DTU Civil Engineering
Department of Civil Engineering

Co-funded by the
Erasmus+ Programme
of the European Union

K-FORCE

SPECIAL MOBILITY STRAND

STRUCTURAL FIRE SAFETY DESIGN:
challenges and shortcomings

Luisa Giuliani
Novi Sad, 6th April 2020

Luisa Giuliani

Associate Professor
Civil Engineering Department
Technical University of Denmark

The European Commission support for the production of this publication does not constitute an endorsement of the contents which reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

OUTLINE

- *Recent major fires*
- *Design shortcomings*
  - *Design fires*
  - *Structural design*
  - *Design process*
- *Conclusive remarks*

Co-funded by the
Erasmus+ Programme
of the European Union

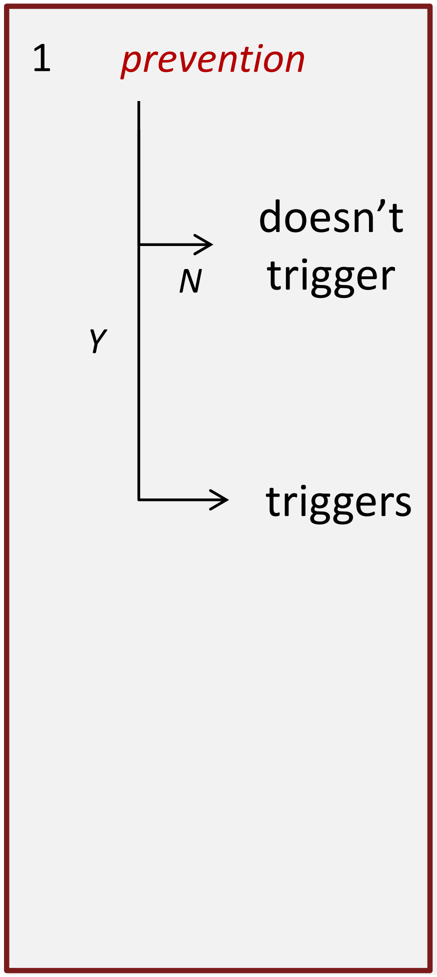
OUTLINE

Recent major fires

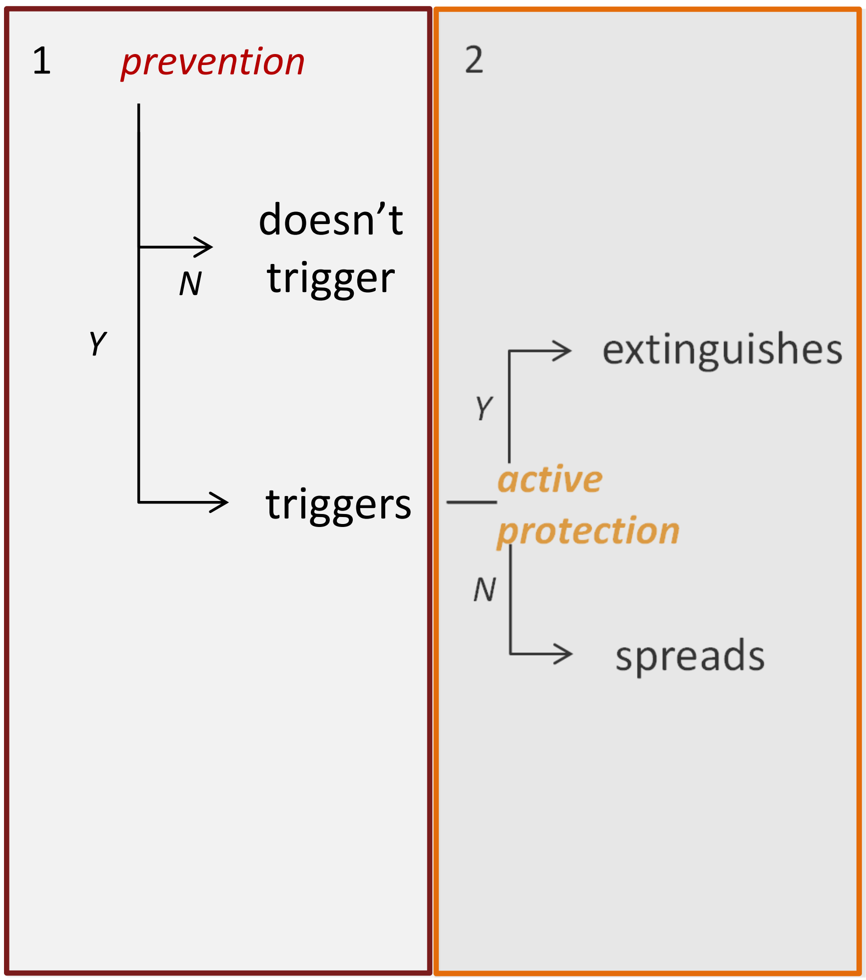
DTU Civil Engineering
Department of Civil Engineering

Co-funded by the
Erasmus+ Programme
of the European Union

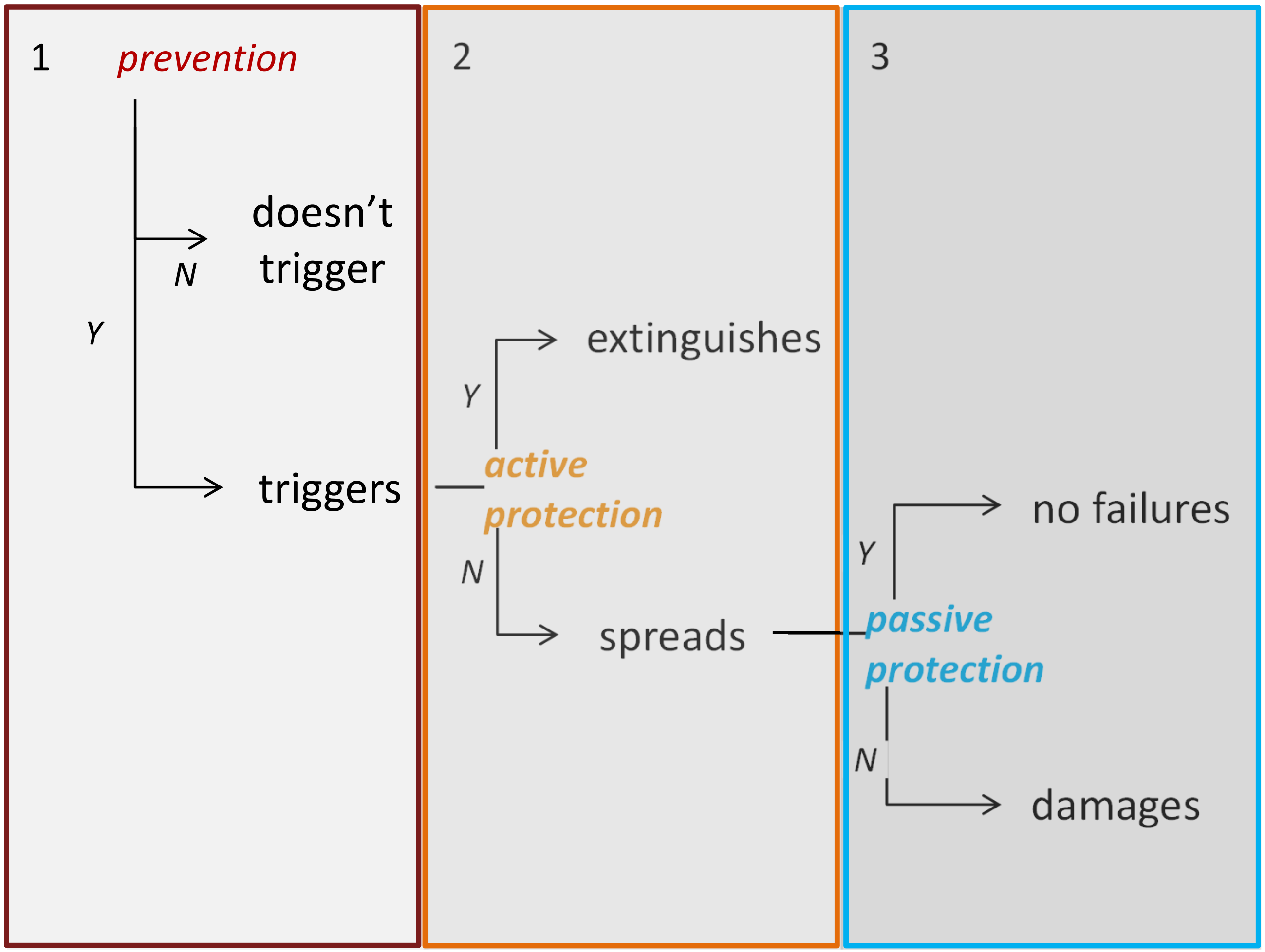
Fire Safety Strategy



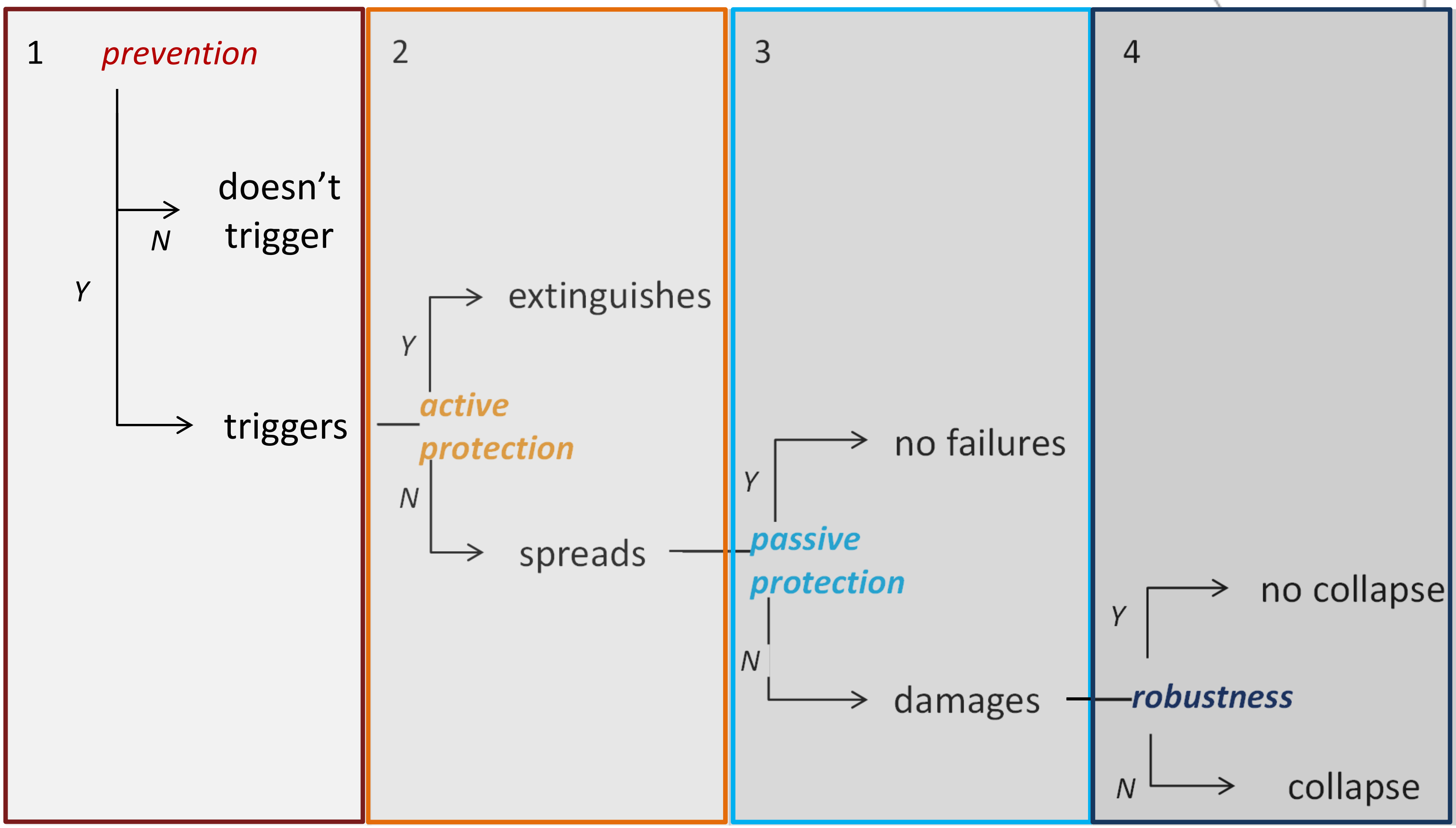
Fire Safety Strategy



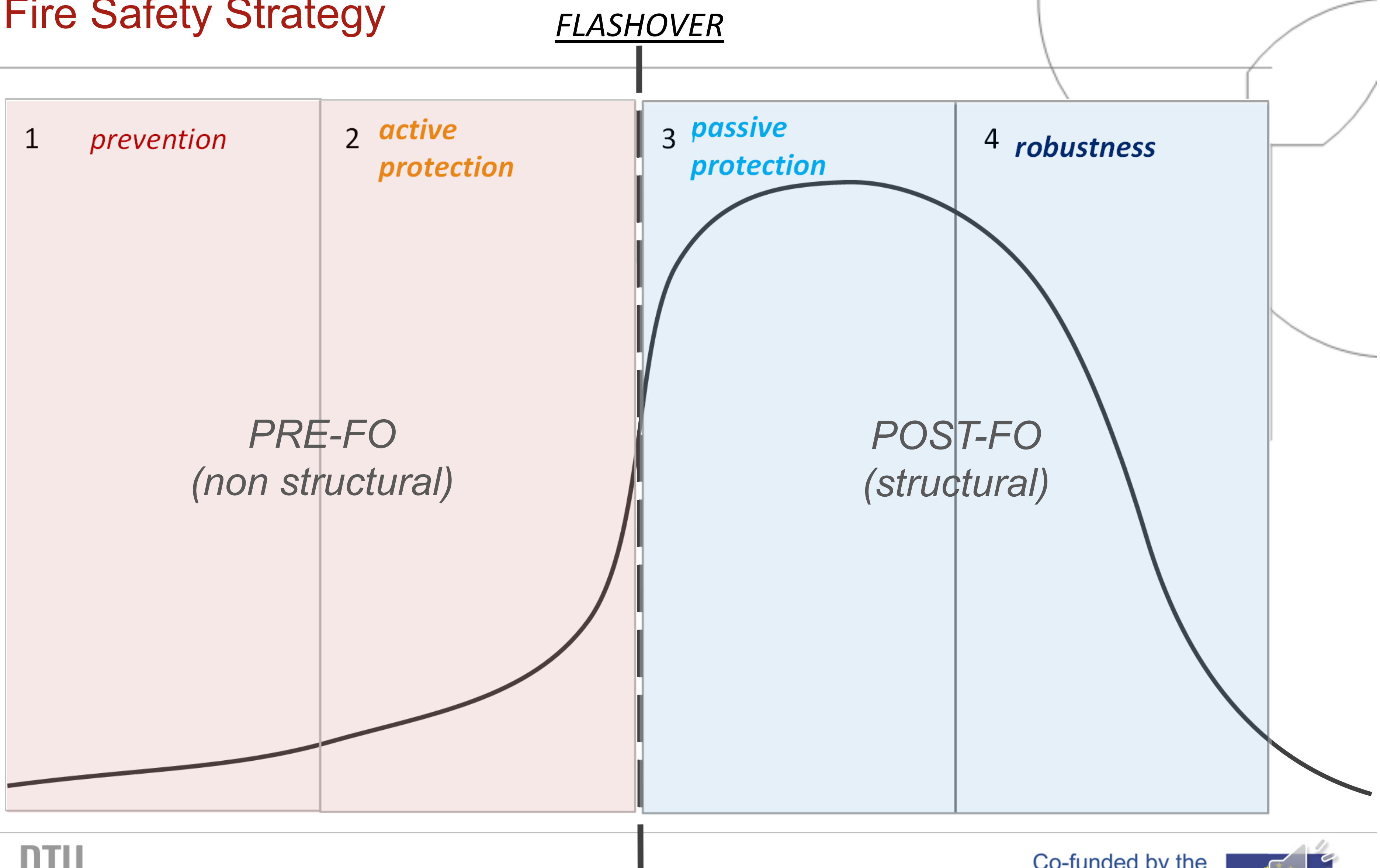
Fire Safety Strategy



Fire Safety Strategy



Fire Safety Strategy



MAJOR FIRES IN TALL BUILDINGS

TVCC HOTEL, Beijing, China, Feb. 2009

Built:	under construction
Height:	44 floors, 158 m
Use:	hotel, not occupied yet
Structure:	steel-framed with concrete core
Fire:	triggered at roof, spread downwards
Cause:	unauthorized firework
Duration:	5 hours
Injuries:	1 casualty (fireman), 7 injuries
Damages:	many floors, no frame, ca. $100mil


