FIRE SEVERITY AND FIRE RESISTANCE IN STRUCTURAL FIRE ENGINEERING (SFE) DESIGN

Ruben Van Coile

I. Introduction – Severity vs resistance

II. Structures and fire – The facts

III. What we want to achieve – The goals

IV. The how – Fire engineering approach

V. Opportunities of SFE (and risks)

    a) Lame substitutions
    b) Clarifying fire severity
    c) More safety, lower cost
    d) More safety, lower lifetime cost
    e) Designing for performance

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17/05/2019, VENICE

Introduction

Resistance vs. Severity

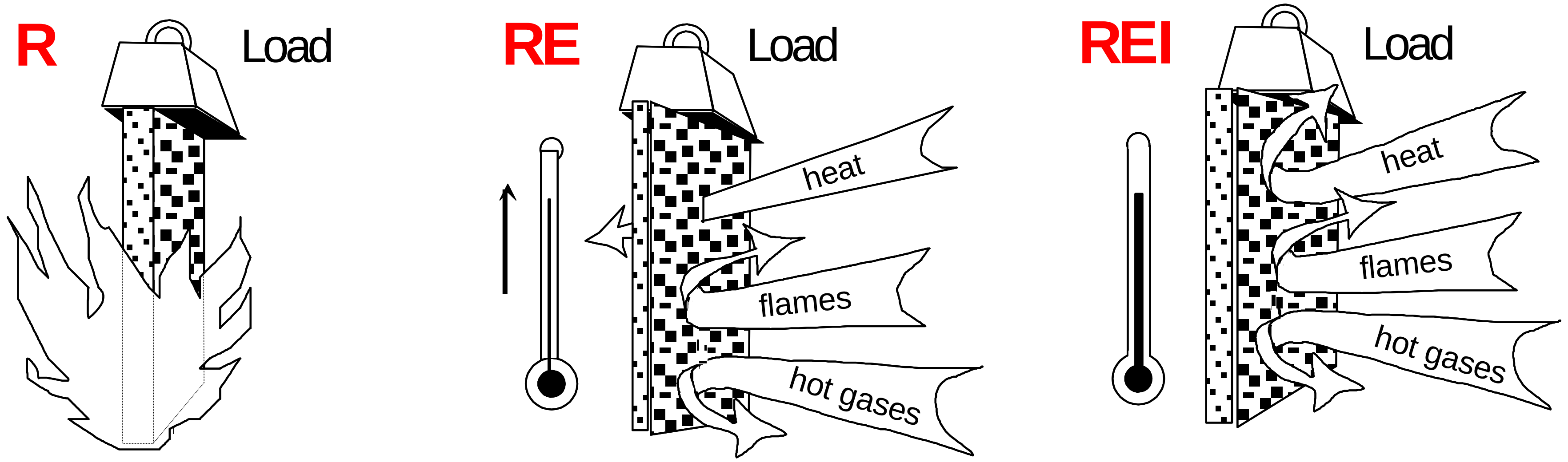
FIRE SEVERITY VS RESISTANCE

The standard framework

Design requirement $r \geq e$

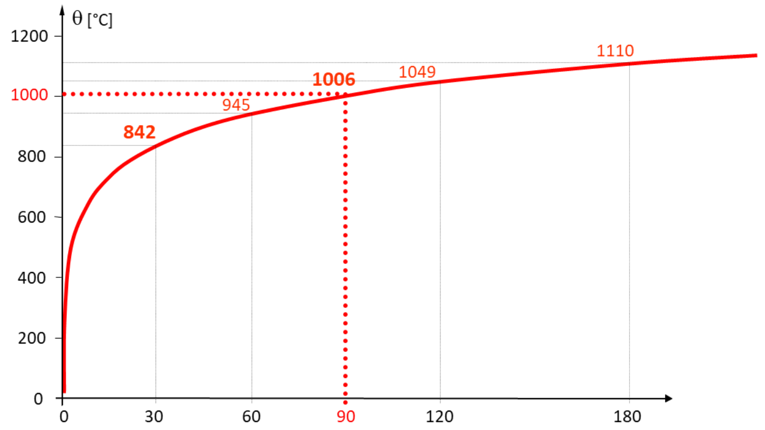
Resistance

(ability to resist fire)



Villa Real, P. (2012). COST Action TU0904 Malta.

www.secowarwick.com



Why?

~~Scientific characterization for safety~~

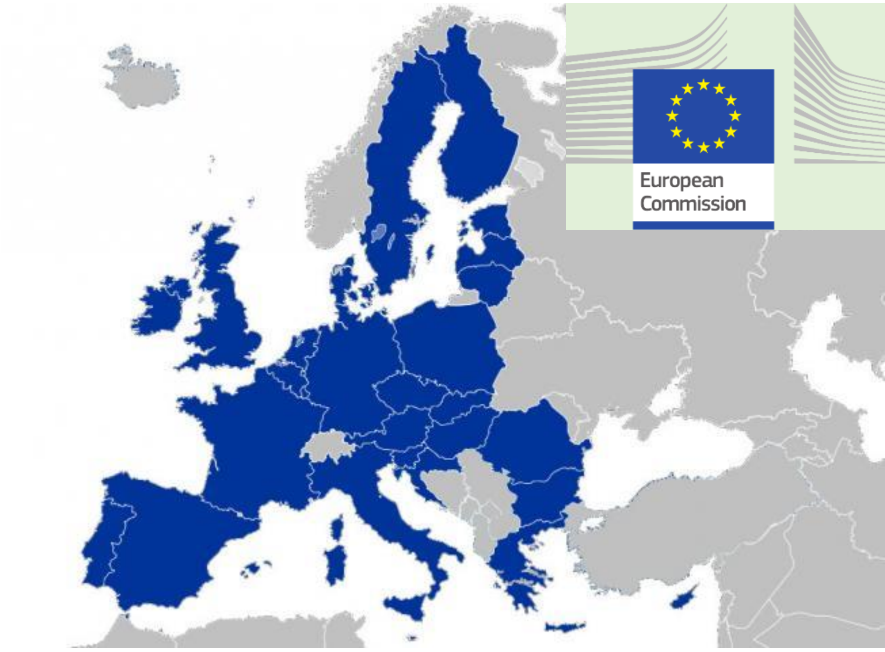
Historic reasons

Construction Products Regulation

Single market

- Free circulation of goods
- Common terminology

http://ec.europa.eu/growth/sectors/construction/product-regulation_en



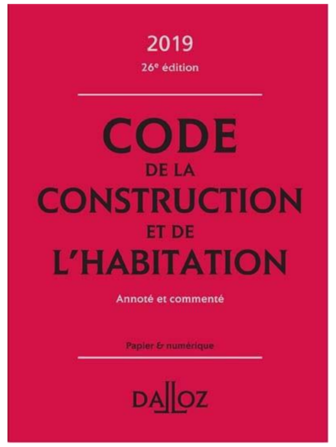
FIRE SEVERITY VS RESISTANCE

The standard framework

Design requirement $r \geq e$

Fire severity

Occupancy type; Building height; Sprinklers



Above 130m

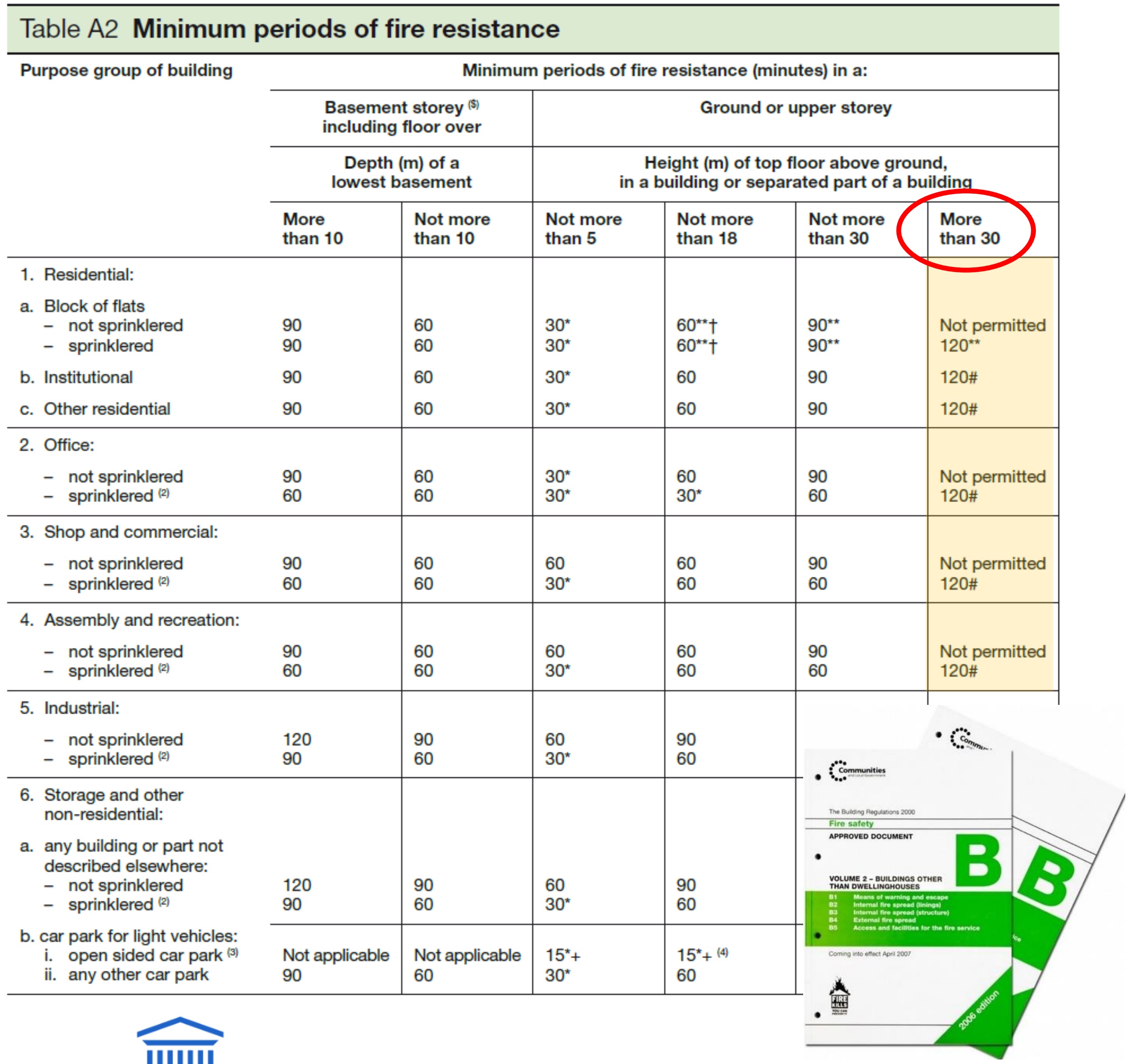


Table A2 Minimum periods of fire resistance

Purpose group of building	Minimum periods of fire resistance (minutes) in a:					
	Basement storey ($) including floor over		Ground or upper storey			
	Depth (m) of a lowest basement		Height (m) of top floor above ground, in a building or separated part of a building			
	More than 10	Not more than 10	Not more than 5	Not more than 18	Not more than 30	More than 30
1. Residential:						
a. Block of flats						
– not sprinklered	90	60	30*	60**†	90**	Not permitted
– sprinklered	90	60	30*	60**†	90**	120**
b. Institutional	90	60	30*	60	90	120#
c. Other residential	90	60	30*	60	90	120#
2. Office:						
– not sprinklered	90	60	30*	60	90	Not permitted
– sprinklered (2)	60	60	30*	30*	60	120#
3. Shop and commercial:						
– not sprinklered	90	60	60	60	90	Not permitted
– sprinklered (2)	60	60	30*	60	60	120#
4. Assembly and recreation:						
– not sprinklered	90	60	60	60	90	Not permitted
– sprinklered (2)	60	60	30*	60	60	120#
5. Industrial:						
– not sprinklered	120	90	60	90		
– sprinklered (2)	90	60	30*	60		
6. Storage and other non-residential:						
a. any building or part not described elsewhere:						
– not sprinklered	120	90	60	90		
– sprinklered (2)	90	60	30*	60		
b. car park for light vehicles:						
i. open sided car park (3)	Not applicable	Not applicable	15*+	15*+ (4)		
ii. any other car park	90	60	30*	60		

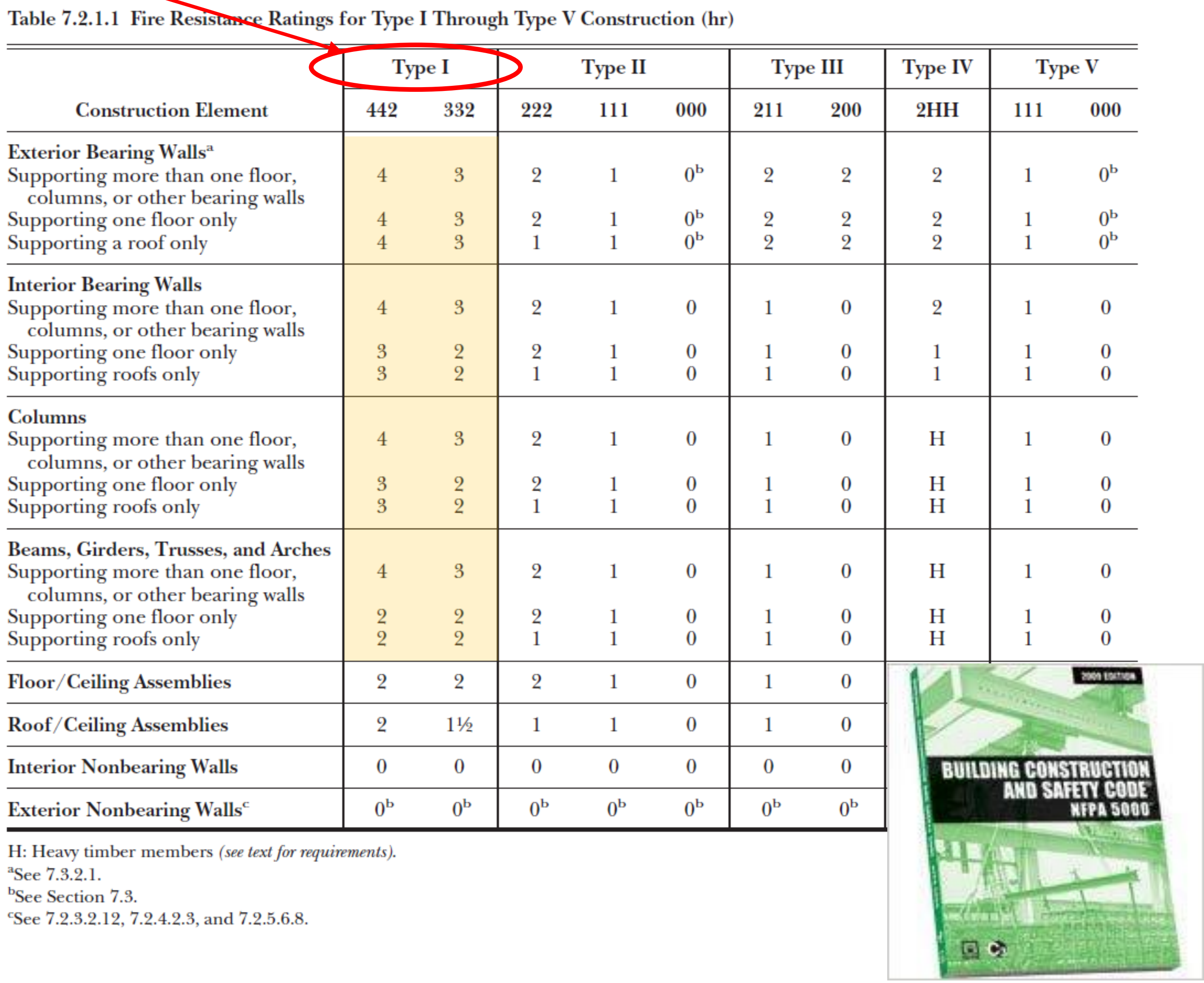


Table 7.2.1.1 Fire Resistance Ratings for Type I Through Type V Construction (hr)

	Type I		Type II			Type III		Type IV	Type V	
Construction Element	442	332	222	111	000	211	200	2HH	111	000
Exterior Bearing Walls^{a}										
Supporting more than one floor, columns, or other bearing walls	4	3	2	1	0^{b}	2	2	2	1	0^{b}
Supporting one floor only	4	3	2	1	0^{b}	2	2	2	1	0^{b}
Supporting a roof only	4	3	1	1	0^{b}	2	2	2	1	0^{b}
Interior Bearing Walls										
Supporting more than one floor, columns, or other bearing walls	4	3	2	1	0	1	0	2	1	0
Supporting one floor only	3	2	2	1	0	1	0	1	1	0
Supporting roofs only	3	2	1	1	0	1	0	1	1	0
Columns										
Supporting more than one floor, columns, or other bearing walls	4	3	2	1	0	1	0	H	1	0
Supporting one floor only	3	2	2	1	0	1	0	H	1	0
Supporting roofs only	3	2	1	1	0	1	0	H	1	0
Beams, Girders, Trusses, and Arches										
Supporting more than one floor, columns, or other bearing walls	4	3	2	1	0	1	0	H	1	0
Supporting one floor only	2	2	2	1	0	1	0	H	1	0
Supporting roofs only	2	2	1	1	0	1	0	H	1	0
Floor/Ceiling Assemblies	2	2	2	1	0	1	0			
Roof/Ceiling Assemblies	2	1½	1	1	0	1	0			
Interior Nonbearing Walls	0	0	0	0	0	0	0			
Exterior Nonbearing Walls^{c}	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}			

H: Heavy timber members *(see text for requirements)*.

[a] See 7.3.2.1.

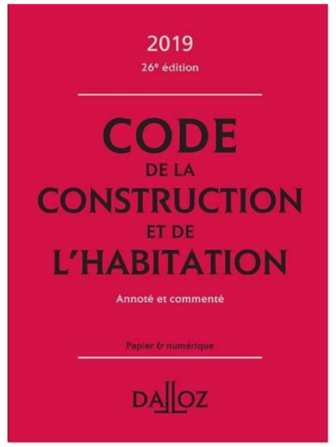
[b] See Section 7.3.

[c] See 7.2.3.2.12, 7.2.4.2.3, and 7.2.5.6.8.

FIRE SEVERITY VS RESISTANCE

The standard framework

BELGISCH STAATSBLAD
MONITEUR BELGE



2019
26e édition
CODE
DE LA
CONSTRUCTION
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L'HABITATION
Annoté et commenté
Papier & numérique
DALLOZ

REEKS BOUWBESLUIT PRAKTIJK
DEEL III
BOUWBESLUIT 2012
MET TOELICHTING EN COMMENTAREN
EDITIE 2013

Design requirement $r \geq e$

Resistance

(standardized test)

Fire severity

(prescribed standardized test result)

The mechanism at work

How is safety achieved?

Innovation fire, 22/05/1967, Brussels

In a standard (prescriptive) framework

progress relies on lessons learned from failure.

Prof. D. Drysdale

Spinardi, et al. (2017). *Fire technology*, *53*(3), 1011-1037.

IS THIS REASONABLE ?

Fire resistance and severity, standard framework

Relative level of complexity	(1) Simple
Design solutions	Prescriptive guidelines
Fire safety job	Code consultancy

urbanlink.be

the-shard.com

dailymail.co.uk

For non-common buildings: adopt a fire engineering approach

WHAT IS FIRE ENGINEERING ?

Institution of Fire Engineers

Fire engineering *is the* ***application of scientific and engineering principles****, rules (codes), and expert judgement,* ***based on an understanding of the phenomena*** *and effects of fire and of the reaction and behavior of people to fire,*

to protect people, property and the environment *from the destructive effects of fire*

IMPLICATION FOR FIRE RESISTANCE?

Understanding of the phenomena	II. Structures and fire – The facts
To protect people, property and the environment	III. What we want to achieve – The goals
Apply scientific and engineering principles	IV. The how – Fire engineering approach

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Structures & fire

“understanding of the phenomena”

FIRE EXPOSURE

Complex phenomenon

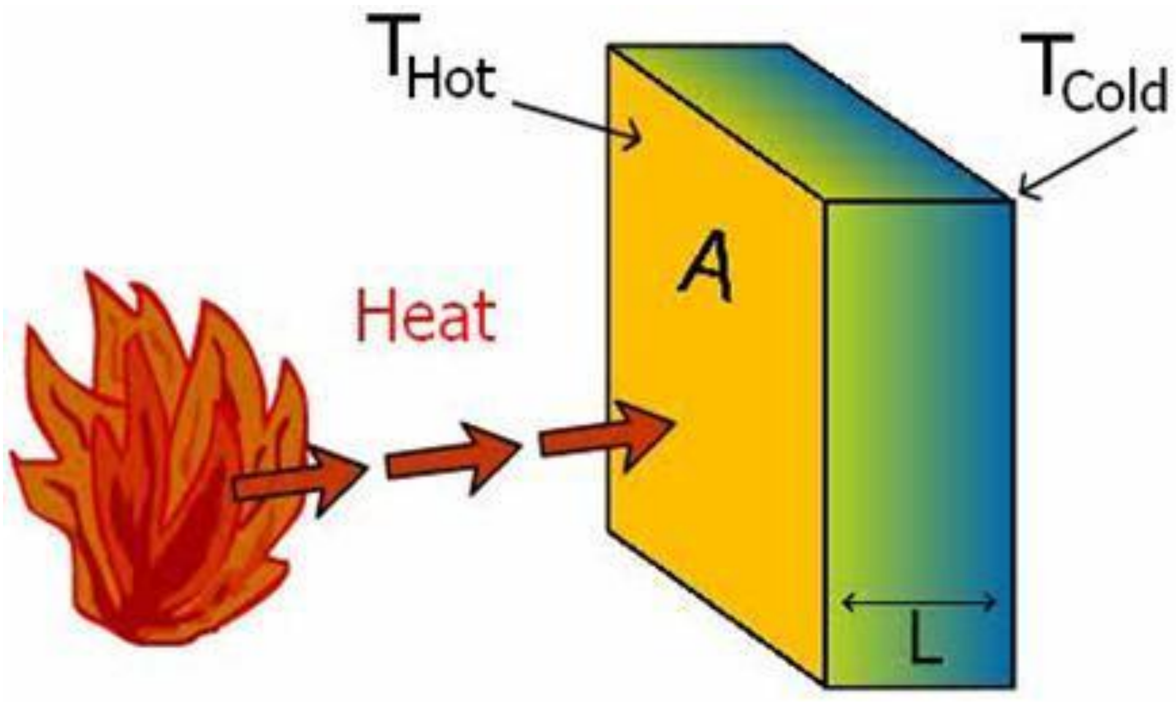
- Ventilation
- Fire load (type; position)
- Compartment (size; lining)
- Fire brigade intervention
- …

Francois Malan. www.flickr.com

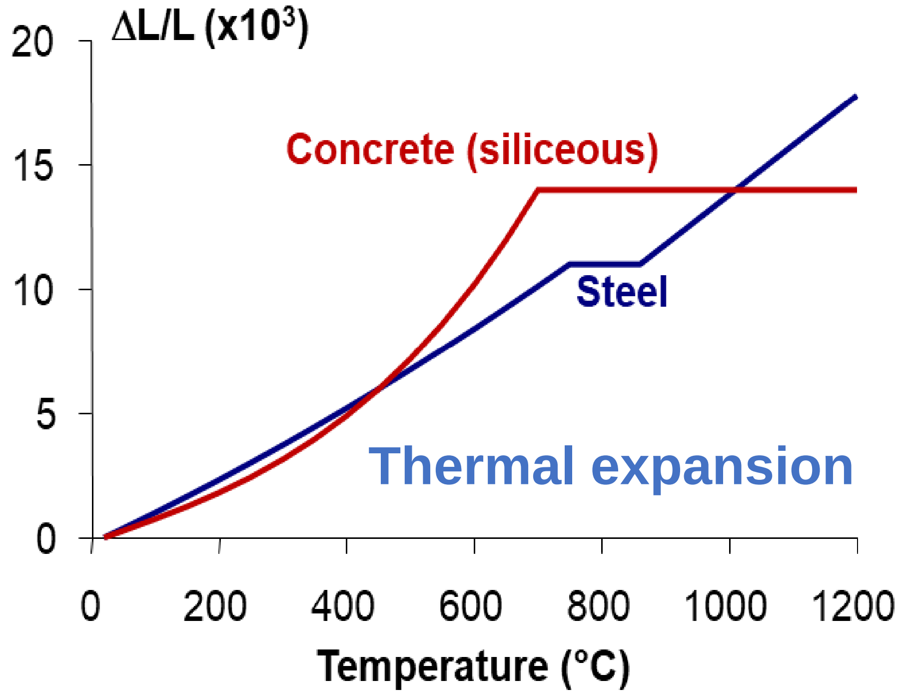
Merseyside Fire and Rescue; https://www.bbc.com/news/uk-england-merseyside-42542556

Beji et al. (2015). *Fire Safety Journal*, *76*, 9-18.

