Fire resistance assessment of timber structures

Basic design methods
Worked examples

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What is Eurocode 5?

Eurocode 5 (EN 1995) provides rules for the design of timber structures.

EN 1995-1-2 is the Fire Part of Eurocode 5
The two other parts of Eurocode 5 are:
EN 1995-1-1 Common rules and rules for buildings
EN 1995-2 Bridges

Scope of EN 1995-1-2

EN 1995-1-2 deals with passive methods of fire protection

EN 1995-1-2 gives design rules for the verification of the

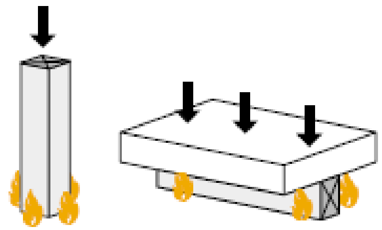
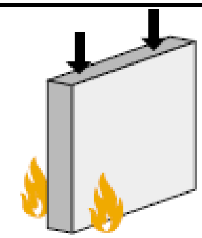
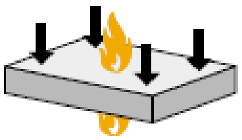
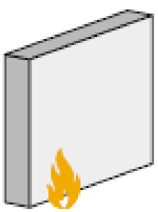
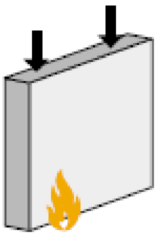
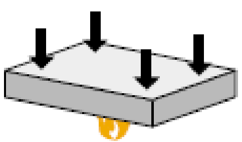
- **load-bearing function**
- **separation function**

Passive methods of fire protection

Main objective: limitation of the spread of fire by guaranteeing

- **the load-carrying capacity of the structure (Requirement on Mechanical Resistance R)**
- **the separating function of walls and floors (Requirement on Insulation I and Integrity E)**

Basic fire requirements

		Fire exposure	Columns / beams	Walls	Floors
R	Load-bearing elements without separating function	On all sides			
EI	Non-load-bearing elements with separating function	On only one side			
REI	Load-bearing elements with separating function	On only one side			

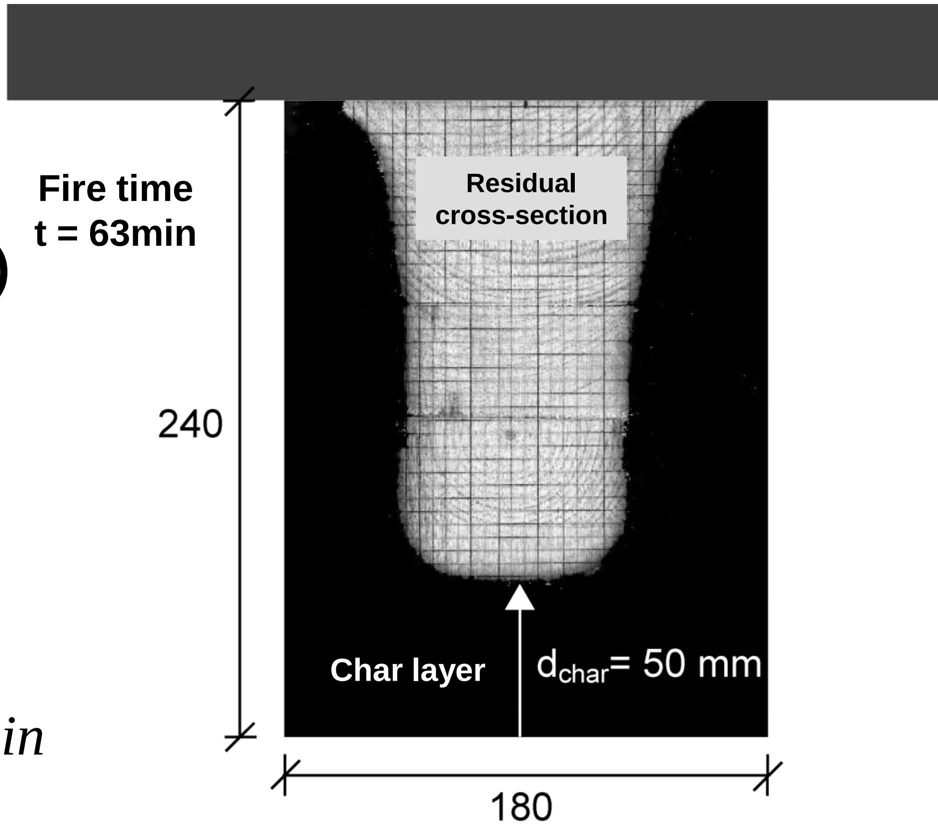

Timber behaviour in fire

Timber behaviour in fire

- **Pyrolysis: thermal degradation of wood producing combustible gases and accompanied by a loss in mass (starting from about 250°C)**
- **Charring rate β:**
  Ratio between charring depth d_{char} and fire time t (in mm/min)

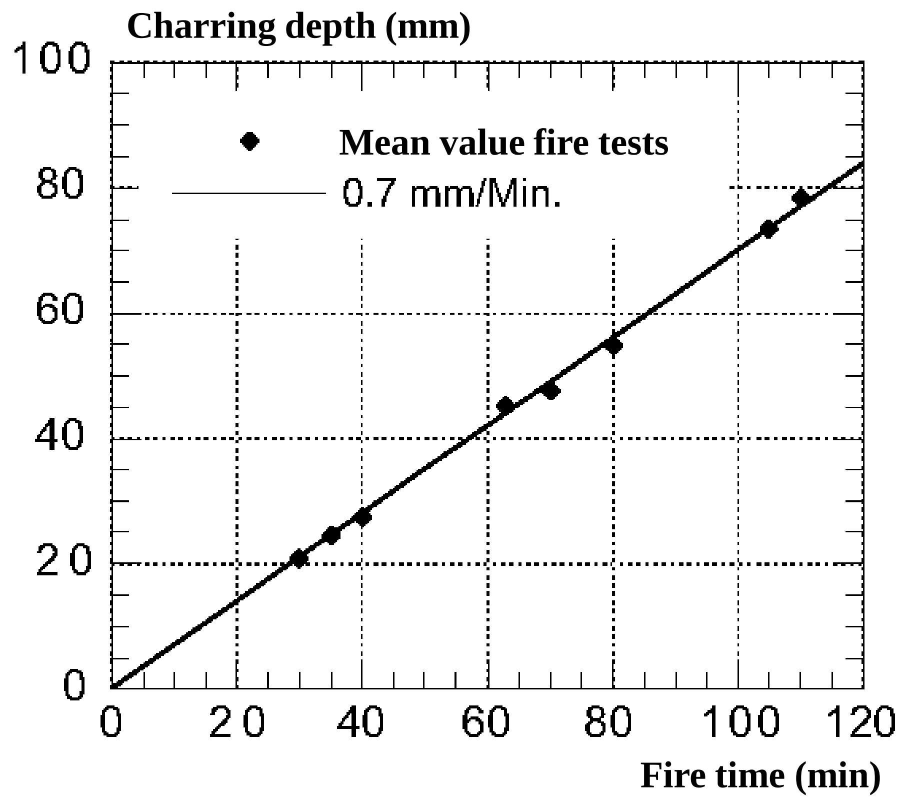
$$\beta = \frac{d_{char}}{t}$$

$$\beta = \frac{d_{char}}{t} = \frac{50mm}{63min} = 0.8\,mm/min$$



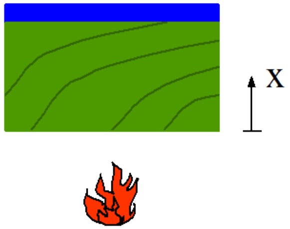
Charring rate

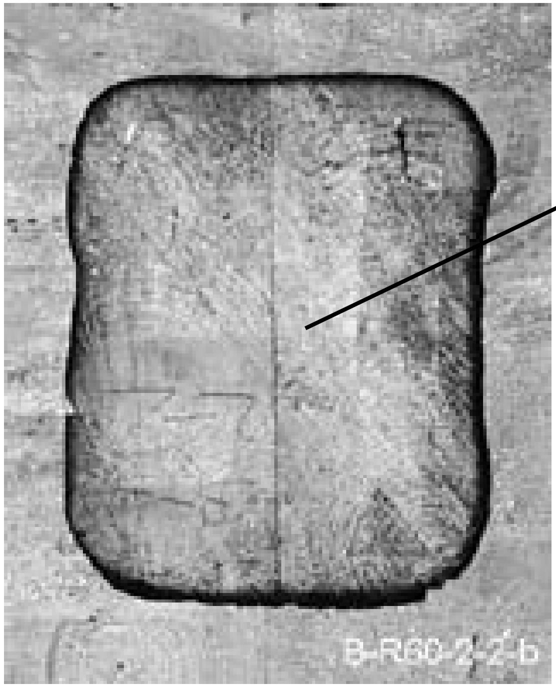
- depends on fire exposure
  - constant value for ISO-fire exposure
- depends on wood species
  - spruce: β ≈ 0.7 mm/Min.
- small influence of moisture content and density of wood



Timber behaviour in fire

- **Char layer protects the residual cross-section from high temperatures**



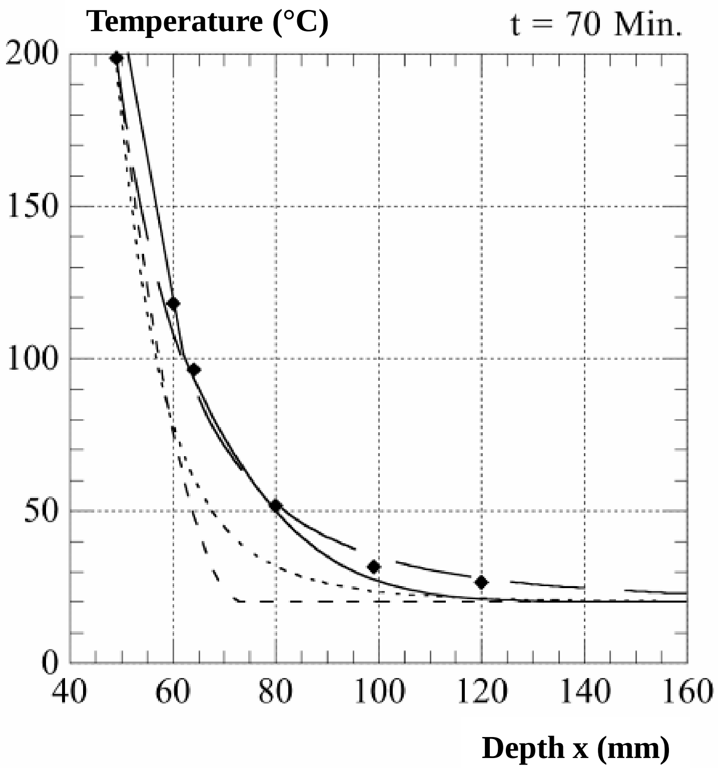


Source: proHolz, Austria

Residual cross-section

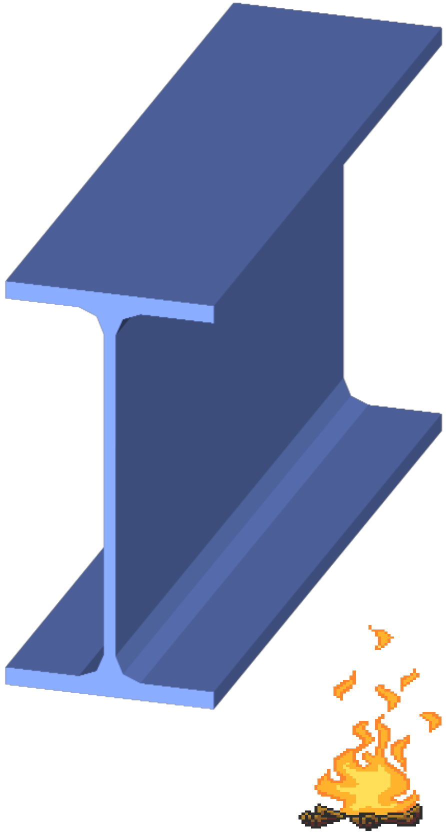
- "cold"

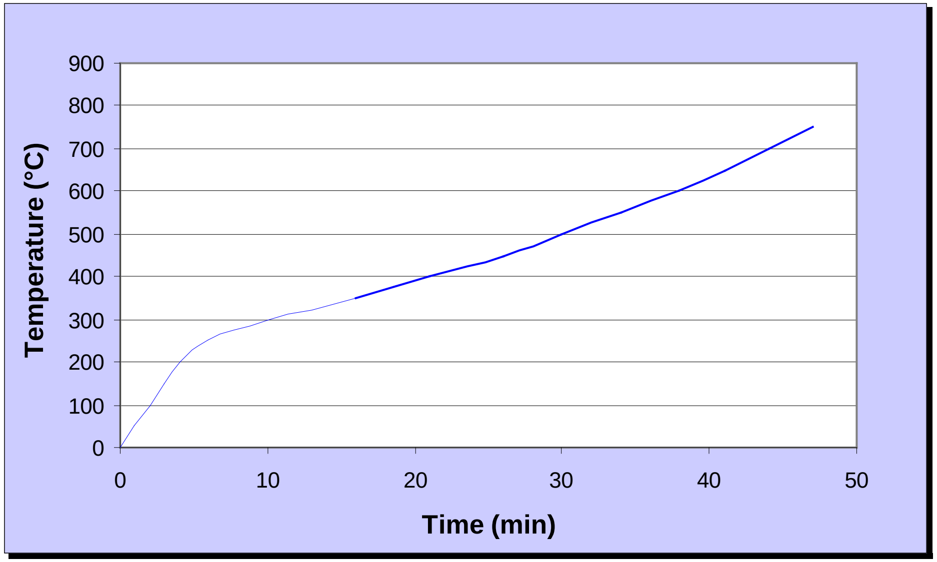
- load-bearing



Intumescent coating systems on steel members

- **Mode of action: intumescent systems expand at a temperature of about 200°C by a factor of 30 to 60 and form a compact insulating layer.**





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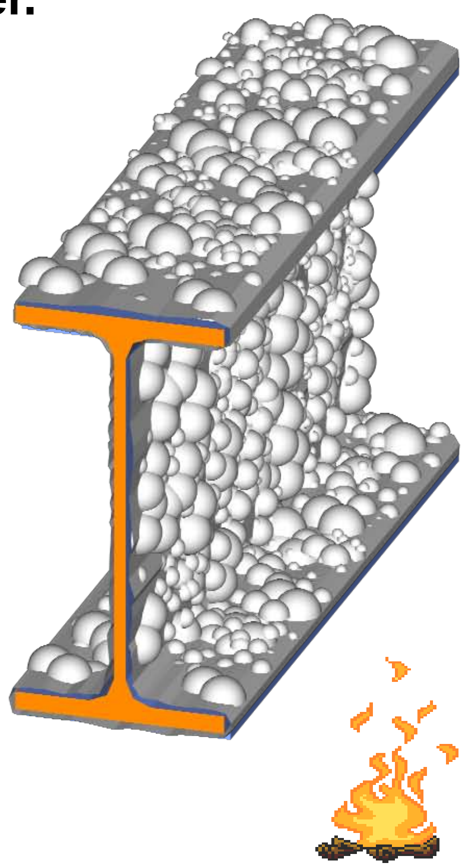

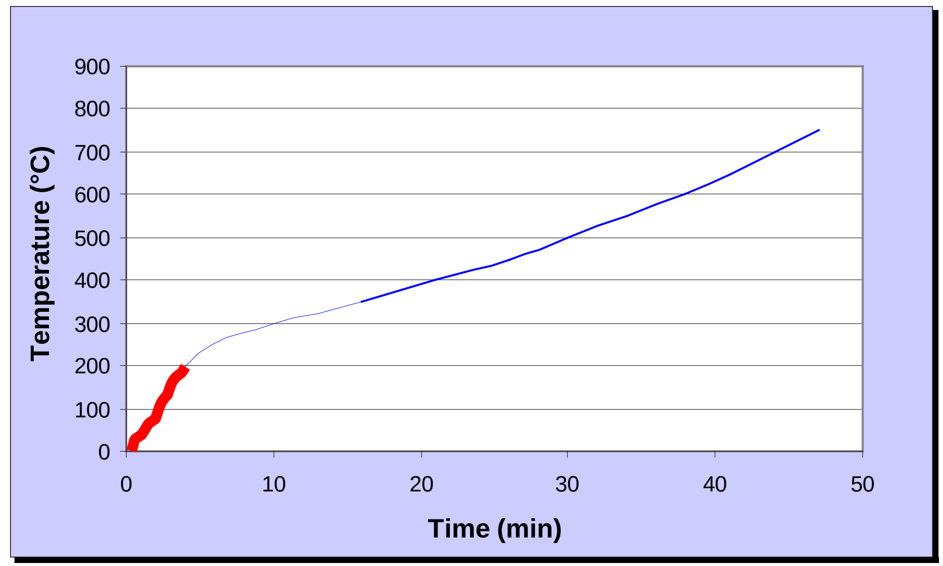

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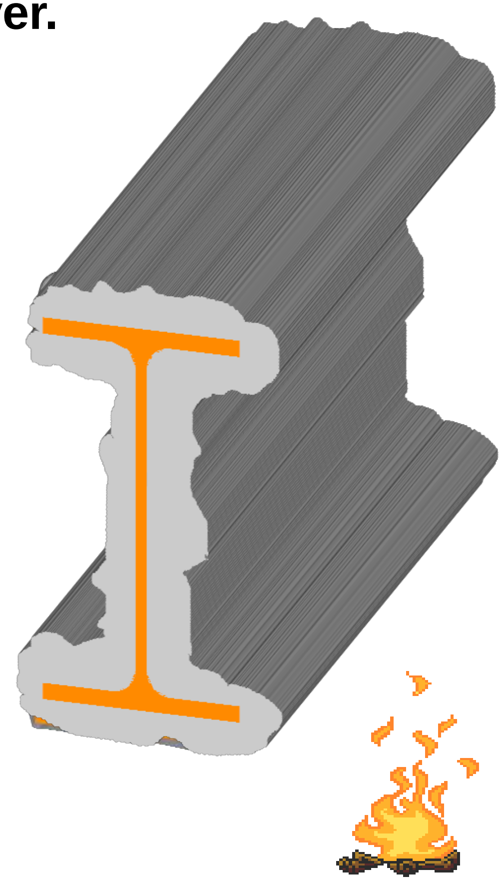
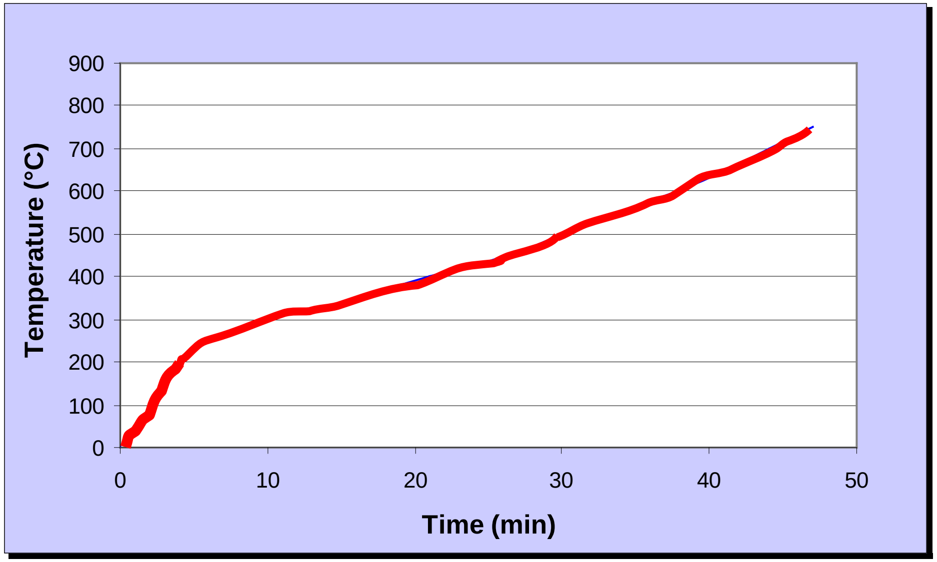




Intumescent coating systems

"Modern manmade intumescent materials applied to steel structural elements are in essence an attempt to replicate what timber does naturally."

