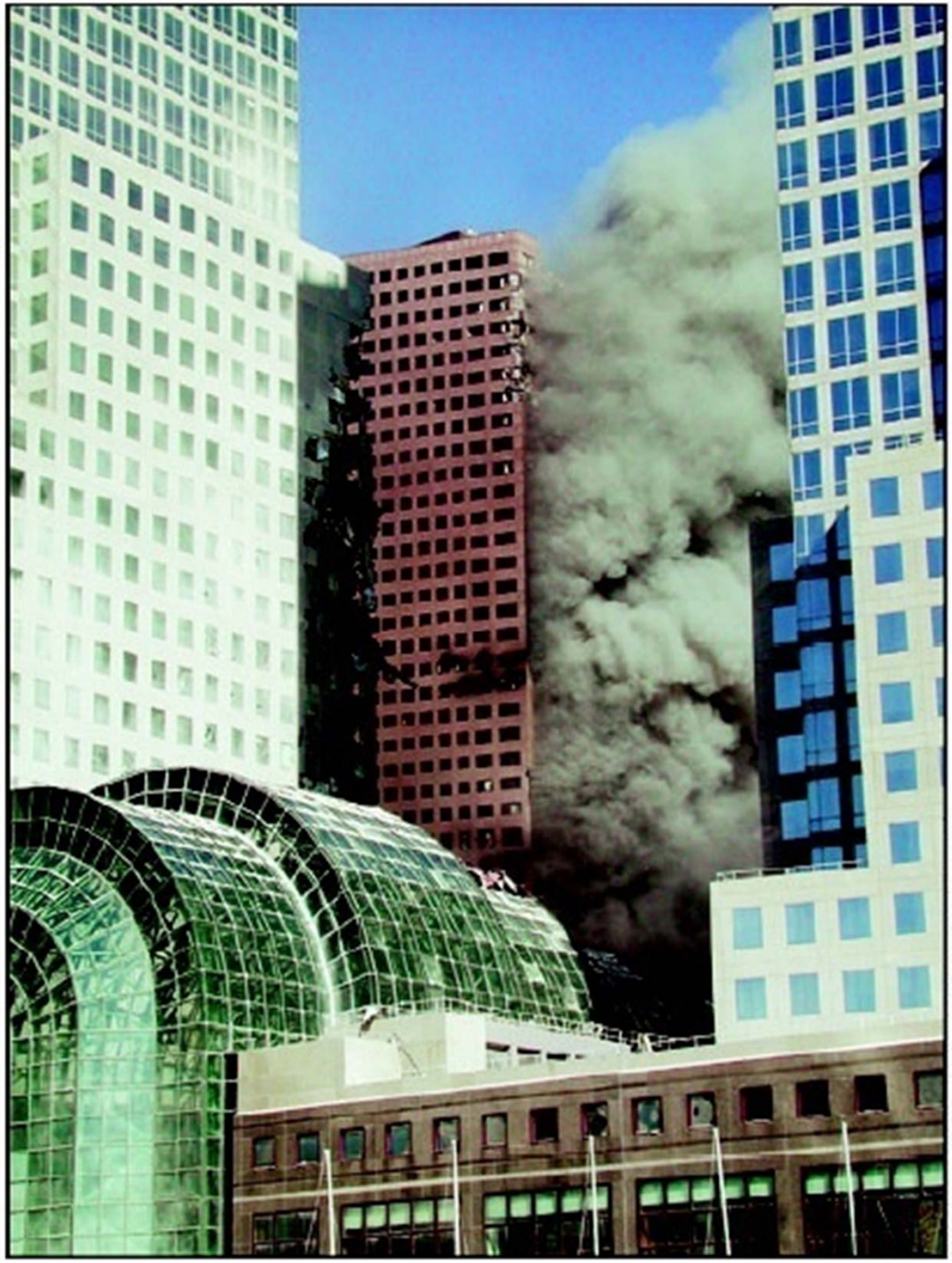
WTC 7

Initiation of crack by part of WTC1's top

WC7 - large fire

WC7

Fire feed of the fuel oil for the back up sets

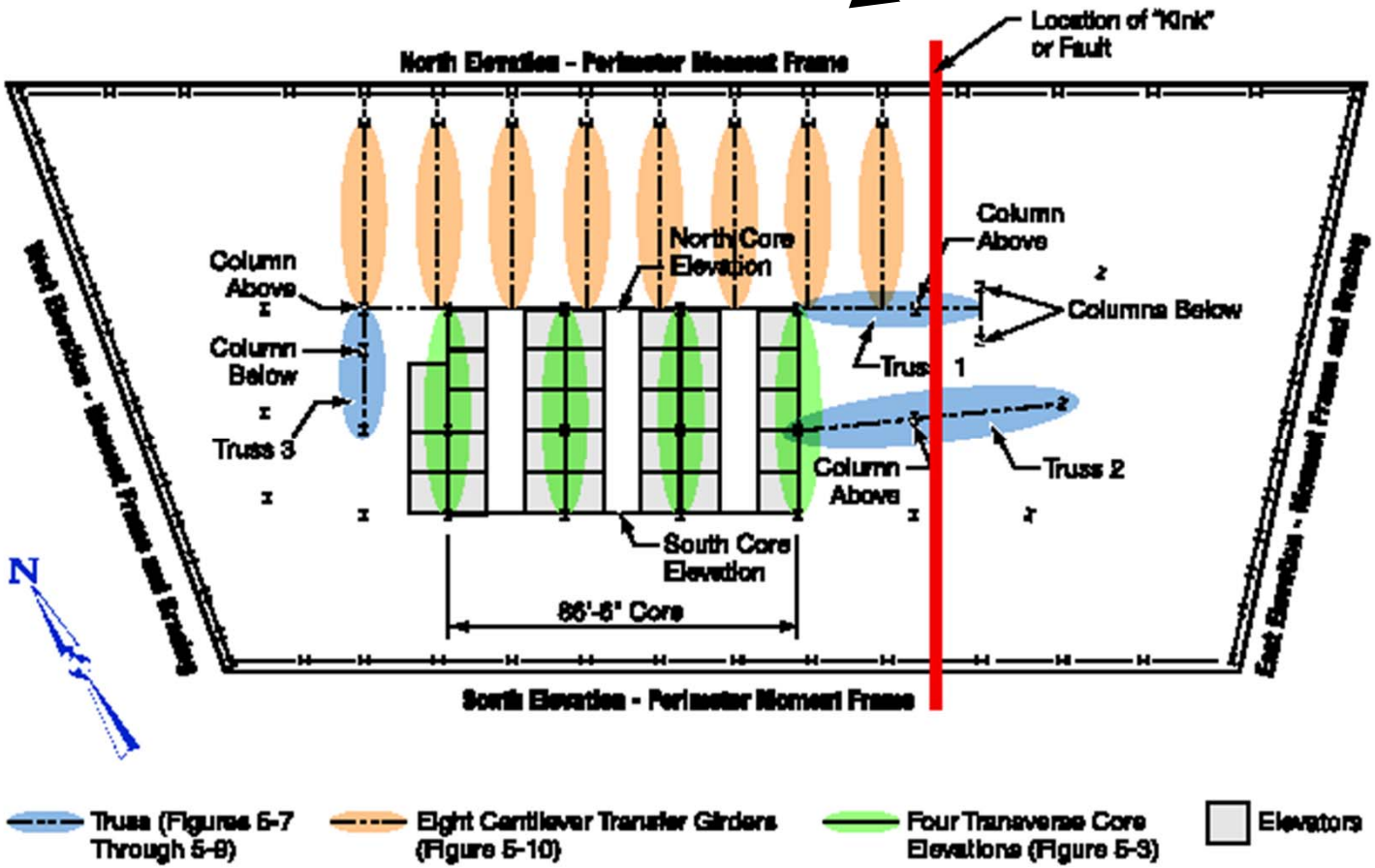


WC7

Initial cracking of building

WTC 7

Position of crack

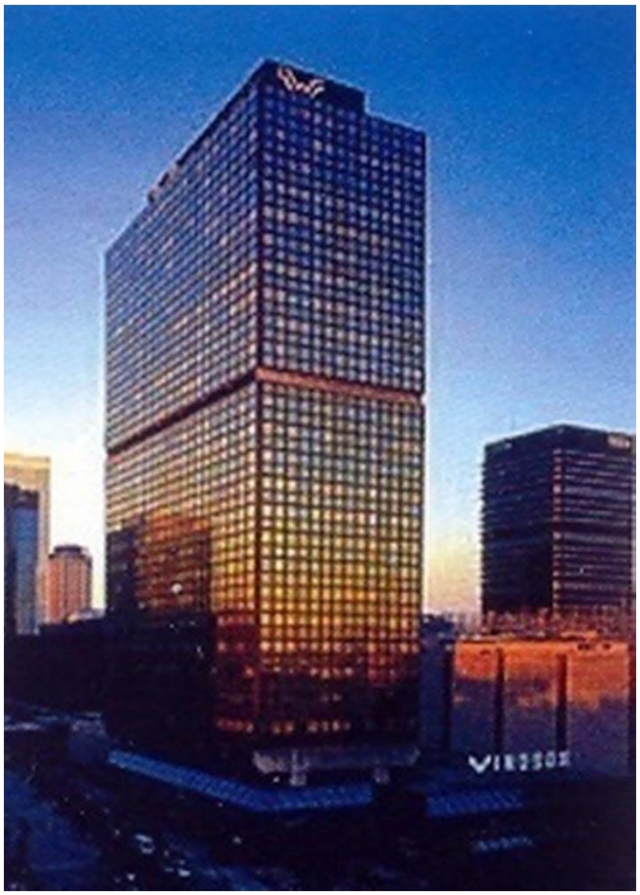


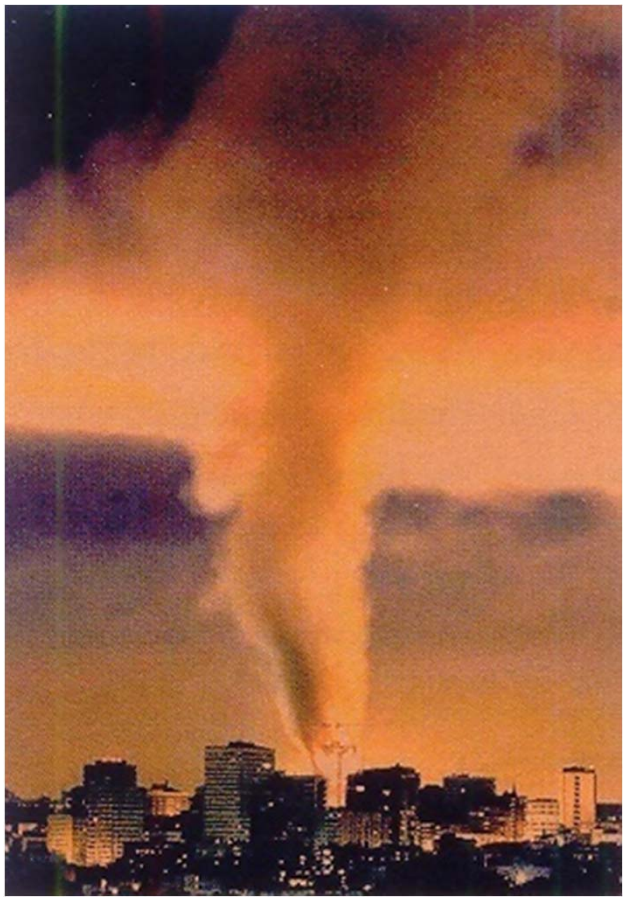
WTC7 progresive colapse at 17:25

WTC7 progresive colapse at 17:25

Windsor Tower Madrid

large fire 13.02.2005





Windsor Tower Madrid

collapse of concrete floors

Windsor Tower Madrid

buckling of steel external columns

Lecture from last disasters

- New materials and new structural solutions needs performance based design
- Robustness and behaviour of the building
- In fire design should be integrated
  - Life safety
  - Financial impact
  - Environmental issues
- Multiple risks
  - Earthquake followed by a fire
  - Explosion followed by a fire

Principles of fire safety

The primary fire safety requirements of national regulations are to:

- Permit safe evacuation of the occupants
- Control fire development
- Prevent fire spread
  E.g.there may be specific boundary conditions when a building is close to its boundary.
- Permit effective fire fighting
- Prevent building collapse

Requirements for fire safety

Regulations specify the following requirements for design of the multistorey building:

- Minimum fire resistance
  - generally in 15 min increments
  - the fire resistance period is the nominal time a building will withstand a nominal standard fire without
    - collapse,
    - the breach of the compartment perimeter, or
    - excessive deformation
- Maximum compartment areas
- Maximum travel distance for means of escape

Active and pasive fire measurements

In office buildings, fire engineering may be used effectively in the following design cases, where:

- Sprinklers or other active systems reduce the risk and severity of a fire
- Detection and alarm systems achieve more rapid evacuation
- An atrium or other large internal enclosure influences effective compartmentation in fire
- A reduction in fire resistance can be argued based on fire load and ventilation conditions
- Means of escape and smoke control in protected escape routes is good

Forms of passive fire protection

There are five forms of passive fire protection:

- Spray protection – applied around the profile
- Board protection – applied as a ‘box’
- Intumescent coating – applied around the profile
- Concrete encasing – forms a rectangular encasement around the member
- Composite member – for example in-filling of tubular columns

EU legislation

- **Construction Products Directive**, Council Directive 89/106/EEC, from 21.12. 1988,
  see ANNEX I: Essential requirements
- The Regulations relating to fire cover:
  - Load-bearing capacity
  - Spread of fire and smoke
  - Spread of the fire to neighbouring construction
  - Occupants can leave
  - Safety of rescue teams

Covers life safety only

Direct fire loss
example in % of GDP

• Slovenia	0,07
• Poland	0,07
• Czech Republic	0,10
• Japan	0,10
• USA	0,10
• United Kingdom	0,13
• Finland	0,15
• Germany	0,16
• Sweden	0,17
• Canada	0,17
• Italy	0,18
• France	0,19
• Denmark	0,20
• Norway	0,25

Average of 2002 – 2004

Source: www.data360.org

Number of deaths in fires

example, per 100,000 inhabitants

• Switzerland	0,51
• Spain	0,61
• New Zealand	0,96
• United Kingdom	0,97
• Canada	1,15
• Norway	1,27
• Czech Republic	1,29
• Austria	1,31
• Sweden	1,32
• USA	1,39
• Denmark	1,55
• Japan	1,79
• Finland	2,08
• Hungary	2,10

Average of 2002 – 2004

Source: www.data360.org

Eurocodes for fire design

- **EN 1991-1-2:2002** Actions on structures exposed to fire
  - Concept of fire design
  - Fire behaviour
  - Mechanical loading during fire
- **EN 199x-1-2:2005** Structural fire design
  - Thermal response
  - Material behaviour
  - Structural response

Eurocode 2: Design of concrete structures

Eurocode 3: **Design of steel structures**

Eurocode 4: **Design of composite steel and concrete structures**

Eurocode 5: Design of timber structures

Eurocode 9: Design of aluminium structures

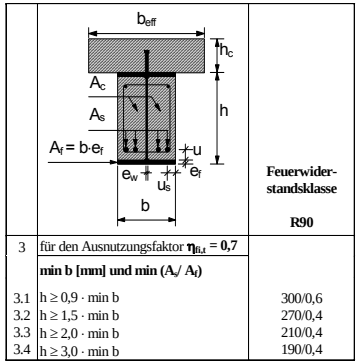
Verification methods

Example

Eurocode 4: Composite steel and concrete structures

Level 1

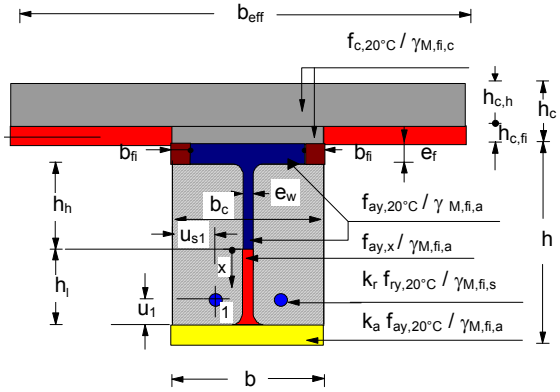
Tabulated data



		Feuerwiderstandsklasse
		R90
3	für den Ausnutzungsfaktor $\eta_{fi,t} = 0,7$	
	min b [mm] und min (A_c/ A_f)	
3.1	h ≥ 0,9 · min b	300/0,6
3.2	h ≥ 1,5 · min b	270/0,4
3.3	h ≥ 2,0 · min b	210/0,4
3.4	h ≥ 3,0 · min b	190/0,4

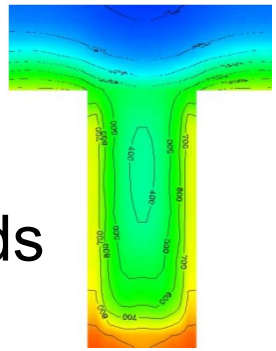
Level 2

Simplified calculation methods



Level 3

General calculation methods



From: Prof. Peter Schaumann
Institute for Steel Construction

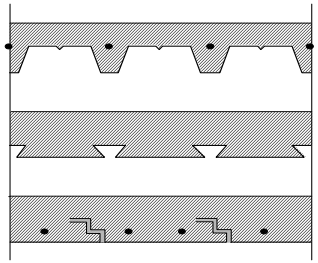
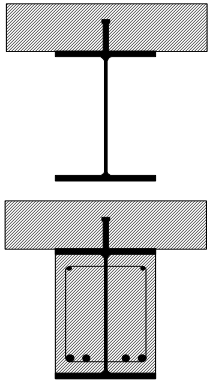
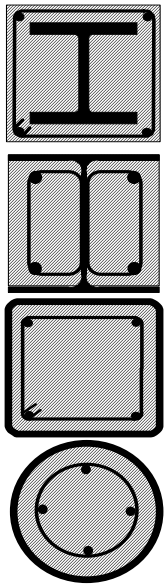
Leibniz Universität Hannover