RESPONSE – MATERIAL LEVEL



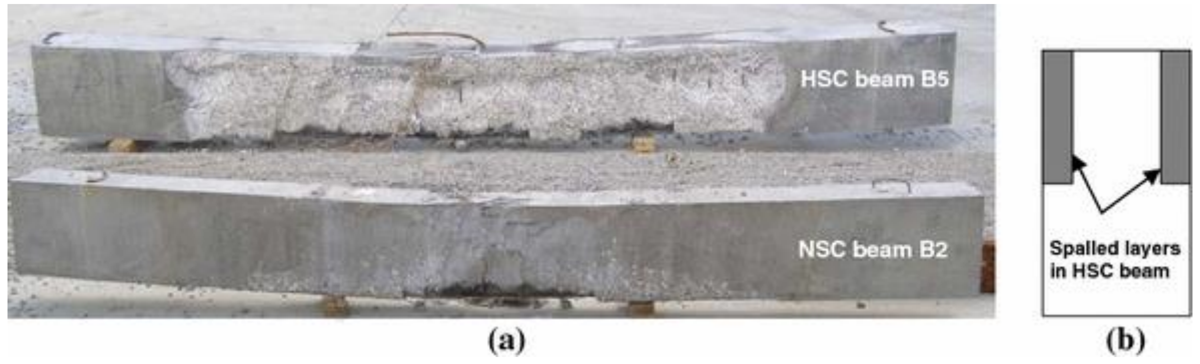
www.nist.gov



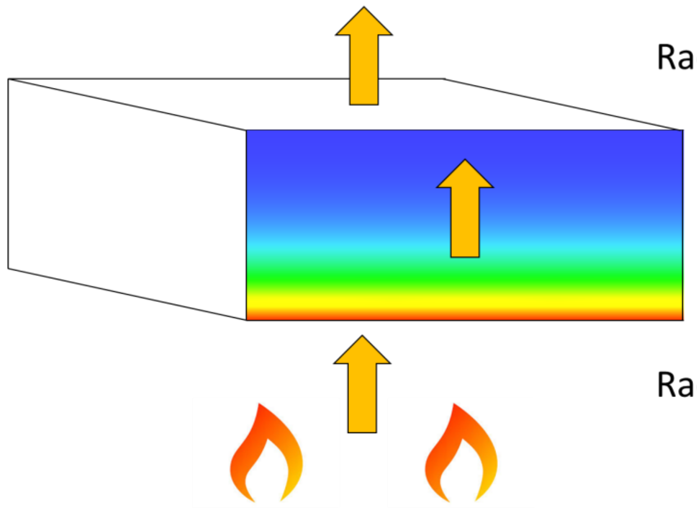
Thermal expansion

Gernay, T. (2018). Lecture notes Structural Fire Engineering.

Concrete spalling



Dwaikat, M.B. & Kodur, V.K.R. Fire Technol (2010) 46: 251

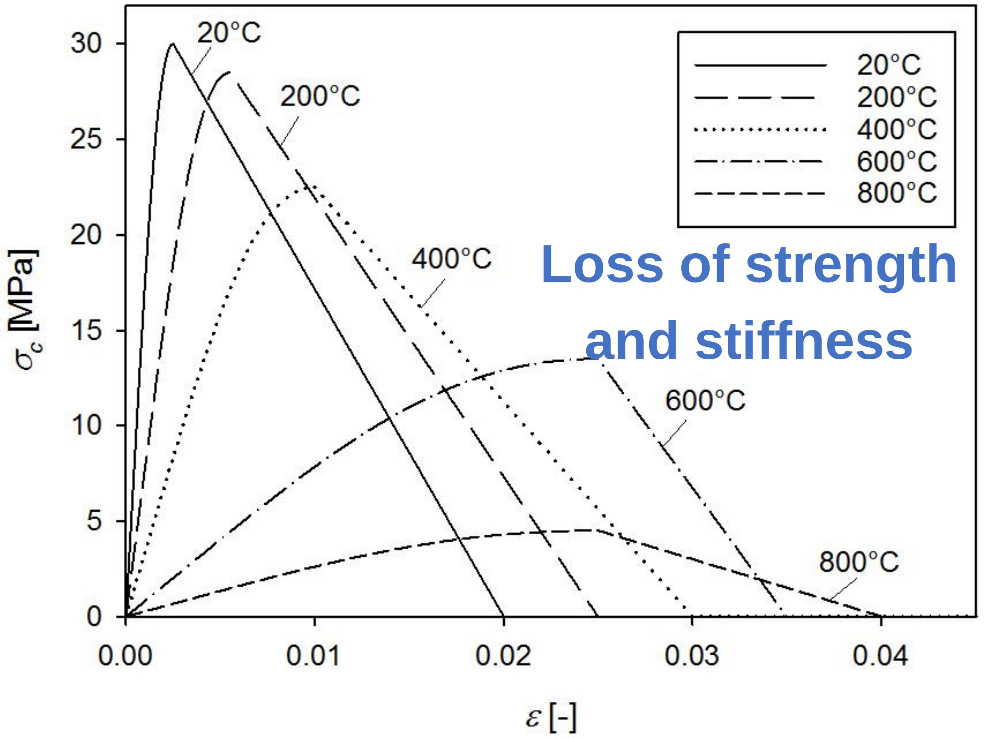


Radiation and convection or conduction

Conduction

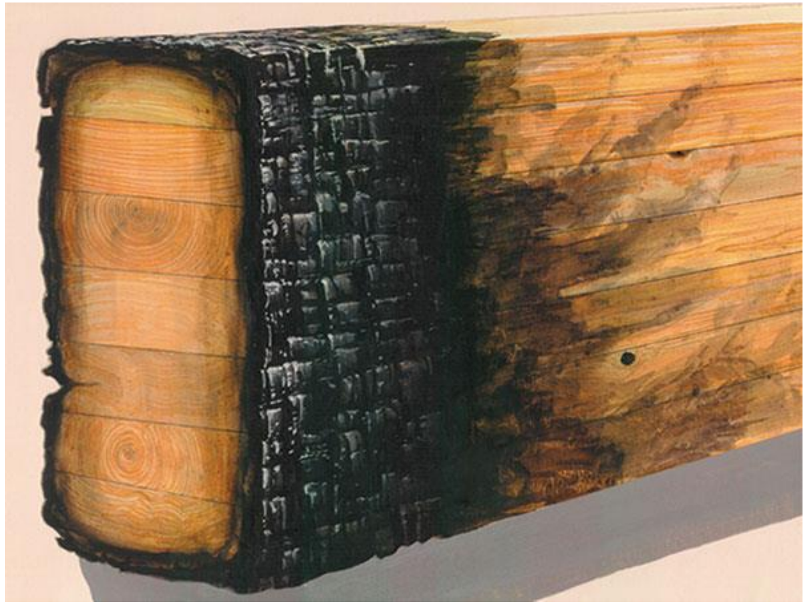
Radiation and convection

Fire definition



Loss of strength and stiffness

Timber charring



White & Woeste (2013). *STRUCTURE magazine, November 2013*, 38-40.

RESPONSE – ELEMENT LEVEL

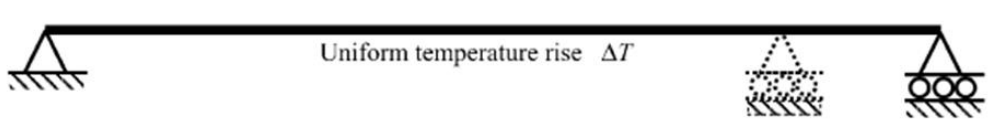
Uniform temperature effects

Non-uniform temperature effects

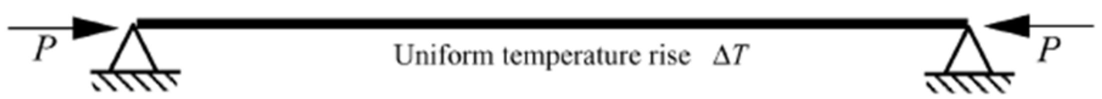
Thermal expansion

Restrained

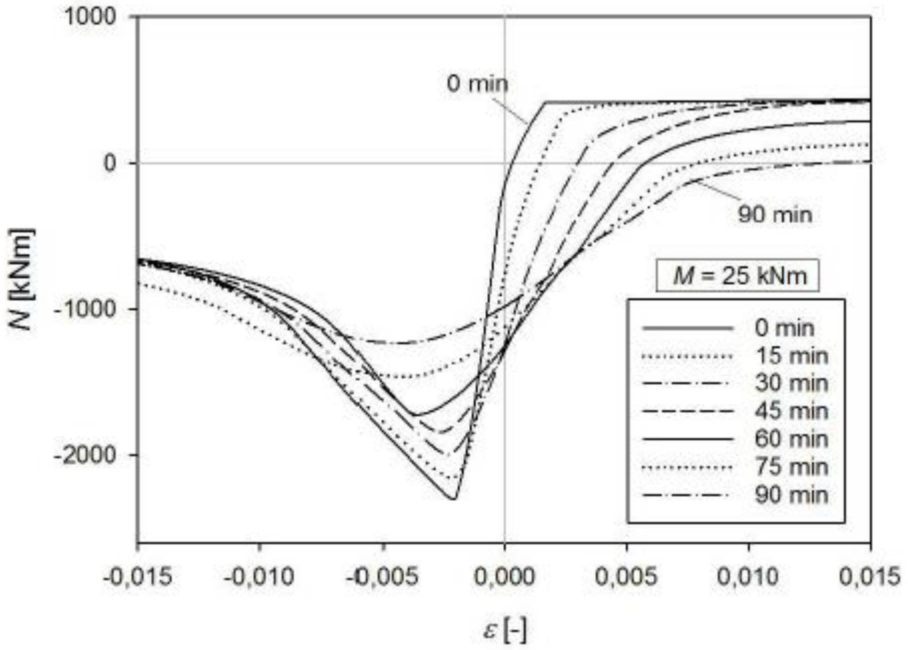
uniform temperature increase Δ*T*, averaged *α*



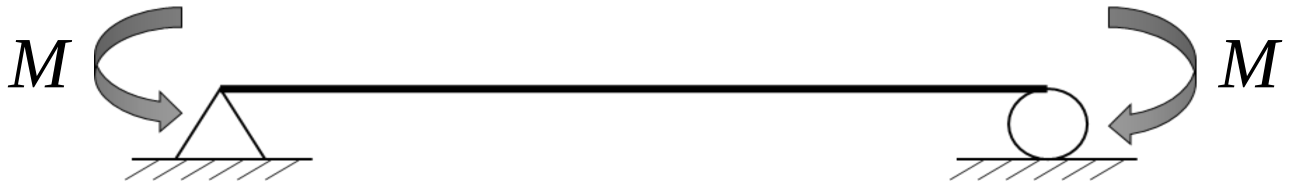
Usmani et al. (2001). *Fire Safety Journal*, *36*(8), 721-744.



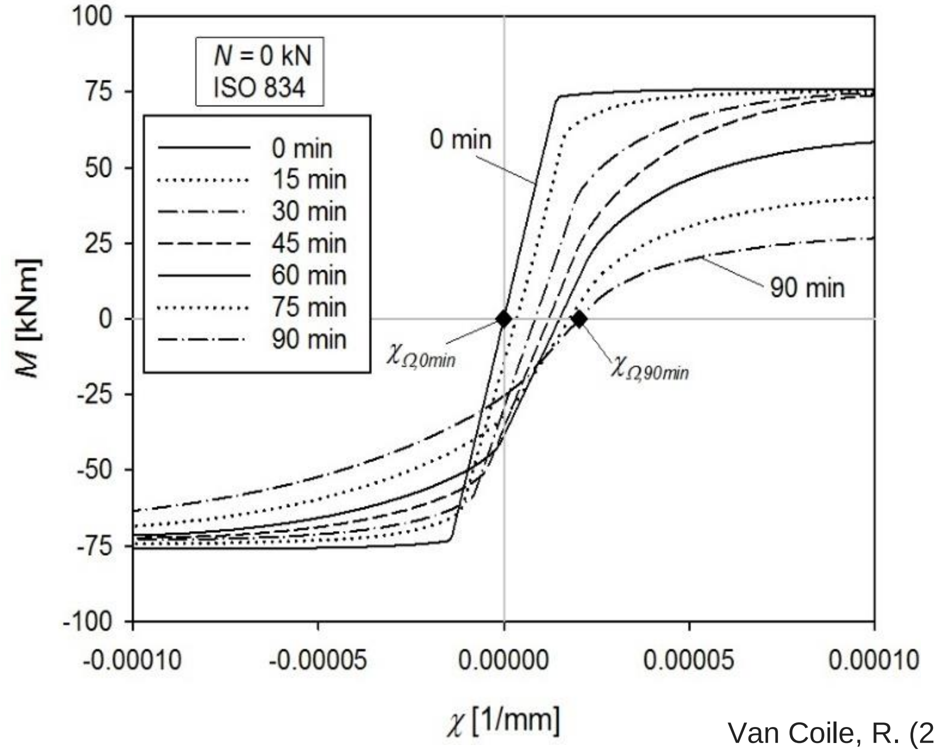
$$P = EA\varepsilon_m = -EA\varepsilon_T = -EA\alpha\Delta T$$



uniform temperature gradient Δ*T, averaged *α***

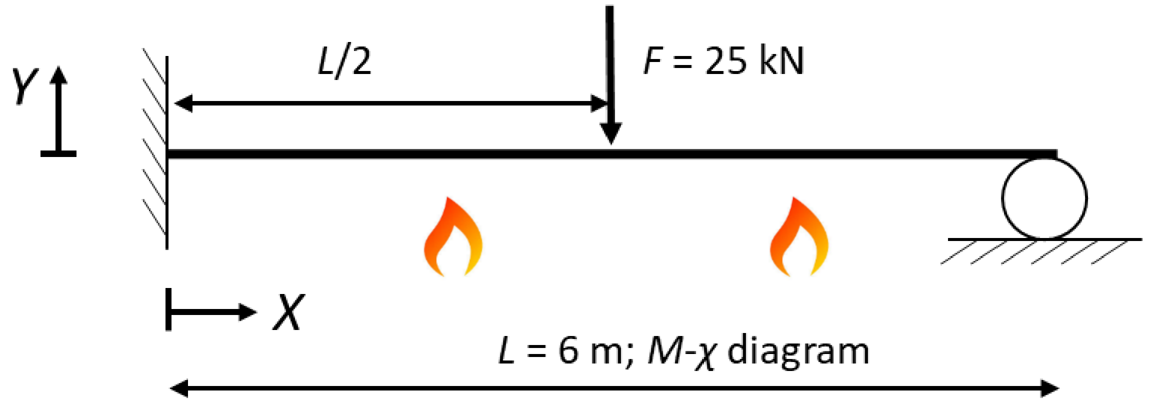


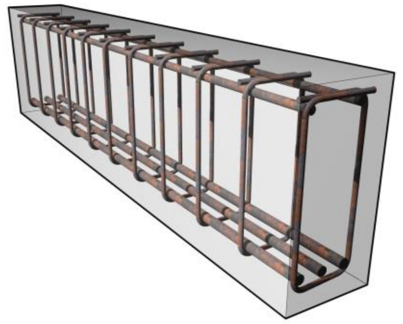
$$M = EI\chi_{th} = EI\alpha\Delta T^*$$

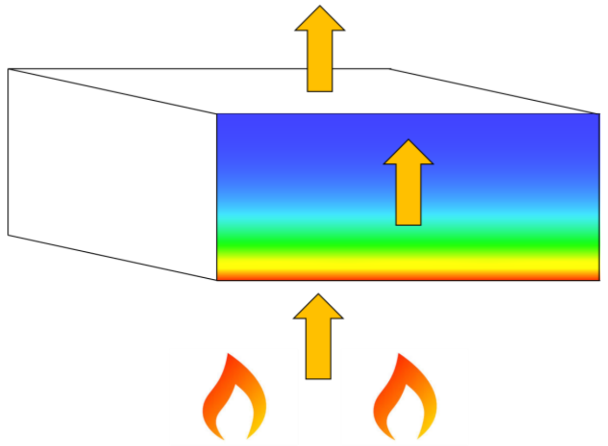


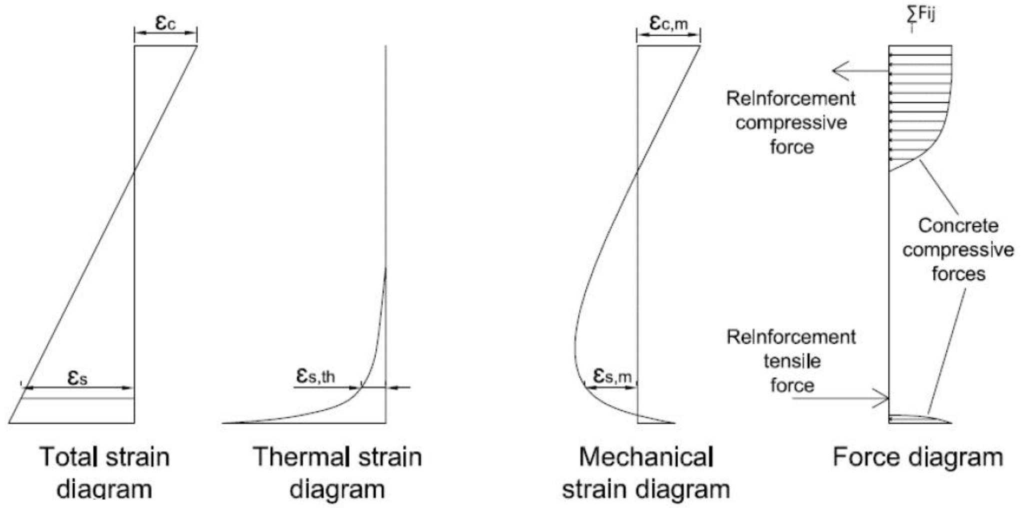
Van Coile, R. (2016)

RESPONSE – ELEMENT LEVEL – EXAMPLE

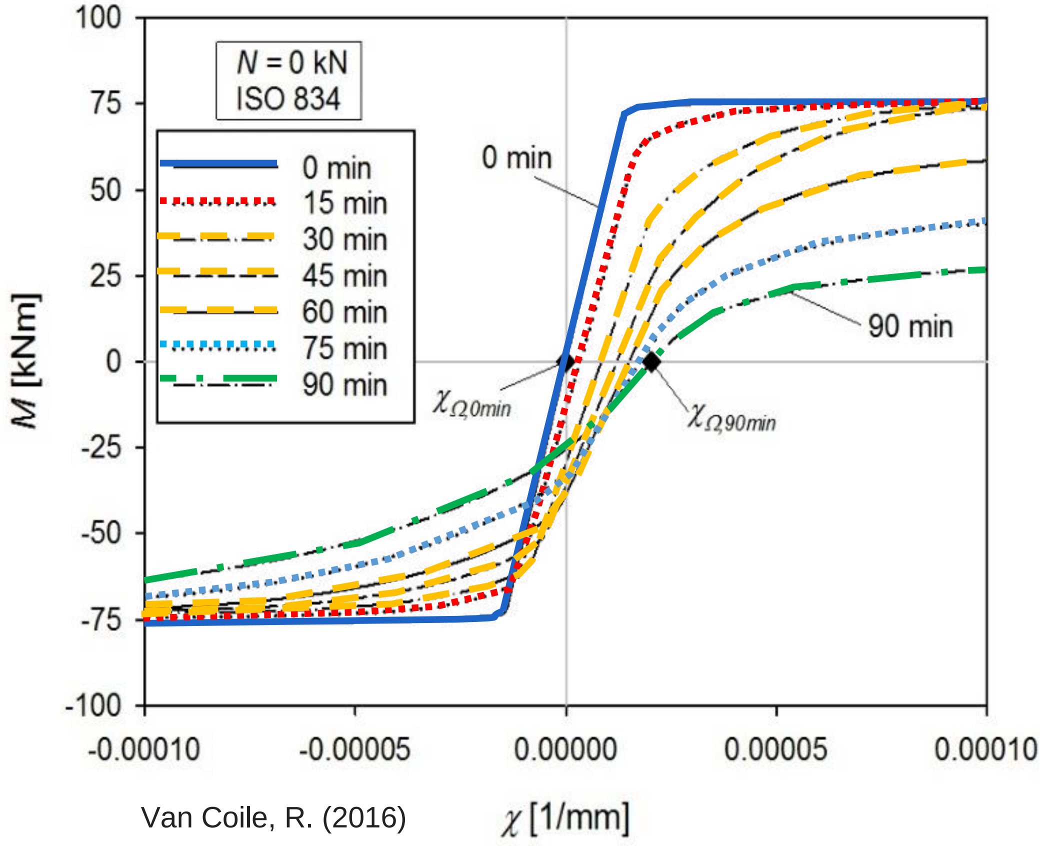




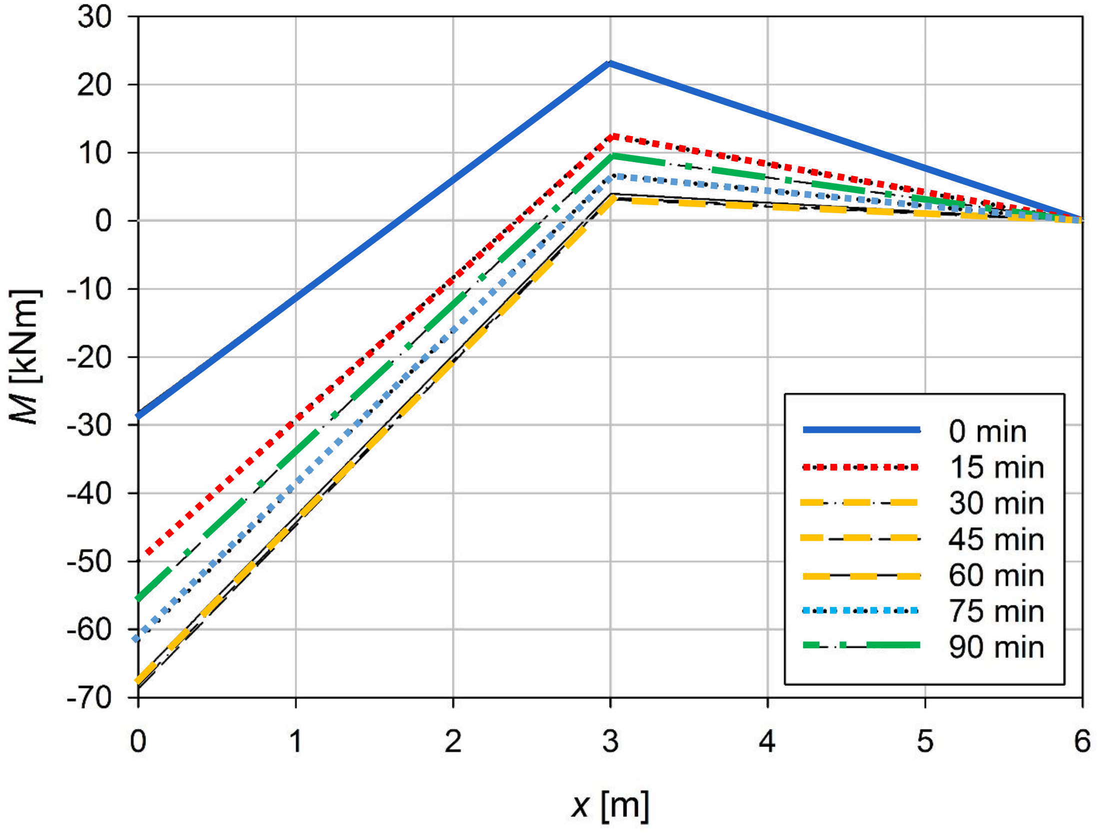




Internal restraint / compatibility



Van Coile, R. (2016)

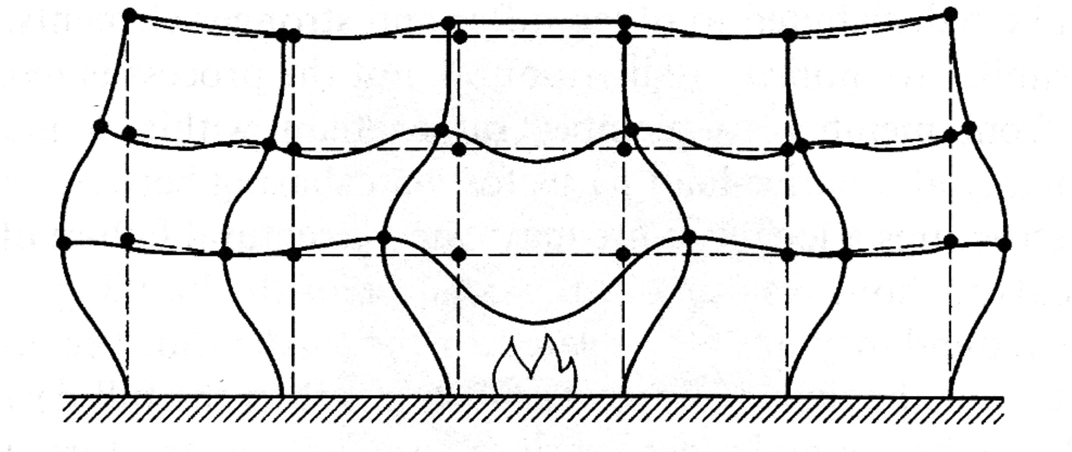


RESPONSE – SYSTEM LEVEL & COOLING

Interaction with remainder of structure

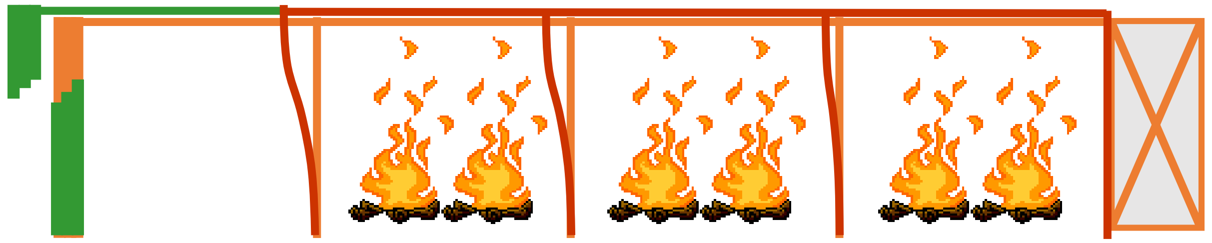
Wikipedia. Broadgate fire.