From paper "Overview of design issues for tall timber buildings", I. Smith, A. Frangi, Structural Engineering International SEI 2/2008

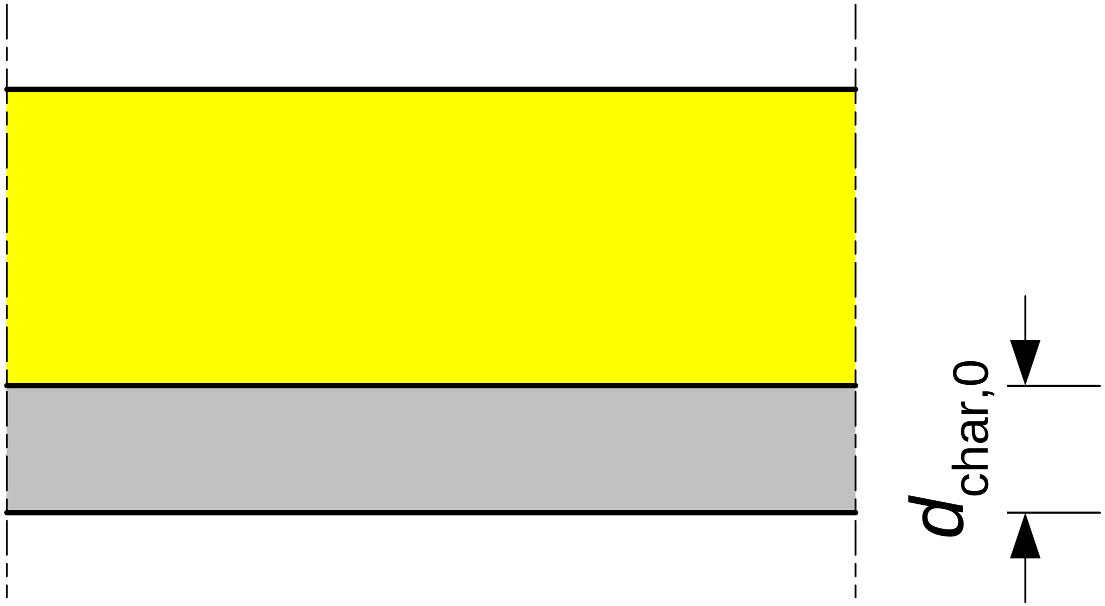
Material behaviour in fire

Fire resistance of timber elements

Basic strategies

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

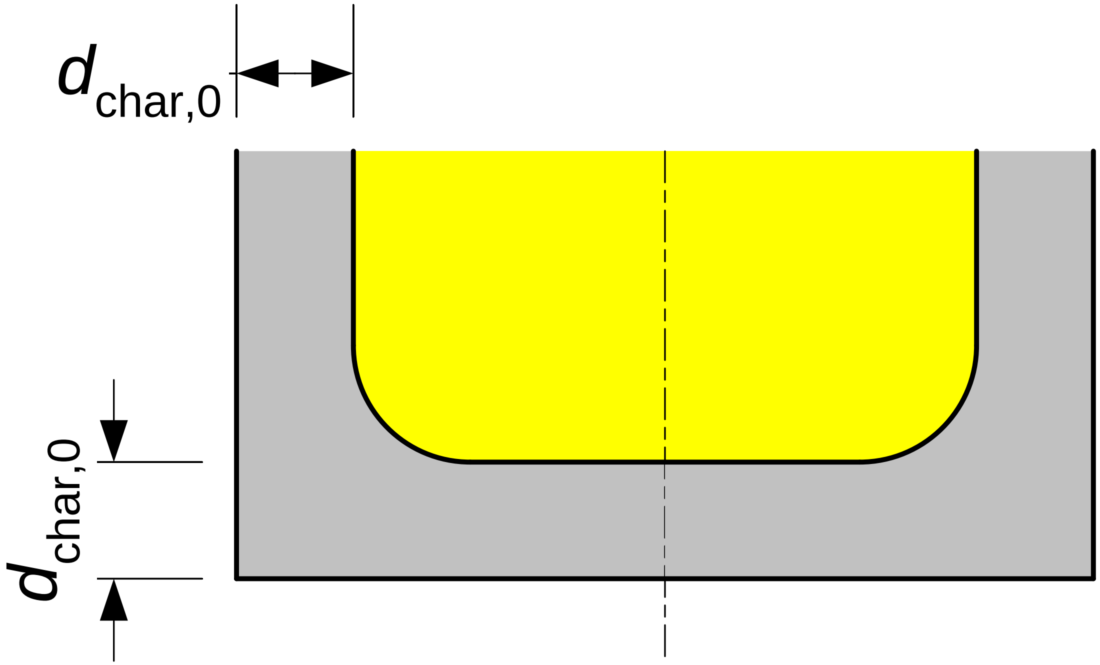
Charring



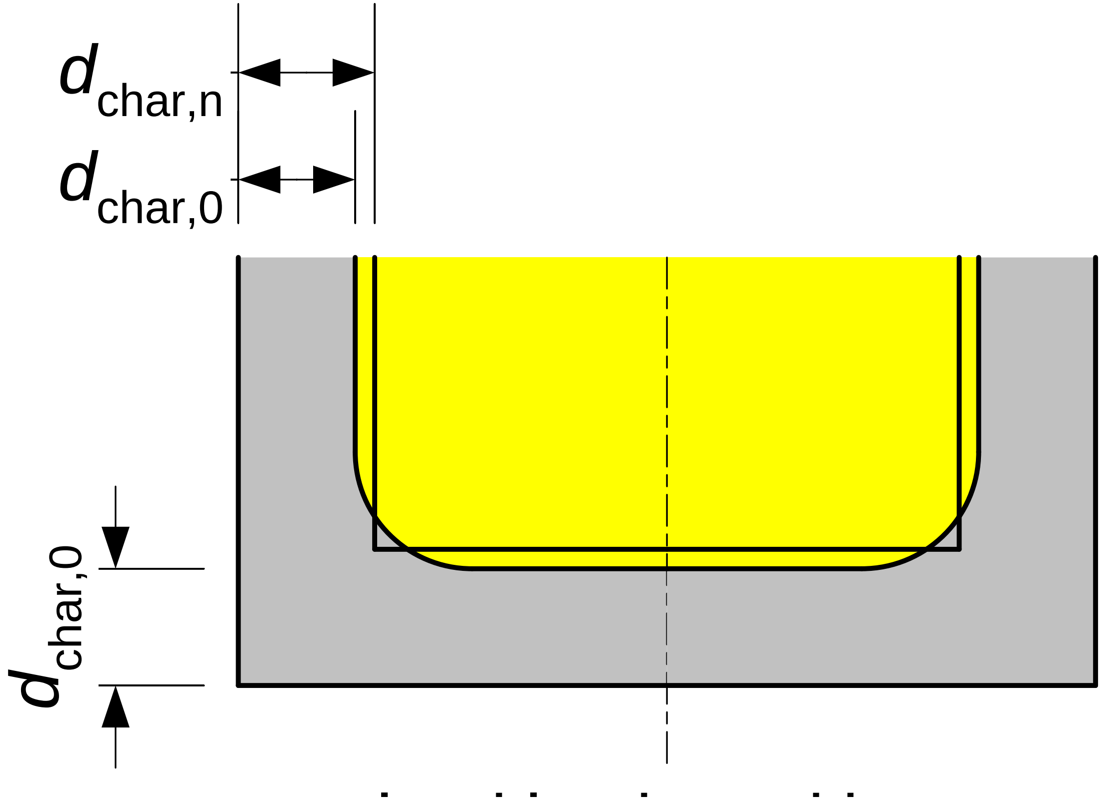
timber slab

One-dimensional charring: charring rate β_0

Charring



Charring



Notional charring: notional charring rate β_n

Equivalent residual cross-section

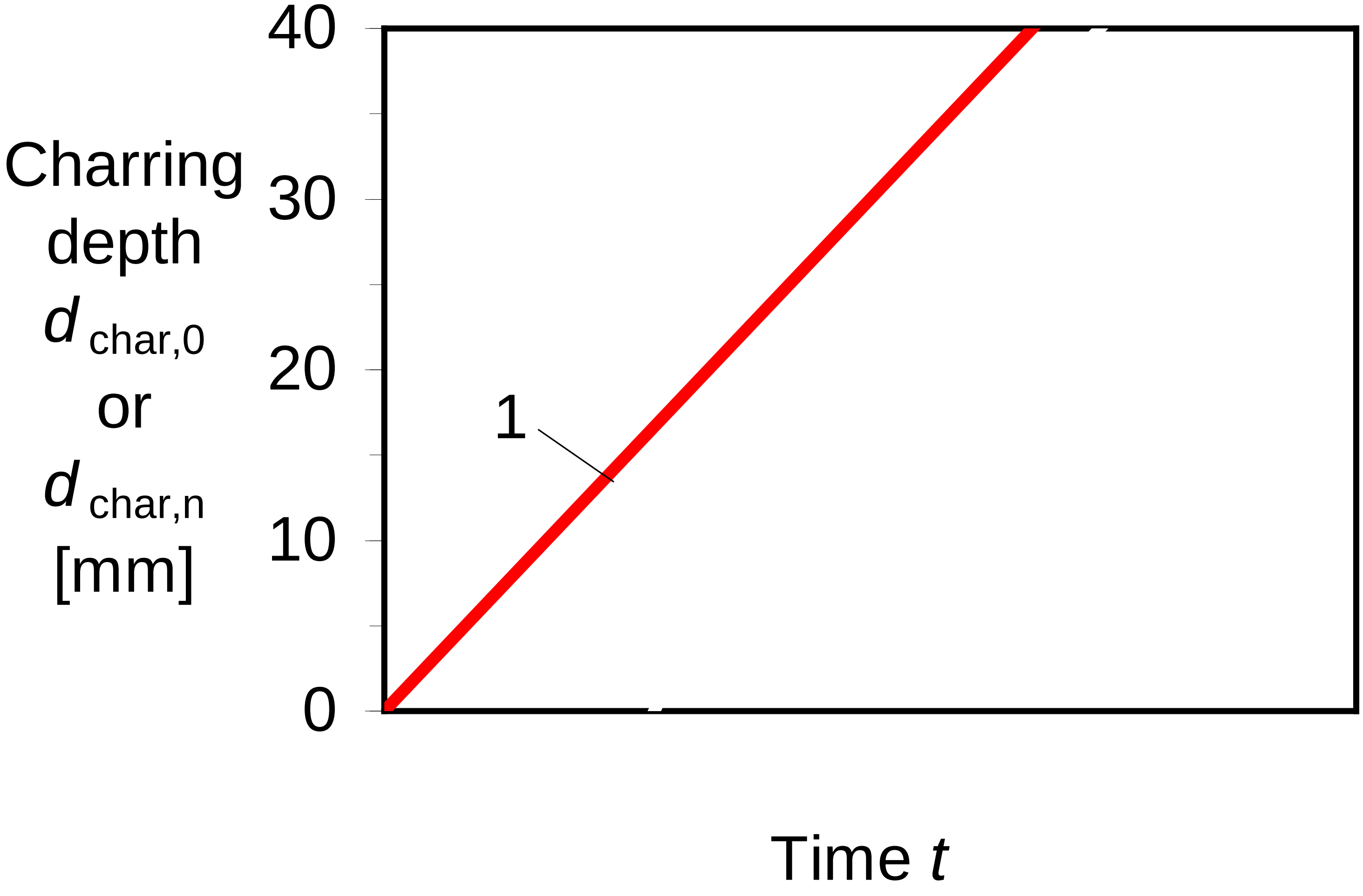
Charring rates according to EN 1995-1-2

Table 3.1 – Design charring rates β_0 and β_n of timber, LVL, wood panelling and wood-based panels

	β_0 mm/min	β_n mm/min
a) Softwood and beech		
Glued laminated timber with a characteristic density of ≥ 290 kg/m^3	0,65	0,7
Solid timber with a characteristic density of ≥ 290 kg/m^3	0,65	0,8
b) Hardwood		
Solid or glued laminated hardwood with a characteristic density of 290 kg/m^3	0,65	0,7
Solid or glued laminated hardwood with a characteristic density of ≥ 450 kg/m^3	0,50	0,55
c) LVL		
with a characteristic density of ≥ 480 kg/m^3	0,65	0,7
d) Panels		
Wood panelling	0,9[a]	–
Plywood	1,0[a]	–
Wood-based panels other than plywood	0,9[a]	–

[a] The values apply to a characteristic density of 450 kg/m^3 and a panel thickness of 20 mm; see 3.4.2(9) for other thicknesses and densities.

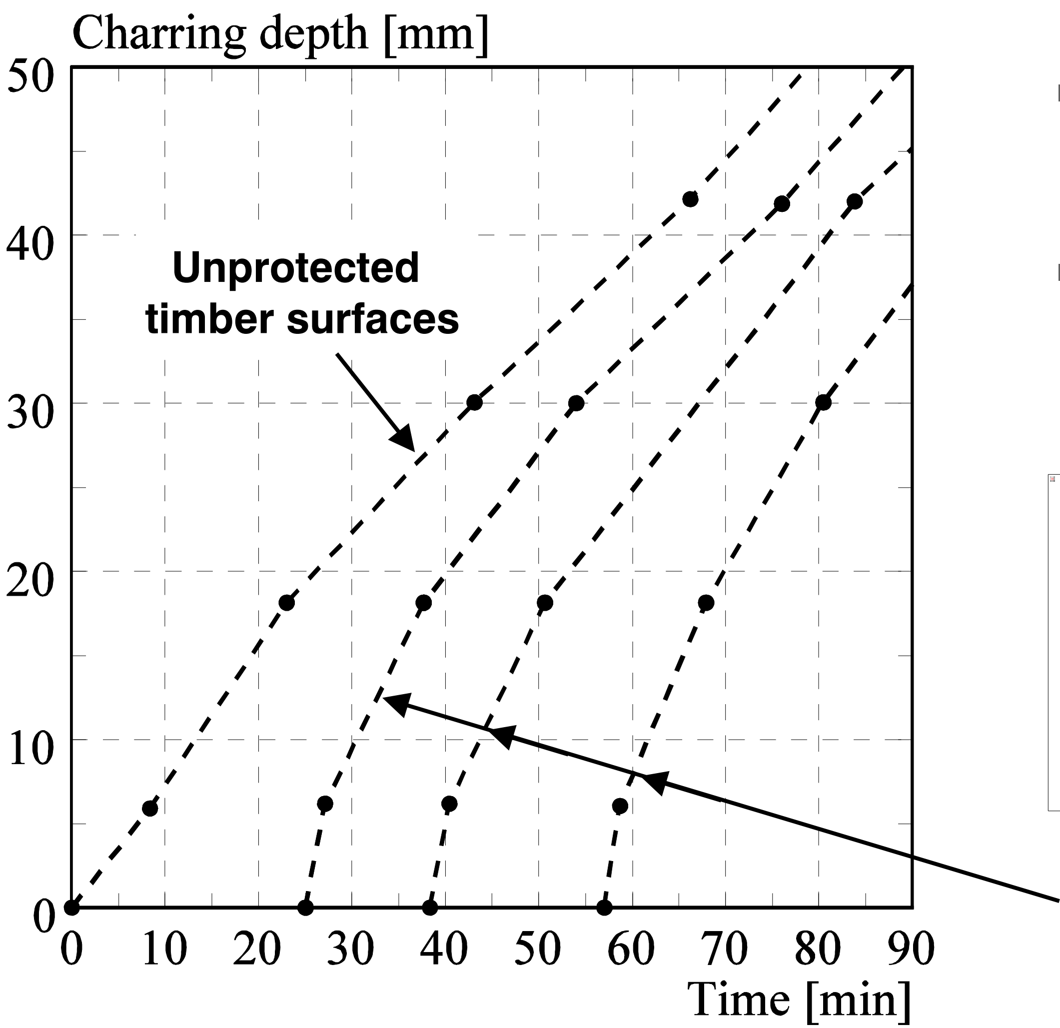
Charring model for unprotected surfaces



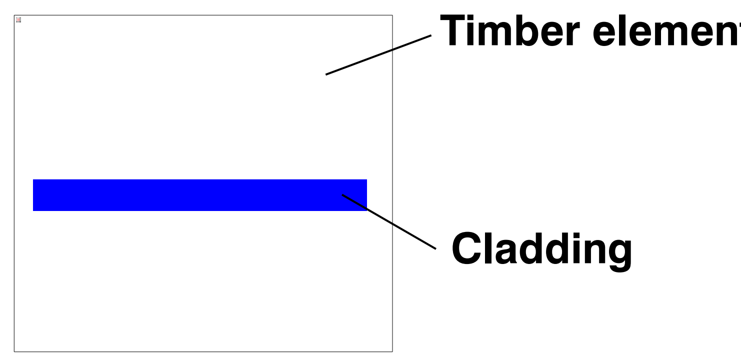
Influence of fall off of cladding

Timber slab after 17 minutes ISO-fire exposure

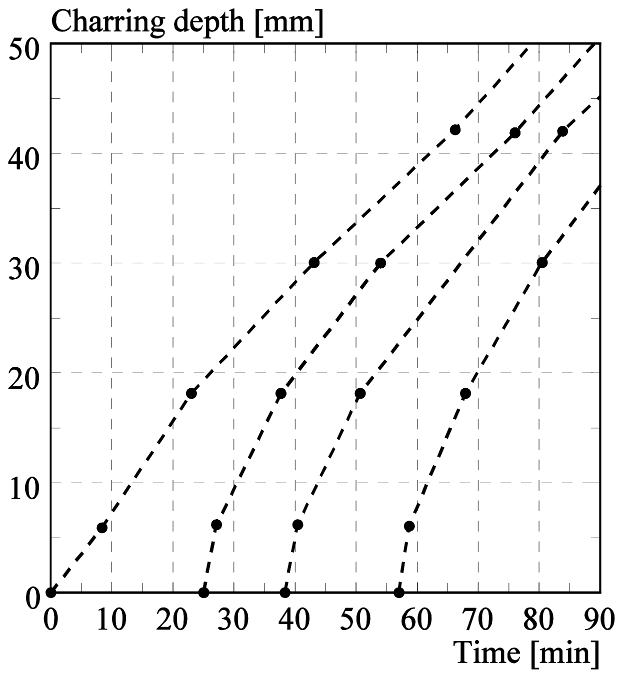
Fire behaviour of initially protected surfaces



- Charring rate not constant
- Increased charring rate after failure of cladding



Fire behaviour of initially protected surfaces



Increased charring rate after failure of cladding

- the temperature in the furnace is already at a high level when the claddings fall off
- no protective char layer exists when the claddings fall off

Charring model for initially protected surfaces

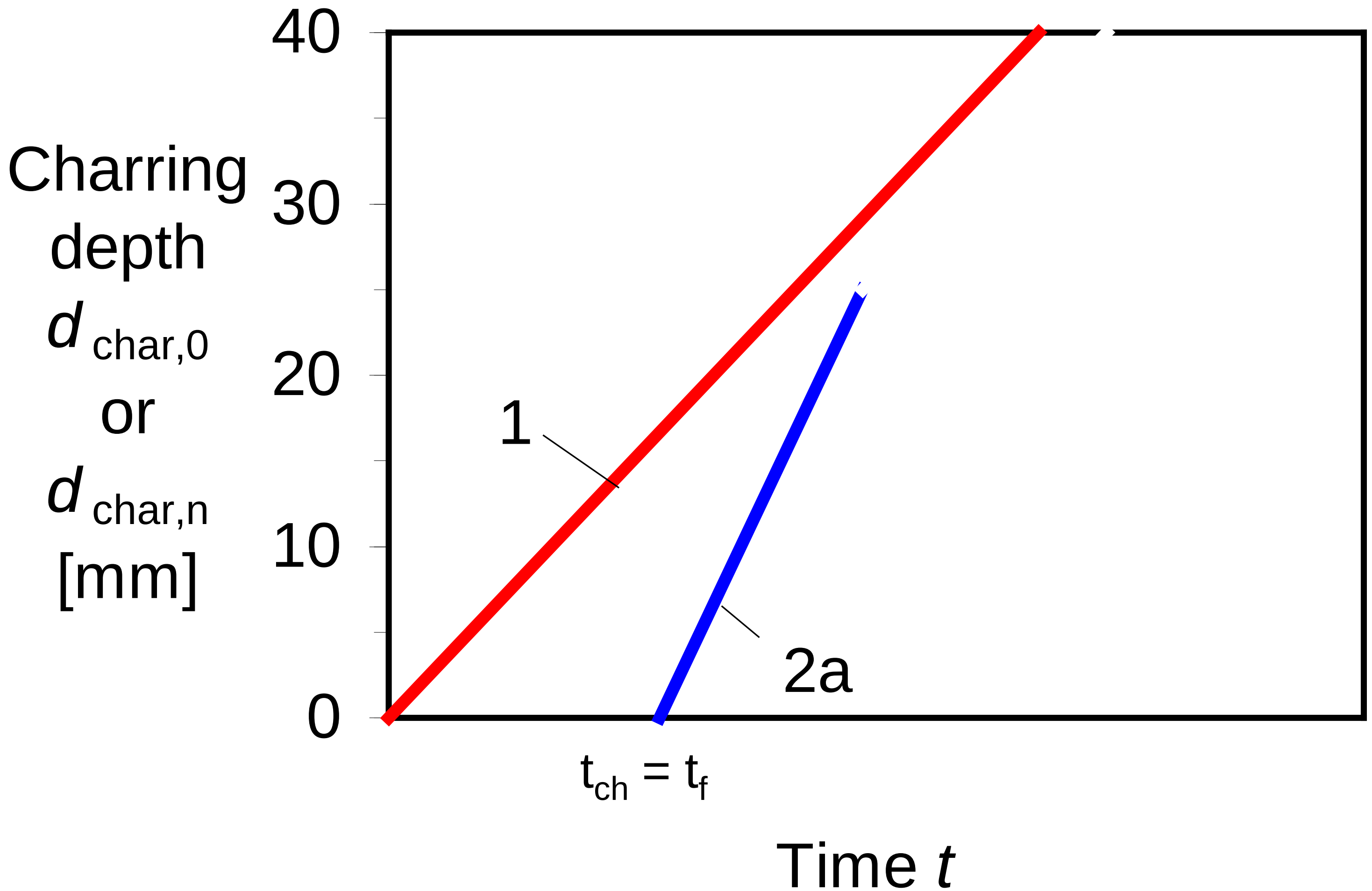
Different charring phases

- t_{ch} = time of start of charring
- t_f = failure time of cladding (fall off)

- For wood-based panels and gypsum plasterboards type A or H: $t_{ch} = t_f$
- For gypsum plasterboards type F: $t_{ch} < t_f$

