2C10
Design for Fire and Robustness

Timisoara, 31.03-11.04.2014

European Erasmus Mundus Master Course

Sustainable Constructions
under Natural Hazards and Catastrophic Events

520121-1-2011-1-CZ-ERA MUNDUS-EMMC

2C10

Examination

1.	Homework: (dead-line 16 April, 14:00)	weight 40 %
2.	Examination on 17 April, 9:00, room to be announced):	
	a) Written test (10 questions from lectures, without any aids), 60 mins	weight 30 %
	b) Worked examples (choice of 2 examples from 4, all aids available), 90 mins	weight 30 %

Notes:

- simple questions covering all 2C10 presentations,
- worked examples similar to homework/ design applications (modifications).

Fire safety

Raul ZAHARIA

Lecture 1: 31/03/2014

European Erasmus Mundus Master Course
Sustainable Constructions
under Natural Hazards and Catastrophic Events
520121-1-2011-1-CZ-ERA MUNDUS-EMMC

Fire safety in buildings

Regulation (EU) No 305/2011 of 9 March 2011

replacing

Construction Products Directive
(Council Directive 89/106/EEC)

- **Annex I**
  Basic requirements for construction works

1. Mechanical resistance and stability

2. Safety in case of fire

3. Hygiene, health and the environment

EU Regulation No 305/2011

2. Safety in case of fire

The construction works must be designed and built in such a way that in the event of an outbreak of fire:

a) the load-bearing capacity **of the construction can be assumed for a specific period of time**

b) the generation and spread of fire and smoke within the construction **works are limited**

c) the spread of fire to neighbouring construction **works is limited**

d) occupants can leave **the construction works or be rescued by other means**

e) the safety of rescue teams **is taken into consideration.**

Fire safety in buildings

- **The requirements of fire safety are clearly defined, taking into consideration the risk posed by fire and the level of acceptable risk.**

  – **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

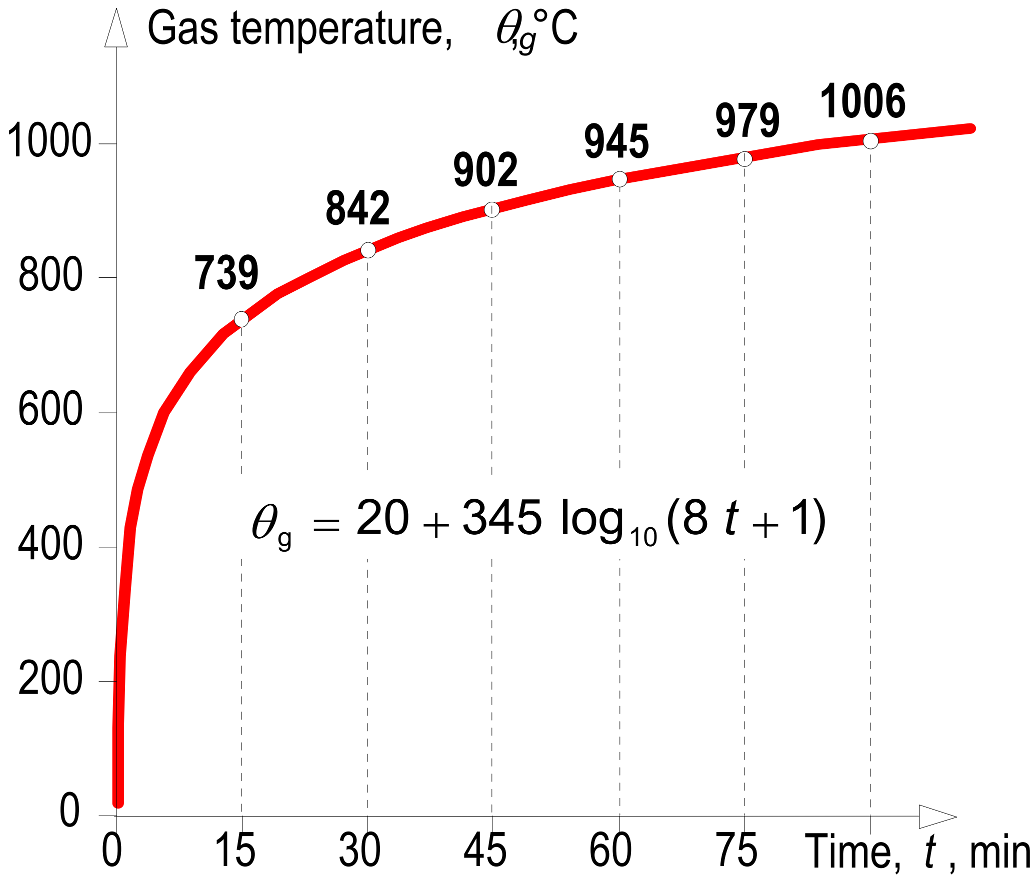
- **Fire resistance times**

	Height of Building (m)			
	<5	<18	<30	>30
Residential (Non Domestic)	30	60	90	120
Offices	30	60	90	120 + Sprinklers
Shops, Commercial, Assembly	60	60	90	
Industrial & Storage	60	90	120	
Car Parks - Open	15	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 (ISO 834) fire curve



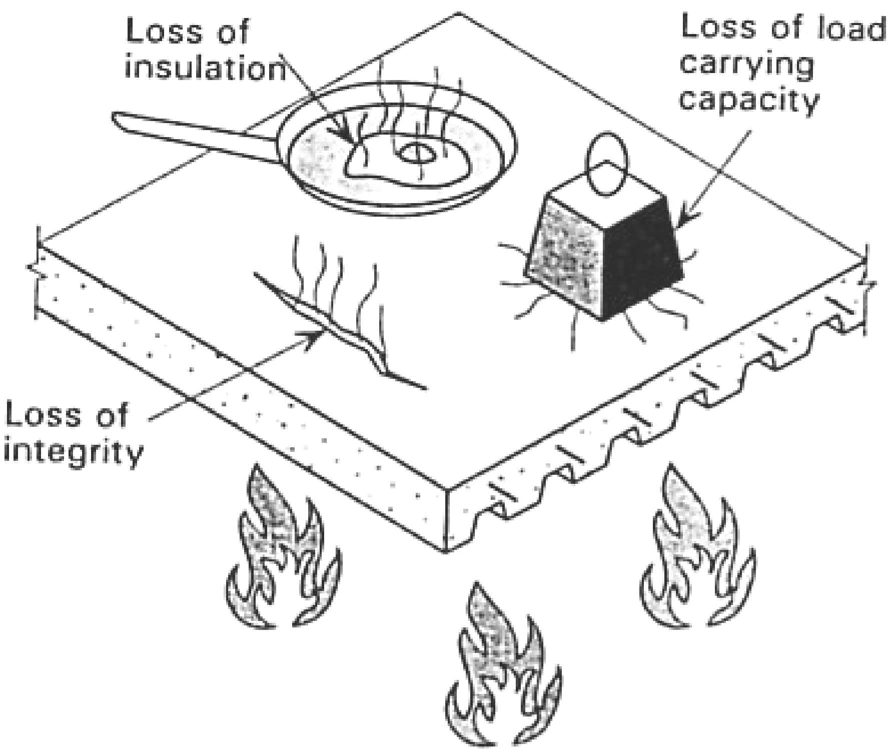
Standard fire resistance

Used for

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

Marked as

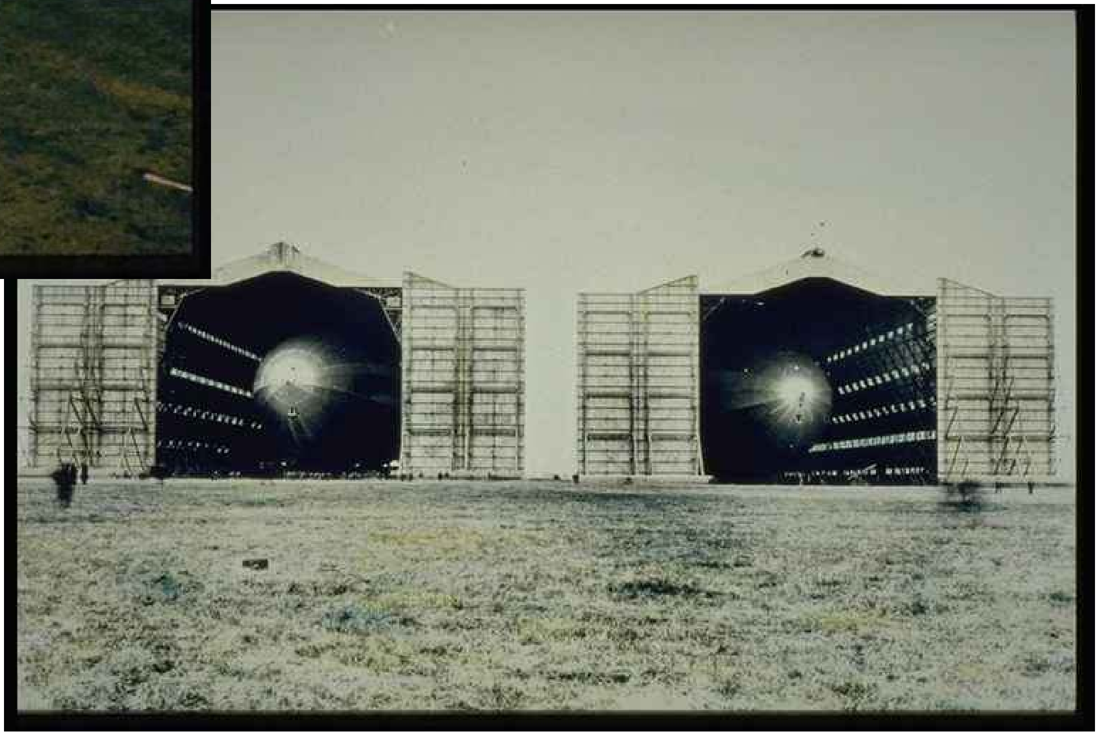
- **R15; RE30; REI90,..**



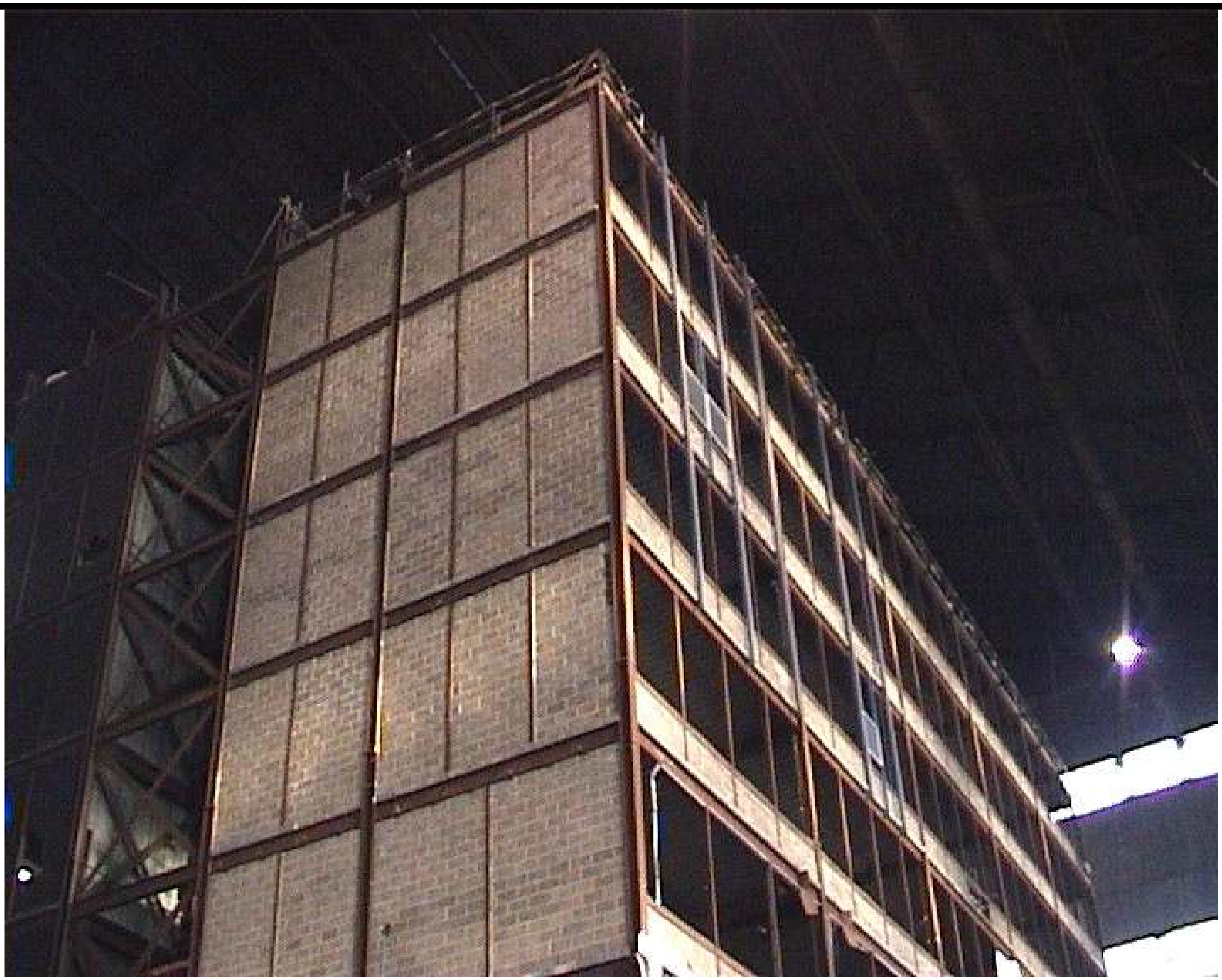
Experimental testing

- Testing material behaviour
- Standard fire tests
- Small scale fire tests
- Large scale fire tests
  - [Cardington laboratory test]

Cardington (UK) fire laboratory – 48 m x 65 m x 250 m



Steel Composite Structure – 8 Floors



Structure finished 1994, plan area 945 m^2

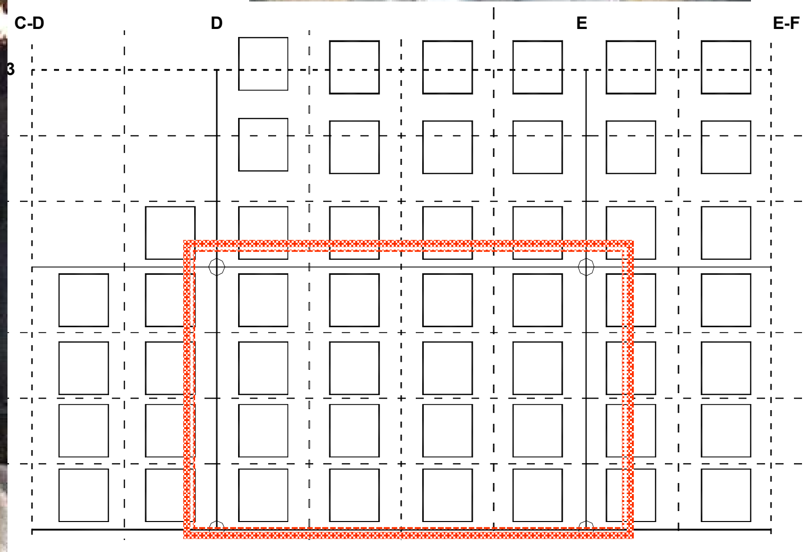
Typical composite structure

beam-column connections - header plates
beam-beam connections - fin plates

Fire Compartment

Mechanical Load

- Permanent 100%
- Live around 50% by sand bags



Fire Load

Timber cribs

History of the Standard fire test

Over 100 years of testing

- **1890's** early attempts
  requested by **insurance companies**

- **1917** First US Standard produced
- **1932** First Edition of BS476 (UK)
- **1933** E119 (US) produced

