Fire Safety Timber Engineering –
Past, present and future

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World Conference on Timber Engineering

Oslo, June 19, 2023

Das Empire State Building in Midtown Manhattan Foto: MIKE SEGAR / REUTERS

Wildfires in the forests

Climate change

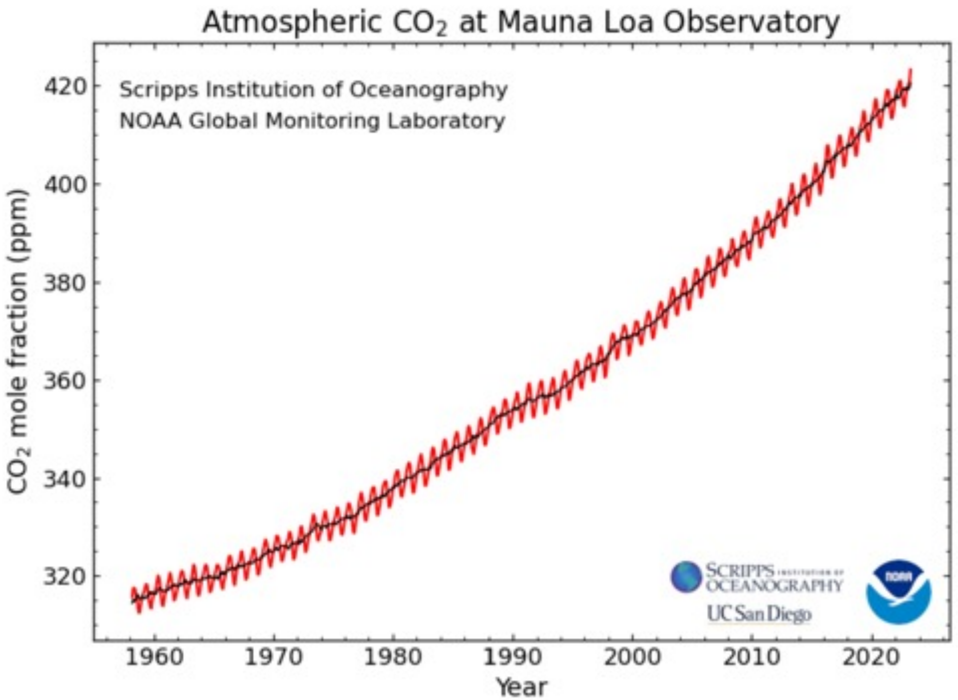
2023 February: 420.41 ppm

2022 February: 419.28 ppm

2021 February: 416.75 ppm

2018 February: 408.53 ppm

2017 February: 406.67 ppm



2°C scenario: 475 ppm

1.5°C scenario: 425 ppm

Fires in the past destroying cities

Fires in the present

Timber: critical points

Fire resistance and separation of walls and floors

Fire behaviour of connections with steel elements

Fire behaviour of glued timber (influence of adhesives)

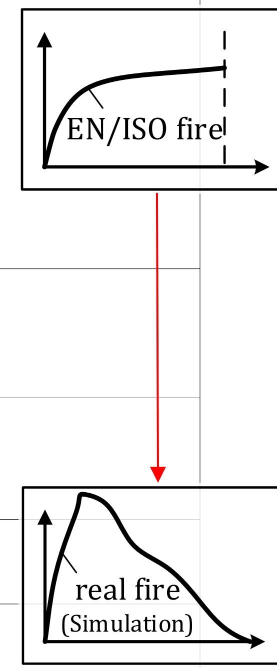
Fire propagation on combustible surfaces and in cavities

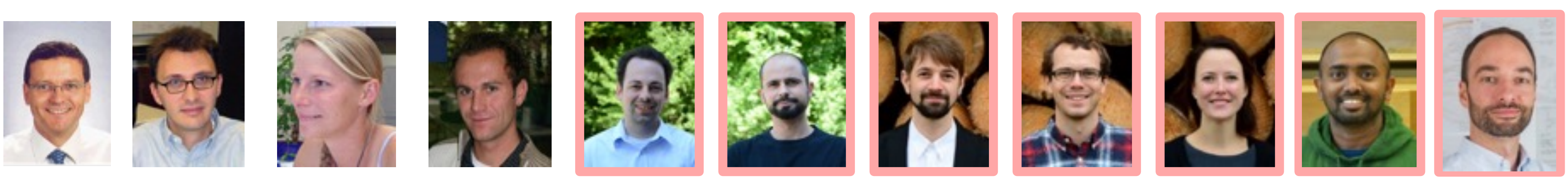
Increase of fire load – fire dynamics

……

Research projects at ETH Zurich (1992-2023)

Fire resistance of timber structures	Experiments
Fire resistance and separating function of walls and floors - Timber-concrete composite slabs - Timber slabs made of hollow core elements - Cross-laminated timber slabs - Light timber frame wall assemblies	Fire tests under ISO-fire
Fire resistance of connections with steel elements	Fire tests under ISO-fire
Fire safety of bonded structural timber elements Glueline integriy in fire	Fire tests under ISO-fire
Natural fire exposure of structural timber	FANCI, Fire simulator
Fire dynamics in timber structures	Compartment fire tests






Walls


Floors

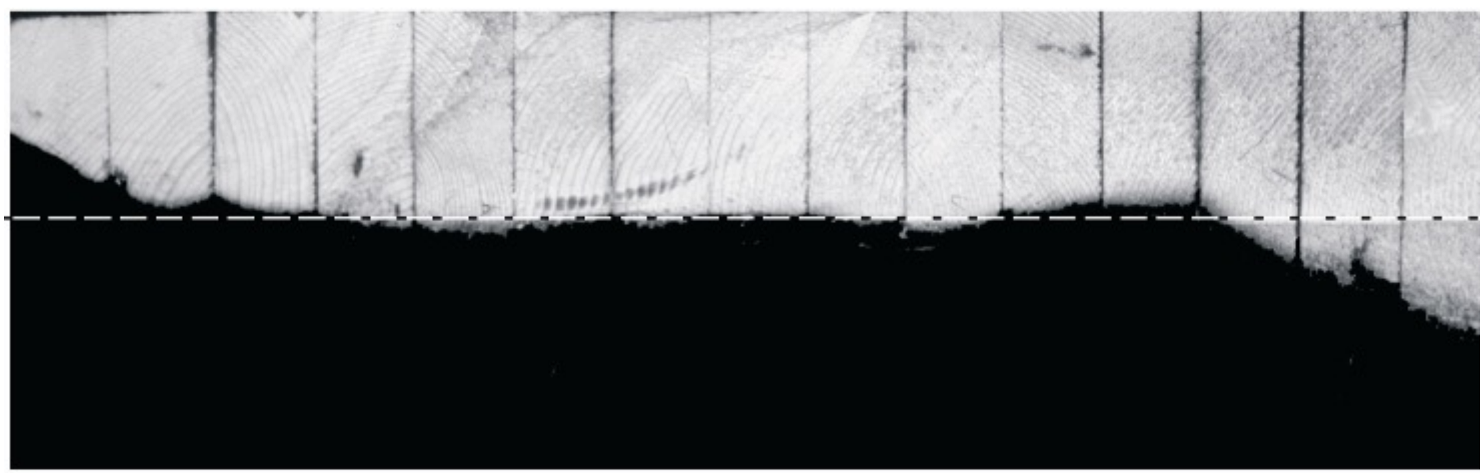

Compartment fire tests

Fire resistance and separating function of walls and floors

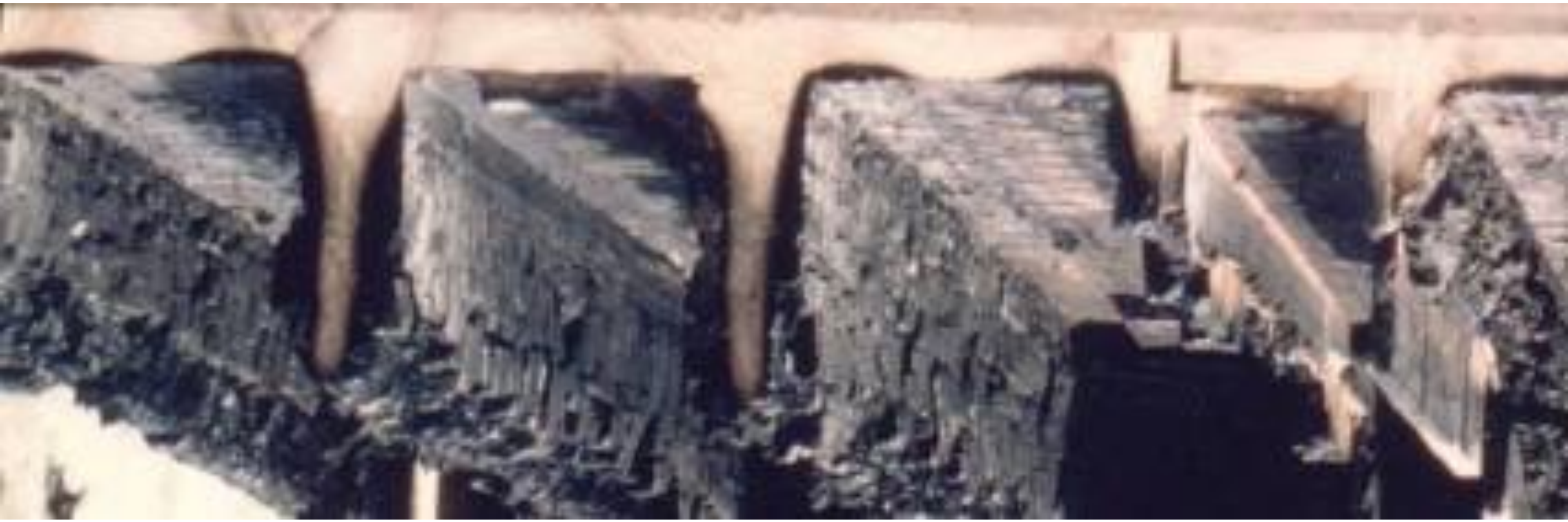
Fire spread after 50 minutes ISO fire by a nailed laminated timber slab withou
additional layer on the fire unexposed side

Fire resistance of nailed laminated timber slabs

- Nailed or dowelled laminated timber slabs with cladding on the fire unexposed side to guarantee the tightness
  - Charring similar to solid wooden slabs
  - Charring rate: about 0.7 mm/min



Fire resistance of slabs made of hollow core elements (small sections)



Residual cross-section of timber slabs made of hollow core elements after 30 min ISO-fire

Fire resistance of timber-concrete composite slabs

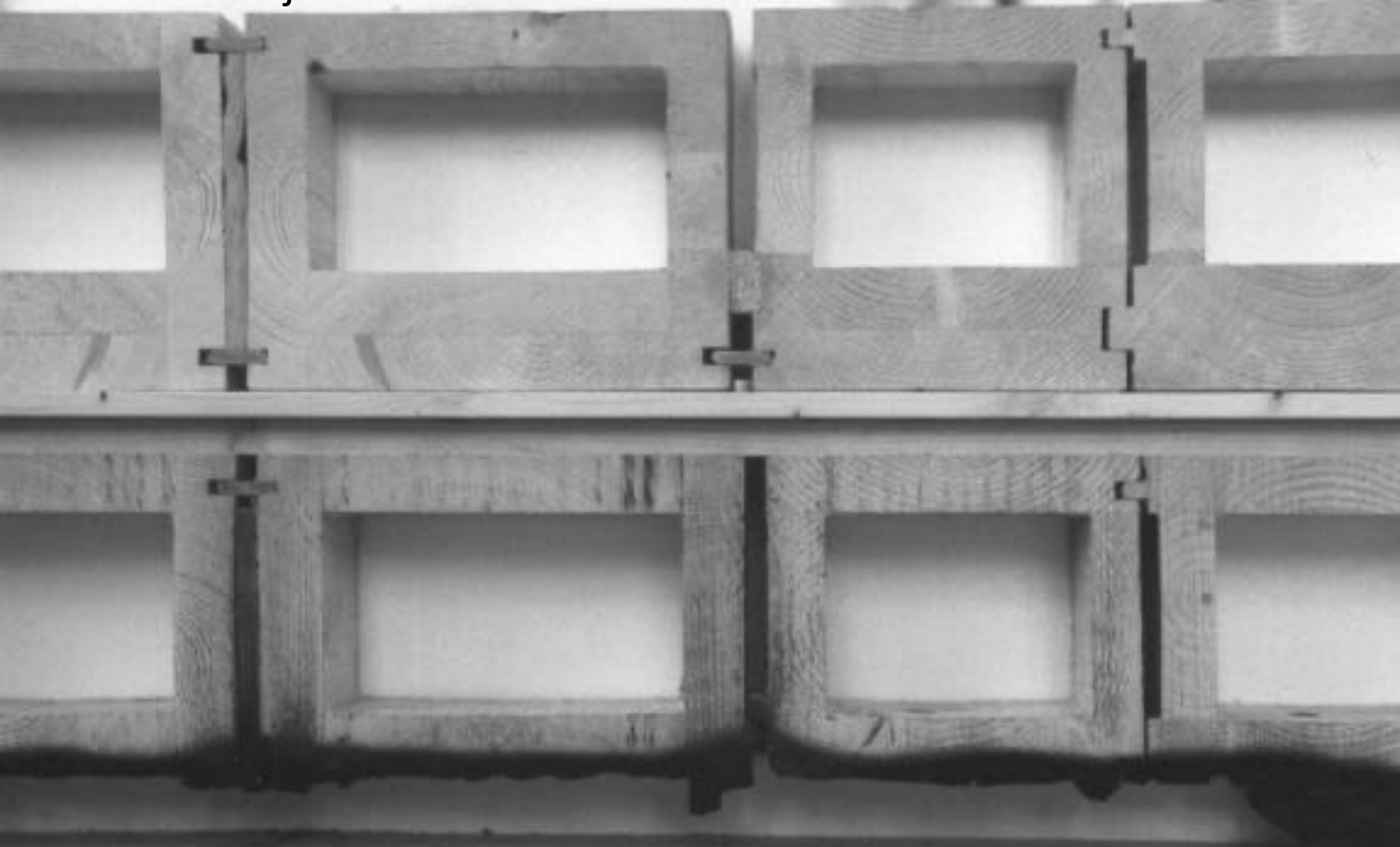
Fire test on loaded timber-concrete composite slab

Fire resistance of timber elements

Basic strategies

- Use of massive large cross-sections
- Increase of cross-sections by charring depth
- Protection of the timber elements with (non-) combustible materials

Influence of joint between timber hollow core elements



Residual cross-section after 60 minutes ISO-fire

Fire separating function of walls and floors

Basic strategies

- Gaps, joints backed by other layers
- Cavities filled with non combustible materials like mineral wool
- Multi-layered timber elements
- Coverings, fire protection system, membranes