Charring model for initially protected surfaces

For wood-based panels and gypsum plasterboards type A or H: $t_{ch} = t_f$



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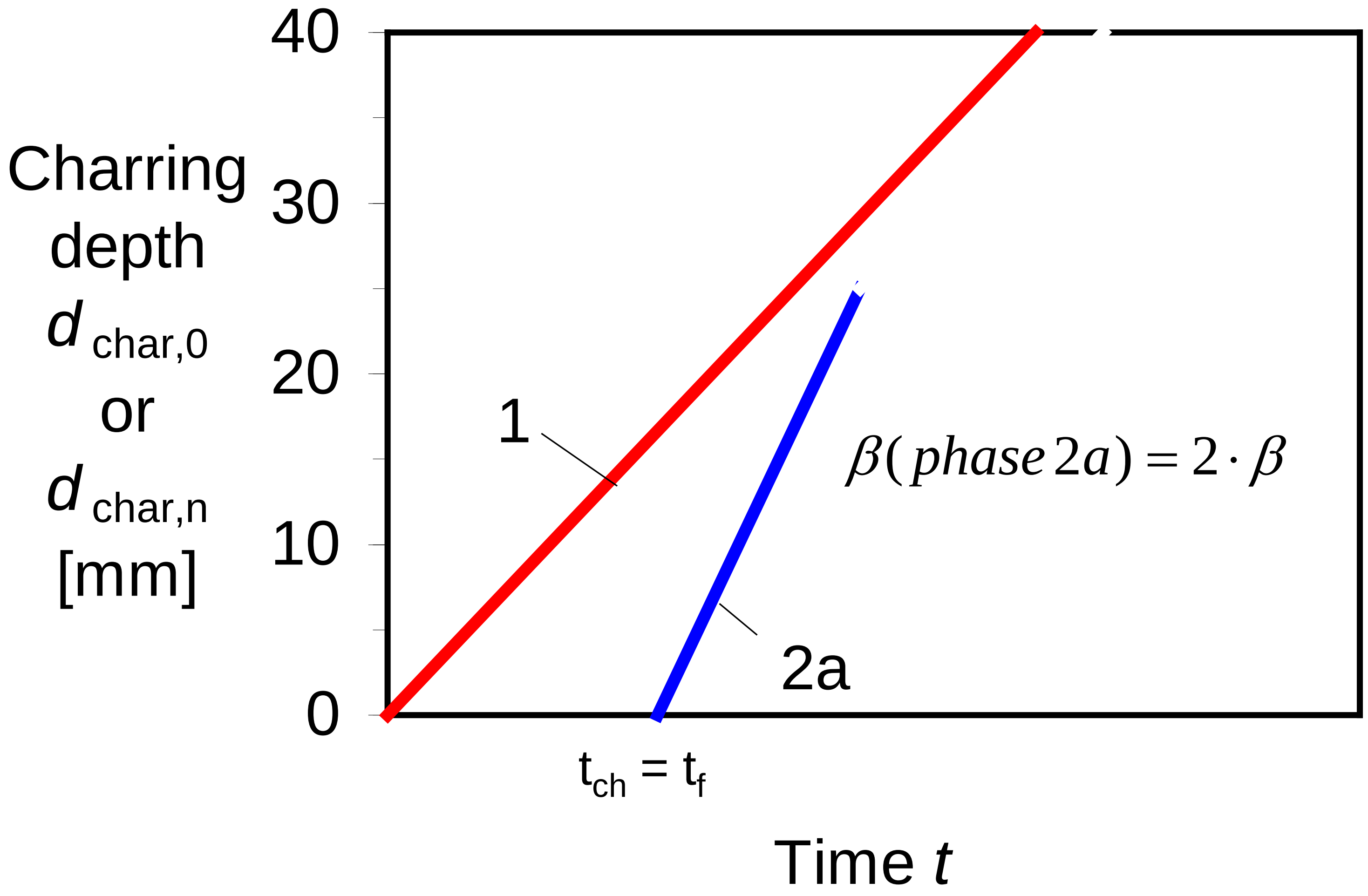

Charring model for initially protected surfaces

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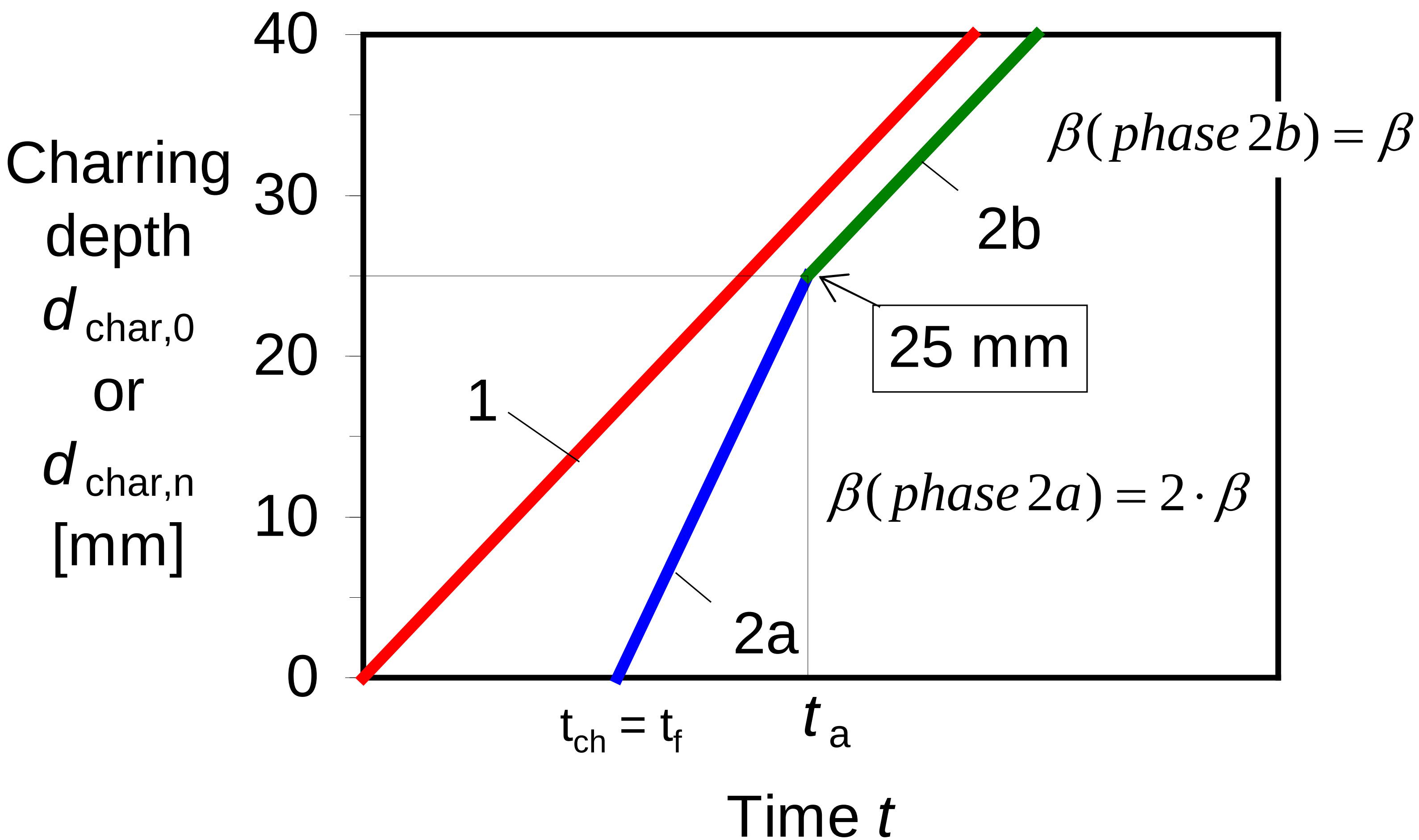
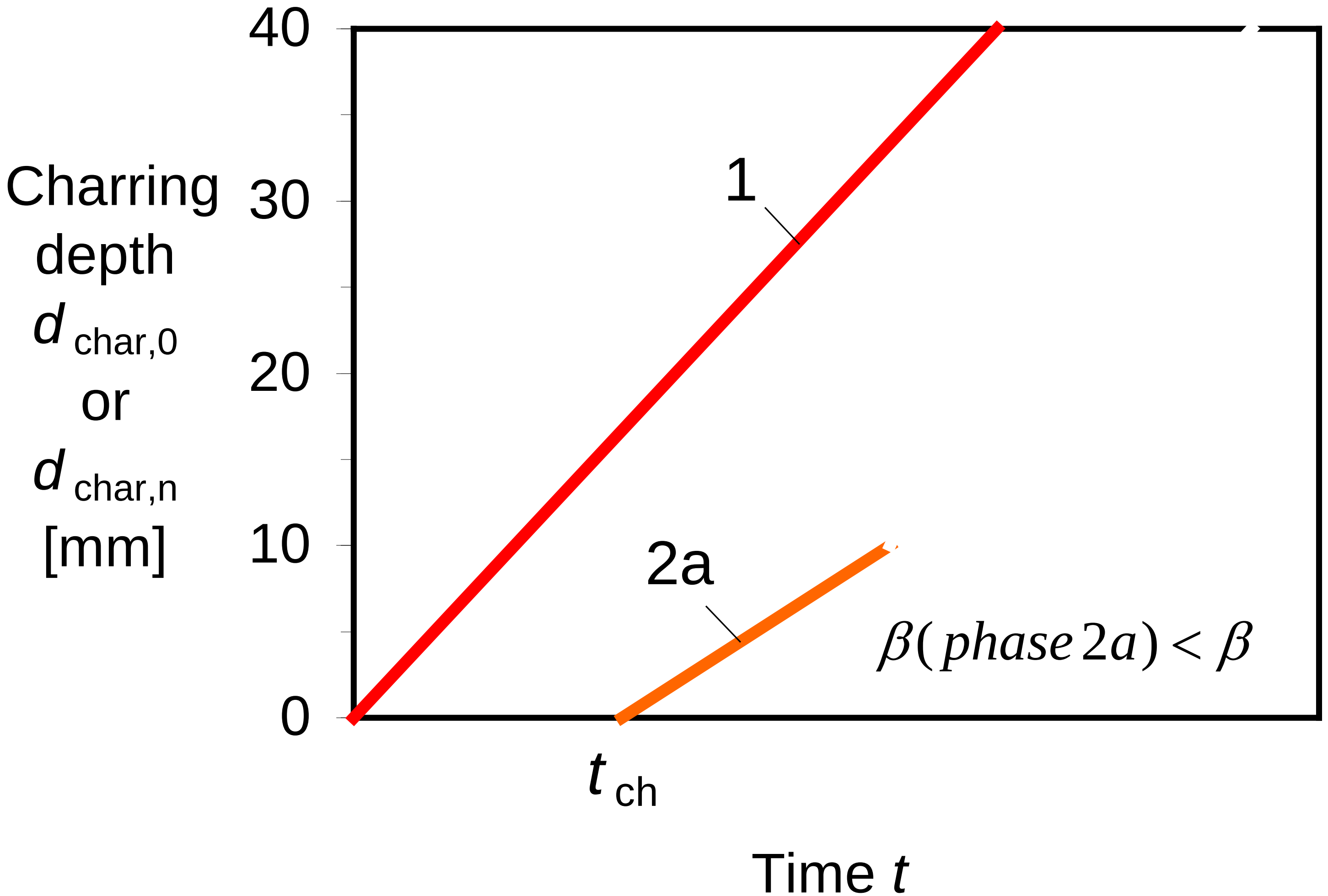


Charring model for initially protected surfaces

For gypsum plasterboards type F: $t_{ch} < t_f$



Charring model for initially protected surfaces

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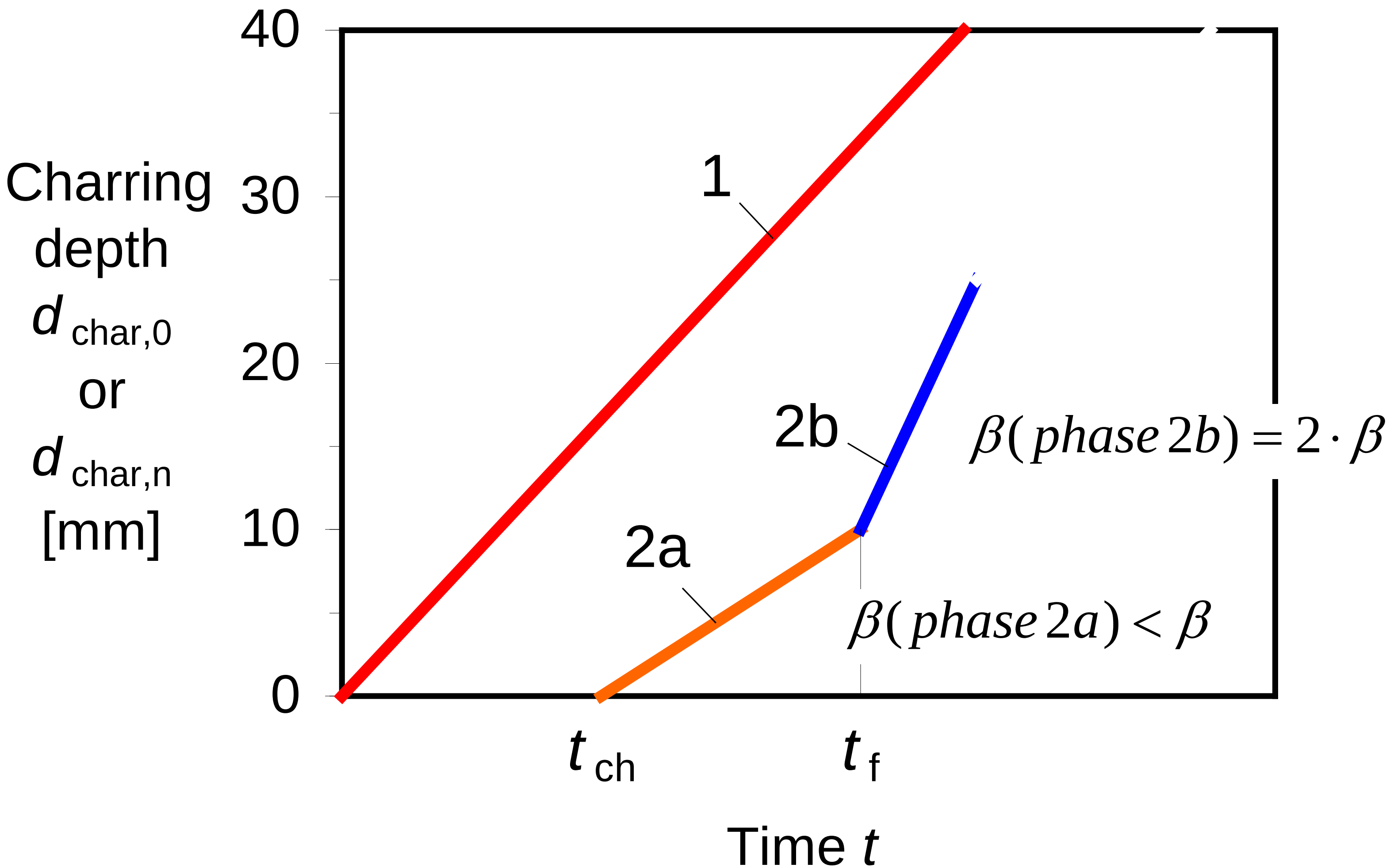

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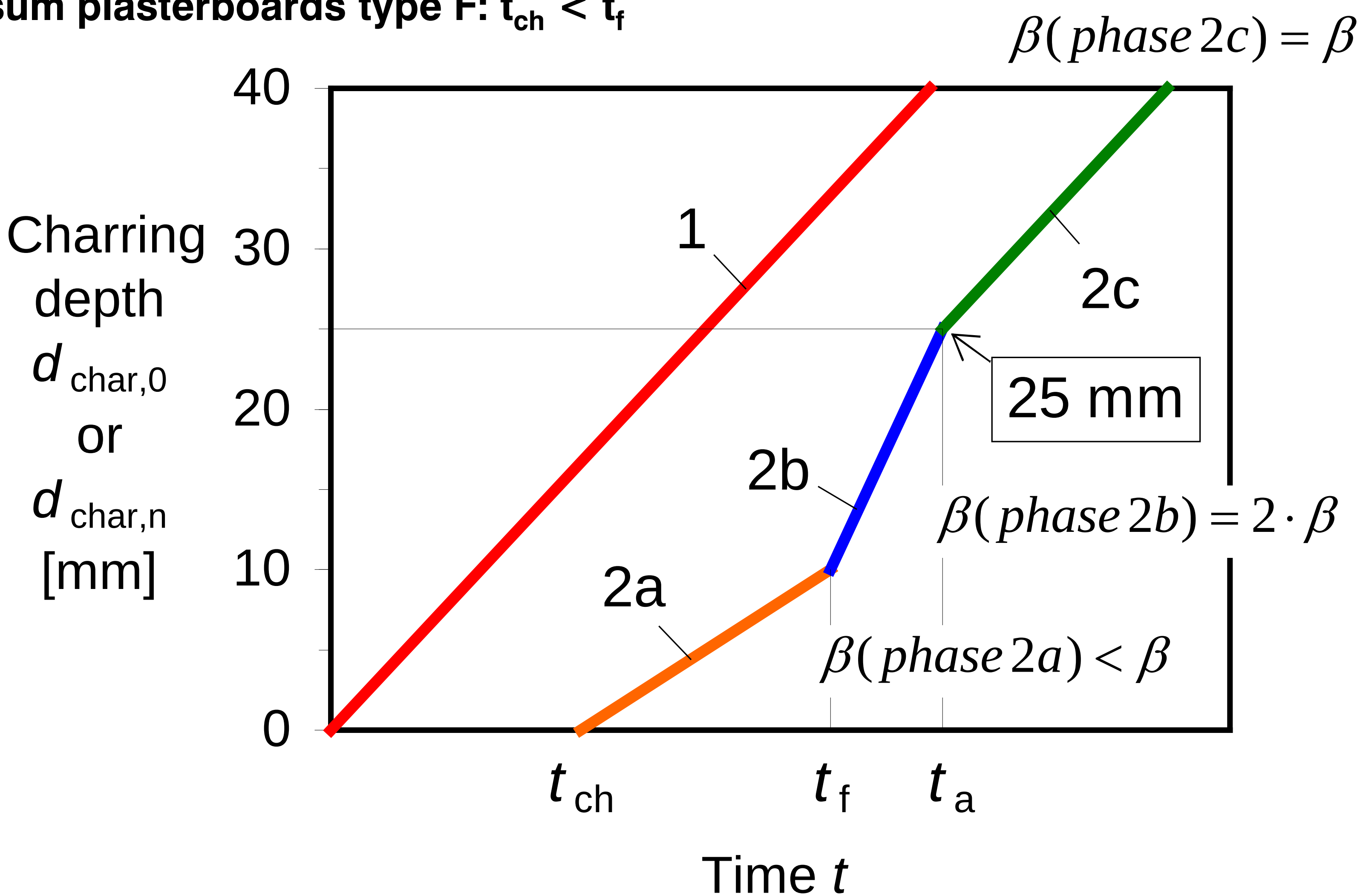
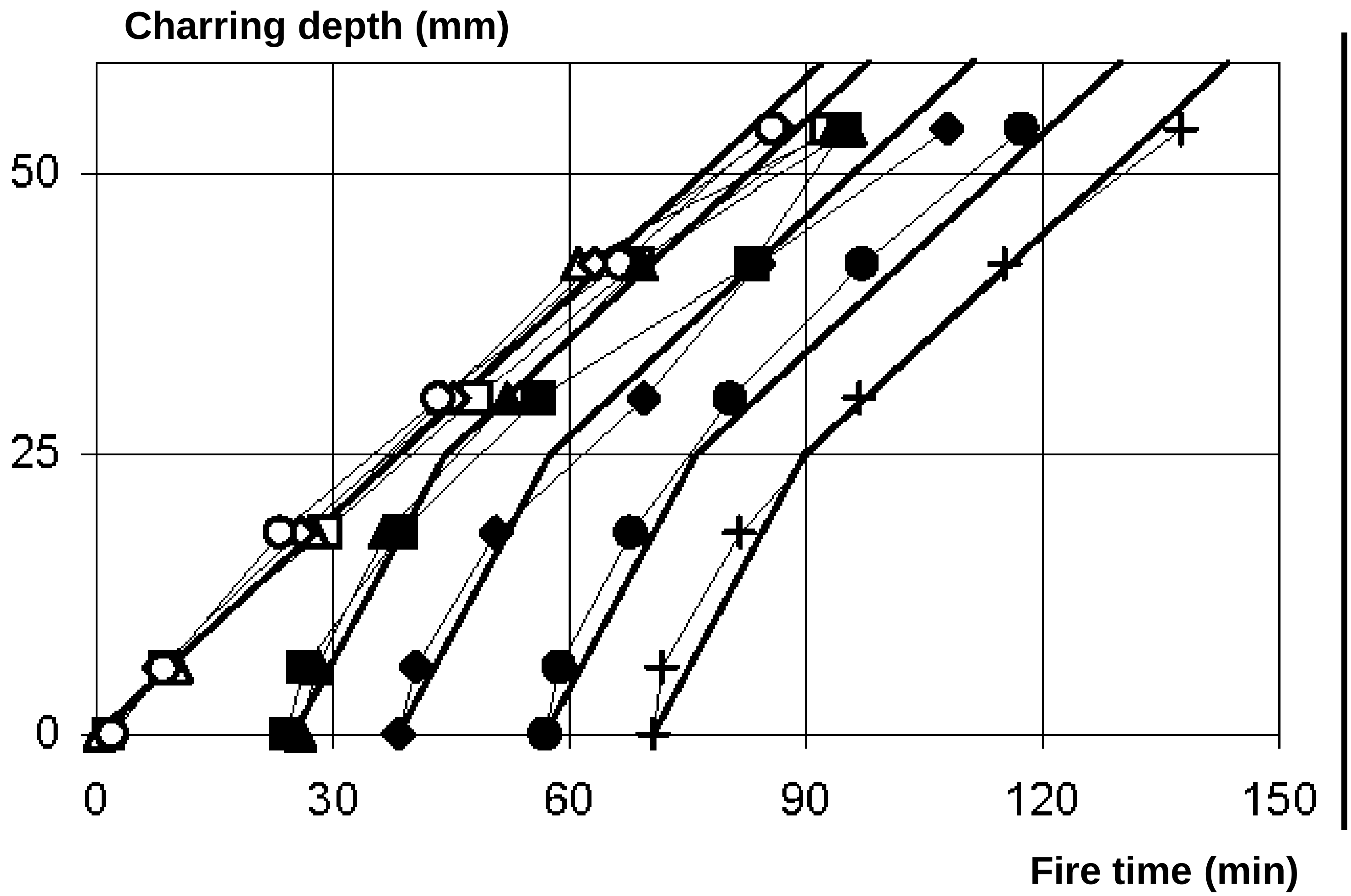


Fire behaviour of initially protected surfaces



Time of start of charring

- **For wood-based panels**

$$t_{ch} = \frac{h_p}{\beta_0}$$

- **For gypsum plasterboards type A, H or F (one layer)**

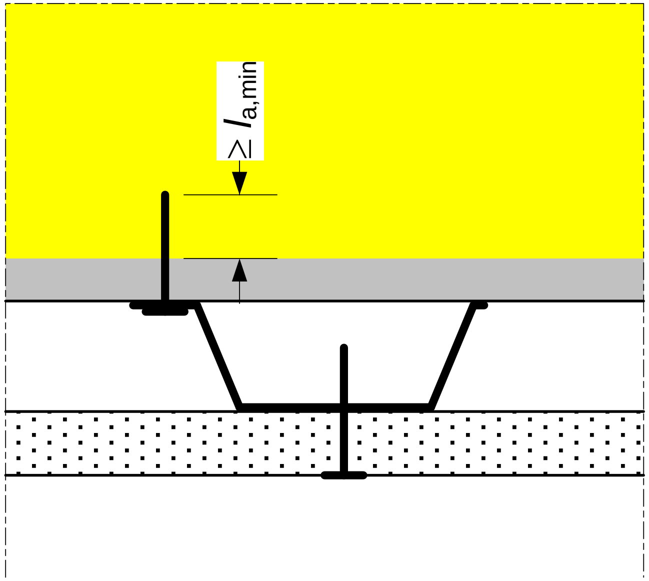
$$t_{ch} = 2{,}8\,h_p - 14$$

$$t_{ch} = 2.8 \cdot 12.5 - 14 = 21 \text{ min}$$

Where h_p is the thickness of the panel, in mm

Failure modes of protective boards

- **Thermal degradation (mechanical failure) of the boards**
- **Pull-out failure of fasteners due to excessive charring of timber member**