Positive effect

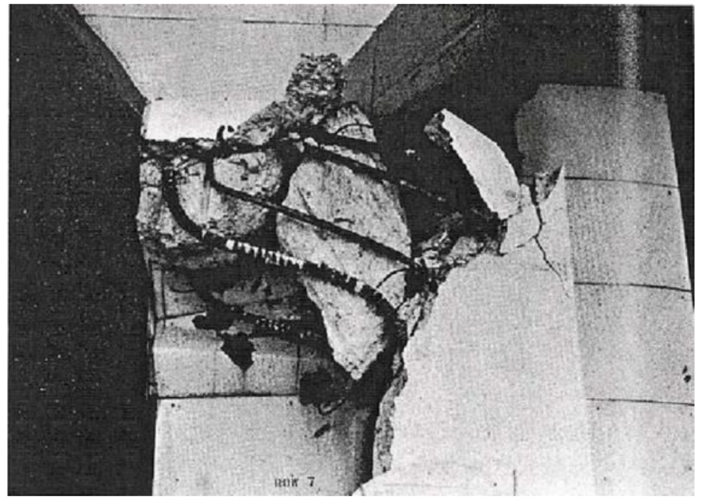


Buchanan and Abu (2017)

Negative effect

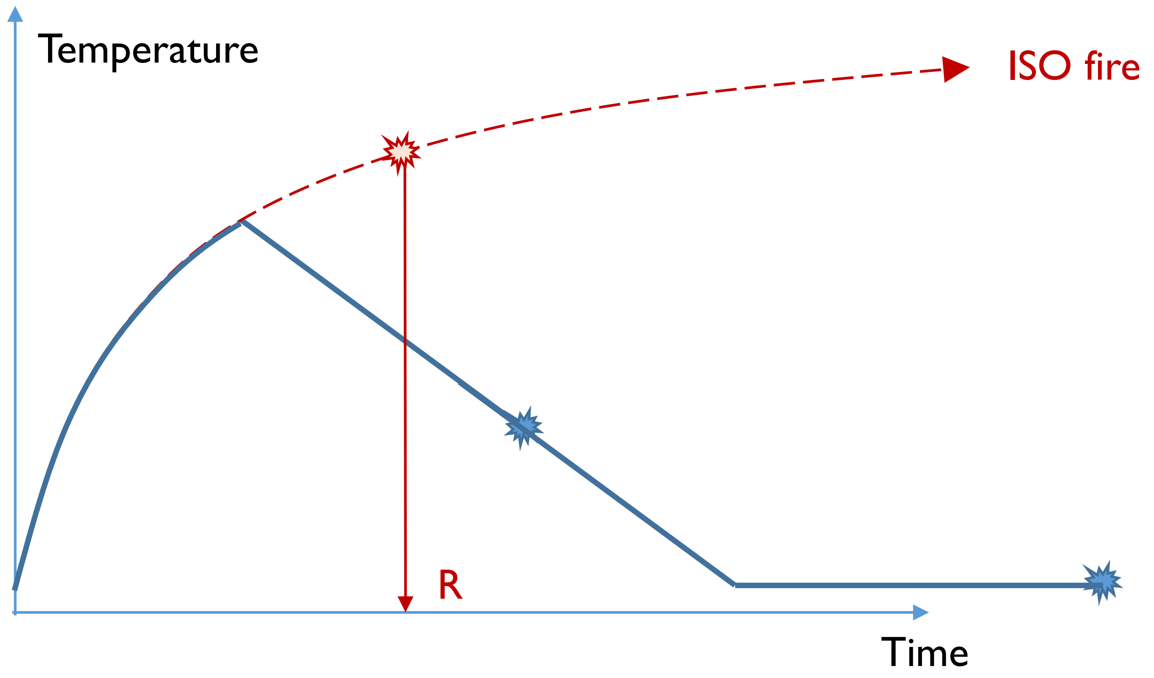


Gernay, T. (2018). Lecture notes Structural Fire Engineering.



Cooling phase failures

- Thermal inertia (further heating)
- Strength loss in cooling
- Tension failure (permanent deformation)



Gernay, T. (2018). Lecture notes Structural Fire Engineering.

Gernay, T. (2019). Fire resistance and burnout resistance of reinforced concrete columns. *Fire Safety Journal*, *104*, 67-78.

CONSEQUENCES

“Iranian firefighters killed in collapse”

Agencia EFE

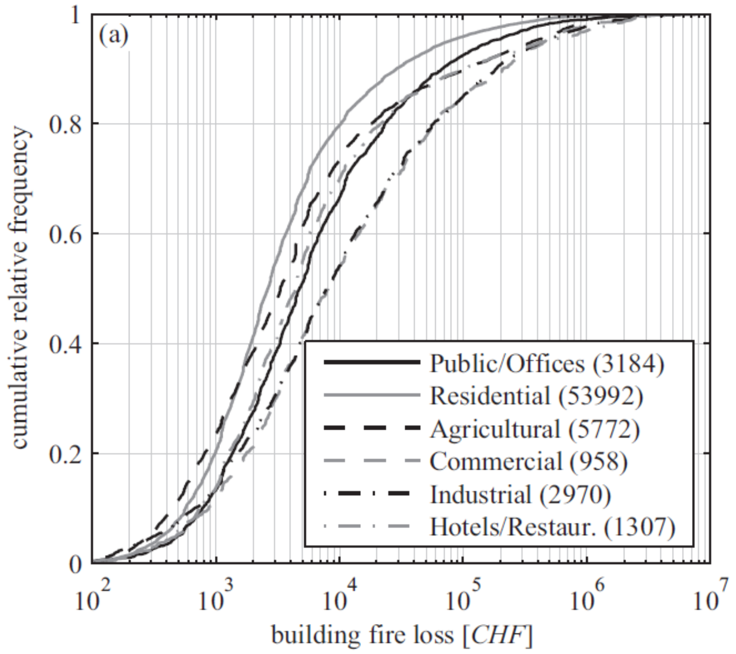
6 months reduced Chunnel service

“Brazil museum fire: ‘incalculable loss’”

Globo.com

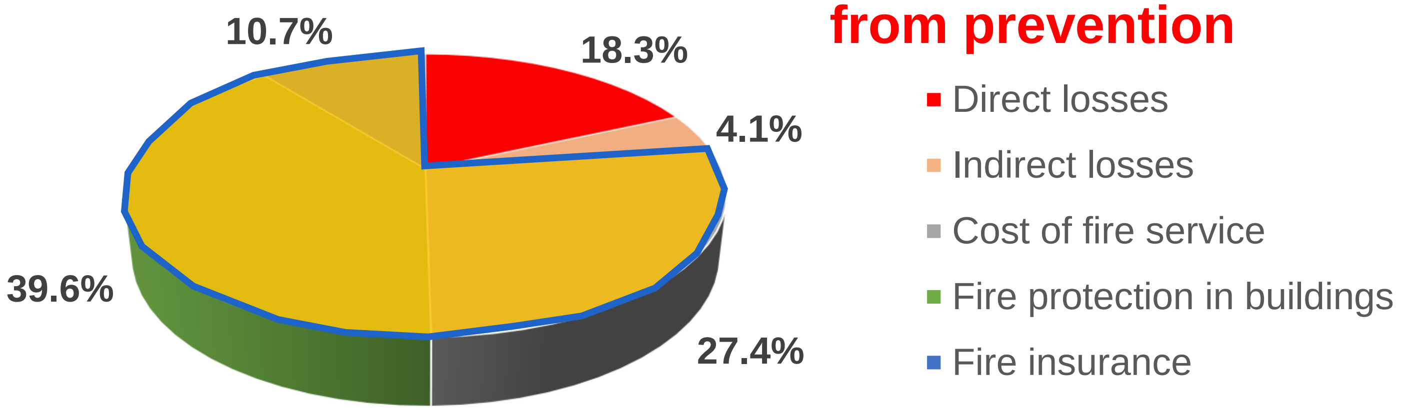
2000-2007 Swiss insurance loss data

Fischer, K. (2014). Doctoral dissertation.



Economic “costs” of fire 2008-2010; 1% GDP

CTIF-World Fire Statistics Center 2016 n°21



75% cost of fire result from prevention

“Sandoz chemical spill”

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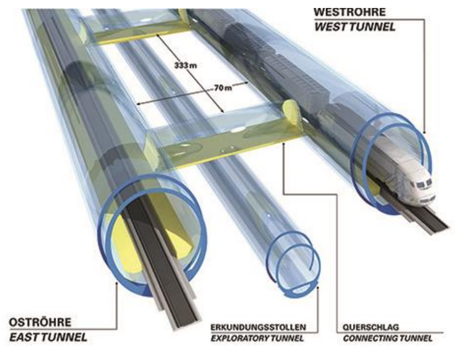
Fire resistance goals

“protect people, property and the environment”



GOALS FOR FIRE SAFETY

Particularly important for structural fire engineering

SFPE Guide to Performance-based Fire Protection Engineering

- **Life safety**
- **Property protection**
- **Environmental protection**
- **Continuity of operations**
- *Historic preservation*

[There is an] *expectation that buildings will not collapse or allow fire to spread*

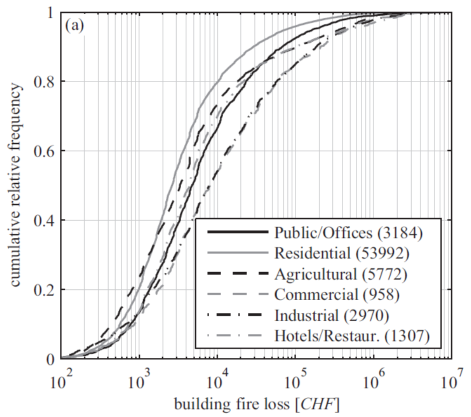
Prof. L. Bisby

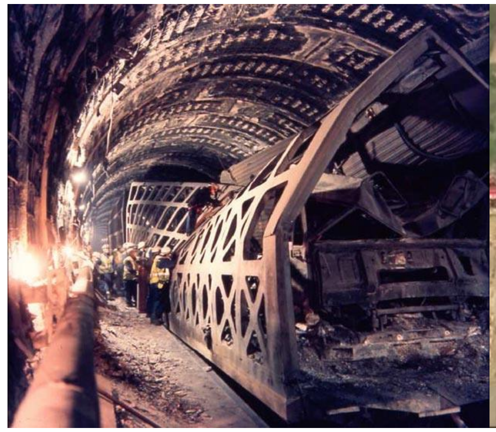
Bisby, L. (2016). Lecture notes Structural Design for Fire

Institution of Fire Engineers

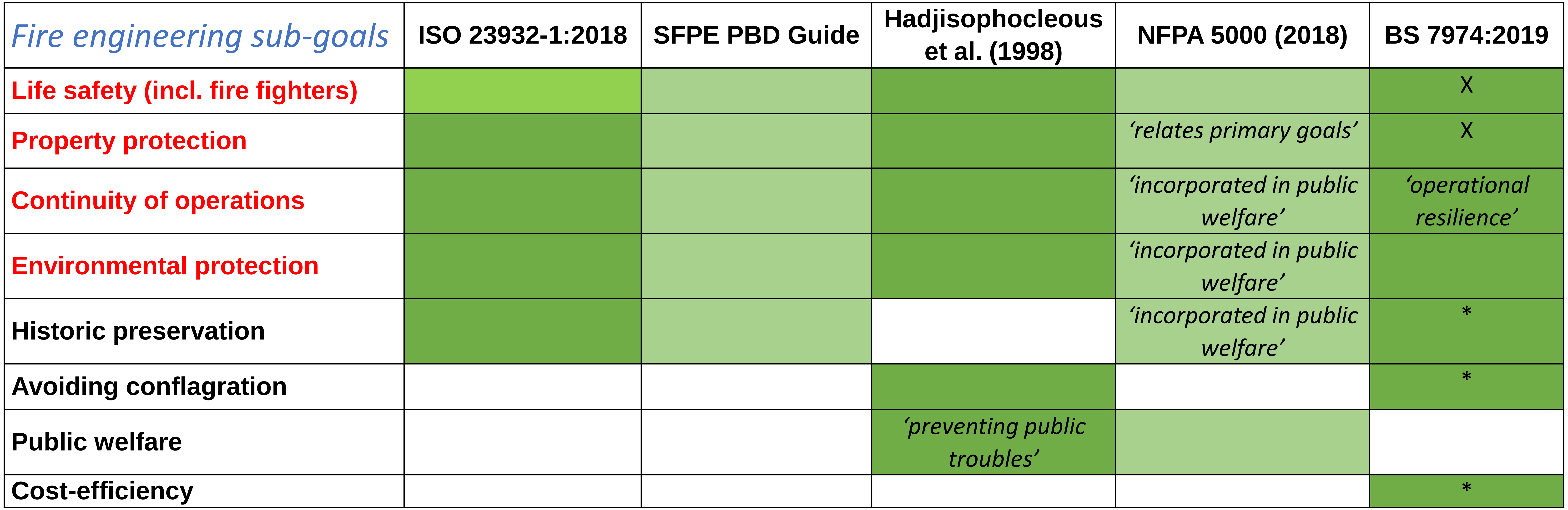
Fire engineering is the ***application of scientific and engineering principles****, rules (codes), and expert judgement,* ***based on an understanding of the phenomena*** *and effects of fire and of the reaction and behavior of people to fire,*

to protect people, property and the environment *from the destructive effects of fire*





GOALS FOR FIRE SAFETY



Fire engineering sub-goals	**ISO 23932-1:2018**	**SFPE PBD Guide**	**Hadjisophocleous et al. (1998)**	**NFPA 5000 (2018)**	**BS 7974:2019**
Life safety (incl. fire fighters)	🟩	🟩	🟩	🟩	X
Property protection	🟩	🟩	🟩	*‘relates primary goals’*	X
Continuity of operations	🟩	🟩	🟩	*‘incorporated in public welfare’*	*‘operational resilience’*
Environmental protection	🟩	🟩	🟩	*‘incorporated in public welfare’*	🟩
Historic preservation	🟩	🟩		*‘incorporated in public welfare’*	*
Avoiding conflagration			🟩		*
Public welfare			*‘preventing public troubles’*	🟩	
Cost-efficiency					*

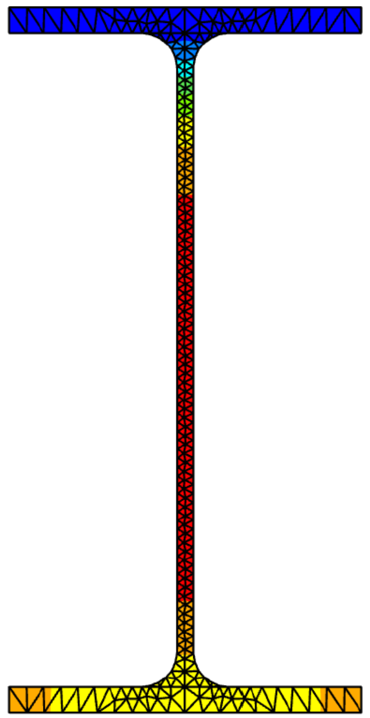
* mentioned in text discussing *‘fire functional objectives’*

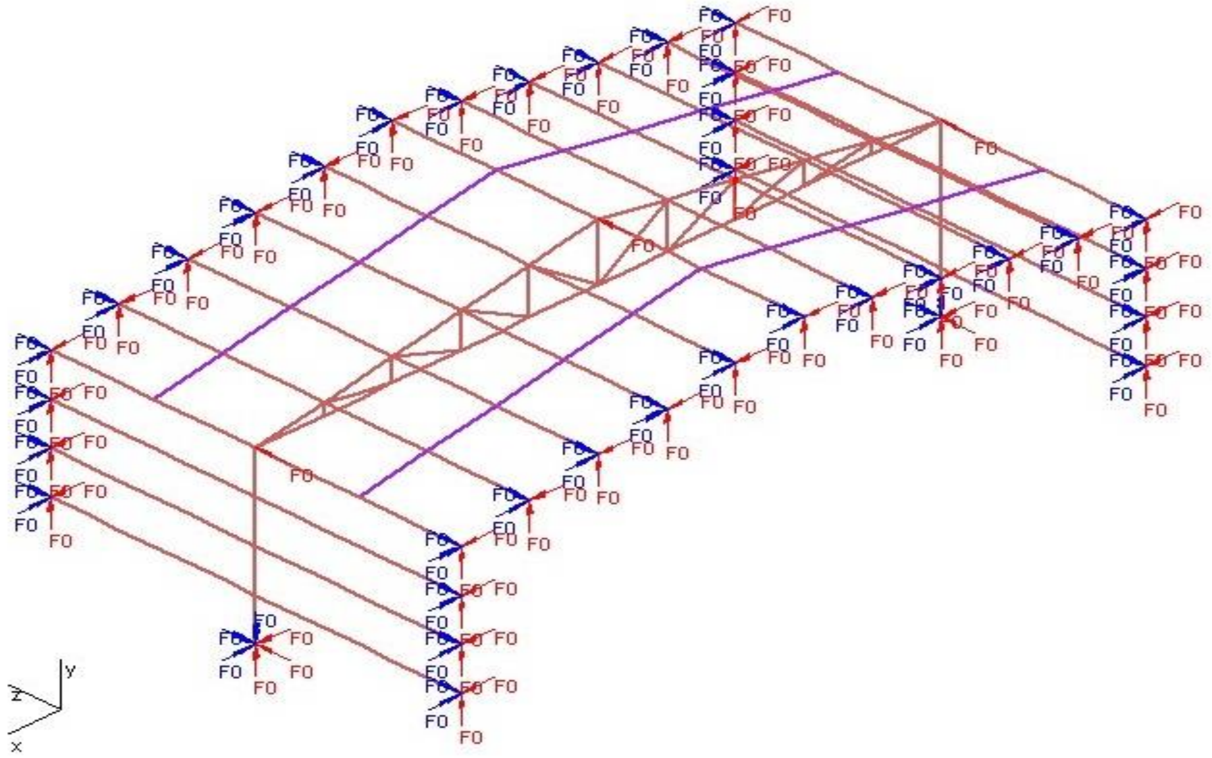
Over-arching Fire Engineering goal: *Controlling fire risks to socio-economically acceptable levels, as part of the overall fire safety strategy*

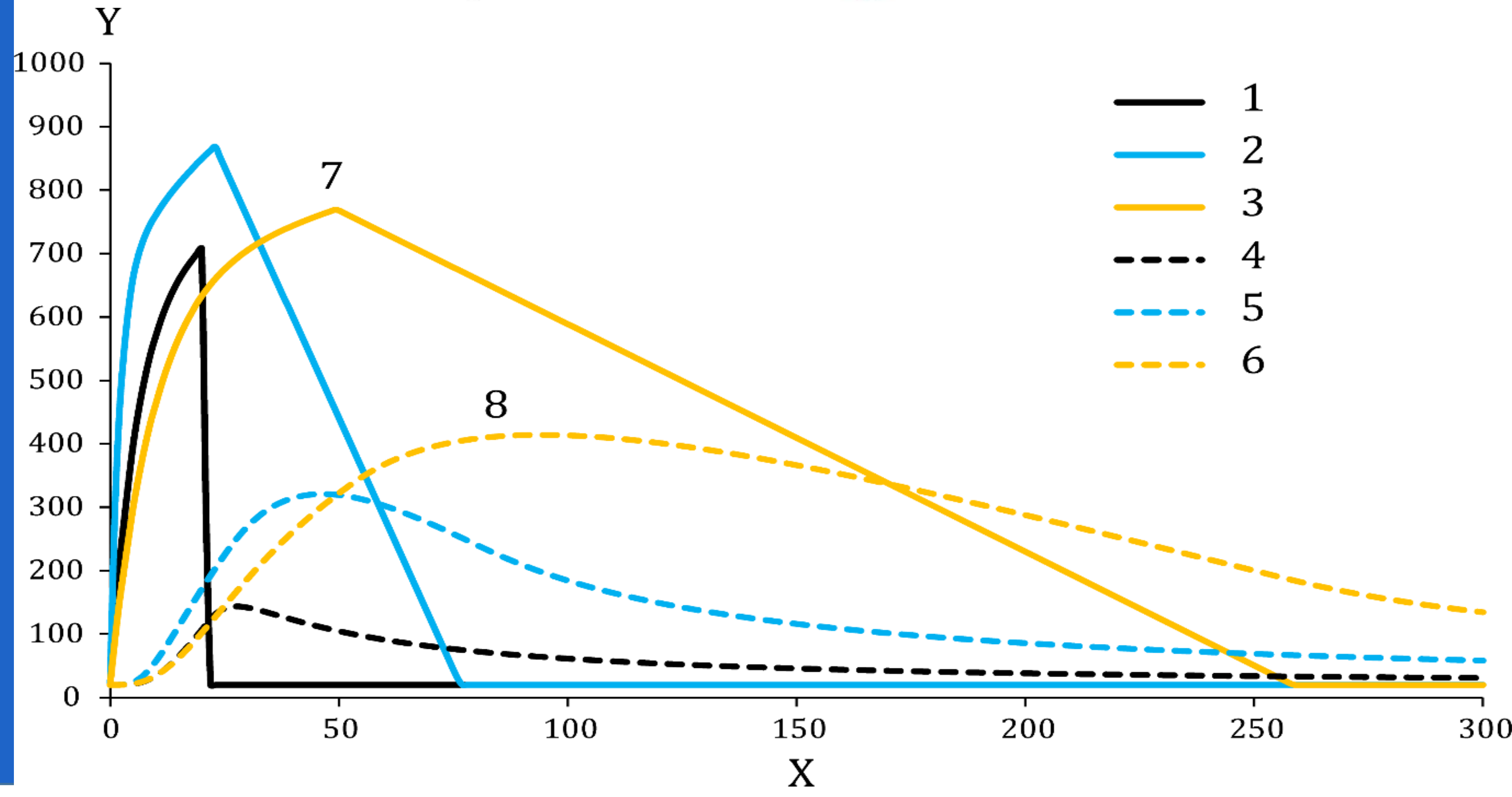
⇨ *Structural Fire Engineering objectives go beyond (indirect) code compliance*

Fire engineering approach

“application of scientific and engineering principles”







Gernay, T., Franssen, J.-M. (2018). SAFIR training. Johns Hopkins University (USA), Université de Liège (BE).

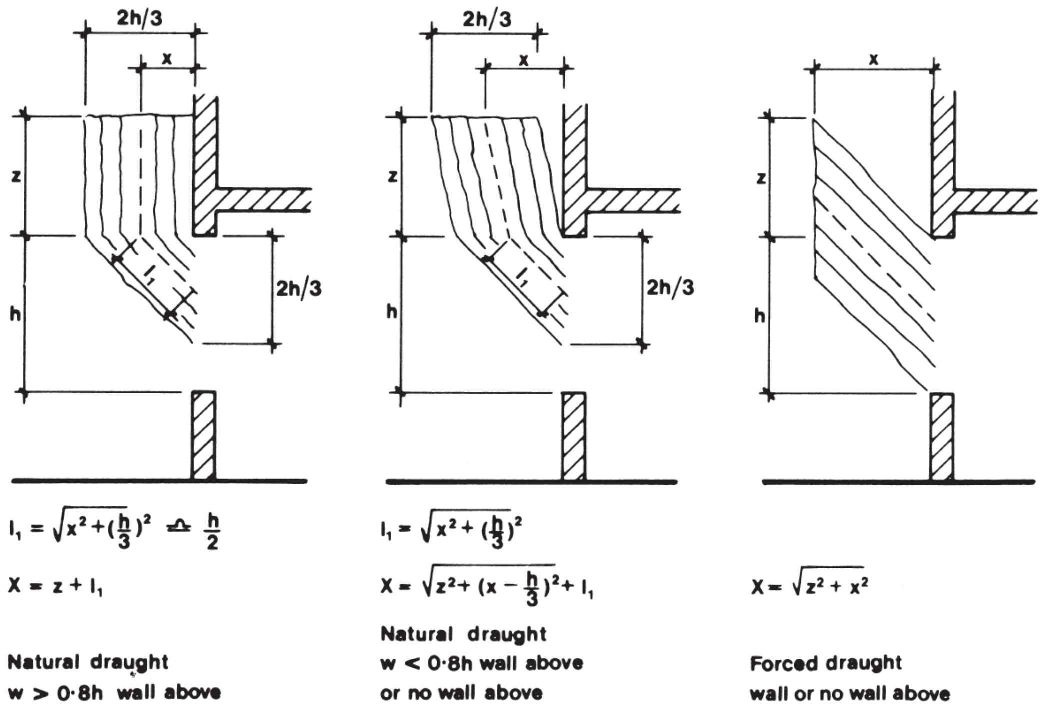
ISO TR 24679-6:2017. Fire safety engineering – Performance of structures in fire – Part 6: Example of an eight storey office concrete building. *International Organization for Standardization*.