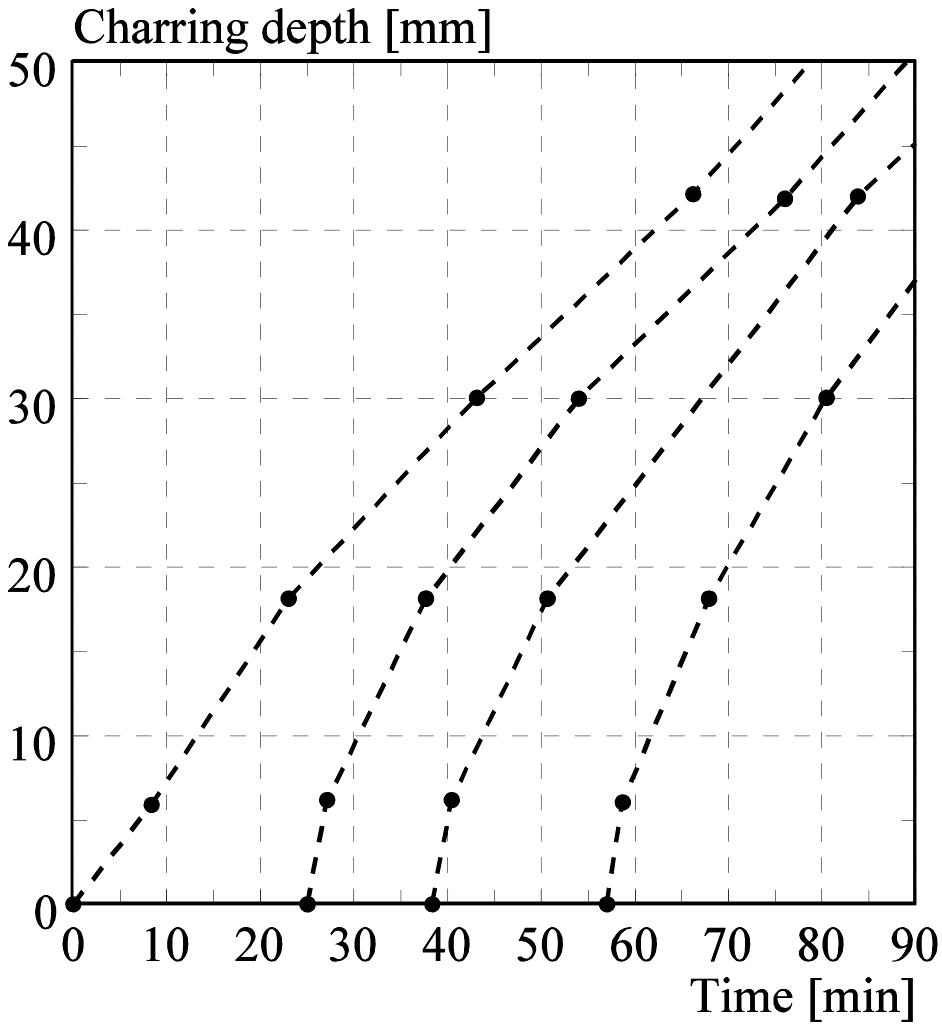
Favorable timber elements

- Timber-concrete composite slabs
- Cross-laminated timber (CLT) elements

Influence of fall off of fire protection system

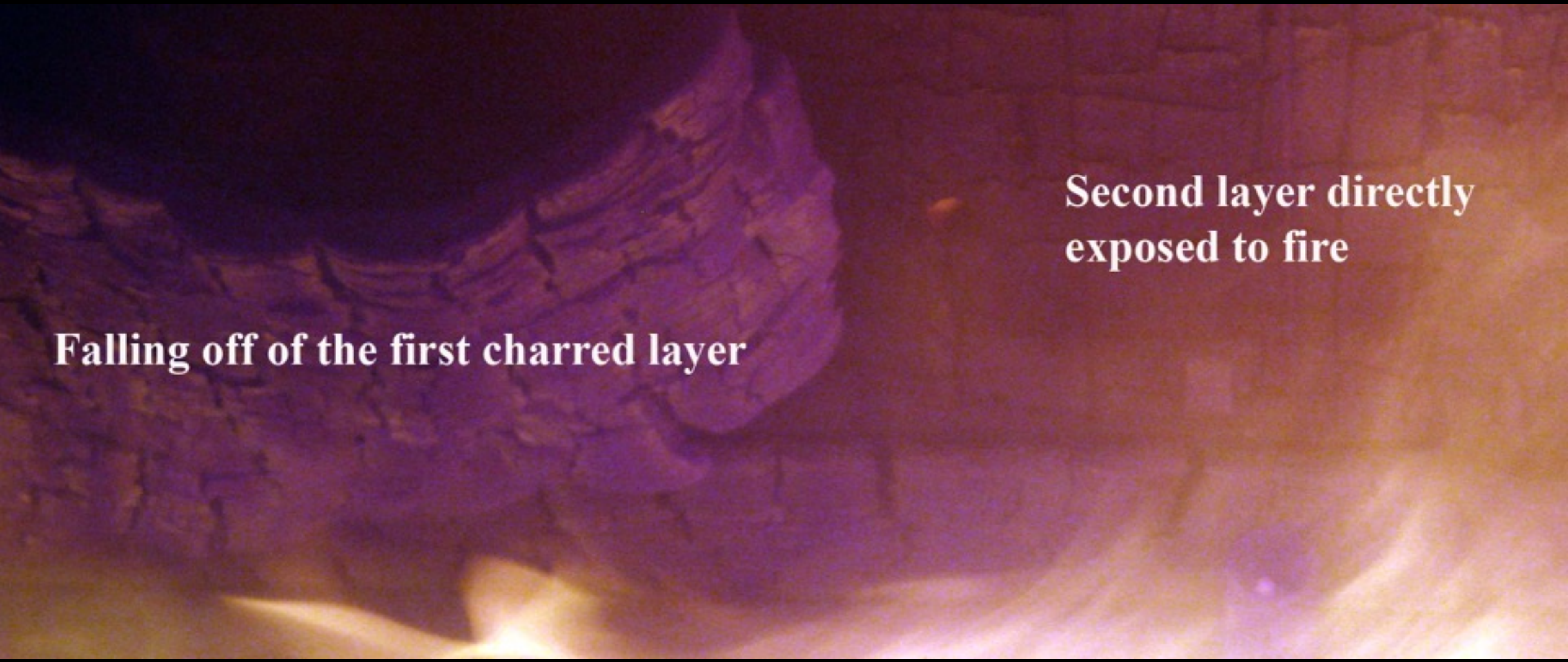
Timber slab after 17 minutes ISO-fire

Influence of fall off of fire protection system



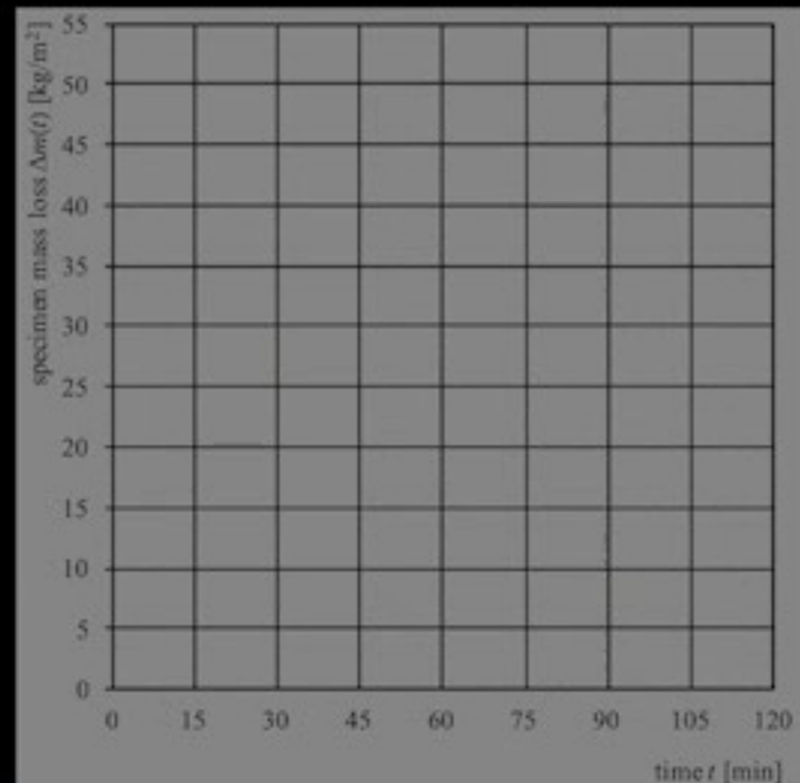
Increased charring rate observed after failure of the fire protection system is due to temperature **high level** while no protective **char-layer** exists to reduce the effect of the temperature. Influence of **preheating** not relevant!

Cross-laminated timber panels after 55 minutes ISO-fire

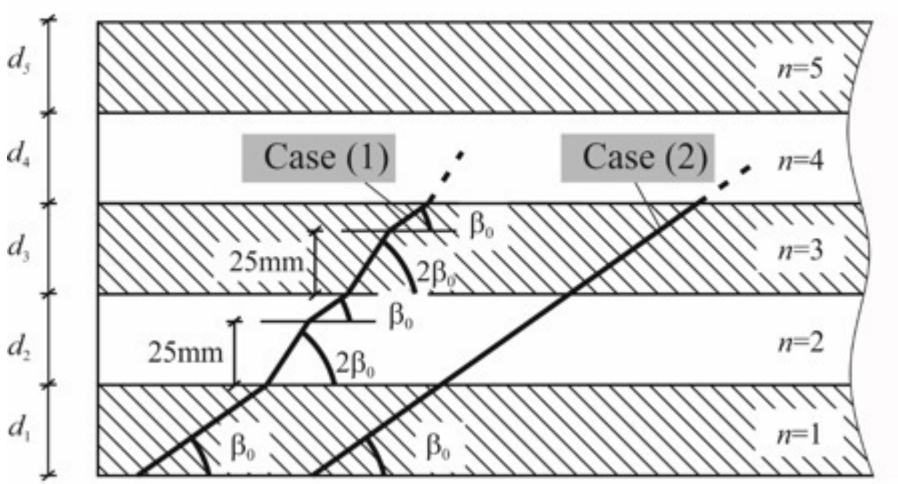

Second layer directly
exposed to fire
Falling off of the first charred layer

1. CLT I


IGNIS
ETH zürich


specimen mass loss Δm(t) [kg/m²]
0
5
10
15
20
25
30
35
40
45
50
55
0
15
30
45
60
75
90
105
120
time t [min]

Simplified charring model ("step model")



with Layer thickness d_n, Charring rate β_0= 0.65 mm/Min

CASE 1

- 1st layer: one-dimensional charring rate

  β_0=0.65 mm/min

- If falling off of 1st layer:

  2· β_0=1.3 mm/min

  until 25mm of char layer has been formed

CASE 2

- If no falling off of 1st layer:

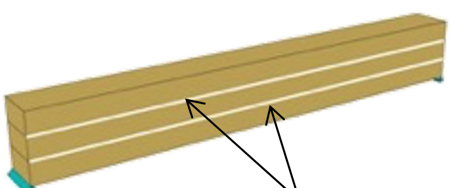
  β_0=0.65 mm/min

Fire safety – Bonded structural timber elements

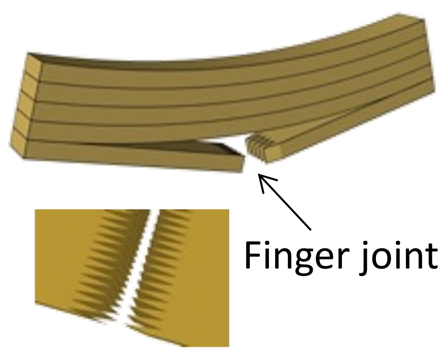
Use of adhesives in bonded structural timber members

Glued laminated timber (glulam)

Between lamellas



Finger joint

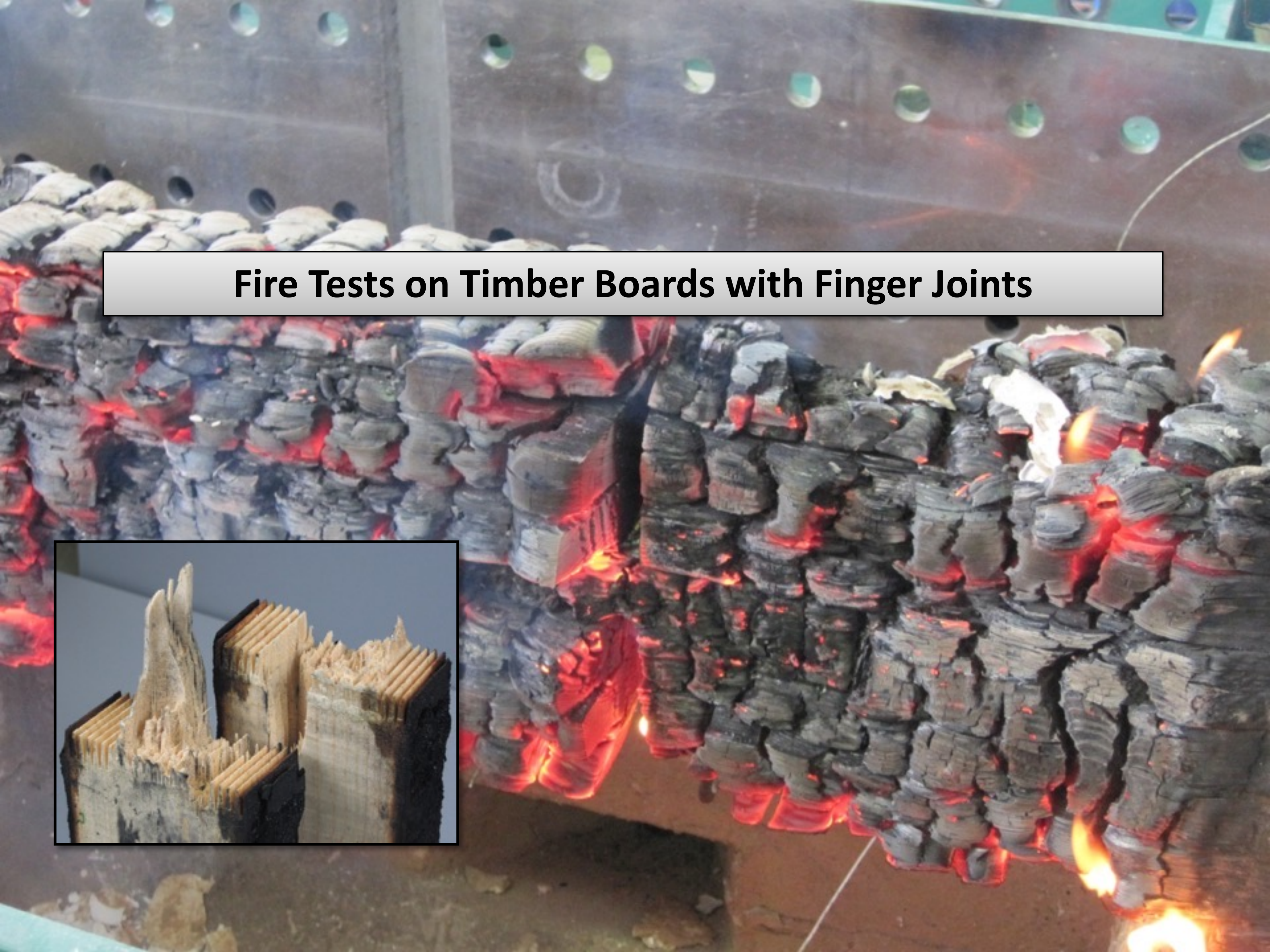


Adhesive has no significant influence on the load-carrying capacity in fire

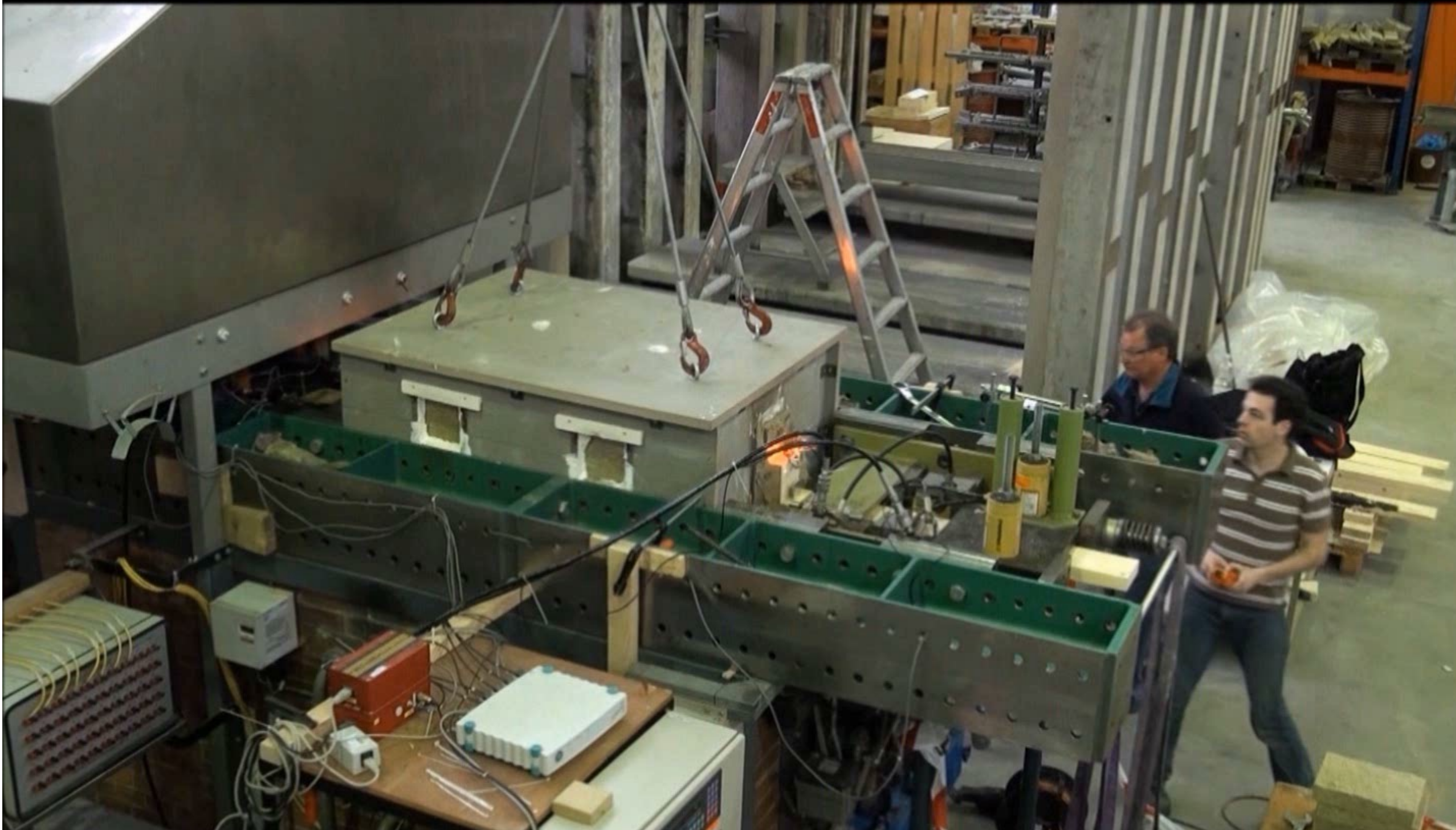
Cross-laminated timber (CLT)