SUSCOS
SUSTAINABLE STEEL AND TIMBER CONSTRUCTIONS

Scope of application Eurocodes

Example
Eurocode 4: Composite steel and concrete structures

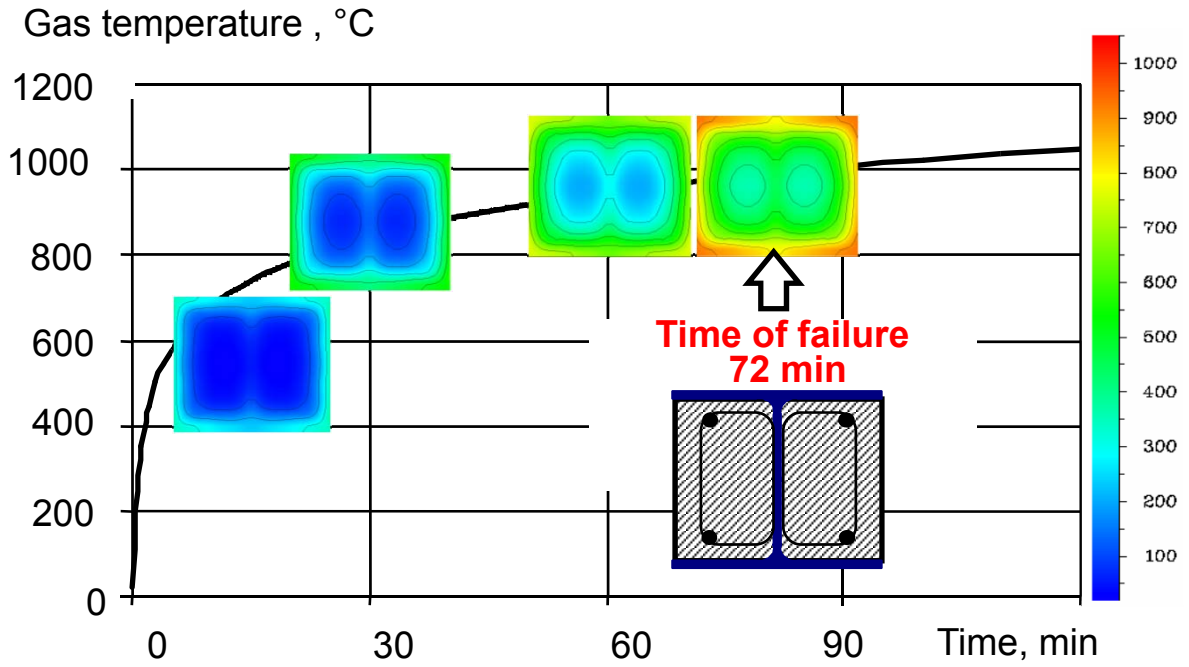
Tabulated data

Composite slabs	Composite beams	Composite columns
		

Accuracy of temperature modelling

For example
Eurocode 4: Composite steel and concrete structures

Calculation - Nominal standard fire curve exposure



From: Prof. Peter Schaumann
Institute for Steel Construction

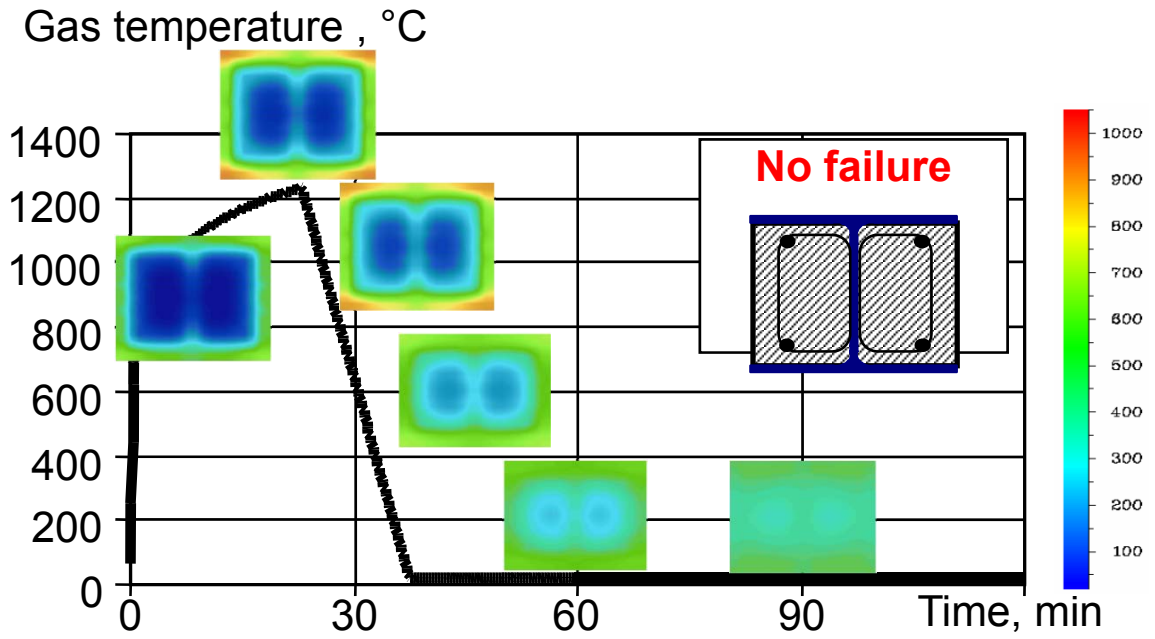
Leibniz Universität Hannover

Accuracy of temperature modelling

Example

Eurocode 4: Composite steel and concrete structures

Calculation – Parametric fire curve exposure



From: Prof. Peter Schaumann
Institute for Steel Construction

Leibniz Universität Hannover

Formative assessment question 2

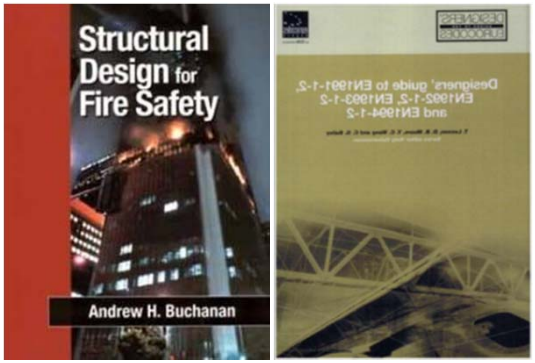
- What passive fire protection is used for steel members?
- Please list the major topics related to fire in EU Construction products directive.
- Which parts of Eurocodes are focussed for fire design?
- Where is described the fire loading?
- Please specify the levels of verification method in Eurocodes.