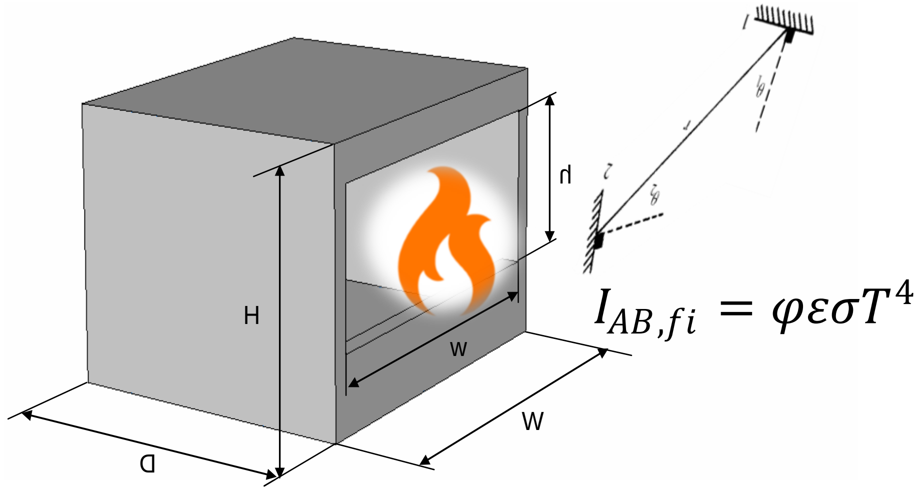
CASE – LONDON HIGH-RISE SCULPTURE

Design beyond prescriptive guidance; **SFE objective: no collapse**

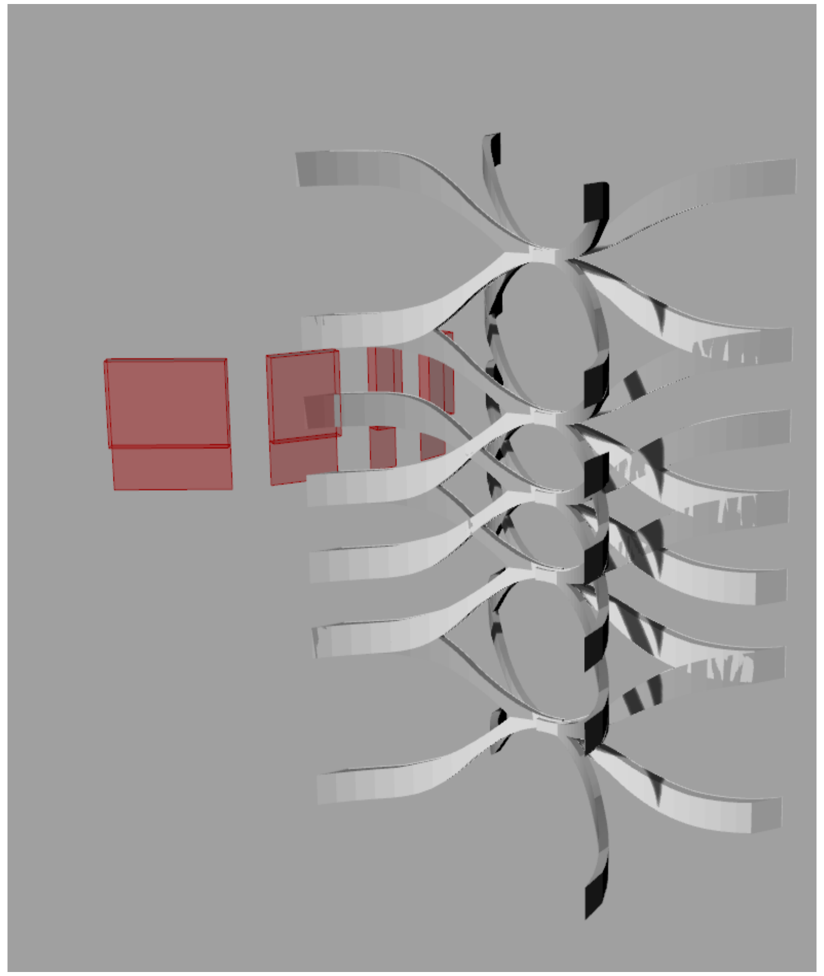
⇨ Evaluate background Eurocodes

Law, M. (1978). Fire safety of external building elements – the design approach.
American Institute of Steel Construction Engineering Journal, 59-74



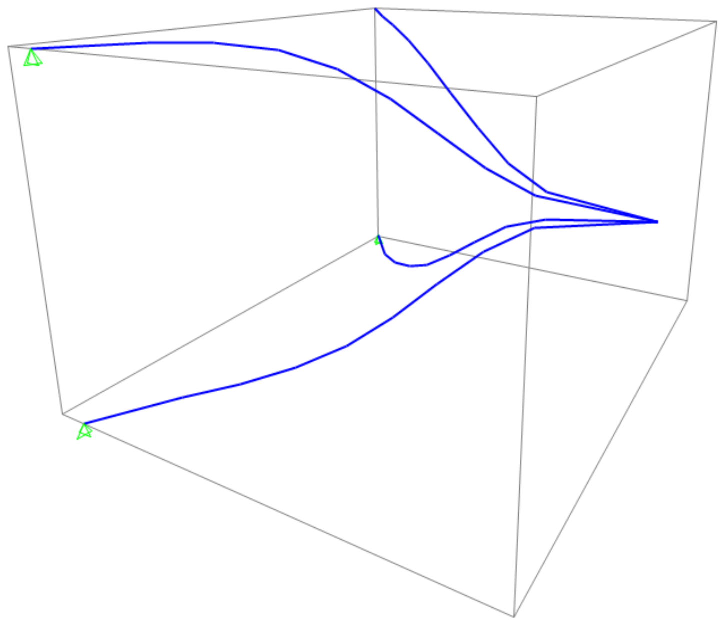


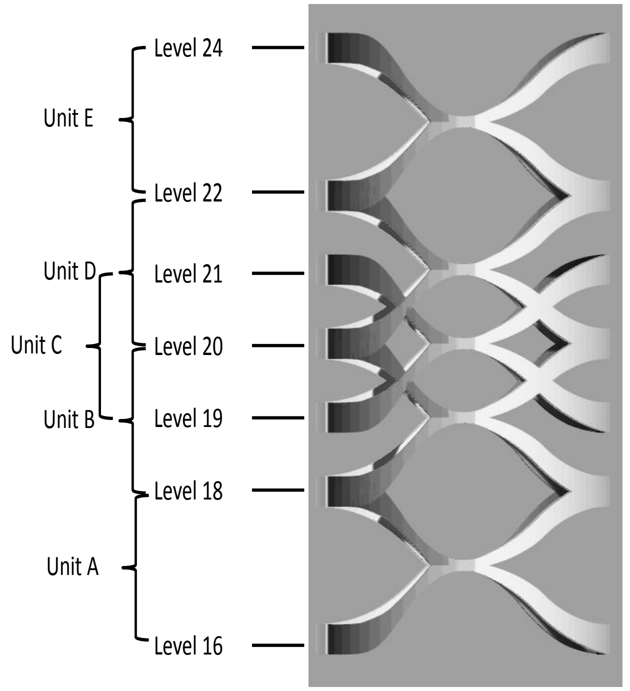
$$I_{AB,fi} = \varphi \varepsilon \sigma T^4$$



Material at elevated temperature

Load redistribution to other connections confirmed





CASE – UNDERWATER TUNNEL PROTECTION

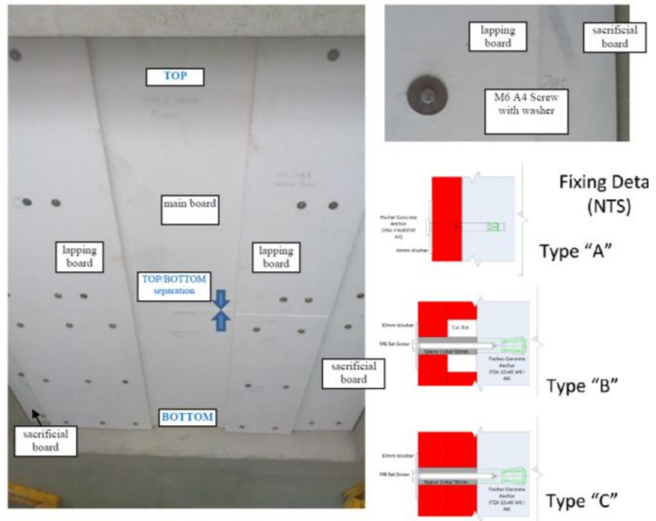
cases.ita-aites.org

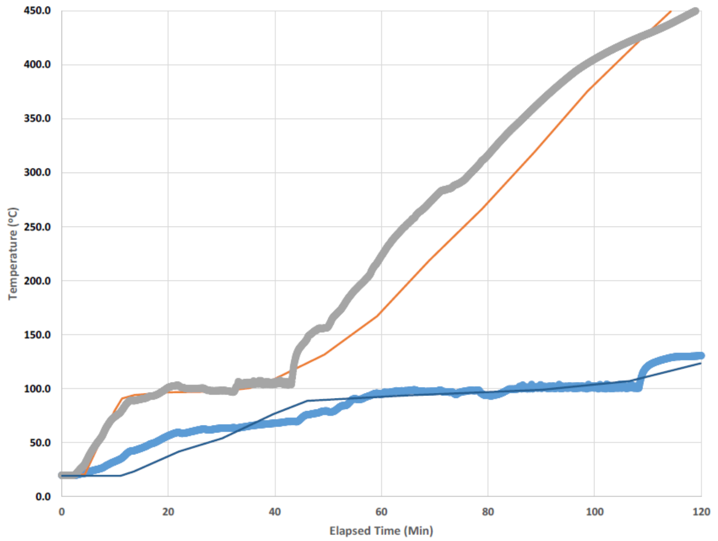
Design beyond prescriptive guidance

SFE objective:

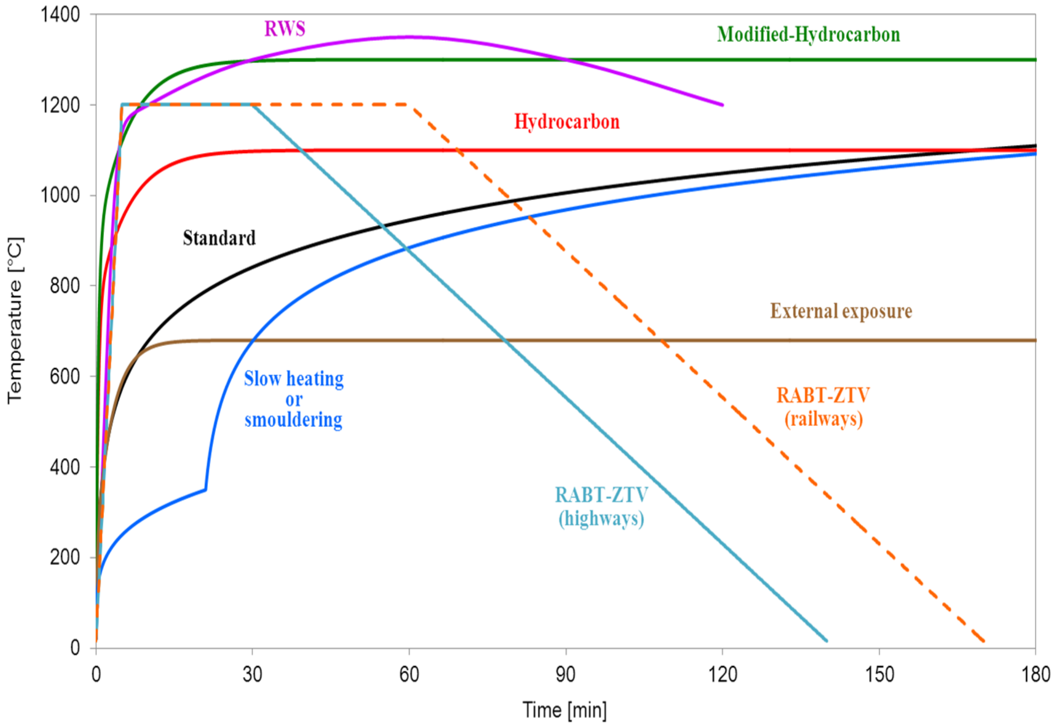
Omega seal < 120°C at 2 hours RWS

Element and dilatation joints vulnerable to fire

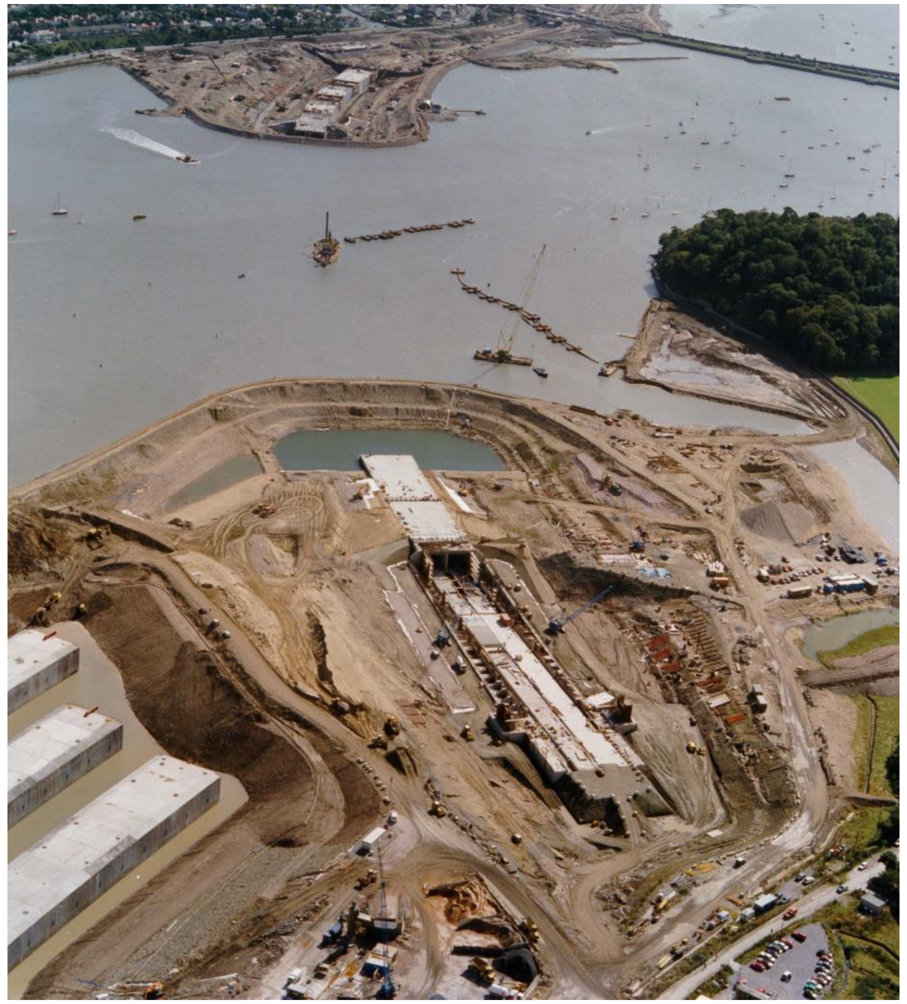


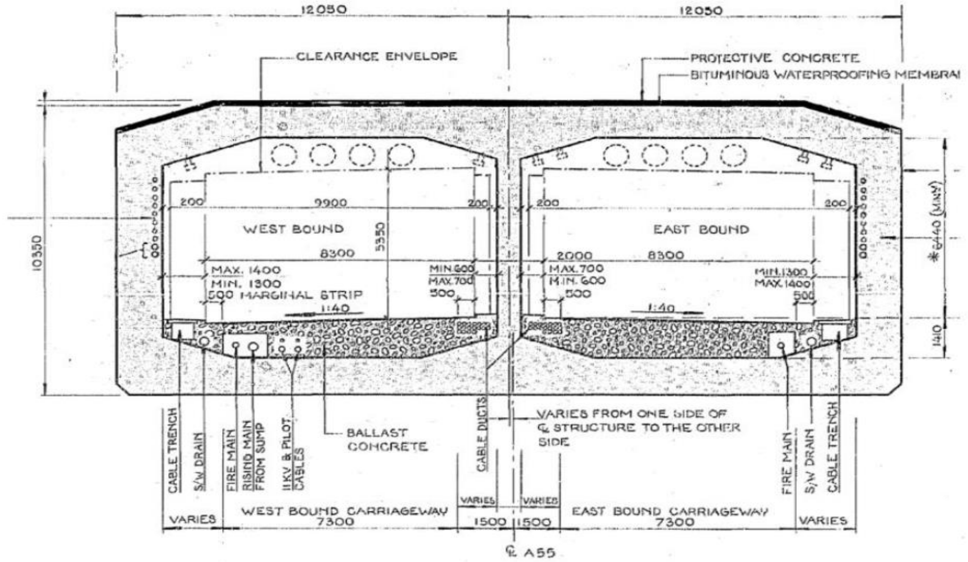


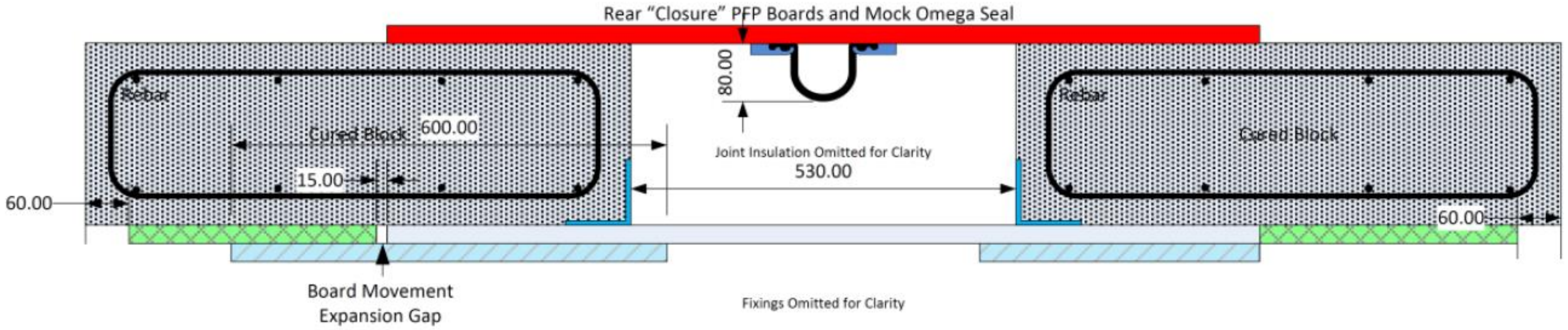
Tarada, F. (2018). Fire protection of tunnel joints for the A55 Conwy immersed tube tunnel. *International Symposium on Tunnel Safety and Security*, 14-16/03, Boras, Sweden.



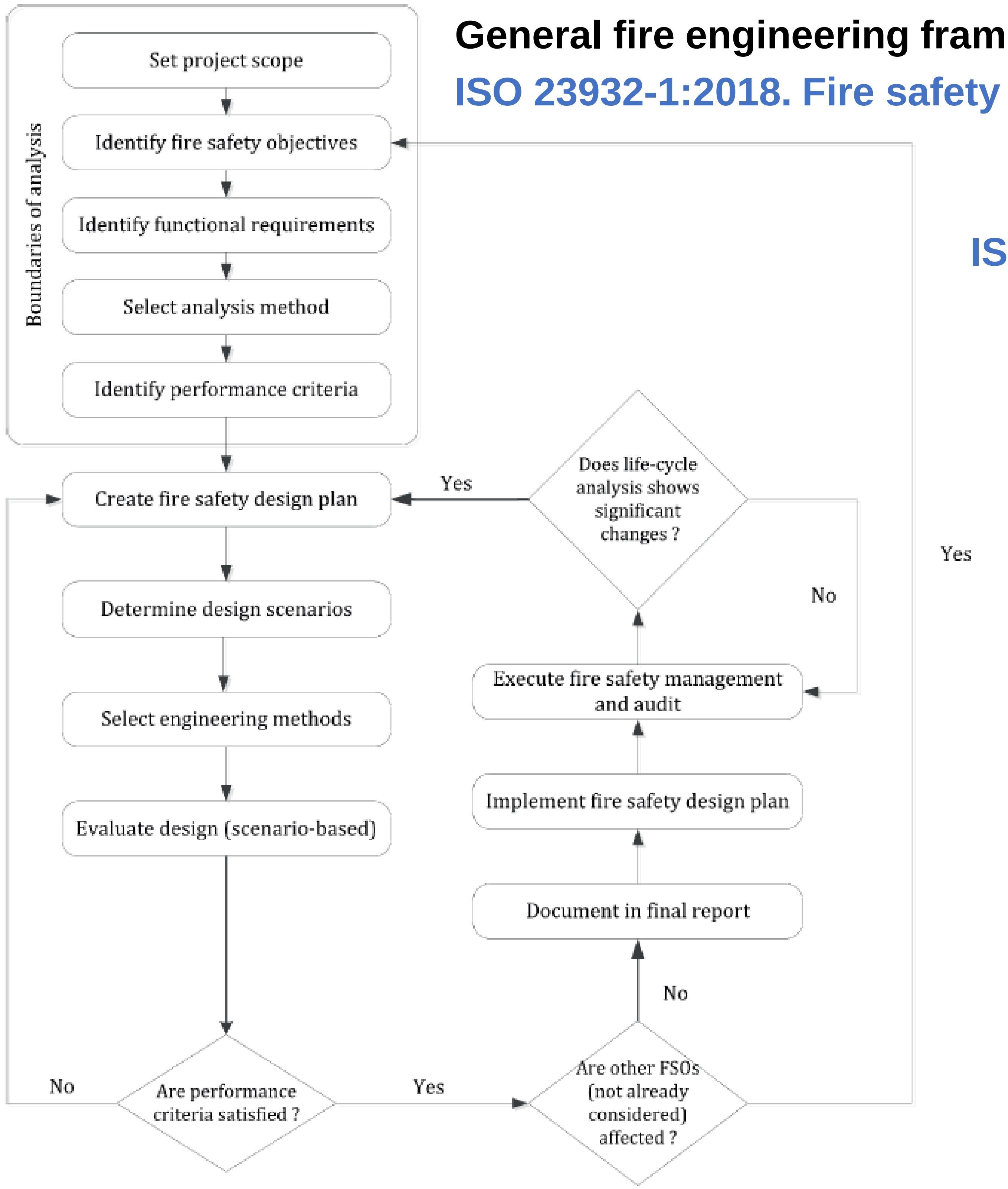
Bisby, L. (2016). Lecture notes Structural Design for Fire







STRUCTURAL FIRE ENGINEERING FRAMEWORK



General fire engineering framework

ISO 23932-1:2018. Fire safety engineering – General principles

‘Normative’ , not procedural

Structural fire engineering framework

ISO 24679-1:2017. Fire safety engineering – Performance of structures in fire

Step 1: Scope of the project (for fire safety of structures)

Step 2: Identifying objectives, functional requirements and performance criteria

Step 3: Trial design plan

Step 4: Design fire scenarios and design fires

Step 5: Thermal response of the structure

Step 6: Mechanical response of the structure

Step 7: Assessment against the fire safety objectives

Step 8: Documentation of the design for fire safety of structures

Introduce step-wise:

ISO TR 24679-6:2017
Fire safety engineering – Performance of structures in fire – Part 6: Example of an eight storey office concrete building

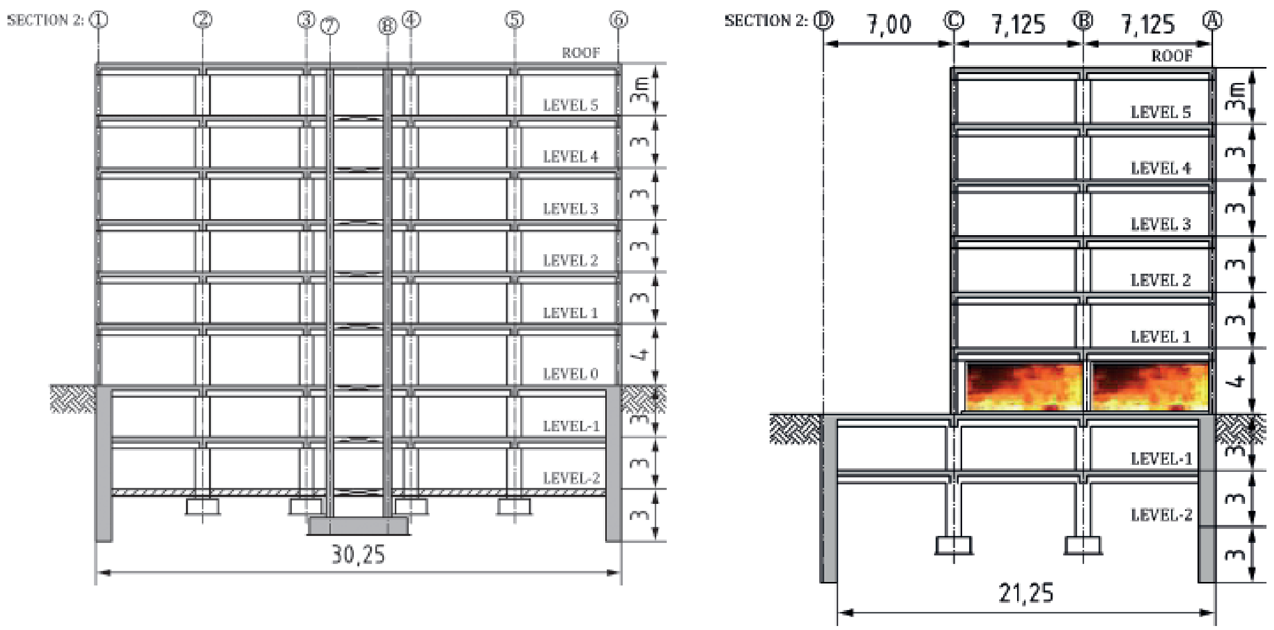
STRUCTURAL FIRE ENGINEERING FRAMEWORK

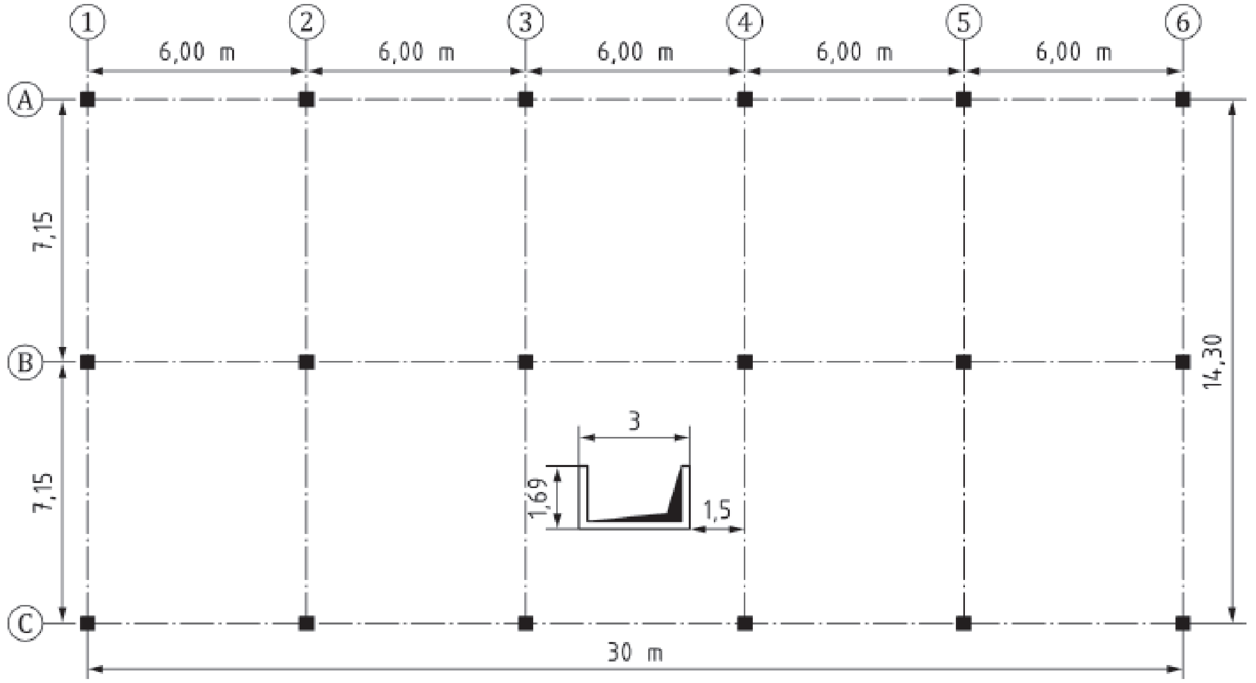
Structural fire engineering framework

ISO 24679-1:2017. Fire safety engineering – Performance of structures in fire

ISO TR 24679-6:2017. Fire safety engineering – Performance of structures in fire – Part 6:
Example of an eight storey office concrete building. *International Organization for Standardization.*