Adhesive has influence on the load-carrying capacity in fire

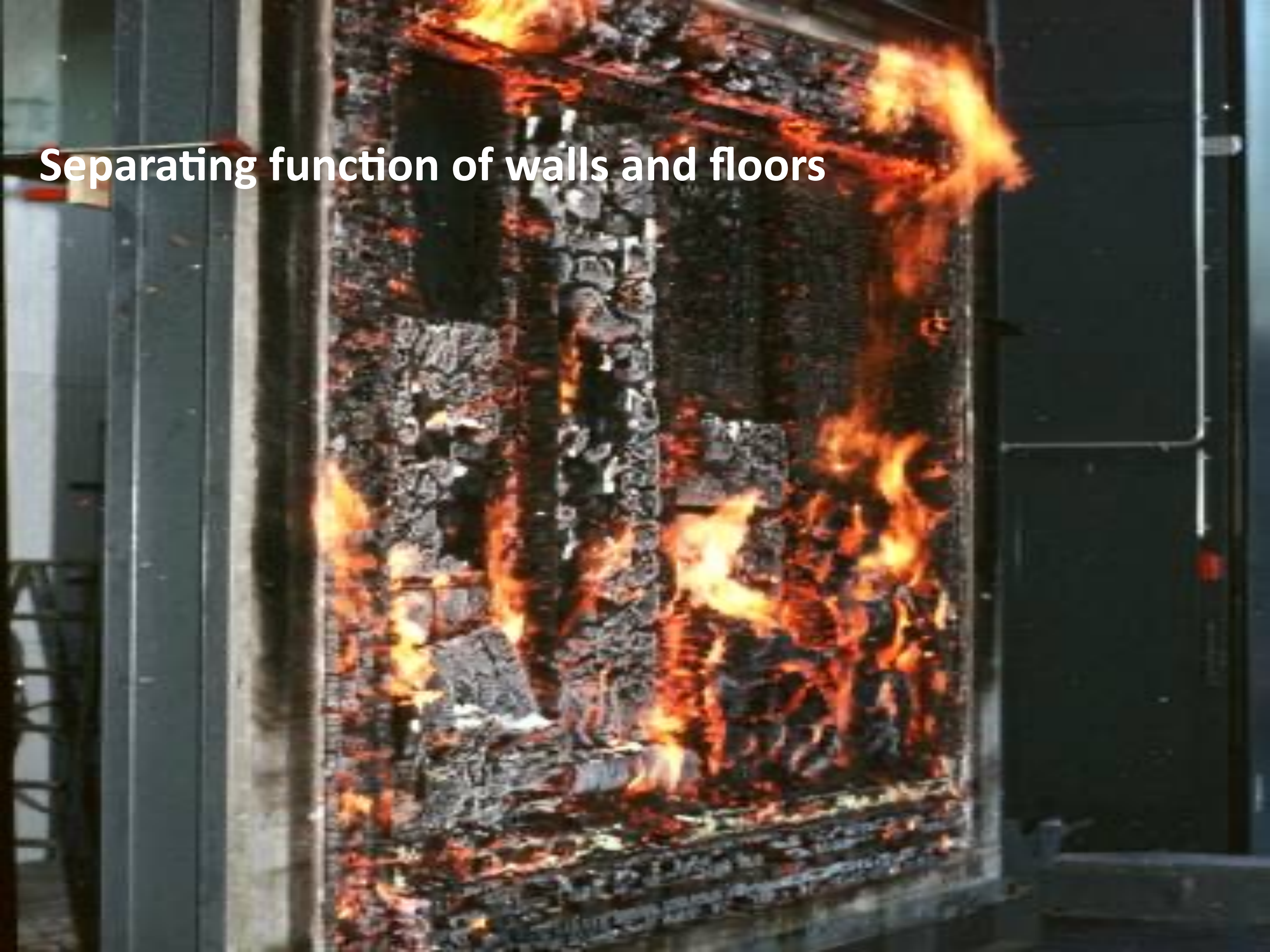
Fire Tests on Timber Boards with Finger Joints



After Failure: Disassembling of the specimen



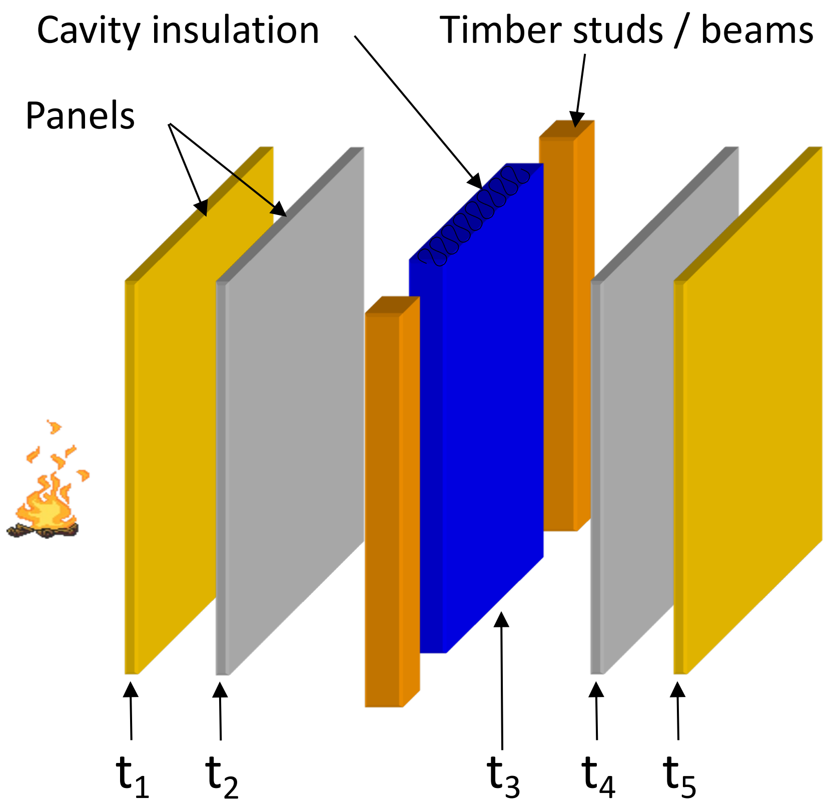
Separating function of walls and floors



Separating function method (simplified method)

Calculation of the time t_{ins} by adding the contribution to the fire resistance of the different layers

$$t_{ins} = \sum_{i=1}^{i=n-1} t_{prot,i} + t_{ins,n}$$



The time of each layer depends on:

- Material and thickness of the layer
- Position of the layer within the assembly

The position has to be considered, because layers influence each other

⇒ $t_1 \neq t_5$

Connections with steel elements in fire

Fire test with a multiple shear steel-to-timber dowelled connection

Connections with steel elements in fire

Connections with **side** steel plates

Connections with **slotted-in** steel plates

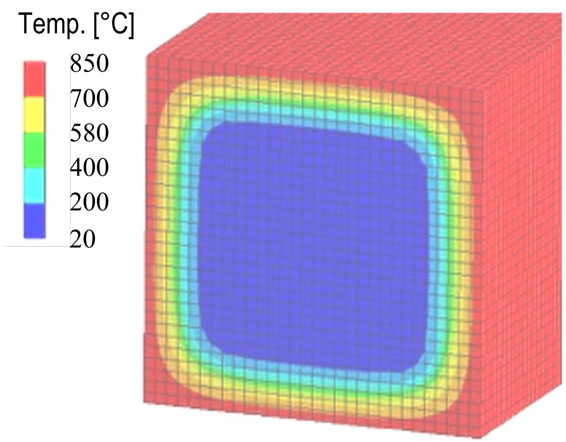
Connection with side steel plates and annular ringed shank nails

Multiple shear steel-to-timber dowelled connection

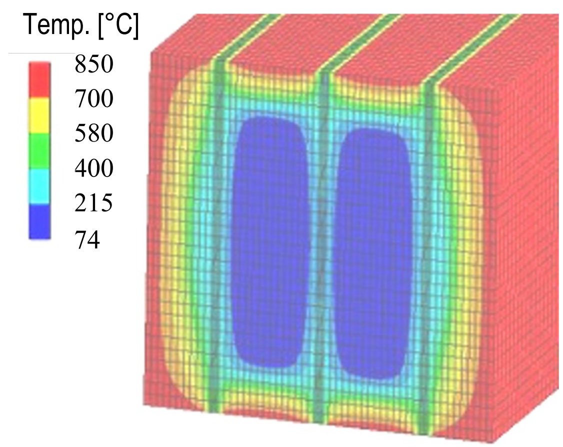
Charring behaviour

Influence of steel plates and steel dowels on charring

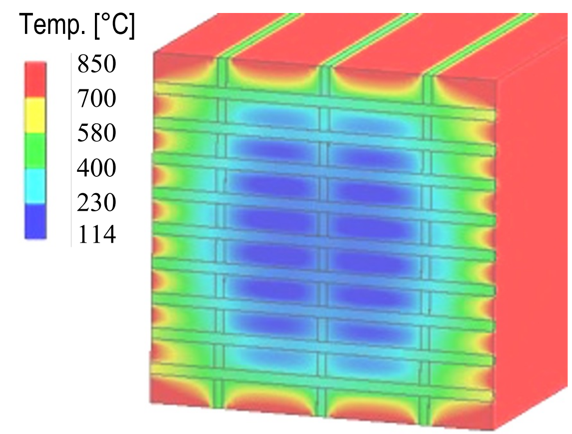
Timber



Timber with steel plates



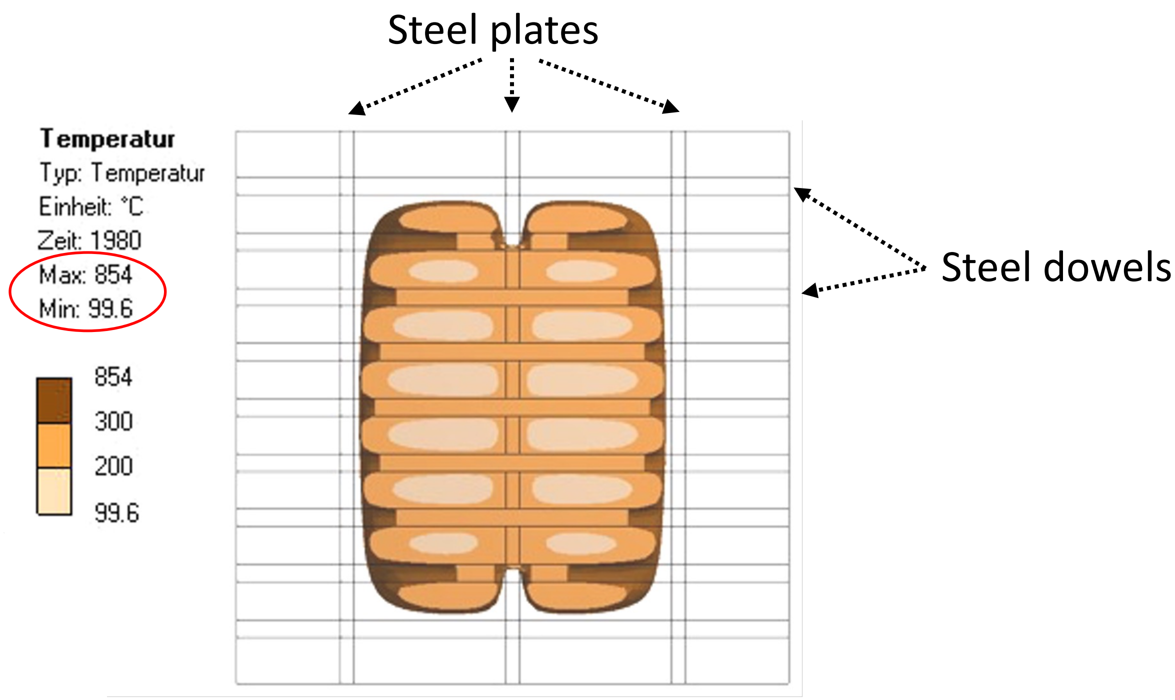
Timber with steel plates and steel dowels



Charring behaviour

Comparison between FE-thermal analysis and fire test

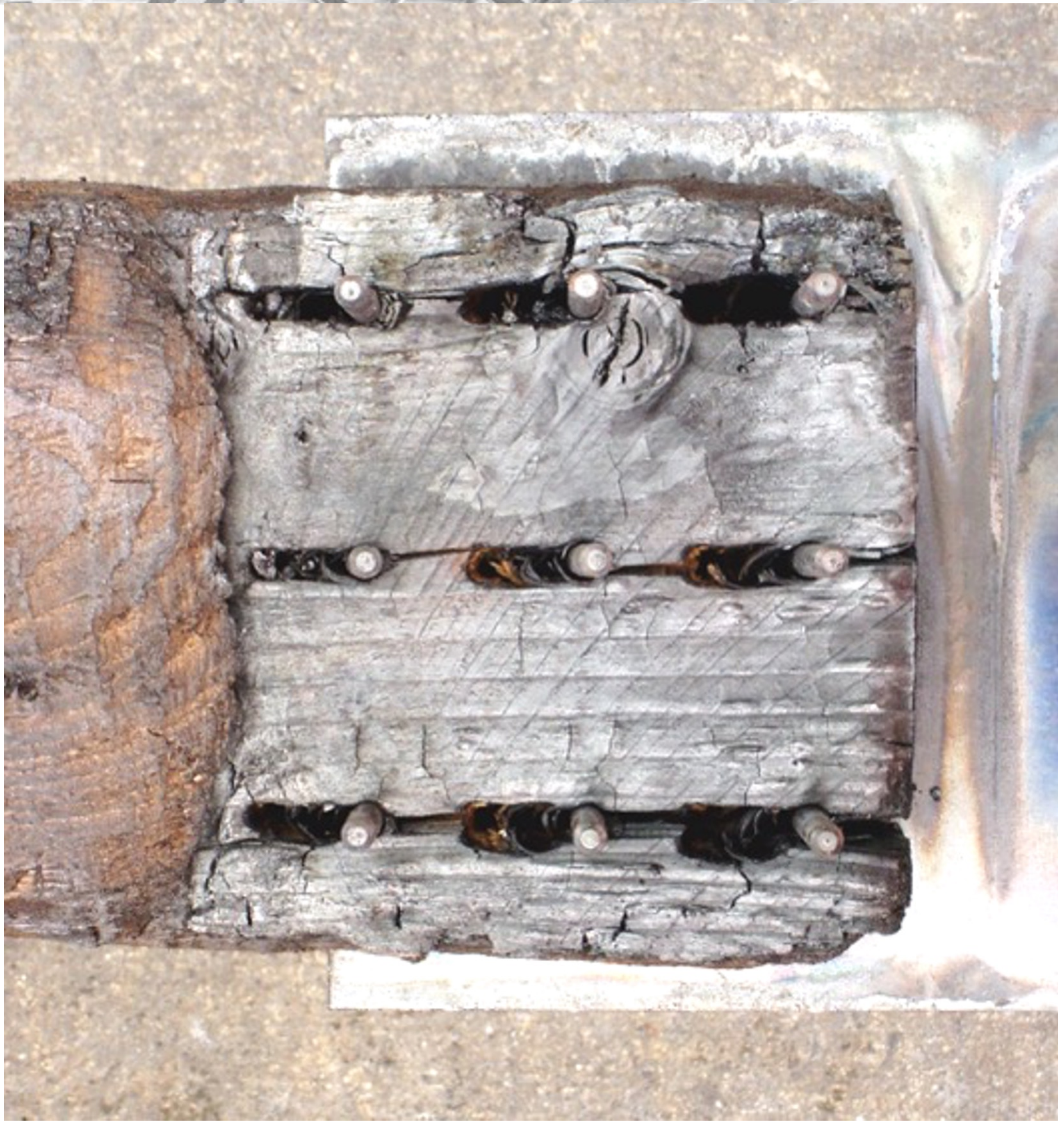
Connection D01.1 (33 min)