Failure modes of protective boards

- **Wood-based panels: $t_{ch} = t_f$**
- **Gypsum plasterboards type A or H: $t_{ch} = t_f$**
- **Gypsum plasterboards type F**
  - **No generic failure times given in EN 1995-1-2**
  - **To be determined by testing (prEN 13381-7)**

Design of timber structures in fire

Verification methods for the load-bearing function

Analysis of

- **entire structure (global analysis)**
- **sub-assemblies (e.g. frames)**
- **members (e.g. walls, floors, columns, beams)**

$$E_{d,fi} \leq R_{d,fi}$$

Verification methods for the load-bearing function

$$E_{d,fi} \leq R_{d,fi}$$

- **Combinations of actions for accidental design situations (EN 1990)**

$$\sum_{j \geq 1} G_{k,j} \text{"+"} P \text{"+"} A_d \text{"+"} (\psi_{1,1} \text{ or } \psi_{2,1}) Q_{k,1} \text{"+"} \sum_{i > 1} \psi_{2,i} Q_{k,i}$$

- **As simplification for residential, social, commercial and administration areas: $E_{d,fi} = 0.6 \cdot E_d$**

Design strength in fire

$$f_{\mathrm{d,fi}} = k_{\mathrm{mod,fi}} \frac{f_{20}}{\gamma_{\mathrm{M,fi}}}$$

Design strength in fire

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20 % fractile of ”cold” strength

Design strength in fire

$$f_{\mathrm{d,fi}} = k_{\mathrm{mod,fi}} \frac{f_{20}}{\gamma_{\mathrm{M,fi}}}$$

20 % fractile of "cold" strength

$$f_{20} = k_{\mathrm{fi}}\, f_{\mathrm{k}}$$

Design strength in fire

$$f_{20} = k_{fi} \, f_k$$

Table 2.1 — Values of k_{fi}

	k_{fi}
Solid timber	1,25
Glued-laminated timber	1,15
Wood-based panels	1,15
LVL	1,1
Connections with fasteners in shear with side members of wood and wood-based panels	1,15
Connections with fasteners in shear with side members of steel	1,05
Connections with axially loaded fasteners	1,05

Design strength in fire

$$f_{d,fi} = k_{mod,fi} \frac{f_{20}}{\gamma_{M,fi}}$$

20 % fractile of strength

modification factor (elevated temperature and moisture)

Design strength in fire

$$f_{\mathrm{d,fi}} = k_{\mathrm{mod,fi}} \frac{f_{20}}{\gamma_{\mathrm{M,fi}}}$$

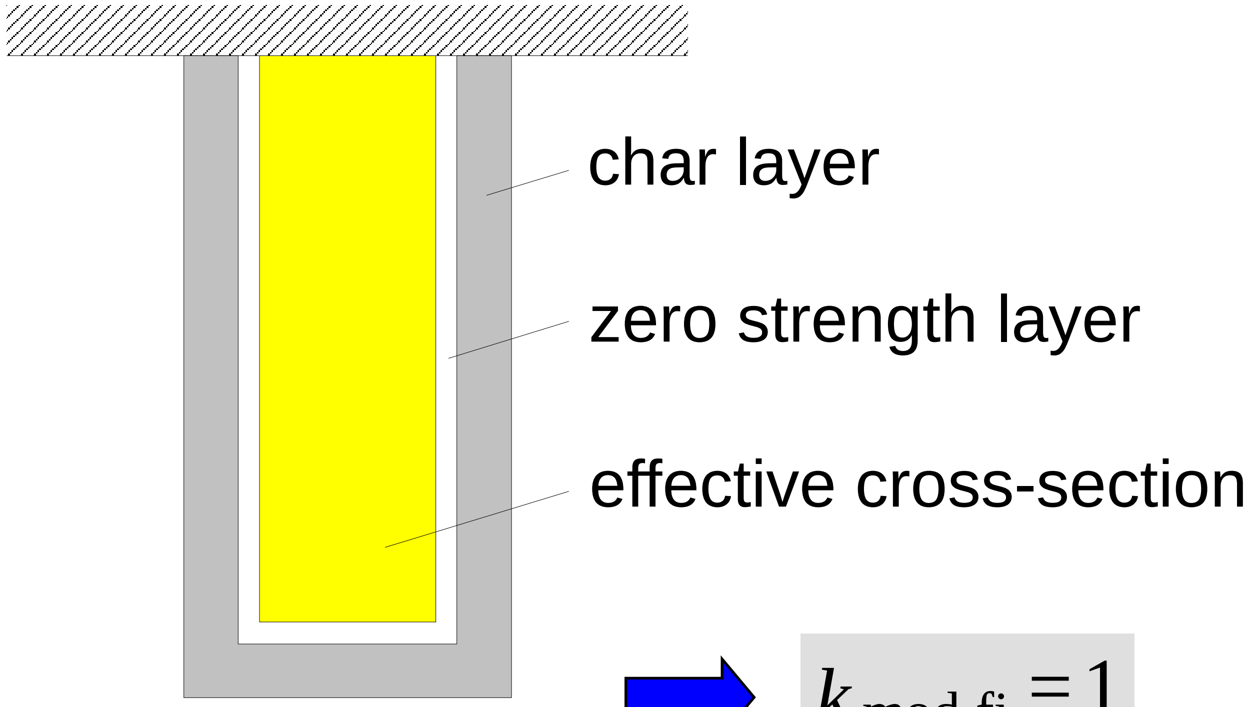
20 % fractile of strength

modification factor (elevated temperature and moisture)

partial factor = 1,0

Design of timber structures in fire

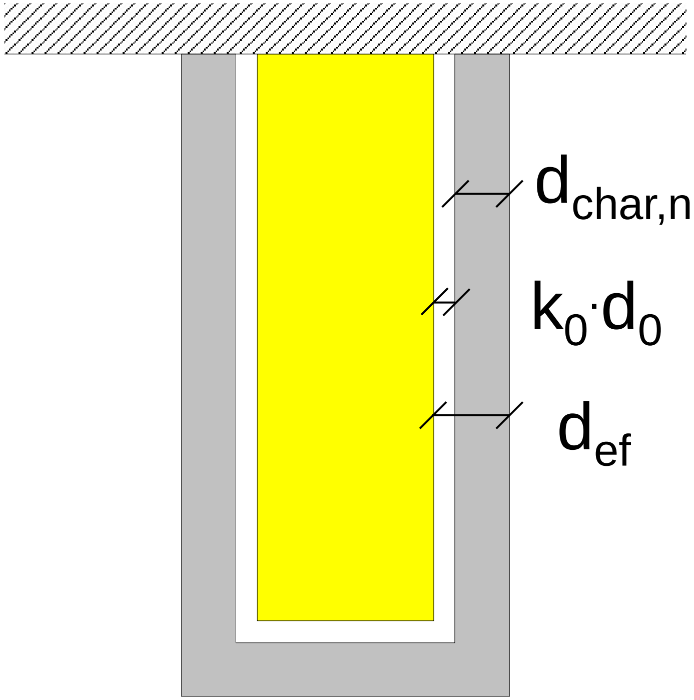
Reduced cross-section method



$$k_{\text{mod,fi}} = 1$$

Design of timber structures in fire

Reduced cross-section method



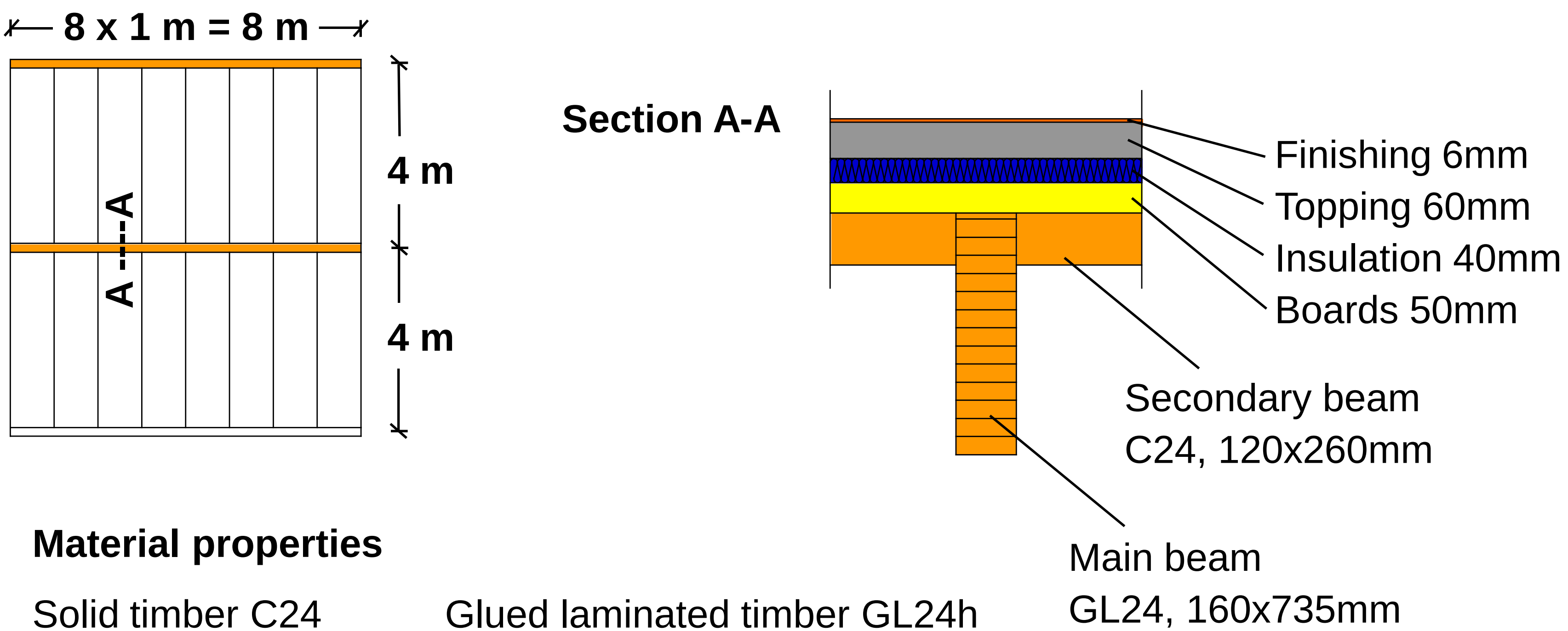
$$d_{ef} = d_{char,n} + k_0 \cdot d_0$$

$$d_0 = 7 \text{ mm}$$

$$k_{mod,fi} = 1.0$$

$$f_{d,fi} = f_{20} = k_{fi} \cdot f_k$$

Worked example



Material properties

Solid timber C24

$f_{m,k}$ = 24 N/mm²

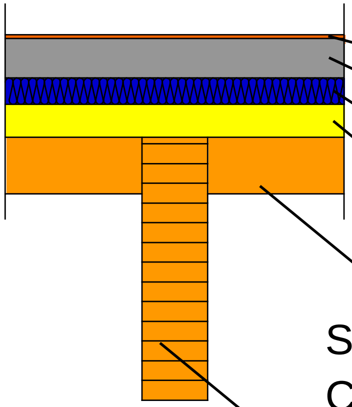
$f_{c,0,k}$ = 21 N/mm²

E_{mean} = 11'000 N/mm²

Glued laminated timber GL24h

$f_{m,k}$ = 24 N/mm²

Worked example



1. Actions

1.1 Perm. load

Finishing	0.09 kN/m^2
Topping	1.32 kN/m^2
Insulation	0.06 kN/m^2
Boards	0.28 kN/m^2
	1.75 kN/m^2
Partitions	1.00 kN/m^2

1.2 Self weight

Secondary beam	120/260 mm	a=1m => 0.17 kN/m^2
Main beam	160/735 mm	a=4m => 0.17 kN/m^2

1.3 Live load Residential 2.0 kN/m^2 (ψ_2 = 0.3)

Worked example

2. Secondary beam – Fire resistance R 30

Solid timber 120/260 mm (C24)

=> Notional charring rate β_n = 0.8 mm/min

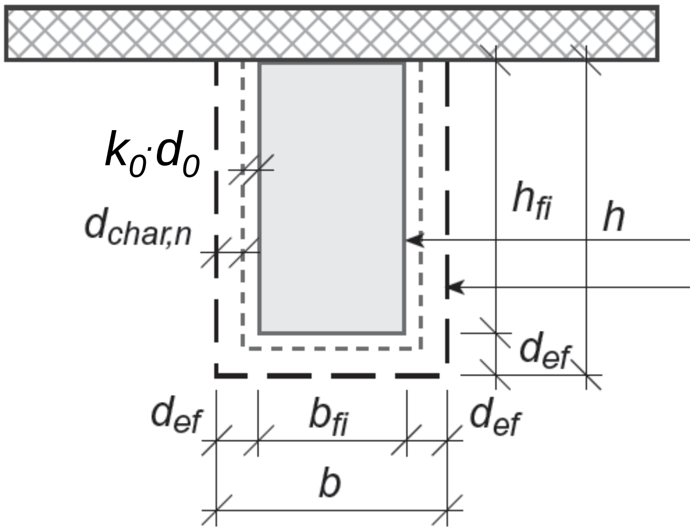
Fire exposure on 3 sides, $t_{fi,req}$ = 30 min

b_{fi} = 120 - 2 · (30 · 0.8 + 7) = 58 mm

h_{fi} = 260 - (30 · 0.8 + 7) = 229 mm

W_{fi} = = $506.9 \cdot 10^3$ mm³

$f_{m,d,fi} = k_{fi} \cdot f_{m,k}$ = 1.25 · 24 = 30.0 N/mm²



$$M_{d,fi} = \frac{(1.75 + 1.0 + 0.17 + 0.3 \cdot 2) \cdot 1 \cdot 4^2}{8} = 7.0\ \text{kNm}$$

$$\sigma_{d,fi} = \frac{M_{d,fi}}{W_{fi}} = 13.9\ \text{N/mm}^2 \quad \leq \quad f_{m,d,fi} = 30.0\ \text{N/mm}^2$$ ☺

Worked example

3. Main beam – Fire resistance R 30

Glued laminated timber 160/735 mm (GL24h)

=> Notional charring rate β_n = 0.7 mm/min

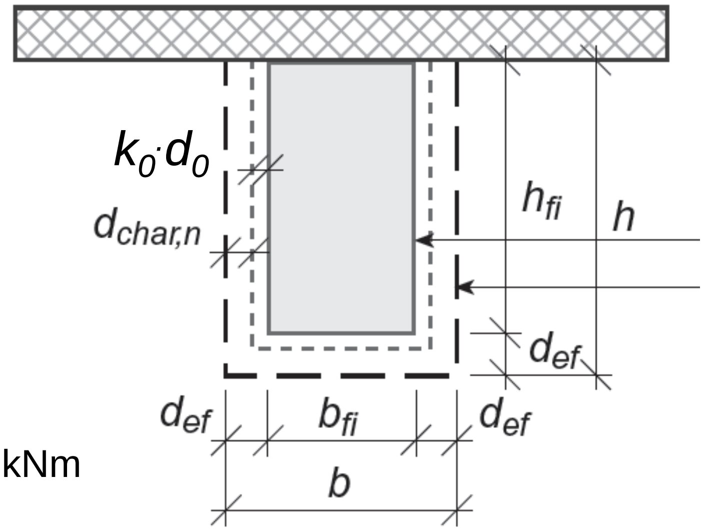
Fire exposure on 3 sides, $t_{fi,req}$ = 30 min

$b_{fi} = 160 - 2 \cdot (30 \cdot 0.7 + 7) = 104$ mm

$h_{fi} = 735 - (30 \cdot 0.7 + 7) = 707$ mm

$W_{fi} = \quad = 8664 \cdot 10^3$ mm^3

$f_{m,d,fi} = k_{fi} \cdot f_{m,d} = 1.15 \cdot 24 = 27.6$ N/mm^2

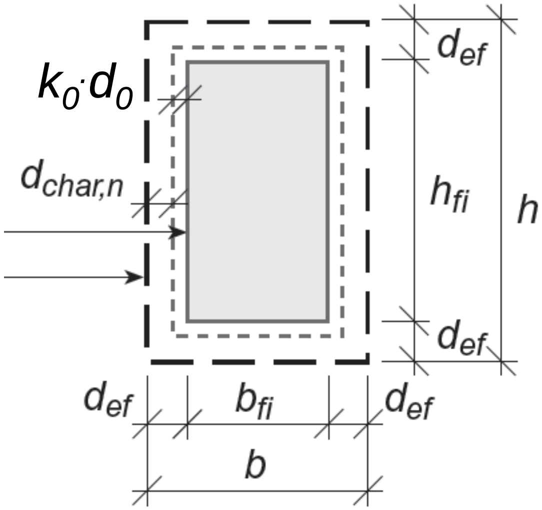


$$M_{d,fi} = \frac{(1.75 + 1.0 + 0.17 + 0.17 + 0.3 \cdot 2) \cdot 4 \cdot 8^2}{8} = 118.1\,\text{kNm}$$

$$\sigma_{d,fi} = \frac{M_{d,fi}}{W_{fi}} = 13.6\,\text{N/mm}^2 \quad \leq \quad f_{m,d,fi} = 27.6\,\text{N/mm}^2$$ ☺

Worked example

4. Column – Fire resistance R 30



Solid timber 160/160 mm (C24)

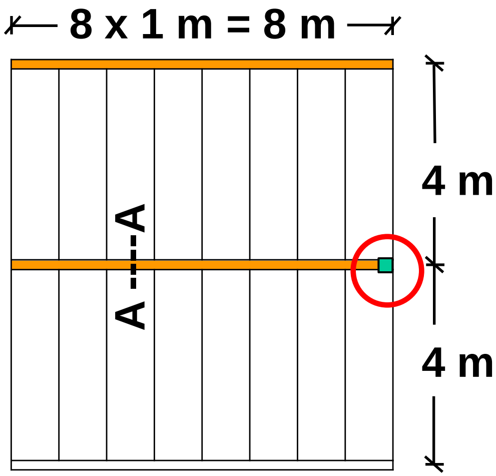
=> Notional charring rate β_n = 0.8 mm/min

Fire exposure on 4 sides, $t_{fi,req}$ = 30 min

$b_{fi} = 160 - 2 \cdot (30 \cdot 0.8 + 7) = 98$ mm

$h_{fi} = 160 - 2 \cdot (30 \cdot 0.8 + 7) = 98$ mm

$A_{fi} = 9.6 \cdot 10^3$ mm²



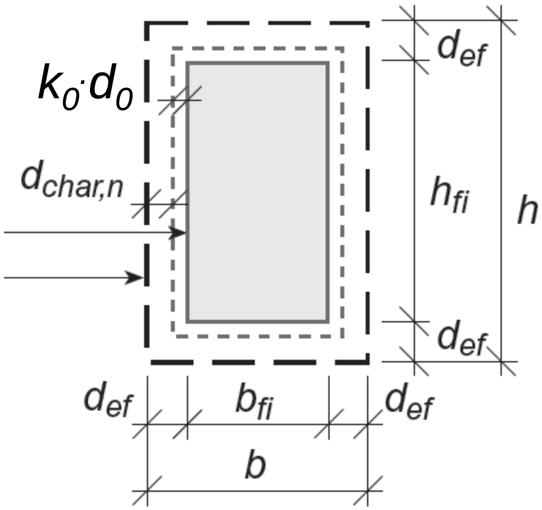
$$N_{d,fi} = \frac{(1.75 + 1.0 + 0.17 + 0.17 + 0.3 \cdot 2) \cdot 4 \cdot 8}{2} = 59.0\ \text{kN}$$

$$\sigma_{d,fi} = \frac{N_{d,fi}}{A_{fi}} = 6.1\,\text{N/mm}^2 \leq f_{c,0,d,fi} = k_{c,fi} \cdot k_{fi} \cdot f_{c,0,k}$$

Worked example

4. Column – Fire resistance R 30

Buckling length: ℓ = 3.0m



$$i_{fi} = \sqrt{\frac{I_{fi}}{A_{fi}}} = \sqrt{\frac{98 \cdot 98^3 / 12}{98 \cdot 98}} = 28.3\,mm$$