By WiNG - Own work, Public Domain, https://commons.wikimedia.org/w/index.php?curid=5907746

HIGHLIGHTS

Fire triggers: firework

Fire spread: flammable facade

MAJOR FIRES IN TALL BUILDINGS

SHANGHAI APARTMENT, China, Nov 2010

Built: sprinkled

Height: 28 stories, 85 m

Use: residential

Fire: started at 10th floor, spread to the roof through façade and then moved inside the building

Cause: unauthorized welding work and polyurethane foam insulated façade

Duration: several hours, but very rapid spread through facade (ca. 10 min)

Casualties: 58 casualties, 70 injured

By monkeyking (Peijin Chen), CC BY 2.0, https://commons.wikimedia.org/w/index.php?curid=12082626

<u>HIGHLIGHTS</u>

Fire triggers: welding spark

Fire spread: flammable facade

MAJOR FIRES IN TALL BUILDINGS

SHENYANG HOTEL, China, Feb 2011

Cause: firework on the roof of adjacent building
Spread: aluminium cladding façade
Note: fire spread on adjacent building

TAMWEEL TOWER, Dubai, Emirates, 2012

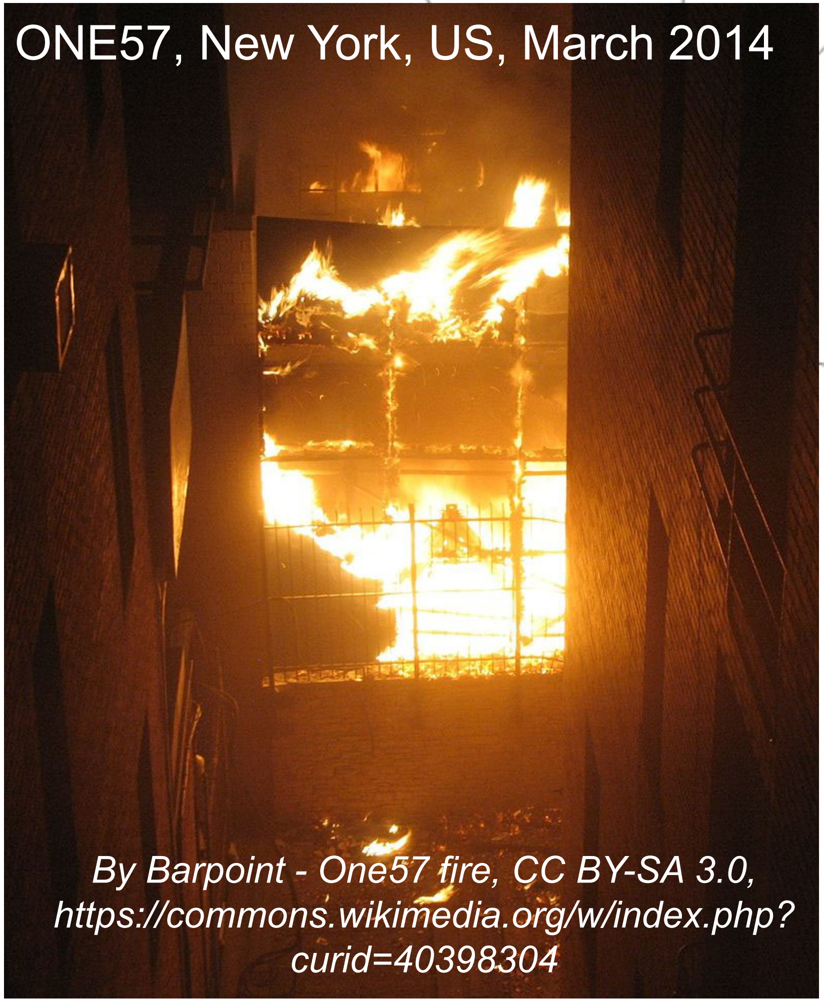
Cause: cigarette butts onto waste material
Spread: aluminium and fiberglass cladding façade

GROZNY BUILDING, Cechnya, 2013

Cause: worker with gas burner
Spread: combustible cladding
Note: flaming debris

ONE57, New York, US, March 2014

Cause: still unknown
Note: fire spread to adjacent building



By Barpoint - One57 fire, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=40398304

MAJOR FIRES IN TALL BUILDINGS

MARINA TORCH TOWER, Dubai, 2015&2017

Fire: grill on a balcony
Spread: combustible cladding façade
Note: flaming debris
new fire in 2017 after façade renovation

DOWNTOWN HOTEL, Dubai, New Year 2015/2016

Fire: short circuit
Spread: very rapid through façade
Note: 13 h long fire

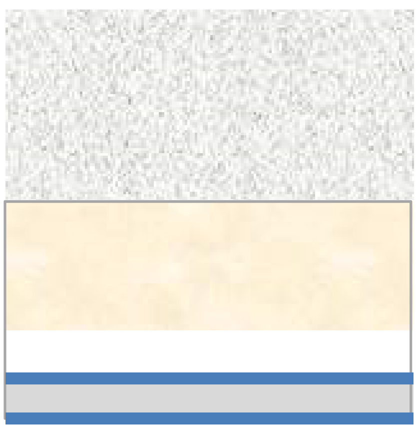
NEO200, Melbourne, AU 2015&2019

Fire: cigarette smoldering ignited façade
Spread: very rapid through façade
Note: another fire (one floor only) in 2015
cladding similar to Lacrosse building burned in 2014 in Melbourne and to Grenfell Tower

Ref.: Leisted: ”Fire Performance of Steel-faced Insulation Panels […]”, PhD Thesis, DTU, Denmark, 2018
Ref.: Crewe et al.: “Fire Performance of Sandwich Panels in a Small Room Test, Fire Technology 54, 2018

GRENFELL TOWER, London, UK, 2017

Built:	1974
Height:	24 stories
Use:	residential
Fire cause:	faulty freezer in one apartment,
Spread:	through newly installed composite cladding
Duration:	60 h
Injuries:	70 injured, 80 casualties
Damages:	to be demolished



COMPOSITE CLADDING

Pre-fabricated concrete wall

PIR foam plate (150 mm)

Ventilation gap (50 mm)

Aluminium-polyethilene sandwich plates (3mm each)

By Natalie Oxford, CC BY 4.0; https://commons.wikimedia.org/w/index.php?curid=59913134

Co-funded by the Erasmus+ Programme of the European Union

FIRE-INDUCED COLLAPSE

PLASCO BUILDING, Theran, Iran, Jan 2017

Height:	17 stories, 42 m
Use:	residential + shopping mall
Structure:	steel frame with bracing
Fire:	spread from 9th floor upwards
Cause:	faulty electrical connection
Duration:	collapse after 4 hours
Injuries:	26 casualties (16 firemen), 230 injured (70 by collapse)
Damages:	complete collapse

HIGHLIGHTS

Structure: steel

Collapse: after 4 h fire – fire fighter safety

FIRE-INDUCED COLLAPSE

WILTON PAES DE ALMEIDA,
Sao Paulo, Brazil, May 2018

Built:	1968, 85 m
Height:	26 stories (24 above ground)
Use:	residential + shopping mall
Structure:	steel frame with concrete floors
Fire:	spread from 5th floor
	spread also to adjacent buildings
Cause:	short circuit
Duration:	90 min
Injuries:	7 casualties + 2 missing
Damages:	complete collapse; damages from debris to adjacent church

HIGHLIGHTS

Fire spread: to adjacent building

Structure: steel

FIRE-INDUCED COLLAPSE

Date	Location	Construction type	Notes
2000	Textile factory, Alexandria, Egypt	Concrete	Collapse after 9 h of fire
2001	WTC1, WTC2, WTC7, New York, US	Steel frame	Complete collapse
2004	12 story building, Cairo, Egypt	R.C.	4 stories illegally added
2005	Windsor Tower, Madrid, Spain	Composite	Collapse standstill at technical floor
2008	Technical University of Delft, Netherland	R.C	Northern wing collapse
2017	Plasco Building, Theran, Iran	Steel	Complete collapse
May 2018	Wilton Paes De Almeida, Sao Paulo, Brazil	Steel	Complete collapse

BRE Test: https://www.youtube.com/watch?v=4bjMLFx4IQg

CAR PARK FIRES

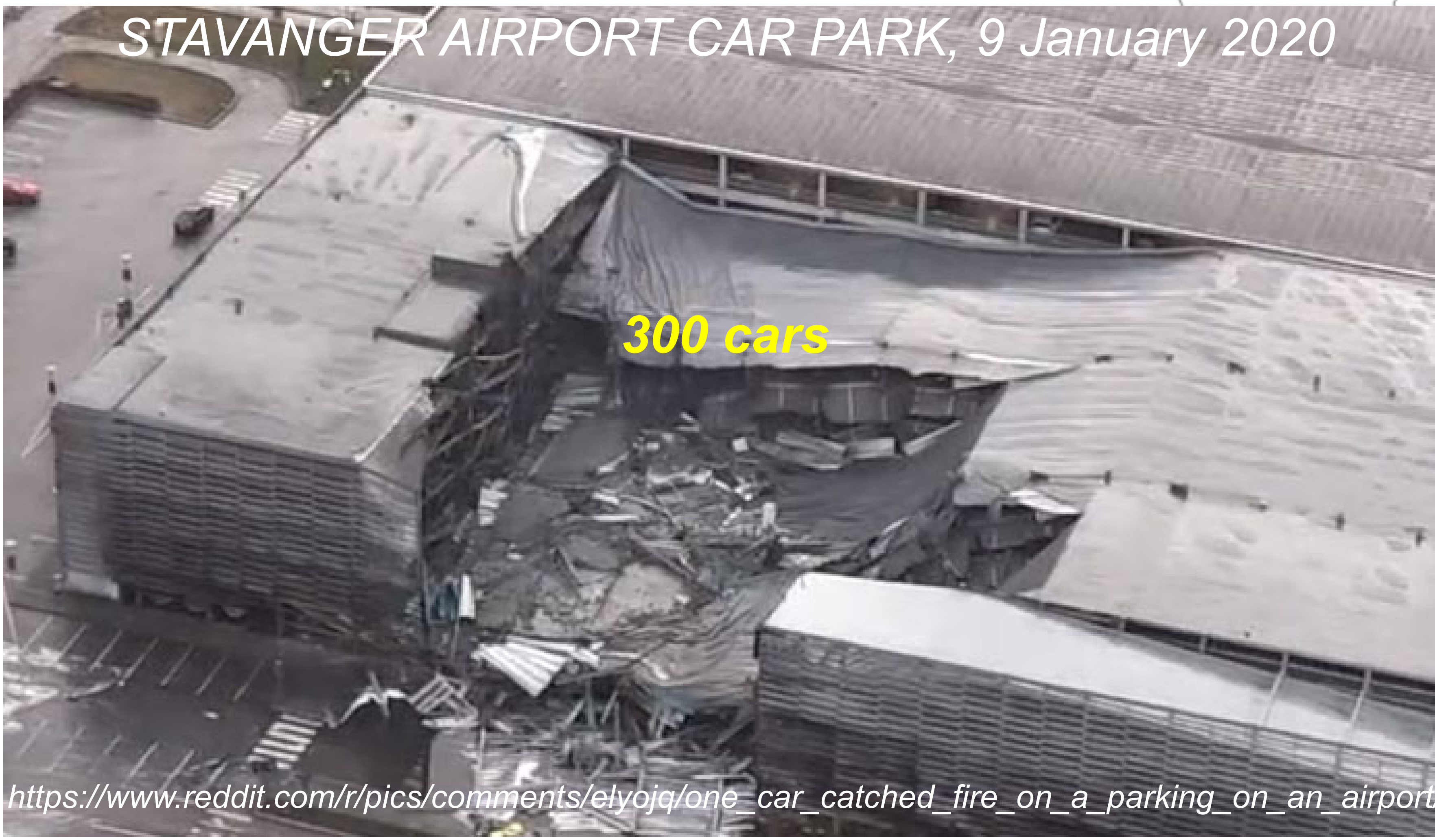
CAR PARK FIRES *(from 2001 with more than 10 cars involved in the fire)*

Date	Location	Burned cars	Construction type	Notes
2001-09-16	Fasanvænget, Kokkedal, Denmark	30	Open	70 people evacuated
2002-10-13	Schiphol airport, Netherlands	51	Open	
2004-04-06	Jacob Hansensvej Odense, Denmark	10	Open	Collapse of the steel shelter
2008-12-26	Kilmarnock's Foregate multi-storey	11		
2010-08-30	Stansted airport, UK	24	Open air	High wind reported
2013-10-14	Olympic Park Aquatic Center, Sydney, AU	80	Open air	11 killed, 15 injured
2014-04-25	Edinburgh Airport Parking Facility, UK	21	Open air	
2015-07-30	Oldham Tesco carpark fire	15	Closed	
2016-03-25	Nygaards Plads Brøndby, Denmark	19	Open	

CAR PARK FIRES *(from 2001 with more than 10 cars involved in the fire)*

Date	Location	Burned cars	Construction type	Notes
2016-03-25	Nygaards Plads Brøndby, Denmark	19	Open	
2016-08-03	Dance Festival Andanças, Portugal	422	Open air	
2016-08-15	West Car Park at Boomtown Fair Festival, Winchester, Hampshire, UK	82	Open air	
2017-04-16	Von Lingens Väg Malmö, Sweden	30	Closed	
2018-01-01	Echo Arena, Liverpool, UK	1400	Open	to be demolished
2018-09-17	Kings Plaza Shopping Center, Brooklyn, NY, US	120	Closed	
2019-01-31	Newark Liberty airport, New Jersey, US	17	Open air	
2019-09-02	Douglas Village Shopping Mall, Cork, IE	60	Open	
09-01-2020	Stavanger airport, Norway	300	Open	steel structure collapsed

CAR PARK FIRE-INDUCED COLLAPSE



OUTLINE

- *Recent major fires*
- *Design shortcomings*
  - ➢ *Design fires*

Co-funded by the
Erasmus+ Programme
of the European Union

DESIGN FIRES

POST-FO FIRES
(limited compartment size and ventilation)

LOCAL FIRE
(large, well-ventil. areas)

a

NOMINAL

STANDARD FIRE
(+ RESISTANCE CLASS)

assumed
time limit

b

ANALYTICAL

PARAMETRIC FIRE
(q, b, O)

assumed
compartment proper.

c

NUMERICAL/EXPER.

CFD SIMULATION
(based on experim. HRR)

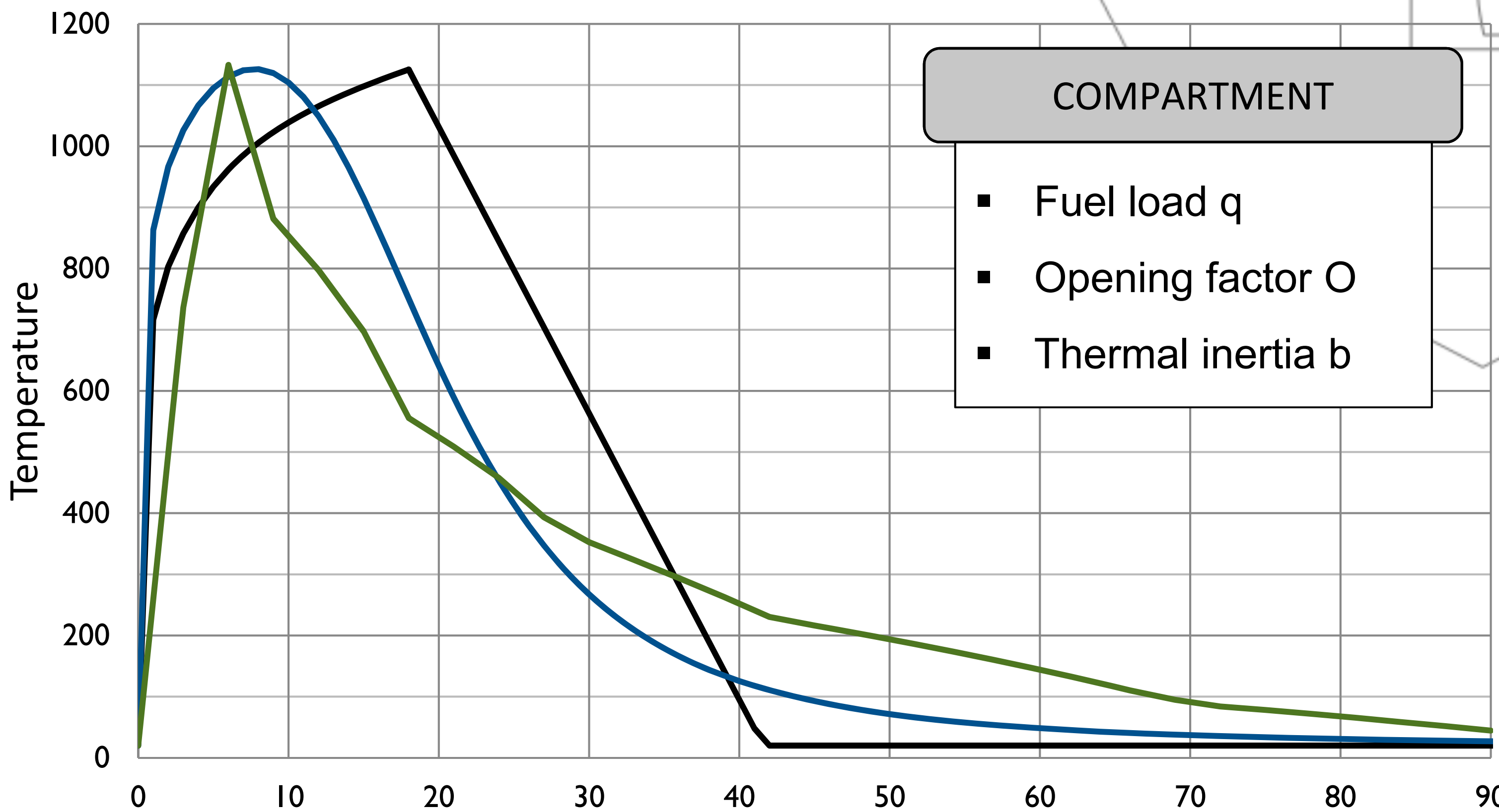
assumed
fire spread

<u>SW Fire</u>: *Petterson&al.: "Fire engineering design of steel structures", Lund University, 1976*
<u>EN Fire</u>: *EN1991-1-2 Eurocode 1; <u>DS Fire</u>: DS/EN1991-1-2 DK NA, "Danish National Annex to Eurocode 1*