FEM (33 min)

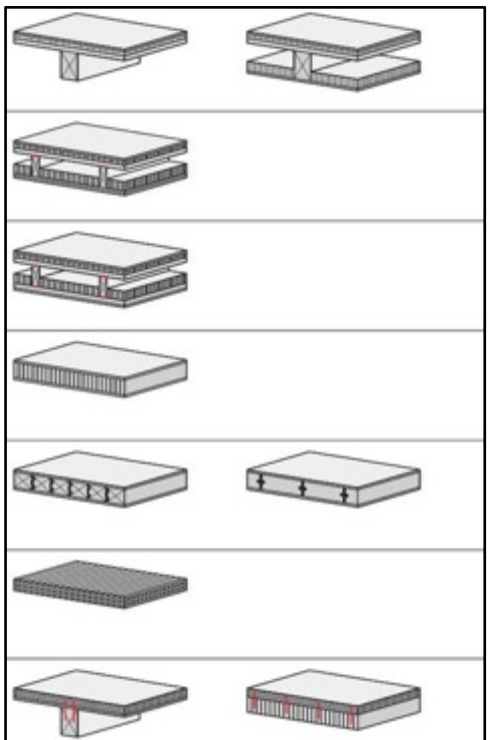
Results of fire tests

Connections failed by embedment failure, i.e. failure mode I according to the Johansen yield model



Tall timber buildings and mass timber

- More severe requirements
- Design for burnout?



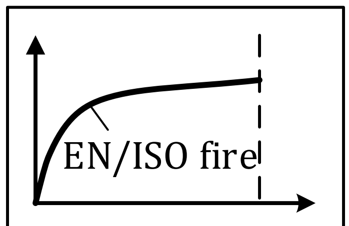
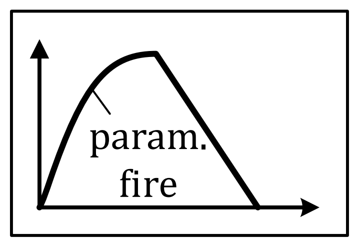


Image: Matt Hughes

Image: Woschitz Group



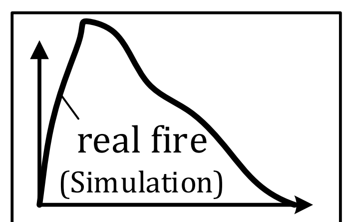


Image: PLP

Influence of combustible surfaces (1999)

Fire after 7 minutes after fire ignition

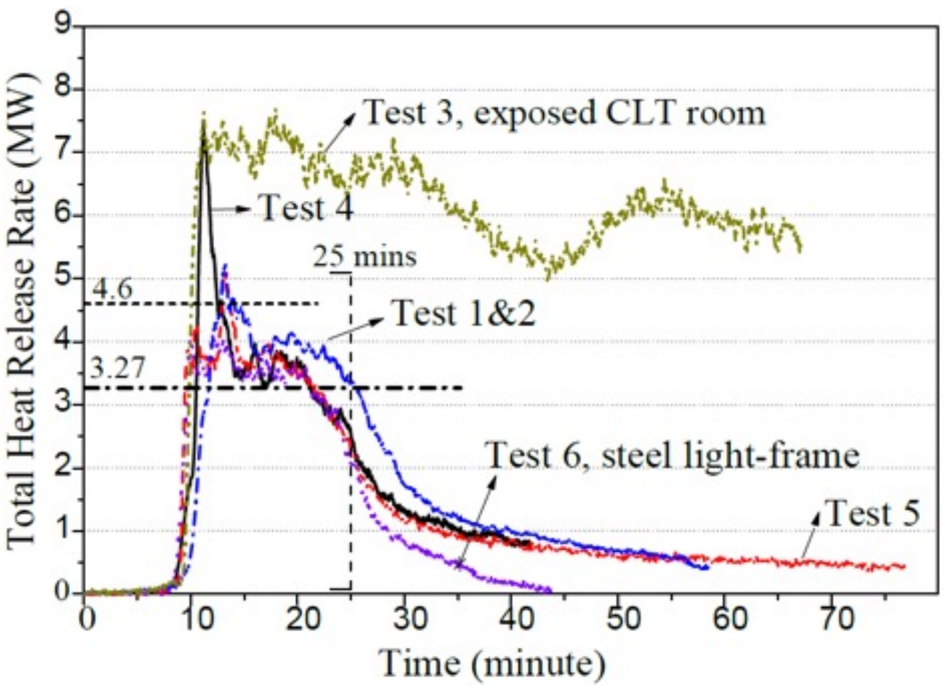
Combustible

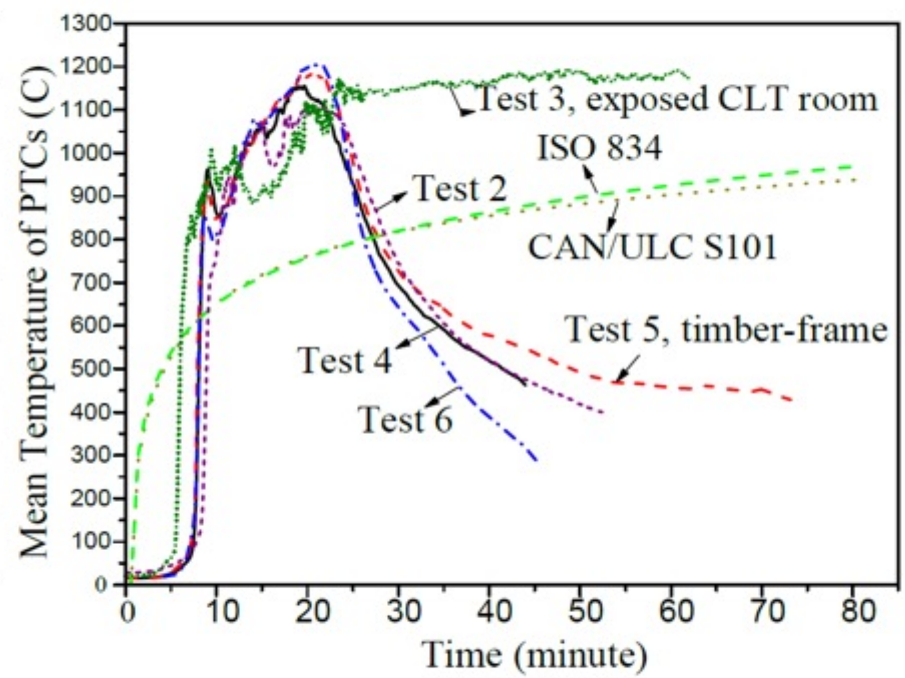
Non combustible

Influence of combustible surfaces

Recently many compartment fire tests

- CLT Compartment Fire Tests 2012, Carleton University, Ottawa, Canada
- CLT Compartment Fire Tests 2016, Arup and University of Edinburgh, UK
- CLT Compartment Fire Tests 2017, NFPA Fire Protection Research Foundation
- CLT two-story, full-scale fire tests 2017, ForestProducts Laboratory (FPL), American Wood Council (AWC), U.S. Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF)
- ……

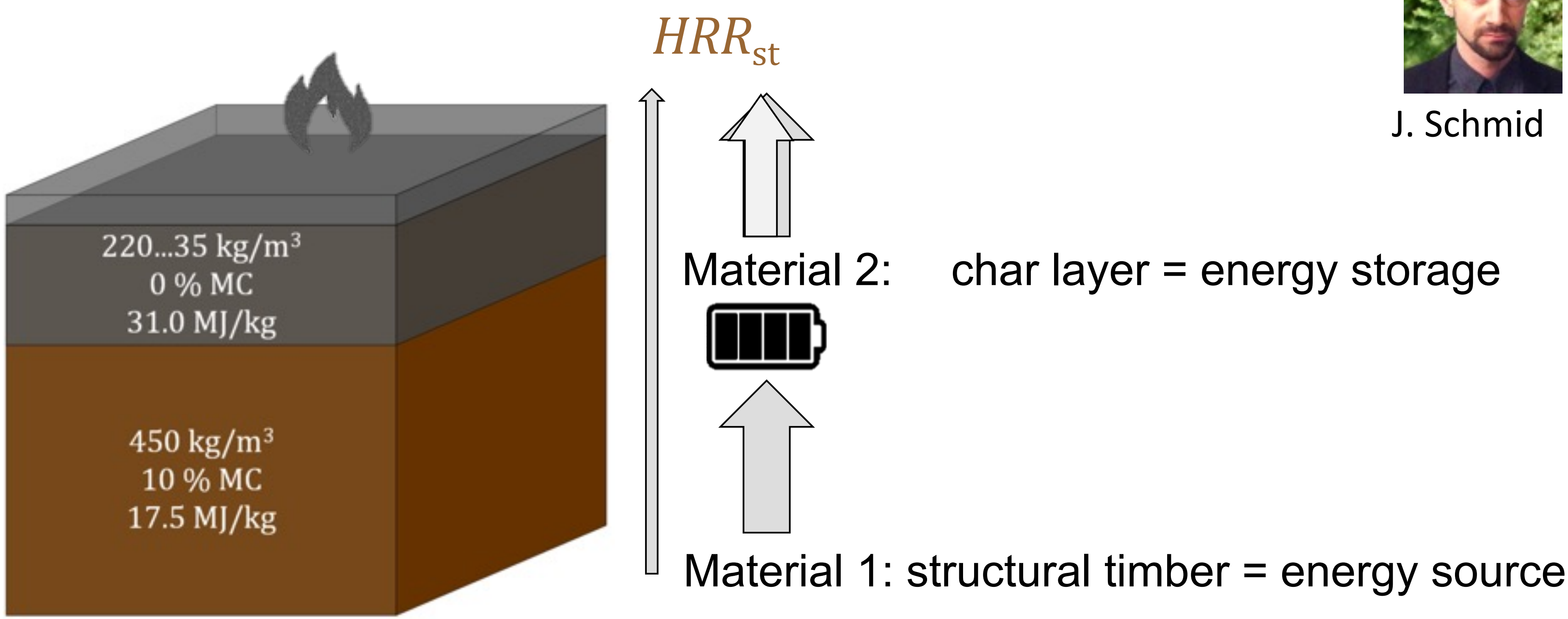




CLT Compartment Fire Tests 2012, Carleton University, Ottawa, Canada

Timber Charring and Heat Storage (TiCHS) - Model

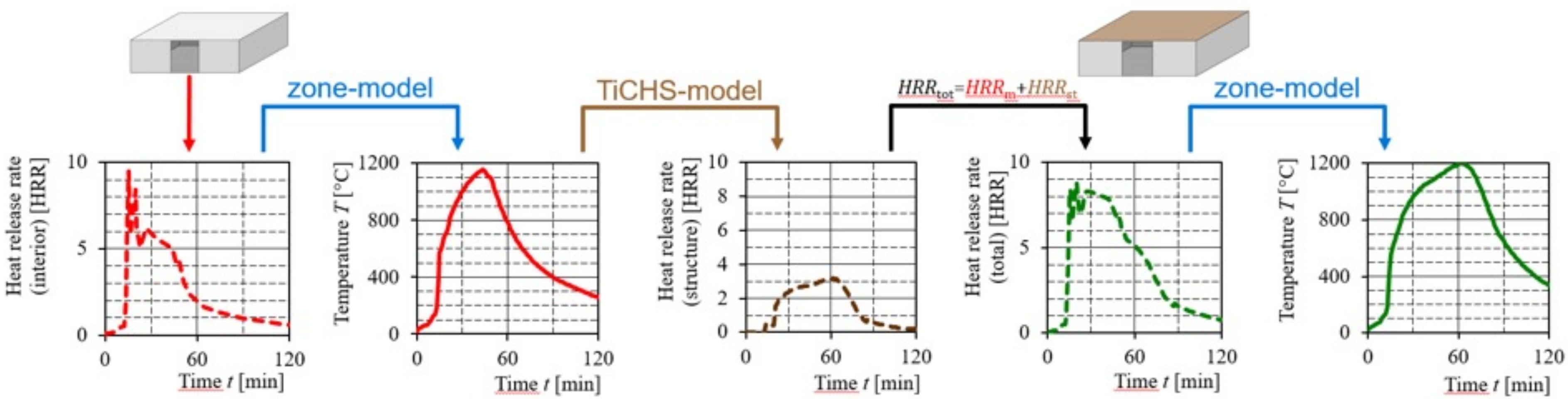
Design model considering the influence of the char layer



Timber Charring and Heat Storage (TiCHS) - Model

Procedure

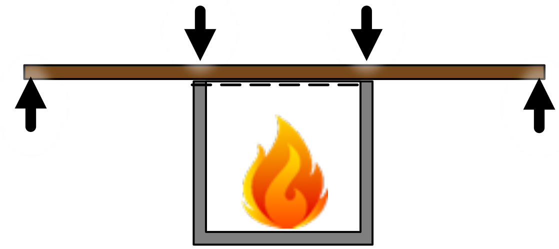
- Calculation of the energy balance structure-compartment-exterior → zone-model + TiCHS-model
- Novelty: Calculation of the “sum” of the movable fire load and the structural fire load



Fire load = movable fire load ”+” structural fire load

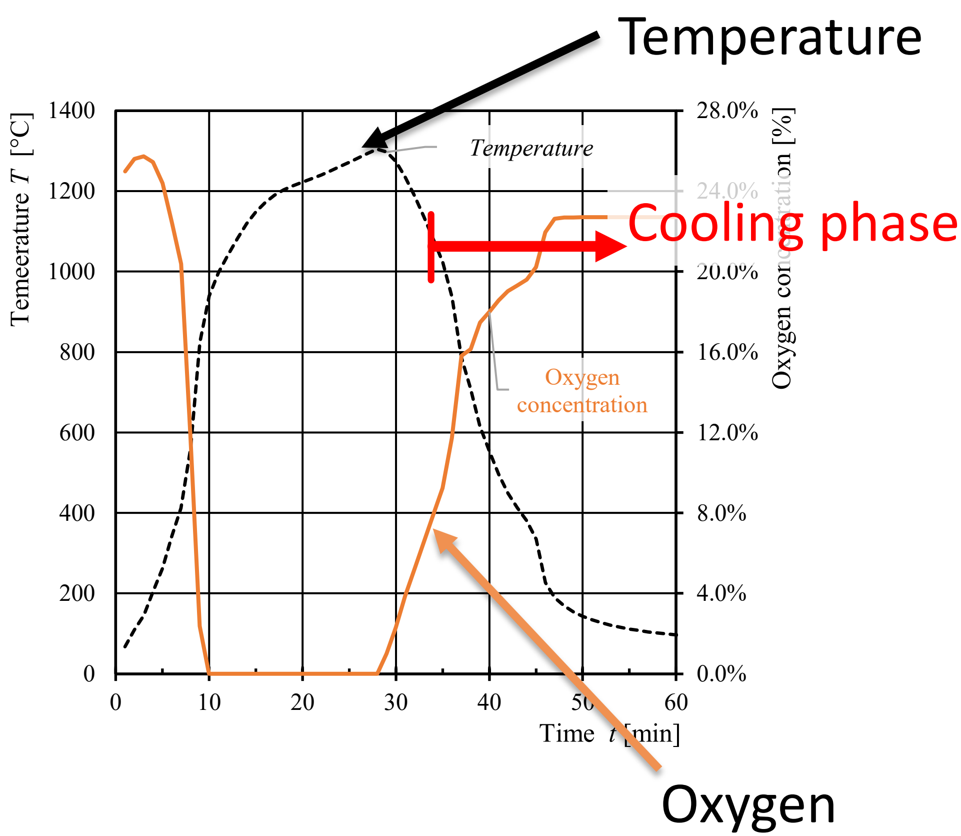

E-THERM
ETH zürich
E-THERM
New fire simulator
at ETH Zurich

New fire simulator at ETH Zurich



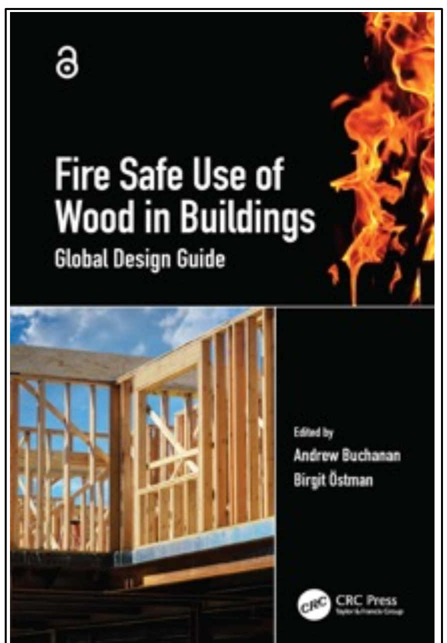
Full scale specimens (4-point bending)