Educational materials

- Text books
  - Designers' Guide to EN 1991-1-2, EN 1993-1-2 and EN 1994-1-2: Handbook for the Fire Design of Steel,

    Composite and Concrete Structures to the Eurocodes,
    D. Moore, T. Lennon, C. Bailey, Y. Wang, Thomas Telford, 2007,
    ISBN 0727731572.
  - Structural Design for Fire Safety,

    A.H.Buchanan, Wiley, 2001, ISBN 0471889938.
  - Others at www.steelconstruct.com
- Internet
  - AccessSteel
  - Difisek+



Tools on internet

URL: www.access-steel.com

- **AccessSteel** a hypertext engine for structutral steel
- Support EC3, EC4
  - Case studies
  - Design procedures
  - Flow charts
  - NCCI's
  - Worked examples
  - Tables
- Tables and simplifed fire design
  - 30 % of lectures

Tools on internet

URL: www.difisek.eu

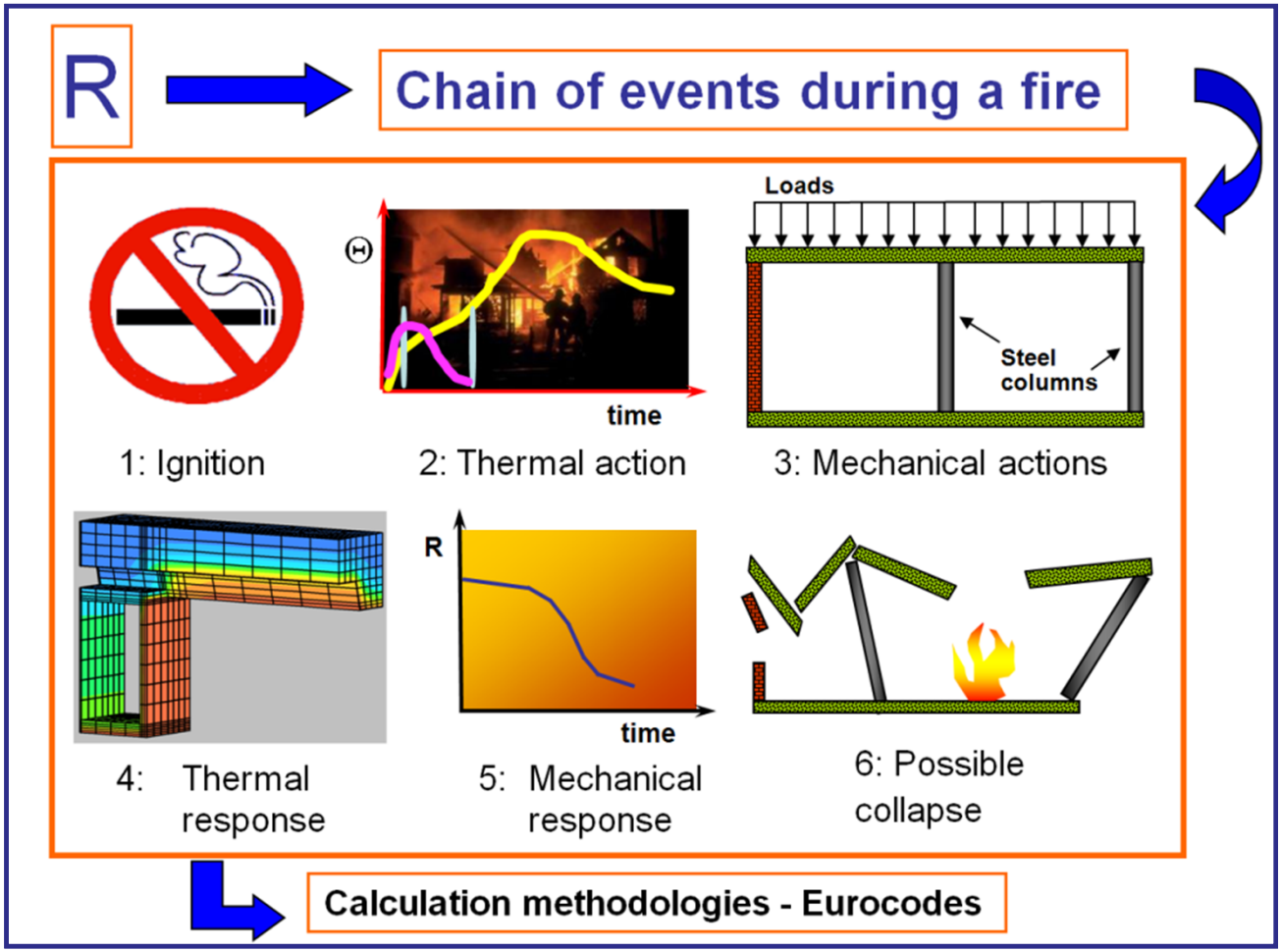
DIFISEK+ lectures and text

- Thermal & Mechanical Actions
- Thermal Response
- Mechanical Response of Structures in Fire
- Software for Fire Design
- Worked Examples
- Illustration of Completed Projects