- **1985** ISO 834
- **2003** EN 1991-1-2

Fire test of intumescent coating

Prescriptive approach - Advantages

- Limited design effort
- Experience has shown that it works
- Easily understood by all parties
- Based on nominal standard fire tests

Prescriptive approach - Disavantages

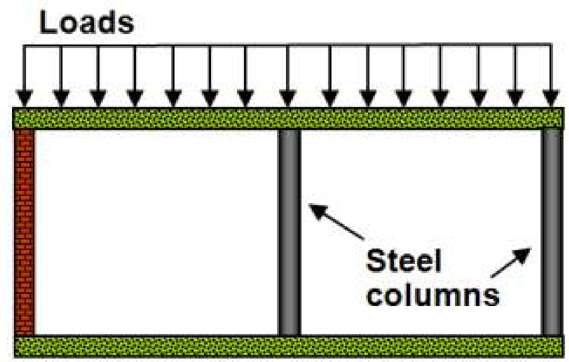
- Actual structural behaviour ignored
- Effect of real fires ignored
- Levels of safety and robustness unknown
- Optimum solution in terms of
  - life safety unknown
  - economical impact unknown
  - environmental damage unknown

R

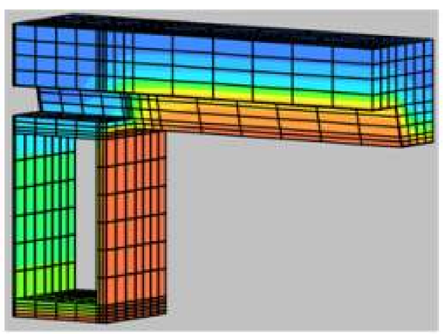
Chain of events during a fire

1: Ignition

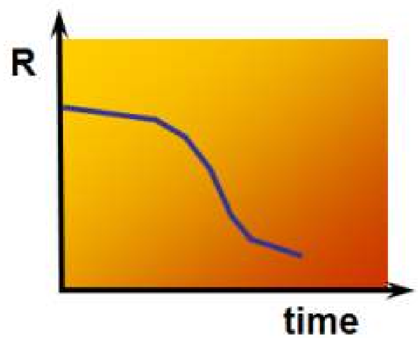
2: Thermal action



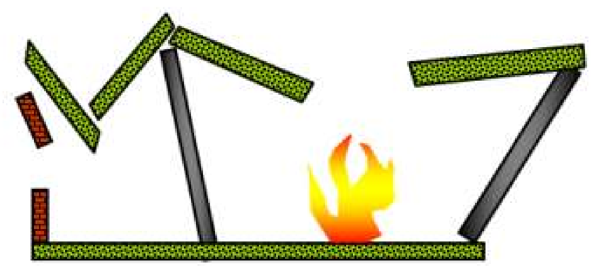
3: Mechanical actions



4: Thermal response



5: Mechanical response



6: Possible collapse

Calculation methodologies - Eurocodes

Eurocodes for fire design

Eurocode	At room temperature	In case of fire
0 : Basis of design	EN 1990	-
1 : Actions	EN 1991-1-1	EN 1991-1-2
2 : Concrete structures	EN 1992-1-1	EN 1992-1-2
3 : Steel structures	EN 1993-1-1	EN 1993-1-2
4 : Composite steel-concrete structures	EN 1994-1-1	EN 1994-1-2
5 : Timber structures	EN 1995-1-1	EN 1995-1-2
6 : Masonry structures	EN 1996-1-1	EN 1996-1-2
7 : Geotechnical design	EN 1997	-
8 : Earthquake resistance	EN 1998	-
9 : Aluminium alloy structures	EN 1999-1-1	EN 1999-1-2

Eurocodes for fire design

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

Eurocode 2: Design of concrete structures

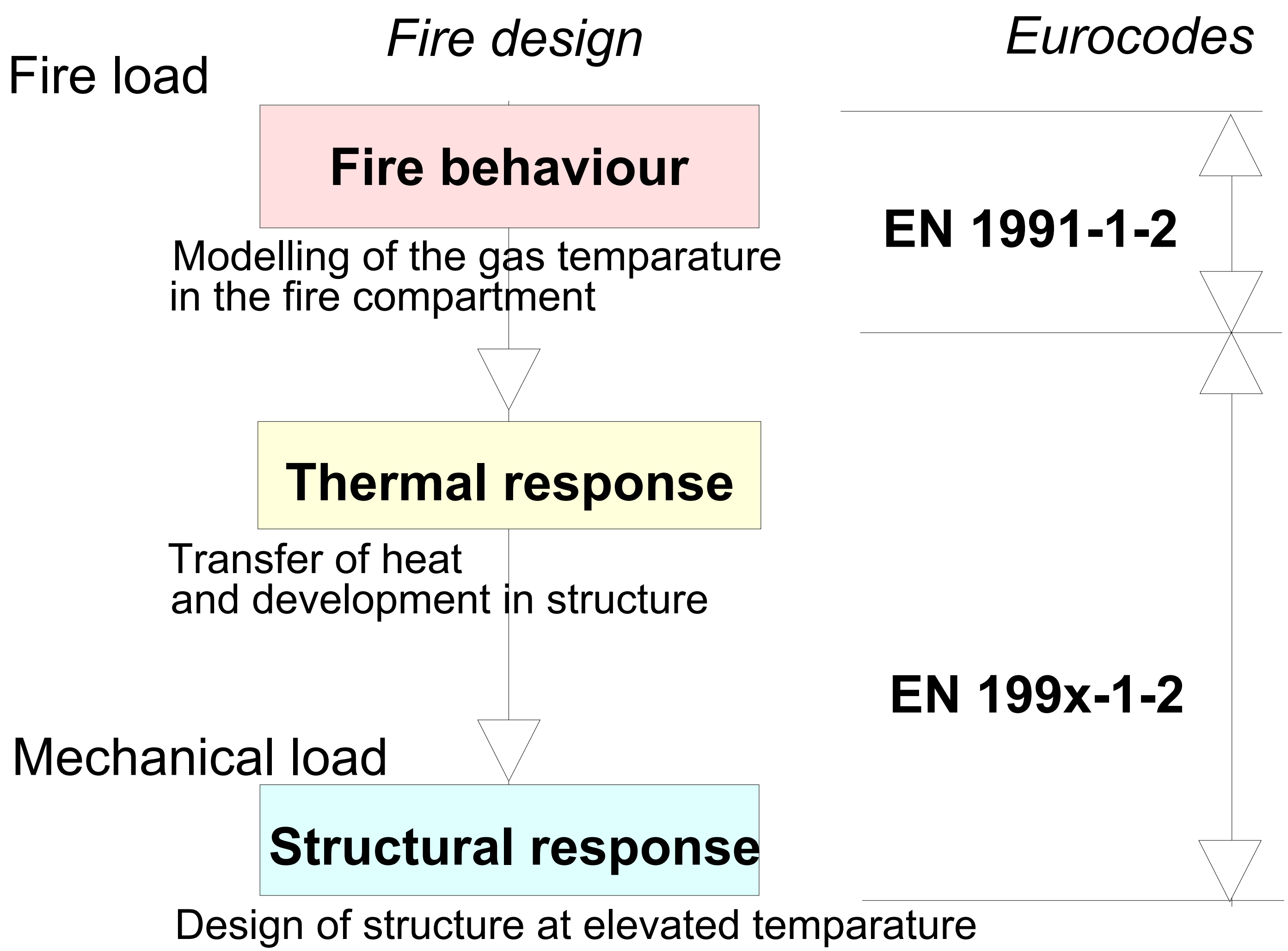
Eurocode 3: Design of steel structures

Eurocode 4: Design of composite steel and concrete structures

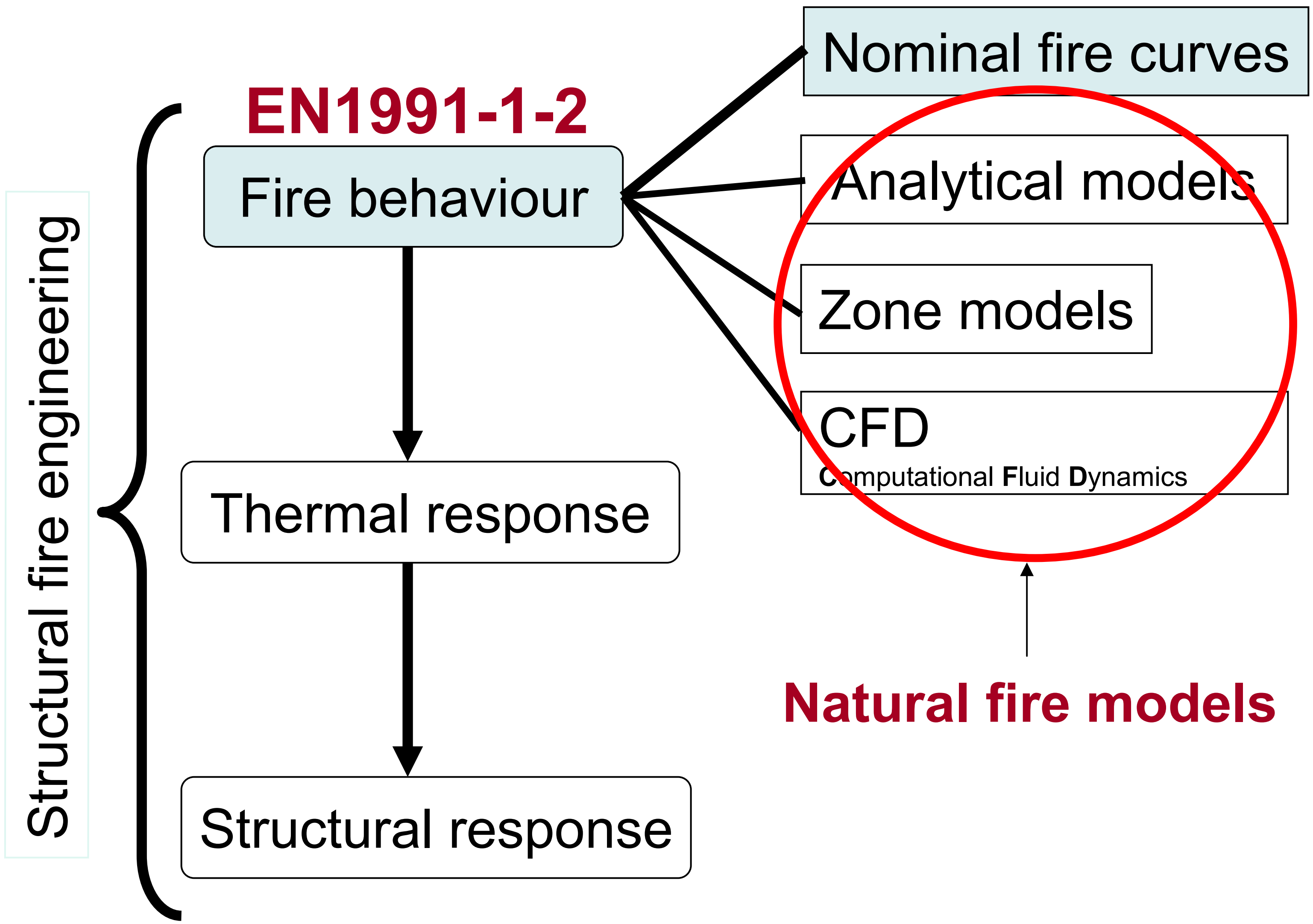
Eurocode 5: Design of timber structures

Eurocode 6: Design of masonry structures

Eurocode 9: Design of aluminium structures

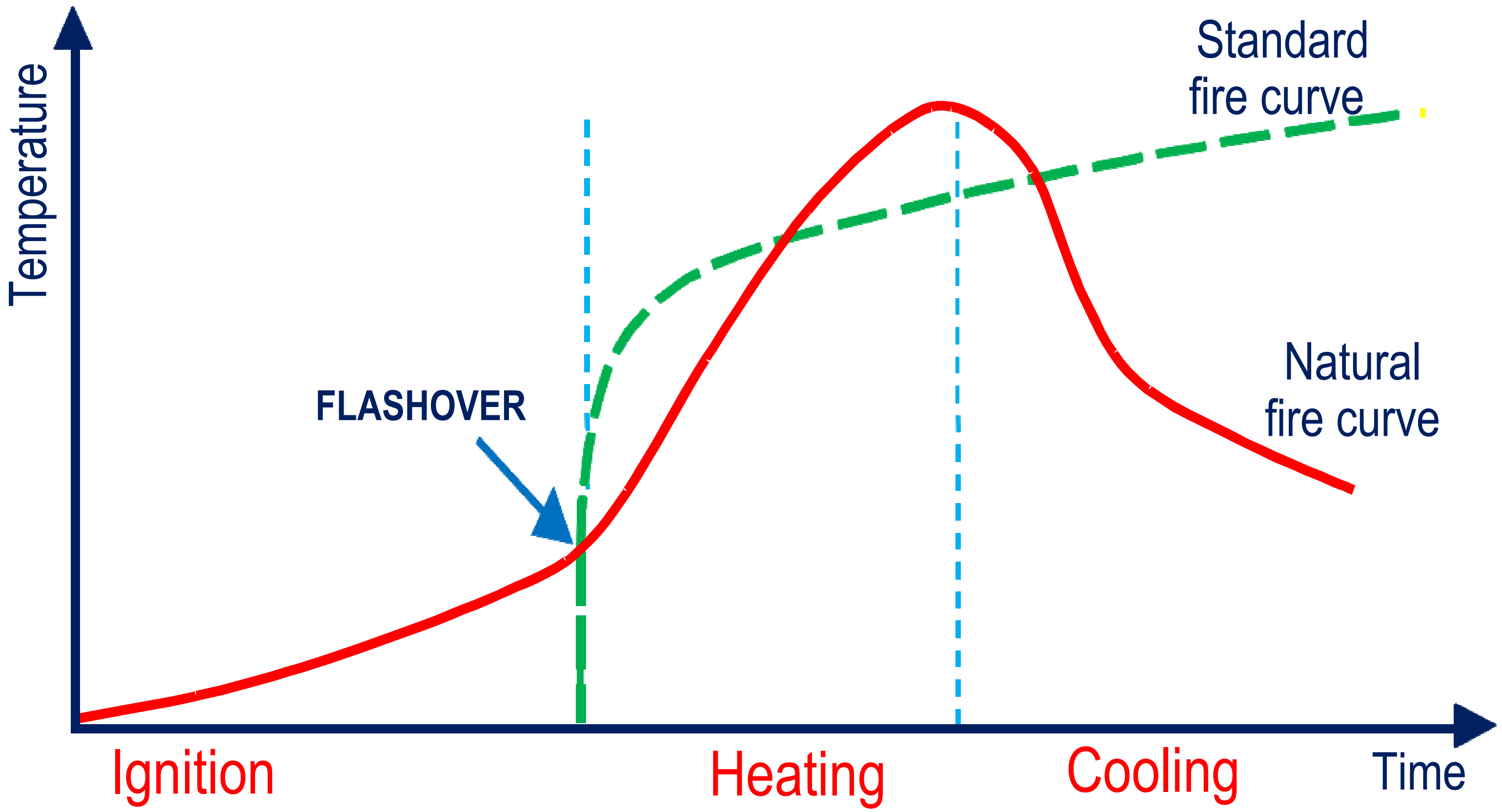

Fire design
Eurocodes
Fire load
Fire behaviour
Modelling of the gas temparature
in the fire compartment
EN 1991-1-2
Thermal response
Transfer of heat
and development in structure
EN 199x-1-2
Mechanical load
Structural response
Design of structure at elevated temparature