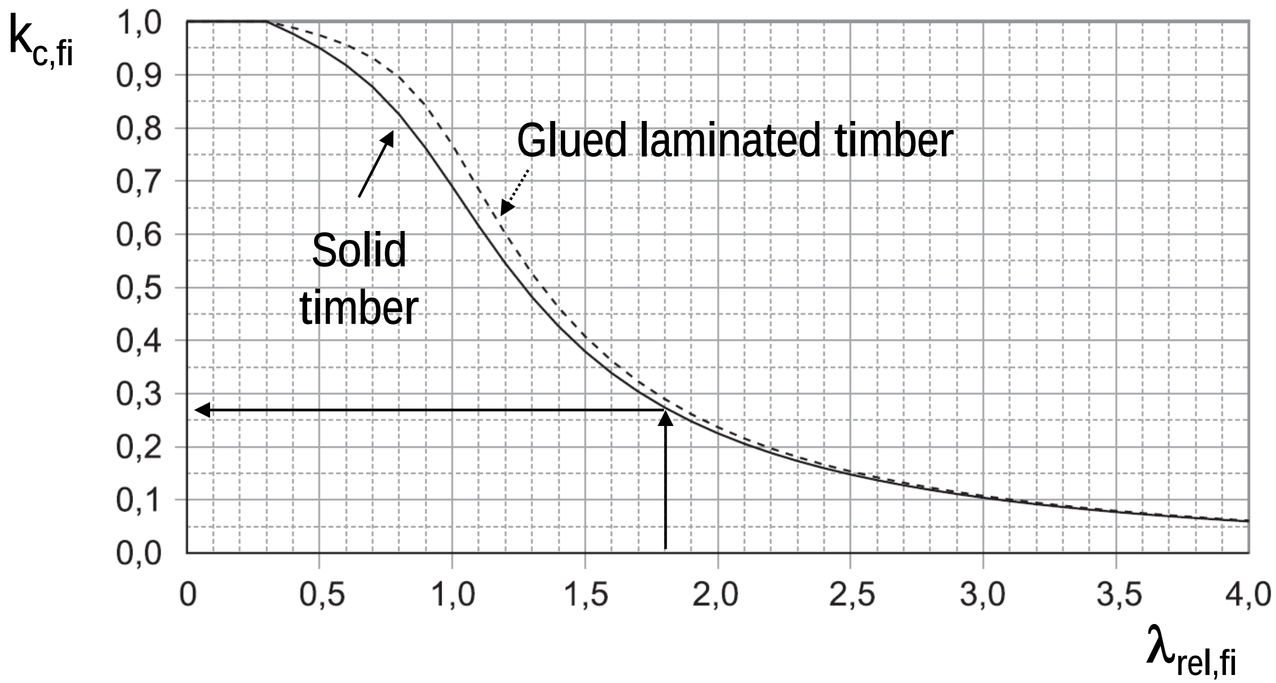
$$\lambda_{fi} = \frac{\ell}{i_{fi}} = \frac{3000}{28.3} = 106.0$$

$$\lambda_{rel,fi} = \frac{\lambda_{fi}}{\pi} \cdot \sqrt{\frac{f_{c,0,k}}{E_{0,05}}} = \frac{\lambda_{fi}}{\pi} \cdot \sqrt{\frac{f_{c,0,k}}{2/3 \cdot E_{mean}}} = \frac{106}{3.14} \cdot \sqrt{\frac{21}{2/3 \cdot 11000}} = 1.8$$

Worked example

4. Column – Fire resistance R 30

$$\lambda_{rel,fi} = \frac{\lambda_{fi}}{\pi} \cdot \sqrt{\frac{f_{c,0,k}}{E_{0,05}}} = \frac{\lambda_{fi}}{\pi} \cdot \sqrt{\frac{f_{c,0,k}}{2/3 \cdot E_{mean}}} = \frac{106}{3.14} \cdot \sqrt{\frac{21}{2/3 \cdot 11000}} = 1.8 \quad => \quad k_{c,fi} = 0.27$$



Worked example

4. Column – Fire resistance R 30

Solid timber 160/160 mm (C24)

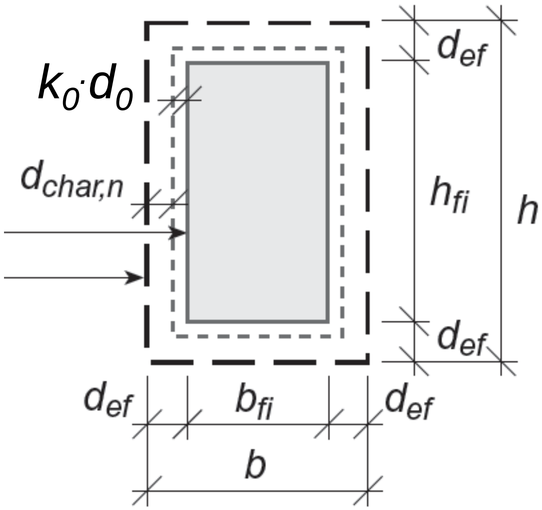
=> Notional charring rate β_n = 0.8 mm/min

Fire exposure on 4 sides, $t_{fi,req}$ = 30 min

$b_{fi} = 160 - 2 \cdot (30 \cdot 0.8 + 7) = 98$ mm

$h_{fi} = 160 - 2 \cdot (30 \cdot 0.8 + 7) = 98$ mm

$A_{fi} = \quad = 9.6 \cdot 10^3$ mm²



$$N_{d,fi} = \frac{(1.75 + 1.0 + 0.17 + 0.17 + 0.3 \cdot 2) \cdot 4 \cdot 8}{2} = 59.0\,\text{kN}$$

$$\sigma_{d,fi} = \frac{N_{d,fi}}{A_{fi}} = 6.1\,\text{N/mm}^2 \leq \quad f_{c,0,d,fi} = 0.27 \cdot 1.25 \cdot 21 = 7.1\,\text{N/mm}^2$$ ☺

Fire resistance of 60 minutes?

Basic strategies

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

Worked example

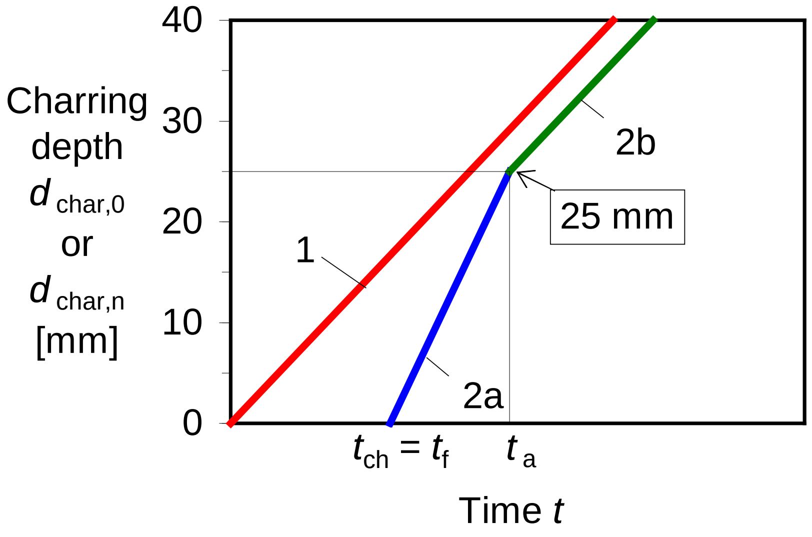
5.1 Column – Fire resistance R 60

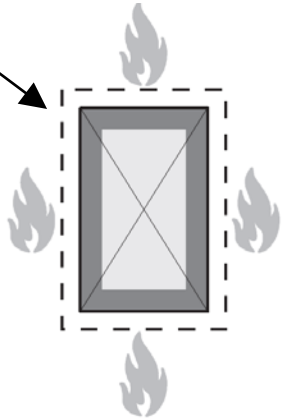
Solid timber 160/160 mm (C24) => Notional charring rate β_n = 0.8 mm/min

Fire exposure on 4 sides, $t_{fi,req}$ = 60 min

Protection with gypsum plasterboards, Type A, single layers, 18mm

$$t_{ch} = 2.8 \cdot h_p - 14 = 2.8 \cdot 18 - 14 = 36\,\text{min}$$





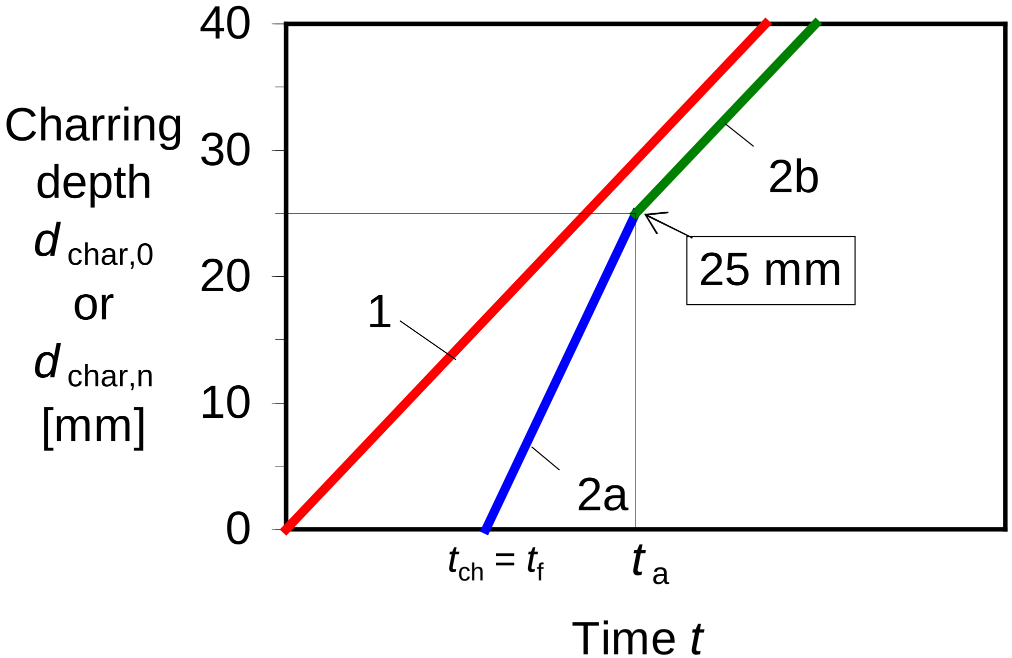
Worked example

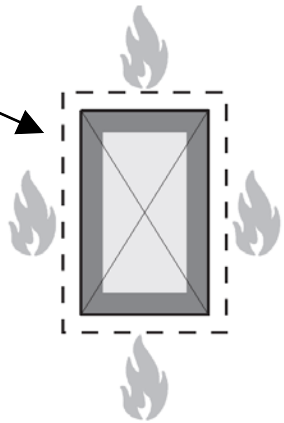
5.1 Column – Fire resistance R 60

Protection with gypsum plasterboards, Type A, single layers, 18mm

$$t_{ch} = 2.8 \cdot h_p - 14 = 2.8 \cdot 18 - 14 = 36 \text{ min}$$

$$t_a = 36 + \frac{25}{2 \cdot \beta_n} = 36 + \frac{25}{2 \cdot 0.8} = 51.5 \text{ min}$$





Worked example

5.1 Column – Fire resistance R 60

Solid timber 160/160 mm (C24)

=> Notional charring rate β_n = 0.8 mm/min

Fire exposure on 4 sides, $t_{fi,req}$ = 60 min

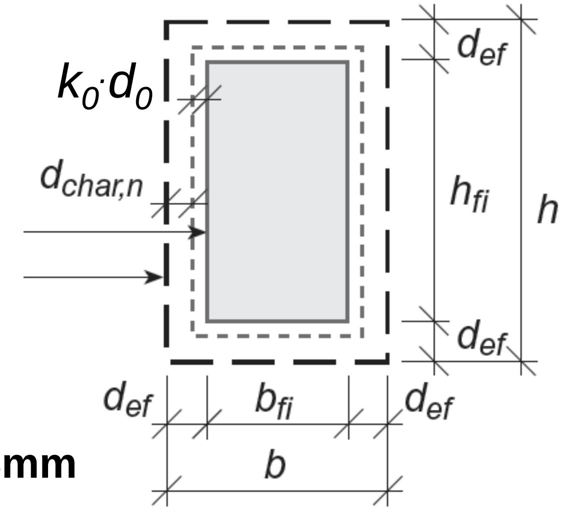
Protection with gypsum plasterboards, Type A, 18mm

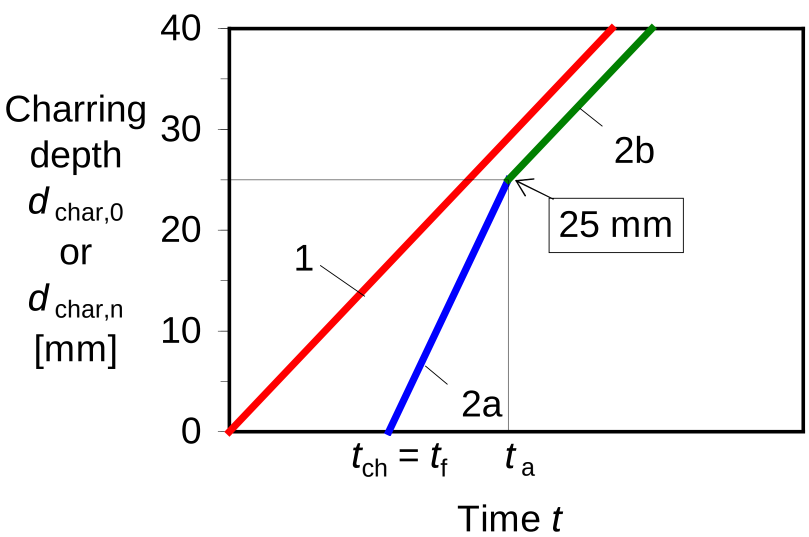
t_{ch} = 36 min; t_a = 51.5 min

$b_{fi} = 160 - 2 \cdot (25 + 8.5 \cdot 0.8 + 7) = 82.4$ mm

$h_{fi} = 160 - 2 \cdot (25 + 8.5 \cdot 0.8 + 7) = 82.4$ mm

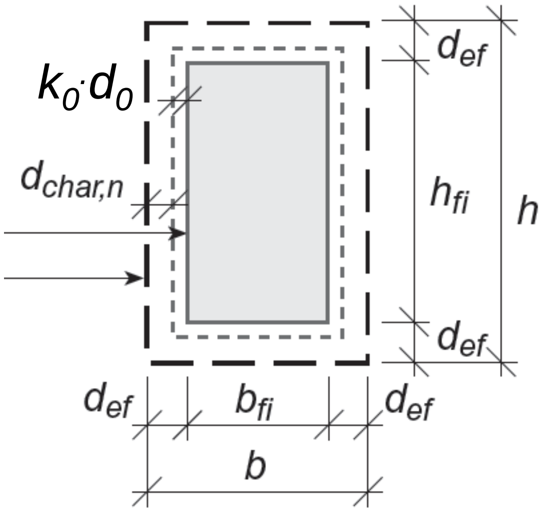
A_{fi} = = $6.8 \cdot 10^3$ mm²





Worked example

5.1 Column – Fire resistance R 60



Buckling length: ℓ = 3.0m

$$i_{fi} = \sqrt{\frac{I_{fi}}{A_{fi}}} = \sqrt{\frac{82.4 \cdot 82.4^3 / 12}{82.4 \cdot 82.4}} = 23.8\,\text{mm}$$

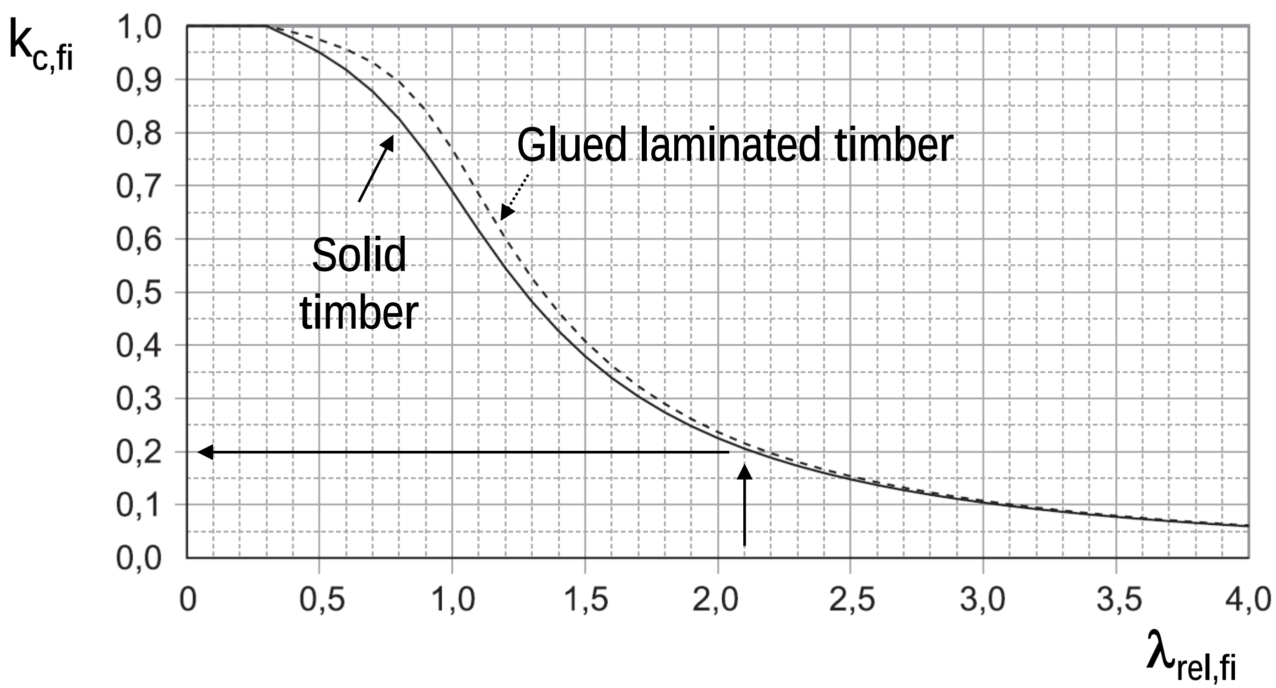
$$\lambda_{fi} = \frac{\ell}{i_{fi}} = \frac{3000}{23.8} = 126.0$$

$$\lambda_{rel,fi} = \frac{\lambda_{fi}}{\pi} \cdot \sqrt{\frac{f_{c,0,k}}{E_{0,05}}} = \frac{\lambda_{fi}}{\pi} \cdot \sqrt{\frac{f_{c,0,k}}{2/3 \cdot E_{mean}}} = \frac{126.0}{3.14} \cdot \sqrt{\frac{21}{2/3 \cdot 11000}} = 2.1$$

Worked example

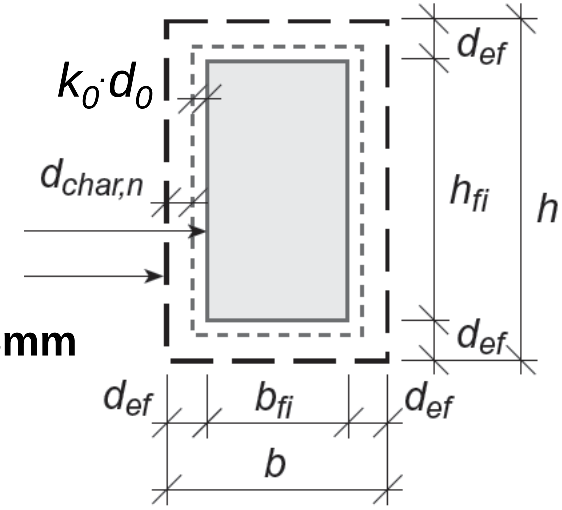
5.1 Column – Fire resistance R 60

$$\lambda_{rel,fi} = \frac{\lambda_{fi}}{\pi} \cdot \sqrt{\frac{f_{c,0,k}}{E_{0,05}}} = \frac{\lambda_{fi}}{\pi} \cdot \sqrt{\frac{f_{c,0,k}}{2/3 \cdot E_{mean}}} = \frac{126.0}{3.14} \cdot \sqrt{\frac{21}{2/3 \cdot 11000}} = 2.1 \quad => \quad \boxed{k_{c,fi} = 0.20}$$



Worked example

5.1 Column – Fire resistance R 60



Solid timber 160/160mm (C24)

=> Notional charring rate β_n = 0.8 mm/min

Fire exposure on 4 sides, $t_{fi,req}$ = 60 min

Protection with gypsum plasterboards, Type A, 18mm

t_{ch} = 36 min; t_a = 51.5 min

$b_{fi} = 160 - 2 \cdot (25 + 8.5 \cdot 0.8 + 7) = 82.4$ mm

$h_{fi} = 160 - 2 \cdot (25 + 8.5 \cdot 0.8 + 7) = 82.4$ mm

$A_{fi} = \quad = 6.8 \cdot 10^3$ mm²

$$N_{d,fi} = \frac{(1.75 + 1.0 + 0.17 + 0.17 + 0.3 \cdot 2) \cdot 4 \cdot 8}{2} = 59.0\ \text{kN}$$

$$\sigma_{d,fi} = \frac{N_{d,fi}}{A_{fi}} = 8.7\ \text{N/mm}^2 \leq f_{c,0,d,fi} = 0.20 \cdot 1.25 \cdot 21 = 5.3\ \text{N/mm}^2$$

☹

Worked example

5.2 Column – Fire resistance R 60

Increase of cross-sections by charring depth (≈ 30 · 0.8 = 24mm)

Solid timber **210/210 mm** (C24) => Notional charring rate β_n = 0.8 mm/min

Fire exposure on 4 sides, $t_{fi,req}$ = 60 min

$b_{fi} = 210 - 2 \cdot (60 \cdot 0.8 + 7) = 100$ mm

$h_{fi} = 210 - 2 \cdot (60 \cdot 0.8 + 7) = 100$ mm

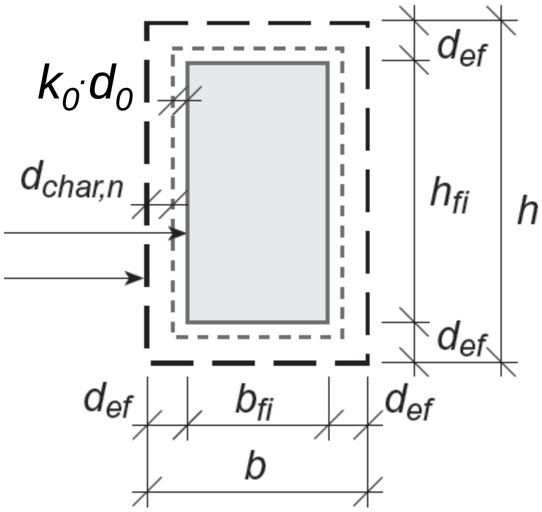
$A_{fi} = \quad = 10 \cdot 10^3$ mm²

$$N_{d,fi} = \frac{(1.75 + 1.0 + 0.17 + 0.17 + 0.3 \cdot 2) \cdot 4 \cdot 8}{2} = 59.0\,\text{kN}$$

$$\sigma_{d,fi} = \frac{N_{d,fi}}{A_{fi}} = 5.9\,\text{N/mm}^2 \leq f_{c,0,d,fi} = k_{c,fi} \cdot k_{fi} \cdot f_{c,0,k}$$