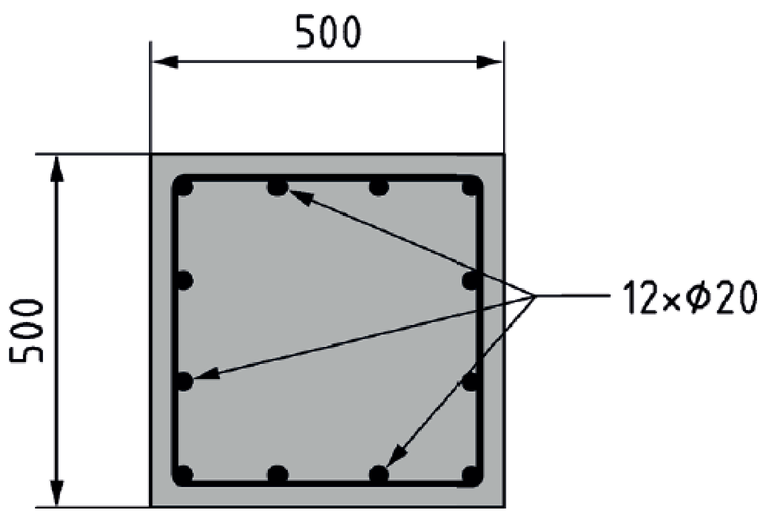
Step 1: Scope of the project (for fire safety of structures)





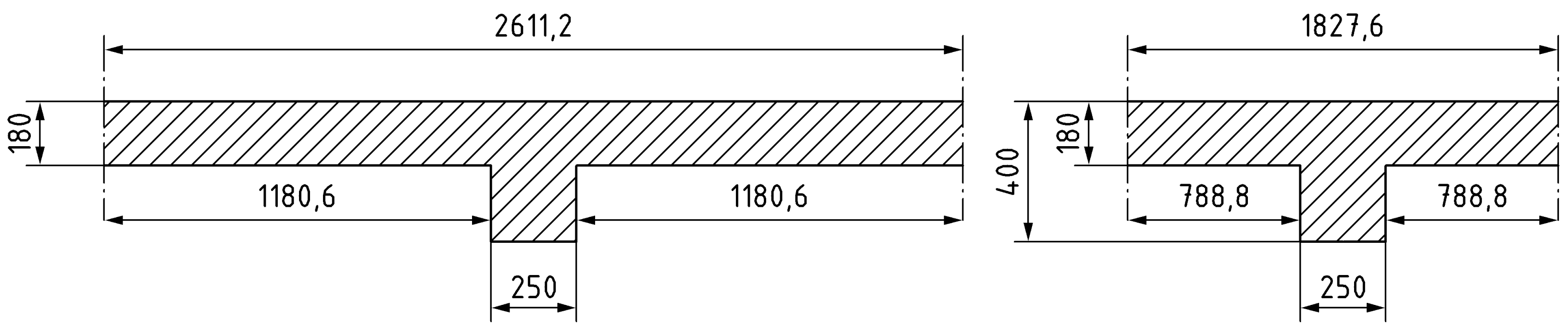
Eurocode reference building

Biasoli et al. (2014). ec.europa.eu



Open plan office, 420 m^2

	Load	Value of load
Dead load	Self-weight	25 kN/m^3
	Finishing	1,5 kN/m^2
Live load	Office	4 kN/m^2



STRUCTURAL FIRE ENGINEERING FRAMEWORK

Structural fire engineering framework

ISO 24679-1:2017. Fire safety engineering – Performance of structures in fire

ISO TR 24679-6:2017. Fire safety engineering – Performance of structures in fire – Part 6:
Example of an eight storey office concrete building. *International Organization for Standardization.*

Step 2: Identifying obectives, functional requirements and performance criteria

Objectives

Life safety (incl. fire-fighters)

Conservation of property

Continuity of operations

Functional requirement

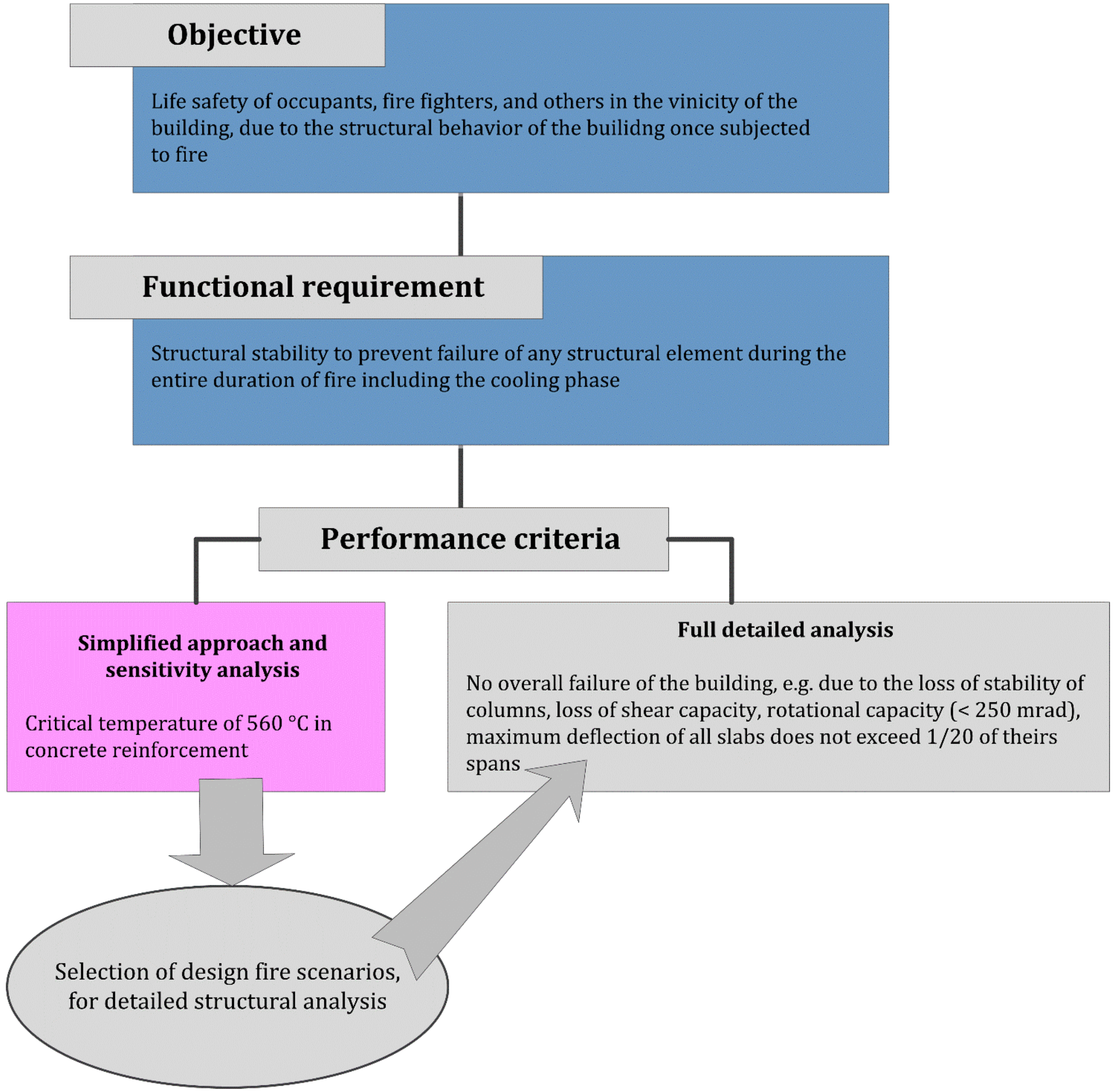
Structural stability for full fire duration, including cooling phase

Performance criteria

No loss of stability in advanced numerical analysis

Maximum slab deflection L/20

Rotation < 250 mrad



Objective

Life safety of occupants, fire fighters, and others in the vinicity of the building, due to the structural behavior of the builidng once subjected to fire

Functional requirement

Structural stability to prevent failure of any structural element during the entire duration of fire including the cooling phase

Performance criteria

Simplified approach and sensitivity analysis

Critical temperature of 560 °C in concrete reinforcement

Full detailed analysis

No overall failure of the building, e.g. due to the loss of stability of columns, loss of shear capacity, rotational capacity (< 250 mrad), maximum deflection of all slabs does not exceed 1/20 of theirs spans

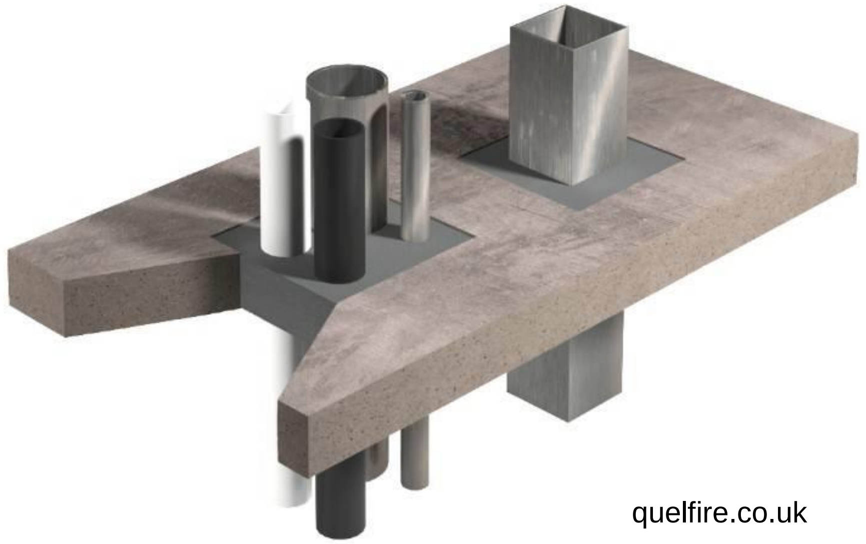
Selection of design fire scenarios, for detailed structural analysis

STRUCTURAL FIRE ENGINEERING FRAMEWORK

Structural fire engineering framework

ISO 24679-1:2017. Fire safety engineering – Performance of structures in fire

ISO TR 24679-6:2017. Fire safety engineering – Performance of structures in fire – Part 6:
Example of an eight storey office concrete building. *International Organization for Standardization.*


quelfire.co.uk

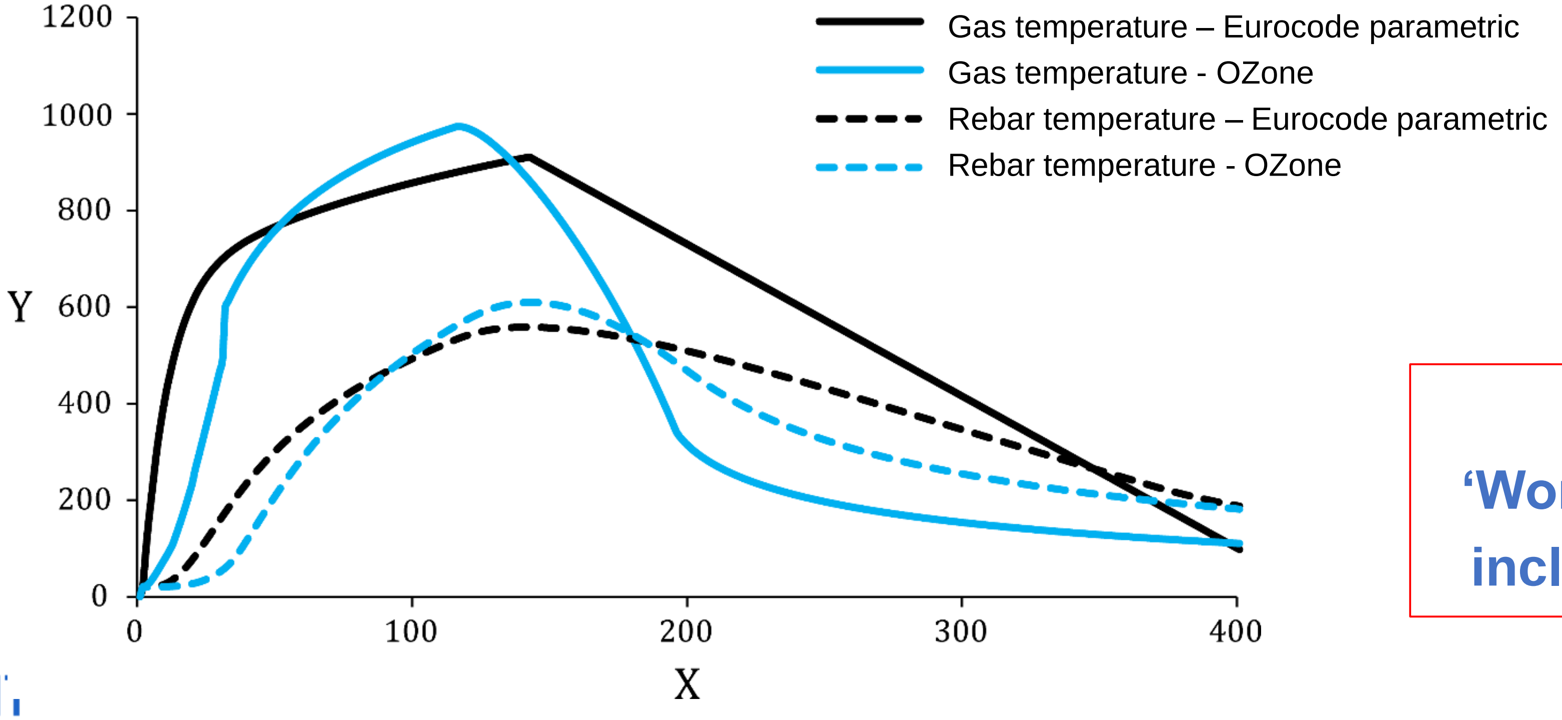
Step 3: Trial design plan

Eurocode reference building, with floor compartmentation

Step 4: Design fire scenarios and design fires

Eurocode parametric fire, design fire load 912 MJ/m^2; opening factor 0,02 m$^{1/2}$

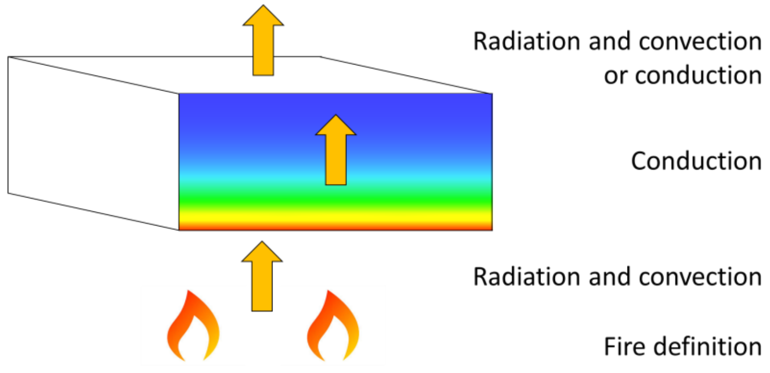
Heidari et al. (2018). *Fire Technology*, in press.

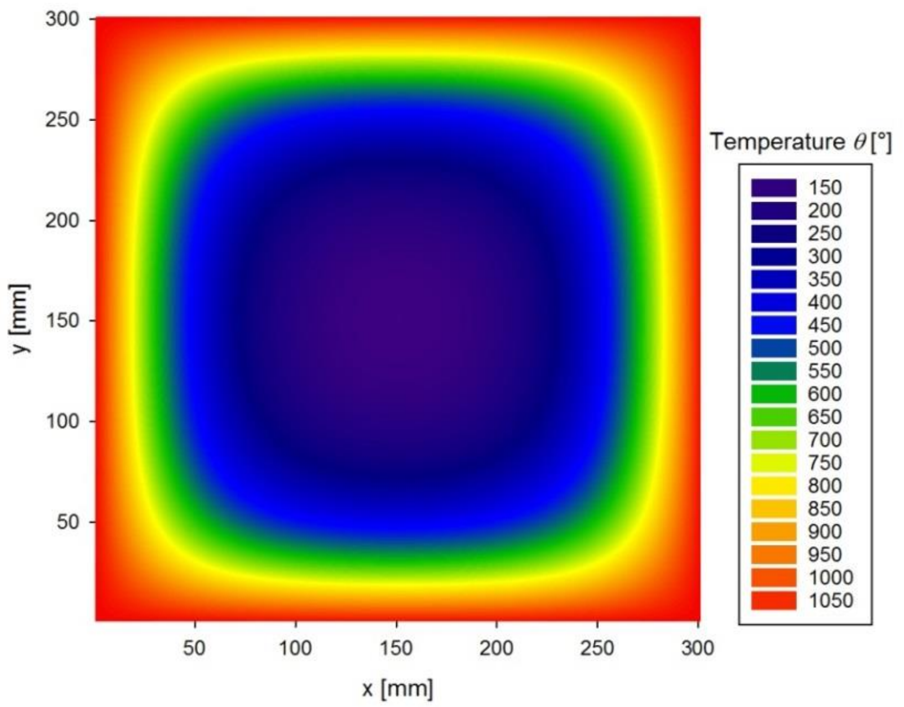


Step 5: Thermal response of the structure

SAFIR

Franssen, J. M., & Gernay, T. (2017). Modeling structures in fire with SAFIR®: theoretical background and capabilities. *Journal of Structural Fire Engineering*, *8*(3), 300-323.





Fire severity ~
'Worst credible' scenario
including cooling phase

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STRUCTURAL FIRE ENGINEERING FRAMEWORK

Structural fire engineering framework

ISO 24679-1:2017. Fire safety engineering – Performance of structures in fire

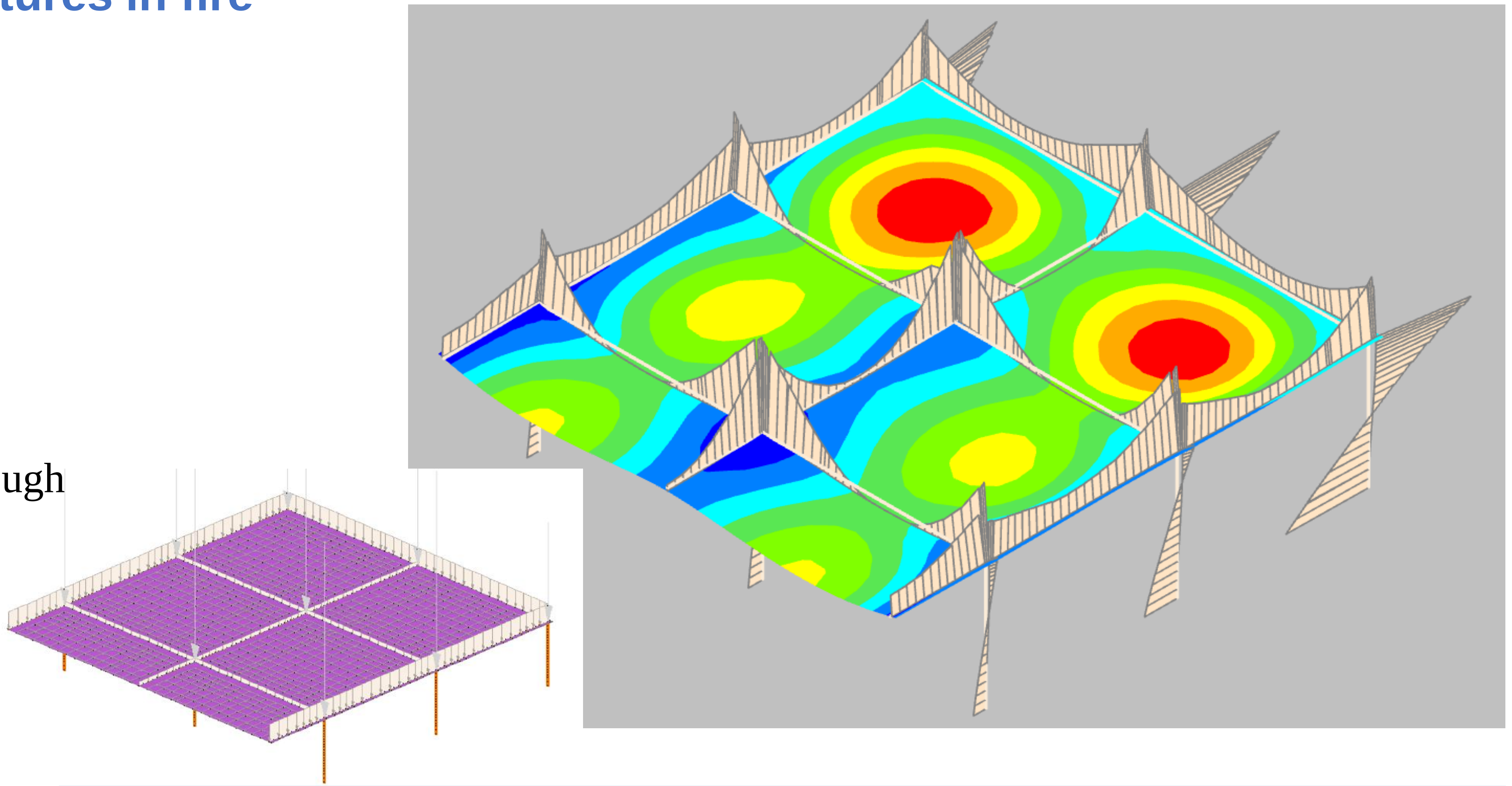
ISO TR 24679-6:2017. Fire safety engineering – Performance of structures in fire – Part 6: Example of an eight storey office concrete building. *International Organization for Standardization.*

Step 6: Mechanical response of the structure

SAFIR

Franssen, J. M., & Gernay, T. (2017). Modeling structures in fire with SAFIR®: theoretical background and capabilities. *Journal of Structural Fire Engineering*, *8*(3), 300-323.

(i) plane sections remain plane (Bernoulli hypothesis);
(ii) effects of non-uniform temperature distribution in the section considered through a fiber model;
(iii) shear energy of the plane sections ignored;
(iv) uniaxial constitutive models;
(v) large displacements are considered but strains are assumed small.



Sauca, et al. (2016). Analysis of a concrete building exposed to natural fire. *Applications of Structural Fire Engineering*.