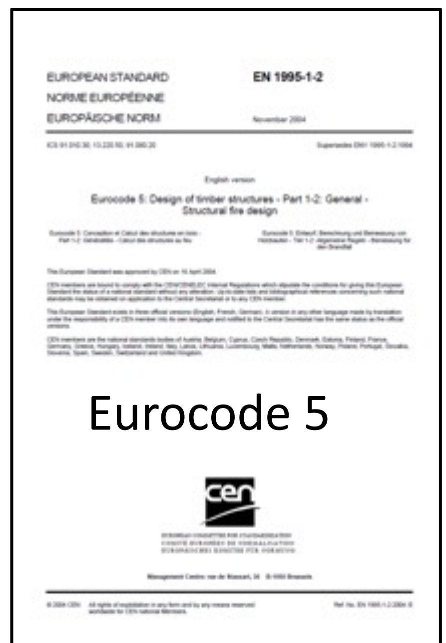
Any fire environment (time-temperature **AND** oxygen concentration)

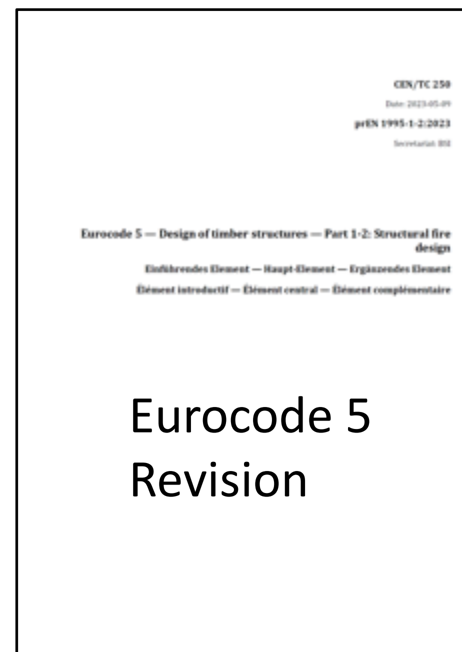


Fire design of timber structures

Novel calculation models for fire resistance of timber structures were developed based on extensive element and full scale testing



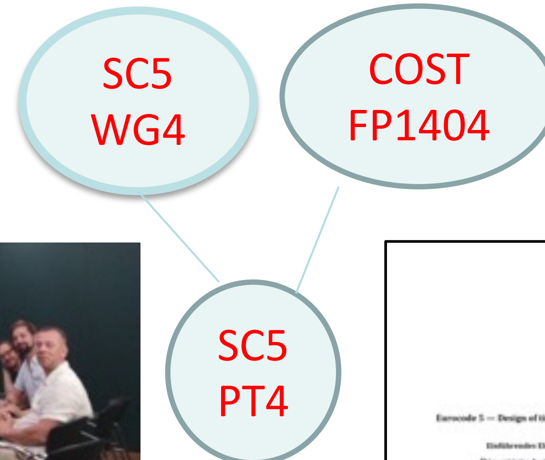




New Eurocode 5, fire part (prEN 1995-1-2)

CEN TC250 SC5 PT4

Project Team for drafting the fire part of Eurocode 5



Members PT
Andrea Frangi (Chair, ETH Zurich)
Jouni Hakkarainen (Eurofins)
Alar Just (Rise & Taltech)
Joachim Schmid (ETH Zurich)
Norman Werther (TU Munich)

Additional members PT+
Renaud Blondeau (Stora Enso)
Harald Krenn (KLH)
Gordian Stapf (Henkel)


CEN/TC 250
prEN 1995-1-2:2023
Eurocode 5 — Design of timber structures — Part 1-2: Structural fire design

Tasks

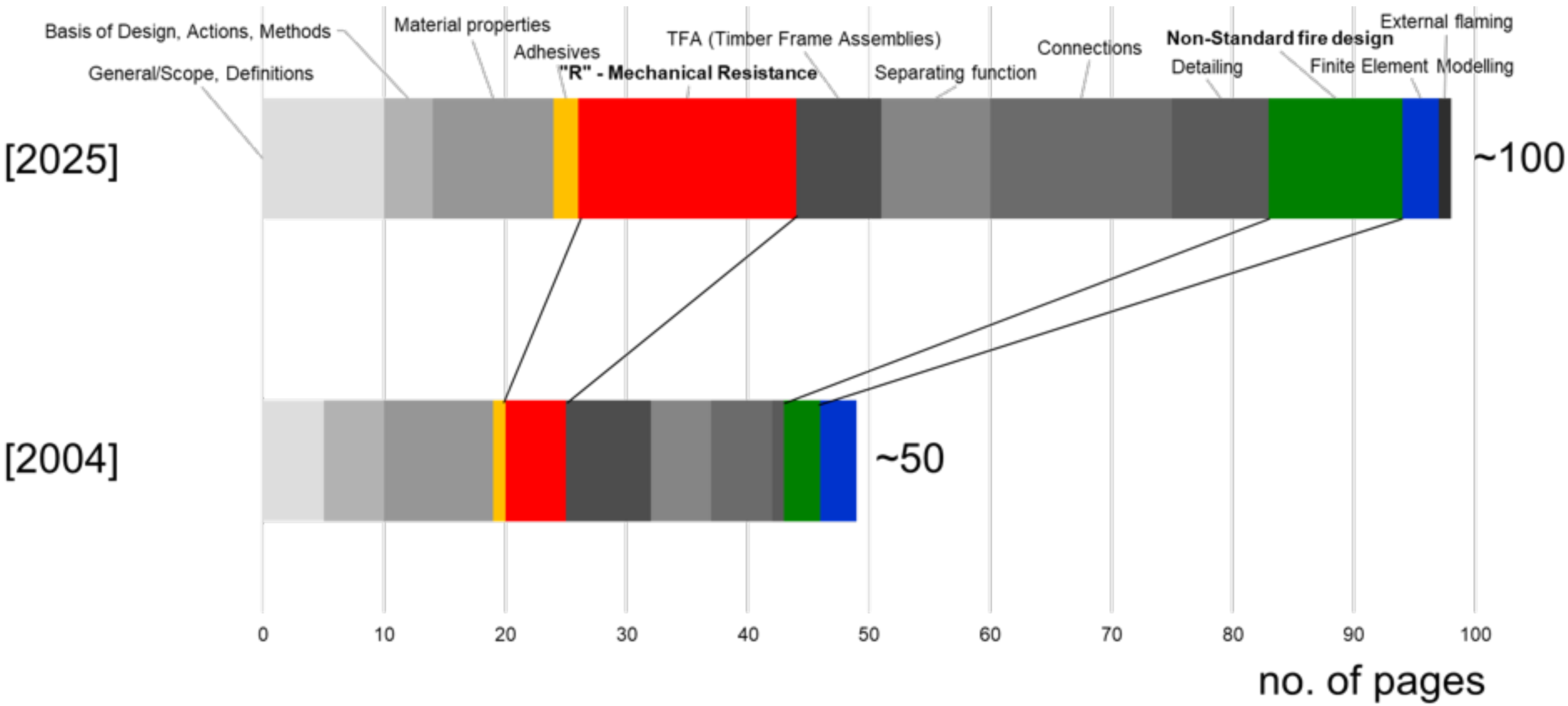
June 2018	Start of the work
April 2019	1st draft
April 2020	2nd draft
October 2020	3rd draft
April 2021	Final draft
September 21	Informal Enquiry
September 23	Formal Enquiry
April 25	Formal Vote
September 27	Last standard piblication
30 March 2028	Withdrawal Eurocodes

New Eurocode 5, fire part (prEN 1995-1-2)

	1. Draft	2. Draft	3. Draft	Final draft	Informal Enquiry
Doc. No.	22	46	69	87	93
Date	04.05.2019	03.05.2020	31.10.2020	03.05.2021	05.09.2021
Pages tot.	75	134	138	149	148
Pages Main part	74	106	99	103	98
Pages Annexes	1	28	39	46	50
Comments received	265	624	364	-	396

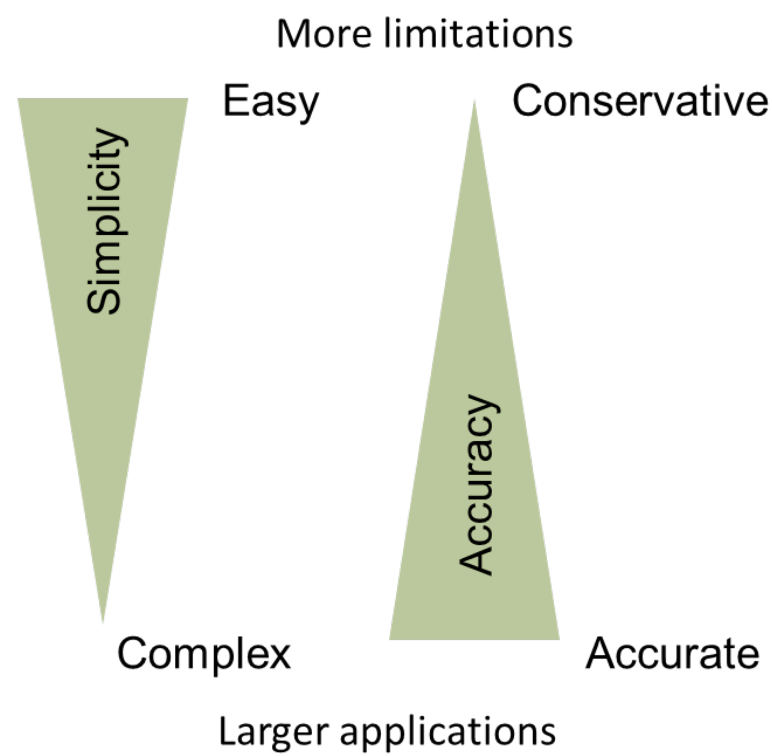
A long democratic process towards consensus…….

New Eurocode 5, fire part (prEN 1995-1-2)



New Eurocodes prEN 199x-1-2

- 6 Tabulated design data
  - 6.1 xx
  - 6.2 xx
  - .....
- 7 Simplified design methods
  - 7.1 xx
  - 7.2 xx
  - ....
- 8 Advanced design methods
  - 8.1 xx
  - 8.2 xx
  - ....



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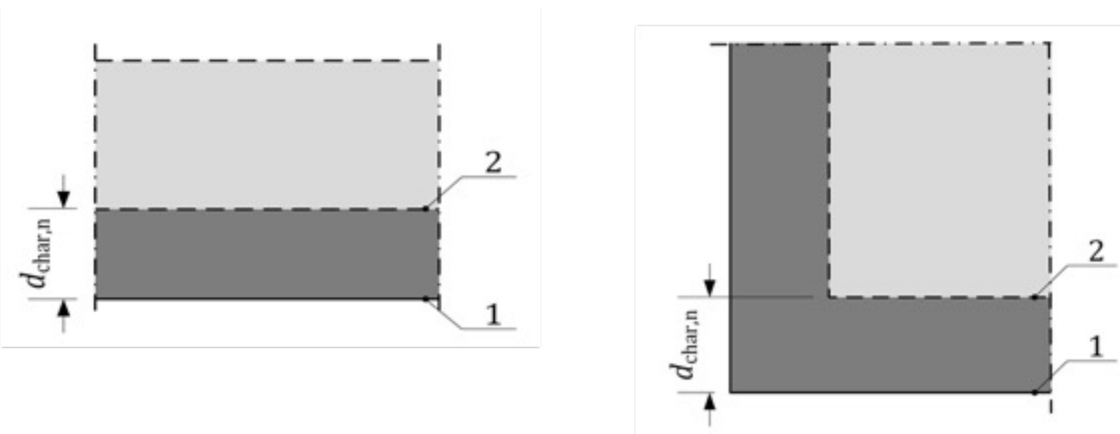
The European charring model



a) One-dimensional charring   b) Two-dimensional charring.

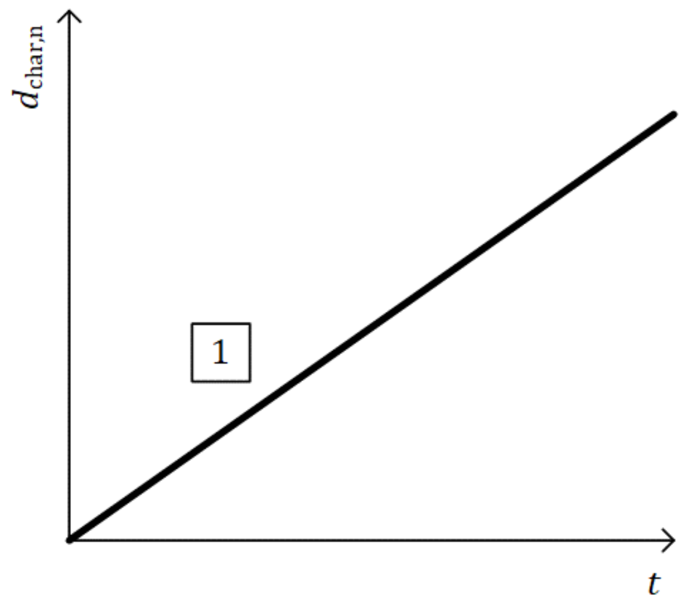
Key: 1 Fire exposed side
2 Residual cross-section

$$d_{char,n} = \beta_n \cdot t$$

$d_{char,n}$	notional charring depth **within one charring phase** in mm;
β_n	notional design charring rate **within one charring phase** in mm/min;
t	time for the charring phase considered, in min.