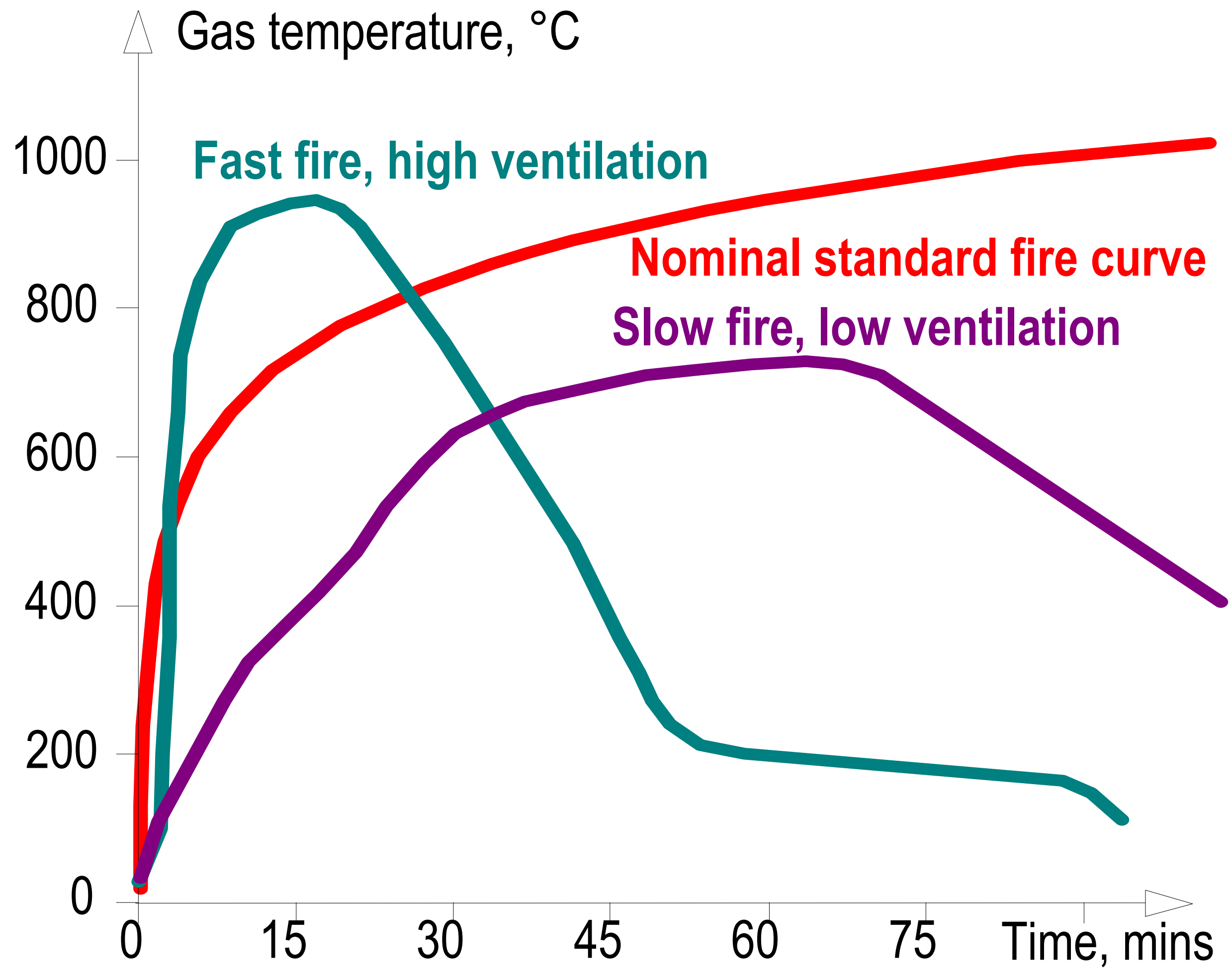
Fire behaviour




Heat
Fuel
Oxygen

Three phases of natural fire

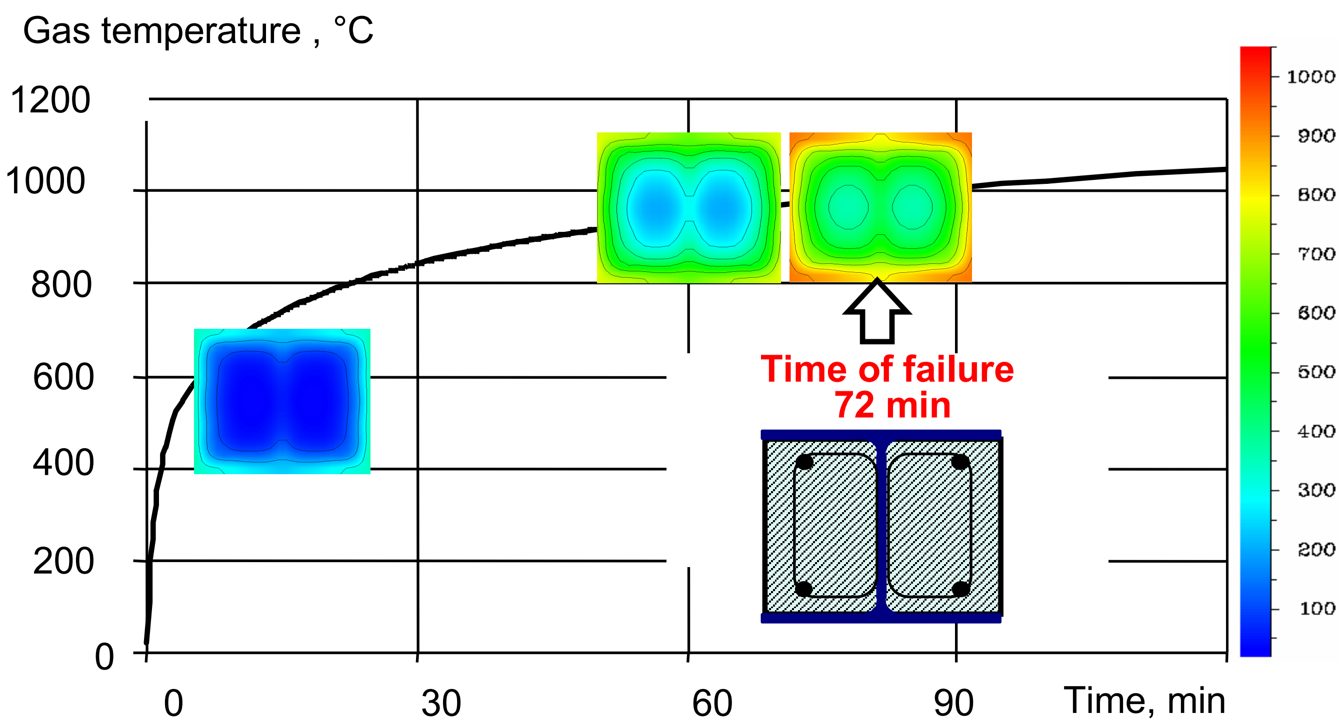



Gas temperature, °C
1000
800
600
400
200
0
Fast fire, high ventilation
Nominal standard fire curve
Slow fire, low ventilation
0
15
30
45
60
75
Time, mins