Step 7: Assessment against the fire safety objectives

Structural stability up to full burnout confirmed

Maximum deflections do not exceed L/20

Rotation does not exceed 250 mrad

⇨

‘Burnout resistance’
confirmed for
‘worst credible scenario’

⇨

Step 8: Documentation of the design for fire safety of structures

Life safety (fire fighters)

Other floors unaffected
(strengthening required)
Conservation of property
Continuity of operations

More info vs prescriptive

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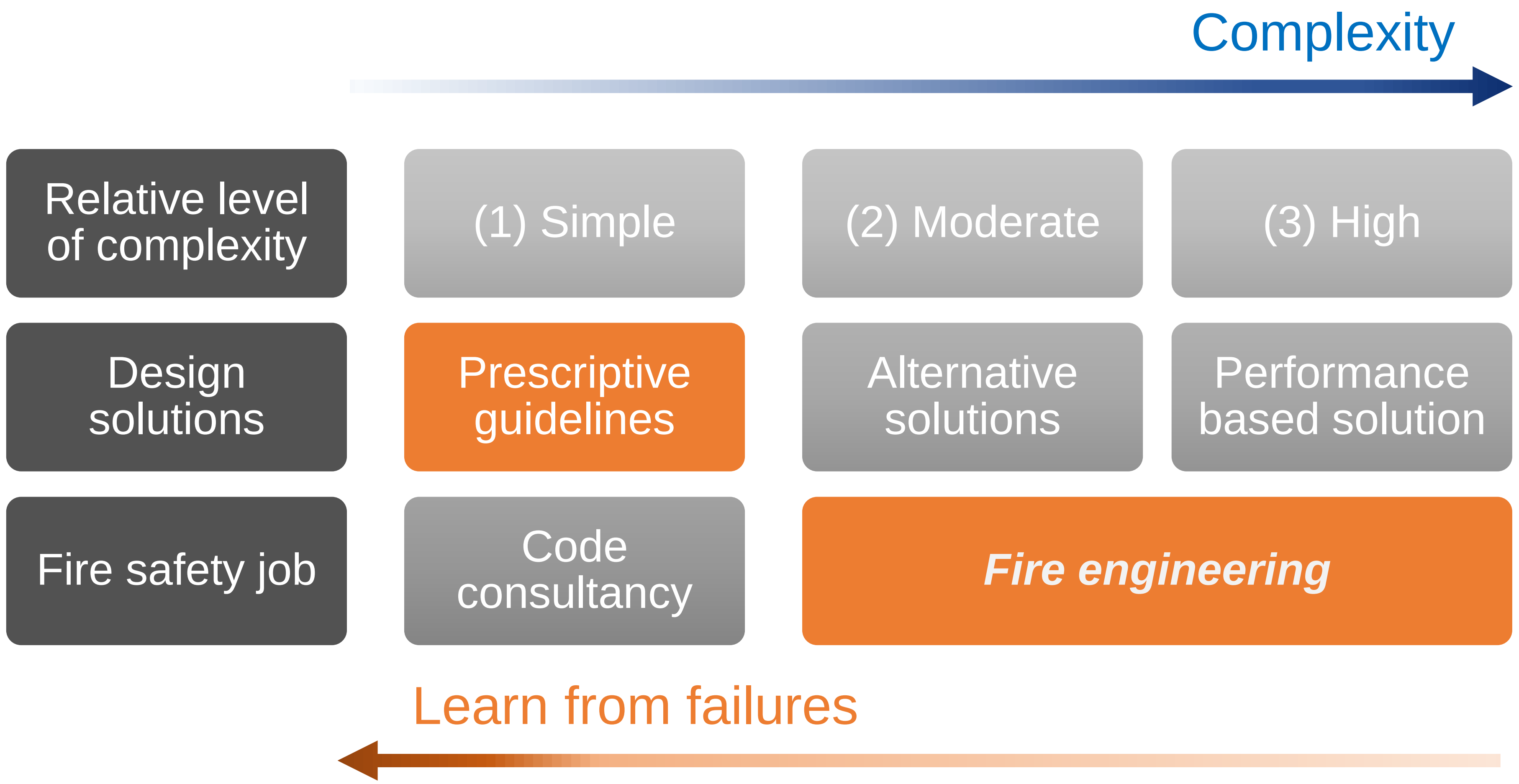
STRUCTURAL FIRE ENGINEERING FRAMEWORK



Complexity

Relative level of complexity	(1) Simple	(2) Moderate	(3) High
Design solutions	Prescriptive guidelines	Alternative solutions	Performance based solution
Fire safety job	Code consultancy	*Fire engineering*	

Learn from failures

Institution of Fire Engineers

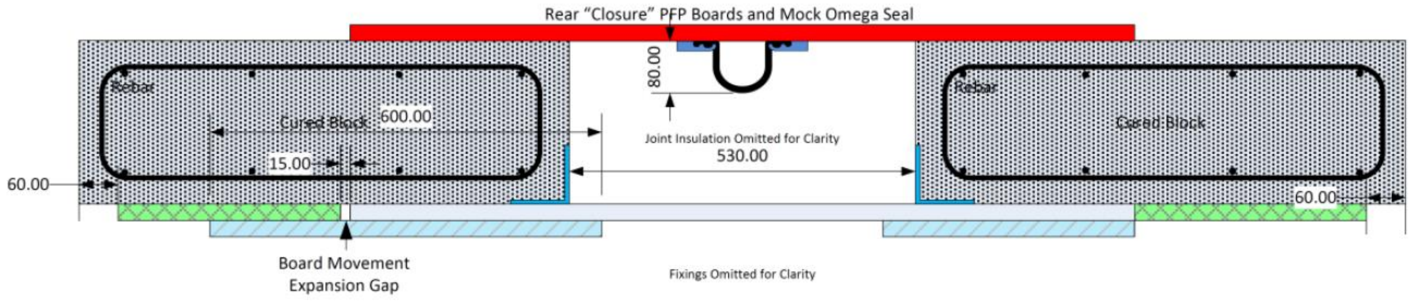
Fire engineering *is the*

application of scientific and engineering principles*,*

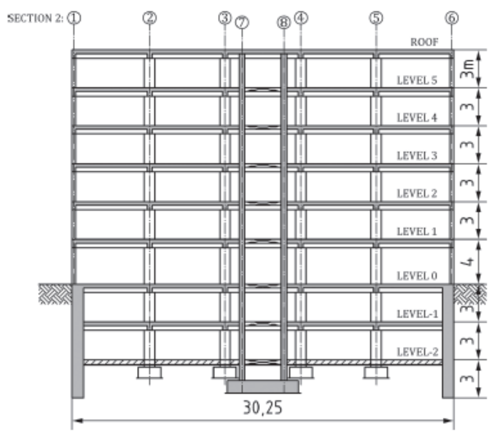
based on an understanding of the phenomena

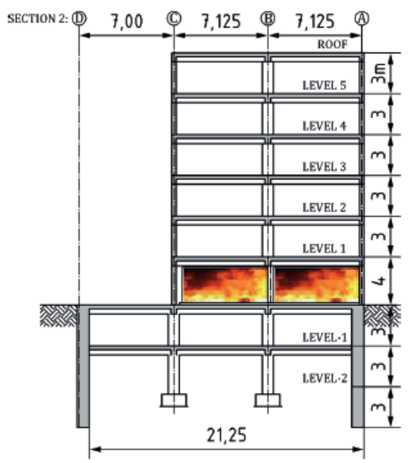
to protect people, property and the environment *from fire*

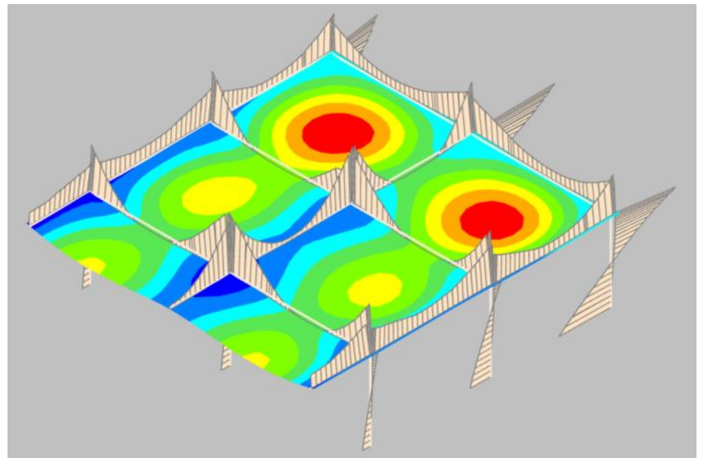
Design beyond prescriptive guidance



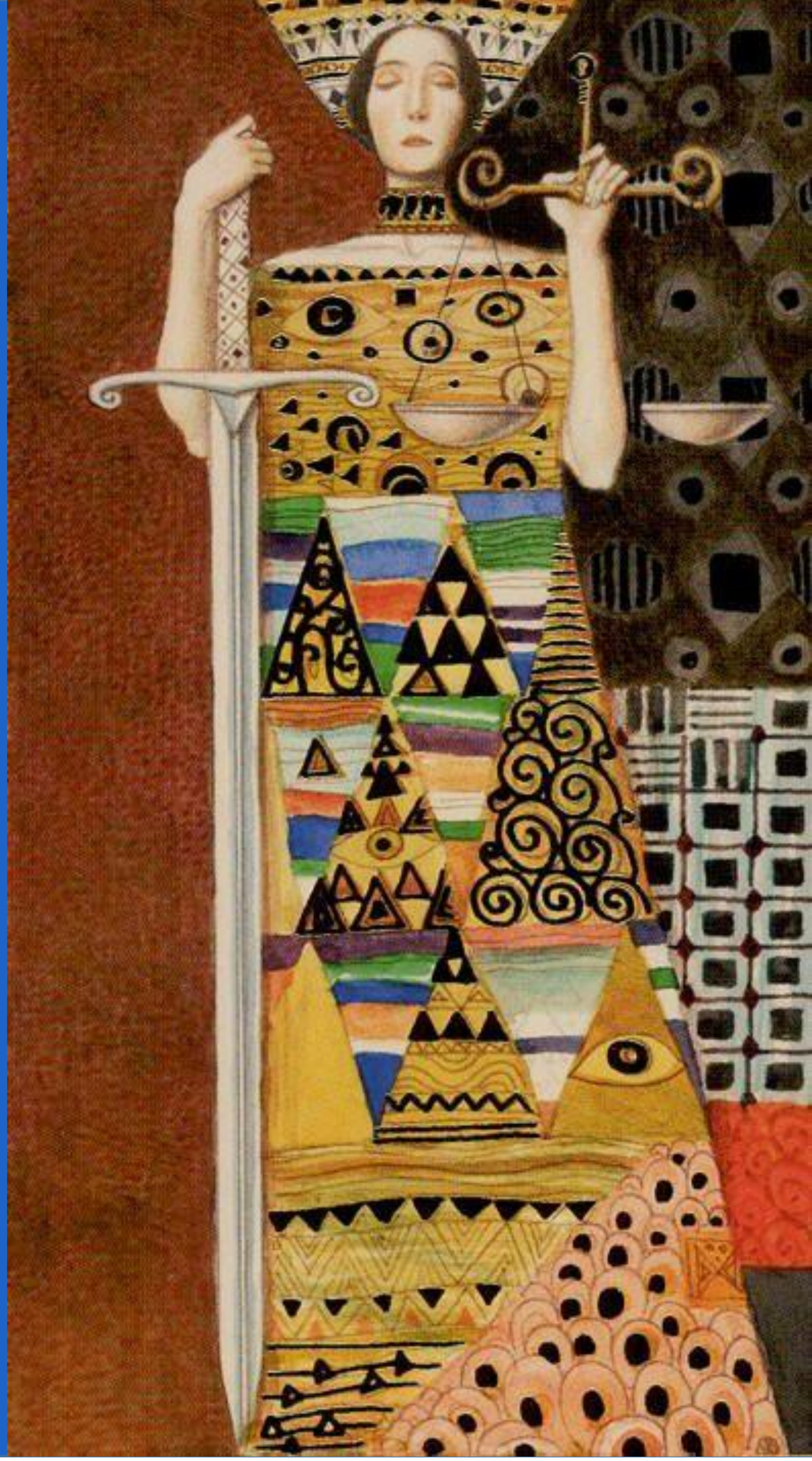
Clear target performance (vs prescriptive)







Structural fire engineering: risk and opportunities



RISK OF INAPPROPRIATE USE

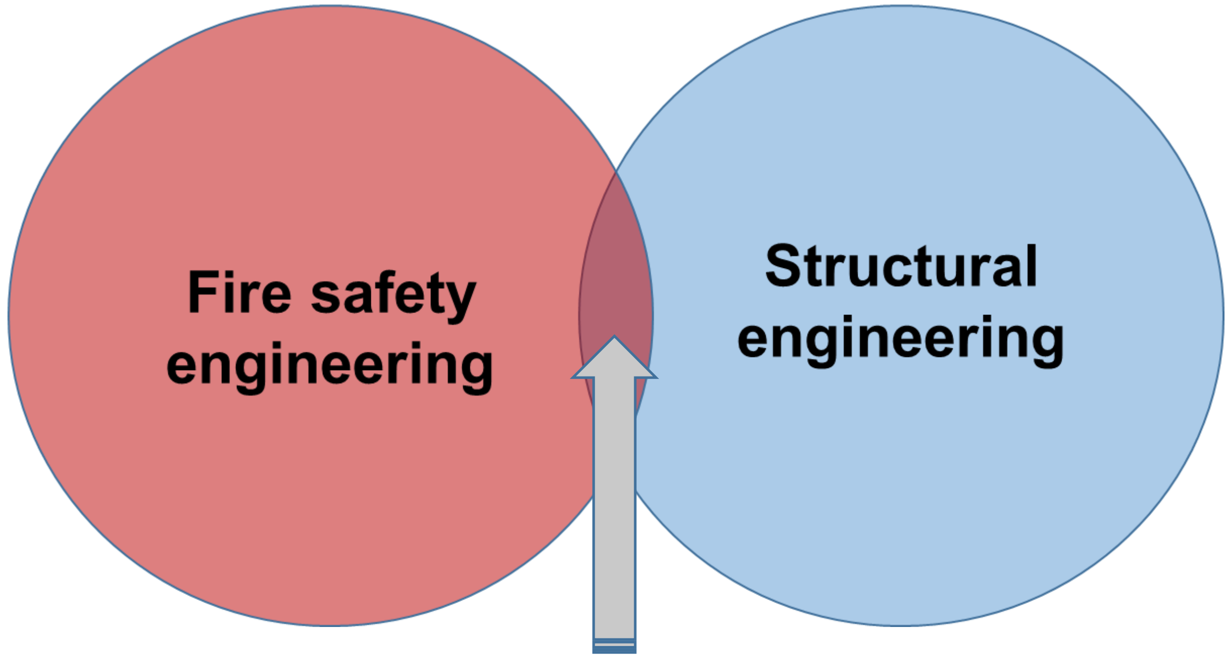
To assess relative to the fire safety goals / objectives

***Application scientific and engineering principles**,*

understanding of the phenomena

to protect people, property and the environment

Prof. G. Rein, Imperial College



Fire safety engineering

Structural engineering

Structural design for fire safety

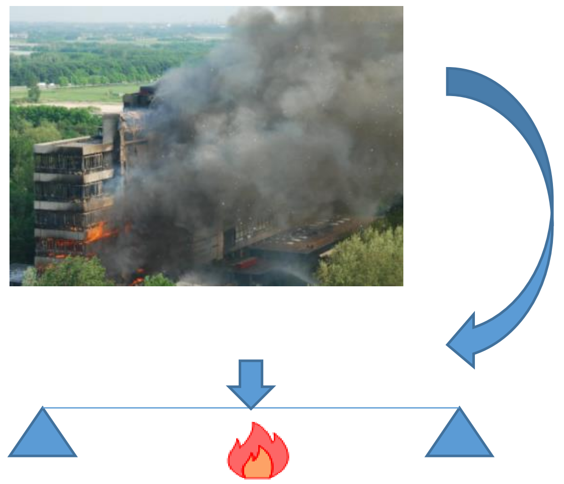
Hopkin, D. (2018). Guest lecture Ghent University.

Lame substitution of the 1st kind

Structural engineering replaced by pseudo-science

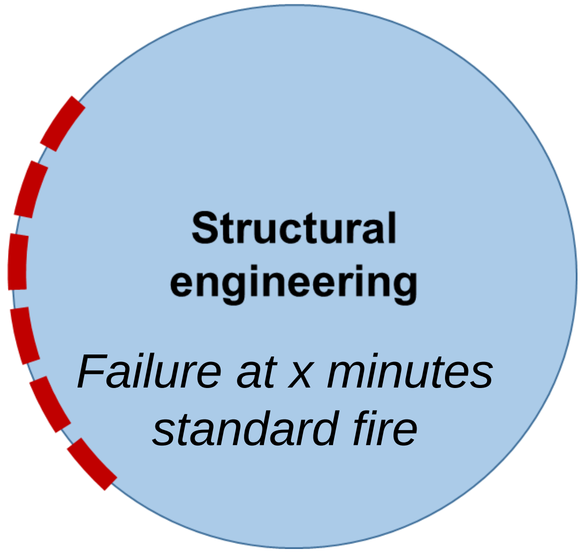
Fire safety engineering

Failure at x°C



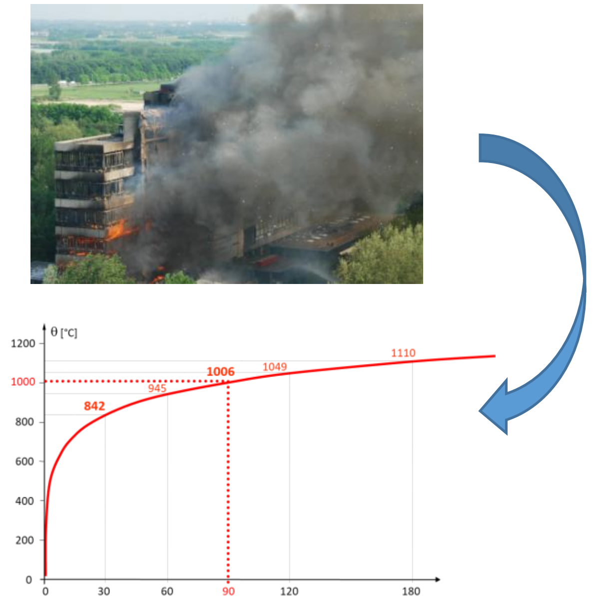
Lame substitution of the 2nd kind

Fire engineering replaced by pseudo-science



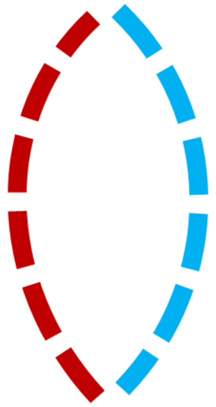
Structural engineering

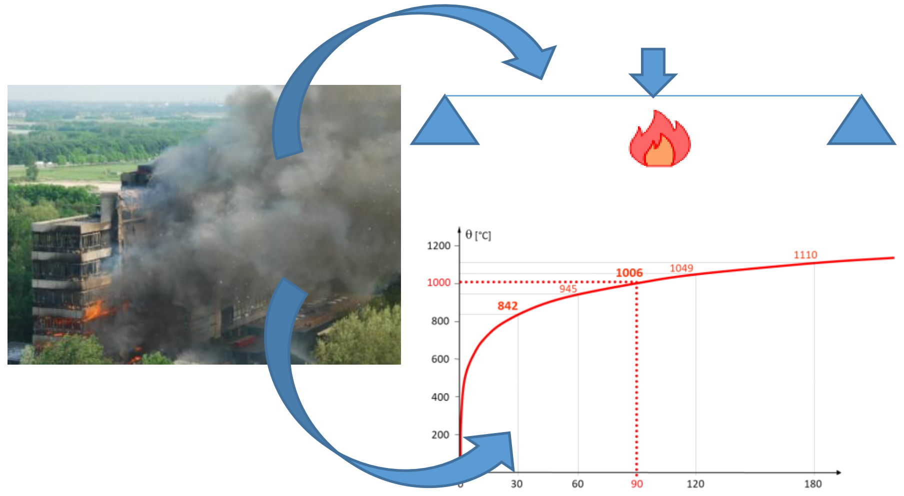
Failure at x minutes standard fire



Lame substitution of the 3rd kind

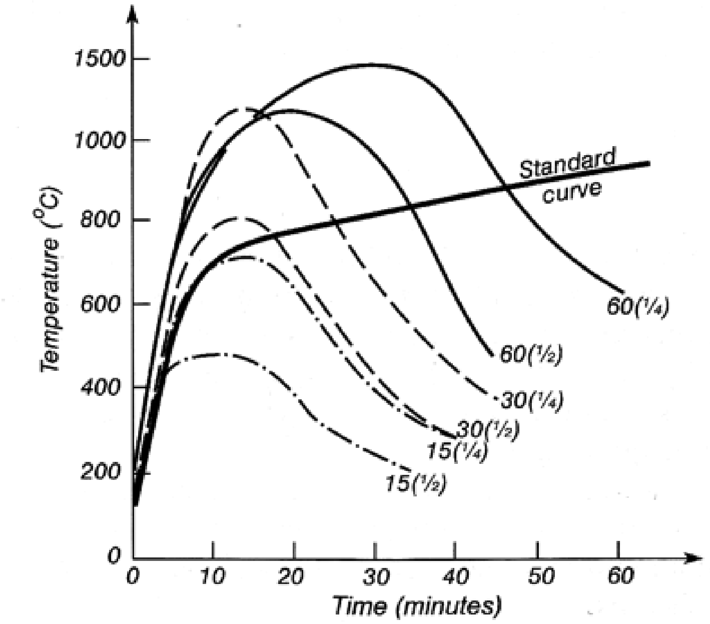
Both structural and fire engineering replaced by pseudo-science



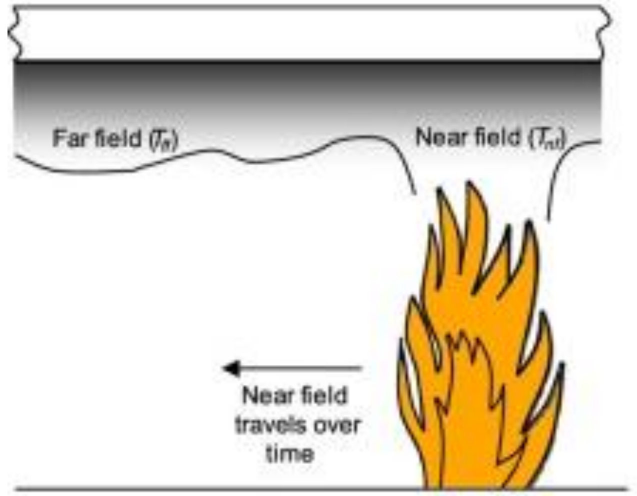


OPPORTUNITY – CLARIFYING FIRE SEVERITY (1)

Compartment fires don’t resemble the ISO curve…

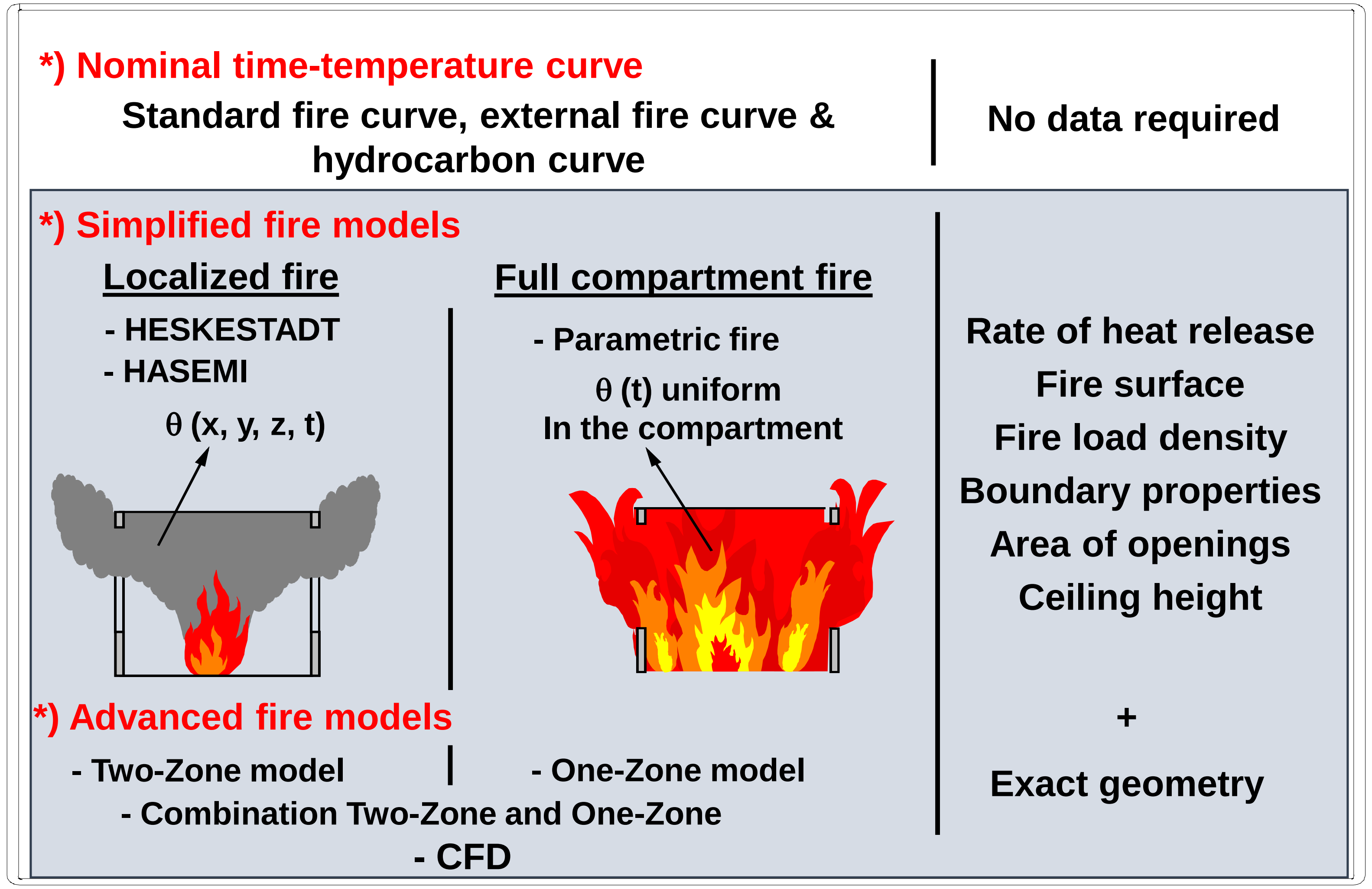


Buchanan, A. H., & Abu, A. K. (2017).
Structural design for fire safety. John Wiley & Sons.