DESIGN FIRES: parametric fires

PARAMETRIC FIRES

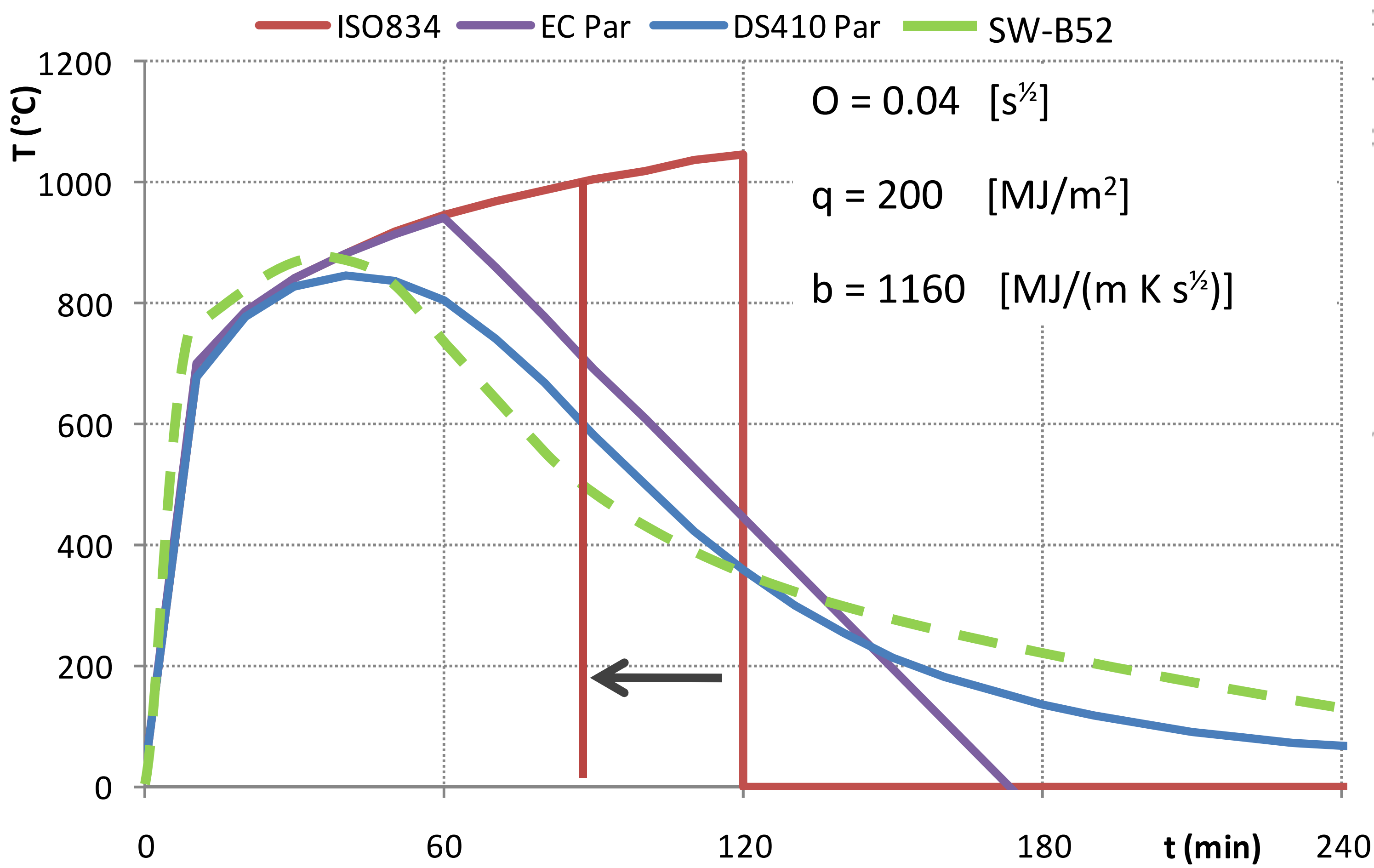
SW parametric | DS parametric | EN parametric



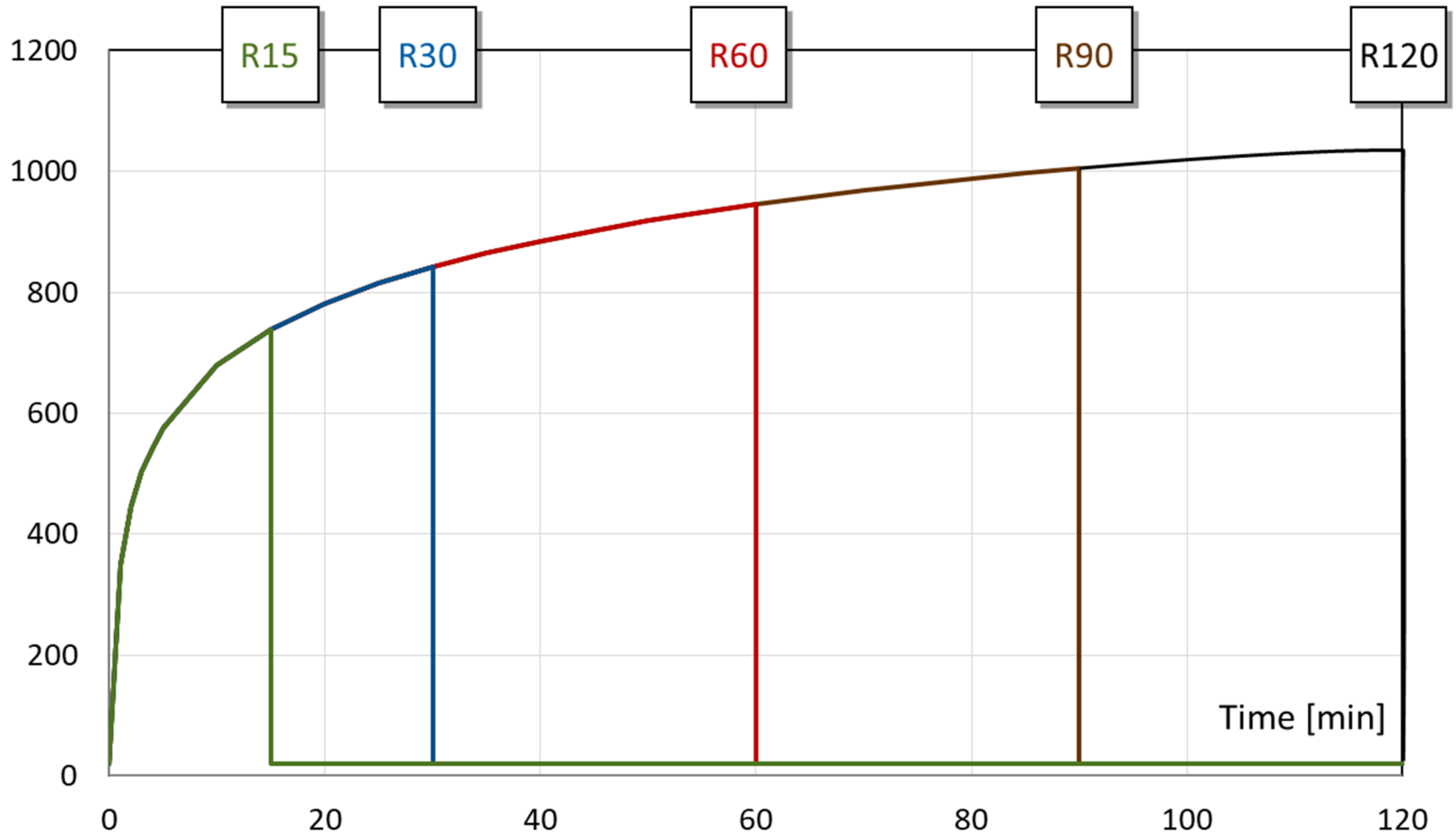
COMPARTMENT

- Fuel load q
- Opening factor O
- Thermal inertia b

DESIGN FIRES: standard fire and resistance class



DESIGN FIRES: standard fire and resistance class



Co-funded by the
Erasmus+ Programme
of the European Union

<u>Source</u>: Pustorino et al: "Regola Technical Prescrittiva", Interim Report n 2, Promozione Acciaio, 11 July 2006

DESIGN FIRES: resistance classes in Europe

Occupancy		B	CH	D	F	I	L	NL	FIN	E	UK
small-size offices	sprinkler	60	0-30	-	60	60	90	60	60	60	30
	no sprinkler	60	-	90	60	60	90	60	60	60	60
medium-size offices	sprinkler	120	60-90	-	120	90	90	60	120	120	120
	no sprinkler	120	90	90	120	90	120	90	120	120	0
schools	sprinkler	60	0-30	-	60	60	90	60	60	60	60
	no sprinkler	60	90	60	60	60	60	60	60	60	60
hospitals	sprinkler	120	60	-	60	120	90-120	120	60	120	90
	no sprinkler	120	90	90	60	120	120	120	60	120	90
car parks	closed	120	60	90	30-90	90	60	-	60	90	120
	open	60	0	0	30-90	90	90	60	60	90	15*

*Side open car park less than 30 m high (Approved Document B, 2006)

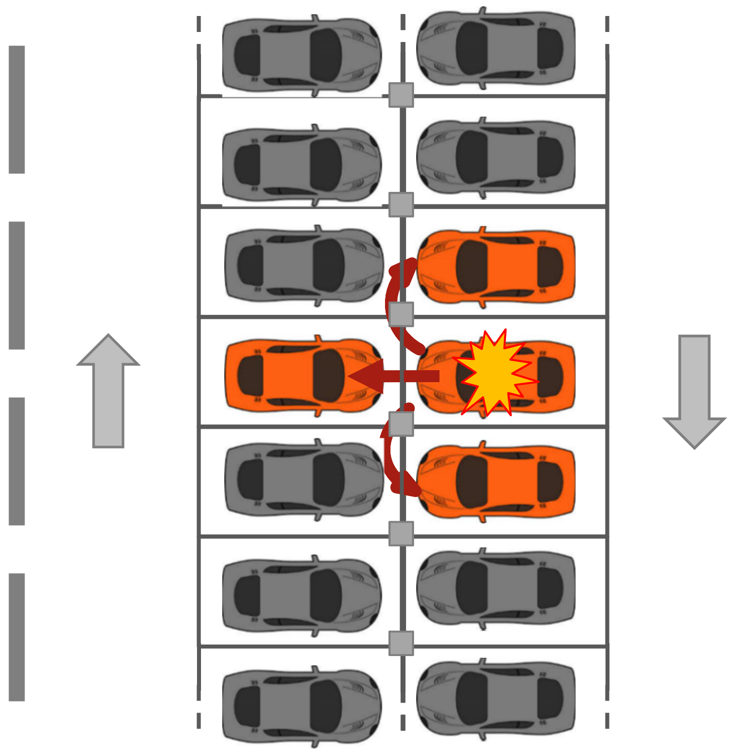
Use of uninsulated steel is possible!

Ref.: *Schleich et al.: "Development of design rules for steel structures subjected to natural fires in closed car parks, European Commission Report, EUR 18867, Brussels, Belgium, 1999*

DESIGN FIRES: numerical/experimental

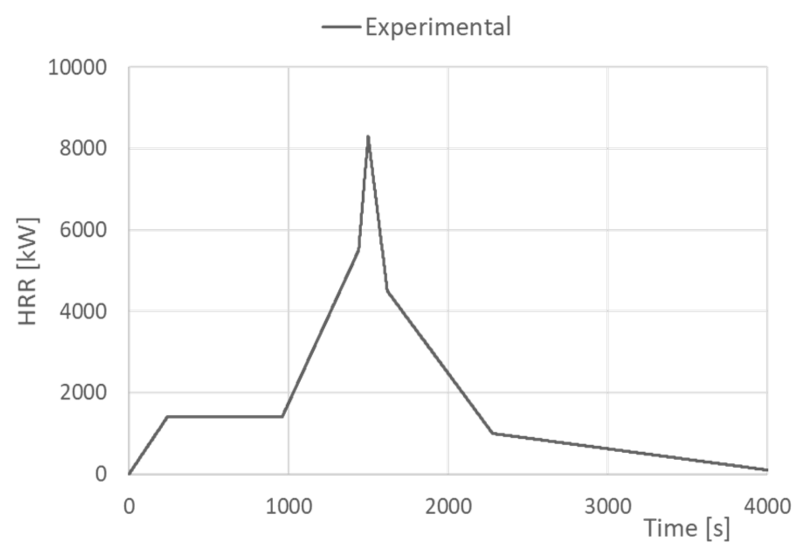
Fire scenario: local fire

CTICM LARGE SCALE TEST
3-4 cars, 12 min one car to another



Fire load: experimental HRR

CALORIMETRIC HOOD TEST
- Lower ventilation & thermal feedback from ceiling
- New cars (higher energy content)
- Alternative fuels (batteries, hydrogen)



DESIGN FIRES: fuel load

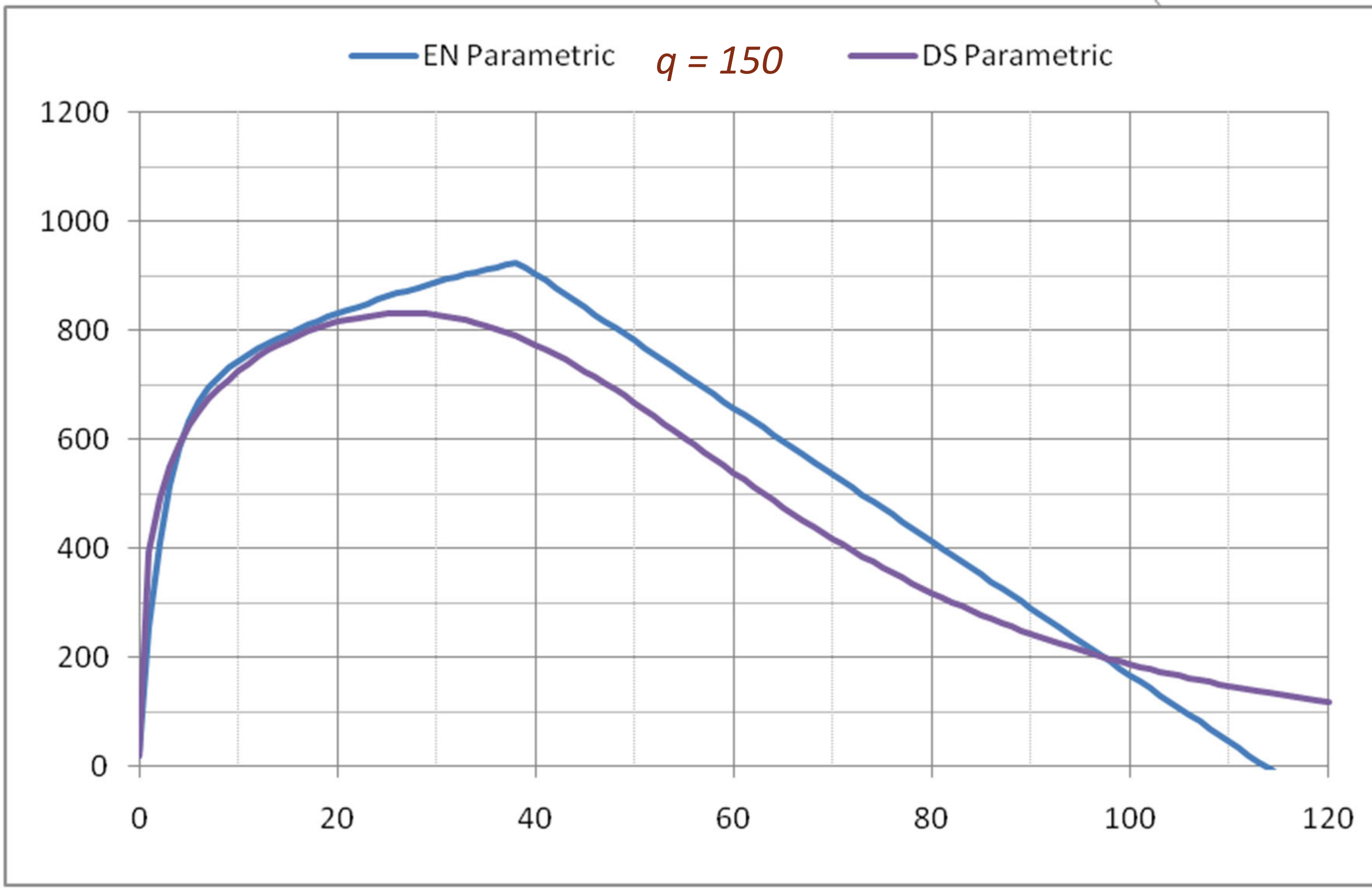
Year	1995	2007	2018	2018 (EV)
Car (1 ton)	7.5 GJ [1]	8.5 GJ [1]	10.5 GJ [2]	10.5 GJ [2]
Gasoline (40 l)	1.5 GJ	1.5 GJ	1.5 GJ	
Battery (64 kWh)				4.5 GJ [3]
Total fuel load	**9 GJ**	**10 GJ**	**12 GJ**	**15 GJ**