Worked example

5.2 Column – Fire resistance R 60



Buckling length: $\ell = 3.0\text{m}$

$$i_{fi} = \sqrt{\frac{I_{fi}}{A_{fi}}} = \sqrt{\frac{100 \cdot 100^3 / 12}{100 \cdot 100}} = 28.9 \text{ mm}$$

$$\lambda_{fi} = \frac{\ell}{i_{fi}} = \frac{3000}{28.9} = 103.8$$

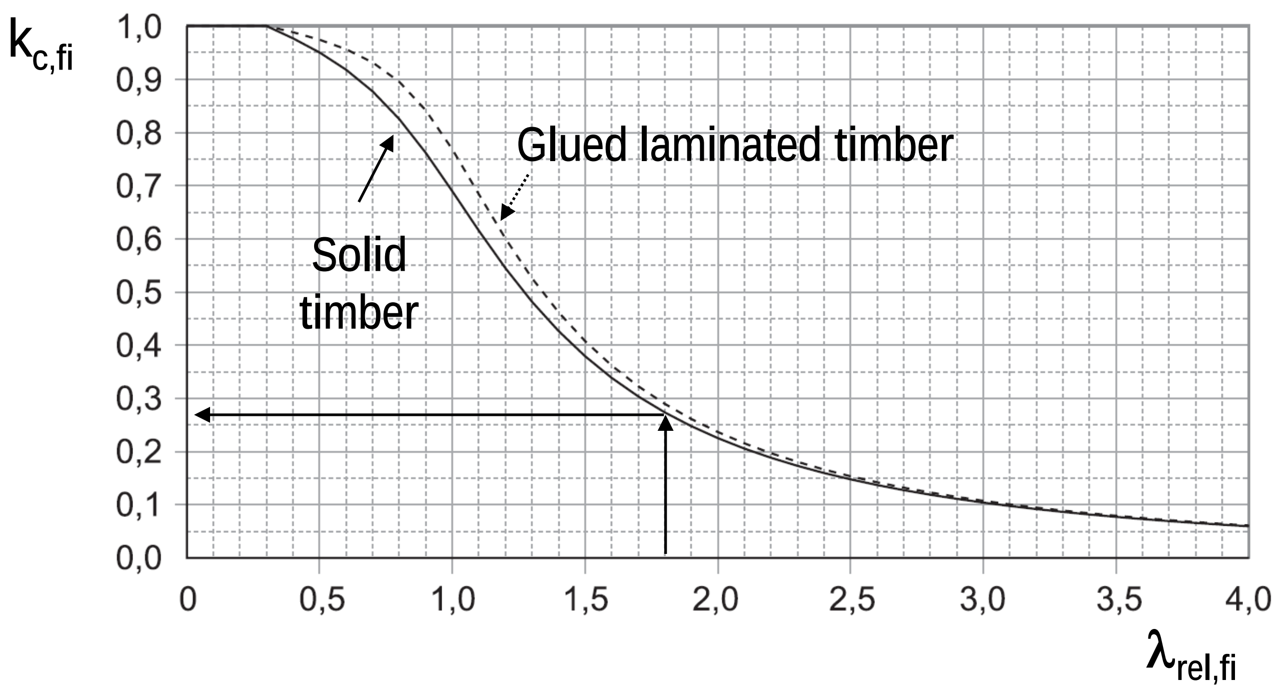
$$\lambda_{rel,fi} = \frac{\lambda_{fi}}{\pi} \cdot \sqrt{\frac{f_{c,0,k}}{E_{0,05}}} = \frac{\lambda_{fi}}{\pi} \cdot \sqrt{\frac{f_{c,0,k}}{2/3 \cdot E_{mean}}} = \frac{103.8}{3.14} \cdot \sqrt{\frac{21}{2/3 \cdot 11000}} = 1.8$$

Worked example

5.2. Column – Fire resistance R 60

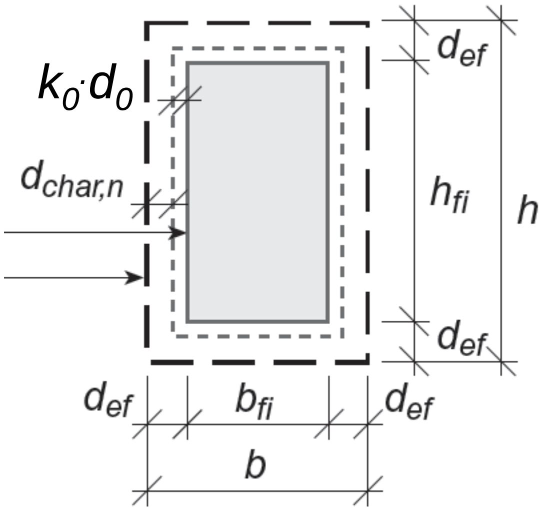
$$\lambda_{rel,fi} = \frac{\lambda_{fi}}{\pi} \cdot \sqrt{\frac{f_{c,0,k}}{E_{0,05}}} = \frac{\lambda_{fi}}{\pi} \cdot \sqrt{\frac{f_{c,0,k}}{2/3 \cdot E_{mean}}} = \frac{103.8}{3.14} \cdot \sqrt{\frac{21}{2/3 \cdot 11000}} = 1.8$$

=> $k_{c,fi} = 0.27$



Worked example

5.2. Column – Fire resistance R 60



Solid timber 210/210 mm (C24)

=> Notional charring rate β_n = 0.8 mm/min

Fire exposure on 4 sides, $t_{fi,req}$ = 30 min

$b_{fi} = 210 - 2 \cdot (60 \cdot 0.8 + 7) = 100$ mm

$h_{fi} = 210 - 2 \cdot (60 \cdot 0.8 + 7) = 100$ mm

$A_{fi} = \qquad = 10 \cdot 10^3$ mm²

$$N_{d,fi} = \frac{(1.75 + 1.0 + 0.17 + 0.17 + 0.3 \cdot 2) \cdot 4 \cdot 8}{2} = 59.0\,\text{kN}$$

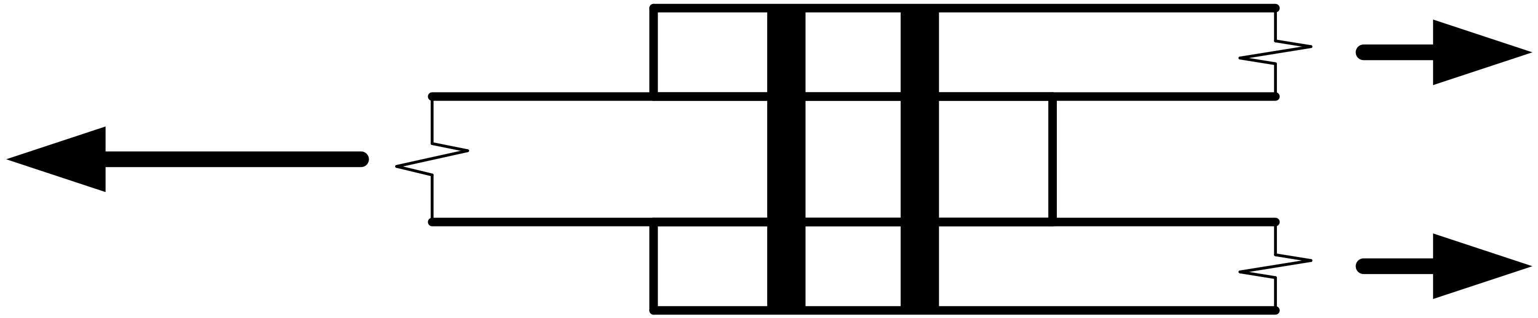
$$\sigma_{d,fi} = \frac{N_{d,fi}}{A_{fi}} = 5.9\ \text{N/mm}^2 \leq \ f_{c,0,d,fi} = 0.27 \cdot 1.25 \cdot 21 = 7.1\,\text{N/mm}^2$$

☺

Connections in fire

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

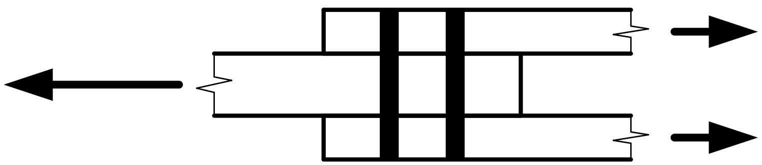
Connections

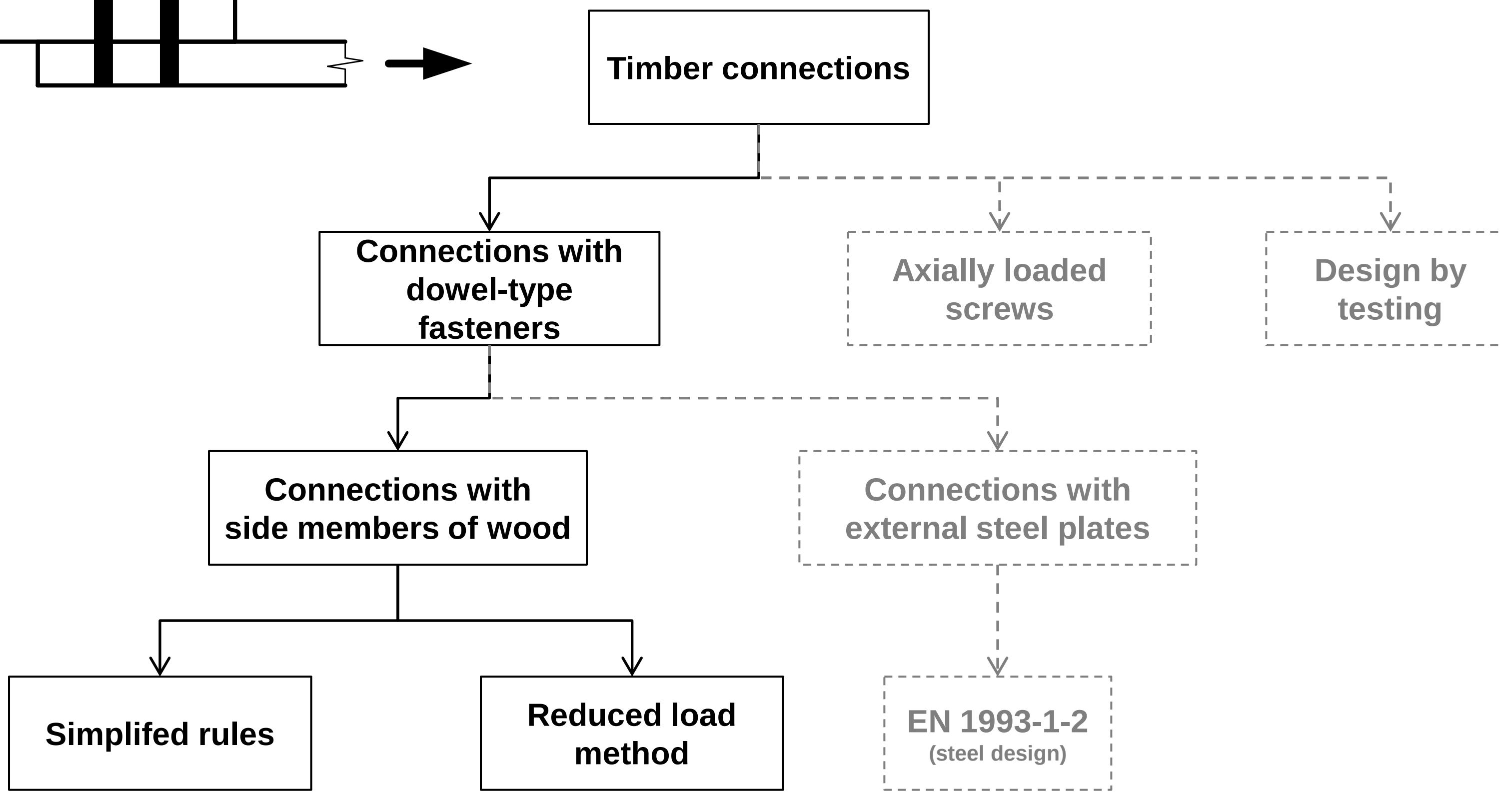


Only symmetrical three-member connections

Dowel-type fasteners (nails, bolts, dowels, screws) and connectors (split-ring, shear-plate and toothed-plate connectors)

Connections

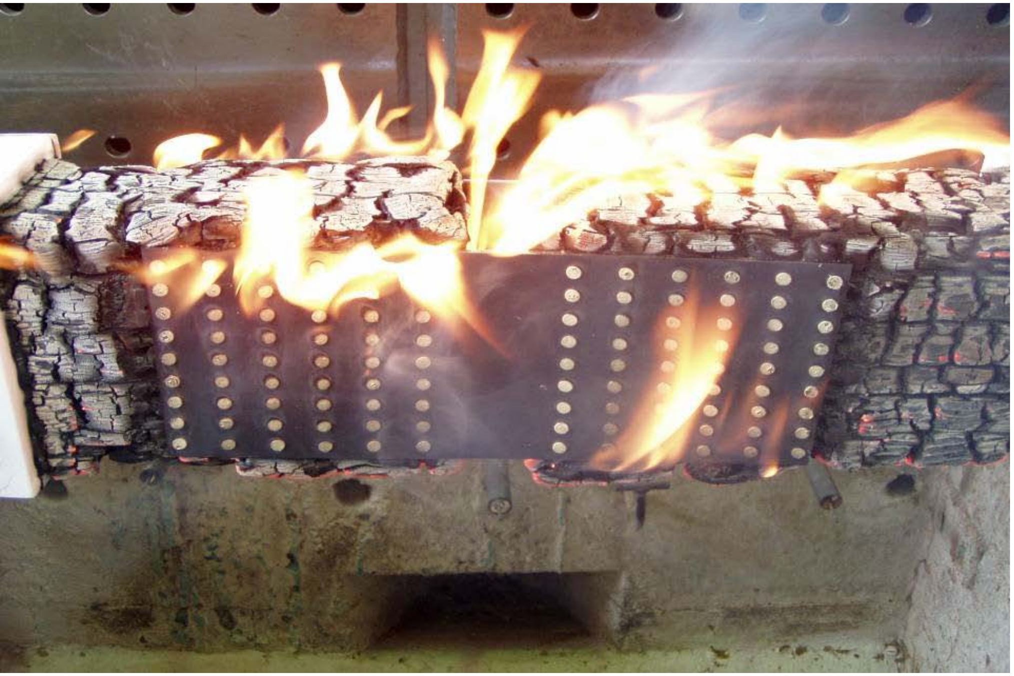




Connections with steel elements in fire

Connections with side steel plates

Connections with slotted-in steel plates



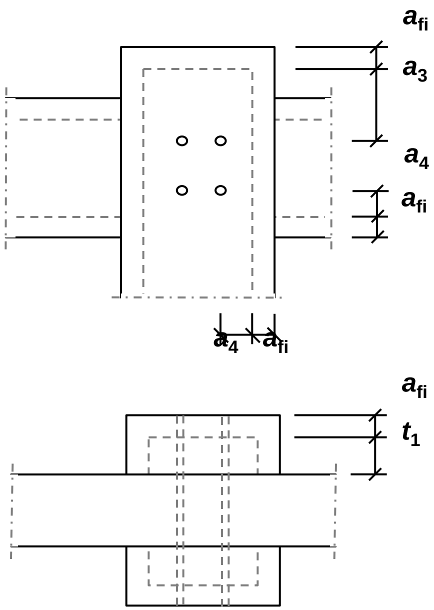
Connection with side steel plates and annular ringed shank nails

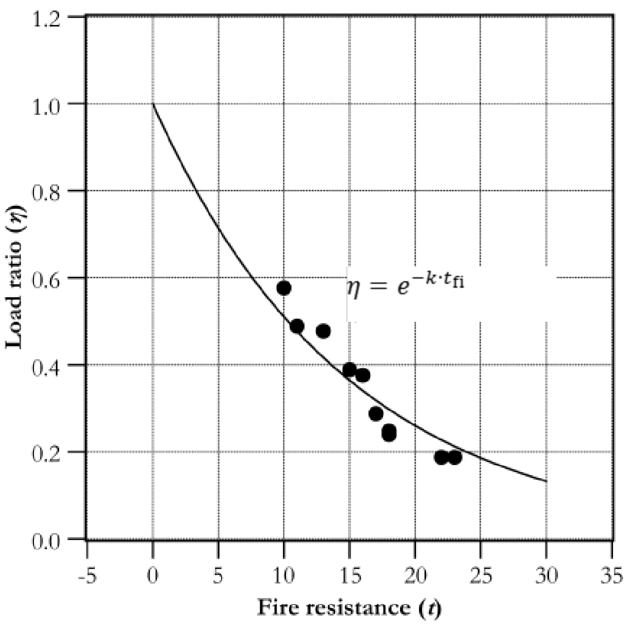
Multiple shear steel-to-timber dowelled connection

Connections with side members of wood

Simplified rules – fire resistance determined by thickness of side members and protective panels, and fastener end/edge distances

Reduced load method – 'load-carrying capacity vs time' assumed as one-parameter exponential empirical model





Simplified rules – unprotected connections

Connections designed according to EN 1995-1-1

Fastener / connector type	Fire resistance $t_{d,fi}$ [min.]	Provisions
Nails	15	$d \geq 2{,}8$ mm
Screws	15	$d \geq 3{,}5$ mm
Bolts	15	$t_1 \geq 45$ mm
Dowels	20	$t_1 \geq 45$ mm
Connectors (EN 912)	15	$t_1 \geq 45$ mm

d is the diameter of the fastener

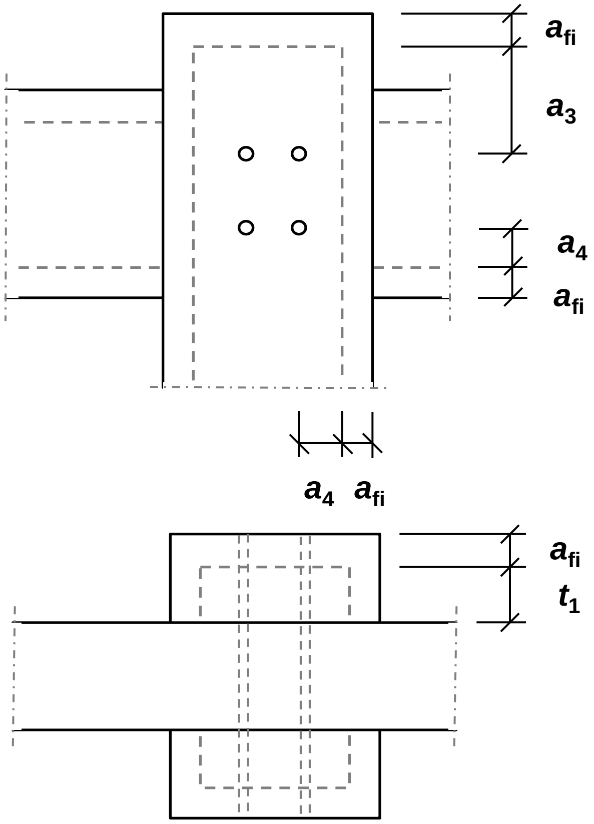
t_1 is the thickness of the side member

Simplified rules – unprotected connections

Greater fire resistance (not exceeding 30 min.) by increasing:

- thickness of side members
- width of the side members
- end / edge distance to fasteners

$$a_{\mathrm{fi}} = \beta_{\mathrm{n}} \cdot k_{\mathrm{flux}} \cdot \left(t_{\mathrm{req}} - t_{\mathrm{d,fi}}\right)$$

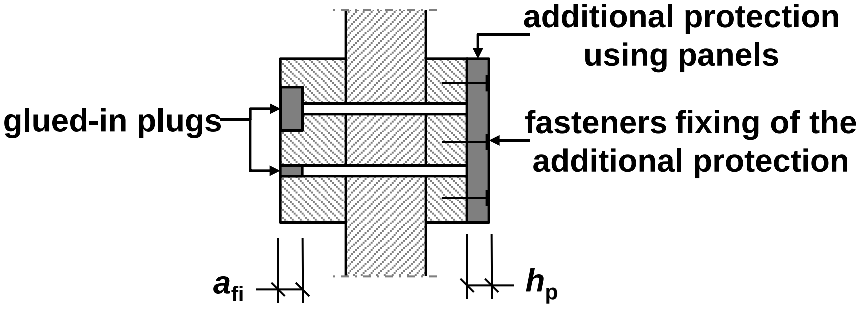


β_n	is the notional charring rate
k_{flux}	is a coefficient taking into account increased heat flux through the fastener
t_{req}	is the required fire resistance
$t_{d,fi}$	is the fire resistance of the unprotected connection (previous table)

Simplified rules – protected connections

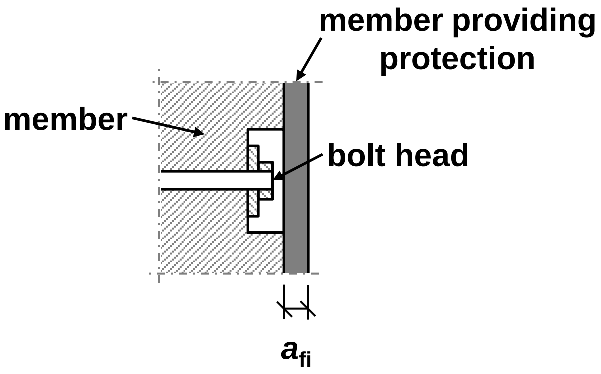
Wood panelling, wood-based panels or gypsum plasterboard type A or H

$$t_{ch} \geq t_{req} - 0.5 \cdot t_{d,fi}$$



Gypsum plasterboard type F

$$t_{ch} \geq t_{req} - 1.2 \cdot t_{d,fi}$$



t_{ch} is the time until start of charring of the protected member $t_{ch} = t_{ch}\ (h_p)$

t_{req} is the required fire resistance

$t_{d,fi}$ is the fire resistance of the unprotected connection

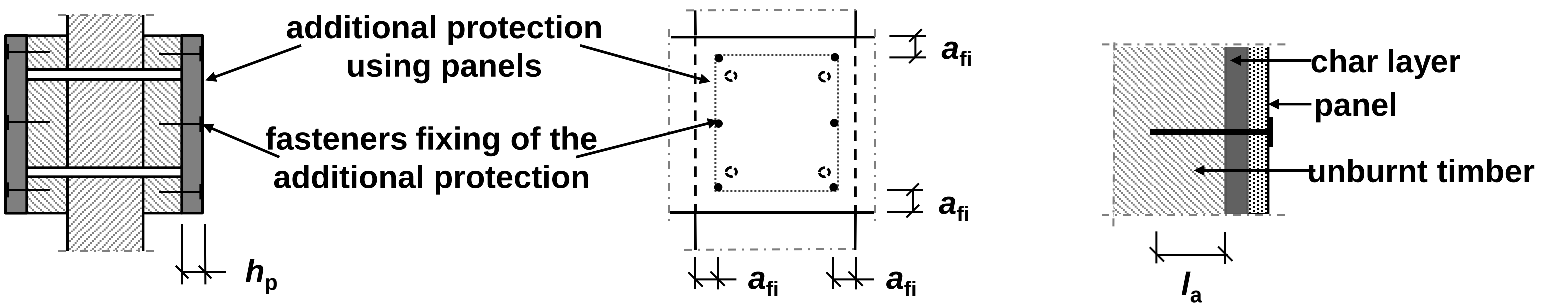
Simplified rules – protected connections