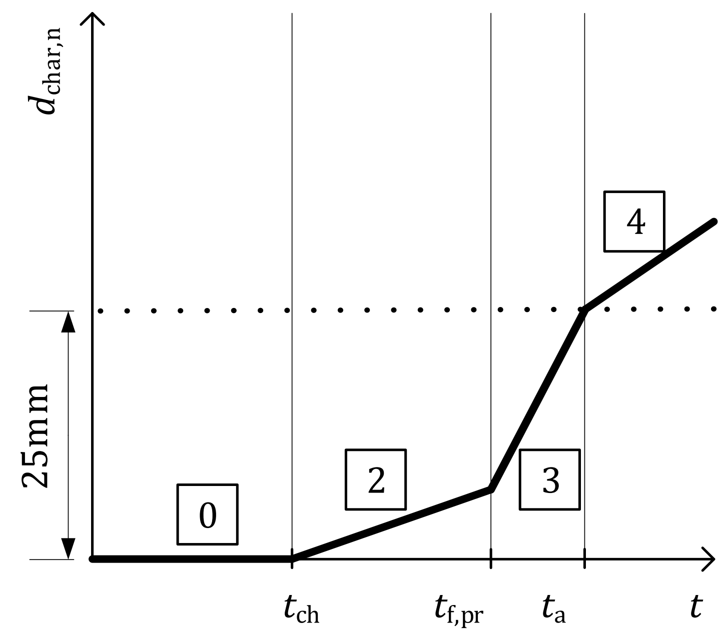
Charring phases (bond line integrity is maintained)

Initially **unprotected** sides of timber members



– Normal charring phase (Phase 1)

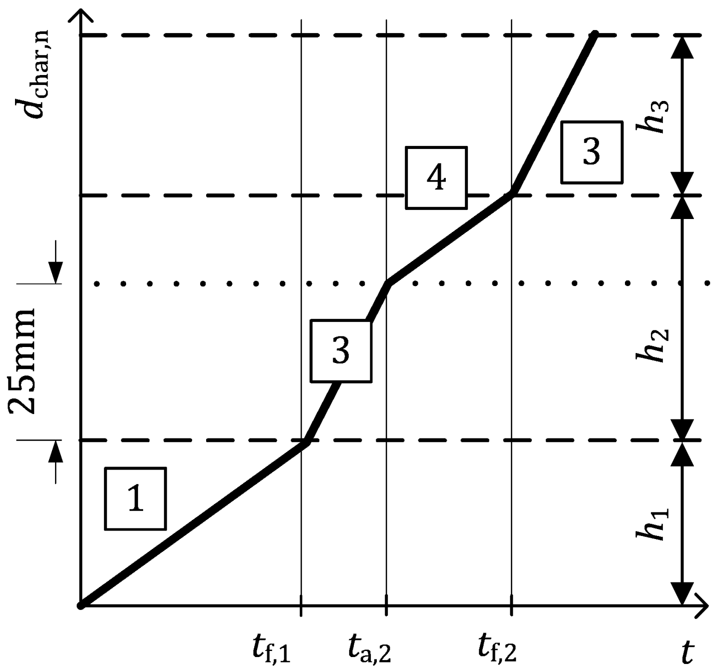
Initially **protected** sides of timber members



– Encapsulated phase (Phase 0)
– Protected charring phase (Phase 2)
– Post-protected charring phase (Phase 3)
– Consolidated charring phase (Phase 4)

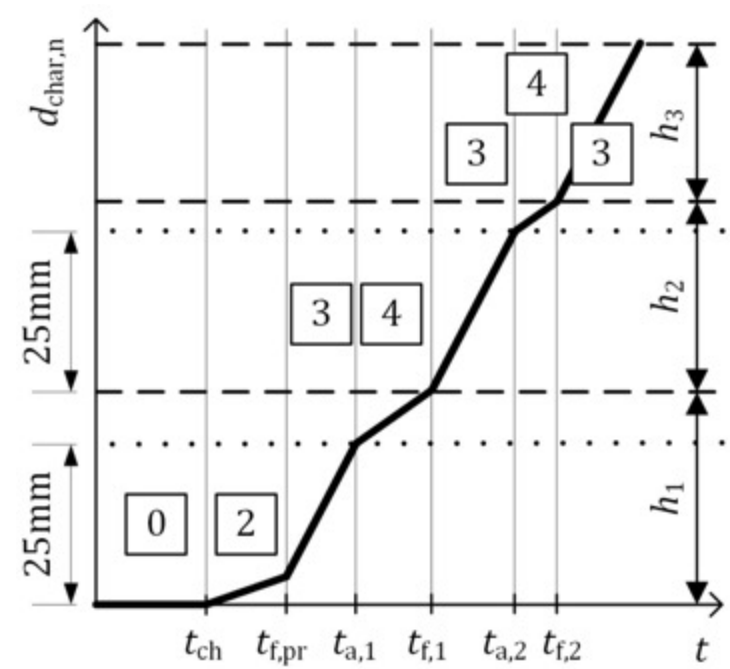
Charring phases (bond line integrity is **not** maintained)

Initially **unprotected** sides of timber members



- Normal charring phase (Phase 1)
- Post-protected charring phase (Phase 3)
- Consolidated charring phase (Phase 4)

Initially **protected** sides of timber members



- Encapsulated phase (Phase 0)
- Protected charring phase (Phase 2)
- Post-protected charring phase (Phase 3)
- Consolidated charring phase (Phase 4)

Failure time of panels initially exposed to fire

Panels		Vertical t_f [min]	Vertical h_p [mm]	Horizontal t_f [min]	Horizontal h_p [mm]
Gypsum plasterboards	Type F, one layer	$t_f = 4{,}6 \cdot h_p - 25$	$9 \leq h_p \leq 18$	$t_f = 1{,}3 \cdot h_p + 9$	$9 \leq h_p \leq 18$
Gypsum plasterboards	Type F, two layers or Type F[a] + A	$t_f = 4{,}4 \cdot h_p - 50$	$25 \leq h_p \leq 36$	$t_f = 1{,}5 \cdot h_p + 15$	$25 \leq h_p \leq 36$
Gypsum plasterboards	Type A, one layer	$t_f = 2{,}1 \cdot h_p - 6$	$9 \leq h_p \leq 18$	$t_f = 2{,}1 \cdot h_p - 9$	$9 \leq h_p \leq 18$
Gypsum plasterboards	Type A, two layers	$t_f = 1{,}8 \cdot h_p - 4$	$25 \leq h_p \leq 36$	$t_f = 1{,}7 \cdot h_p - 13$	$25 \leq h_p \leq 36$
Gypsum fibreboards, one layer		$t_f = 3{,}8 \cdot h_p - 21$	$9 \leq h_p \leq 18$	$t_f = 1{,}3 \cdot h_p + 7$	$9 \leq h_p \leq 18$
Gypsum fibreboards, two layers		$t_f = 3{,}7 \cdot h_p - 42$	$25 \leq h_p \leq 36$	$t_f = 1{,}3 \cdot h_p + 14$	$25 \leq h_p \leq 36$

where

h_p is the thickness of the single panel or the total thickness of multiple panels, in mm.

[a] Type F directly exposed to fire.

Tabulated design data for start of charring and failure times

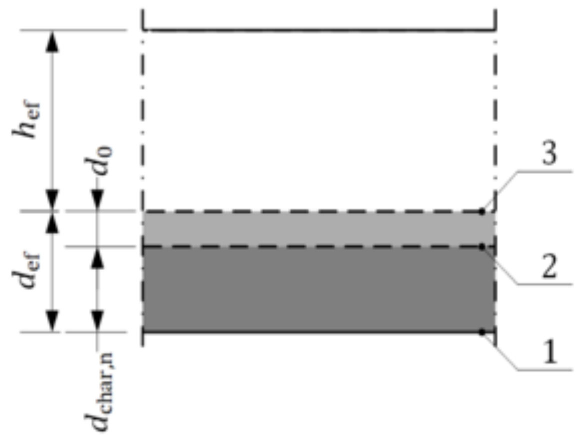
Panels	Thickness of the fire protection system h_p [mm] [a]		Layers backed by insulation [b]		Layers backed by panel [c]	
	layer 1 h_1	layer 2 h_2	Start of charring t_{ch} [min]	Failure time $t_{f,pr}$ [min]	Start of charring t_{ch} [min]	Failure time $t_{f,pr}$ [min]
Gypsum plasterboard Type A	12,5	-	17	20	22	22
	15	-	22	25	28	28
	18	-	29	32	35	35
	12,5	12,5	28	41	39	45
	15	15	36	50	49	55
	18	18	47	61	60	67
Gypsum plasterboard Type F	12,5	-	17	32	24	35
	15	-	22	44	30	48
	18	-	29	58	37	63
	12,5	12,5	39	60	49	66
	15	15	50	82	60	90
	18	18	63	108	75	119
Gypsum plasterboard Type F + Type A (Type F is layer 1)	12,5	12,5	39	60	49	66
	15	12,5	45	71	55	78
Gypsum fibreboard	12,5	-	17	26	24	29
	15	-	22	36	30	39
	18	-	29	47	37	52
	12,5	12,5	39	50	49	55
	15	15	50	69	60	76
	18	18	63	91	75	100

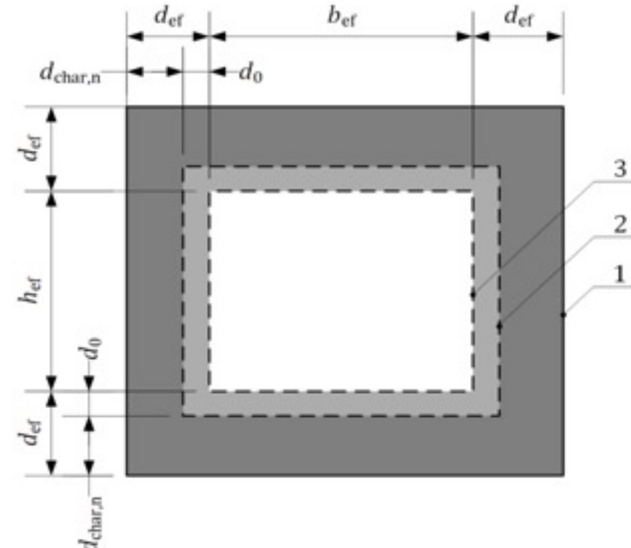
Tabulated design data for CLT

Table 6.6 — Values of the depth of the effective cross-section h_{ef} in mm for initially protected floors made of CLT with bond line integrity maintained

# of layers	Layup [mm]	Total thickness [mm]	h_{ef} [mm]		
			30 min with $t_{ch} \geq$ 20 min	**60 min** with $t_{ch} \geq$ 30 min	**90 min** with $t_{ch} \geq$ 60 min
3	20-20-20	60	18	16	16
3	40-40-40	120	95	38	38
5	20-20-20-20-20	100	58	56	56
5	40-20-20-20-40	140	115	78	78
5	40-20-40-20-40	160	135	98	98
5	40-30-40-30-40	180	155	108	108
5	40-40-40-40-40	200	175	118	118

Design of timber members - Effective cross-section method





1 Fire exposed side
2 Residual cross-section
3 Effective cross-section

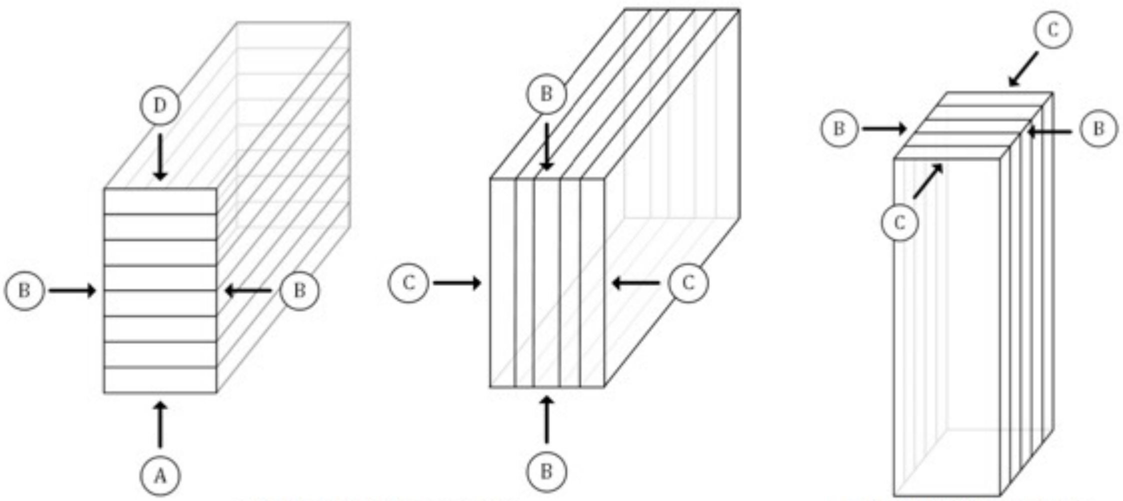
d_0 is the zero-strength layer depth
$d_{char,n}$ is the notional charring depth
d_{ef} is the effective charring depth
k_{side} is the number of respective sides exposed to fire

$$d_{ef} = d_{char,n} + d_0$$

$$b_{ef} = b - k_{side} \cdot d_{ef}$$

$$h_{ef} = h - k_{side} \cdot d_{ef}$$

Design of linear timber members



a) Horizontal member b) Vertical member

Figure 7.4 – Definition of the charring direction for linear timber members

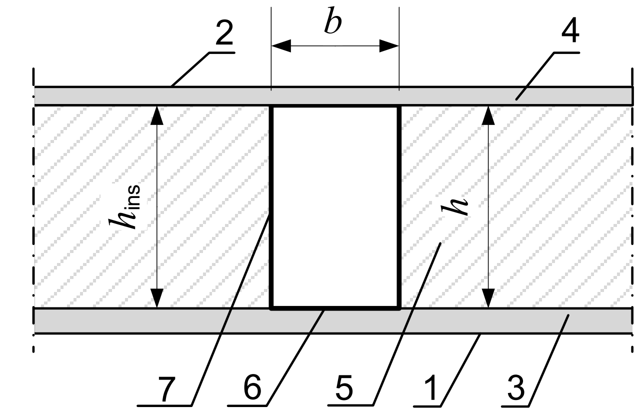
Table 7.2 – Post-protection factor k_3 for linear timber members made of GLT, CLT and GLVL

Charring direction	**Layer**	
	first layer	other layers
A	2	2
B	2	not applicable
C	2	1,3
D	2	not applicable

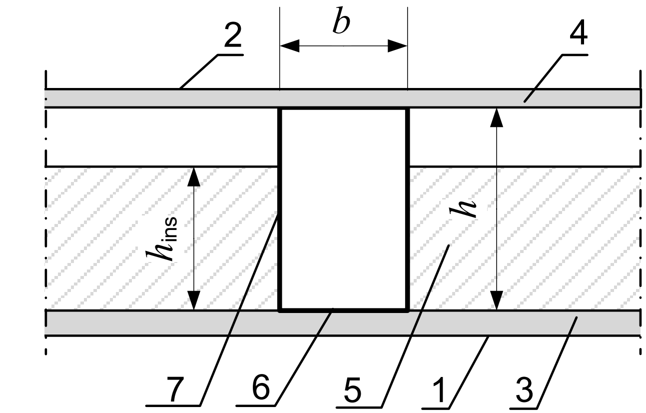
Caused by:

- first layer: Fall-off of protection system
- other layers: Fall-off of charred layer

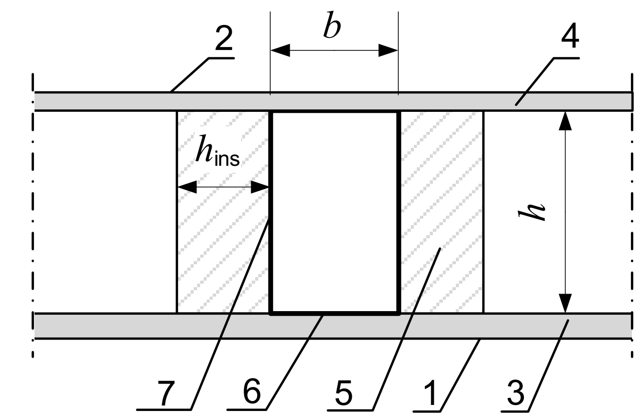
Design of timber frame assemblies



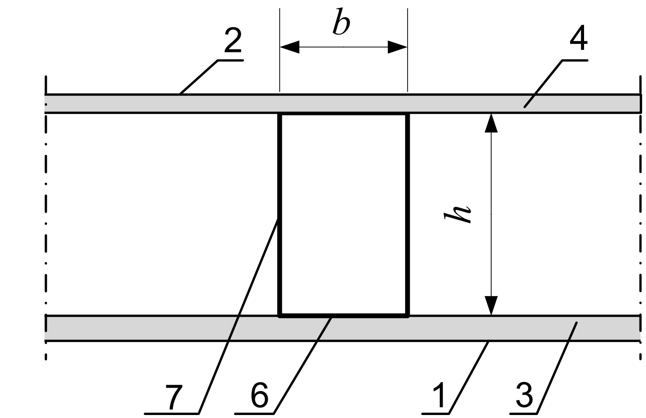
(a) fully insulated cavities (PL1 to PL 3)



(b) partially insulated cavities (PL1 to PL 3)