(1) Christiansen T.: "Fire load on car parks (in Danish)," M.Sc. Thesis Report, Department of Civil Engineering, Technical University of Denmark, Lyngby, Denmark, 2007

(2) Extrapolation based on fuel load increment in the previous years

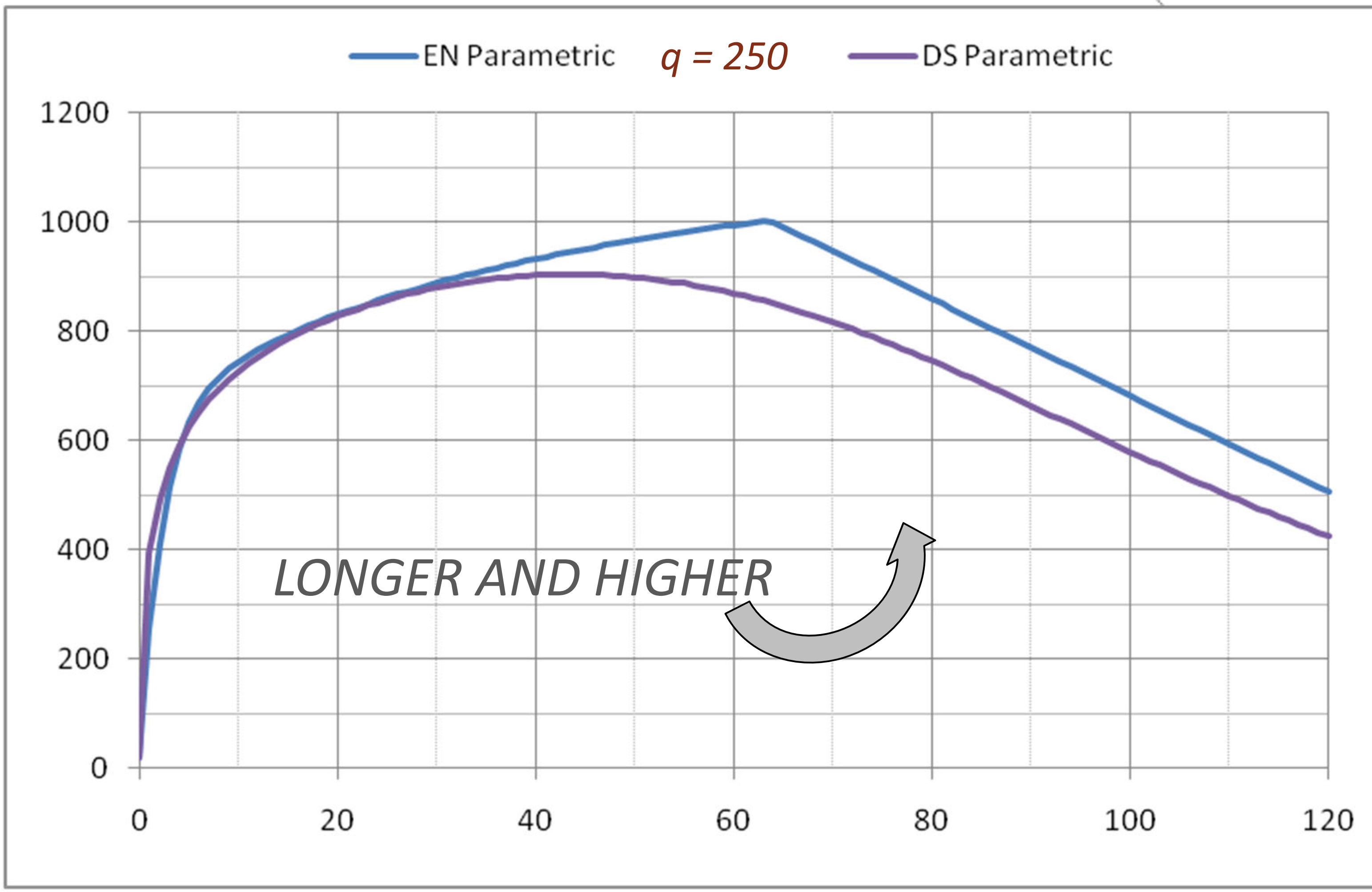
(4) Based on data presented in: Larsson F.: "Battery aspects on fires in electrified vehicles," in *Proc. of the 3rd Int. Conf. on Fire in Vehicles, pp. 209-220*, Berlin, Germany, October 2014.

DESIGN FIRES: fuel load



Co-funded by the
Erasmus+ Programme
of the European Union

DESIGN FIRES: fuel load



Co-funded by the
Erasmus+ Programme
of the European Union

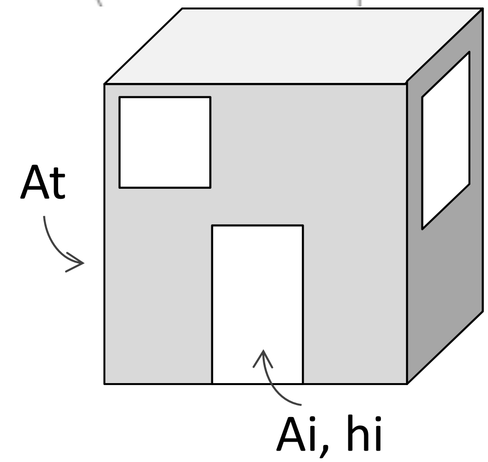
Source: Huizinga et al.: "Effect of triple glazing […] on […] fire safety", IFireSS 2017, Naples, Italy, June 7-9, 2017