Simplified and advanced design

DIFISEK+

Example - Basic design procedure



Case studies

- The case studies for fire design may be found on web
  - Difisek+

    URL: www.difisek.eu

  - AccessSteel

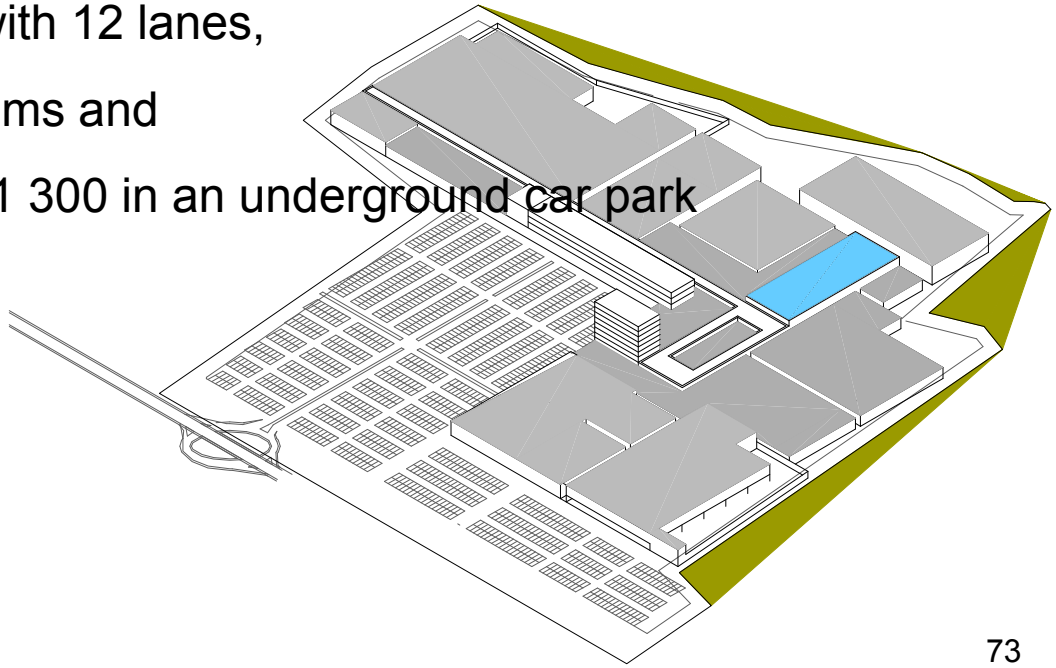
    URL: www.access-steel.com

Case study

from AccessSteel - Fire Engineering of "Las Cañas" Shopping Centre, Viana, Spain

A major shopping centre, providing 65 000 m^2 floor area for a variety of uses:

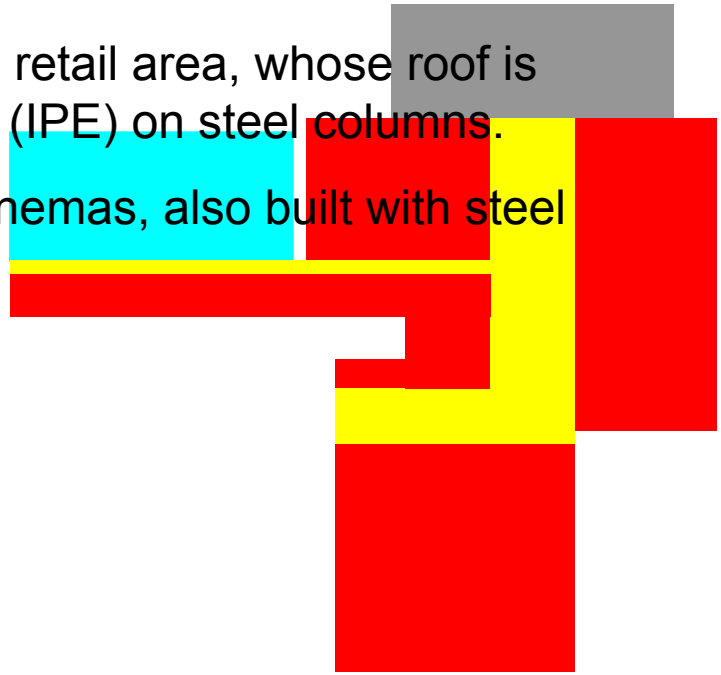
- 80 shops (including a supermarket),
- 12 cinemas,
- 1 discotheque,
- 1 bowling centre with 12 lanes,
- 1 hotel with 75 rooms and
- 3 130 car places, 1 300 in an underground car park



Case study

the shopping centre layout

- The yellow area corresponds to the main corridor, built with IPE columns and trusses (HEB profiles with welded joints) which support the beams and purlins of the roof structure.
- The blue area is a supermarket, attached to the corridor on one side. Its roof is supported by timber beams resting on steel columns.
- The red area corresponds to the retail area, whose roof is supported by continuous beams (IPE) on steel columns.
- The grey area corresponds to cinemas, also built with steel columns.

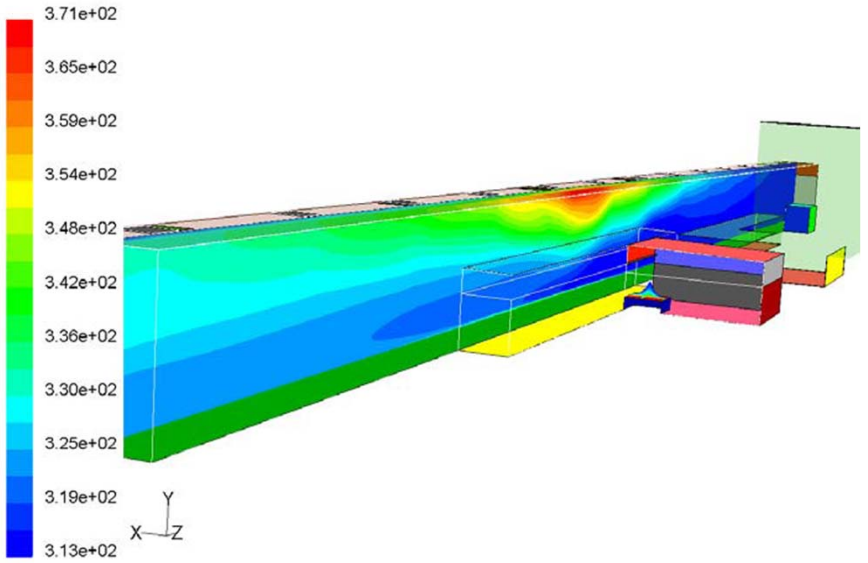


Case study

Smoke control

Smoke control is a major concern in this kind of buildings, for the following reasons:

- A high number of people.
- Occupants do not know the building.
- The egress routes can be affected by smoke coming from a fire.
- A smoke control system was verified by simulations, using analytical methods.



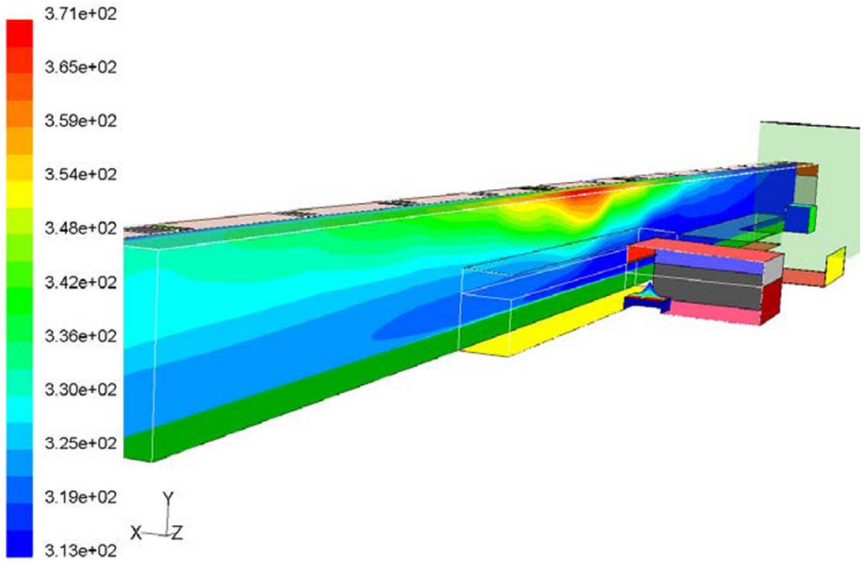
Hot gases in the main corridor due to a fire in a shop.
Temperature contours in K

Case study

Fire scenarios

Several fire scenarios were studied to cover different three main fire safety goals:

- Structural stability of the shops adjacent to the main corridor.
- Structural stability of the supporting elements of the corridor.
- Verification of the smoke control system formed by smoke vents and draft curtains.