(c) side protection of timber member with cavity insulation PL1



(d) void cavities

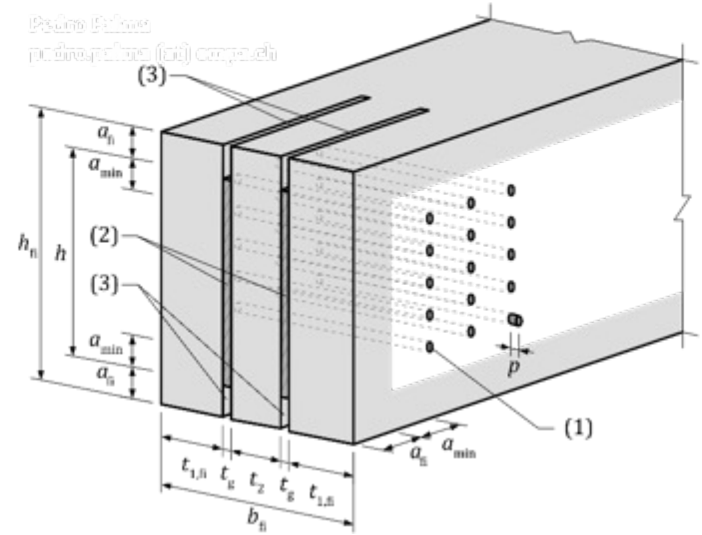
Key:

1 Fire exposed side of the timber frame assembly
2 Unexposed side of the timber frame assembly
3 Fire protection system, cladding on the fire exposed side
4 Cladding on the unexposed side
5 Cavity insulation
6 Fire exposed side of the timber member
7 Lateral side of the timber member
b Width of the initial cross-section of the timber member
h Height of the initial cross-section of the timber member
h_{ins} Thickness of the cavity insulation

Design of connections

Exponential reduction method

$$R_{k,fi} = R_k \cdot e^{\left(-c_1 \cdot t_{req} + c_2 \cdot t_{1,fi} + c_3\right)}$$



Tabulated design method

Fire resistance time, t_{fi}	$t_{1,fi}$			a_{fi}
	$\eta_{fi} \le 0,1$	$\eta_{fi} \le 0,2$	$\eta_{fi} \le 0,3$	
30 min	≥ 30	≥ 35	≥ 40	≥ 0
60 min	≥ 60	≥ 70	≥ 80	≥ 40
90 min	≥ 90	≥ 105	≥ 120	≥ 80
120 min	≥ 120	≥ 140	≥ 160	≥ 120

Advanced design methods

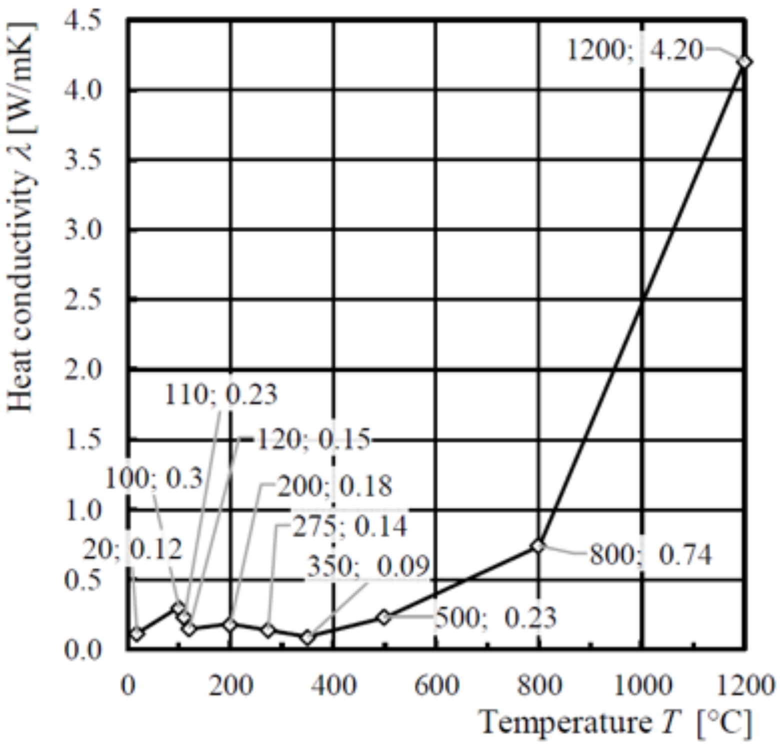
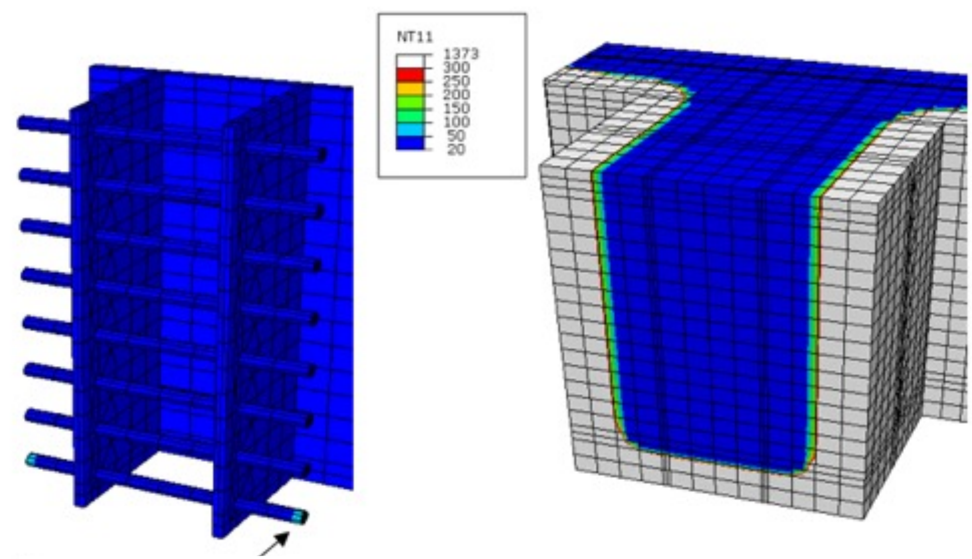


Figure 8.3 – Heat conductivity as function of temperature for timber members and wood-based panels except OSB and plywood.



Max temperature after 90 min ISO-fire

Fotos: ETH

Detailing

Rules for

- dimensions and spacings
- fixing and connections of panels, gaps of joints
- fixing of cavity insulation
- joints in and between elements
- penetrations and openings

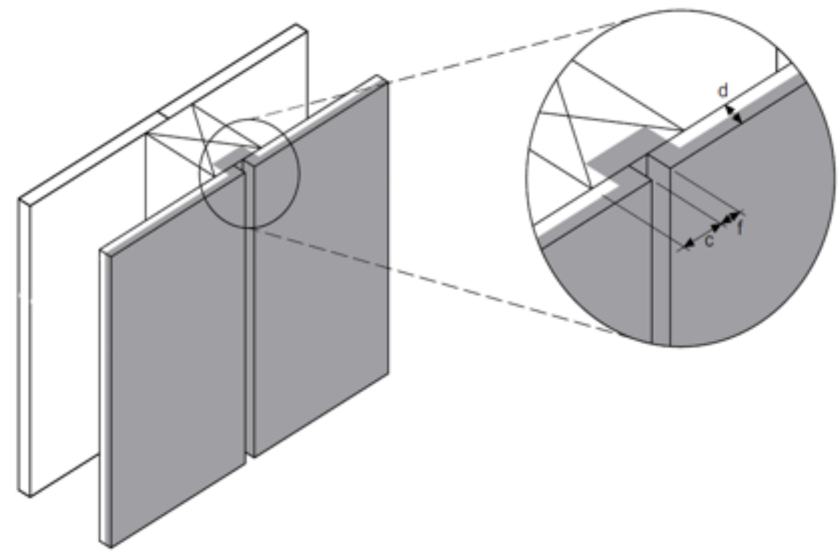
Table 9.1 – Perimeter spacing between fasteners for the fire exposed layer of wood-based panels, wood panelling, gypsum plasterboards and gypsum fibreboards[a]

Staples		Nails		Screws	
Wall	Ceiling	Wall	Ceiling	Wall	Ceiling
Maximum spacing of fasteners for wood-based panels and wood panelling					
150	150	150	150	250	250
Maximum spacing of fasteners for gypsum plasterboards					
80	80	120	120	250	170
Maximum spacing of fasteners for gypsum fibreboards					
200	150	200	150	250	200

[a] Internal spacing may be increased to twice the values given in the table, but not more than 300 mm

EN 1995-1-2:2004

Very few general rules (2 pages)
No rules for joints between the elements, penetrations



Annex B Assessment of the bond line integrity in fire

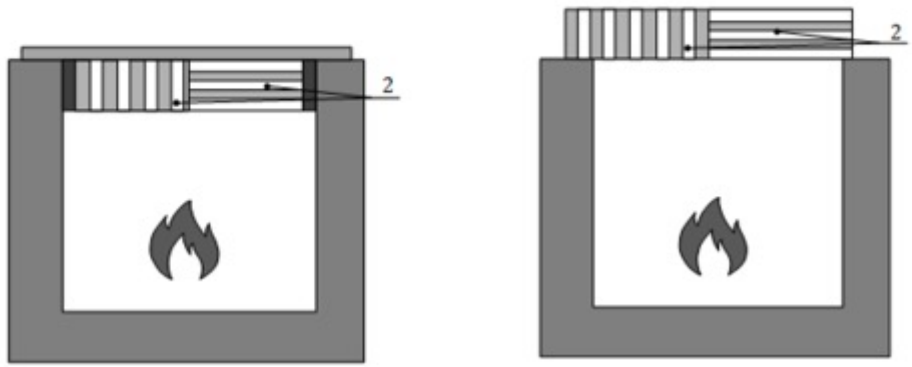


Table B.1 – Assessment of the bond line integrity in fire

Bond line integrity maintained	$\beta_{mean,specimen} \leq 1,05 \cdot \beta_{mean,reference}$
Bond line integrity not maintained	$\beta_{mean,specimen} > 1,05 \cdot \beta_{mean,reference}$

EN 17224:2019 (E)

CEN/TC 193

Date: 2019-07

EN 17224:2019

CEN/TC 193

Secretariat: UNE

Performance of wood adhesives at high temperatures and fire - Test method, evaluation and classification~~Determination of compressive shear strength of wood adhesives at elevated temperatures~~

Thermal actions for structural fire loads of timber structures: new Annex H of EN 1991-1-2

$$RHR_i = H_{\mathrm{i}} \cdot \dot{\mathrm{m}}_{\mathrm{i}}$$

$$RHR_{st} = \left(H_{\mathrm{ww}} \cdot \dot{\mathrm{m}}_{\mathrm{ww}} - H_{\mathrm{ch}} \cdot \dot{\mathrm{m}}_{\mathrm{ch,tm}}\right) + \left(H_{\mathrm{ch}} \cdot \dot{\mathrm{m}}_{\mathrm{ch,ox}}\right)$$

Glowing and smouldering combustion: Decay of the char layer

RHR_{st}	is the rate of heat release by the structural fuel load per unit area, in MW/m²;
H_i	is the net calorific value of the material i, in MJ/kg;
$\dot{\mathrm{m}}_{\mathrm{i}}''$	is the area specific mass loss rate of the material i, in kg/(m²s);
ww	is the index for the wet wood;
ch	is the index for the char layer;
ox	is the index for the oxidation;
tm	is the index for the thermal modification of the wood material to the char material.

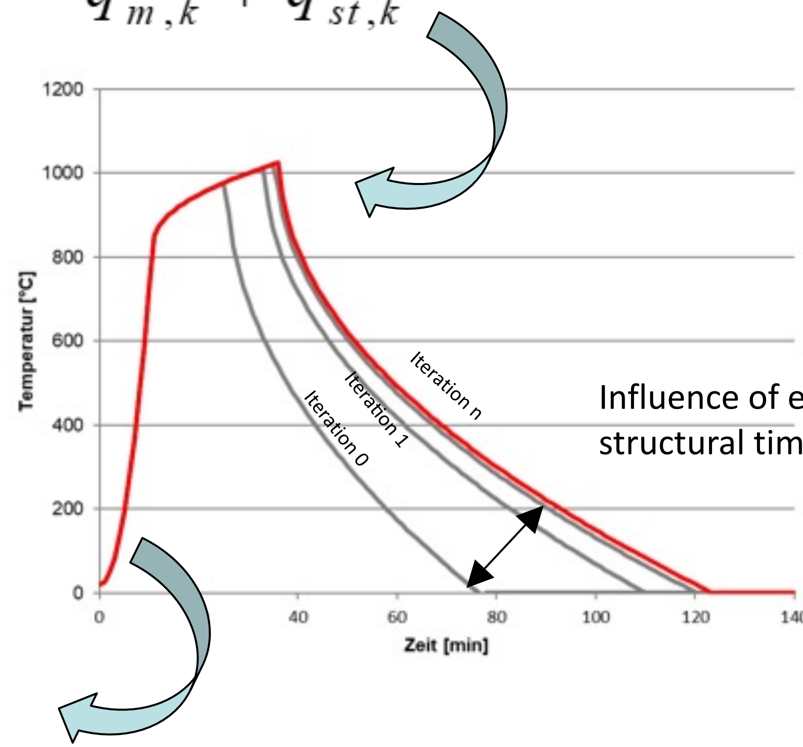
Design of timber structures exposed to physically based design fires: new Annex A of EN 1995-1-2

$$RHR_{st} = s_{10} \cdot \beta_{st} \cdot \alpha_{st}$$

$$q_{f,k} = q_{m,k} + q_{st,k}$$

→ Factor s_{10} describes the rate of heat release per 1m^2 and 1mm/min

→ Factor α_{st} describes ratio between energy storage vs. heat release



Influence of exposed structural timber

$$d_{char,t} = \left(\frac{\int_0^t \left(T^2\right) dt}{1,35 \cdot 10^5} \right)^{\frac{1}{1,6}}$$

EN 1995-1-2:2025 vs EN 1995-1-2:2004

- The European charring model
  - Notional design charring rate
  - Failure time of the fire protection system
  - ....
- Effective cross-section method
  - New rules for CLT
  - New rules for TCC
  - Revised rules for Timber Frame Assemblies
  - ....
- Revised rules for connections
  - Extension up to 120 min
  - ....
- Revised rules for detailing
- Design of timber structures exposed to physically based design fires

Evolution – consensus – future

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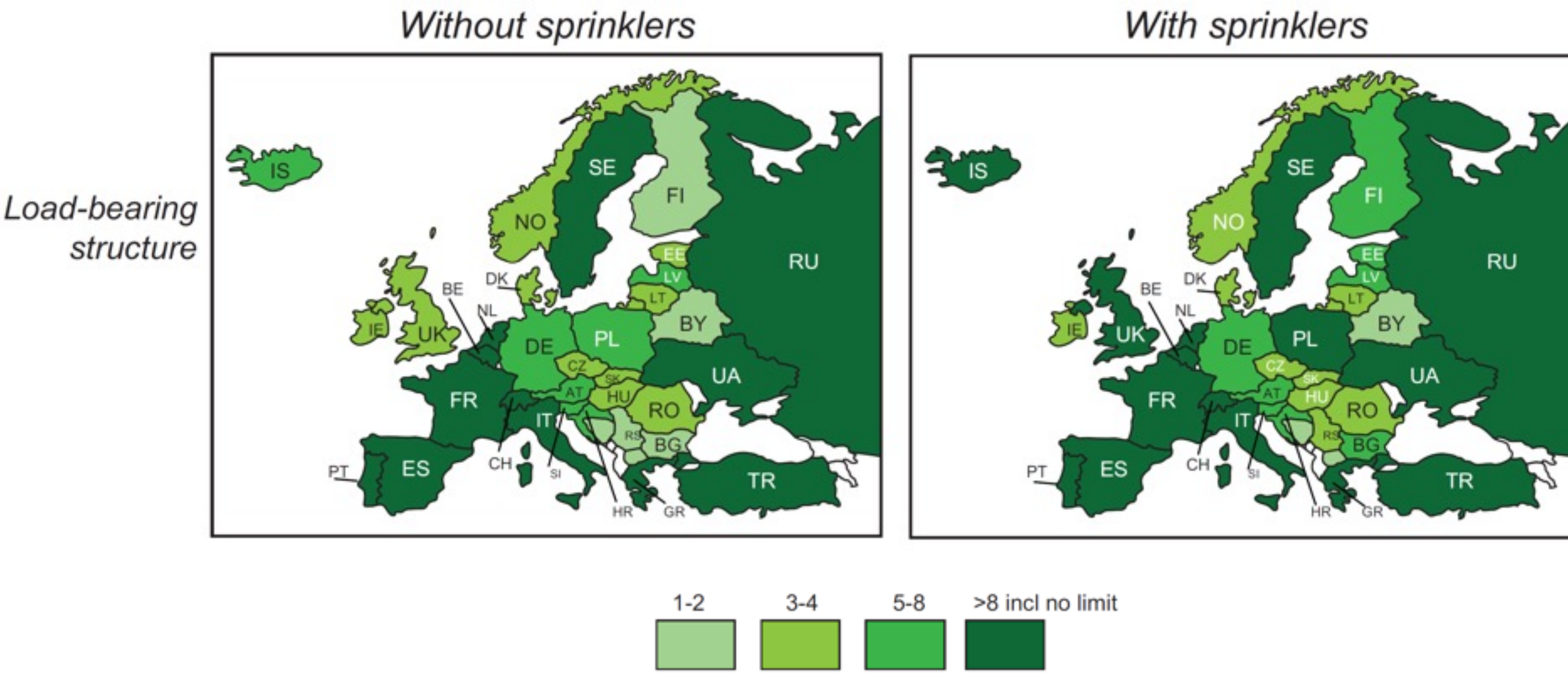