DESIGN FIRES: ventilation

Opening factor: $O = A \sqrt{h_{av}} / A_t \quad [m^{½}]$

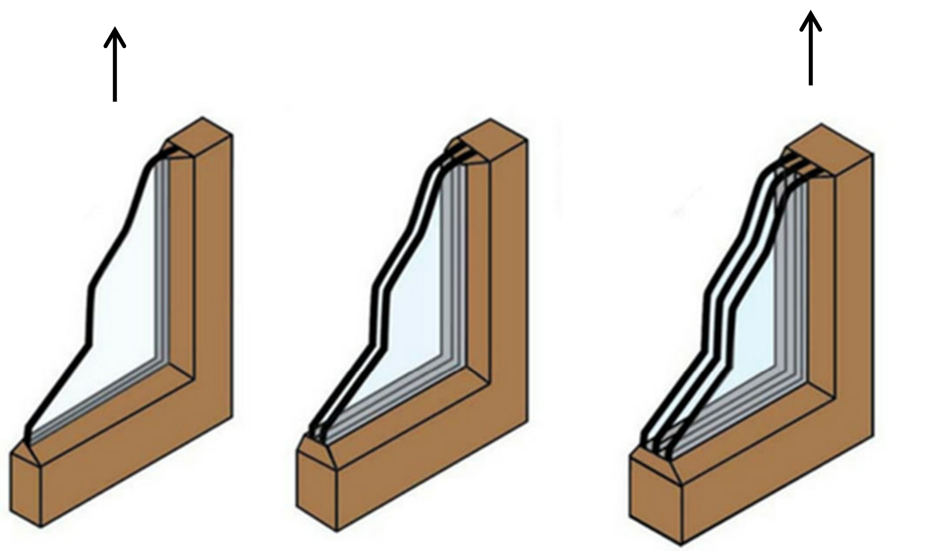
$A = \Sigma_i A_i$

$h_{av} = \Sigma_i A_i h_i / A$

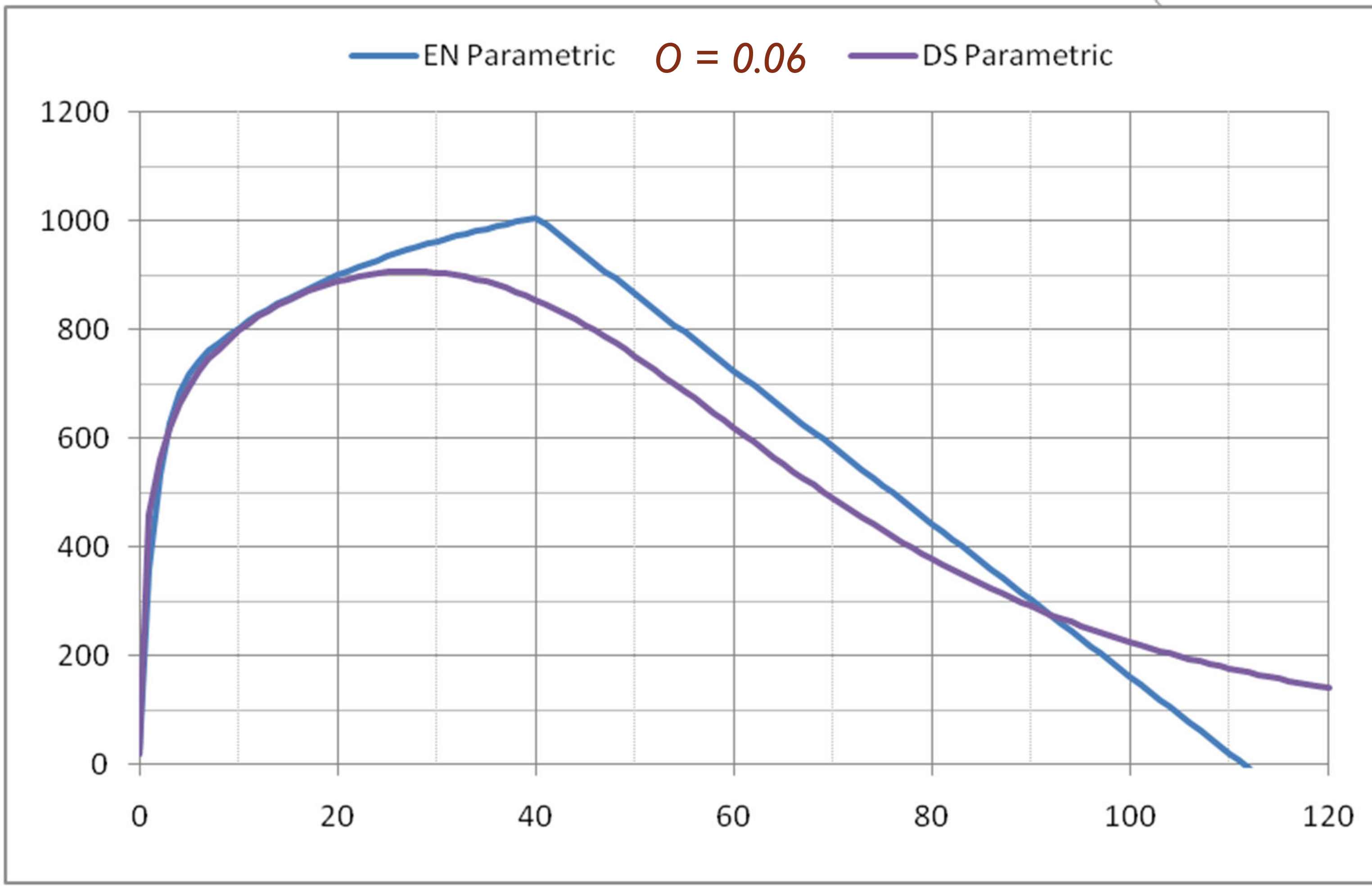


BREAK BEFORE FO

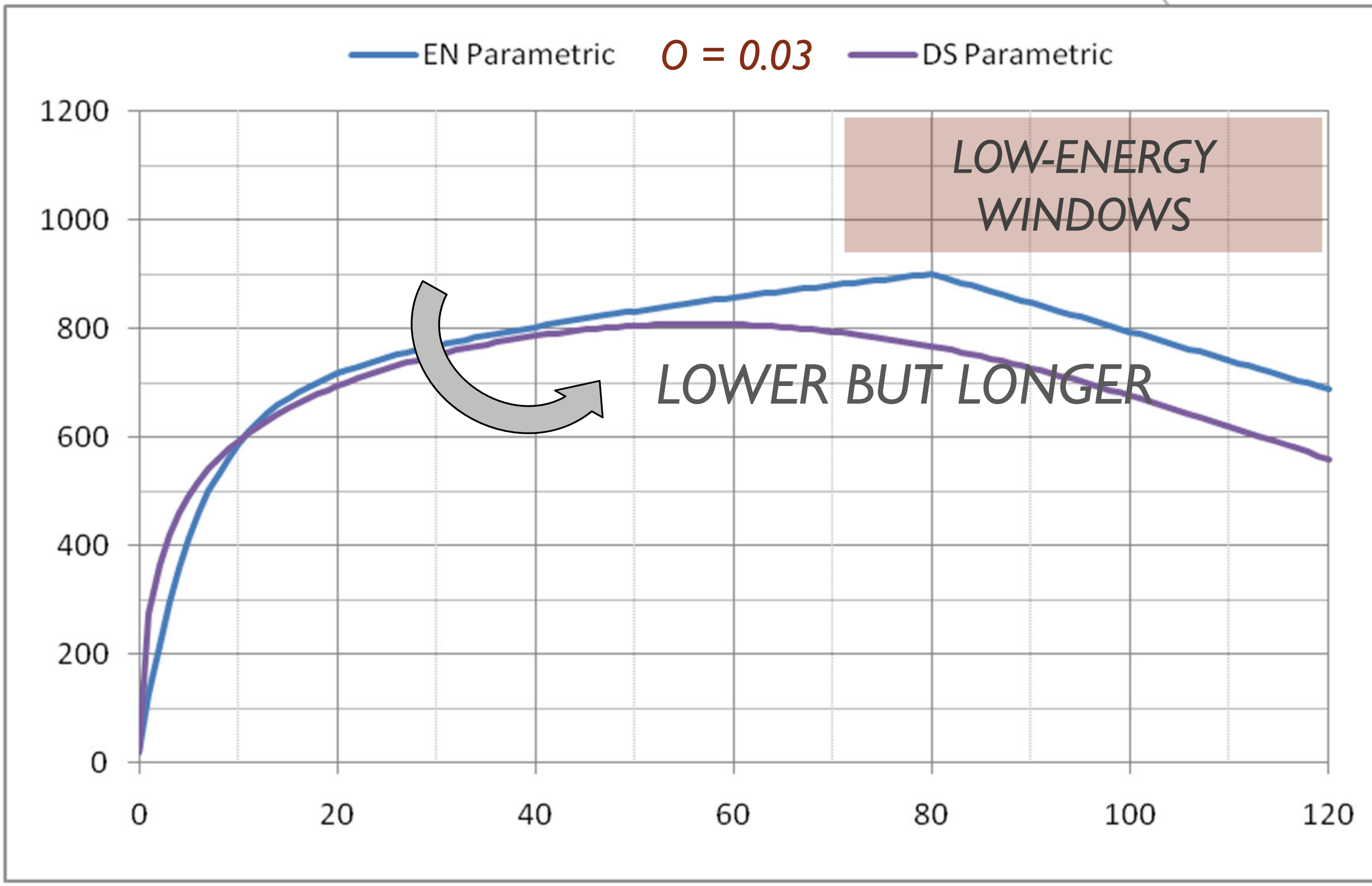
MAY NOT BREAK



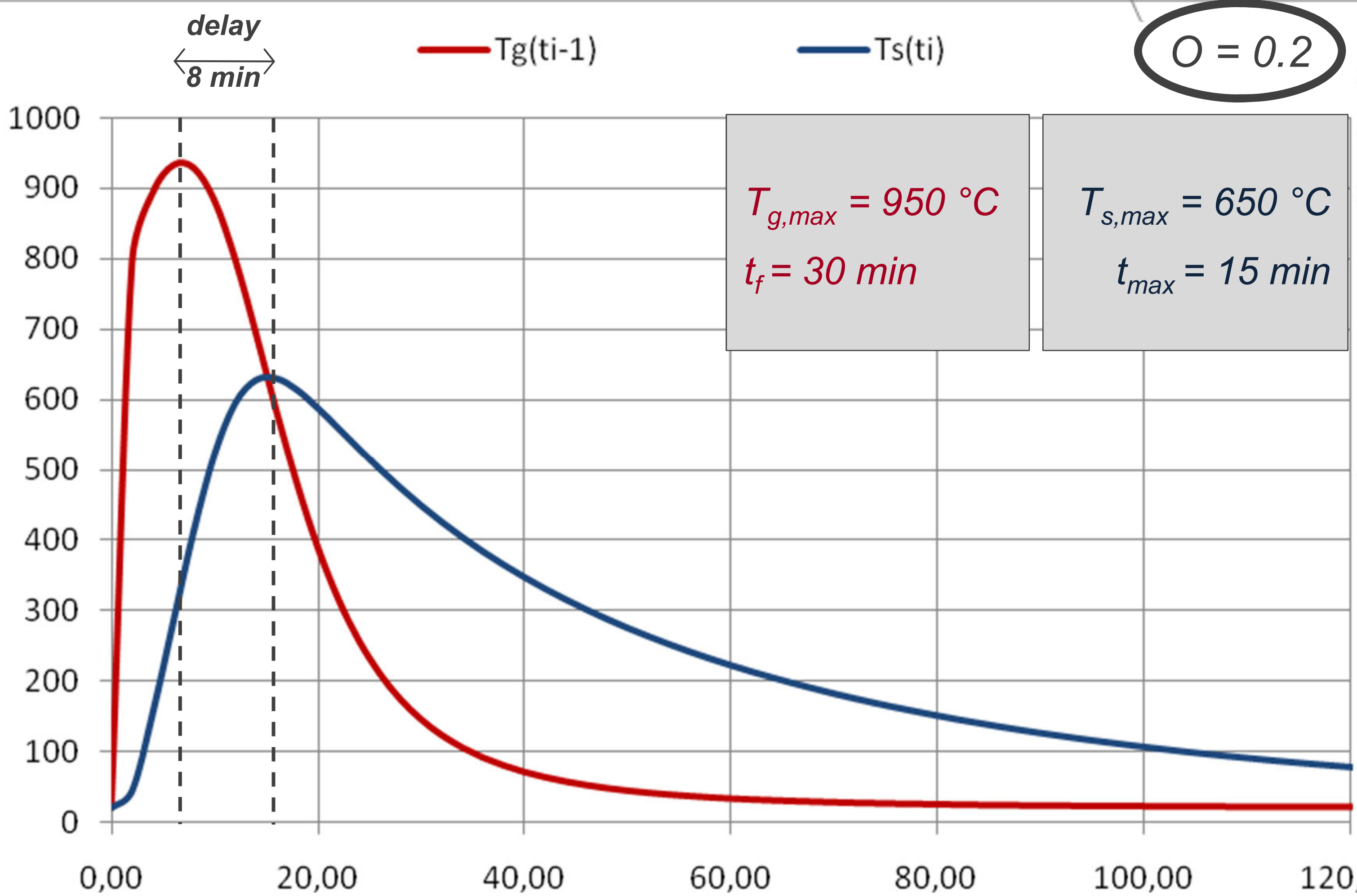
DESIGN FIRES: ventilation



DESIGN FIRES: ventilation



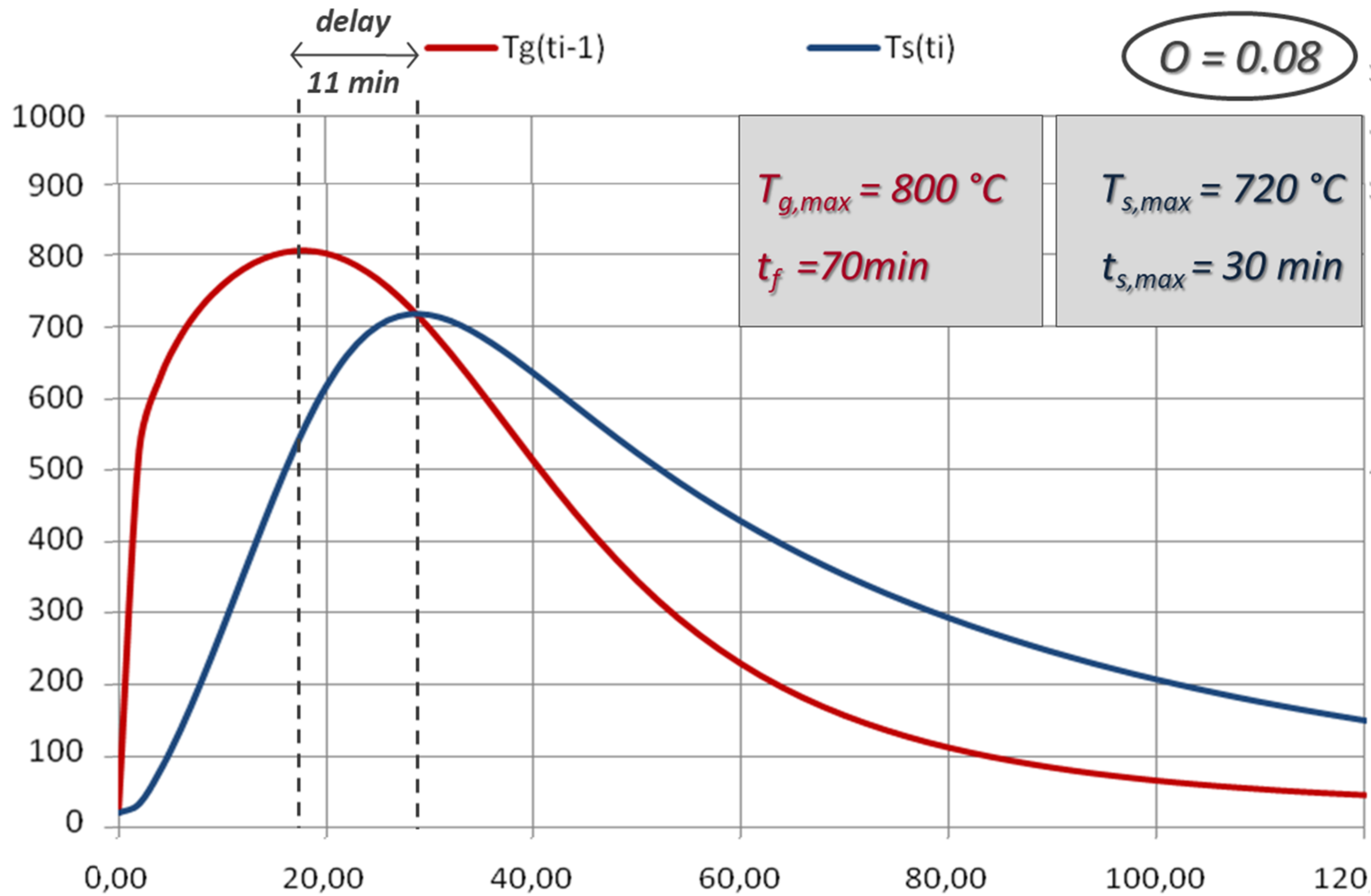
DESIGN FIRES: ventilation



Co-funded by the
Erasmus+ Programme
of the European Union

Ref: EN1993-1-2: Design of steel structures - Structural fire design, Brussels, Belgium, 2005

DESIGN FIRES: ventilation



Source: Petterson&al.: “Fire engineering design of steel structures”, Lund University, 1976

DESIGN FIRES: thermal inertia

Thermal inertia: $b = \sqrt{\rho\, c\, \lambda}$ $[W\, s^{½}\, K^{-1}\, m^{-2}]$

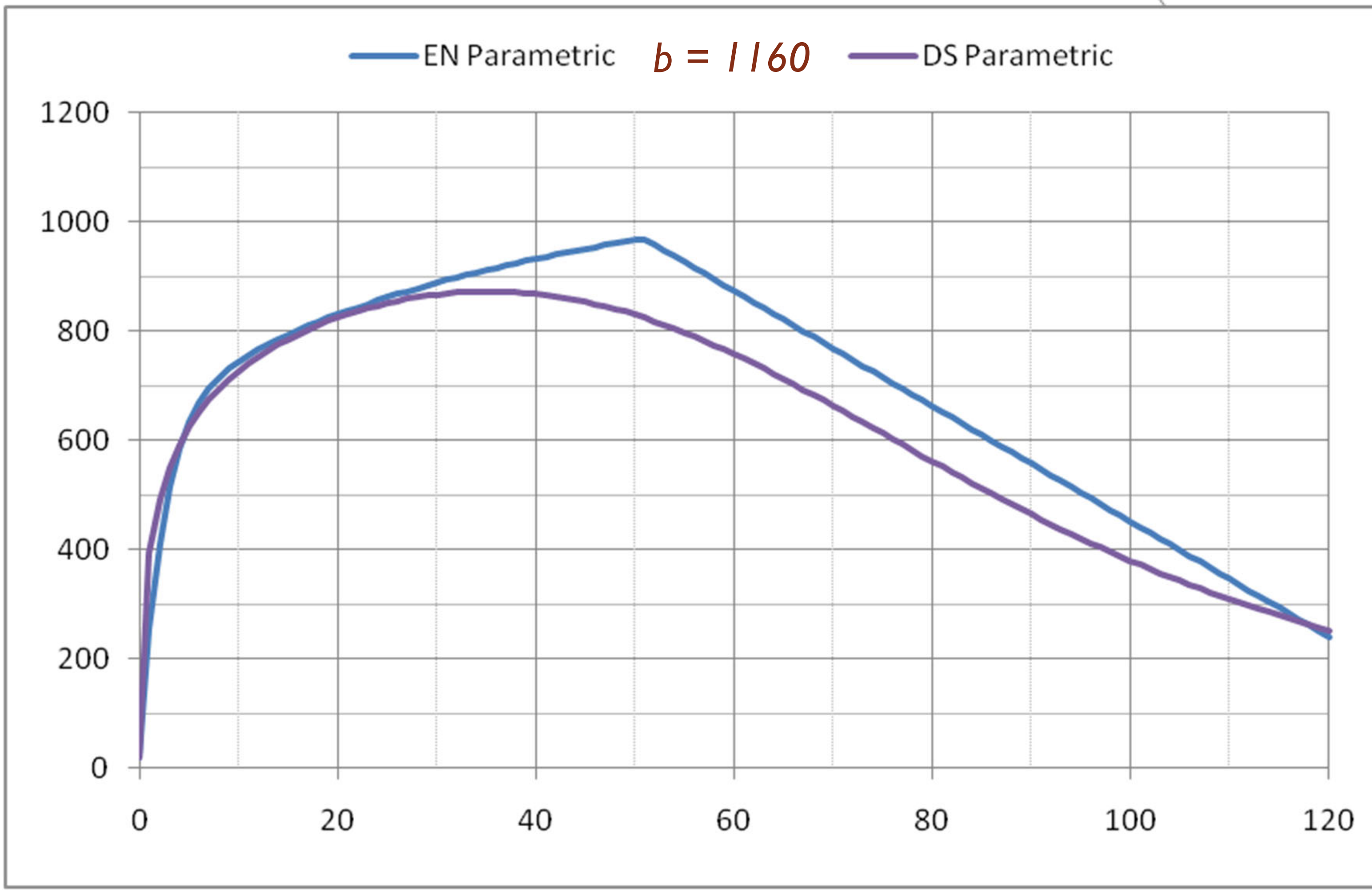
density ← ρ; λ → conductivity

c ↓ specific heat capacity

Compartment type	Material	b $[Ws^{½}K^{-1}m^{-2}]$
A (standard)	Concrete, brick, lightweight concrete	1160
C	50% concrete, 50% lightweight concrete	860
G	20% concrete, 80% two gypsum plaster boards with air gap in-between	800
E	50% lightweight concrete, 33% concrete, 17%m insulating sandwich panel (gypsum, mineral wool, brickwork)	773
H	Two steel sheets with 100 mm mineral wool in-between	386