Importance of the fire model considered

For example
Eurocode 4: Composite steel and concrete structures

Calculation - Nominal standard fire curve

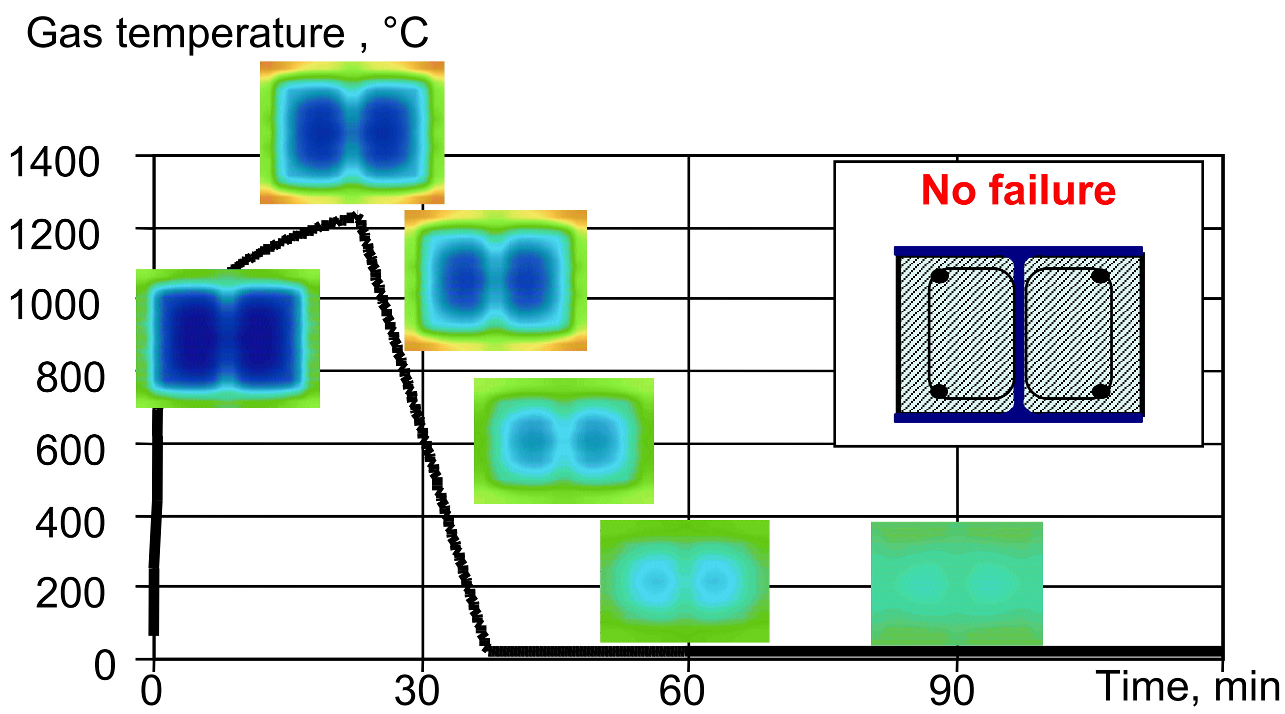


From: Prof. Peter Schaumann
Institute for Steel Construction

Example

Eurocode 4: Composite steel and concrete structures

Calculation – Natural fire model: Parametric fire curve



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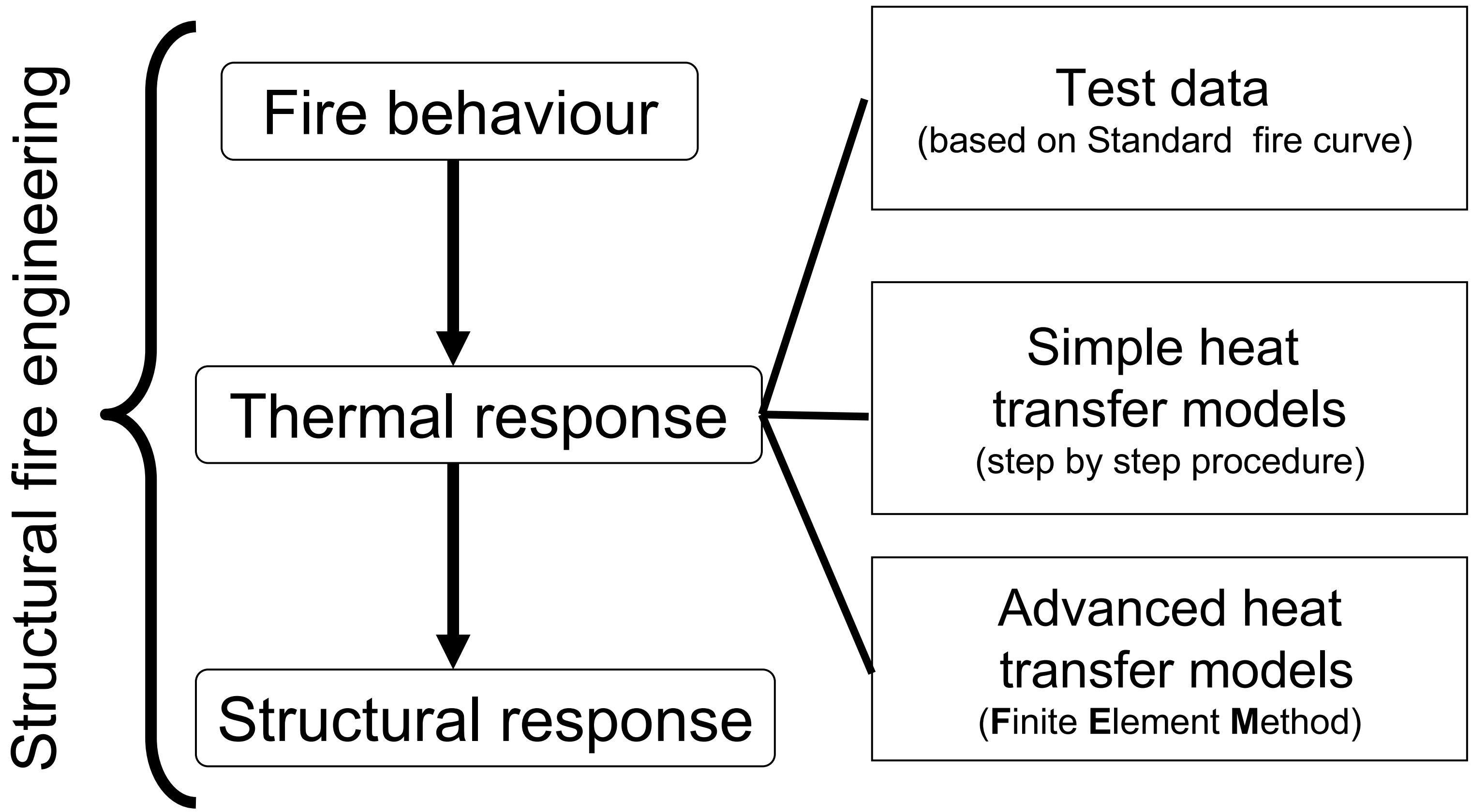
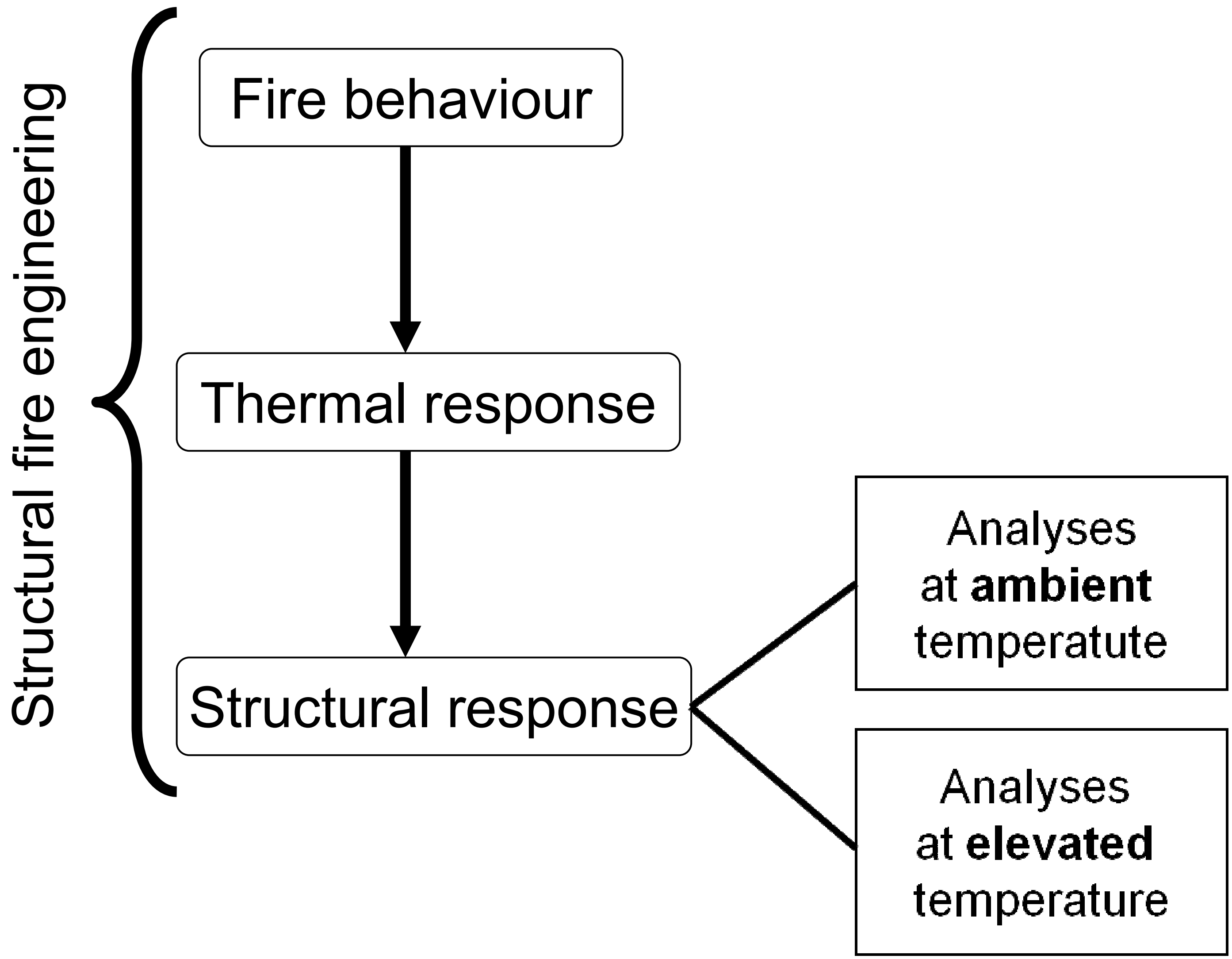
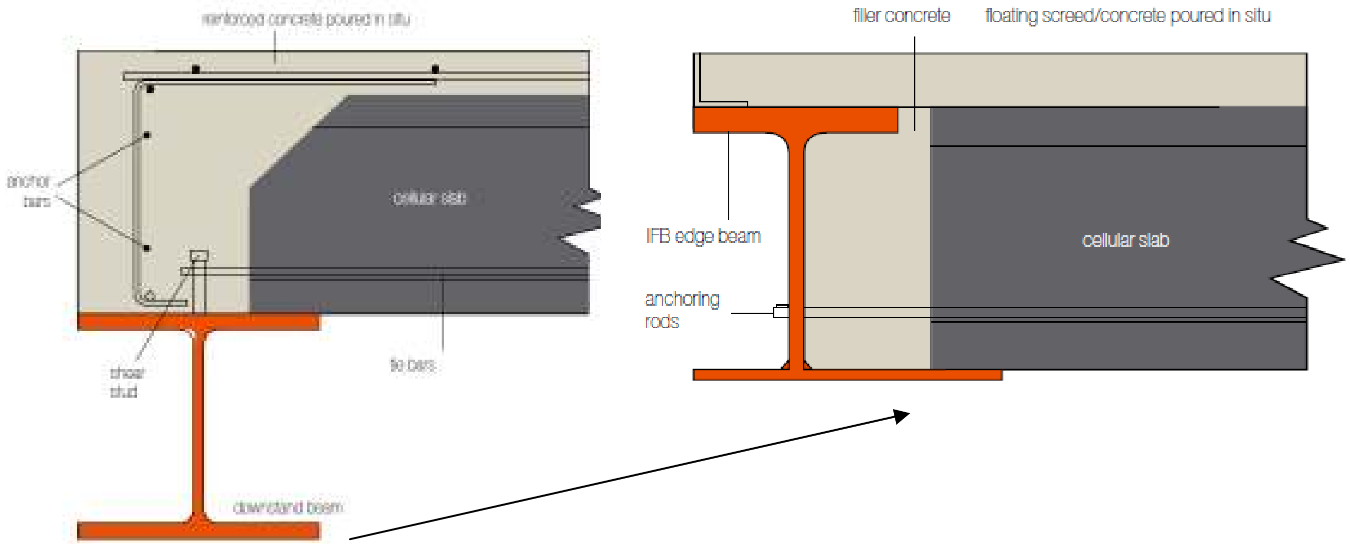
Thermal response

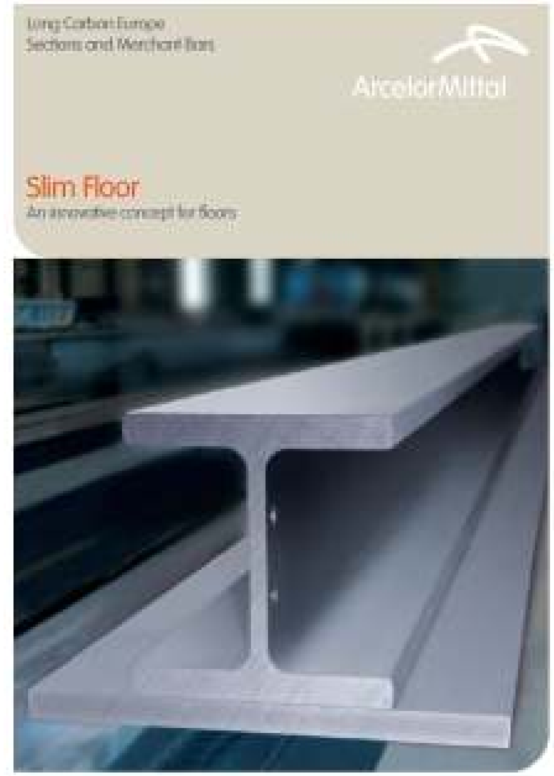


Structural response



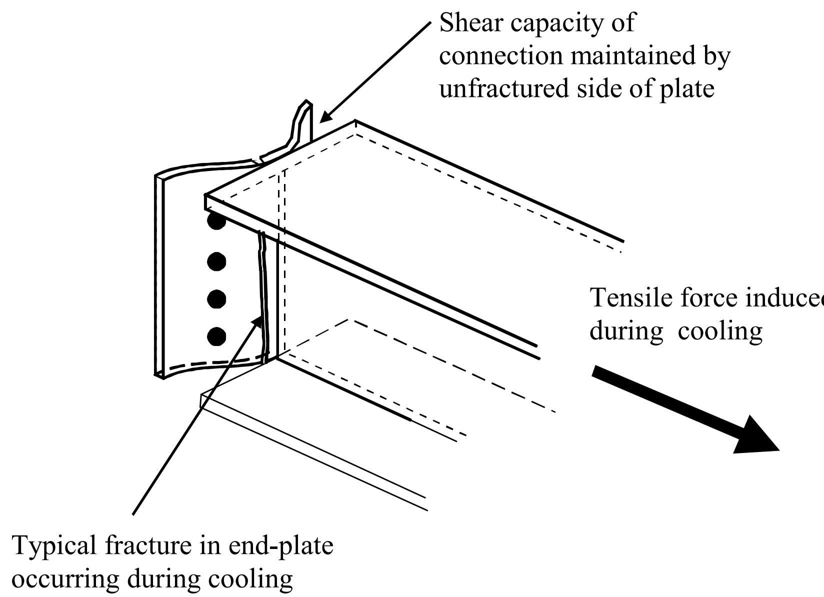
Real structures





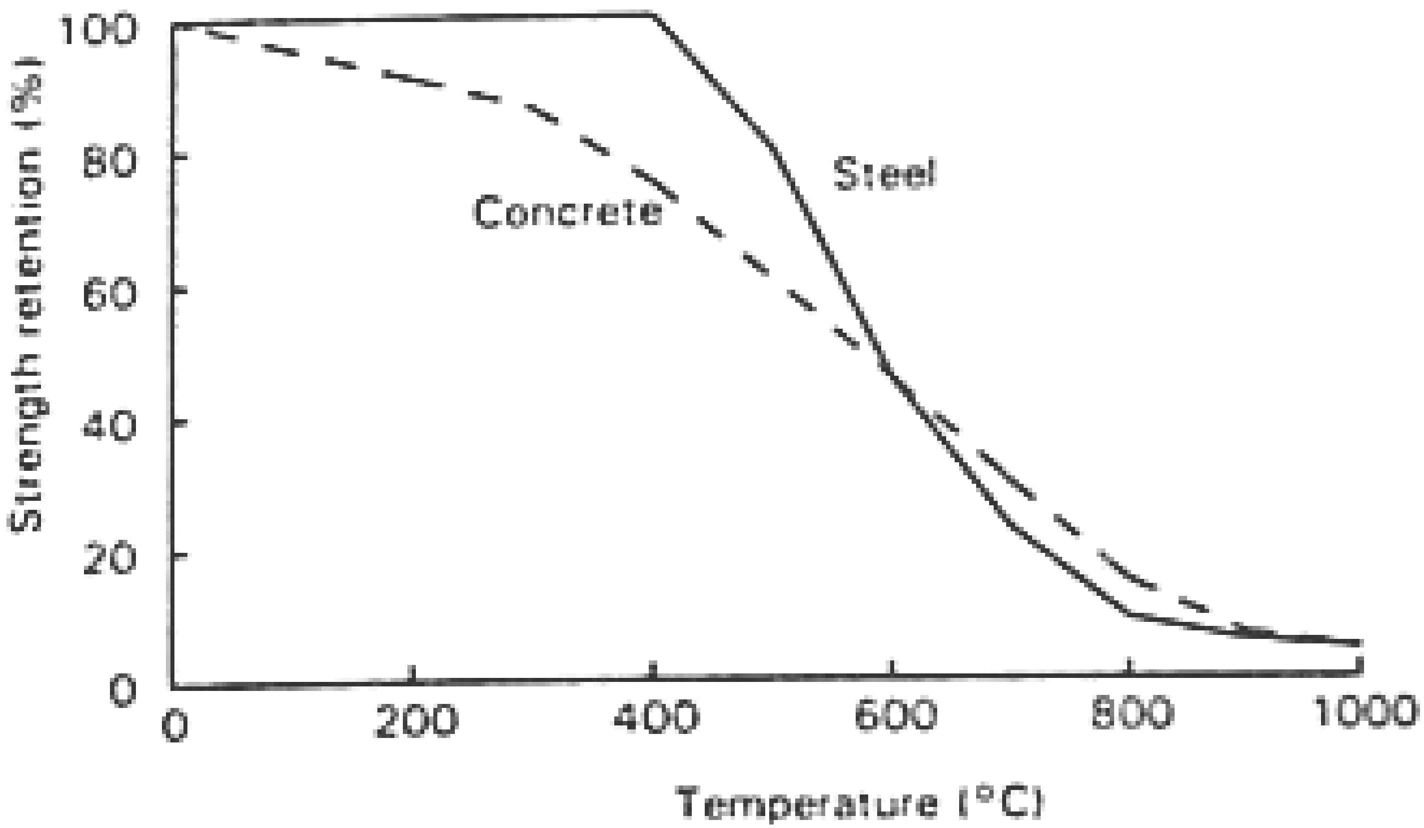
- Today buildings are complex
  - New structural solutions
  - New materials
  - Mixed building technology