Fixing of additional protection by nails or screws

Distance between fasteners
- ≤ 100 mm (along the boards edges)
- ≤ 300 mm (for internal fastenings)

Edge distance of fasteners ≥ a_{fi}

Penetration depth of fasteners
- ≥ 6·*d* (wood-based panels or gypsum plasterboard type A or H)
- ≥ 10·*d* (gypsum plasterboard type F)

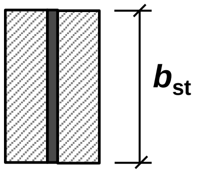


Simplified rules – protected connections

Connections with internal steel plates

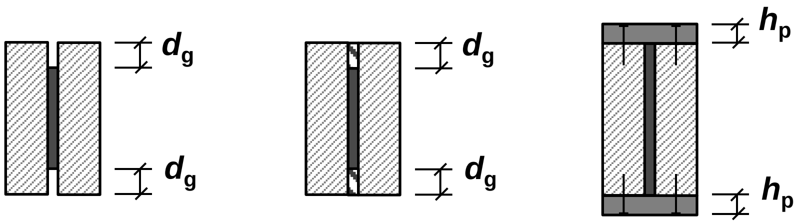
width b_{st} of the steel plate (with unprotected edges)

Unprotected edges in general	R30	$b_{st} \geq 200$ mm
	R60	$b_{st} \geq 280$ mm
Unprotected edges in one or two sides	R30	$b_{st} \geq 120$ mm
	R60	$b_{st} \geq 280$ mm



steel plates narrower than the timber member are protected if

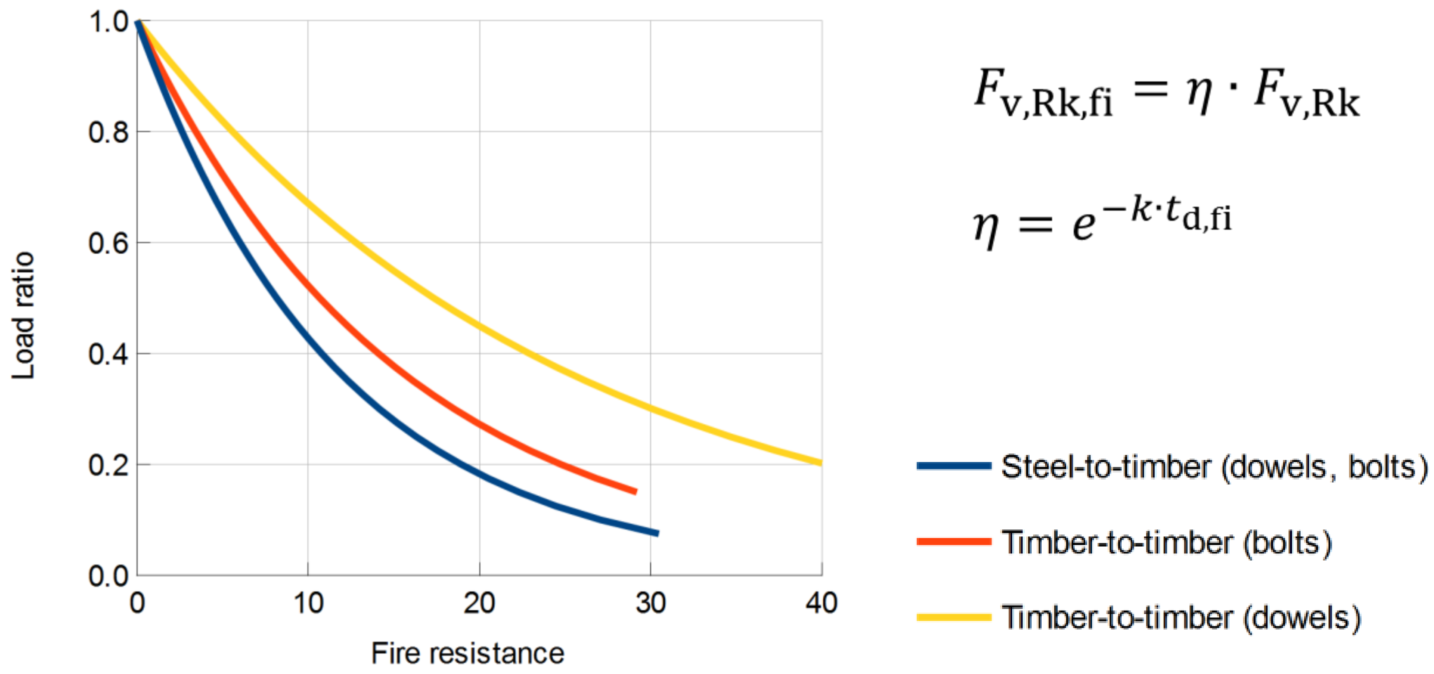
plate thickness ≤ 3 mm	R30	$d_g \geq 30$ mm
	R60	$d_g \geq 60$ mm
joints with glued-in strips or protective wood based boards	R30	d_g or $h_p \geq 10$ mm
	R60	d_g or $h_p \geq 30$ mm



Connections: Reduced load method

'Load-carrying capacity' *vs* Fire resistance

- assumed as one-parameter exponential empirical model
- model parameter k for each connection type and limited to a maximum fire exposure period

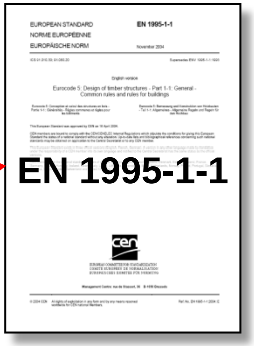


$$F_{v,Rk,fi} = \eta \cdot F_{v,Rk}$$

$$\eta = e^{-k \cdot t_{d,fi}}$$

Connections: Reduced load method

Load-carrying capacity after a given fire exposure



$$F_{\mathrm{v,Rk,fi}} = e^{-k \cdot t_{\mathrm{d,fi}}} \cdot F_{\mathrm{v,Rk}}$$

$$F_{\mathrm{v,Rd,fi}} = e^{-k \cdot t_{\mathrm{d,fi}}} \cdot F_{\mathrm{v,Rk}} \cdot \frac{k_{fi}}{\gamma_{\mathrm{M,fi}}}$$

Connection type	k	Maximum period of validity for k
Nails and screws	0.08	20 min.
Bolts wood-to-wood (*d* ≥ 12)	0.065	30 min.
Bolts wood-to-wood (*d* ≥ 12)	0.085	30 min.
Dowels wood-to-wood[a] (*d* ≥ 12)	0.04	40 min.
Dowels steel-to-wood[a] (d ≥ 12)	0.085	30 min.
Connectors (EN 912)	0.065	30 min.

[a] requires one bolt for every four dowels

$F_{\mathrm{v,Rk}}$ is the characteristic load-carrying capacity at normal temperature

$t_{\mathrm{d,fi}}$ is the design fire resistance (in minutes)

k_{fi} is a factor to convert 5-percentile values to 20-percentile

$\gamma_{\mathrm{M,fi}}$ is the partial safety factor for timber in fire

Connections: Reduced load method

Fire resistance for a given load level

$$t_{d,\mathrm{fi}} = -\frac{1}{k}\ln\left(\eta_{\mathrm{fi}}\cdot\eta_0\cdot\frac{k_{\mathrm{mod}}}{\gamma_{\mathrm{M}}}\cdot\frac{\gamma_{\mathrm{M,fi}}}{k_{\mathrm{fi}}}\right)$$

$t_{\mathrm{d,fi}}$ is the design fire resistance (in minutes)

η_{fi} is the reduction factor for the design load in the fire situation $\eta_{\mathrm{fi}} = \frac{E_{\mathrm{d,fi}}}{E_{\mathrm{d}}} = \frac{G_{\mathrm{k}}+\psi_{\mathrm{fi}}\cdot Q_{\mathrm{k,1}}}{\gamma_{\mathrm{G}}\cdot G_{\mathrm{k}}+\gamma_{\mathrm{Q,1}}\cdot Q_{\mathrm{k,1}}}$

η_0 is the degree of utilisation at normal temperature $\eta_0 = \frac{E_{\mathrm{d}}}{R_{\mathrm{d}}}$

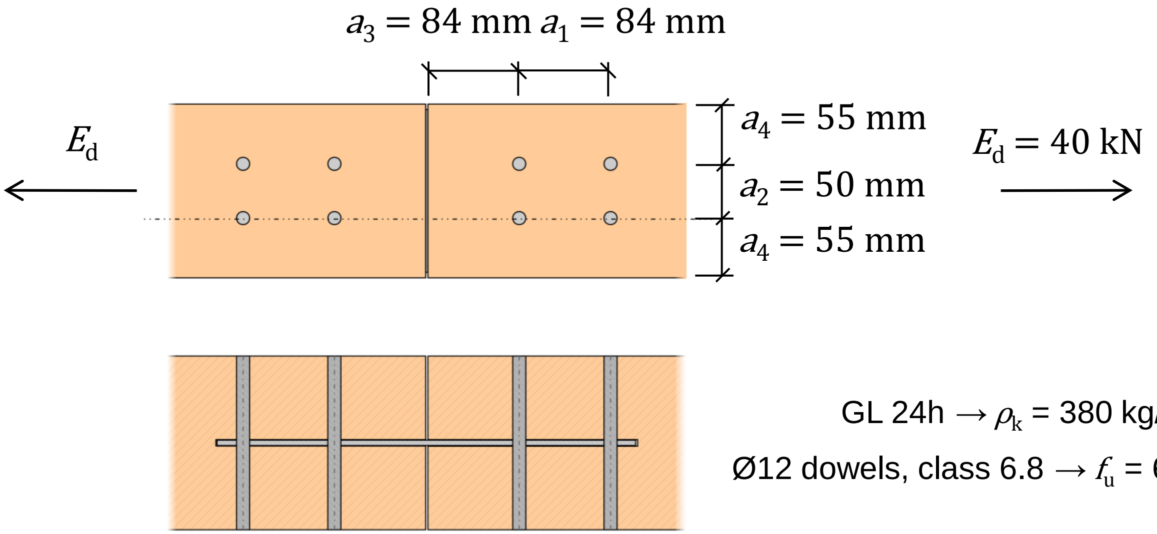
k_{mod} is the modification factor from EN 1995-1-1

$\gamma_{\mathrm{M,fi}}$ is the partial safety factor for timber in fire

γ_{M} is the partial safety factor at normal temperature

Connections: Worked example

Steel-to-timber dowelled connection with internal steel plate



$t_{d,fi} \geq 30$ min ?

GL 24h → ρ_k = 380 kg/m³

Ø12 dowels, class 6.8 → f_u = 600 N/mm²

Connections: Worked example

Load-carrying capacity at normal temperature (EN 1995-1-1, section 8)

- $F_{v,Rk} = 80\ \mathrm{kN}$ (characteristic load-carrying capacity of the connection at normal temperature)
- $F_{v,Rd} = 49\ \mathrm{kN}$ (design load-carrying capacity of the connection at normal temperature, $\gamma_M = 1.3$ and $k_{mod} = 0.8$)

Effect of actions $E_{d,fi,t}$ during fire exposure (EN 1995-1-2, section 2.4.2)

- $\eta_{fi} = \frac{E_{d,fi}}{E_d} = \frac{G_k + \psi_{fi} \cdot Q_{k,1}}{\gamma_G \cdot G_k + \gamma_{Q,1} \cdot Q_{k,1}} \longrightarrow \eta_{fi} = 0.6$ (quite conservative assumption)
- $E_{d,fi} = \eta_{fi} \cdot E_d = 0.6 \times 40\ \mathrm{kN} \longrightarrow E_{d,fi} = 24\ \mathrm{kN}$ (design effect of actions during fire exposure)

Connections: Worked example

Load-carrying capacity after a given fire exposure (EN 1995-1-2, section 6.2.2)

- $F_{\mathrm{v,Rd,fi}} = e^{-k \cdot t_{\mathrm{d,fi}}} \cdot F_{\mathrm{v,Rk}} \cdot \dfrac{k_{fi}}{\gamma_{\mathrm{M,fi}}}$ (Equations 6.5 and 6.6)
- $k = 0.085$ for dowelled steel-to-timber connections (Table 6.3)
- $t_{\mathrm{d,fi}} = 30\ \mathrm{min}$
- $k_{\mathrm{fi}} = 1.15$ for connections with side members of wood (Table 2.1)
- $\gamma_{\mathrm{M,fi}} = 1.0$
- $F_{\mathrm{v,Rk}} = 80\ \mathrm{kN}$
- $F_{\mathrm{v,Rd,fi}} = e^{-0.085 \times 30} \cdot 80 \cdot \dfrac{1.15}{1.0} \longrightarrow F_{\mathrm{v,Rd,fi}} = 7\ \mathrm{kN} \leq E_{\mathrm{d,fi}} = 24\ \mathrm{kN}$ ☹

Connections: Worked example

Fire resistance for a given load level (EN 1995-1-2, section 6.2.2)

- $t_{\mathrm{d,fi}} = -\frac{1}{k} ln\left(\eta_{fi} \cdot \eta_0 \cdot \frac{k_{mod}}{\gamma_M} \cdot \frac{\gamma_{M,fi}}{k_{fi}}\right)$ (Equation 6.7)
- $k = 0.085$ for dowelled steel-to-timber connections (Table 6.3)
- $\eta_{fi} = 0.6$
- $\eta_0 = \frac{E_{\mathrm{d}}}{R_{\mathrm{d}}} = \frac{40\ \mathrm{kN}}{49\ \mathrm{kN}} = 0.82$ (degree of utilisation at normal temperature)
- $k_{\mathrm{mod}} = 0.80$ and $\gamma_{\mathrm{M}} = 1.3$ (EN 1995-1-1, service class 1, medium-term actions)
- $k_{\mathrm{fi}} = 1.15$ and $\gamma_{\mathrm{M,fi}} = 1.0$
- $t_{d,fi} = -\frac{1}{0.085} ln\left(0.6 \times 0.82 \cdot \frac{0.80}{1.3} \cdot \frac{1.0}{1.15}\right) \longrightarrow t_{d,fi} = 15\ \mathrm{min} \leq t_{\mathrm{d},fi,\mathrm{req}} = 30\ \mathrm{min}$

☹

Connections: Worked example

Adding one protective layer of gypsum plasterboard type F

- $t_{\mathrm{ch}} \geq t_{\mathrm{req}} - 1.2 \cdot t_{\mathrm{d,fi}}$ (Equation 6.3, where t_{ch} is the time until start of charring of the protected member)
- $t_{\mathrm{ch}} = 2.8 \cdot h_{\mathrm{p}} - 23$ (Equation 3.12, where h_p is the thickness of the gypsum plasterboard, in mm)
- $t_{\mathrm{req}} = 30\ \mathrm{min}$
- $t_{\mathrm{d,fi}} = 15\ \mathrm{min}$ (calculated according to Equation 6.7, as in the previous slide)
- $h_{\mathrm{p}} \geq \frac{t_{\mathrm{req}} - 1.2 \cdot t_{\mathrm{d,fi}} + 23}{2.8} \rightarrow h_{\mathrm{p}} \geq 13.5\ \mathrm{mm}$ (minimum thickness of the gypsum plasterboard)

Connections: Worked example

Note on the simplified rules:

- According to the simplified rules, the fire resistance would be

  $t_{d,fi} = 20 \text{ min}$ (Table 6.1)

- However, the simplified rules assume load ratios of

  $\eta_{fi} \leq 0.3$,

  which might not always be the case!

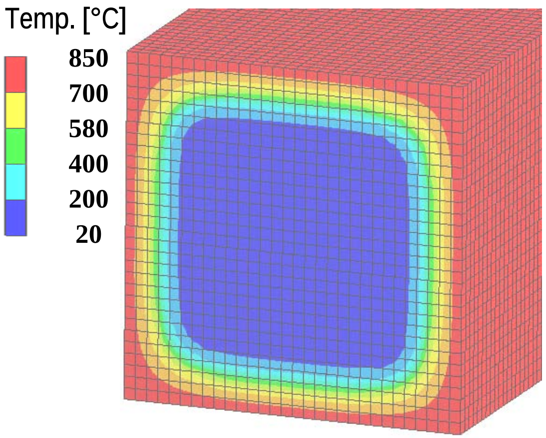
Fire design model for multiple shear steel-to-timber dowelled connections

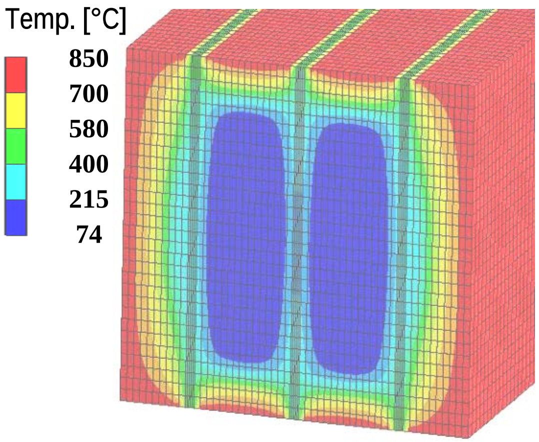
Influence of steel plates and steel dowels on charring

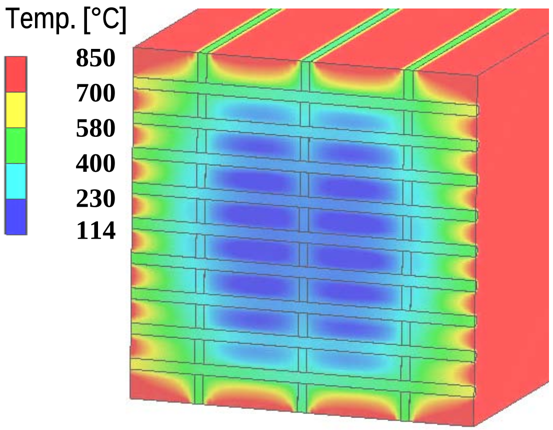
Timber

Timber with steel plates

Timber with steel plates and steel dowels

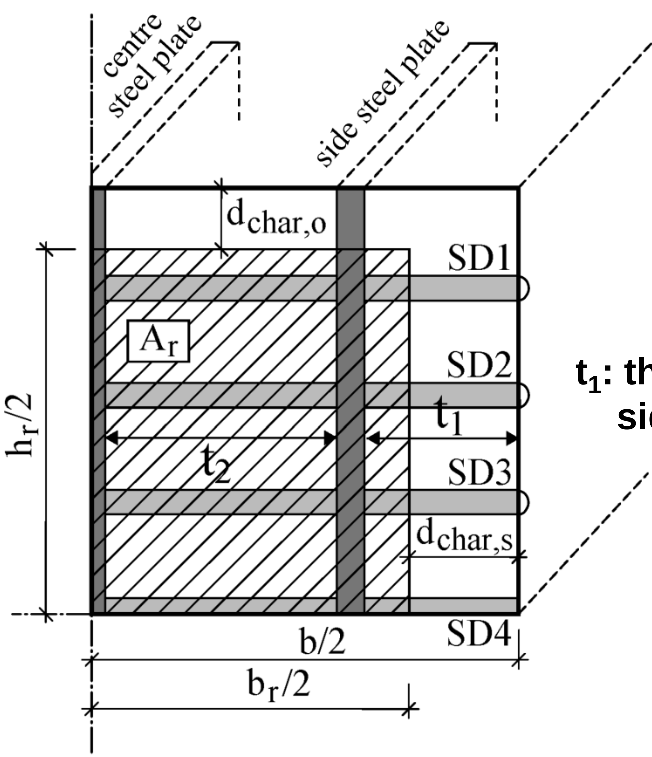






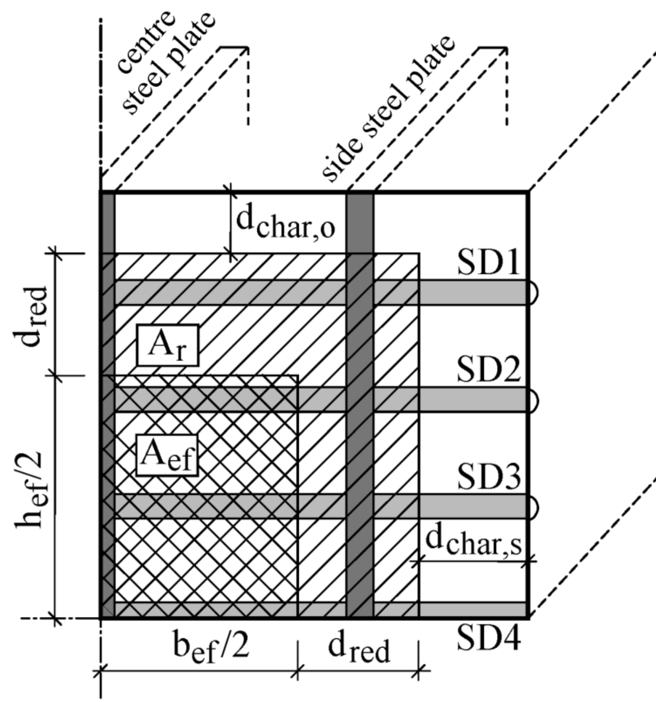
Fire design model for multiple shear steel-to-timber dowelled connections