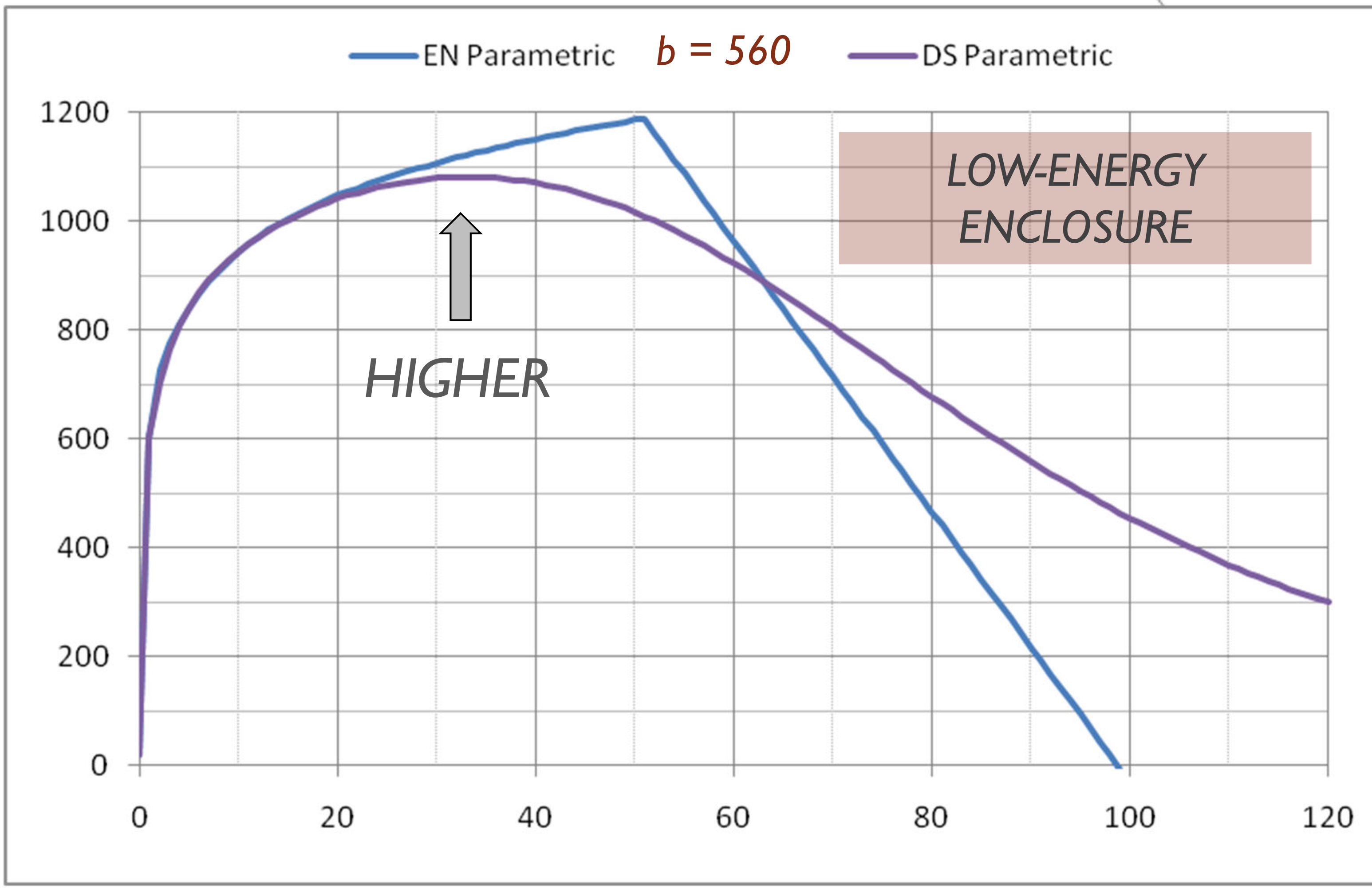
INSULATION

DESIGN FIRES: thermal inertia

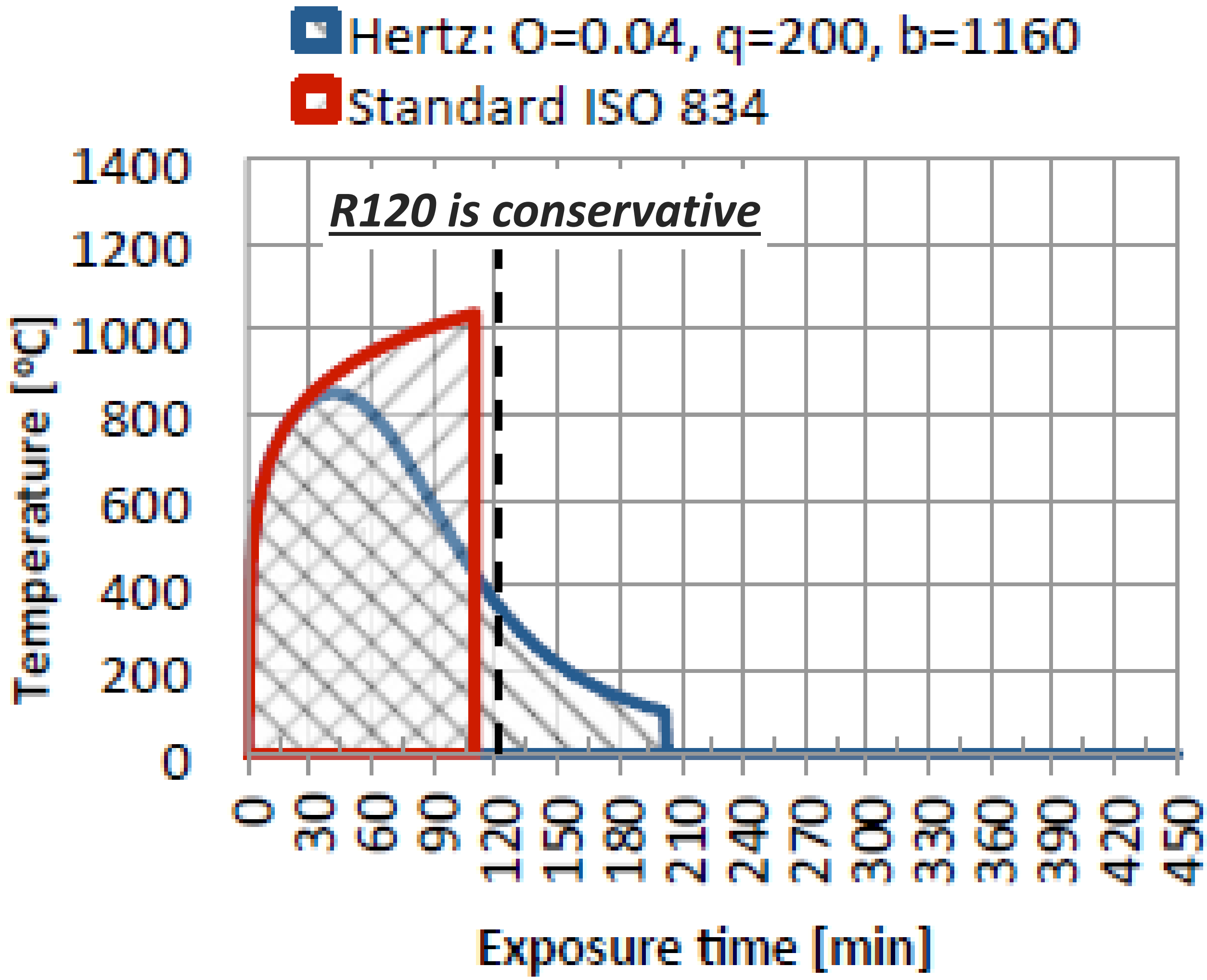


Co-funded by the
Erasmus+ Programme
of the European Union

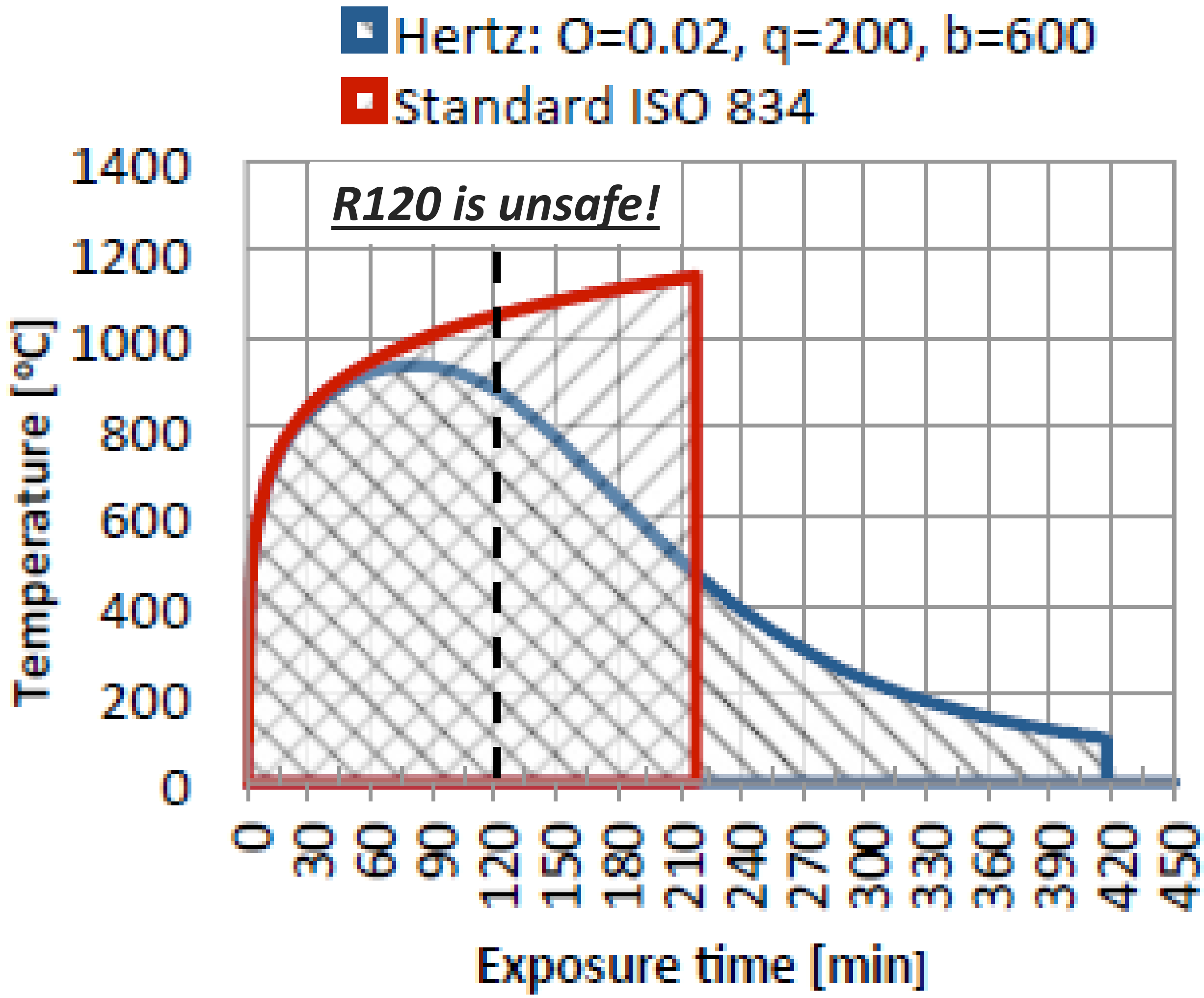
DESIGN FIRES: thermal inertia



DESIGN FIRES: old compartment



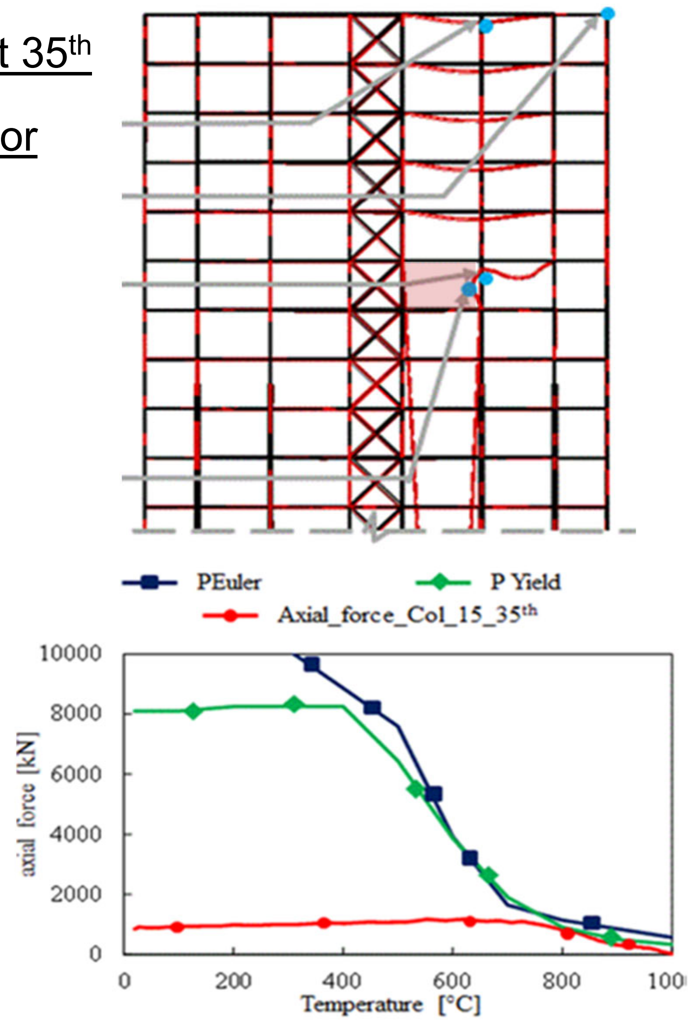
DESIGN FIRES: old compartment



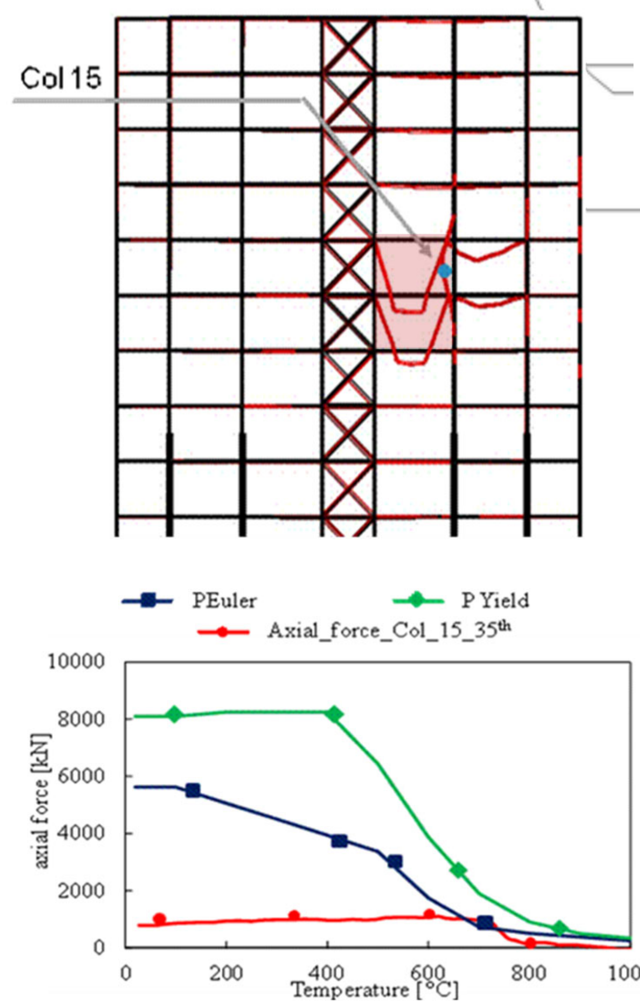
Ref.: Gentili et al.: "Structural Response of Steel High Rise Buildings to Fire", J. of Structural Fire Eng. 4(1), 2013

DESIGN FIRES: vertical fire spread in buildings

Fire at 35th floor



Fire at 35&36th floor



Co-funded by the
Erasmus+ Programme
of the European Union

OUTLINE

- *Recent major fires*
- *Design shortcomings*
  - *Design fires*
  - *Structural design*

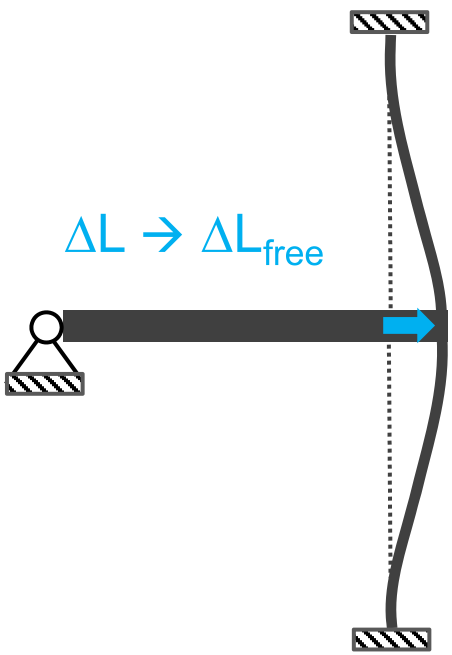
Co-funded by the
Erasmus+ Programme
of the European Union

STRUCTURAL DESIGN: degree of expansion

$$\gamma = \frac{1}{1 + {K_{flex}}^{T} / {K_{ax}}^{T}}$$

γ → 1

LOW RESTRAIN
(top floors)



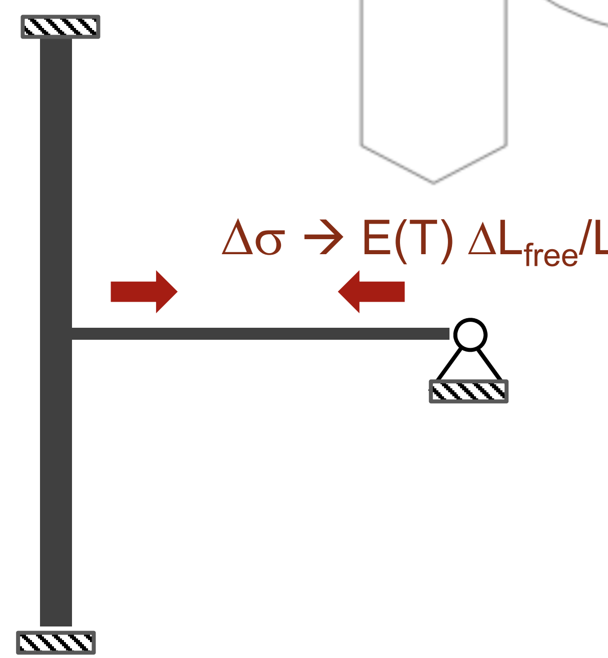
1 > γ > 0

$\Delta L = \gamma \, \Delta L_{free}$

$\Delta\sigma = E(T)\,(1-\gamma)\,\Delta L_{free}/L$

γ → 0

HIGH RESTRAIN
(top floors)



Co-funded by the
Erasmus+ Programme
of the European Union

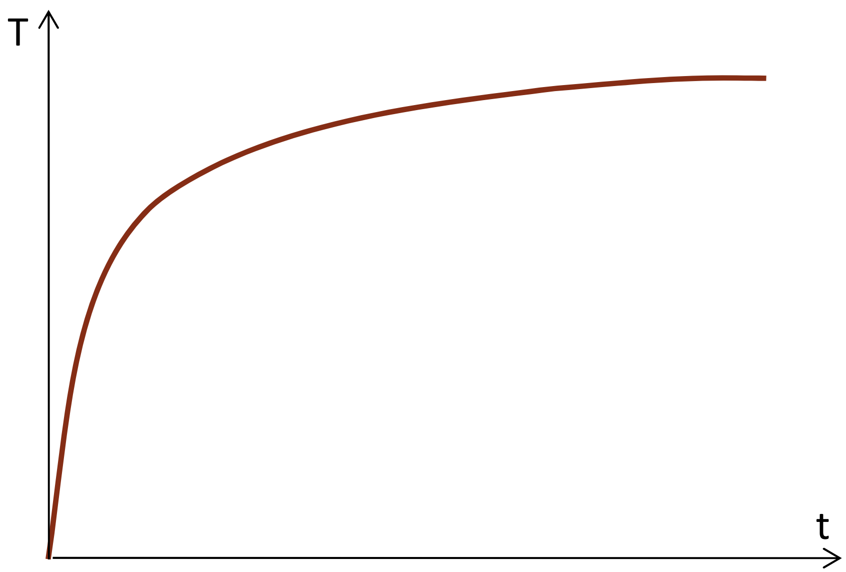
<u>Source</u>: *EN1991-1-2: Actions on structures exposed to fire, Brussels, Belgium, 2002*