Overall behaviour

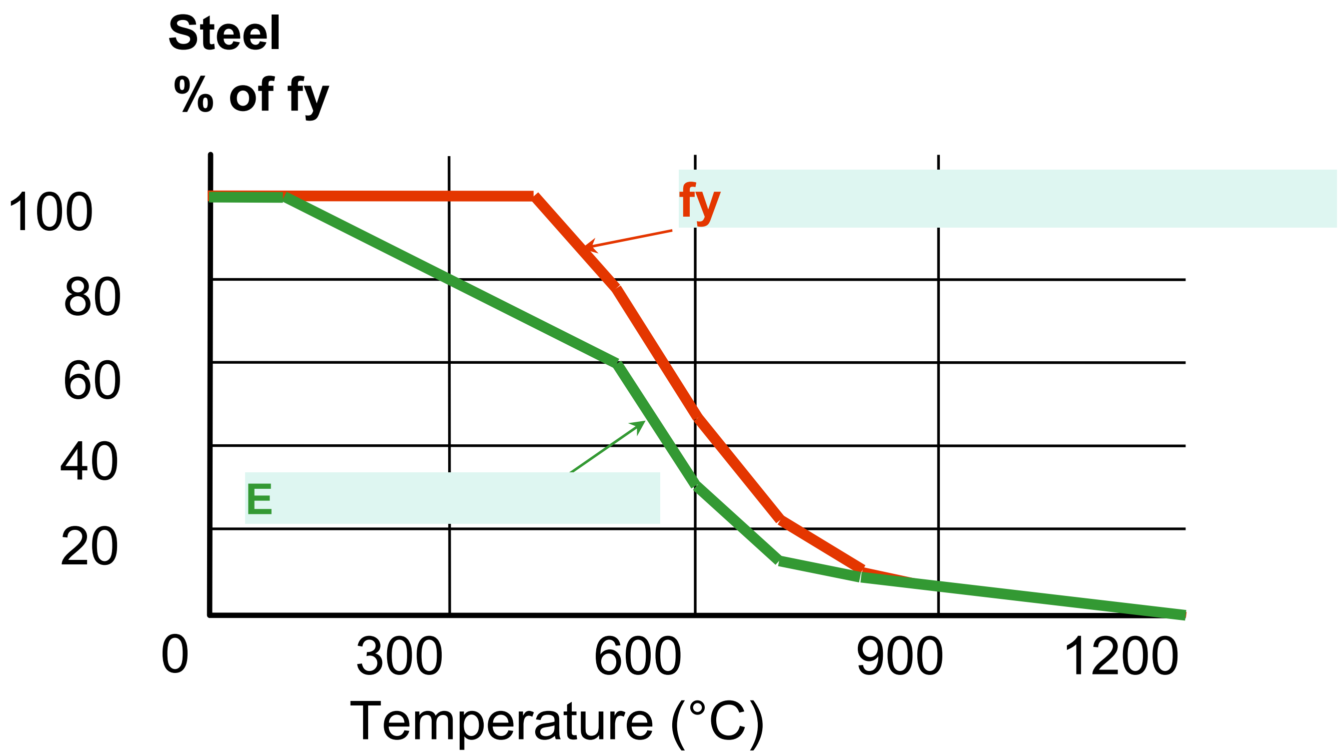


- Cooling phase of fire
  - Connection behaviour
  - The structure may collapse

Material behaviour at elevated temperatures

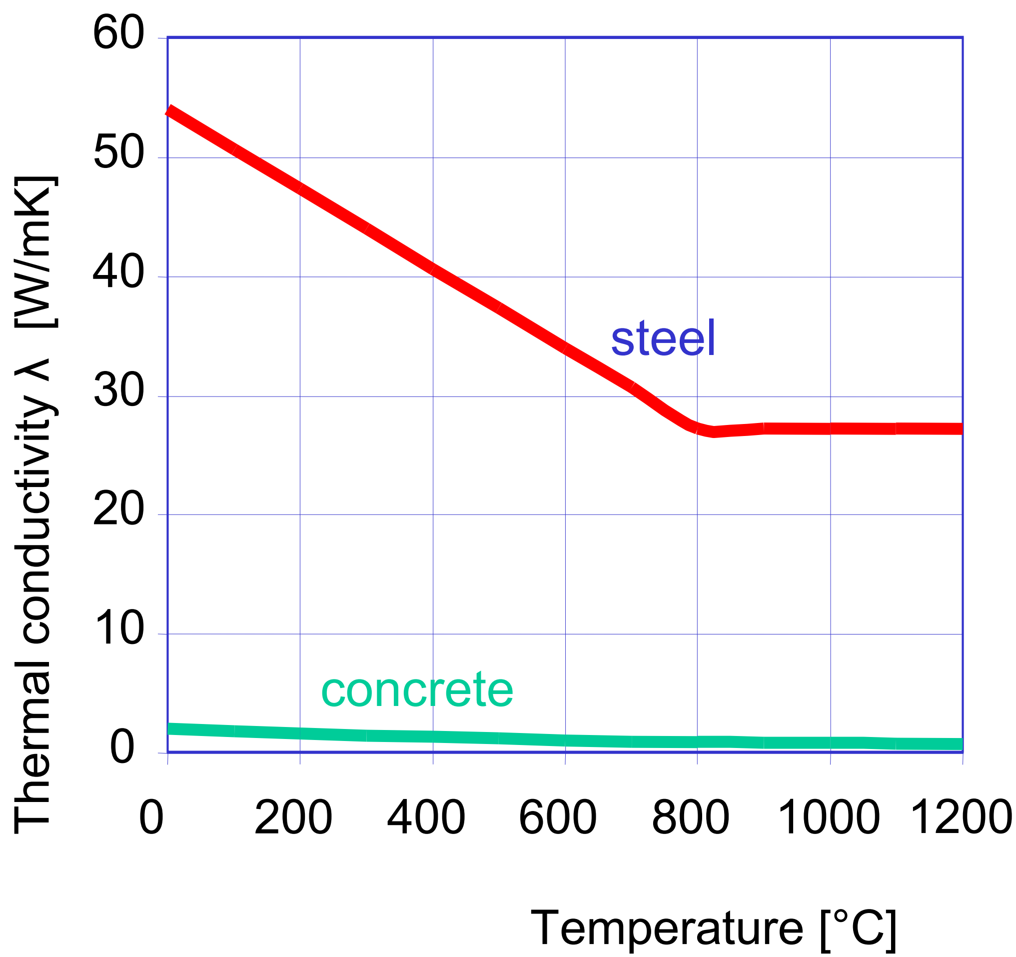


Material behaviour at elevated temperatures



- Young modulus at 600°C reduced aprox. 70%
- Yield limit at 600°C reduced aprox. 50%

Thermal conductivity



Distribution of the temperature on the cross-section

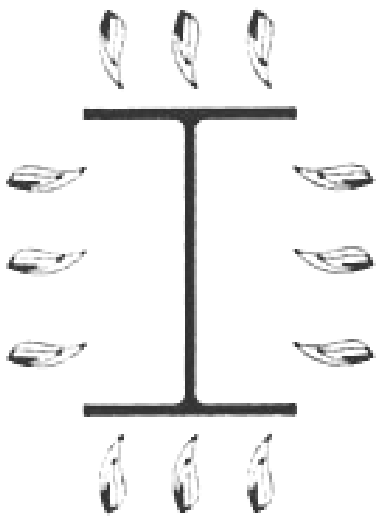
Steel

Section Factor = A_m/V

where:

A_m is the exposed surface area of the member per unit length;

V is the volume of the member per unit length.



High A_m

Low V

leading to

Fast Heating

Low A_m

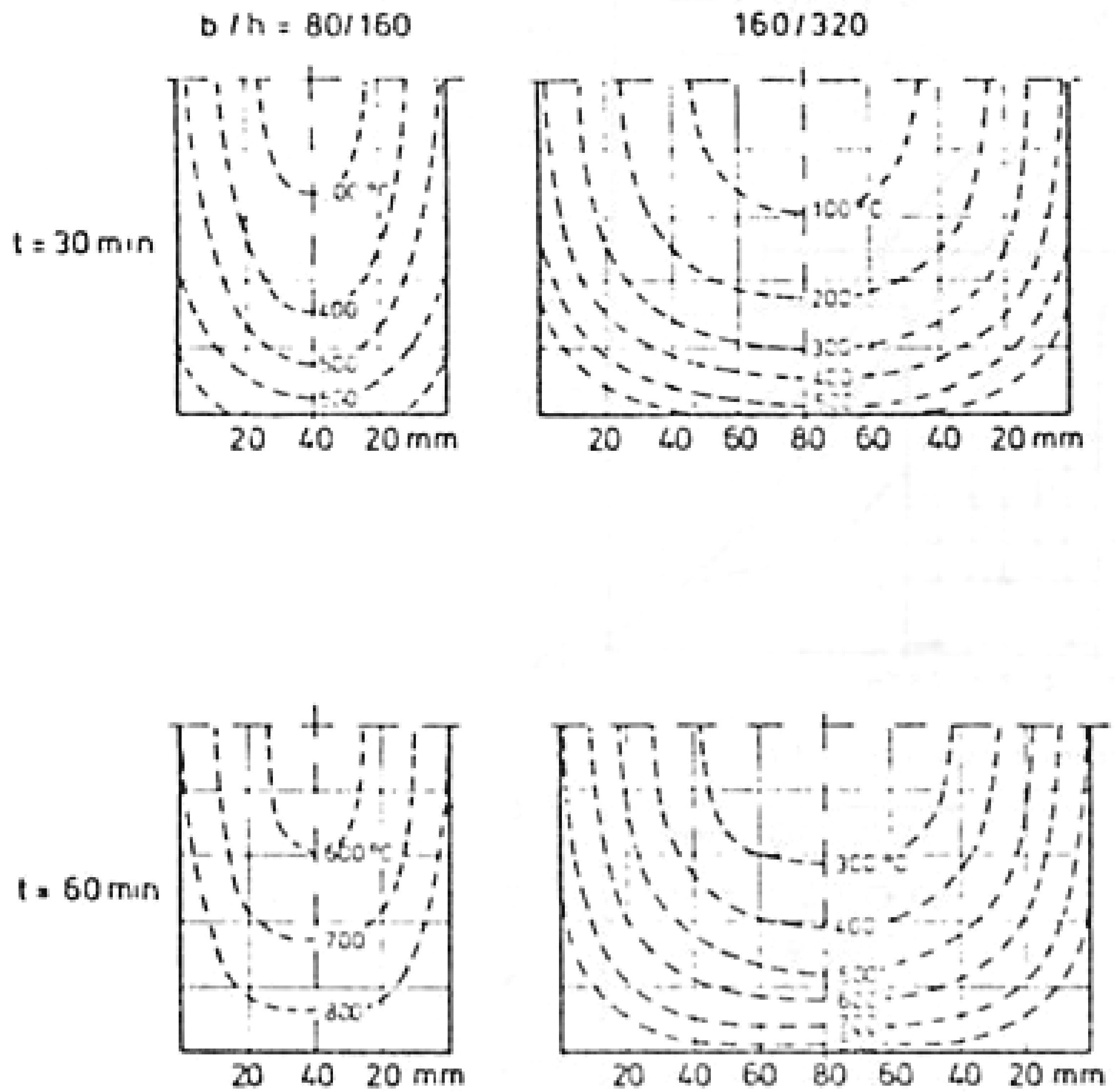
High V

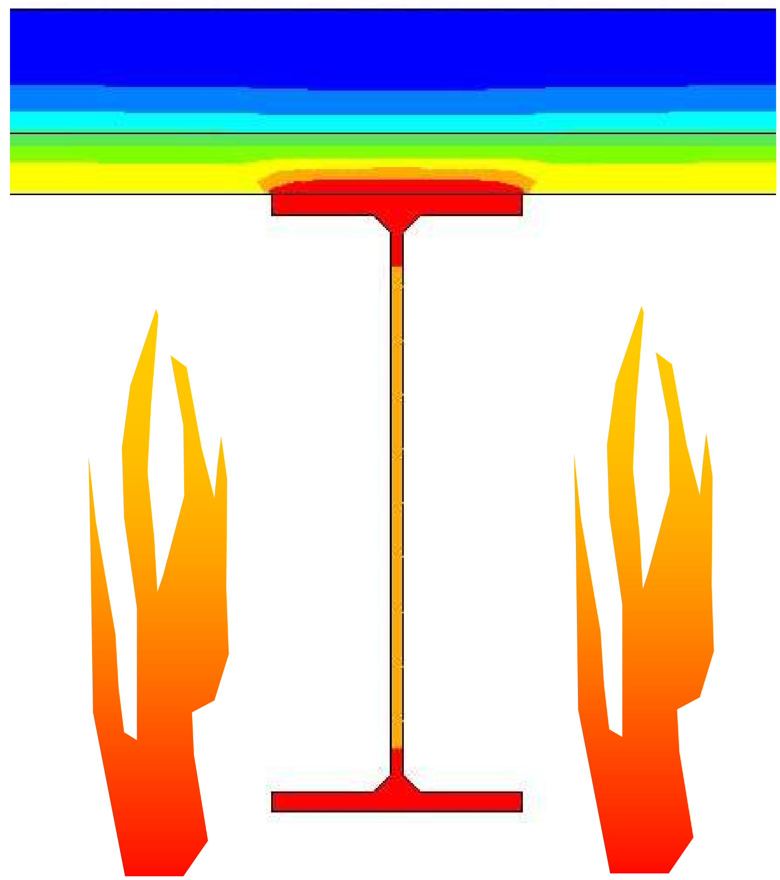
leading to

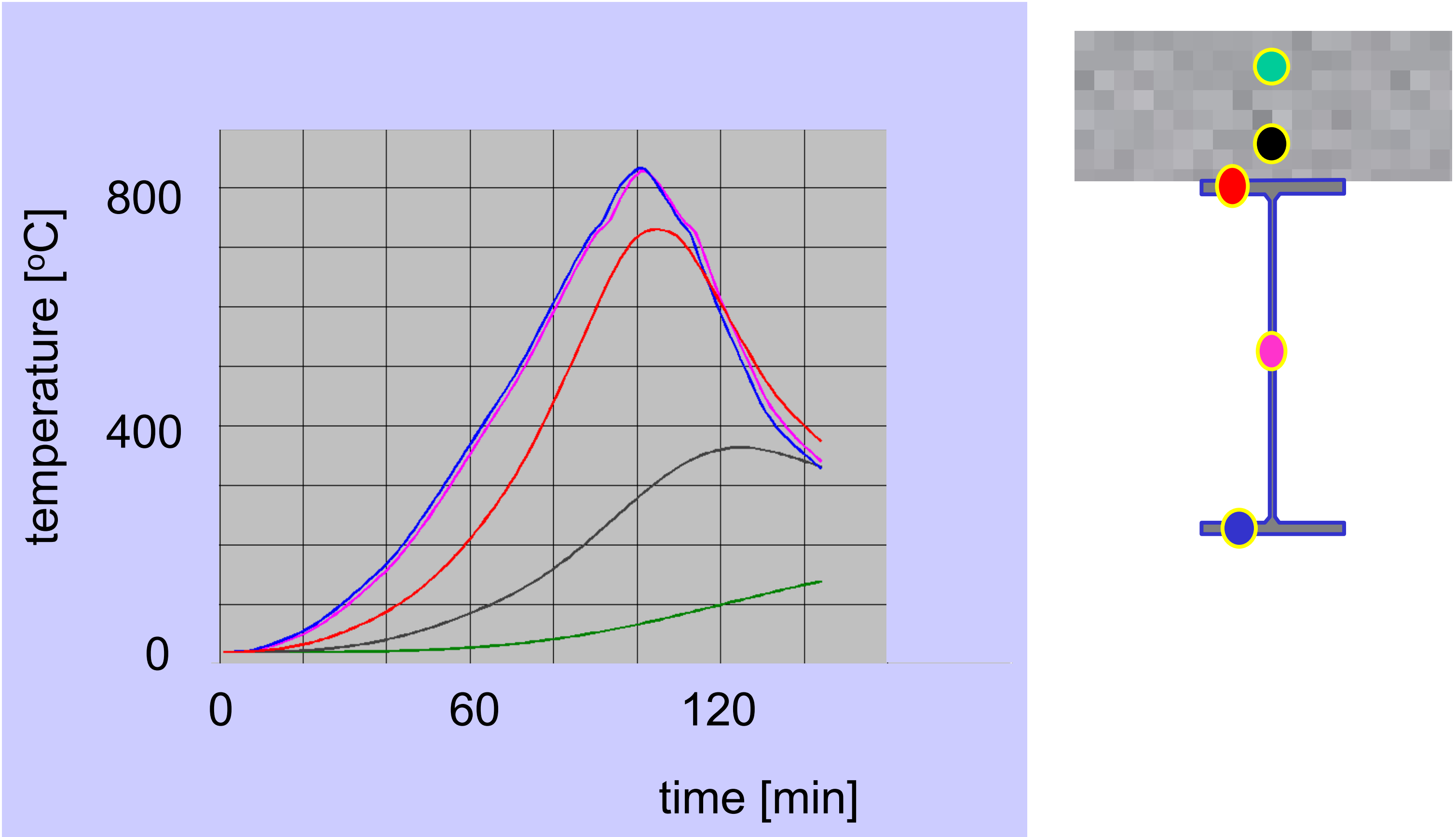
Slow heating

Distribution of the temperature on the cross-section

Concrete







800
400
0
temperature [ºC]
0
60
120
time [min]