Stern-Gottfried & Rein. (2012). *Fire Safety Journal*, *54*, 96-112.

Simplified and advanced fire models provide a better description



***) Nominal time-temperature curve**

Standard fire curve, external fire curve & hydrocarbon curve

No data required

***) Simplified fire models**

Localized fire

- **HESKESTADT**
- **HASEMI**

θ (x, y, z, t)

Full compartment fire

- **Parametric fire**

θ (t) uniform
In the compartment

Rate of heat release
Fire surface
Fire load density
Boundary properties
Area of openings
Ceiling height

+

Exact geometry

***) Advanced fire models**

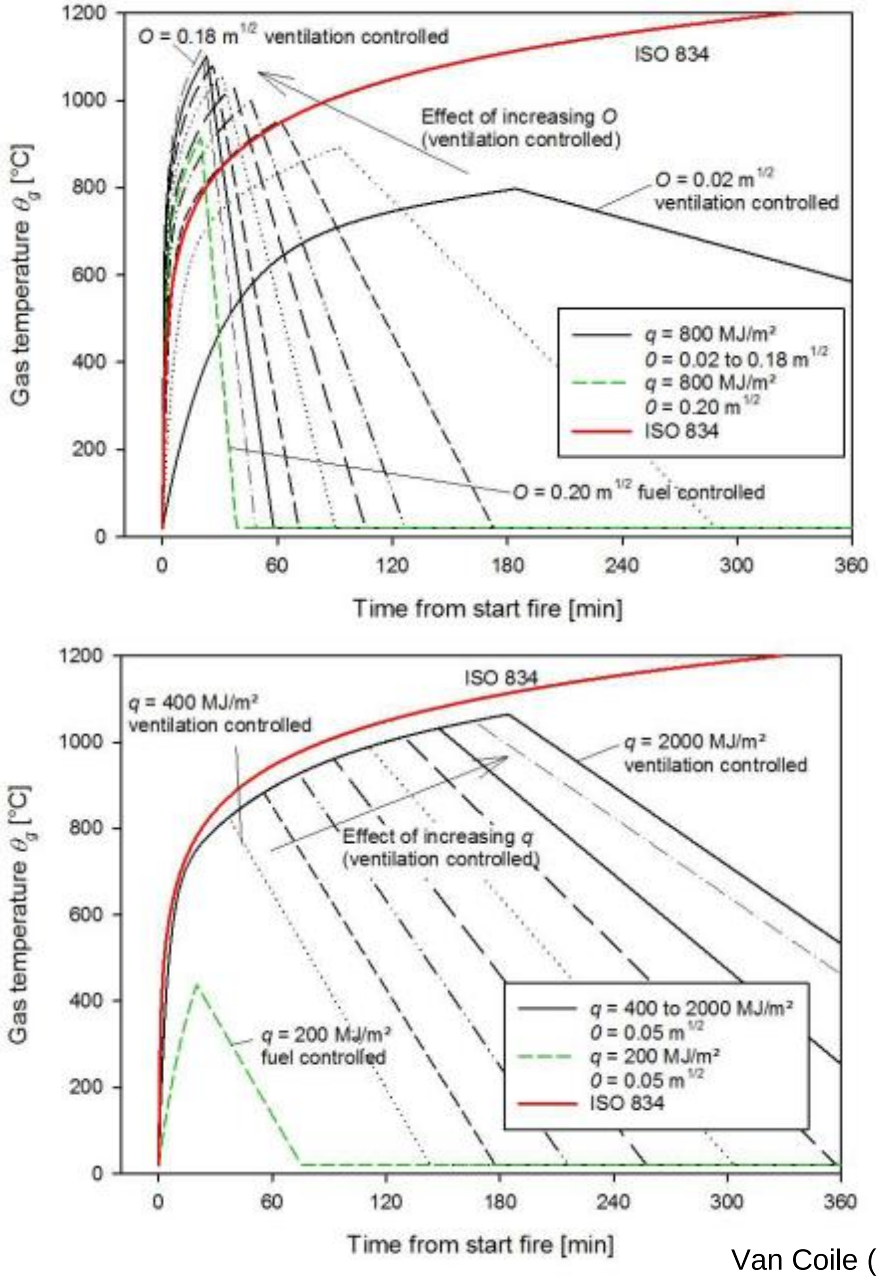
- **Two-Zone model**
- **One-Zone model**
- **Combination Two-Zone and One-Zone**
- **CFD**

DIFISEK (2009); Gernay, T. (2018). Lecture notes Structural Fire Engineering.

Ozone; SAFIR (trial version available)
https://www.uee.uliege.be

The Eurocode parametric fire is particularly popular

- Fire load q_F [MJ/m^2]
- Ventilation condition, *O* [m$^{1/2}$]



Van Coile (2015).

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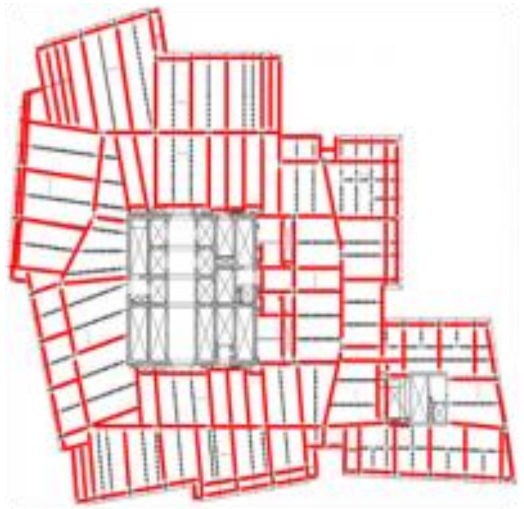
OPPORTUNITY – CLARIFYING FIRE SEVERITY (2)

…but the ISO curve isn't leaving (soon)

- Engineers use it to specify requirements
- Manufacturers to specify their products
- Legislators to set requirements



WSP. The Shard.

The Building Regulations 2000

Fire safety

APPROVED DOCUMENT

B

VOLUME 2 – BUILDINGS OTHER THAN DWELLINGHOUSES

B1 Means of warning and escape

B2 Internal fire spread (linings)

B3 Internal fire spread (structure)

B4 External fire spread

B5 Access and facilities for the fire service

Coming into effect April 2007

2006 edition

Approved Document B (UK)

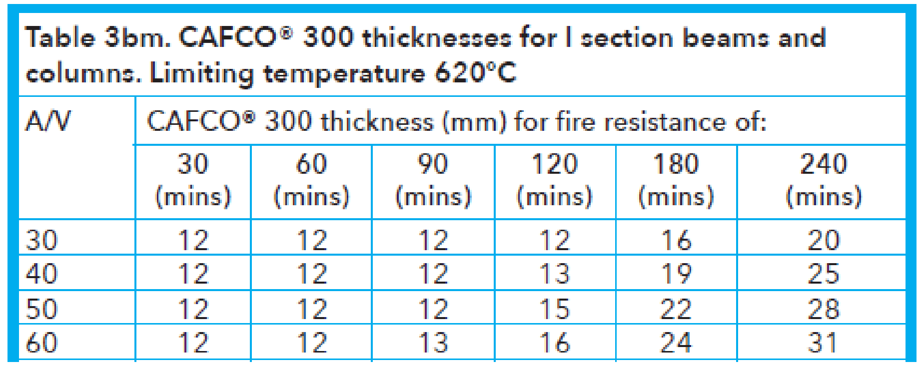


Table 3bm. CAFCO® 300 thicknesses for I section beams and columns. Limiting temperature 620°C

A/V	CAFCO® 300 thickness (mm) for fire resistance of:					
	30 (mins)	60 (mins)	90 (mins)	120 (mins)	180 (mins)	240 (mins)
30	12	12	12	12	16	20
40	12	12	12	13	19	25
50	12	12	12	15	22	28
60	12	12	13	16	24	31

PROMAT. The passive fire protection handbook.

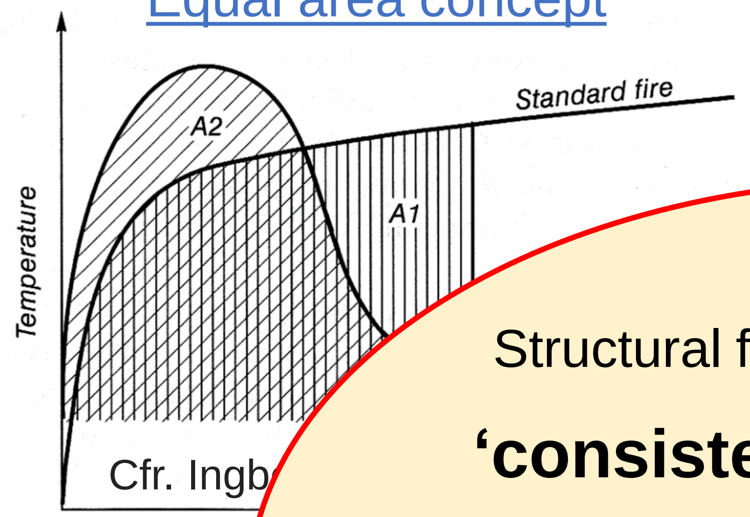
Equivalent standard fire duration

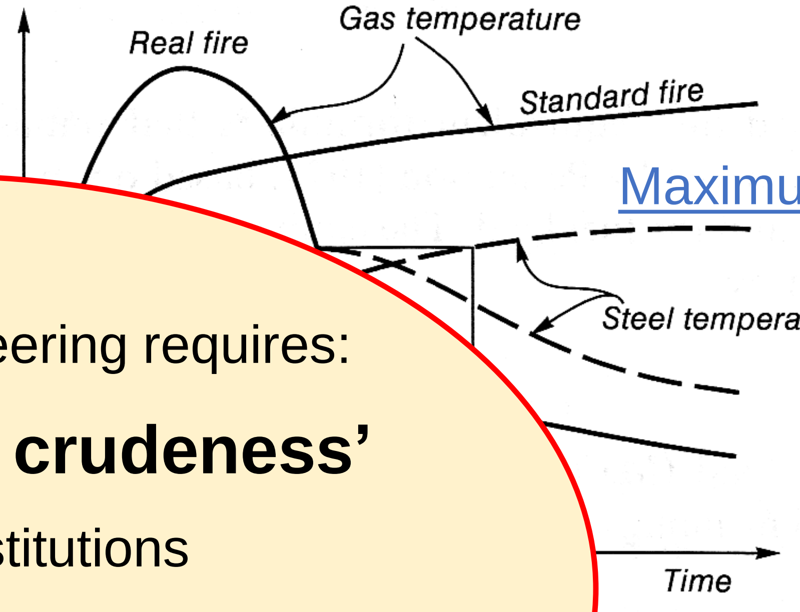
Caution advised: Law, M. (1997). A review of formulae for T-equivalent. *Fire Safety Science*, *5*, 985-996.

"t-equivalent is not a useful parameter for design purposes"

Margaret Law

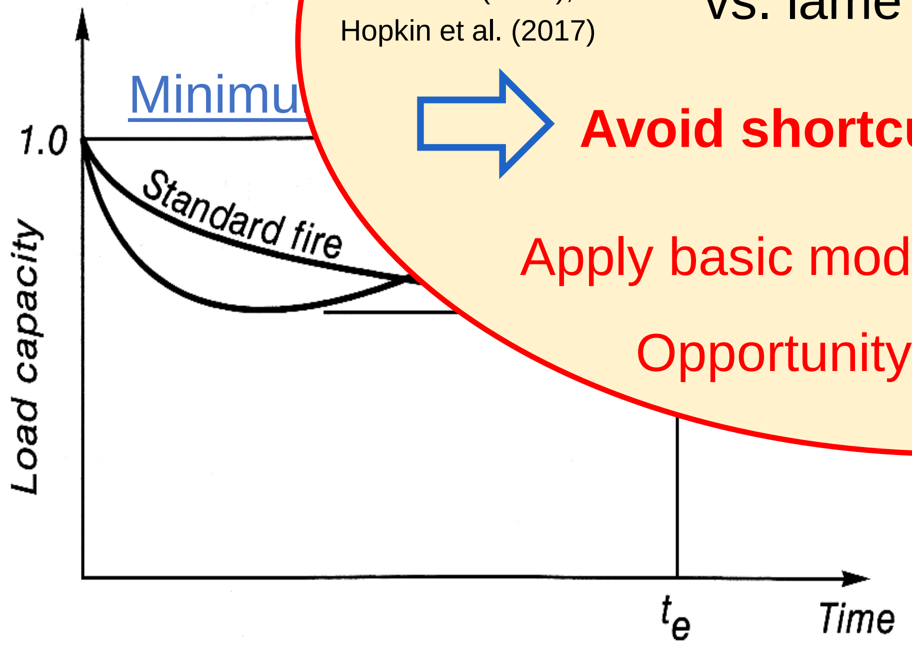
Equal area concept





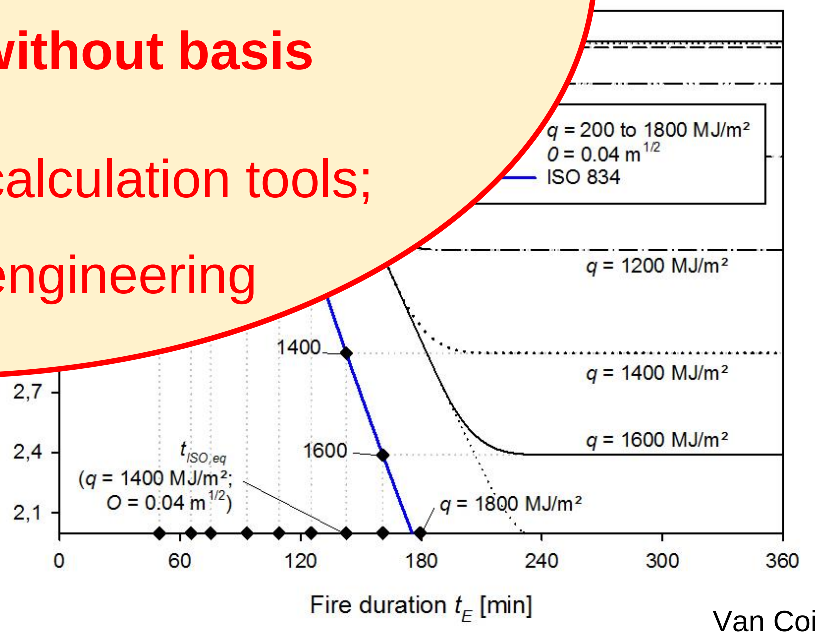
Maximum temperature concept

Minimu



Bisby, L. (2016). Lecture notes Structural Design for Fire

Equal safety concept



Van Coile et al. (2015)

Structural fire engineering requires:

'consistency of crudeness'

vs. lame substitutions

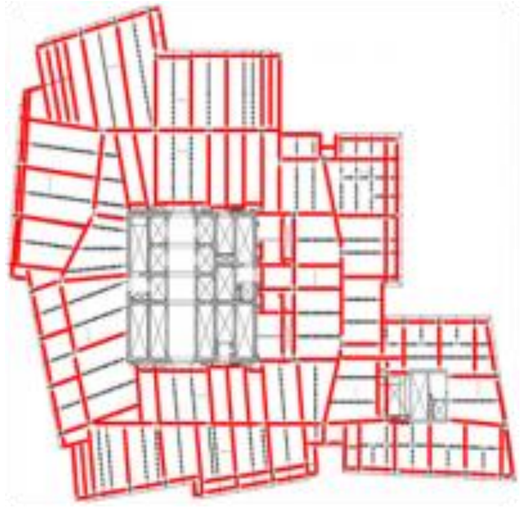
Buchanan (2008);
Hopkin et al. (2017)

Avoid shortcuts without basis

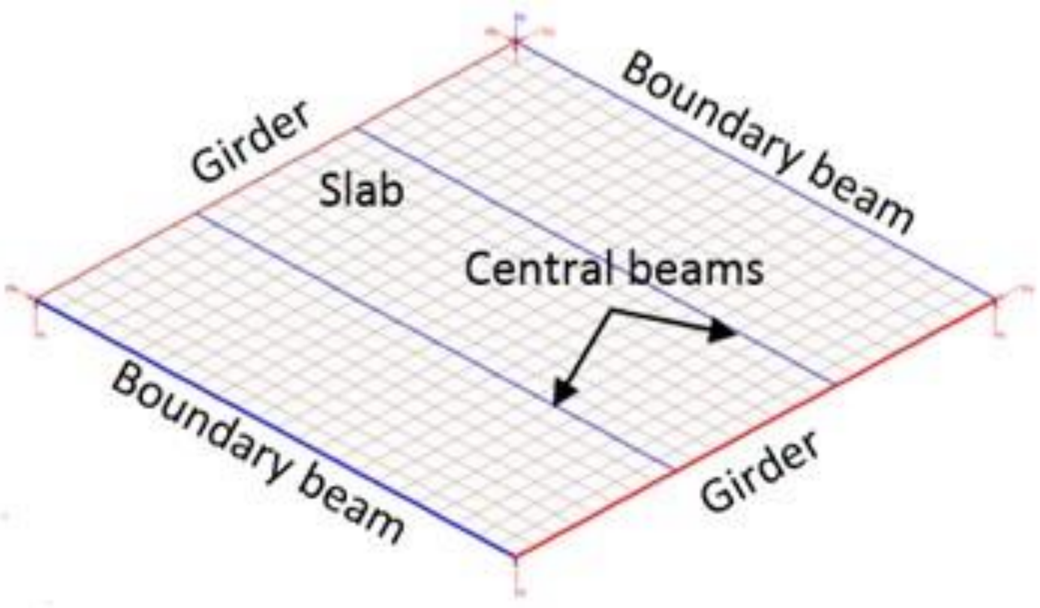
Apply basic modern calculation tools;

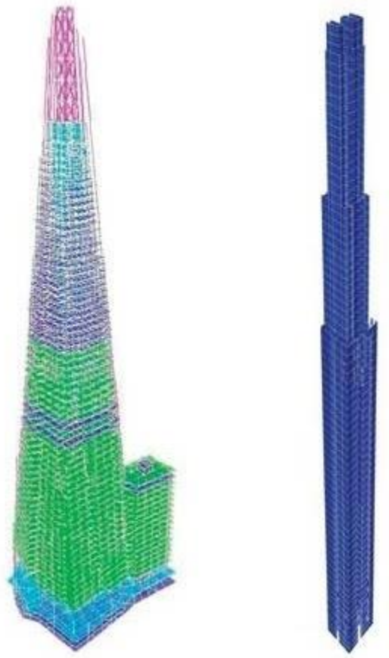
Opportunity for engineering

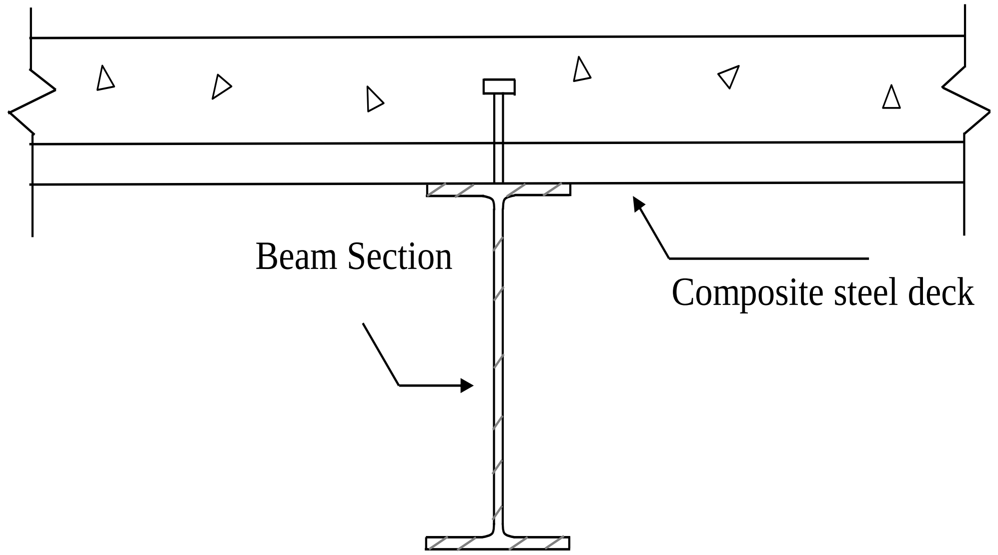
OPPORTUNITY – COST MINIMIZATION



WSP. The Shard.

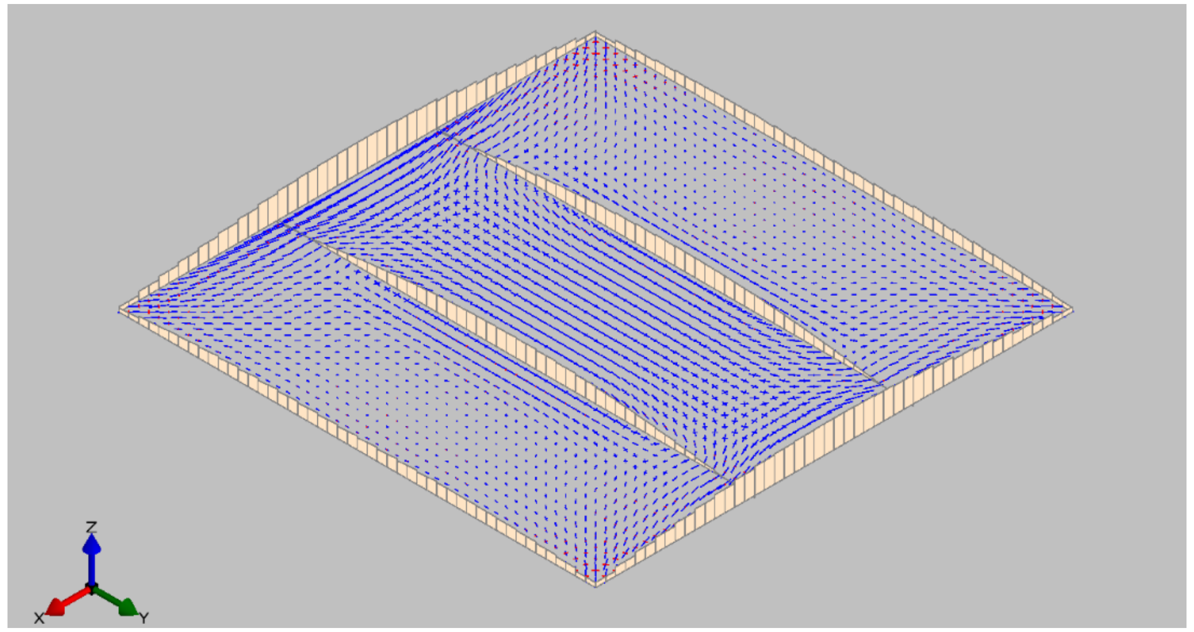




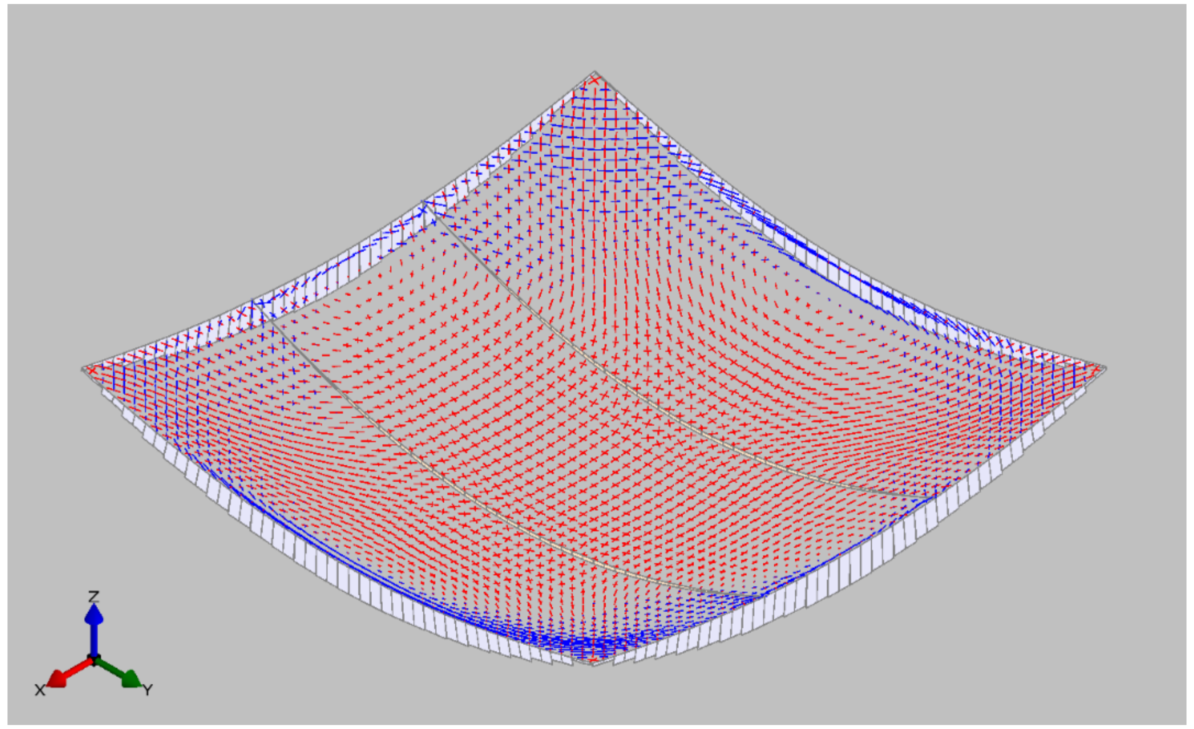


Elhami Khorasani, et al. (2017). Comparative fire analysis of steel-concrete composite buildings designed following performance-based and US prescriptive approaches. *Proceedings of ASFE 2017*, 07-08/09, Manchester, UK, pp. 131-140.