Evolution of Swiss fire regulations

Until 2004

Since 2005

Since 2015


Winterthur, Residential Area Giesserei

Zurich, Residential Area Freilager

Winterthur,
Residential Area Sue&til

Risch-Rotkreuz, S22 Office building

Risch Rotkreuz

Suurstoffi Arbo BF1

15 storeys, 60m, 2019
in 15 weeks!
Sprinkler, R60
Unprotected linear timber members

ETH zürich

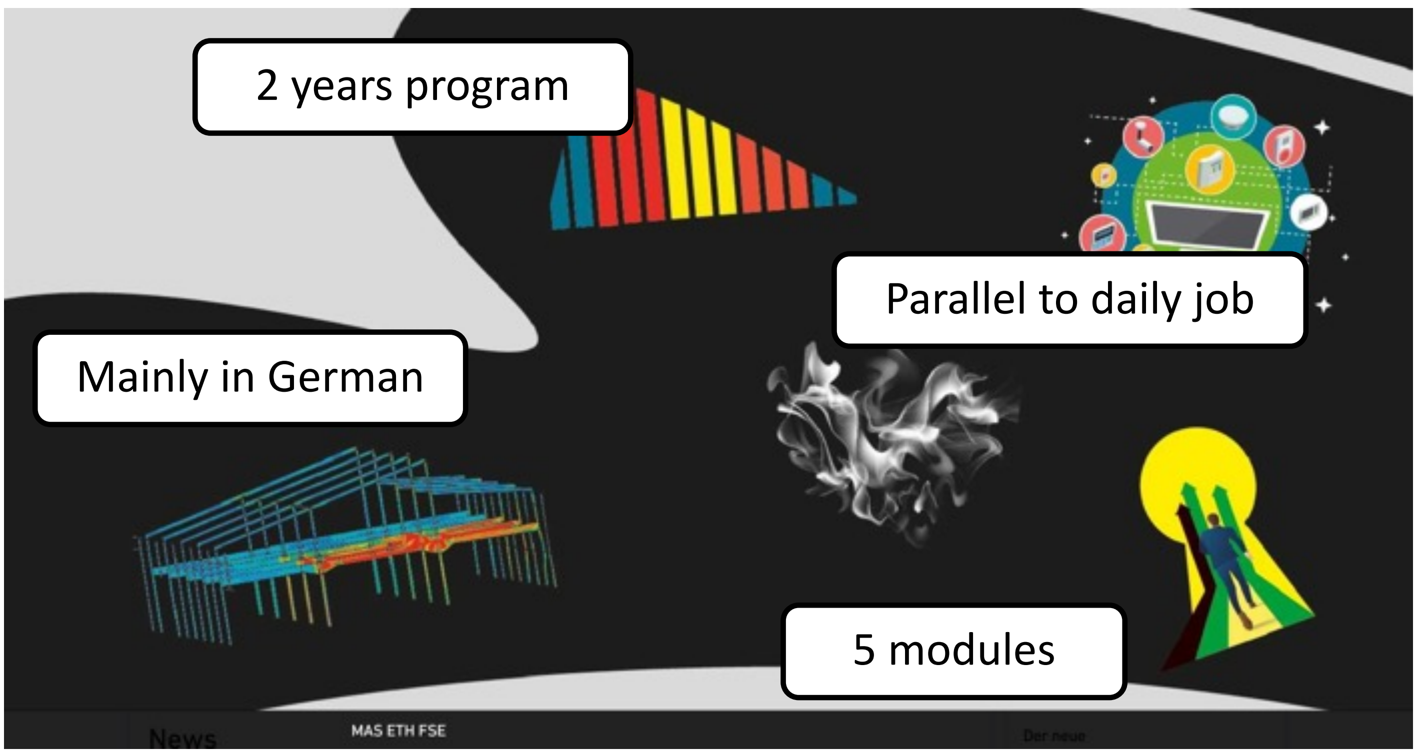
Fire safety of timber structures

Fire safety is not primarily a question of building material but of **concept** (education, quality assurance, careful design and execution, maintenance)

Further education

New Master of Advanced Studies at ETH Zurich:

ETH MAS Fire Safety Engineering
(https://mas-brandschutz.ethz.ch/)



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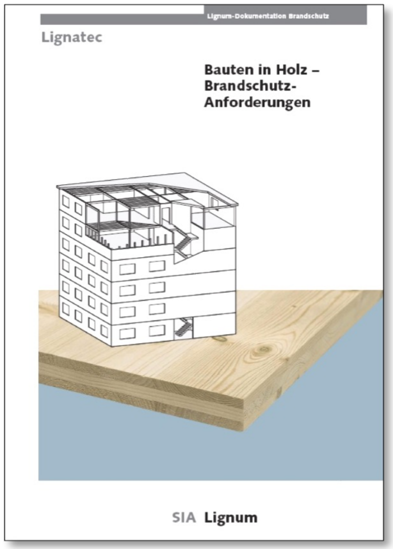
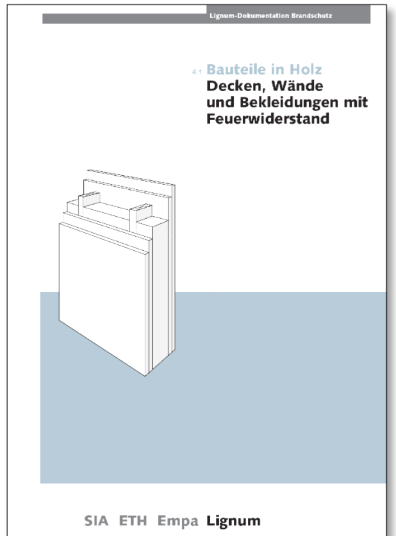
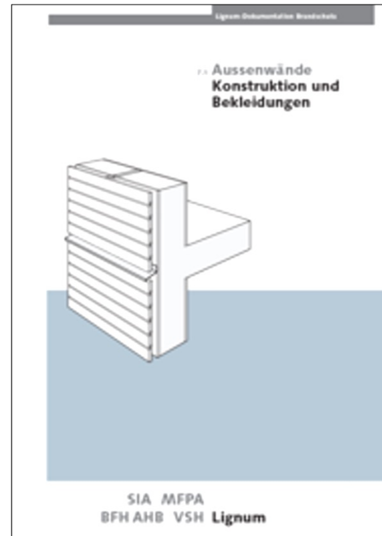
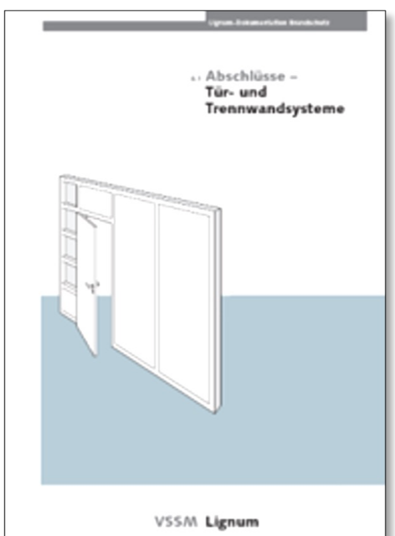
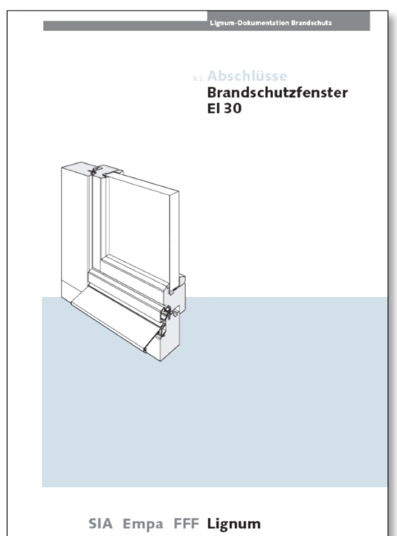
Swiss Lignum-Documentation Fire Safe Timber

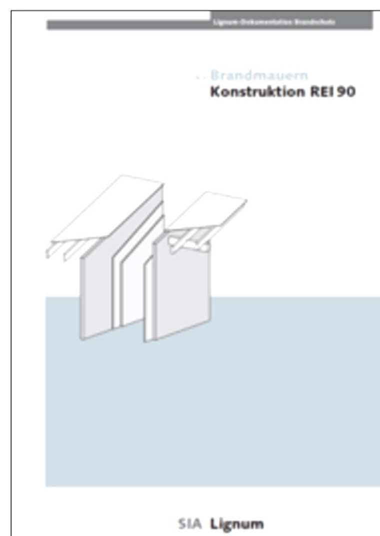


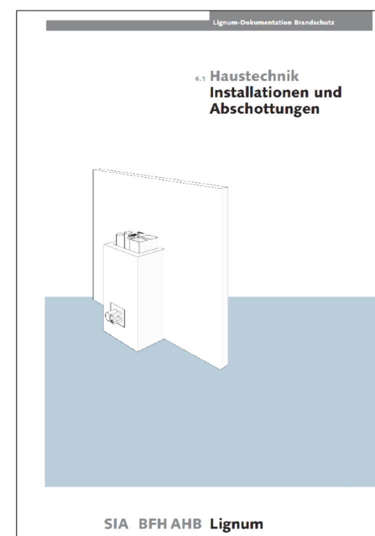






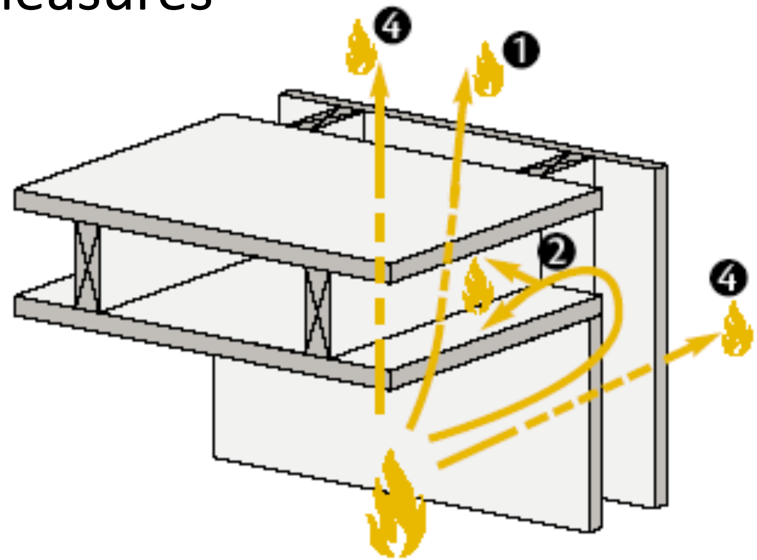






Quality of construction

- Fire safety plan with all fire safety measures
- Careful planning and detailing
- Professionally implementation of fire safety measures during the execution
- Periodic controls and maintenance



- The intensity of maintenance and controls must be set depending of the type of structures and the type and importance of the building

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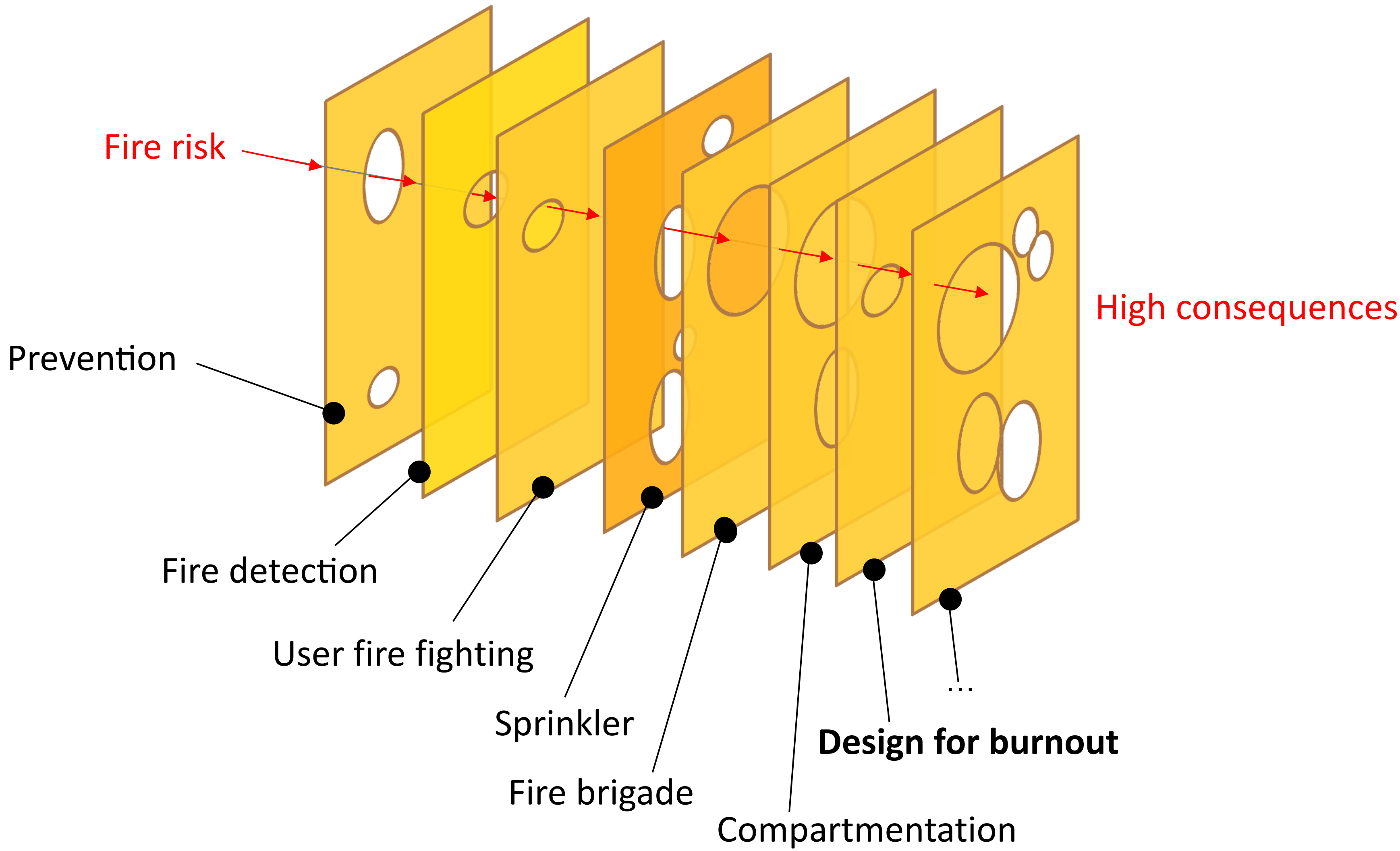
Tall timber buildings in Switzerland

PI, 80m, Zug, 2024

UBS, 108m, Zürich, 2029

Rocket, 100m, Winterthur, 2026

The Swiss cheese approach




«EMPIRE STATE OF WOOD» New York, 440 m