Methods to evaluate the mechanical response of structures in fire

- **Tabulated data**
  - Available for concrete and composite
- **Simple calculation models**
  - Critical temperature (only for steel)
  - Available for steel, concrete and composite

→ ***Usual applications***

- **Advanced calculation models**
  - All types of structures/ materials/ elements
  - Numerical models using dedicated computer programs

→ **Advanced design**

DIFISEK

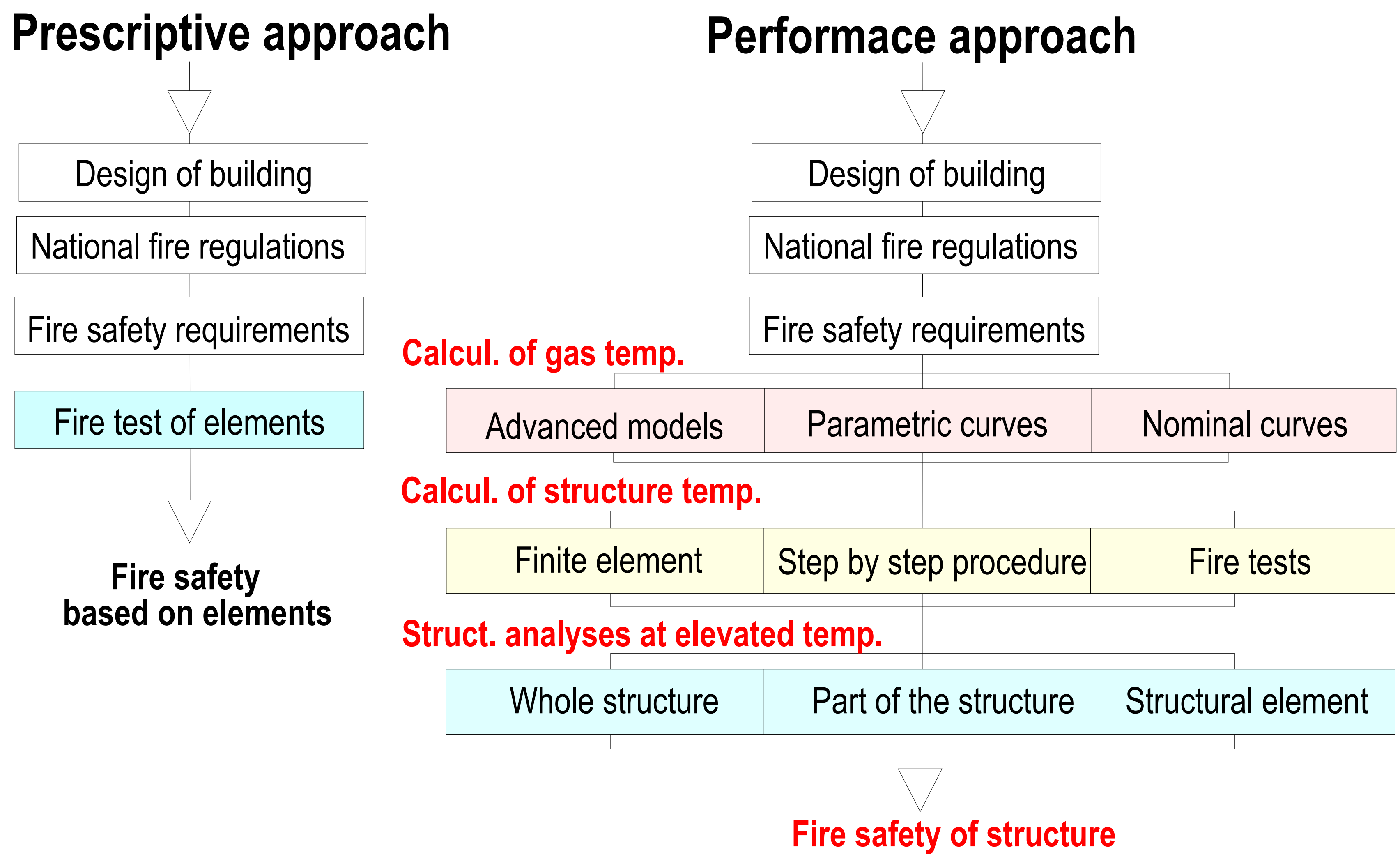
Performance based approach - Avantages

- 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

Performance based approach - Disavantages

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

Conclusion


Prescriptive approach
Design of building
National fire regulations
Fire safety requirements
Fire test of elements
Fire safety
based on elements
Performace approach
Design of building
National fire regulations
Fire safety requirements
Calcul. of gas temp.
Advanced models
Parametric curves
Nominal curves
Calcul. of structure temp.
Finite element
Step by step procedure
Fire tests
Struct. analyses at elevated temp.
Whole structure
Part of the structure
Structural element
Fire safety of structure

Case study - Application of Eurocodes

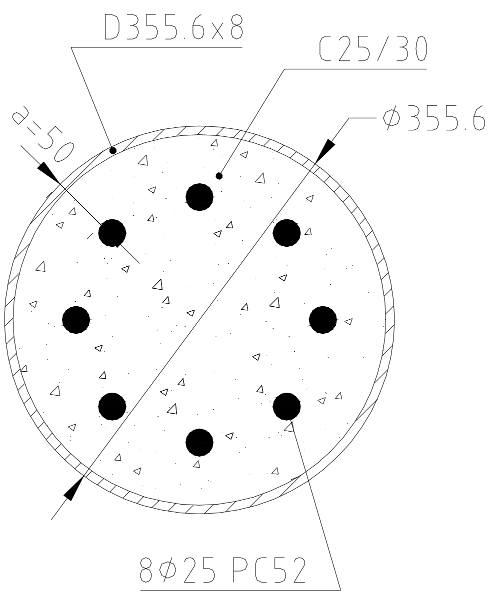
Office building for LINDAB-ROMANIA in Bucharest

Field of activity: systems of steel industrial buildings

OWNER DEMAND:

Visible steel - circular columns

FIRE RESISTANCE DEMAND FOR THE COLUMNS: R120



FIRE RESISTANCE OF COMPOSITE COLUMNS

EN 1994-1-2 EUROCODE 4: Design of composite steel and concrete structures
Part 1.2: General rules - Structural fire design

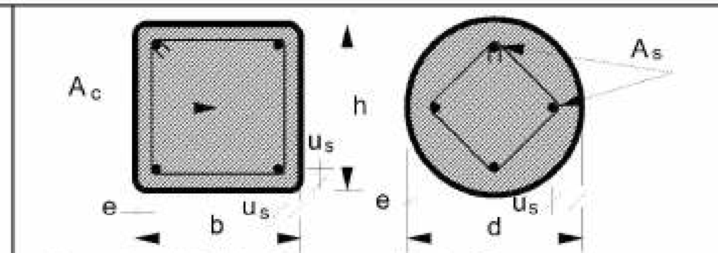
- **Tabulated data method**
- **Simple calculation models**
- **Advanced calculation models**

TABULATED DATA METHOD

Minimum characteristics for R120 ($\eta_{fi,t}$ = 0.3):

- **d_{min} = 260mm < d=355.5 mm**
- **us_{min} = 50mm < us=62.5 mm**
- ***<u>p_{min} = 6% > p=4.4%</u>***

(load level $\eta_{fi,t}$ = 0.148)



	secțiunea de oțel: (b / e) ≥ 25 sau (d / e) ≥ 25	Rezistența la foc standard				
		R30	R60	R90	R120	R180
1	Dimensiuni minime ale secțiunii pentru gradul de încărcare $\eta_{fi,t} \leq 0,28$					
1.1	Dimensiuni minime h sau b sau diametru minim d [mm]	160	200	220	260	400
1.2	Raport minim de armare A_s / (A_c + A_s) in (%)	0	1,5	3,0	6,0	6,0
1.3	Distanța minimă până în axa armăturii u_s [mm]	-	30	40	50	60
2	Dimensiuni minime ale secțiunii pentru gradul de încărcare $\eta_{fi,t} \leq 0,47$					
2.1	Dimensiuni minime h sau b sau diametru minim d [mm]	260	260	400	450	500
2.2	Raport minim de armare A_s / (A_c + A_s) in (%)	0	3,0	6,0	6,0	6,0
2.3	Distanța minimă până în axa armăturii u_s [mm]	-	30	40	50	60
3	Dimensiuni minime ale secțiunii pentru gradul de încărcare $\eta_{fi,t} \leq 0,66$					
3.1	Dimensiuni minime h sau b sau diametru minim d [mm]	260	450	550	-	-
3.2	Raport minim de armare A_s / (A_c + A_s) in (%)	3,0	6,0	6,0	-	-
3.3	Distanța minimă până în axa armăturii u_s [mm]	25	30	40	-	-

SIMPLE CALCULATION MODEL

(using CIDECT Design Charts for fire resistance of concrete filled hollow section columns)

Fire resistance class R120

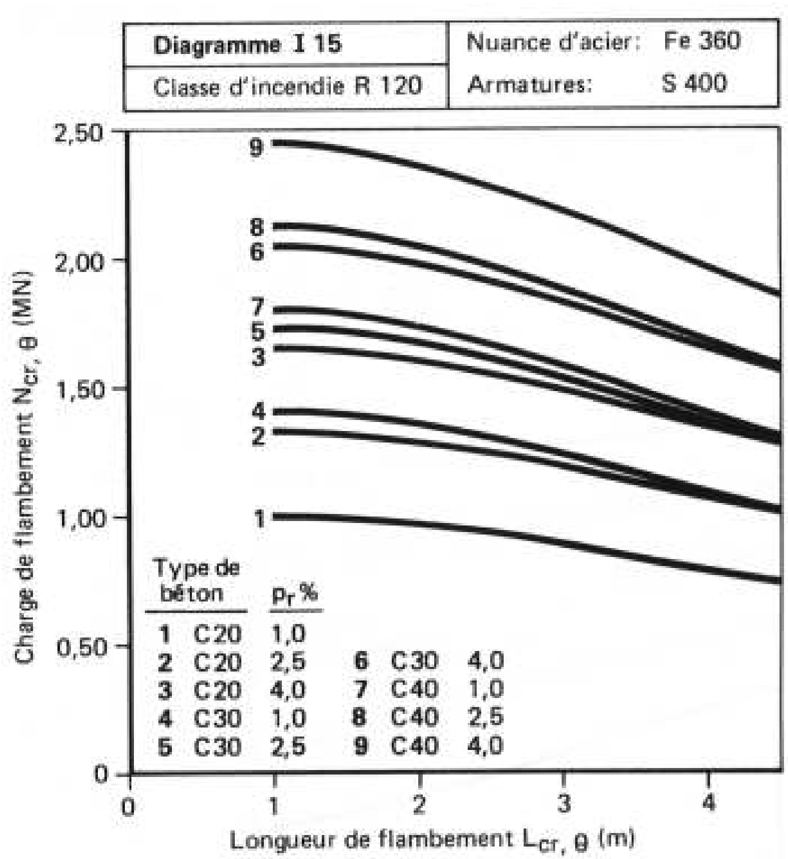
- CHS 355.6x5.6

- buckling length L_f = 3.40m

- reinforcement p=4%

$N_{fi,\theta, Rd} \cong$ 150.000daN

> N_{equ} = 61.428daN



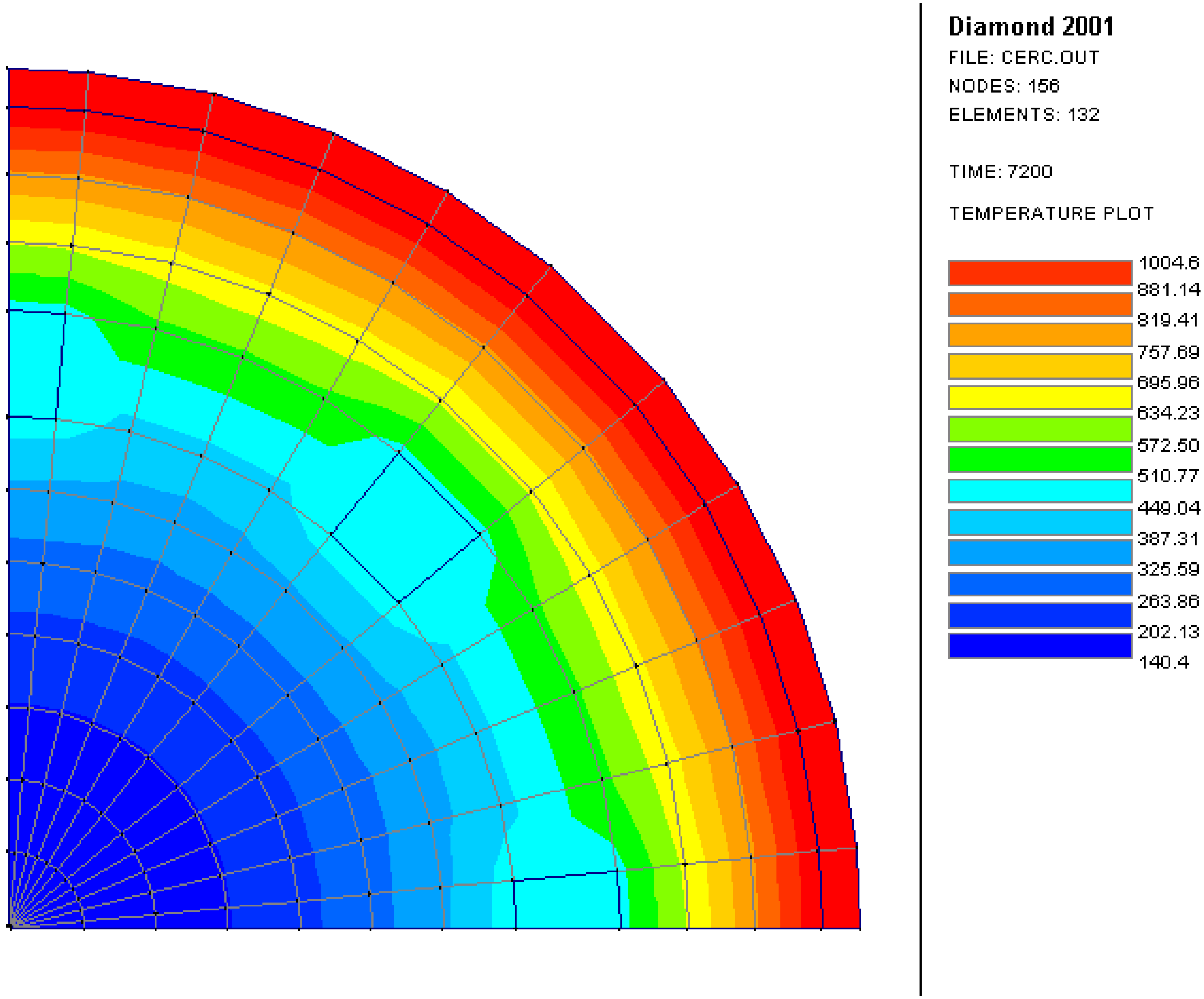
ADVANCED METHOD

SAFIR Program – developed by Prof. Jean - Marc FRANSSEN
Liège University, Belgium