Hot gases in the main corridor due to a fire in a shop.
Temperature contours in K

Case study

final conclusions

- The stability of the steel structure of the corridor was maintained without passive protection.
- The beams inside the shops adjacent to the corridor could also remain unprotected.
- Some columns embedded in masonry walls were recommended not to be protected.
- It was recommended to increase the size and number of smoke curtains in the main corridor to improve the smoke control and users' safety.

For more see at www.access-steel.com

Fire Engineering of "Las Cañas" Shopping Centre, Viana, Spain

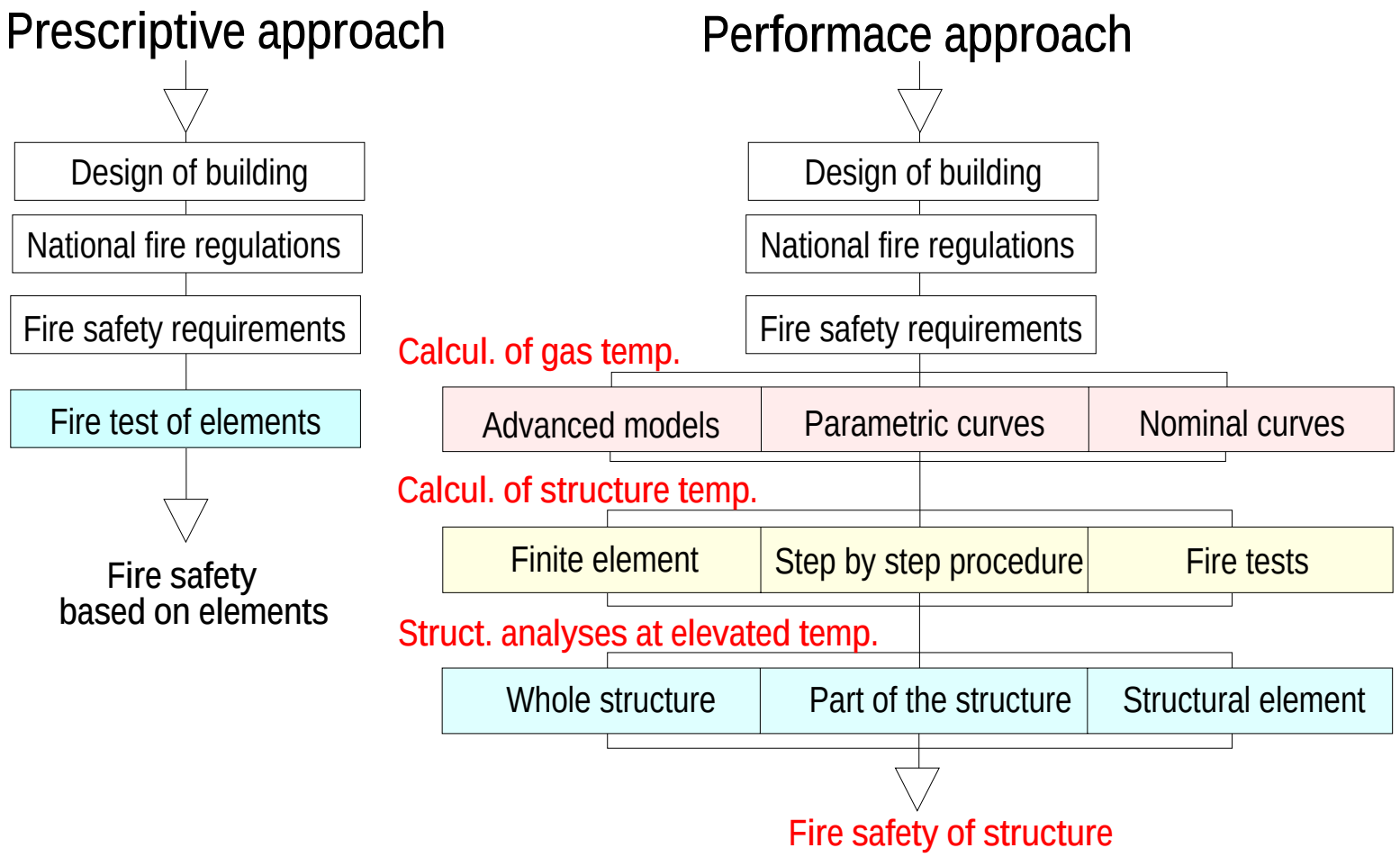
Assessment

- What are the advantages of performance based approach for fire safety of buildings?
- In which part of Eurocode is described te thermal response?
- Which level of verification is covered in internet tool AcessSteel?

Conclusions

- The prescriptive based approach brought a high safety
  for today's buildings
- The performance based approach offers a higher level of
  safety,
  economy, and
  protection of fireman