Normal design situation

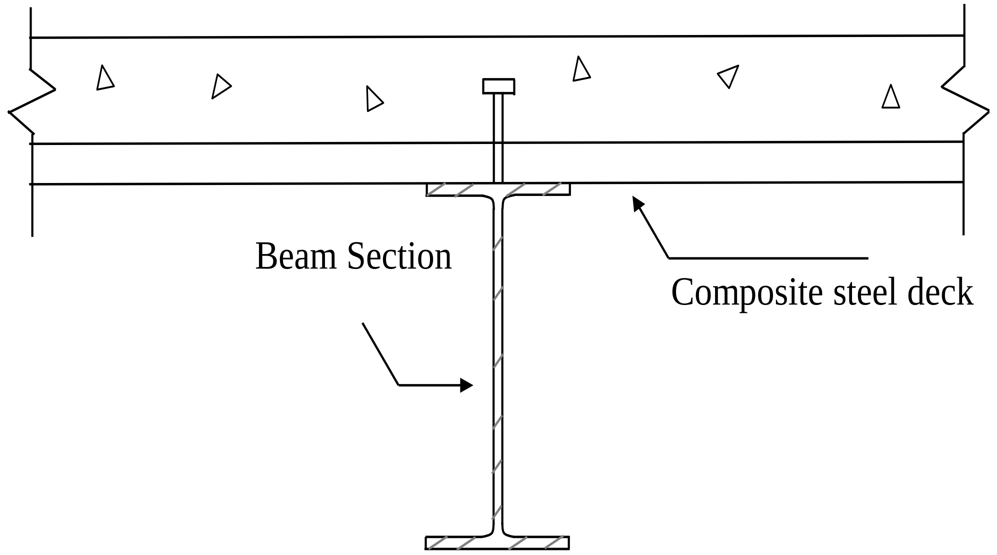


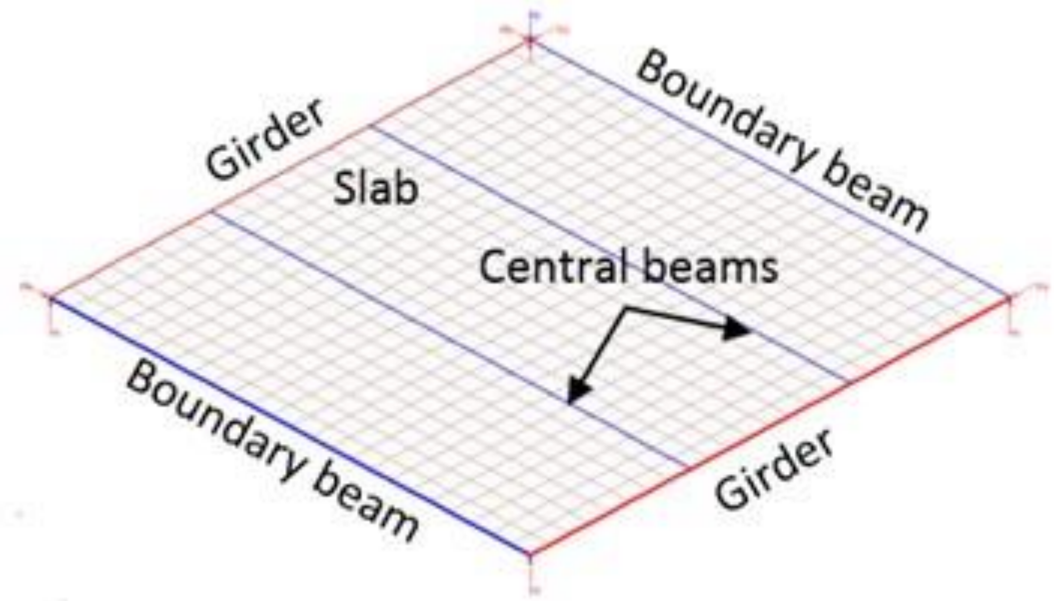
Fire design situation



ISO 24679-1:2017 framework: ***what is the objective?***

OPPORTUNITY – COST MINIMIZATION





Elhami Khorasani, et al. (2017). *Proceedings of ASFE 2017*, 07-08/09, Manchester, UK, pp. 131-140.

- Stability (and compartmentation) maintained including cooling phase;
- Large permanent deformations

OPPORTUNITY – COST OPTIMIZATION (1)

Lifetime cost:

$$\boxed{Y = C + A + D_M + D_L + D_R}$$

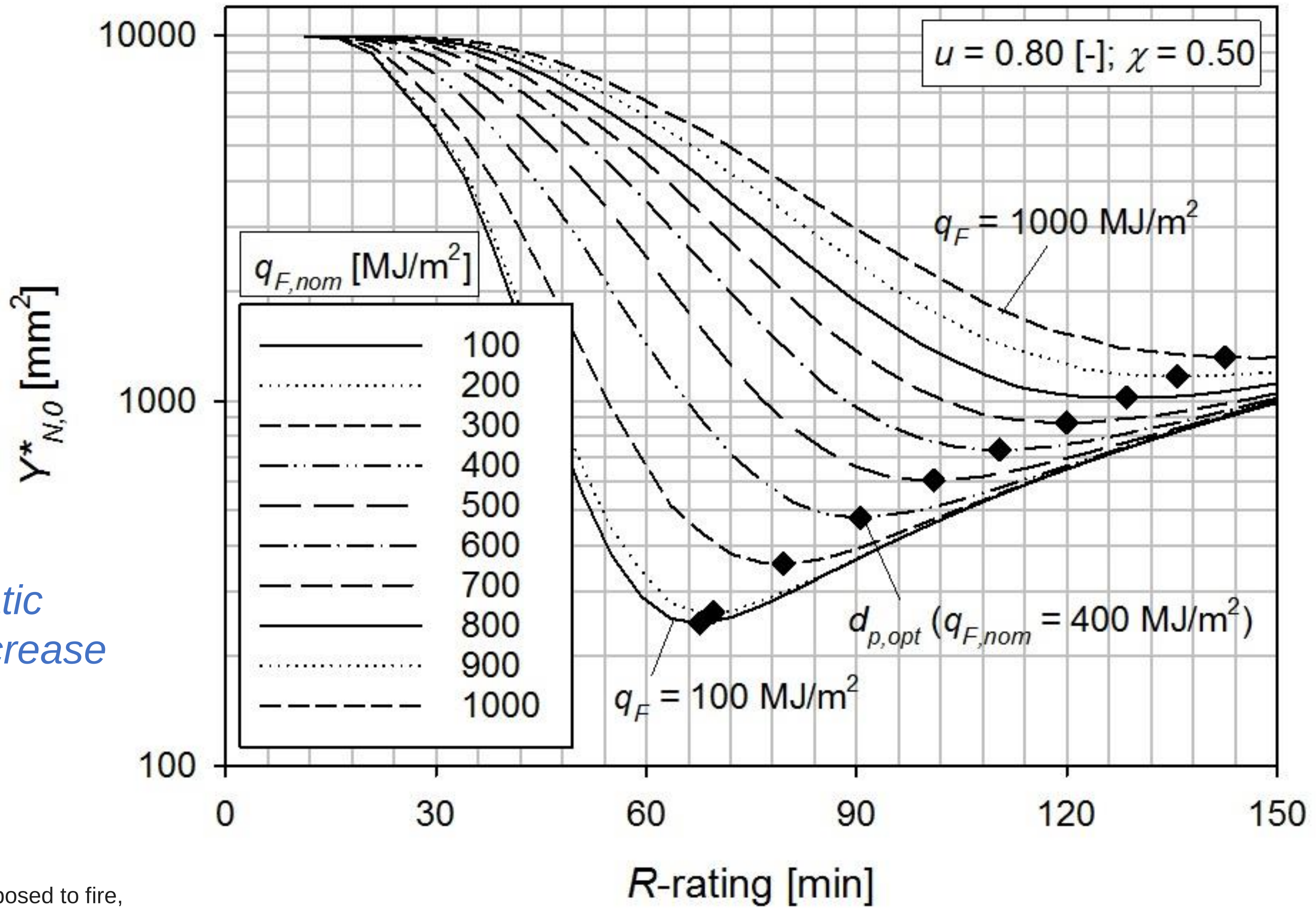
Travelling fire / parametric fire ifo room conditions

Symbol	*Description*
Y	Lifetime cost
C	Total building construction and maintenance cost
A	Obsolescence cost
D_M	Fire-induced material damages
D_L	Fire-induced loss to human life and limb
D_R	Reconstruction cost after fire-induced failure

Cost of fire protection

Fire rating	*Cost* [GBP/m^2]	*Indicative thickness* d_p [mm]*	*Eq. Cost* [GBP/m^2]
30 min	5-8	5	6.0
60 min	8-12	12	10.8
90 min	18-20	19	19.4
120 min	30-35	25	30.0

Quadratic cost increase



Van Coile, R., & Hopkin, D. (2018). Target safety levels for insulated steel beams exposed to fire, based on Lifetime Cost Optimisation. *Proceedings of IALCCE 2018*. Taylor & Francis Group.

OPPORTUNITY – COST OPTIMIZATION (2)

London office building

Description & reference	*Value*	*Units*
Number of occupied storeys	5	[-]
Building height	< 30	[m]
Ignition rate per floor (BSI, 2003)	$6 \cdot 10^{-3}$	[y^{-1}]
Probability of ignition resulting in a fully developed fire (EC, 2002)	0.9	[-]
Nominal fire load density (CEN, 2002b)	400	[MJ/m^2]
Building cost (Turner & Townsend, 2016)	2,700	[£/m^2]
Structural grid	7.5x7.5	[m x m]
Ambient utilisation (u)	0.55	[-]
Load ration (χ)	0.42	[-]
Fire utilisation (u_{fi})	0.31	[-]
Relative total material failure cost (ξ_M), (Kanda and Shah, 1997)	7.0	[-]

ξ_M = 1.4 per floor; all floors affected by failure

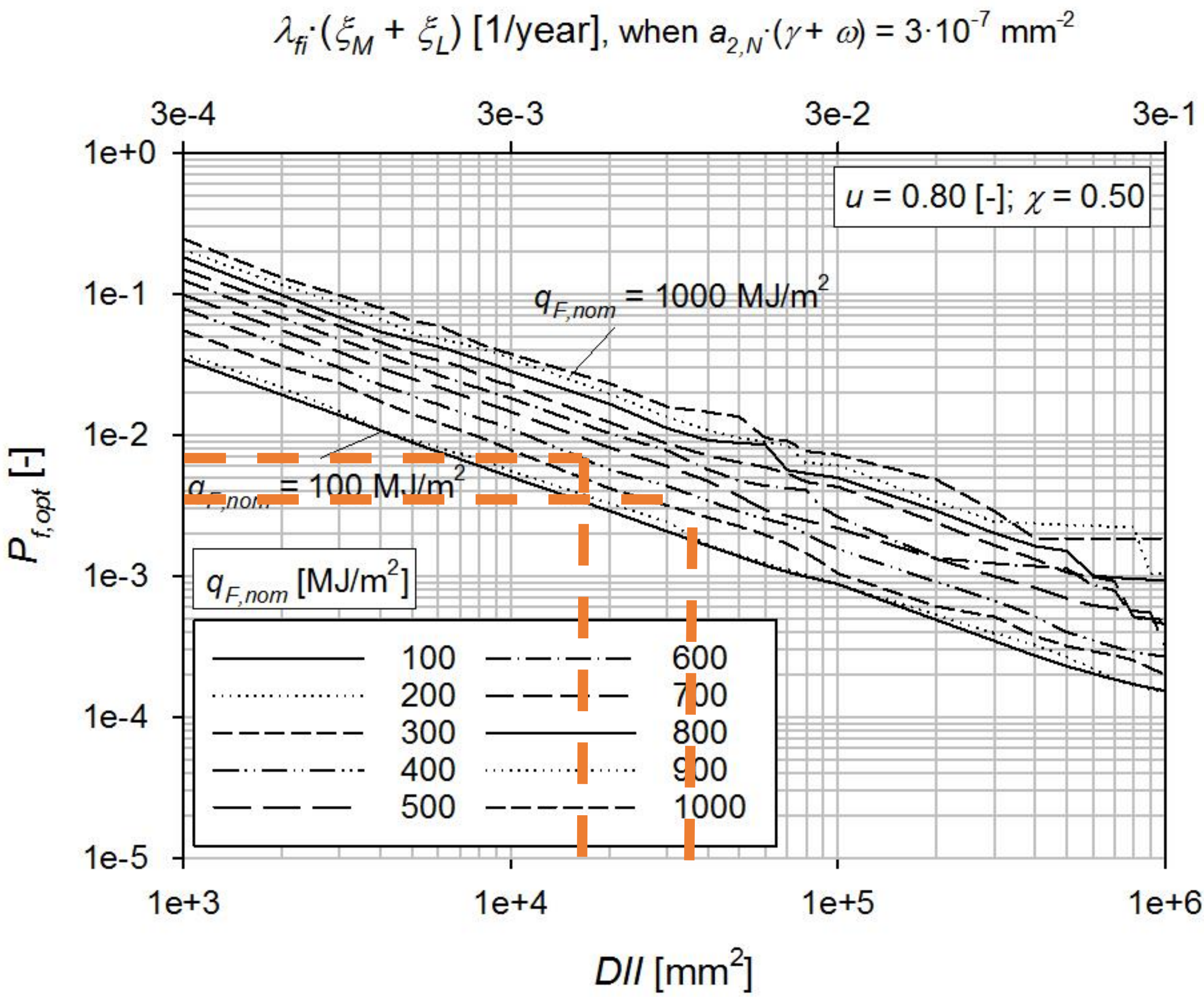
ξ_L = 0 – 9.6 (average of 0 – 10 casualties)

$\gamma = \omega = 0.02$ $a_{2,N} = 7.5\ 10^{-6}\ \text{mm}^{-2}$

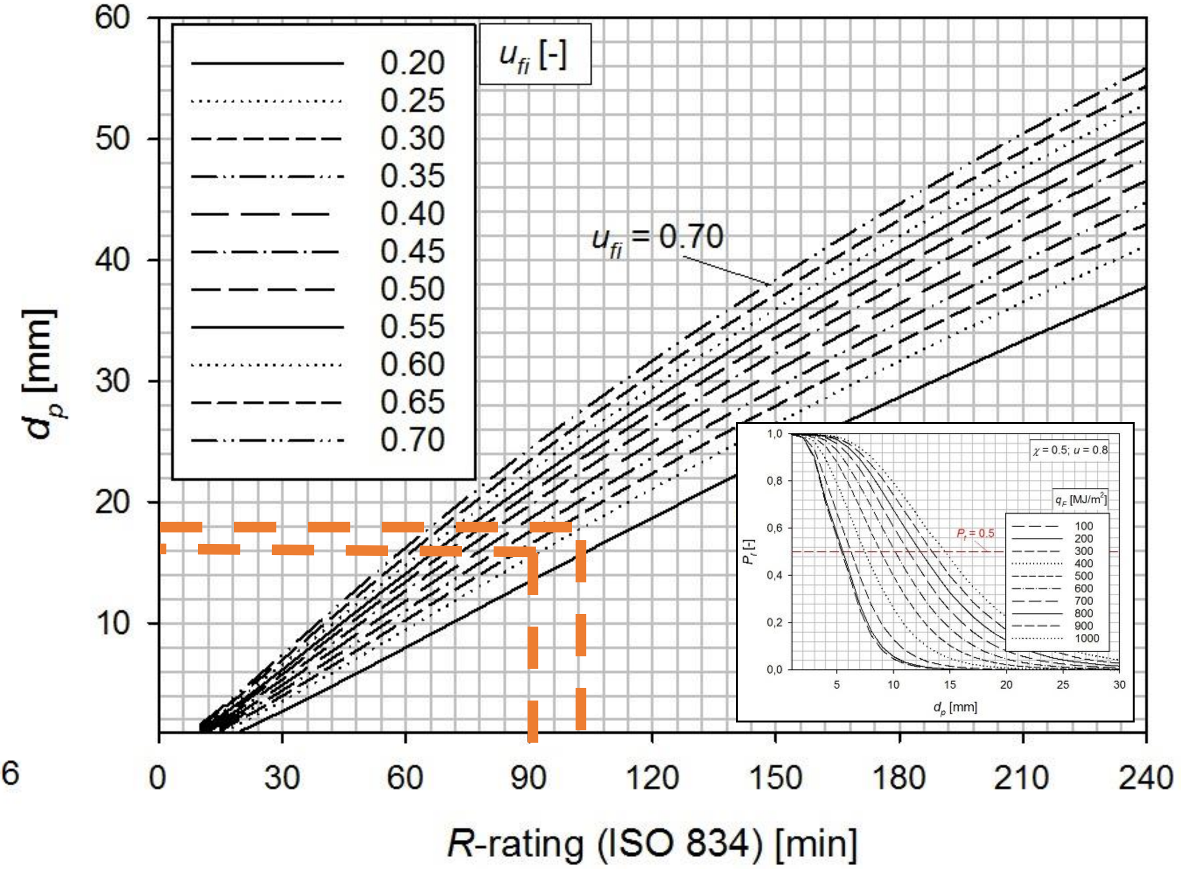
$DII = 1.4\ 10^4\ \text{mm}^2 – 3.3\ 10^4\ \text{mm}^2$

ratio of structural fire damage to investment cost intumescent paint per [mm]²

Optimum failure probability i.f.o. *DII*



P_f i.f.o. protection thickness
Relationship thickness – *R*-rating



Optimum fire-rating R_{opt} = 90 – 100 min

(slightly above UK prescriptive guidance; no practical influence ξ_L)

- Optimized *R*-specifications for high level projects
- Benchmarking prescriptive guidance

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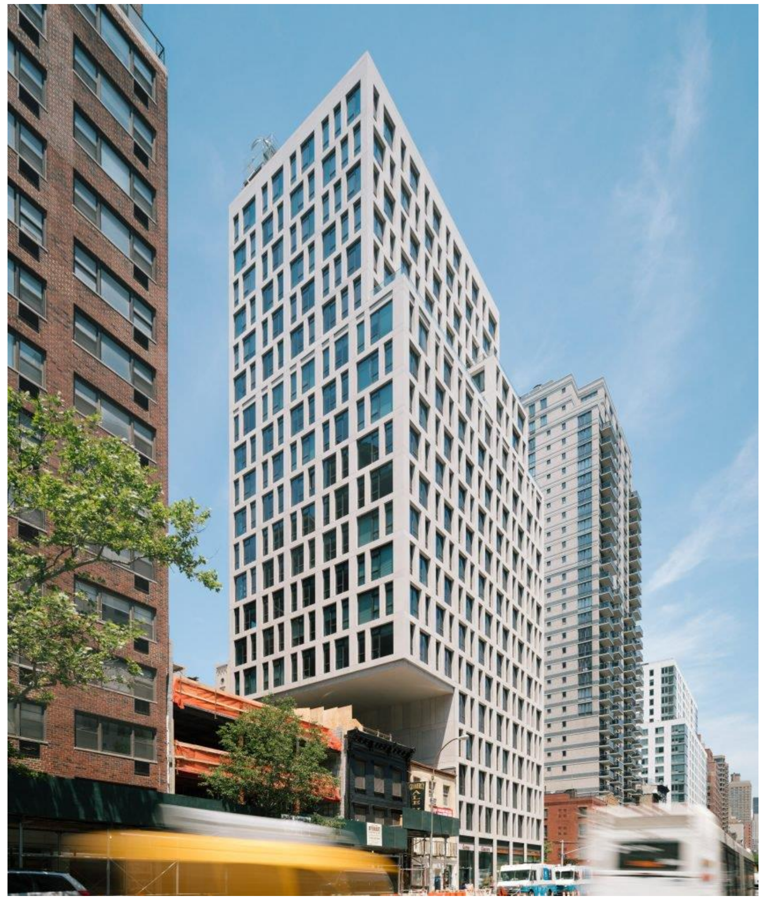
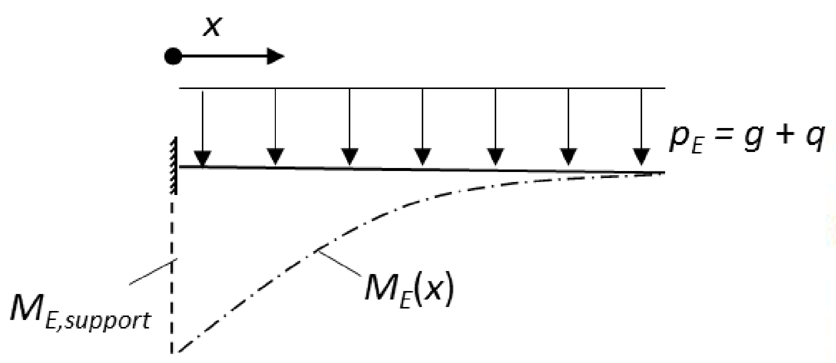
OPPORTUNITY – IMPROVED PERFORMANCE

Exclusive apartments London



Cantilever slab



Length l of the cantilever as decision variable

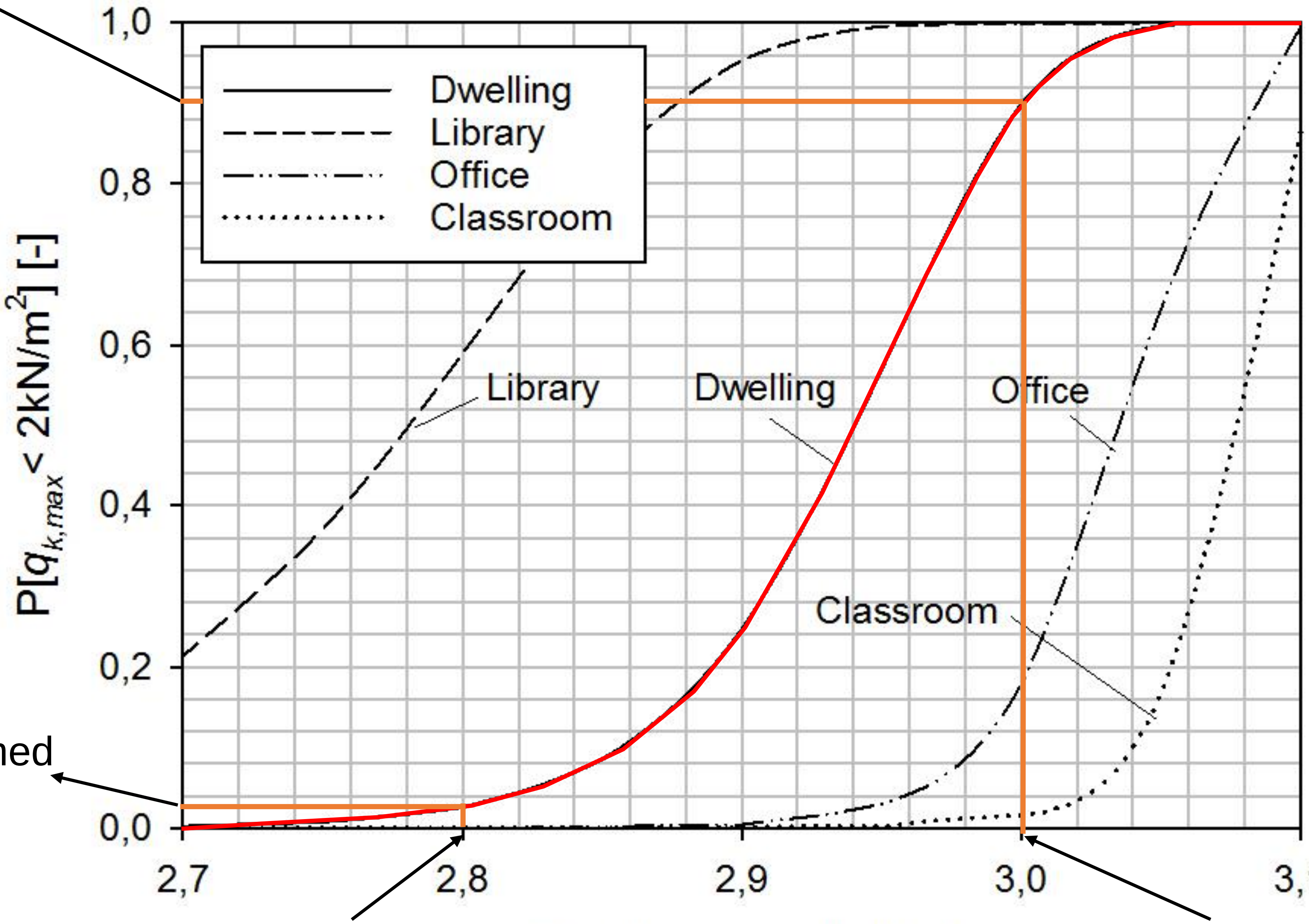
Resilience requirement:

Fire in compartment below may not affect usability (safety) of compartment above

⇨ $q_{k,req}$ = 2 kN/m^2 post-fire

Fragility curves for $q_{k,req}$ = 2kN/m^2

Initial probability of not achieving requirement



P_f for informed design

Informed design for post-fire use

Cantilever length l [m]

Initial prescriptive design

Van Coile, et al. (2017). Design for post-fire use: a case study in fire resilience design. *Proceedings of CONFAB 2014.*

In conclusion:

Fire engineering

application of scientific and engineering principles,

based on an understanding of the phenomena

to protect people, property and the environment *from fire*

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Thank you

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