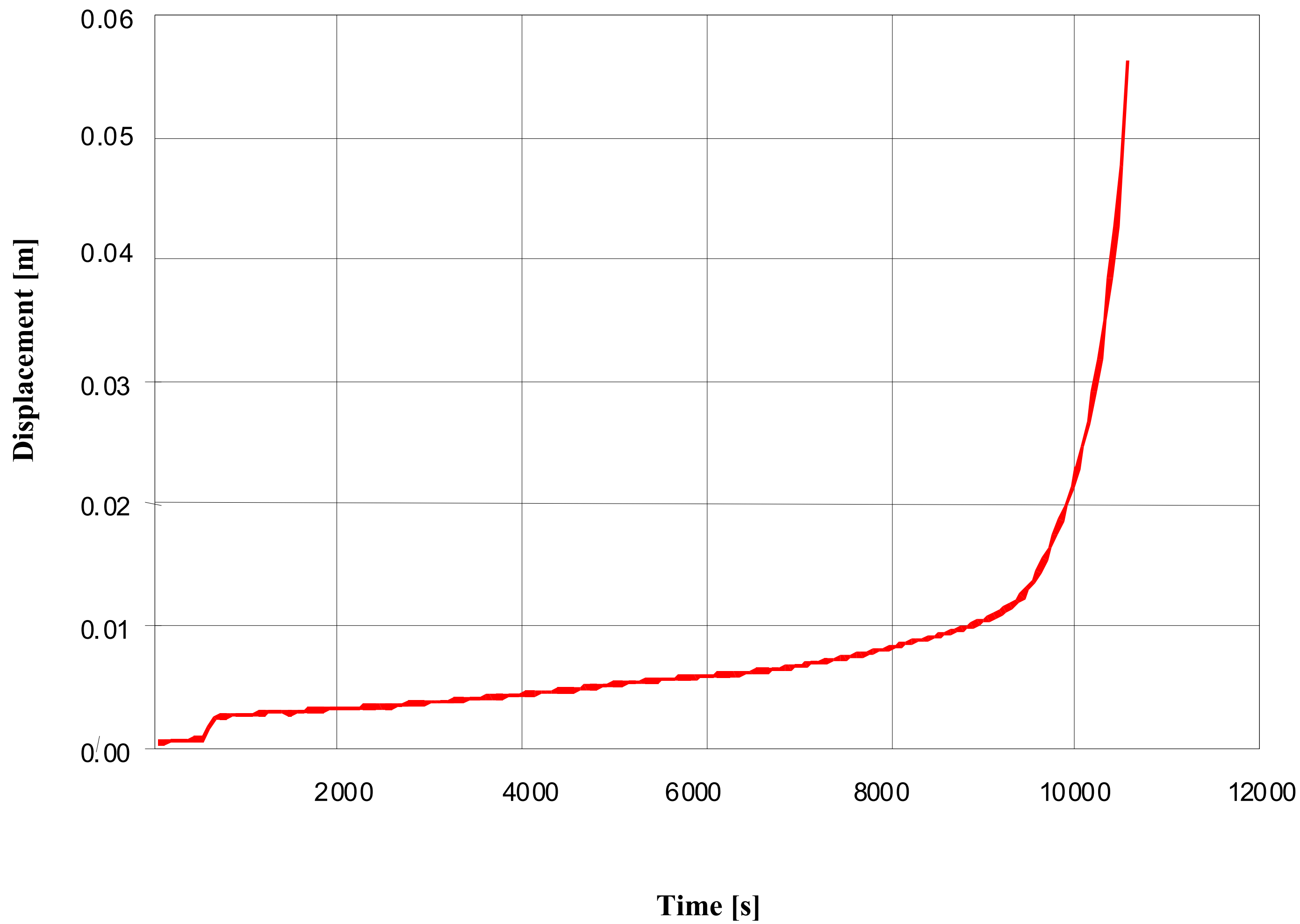
Steps for the analysis of a structure exposed to fire:

First step - predicting the temperature distribution inside the structural members, referred to as 'thermal analysis’

Second step - determining the response of the structure due to static and thermal loading, referred to as 'structural analysis'



Temperature distribution on cross-section after 2h of ISO fire



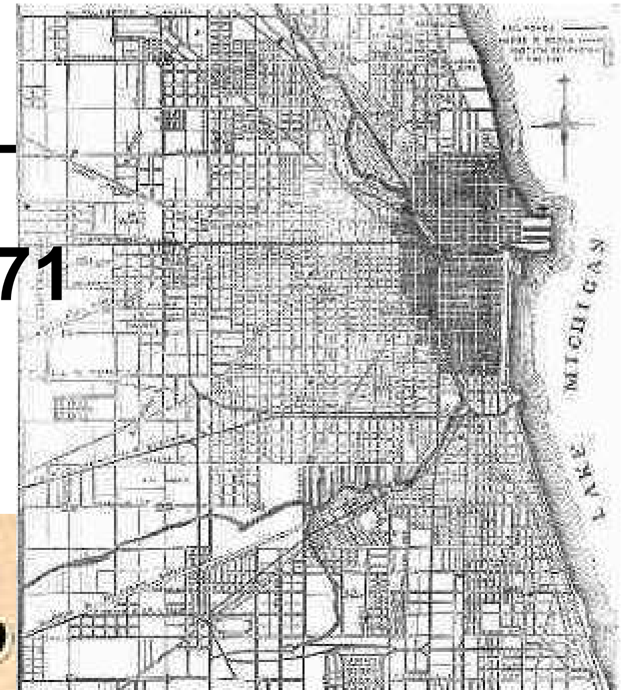
Time - Displacement characteristic
Collapse after 2h56'

Major fire disasters


Great London Fire, 2-5 September 1666

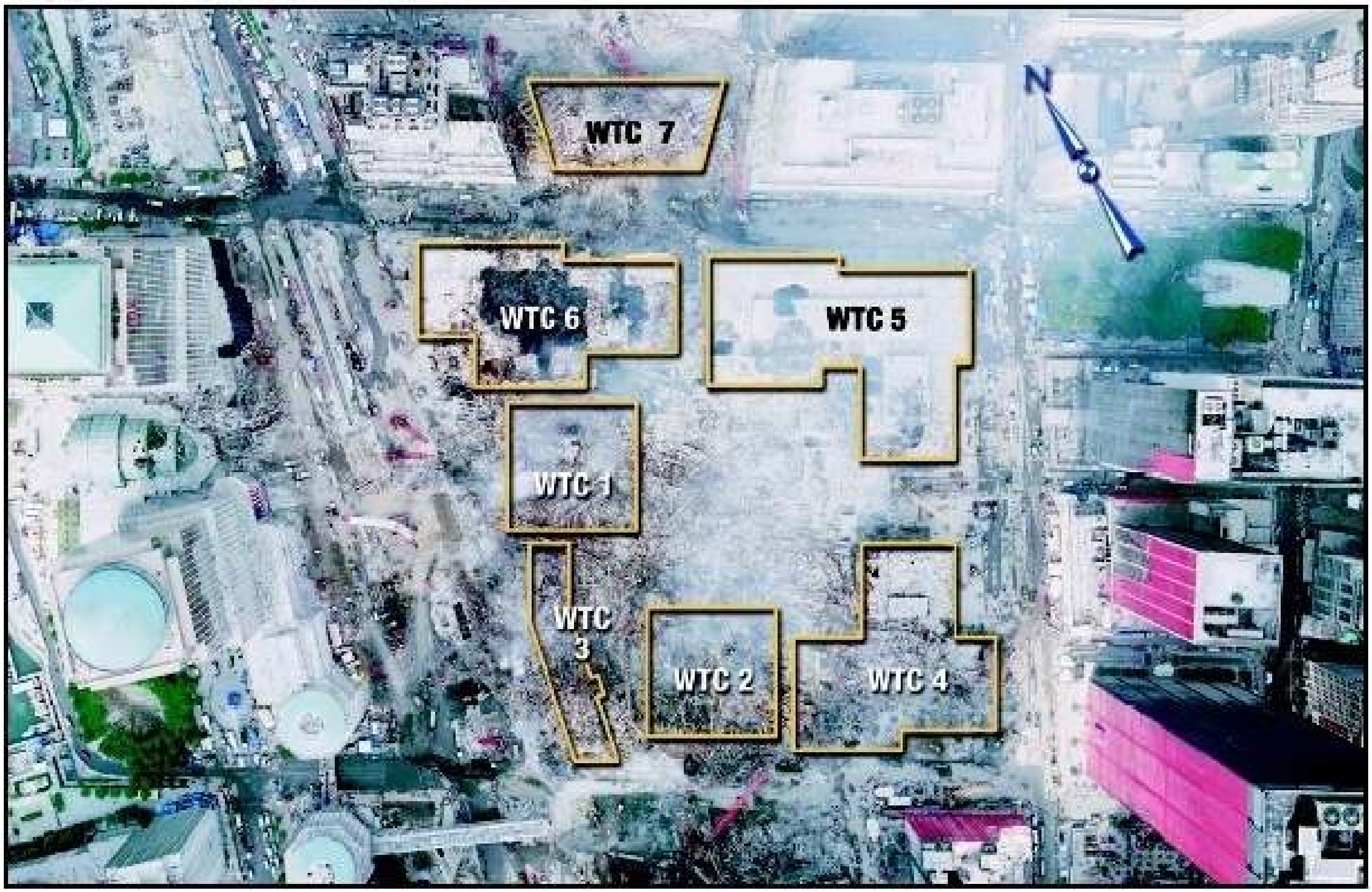
Great Chicago Fire, 8-10 October 1871

Great Chicago Fire, 8-10 October 1871



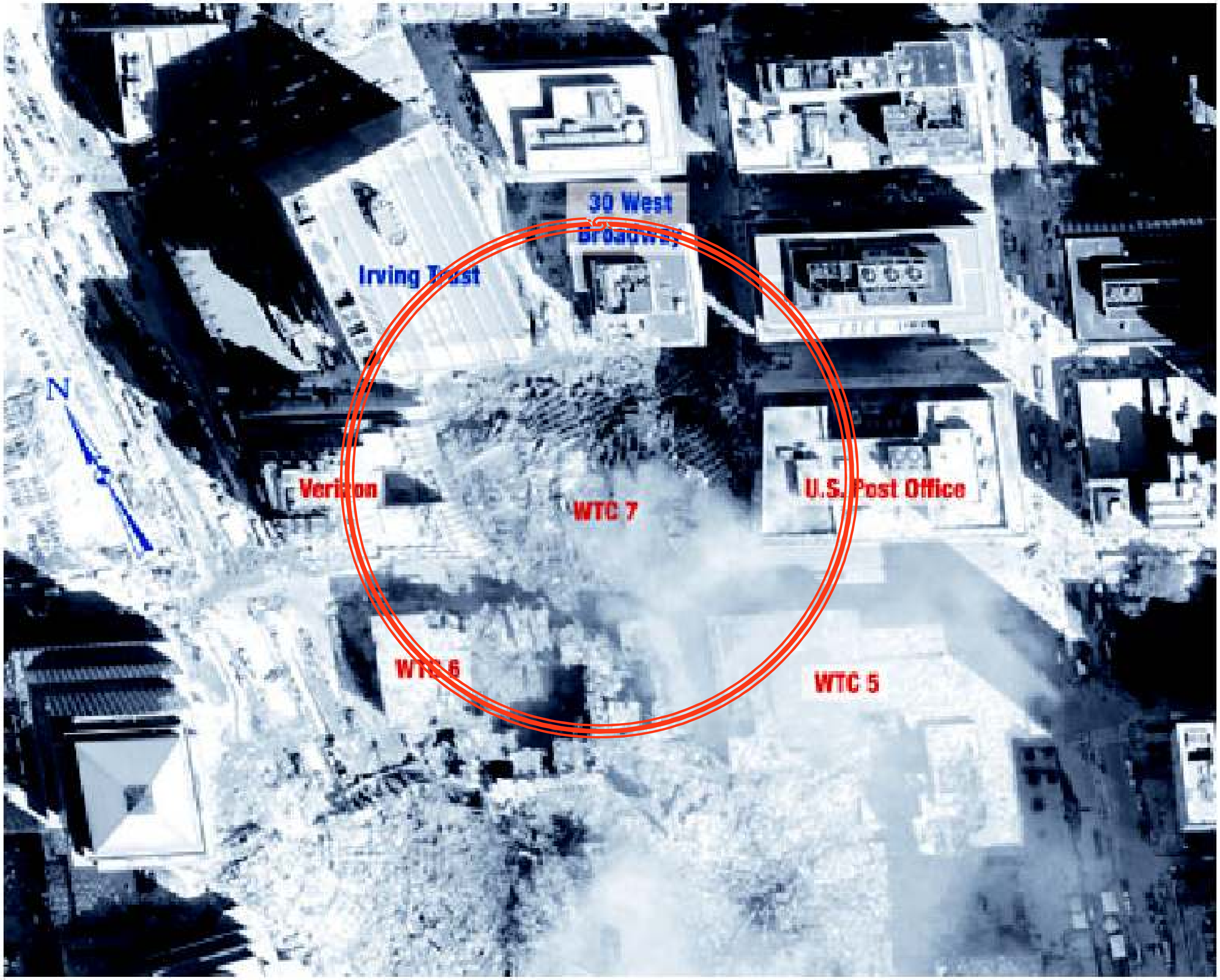
World **T**rade **C**enter **11.09.2001**