STRUCTURAL DESIGN: hindered thermal expansion

INDIRECT STRESSES

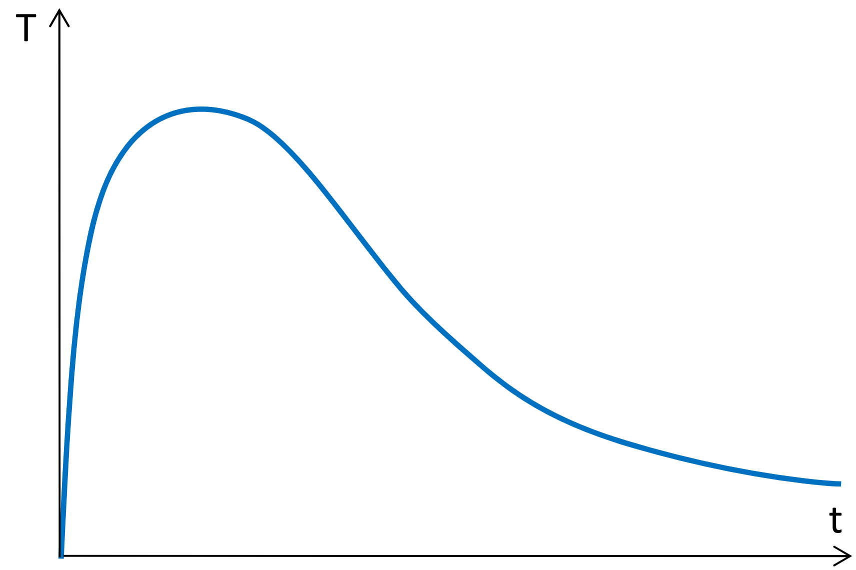
CAN BE DISREGARDED

$$\Delta\sigma_{eigen} = \text{neglected}$$



MUST BE CONSIDERED

$$\Delta\sigma_{eigen} = E^{T}(1-\gamma)\frac{\Delta L^{free}}{L}$$

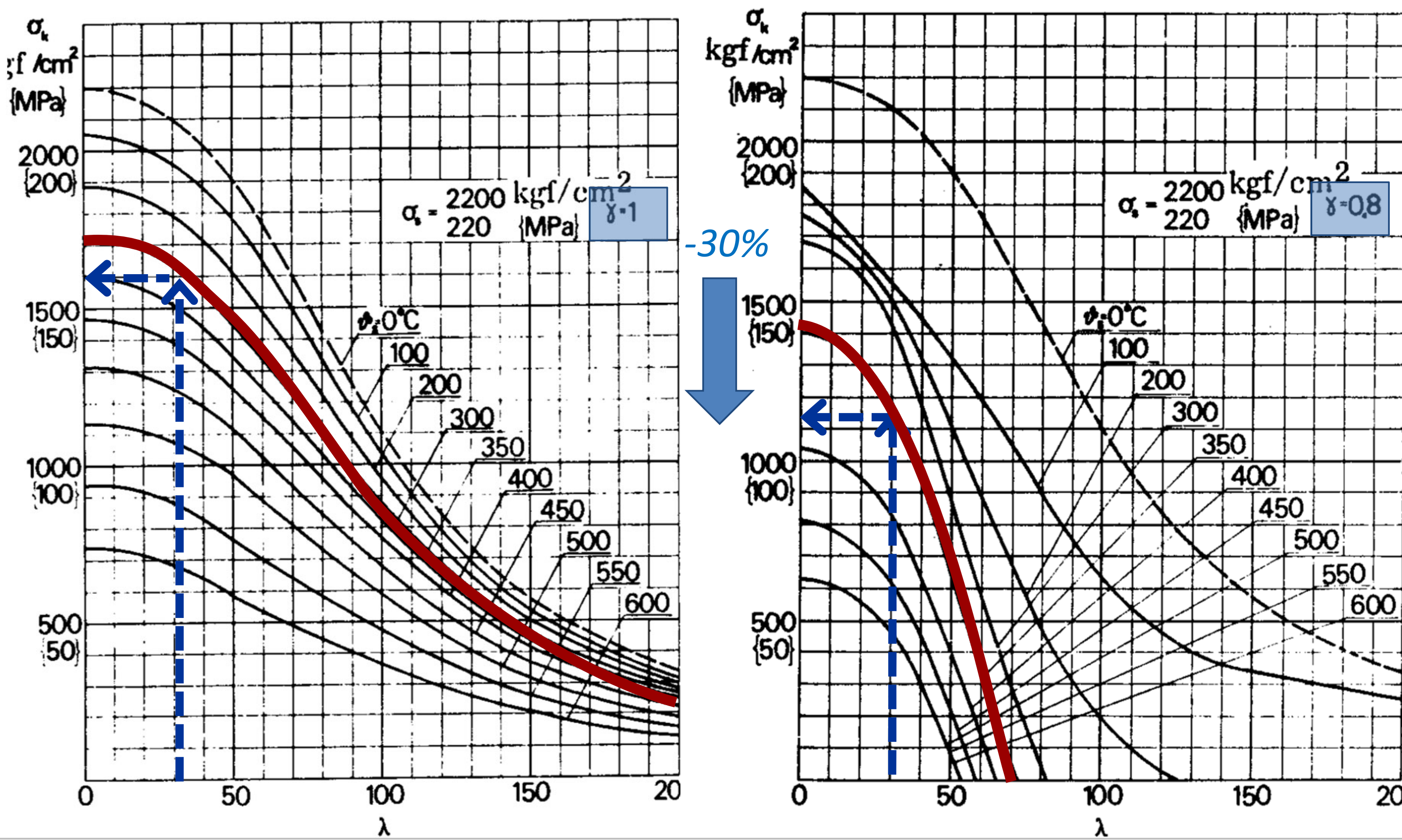


Co-funded by the
Erasmus+ Programme
of the European Union

Source: Petterson&al.: “Fire engineering design of steel structures”, Lund University, 1976

STRUCTURAL DESIGN: hindered thermal expanision

Axial capacity of steel columns hindered in expansion by a continuous beam

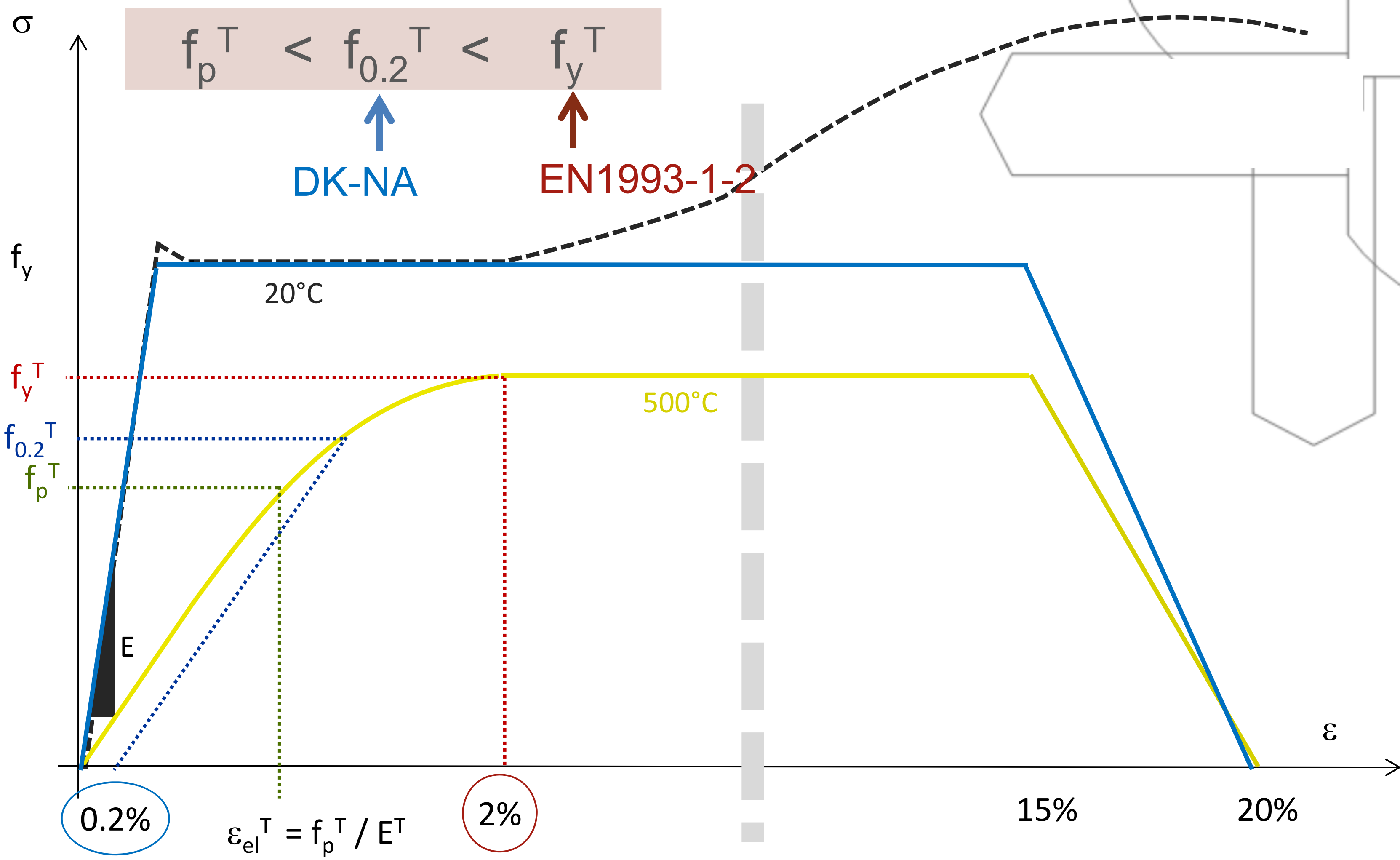


DTU
DTU Civil Engineering
Department of Civil Engineering

Co-funded by the
Erasmus+ Programme
of the European Union

STRUCTURAL DESIGN: mechanical properties

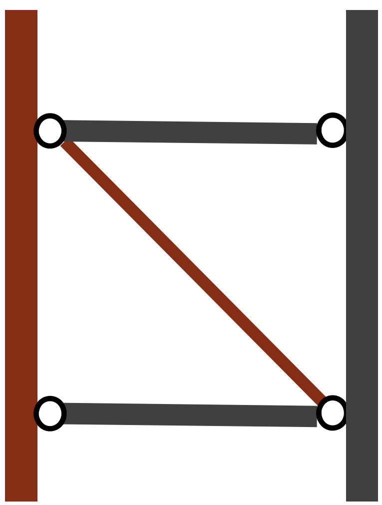
$f_p^T < f_{0.2}^T < f_y^T$

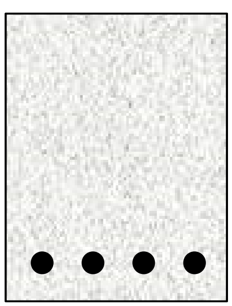


STRUCTURAL DESIGN: mechanical properties

$$f_p^T < f_{0.2}^T < f_y^T$$

- $f_{0.2}^T$: DK-NA proof stress
- f_y^T: EN1993-1-2 effective yielding





DK-NA proof stress →
- Compressed steel elements (columns, bracing)
- Steel bars in R.C. elements

Co-funded by the
Erasmus+ Programme
of the European Union

Ref.: Hertz K.D. (1981): Design of fire exposed concrete structures, Report no. 160 CIB W14/81/20, DTU, DK

STRUCTURAL DESIGN: cold condition

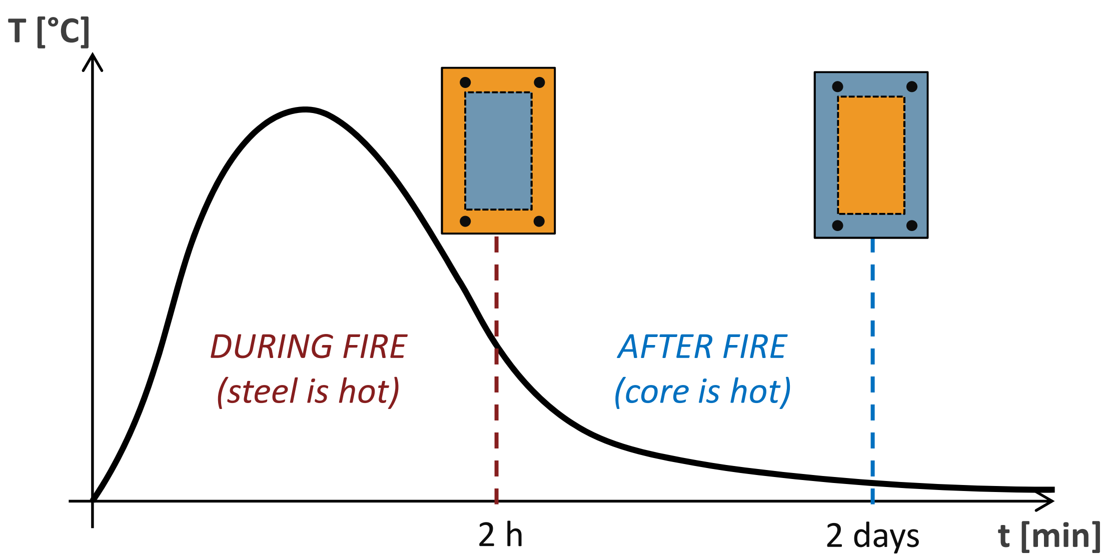
I. DURING FIRE

Outer concrete and reinforcing bars are heated

II. AFTER FIRE

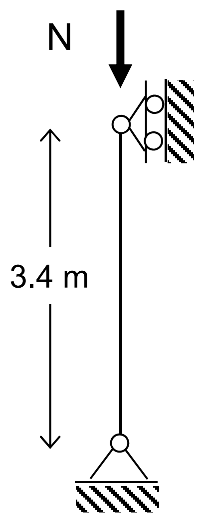
Concrete core is heated, outer bars are cooled down

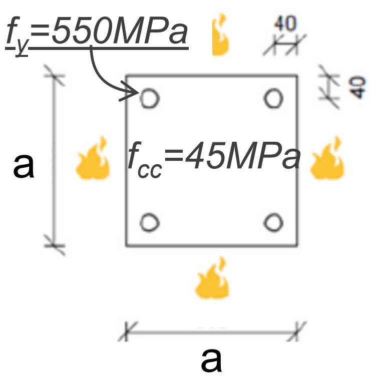
→ *risk of collapse after the fire is extinguished*



Source: *Wollesen N.: ”Comparison of methods for structural design of concrete elements in fire”, DTU, July 2013*

STRUCTURAL DESIGN: cold condition





FIRE q=200 [MJ/m²]		**OLD COMPARTMENT** O=0.04 [m^{-1}] b=1160 [$Ws^{0.5}m^{-2}K^{-1}$]		**NEW COMPARTMENT** O=0.02 [m^{-1}] b=600 [$Ws^{0.5}m^{-2}K^{-1}$]	
a [mm]	Ø [mm]	$N_{cr,HOT}$ [kN]	$N_{cr,COLD}$ [kN]	$N_{cr,HOT}$ [kN]	$N_{cr,COLD}$ [kN]
200	10	550	350	190	150
300	15	2’220	1’650	1’410	1’060
400	20	4’950	3’910	3’680	2’870
500	20	11’070	9’140	9’150	7’410

$N_{cr,HOT}$ → 36% overestimation

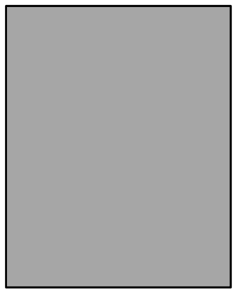
+ old comp. → > 100% overestimation

OUTLINE

- *Recent major fires*
- *Design shortcomings*
  - *Design fire and design loads*
  - *Structural design*
  - *Design process*

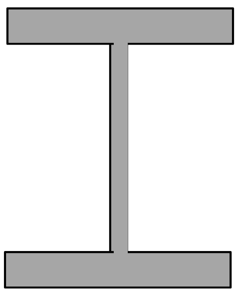
Co-funded by the
Erasmus+ Programme
of the European Union

Design process: optimization and fire verification



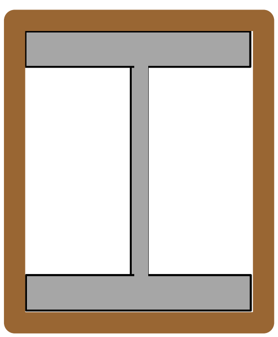
1. PREDIMENSIONING

   Ultimate Limit State (ULS) - Sectional failure



2. OPTIMIZATION IN SERVICE

   Service Limit State (SLS) - Elastic design



3. VERIFICATION IN FIRE

   Accidental Limit State (ALS) - Non-collapse

Optimization is lost when fire design is driving

Co-funded by the
Erasmus+ Programme
of the European Union

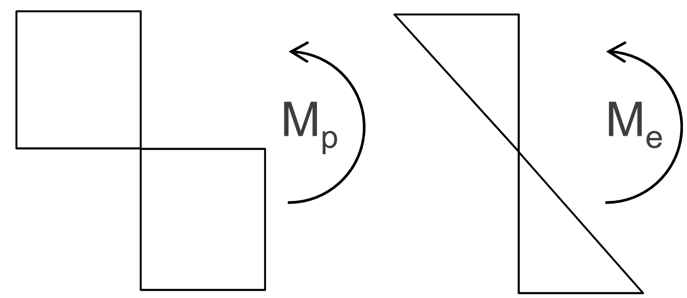
Design process: optimization and fire verification