Conclusion



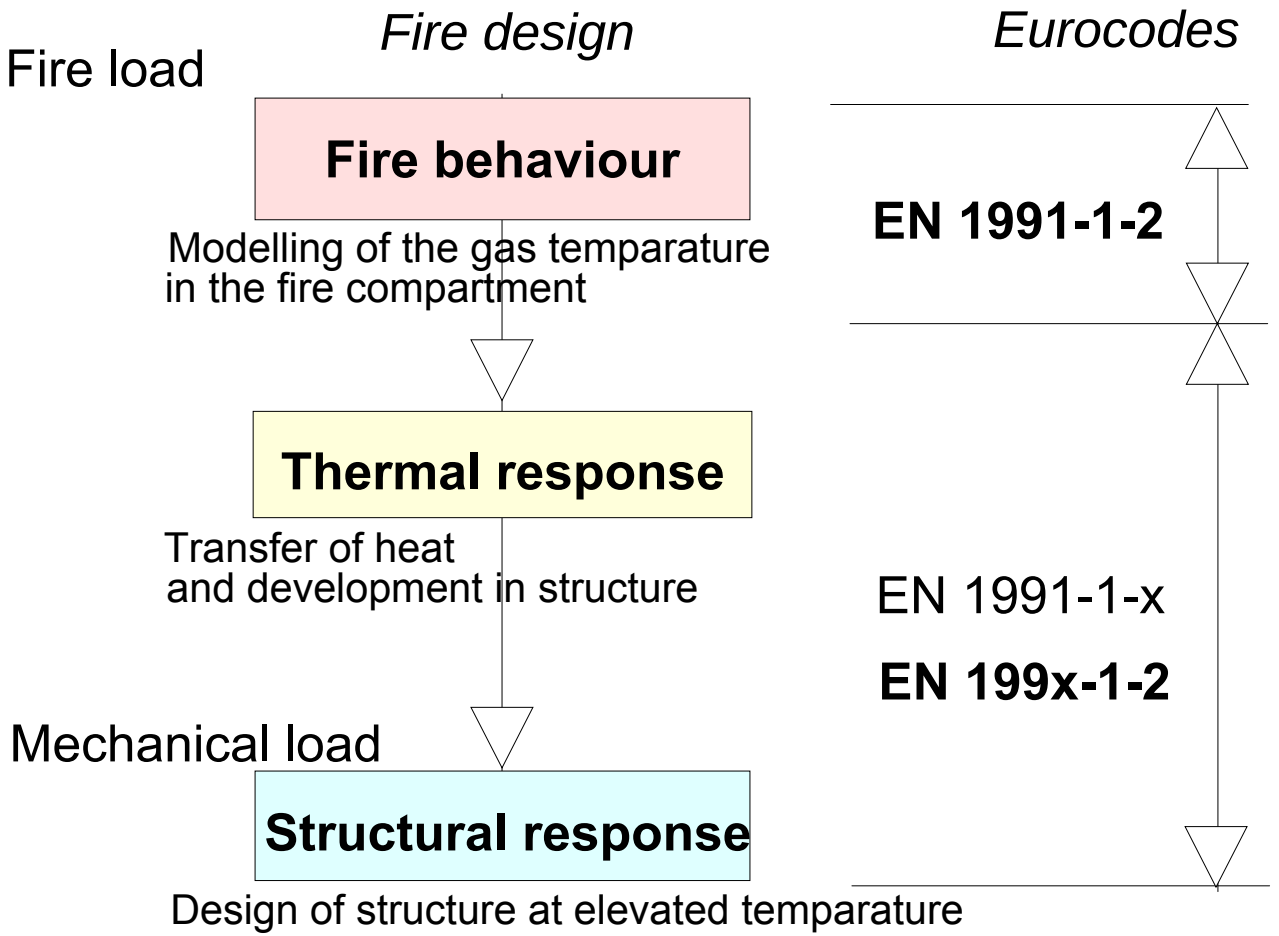
Conclusions

- Conceptual choice of appropriate fire solution may bring a high economical subsequence
- On internet are avaliable educational materials in fire design

Conclusions

- The structural design codes, Eurocodes, have a parts related to fire design EN199x-1-2
- These codes describe design by tables, analytical models and advanced model

Conclusions



Thank you for your kind attention

Notes to users of the lecture

- This session is a basic information about the fire design and requires about 60 min lecturing.
- Further readings on the relevant documents from website of www.access-steel.com and www.difisek.eu.
- The use of relevant standards of national standard institutions are strongly recommended.
- Formative questions should be well answered before the summative questions completed within the tutorial session.
- Keywords for the lecture:

  fire design, prescriptive approach, performance approach, fire protection, Eurocodes.

Notes to users of the lecture

Text documents of advanced fire design of the completed buildingsin Difisek+ case studies at URL: www.difisek.eu are offering:

- Indoor Football Arena, Rauma, Finland
- State Street Bank, Luxembourg, Luxembourg
- Administrative Building of ProfilARBED, Esch/Alzette, Luxembourg
- Köln-Arena, Cologne, Germany
- Bilbao Exhibition Centre, Bilbao, Spain
- City Gate Düsseldorf, Düsseldorf, Germany
- Charles de Gaulle Airport, Paris, France
- Shopping Centre Cactus, Esch/Alzette, Luxembourg
- Shopping Centre Las Cañas, Viana, Spain
- Airbus Hall, Toulouse, France
- Rembrandt Tower, Amsterdam, Netherlands
- Airport Hangar M2, Mošnov, Czech Republic

Notes to users of the lecture

Text documents of fire design of the completed buildings in AccessSteel case
at URL: www.access-steel.com are offering:

- Köln Arena, Germany
- Rembrandt Tower, Amsterdam, Netherlands
- Fire Engineering of "Las Cañas" Shopping Centre, Viana, Spain
- Airbus halls, Toulouse, France
- Indoor Football Arena, Finland
- Office building AOB, Luxembourg
- Terminal 2F, Charles de Gaulle airport, Paris

Notes to users of the lecture

Selection of fire engineering strategy may be find at AcceSteel

- Client guide on the key issues for structural fire resistance
- Scheme development
  - Fire safety strategy for multi-storey buildings for commercial and residential use
  - Selection of appropriate fire engineering strategy for multi-storey commercial and apartment buildings
  - Checklist for fire design of multi-storey office buildings
  - Checklist for fire design of multi-storey apartments
  - Fundamentals of structural fire design
  - Ensuring fire safety

Notes to users of the lecture

The description of features of different pasive fire protection in AccessSteel materials:

- Board fire protection
- Intumescent coatings
- Sprayed fire protection
- Shielded members in fire
- Slim floor systems

Notes for lecturers

- Subject: Bases of fire design
- Lecture duration: 60 min
- Keywords: fire design, prescriptive approach, performance approach, fire protection, Eurocodes
- Aspects to be discussed: advantages and disadvantages of prescriptive and performance approach
- Within the lecturing, the introduction of Eurocode fire design is explained
- Further reading: relevant documents from website of www.access-steel.com and www.difisek.eu
- The reached accuracy in prediction of compartment fire is shown on the prediction of the seveth large scale Cardington fire test
- The reached accuracy in prediction of localized fire is shown on the prediction of Ostrava fire test.