- 17 buildings were damaged



Progresive collapse

WTC building 7

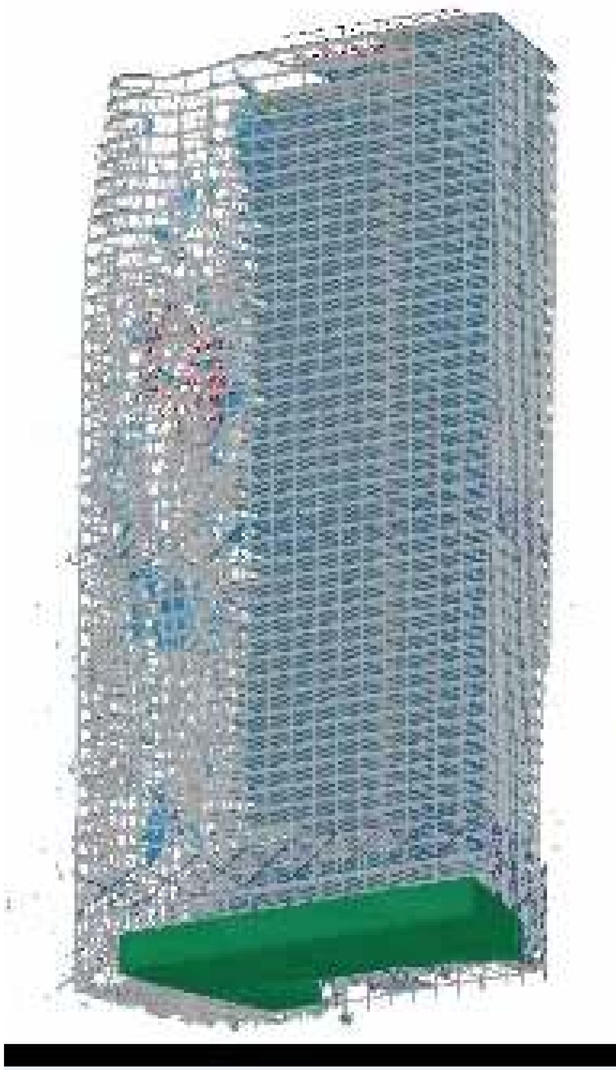


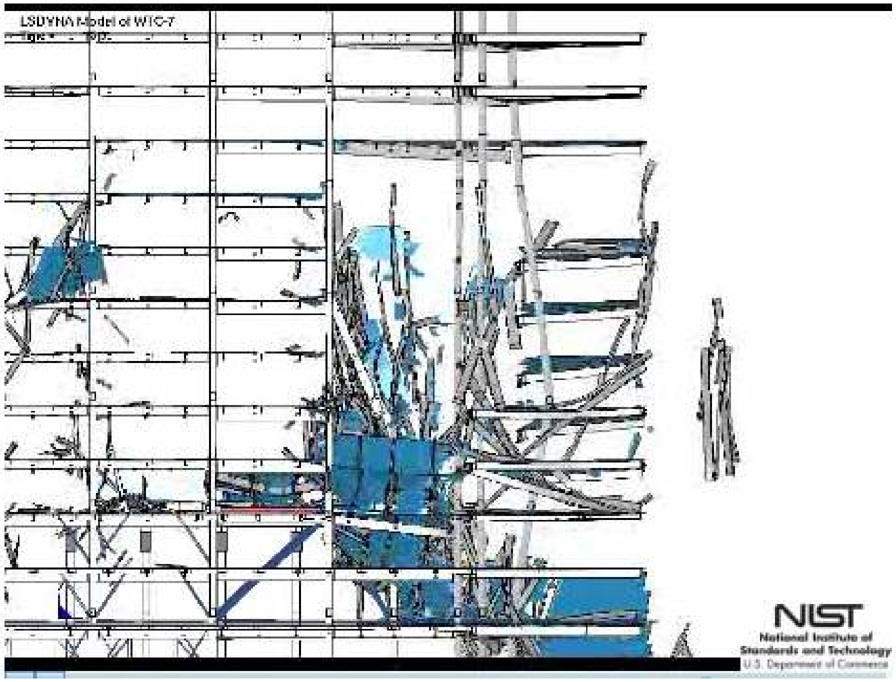
WC7 - large fire

Initial cracking of building

WTC7 progresive colapse

WTC7 – modelling by NIST-US (2008)





WINDSOR TOWER MADRID 13.2.2005

NO SPRINKLERS FORESEEN IN THIS 100 m HIGH BUILDING

Fire after earthquake

- Fire following earthquake can cause substantially loss of life and property, added to the destruction caused by the earthquake, and represents an important threat in seismic regions

- The loss resulting from fires developing after the earthquake may be comparable to those resulting from the earthquake itself

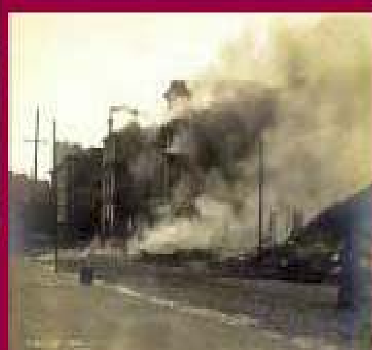
- **When an earthquake occurs:**
  - **it may cause structural and fire protection damage, and thus the building is more vulnerable to a fire**
  - **the loss of water supply or the low water pressure, combined with multiple independent fires, traffic congestion and the limited resources which are not able to respond promptly to all fires, allow to the fire to spread**
  - **the experience of the impact of fire following earthquake indicates that at wind speeds above 9m/s, the fire spread and associated loss increase dramatically**
  - **the increased time needed for firemen to reach the building in fire, associated to the possible lack of the active fire measures and to the increased vulnerability of the building may affect their security**

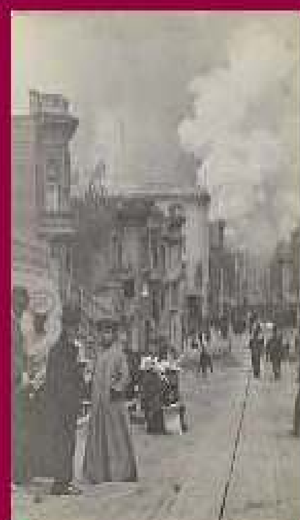
San Francisco, California, 1906

- 7.8 Richter magnitude earthquake
- the "Great fire" scorched 508 city blocks, or 4.7 square miles of San Francisco
- ***"Firestorms fed by fierce winds raged for three days in San Francisco and caused the majority of the damage.."***
- ***"… the earthquake and fire combined to cause the nations' greatest urban tragedy…"***

San Francisco, California, 1906

(The Bancroft Library)





(Courtesy of The San Francisco Museum of Modern Art)

The estimated fire-induced loss is 10 times larger than the one directly induced by the ground motion

Bucharest, Romania, 1977

- **7.2 Richter magnitude earthquake – the strongest in an European capital**
- ***Charles Richter* about Vrancea region (Romania): *"Nowhere in the world doesn't exist such a exposed population to the earthquake from the same source".***
- **29 isolated fires, on partially affected by the earthquake or collapsed buildings**

Kobe, Japan, 1995

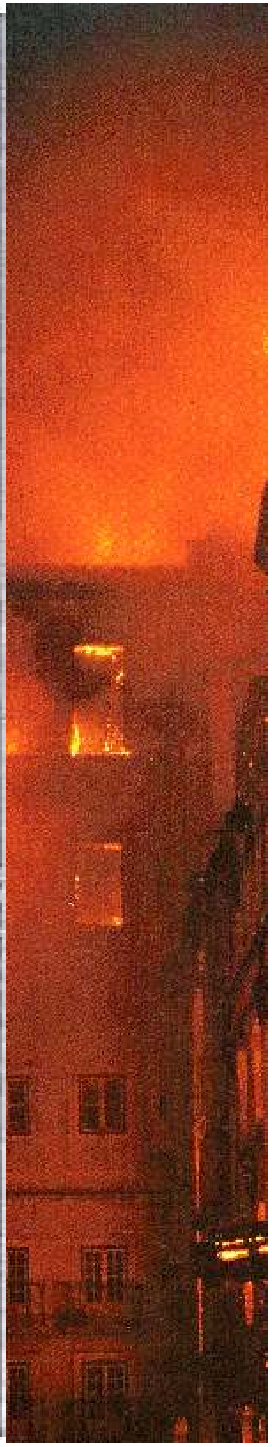
- **7.2 Richter magnitude earthquake**
- ***"When the earthquake hit, fire broken out .. Over 300 fires quickly started, especially among the remains of the wooden buildings"***
- ***"At least a dozen major fires that burned for up to two whole days… before they were brought under control."***
- ***"Research conducted at Kobe University suggests that 500 deaths were due to fires, and that almost 7000 buildings were destroyed by fire alone."***

Kobe, Japan, 1995

DUESSELDORF INTERNATIONAL
AIRPORT
ON FIRE 11.4.1996

designed for fire resistance ISO R120

✹ BUT LACK of ACTIVE
FIRE SAFETY MEASURES
✹ ✹17 FATALITIES



GOETEBORG – SWEDEN DISCO FIRE
30.10.1998
Disco approved for 150 people
with 2 stairwells serving as escape ways

✸ BUT DISCO WAS OVERCROWDED, ONE STAIRWELL CLOSED, and FIRE WAS PUT ON THE OTHER STAIRWELL MISUSED FOR STORAGE of CHAIRS

✸ INSUFFICIENT ESCAPE MEANS
& NO SMOKE DETECTION
✸ ✸ 63 YOUNG PEOPLE DIED

Learning from disasters

- Proper prescriptive rules are very important
- New materials and new structural solutions need performance based design
- In fire design should be integrated
  - Life safety
  - Financial impact
  - Environmental issues
- Multiple risks
  - Earthquake followed by a fire
  - Explosion followed by a fire

Active and pasive fire protection measures

- **Active:**

  - Sprinklers or other active systems like rapid smoke evacuation reduce the risk and severity of a fire

  - Detection and alarm systems achieve more rapid evacuation

  - etc

- **Passive:**

  - Proper compartimentation: an atrium or other large internal enclosure positively influences the effective compartmentation in fire

  - Proper means of escape ensure the evacuation in safe conditions

  - Adequate fire resistance of elements- fire protection

  - etc

Forms of passive fire protection

There are five forms of passive fire protection:

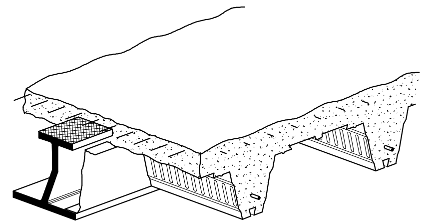
- **Spray protection – applied around the profile**
- **Board protection – applied as a 'box'**
- **Intumescent coating – applied around the profile**
- **Concrete encasing – forms a rectangular encasement around the member**
- **Composite member – for example in-filling of tubular columns**

From AccessSteel Fire safety strategy

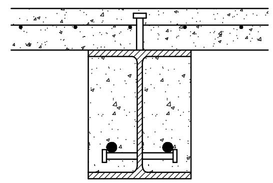
for multi-storey buildings for commercial and residential use

Composite sections

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

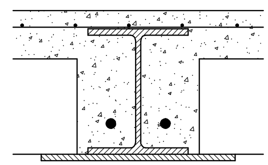


Slab



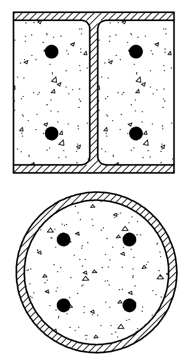
Beams

Patially encased
Slim floor



Columns

Partially encassed
Concrete filled



Recapitulation

Which are the major topics related to fire in EU Construction products directive?

Which are the differencies between the prescriptive approach and the performance based approach for the fire safety of buildings?

Which parts of Eurocodes are focussed for fire design and which Eurocodes include fire design?

In which Eurocode is described the fire loading? How many types of fire models exist?

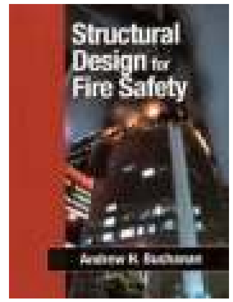
Which are the levels of verification methods in the Eurocodes for fire design?

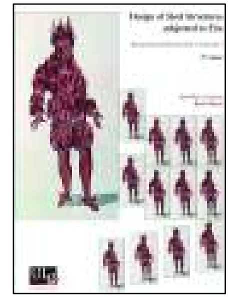
Which is the difference between the passive and active fire protection measures? Give some examples

Further reading

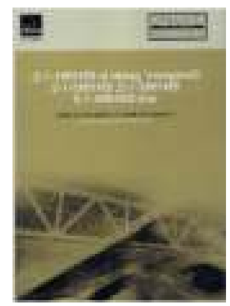
- Further readings on the relevant documents from websites of www.access-steel.com and www.difisek.eu.

- ## Books
  - Buchanan A. H.,
    Structural Design for Fire Safety,
    Wiley, 2001, ISBN 0471889938.

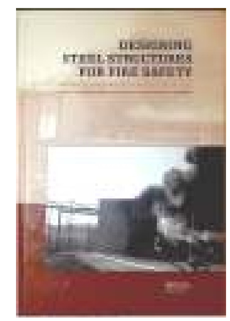




  - Franssen J.M., Zaharia R., Design of steel structures subjected to fire – Background and design guide to EN1993-1-2, Les Editions de l’Universite de Liege, 2005, ISBN 9782874560279

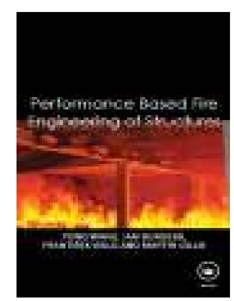


  - D. Moore, T. Lennon, C. Bailey, Y. Wang, Designers' Guide to EN 1991-1-2, EN 1993-1-2 and EN 1994-1-2: Handbook for the Fire Design of Steel, Thomas Telford, 2007, ISBN 0727731572.
  - Franssen J.M., Kodur V., Zaharia R., Designing steel structures for fire safety, Taylor & Francis – Balkema, 2009, ISBN 978041554828



  - Fransen J.M., Vila Real P.,
    Fire design of steel structures,
    ECCS 2011, ISBN978-92-9147-099-0 .

  - Wang Y., Burgess I., Wald F., Gillie M.,
    Performance Based Fire Engineering of Structures
    CRC Press 2012, ISBN: 978-0-415-55733-7.



Selection of fire engineering strategy may be find at Acces-Steel

- **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

Thank you
for your attention

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