STRUCTURAL RESPONSE

PLASTIC BENEFIT

$\beta = M_p / M_e$

Plastic moment M_p *Elastic moment M_e*

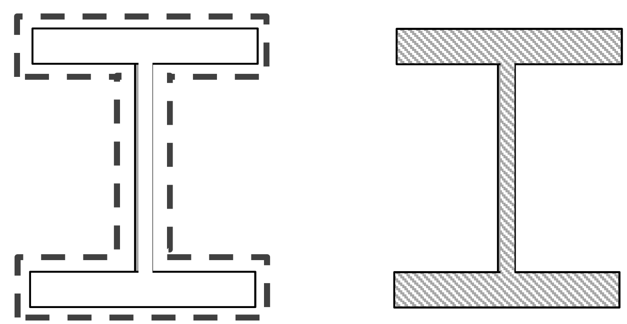


THERMAL RESPONSE

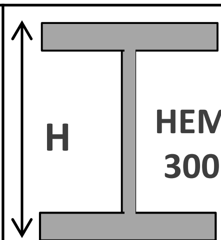
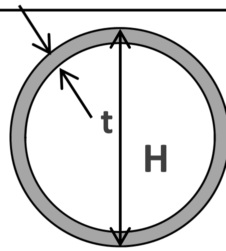
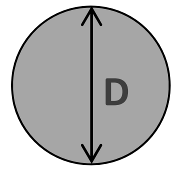
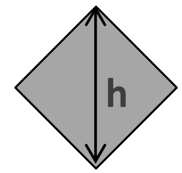
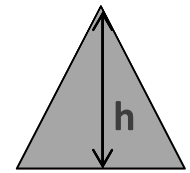
SECTION FACTOR

$SF = A_{in} / V_s$

Exposed surface A_{in} *Steel volume V_s*



Design process: optimization and fire verification

A~1.5E-2 m²	 H, HEM 300	 t, H	 D	 h	 h
PLASTIC MODULUS $W_p = \beta\ W_e$	1.8E-3 m³	7.9E-4 m³	4.1E-4 m³	4.1E-4 m³	9.7E-4 m³
SECTION FACTOR per/ A	(2H+4B-2a) / (Ha+2Bt-2ta) ~ 123 m⁻¹	~ 1 / t = 45 m⁻¹	4 / D = 30 m⁻¹	4 sqr(2) / h = 33 m⁻¹	6 / h = 38 m⁻¹
FIRE RESISTANCE AT t = 30' $W_p(t)=\xi(t)W_p$	1.2E-4 m³	1.1E-4 m³	2.1E-4 m³	1.4E-4 m³	2.3E-4 m³

Design process: optimization and fire verification

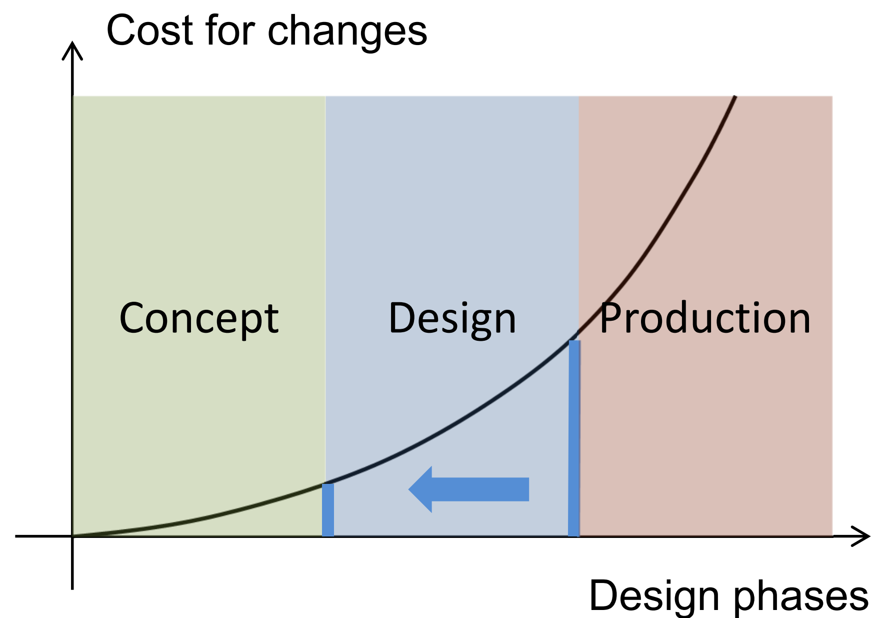
Traditional objective function: cost of steel

FO_old : $C_s = V_s \cdot \rho_s \cdot p_s$

steel weight

steel unitary cost

B.C. (1) : $M_p \geq M_{s,ULS}$



New objective function: cost of steel & insulation

$$FO\_new = C_s + C_{in} = V_s \cdot \rho_s \cdot p_s + A_{in} \cdot d_{in} \cdot \rho_{in} \cdot p_{in}$$

Insulation weight

insulation unitary cost

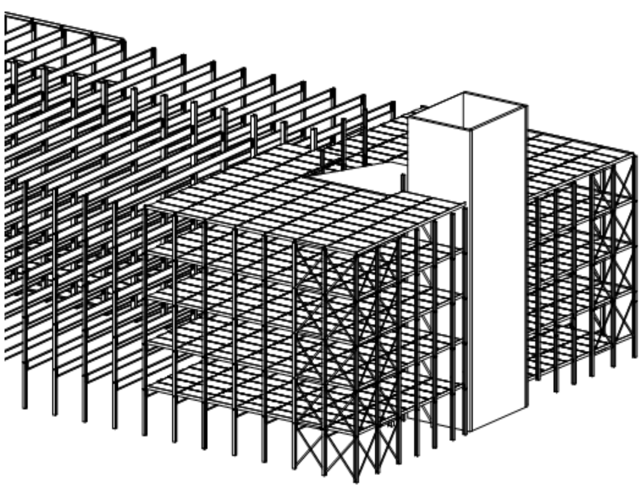
B.C. (2): $\xi(T_s) \cdot M_p \geq M_{s,fi}$

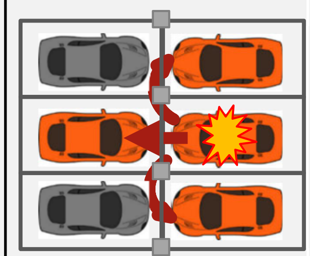
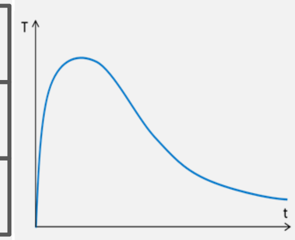
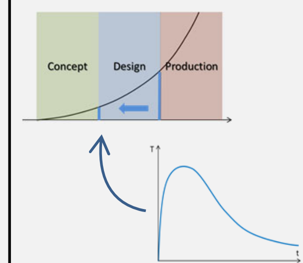
Source: Thaarup & Giuliani: "Optimized design of steel car parks for fully spread fires, NordicSteel 2019

Design process: optimization and fire verification

MULTI-STORY

STEEL CAR PARK



Design fire	Local fire	Fully developed	Fully developed early design stage
			
Profile / Element	Unprotected	Protected	Protected
Beams	IPE550	IPE550	TPS 300x200x12.5
column type 1	HEA240	HEA240	CHS 139.7x12.5
column type 2	HEB240	HEB240	CHS 168.3x12.5
Tension bracings	FL80x8	FL80x8	FL80x8
Total cost (mio €)	2.251	4.200	2.682

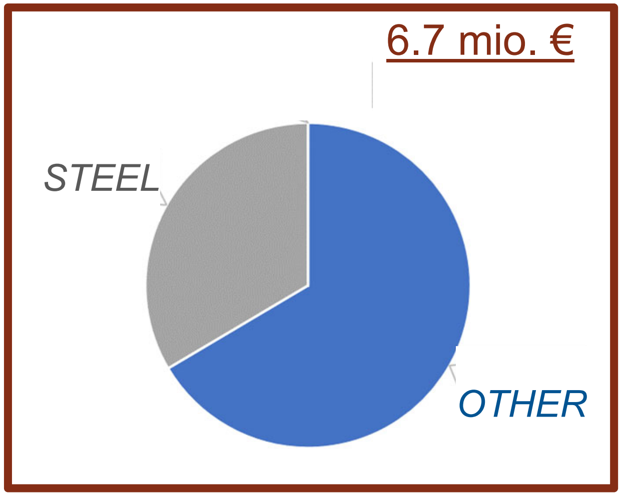
+86%

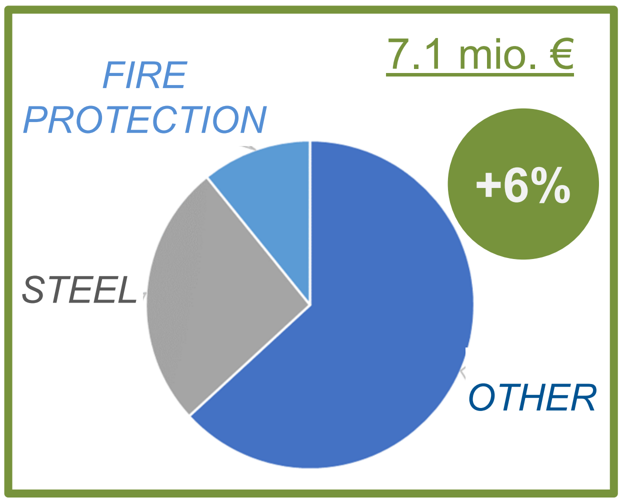
-36%

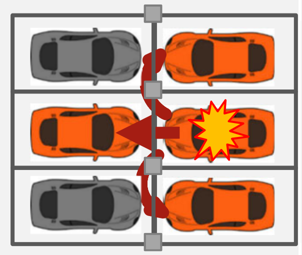
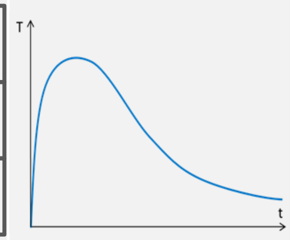
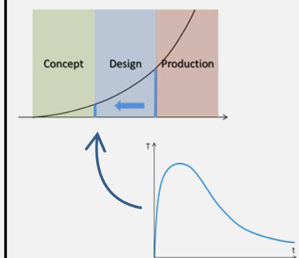
Co-funded by the
Erasmus+ Programme
of the European Union

<u>Source</u>: *Thaarup & Giuliani: "Optimized design of steel car parks for fully spread fires, NordicSteel 2019*

Design process: optimization and fire verification





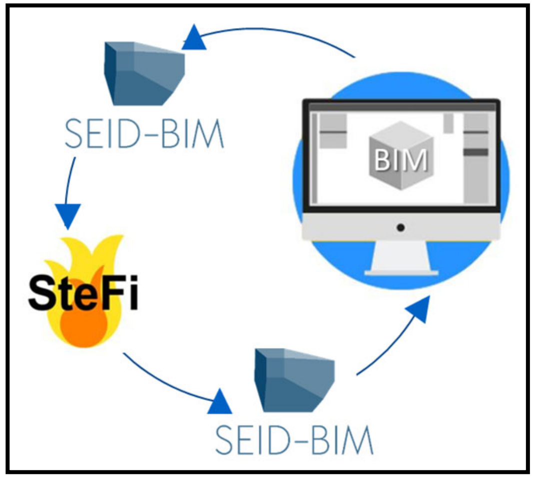
	Local fire	Fully developed	Fully developed early design stage
Design fire			
Profile / Element	Unprotected	Protected	Protected
Beams	IPE550	IPE550	TPS 300x200x12.5
column type 1	HEA240	HEA240	CHS 139.7x12.5
column type 2	HEB240	HEB240	CHS 168.3x12.5
Tension bracings	FL80x8	FL80x8	FL80x8
Total cost (mio €)	2.251	4.200	2.682

+19%

Integrated SFS design

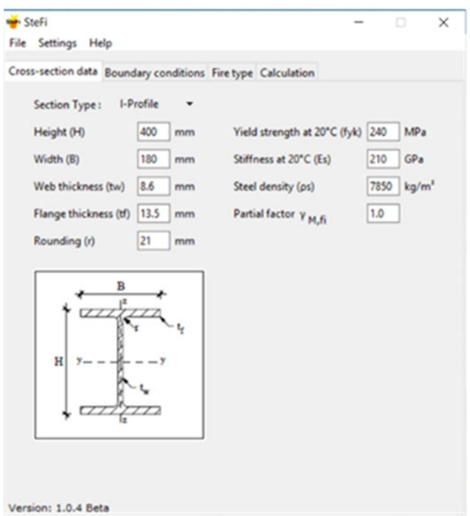
SteFi – Steel in Fire

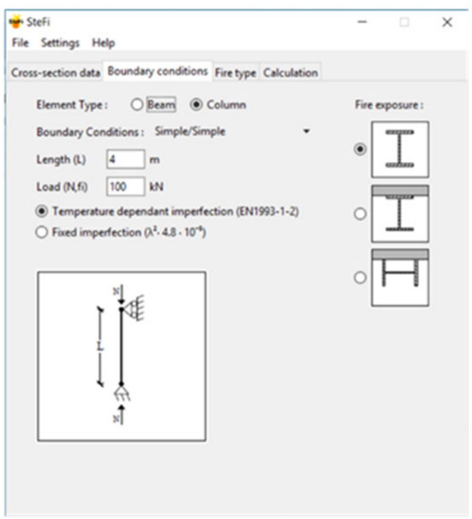
- Standard and Parametric fire
- 0.2% and 2.0% strength
- Libraries for steel profiles and insulation materials
- Calculation of load capacity
- Design of required insulation

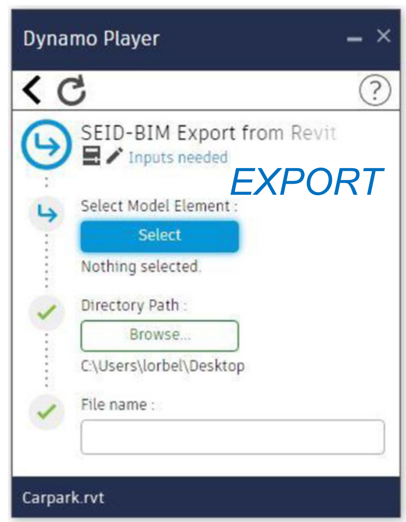


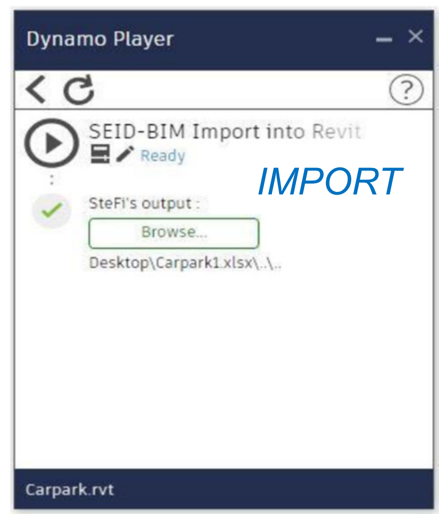
Struct. Exp./Imp. of Data for BIM – SEID-BIM

- Export geometry and material propert. of a steel element from Revit
- Import geometry and material properties of the insulation into Revit
- Compatible with the IFC format









DOWNLOAD: https://www.byg.dtu.dk/Forskning/Publikationer/Software/SteFi

OUTLINE

- *Recent major fires*
- *Design shortcomings*
  - *Design fire*
  - *Structural design*
  - *Design process*
- *Conclusive remarks*

DTU Civil Engineering
Department of Civil Engineering

Co-funded by the Erasmus+ Programme of the European Union

Conclusion

- Major fires and collapses of buildings and car parks indicate shortcoming in current methods for SFS design methods
- Design issues are highlighted on both thermal and mechanical assumptions
  - Fire: local fires in car parks, outdated resistance classes in modern buildings
  - Structure: neglected indirect stresses, effective yielding, neglected cold condition
  - *This is not an exhaustive list!* (timber buildings and connections, reduction of mechanical loads, uncertain performance of intumescent paint, early HCS failure,...)
- Ample margins of improvement: e.g. early inclusion of SFS in design process allows for reduction of costs while maintaining conservative assumptions

Co-funded by the Erasmus+ Programme of the European Union

K-FORCE

DTU
DTU Civil Engineering
Department of Civil Engineering

Co-funded by the
Erasmus+ Programme
of the European Union

Thank you for your attention

Luisa Giuliani – lugi@byg.dtu.dk

Knowledge FOr Resilient soCiEty