Residual cross-section A_r



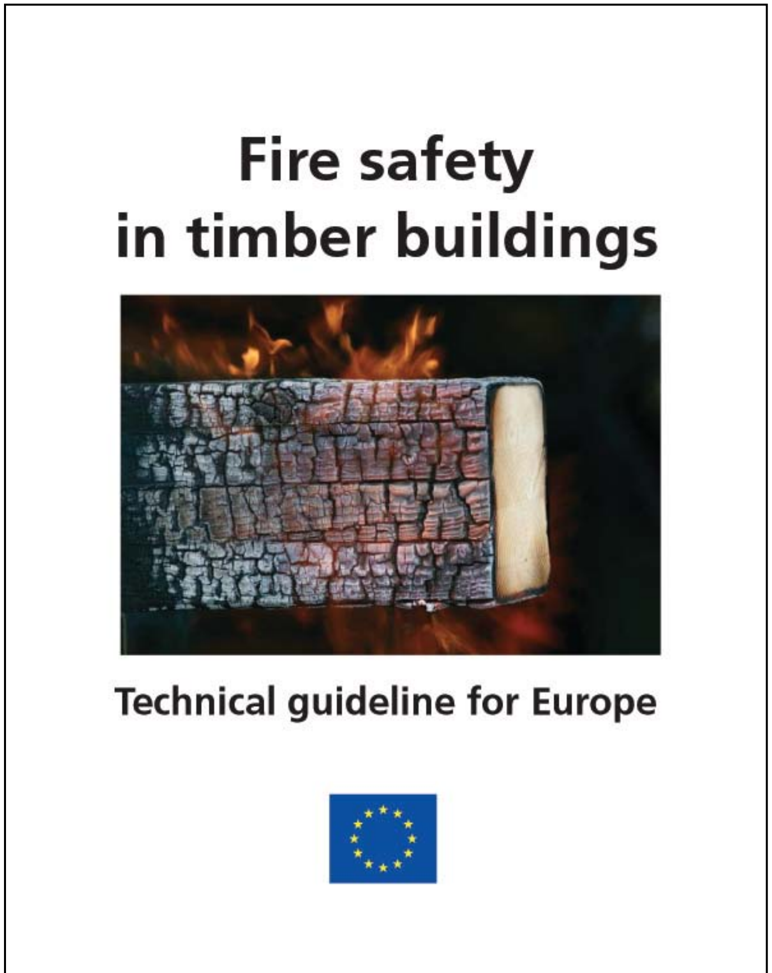
t_1: thickness of timber side member

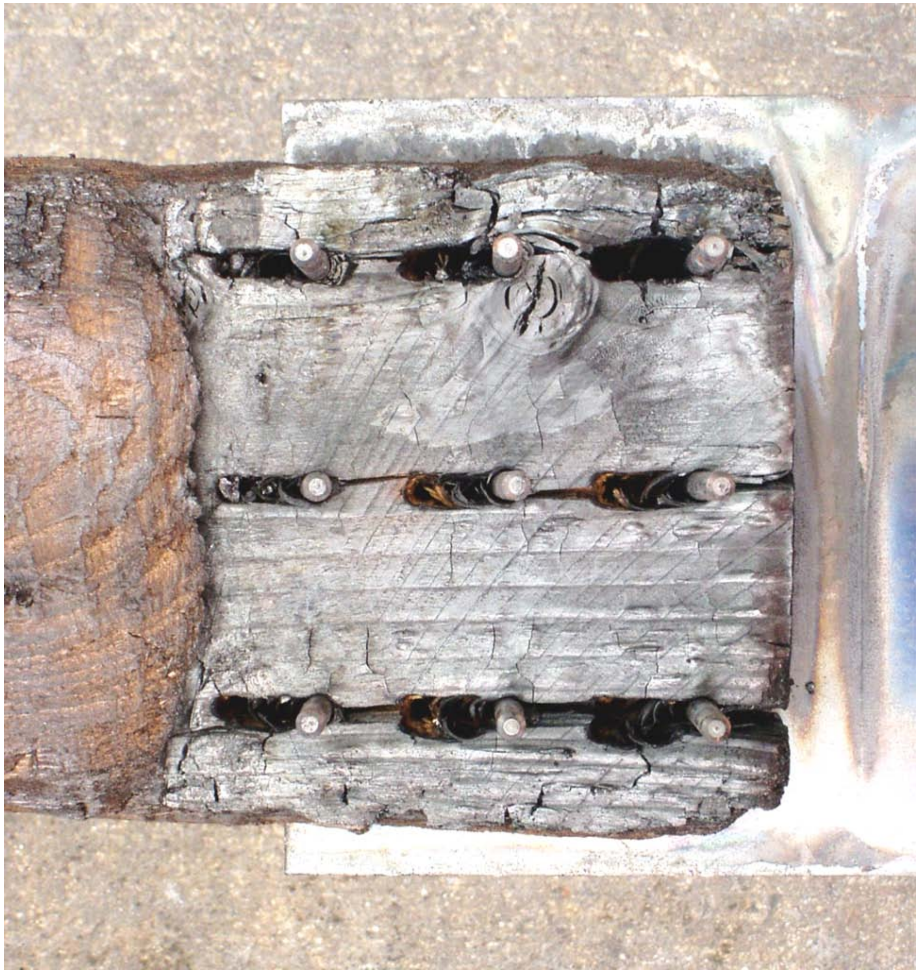
Effective cross-section A_{ef}



$$R_{d,t,fi} = A_{ef} \cdot f_{t,0,k} \cdot k_{fi}$$

Fire design model for multiple shear steel-to-timber dowelled connections





Informative annexes

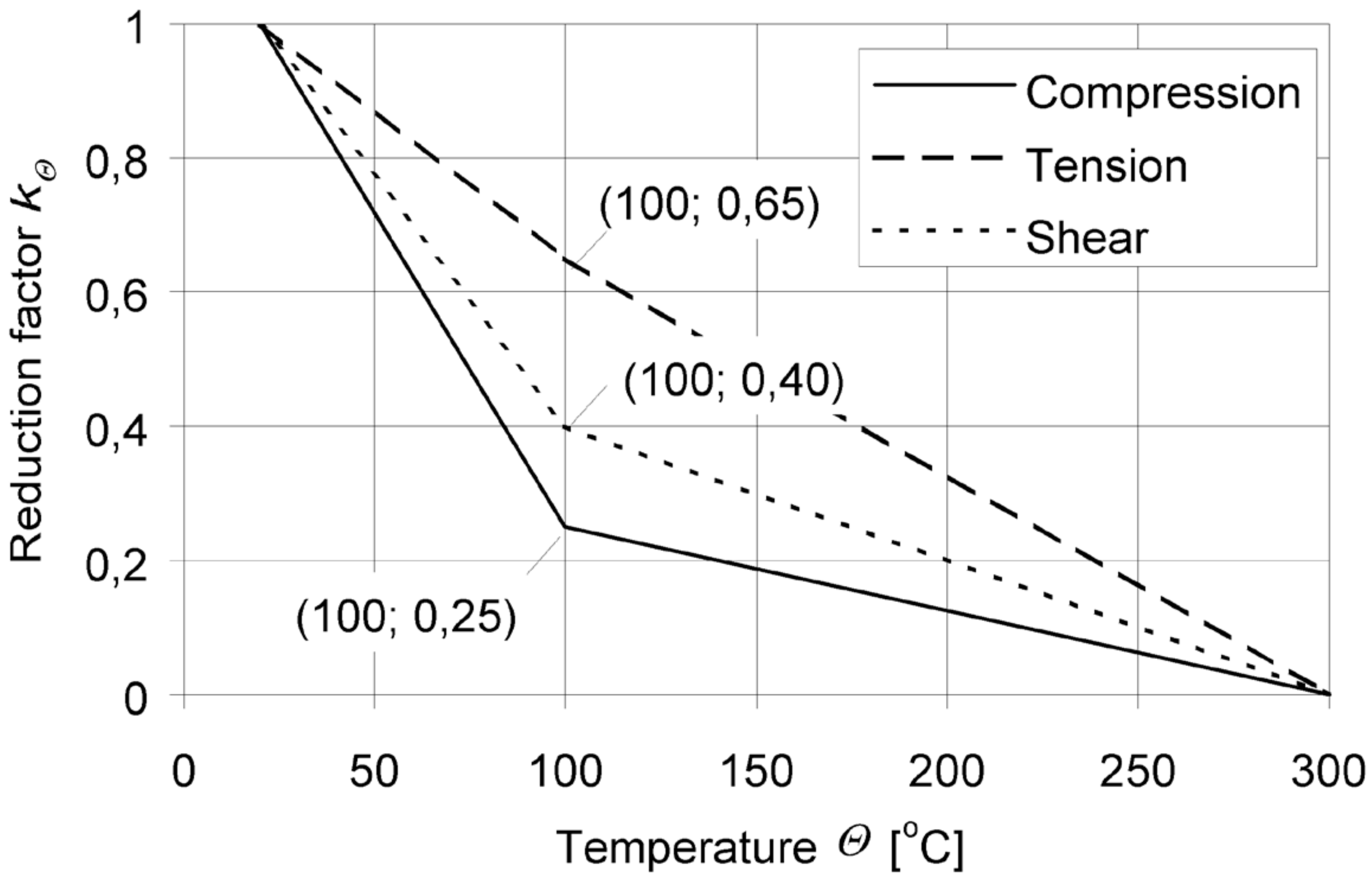
- **Parametric fire exposure**
- **Advanced calculation methods**
- **Load-bearing timber frame assemblies with cavity insulation**
- **Charring of members in wall and floor assemblies with void cavities**
- **Analysis of the separating function of wall and floor assemblies**

Advanced calculation methods (e.g. FE analysis)

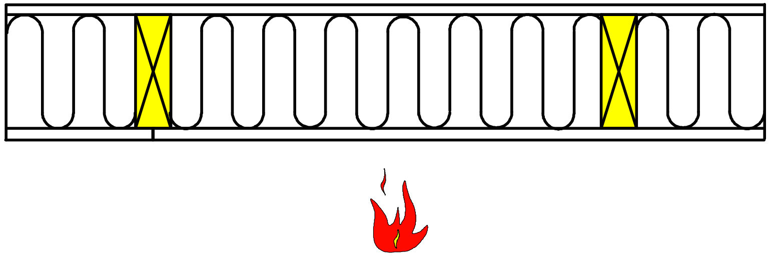
- **Thermal analysis**
  Effective thermal properties include effects of mass transport, and cracking and surface recession of char-layer (only valid for standard fire exposure)

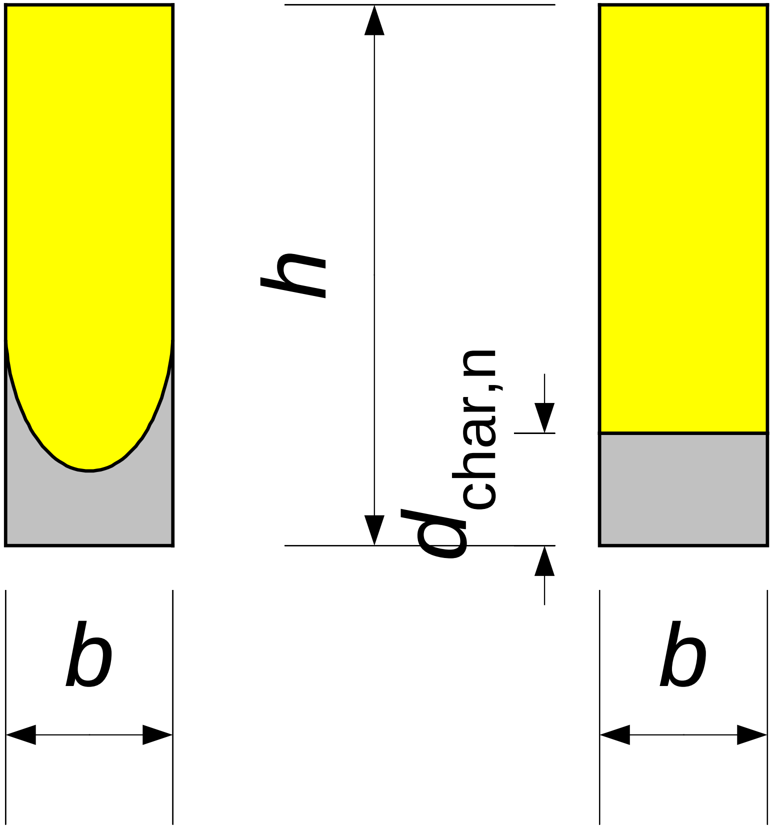
- **Structural analysis**
  Thermo-mechanical properties include transient effects of combined moisture and elevated temperature and mechano-sorptive creep

Advanced calculation methods (e.g. FE analysis)



Timber frame assemblies with cavities completely filled with insulation





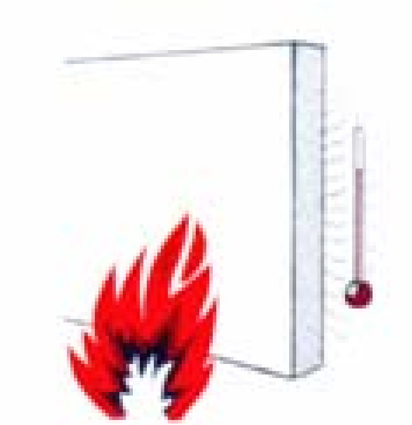
Modification factors $k_{mod,fi}$ are given

Fire separating function of walls and floors

Requirements for separating function

- **Criterion I (insulation)**
  - $\Delta T \leq 140$k
    (average temperature rise)
  - $\Delta T \leq 180$k
    (maximum temperature rise)

- **Criterion E (integrity)**
  - no sustained flaming or hot gases to ignite a cotton pad
  - no cracks or openings in excess of certain dimensions



Insulation I

Integrity E

Separating function of wall and floor assemblies

Components additive method

$$t_{\mathrm{ins}} = \sum_{\mathrm{i}} t_{\mathrm{ins,0,i}}\ k_{\mathrm{pos}}\ k_{\mathrm{j}}$$

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

Separating function of wall and floor assemblies

Components additive method

$$t_{ins} = \sum_{i} t_{ins,0,i} \; k_{pos} \; k_j$$

Basic value of layer i

Separating function of wall and floor assemblies

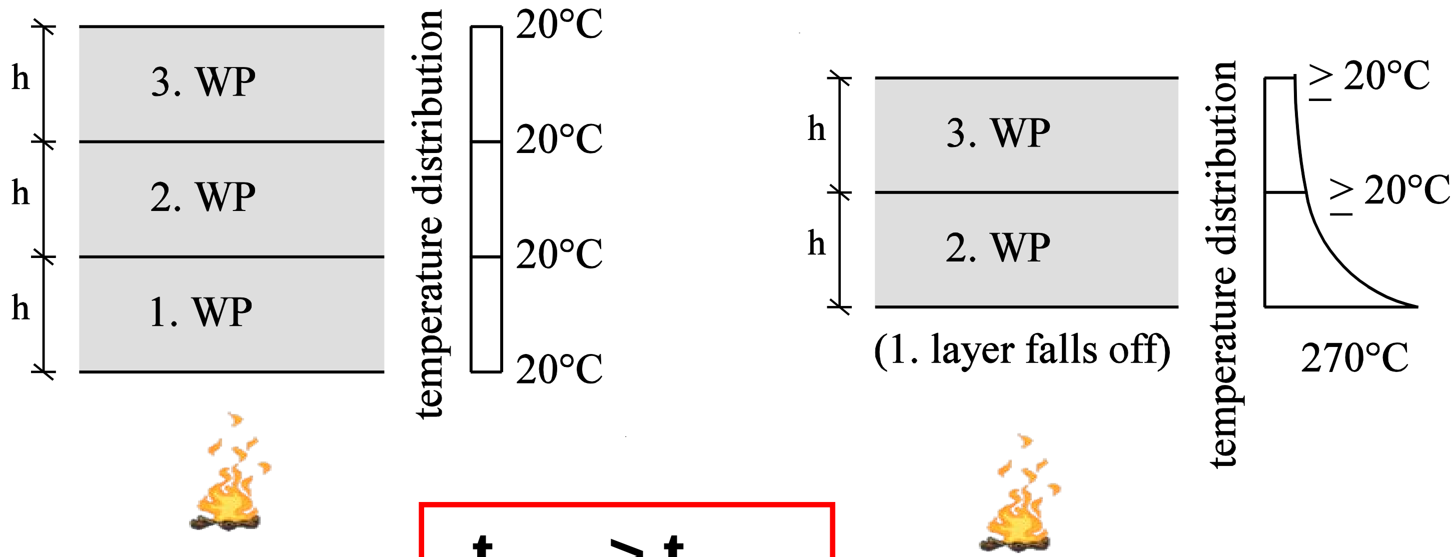
Components additive method

$$t_{\text{ins}} = \sum_{\text{i}} t_{\text{ins,0,i}}\, k_{\text{pos}}\, k_{\text{j}}$$

Position coefficient

Separating function of wall and floor assemblies

Position coefficient k_{pos}



$t_{ins,1} > t_{ins,2}$

The coefficient k_{pos} considers the influence of the position of the layers in the assembly

Separating function of wall and floor assemblies

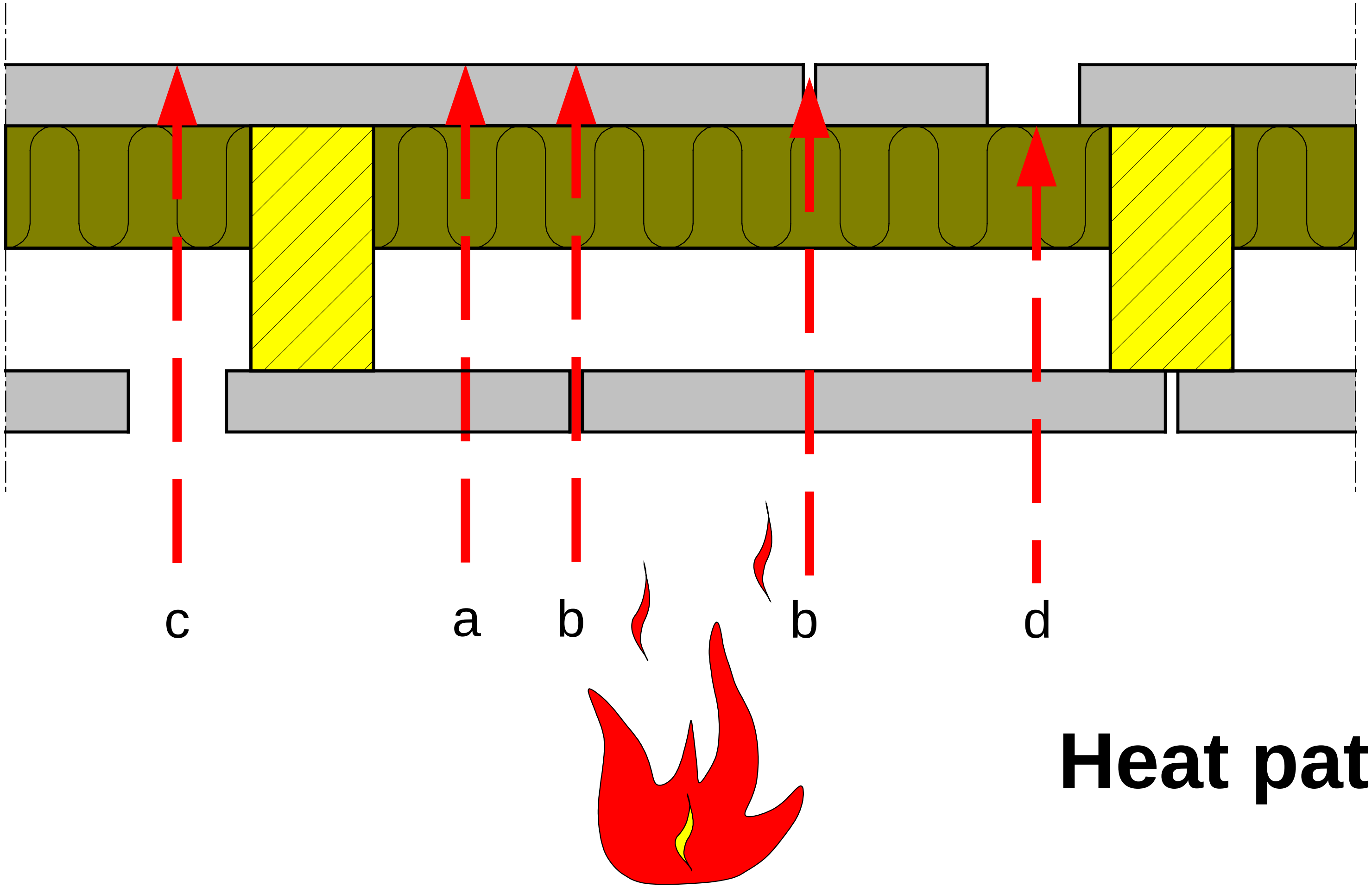
Components additive method

$$t_{\mathrm{ins}} = \sum_{\mathrm{i}} t_{\mathrm{ins,0,i}}\; k_{\mathrm{pos}}\; k_{\mathrm{j}}$$

Joint coefficient for joints not backed by e.g. battens

Separating function of wall and floor assemblies

Components additive method



Heat paths

Separating function: Worked example

1. Wall – Fire resistance EI 60, Geometry

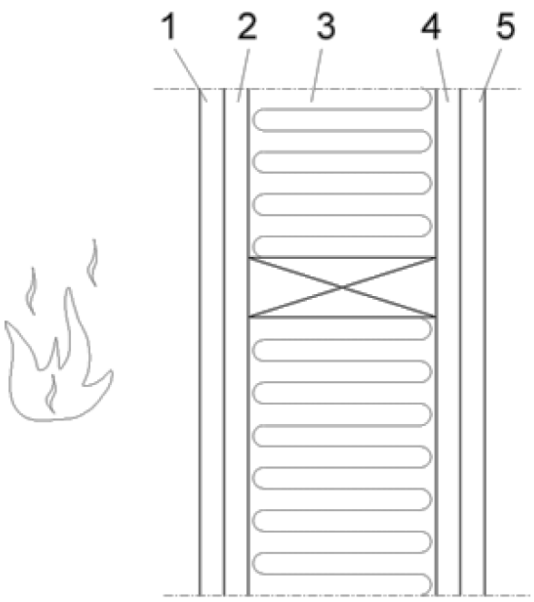
Layer 1: Gypsum plasterboard type A, 12.5 mm

Layer 2: Plywood, 12 mm

Layer 3: Rock fibre batts, 80 mm; ρ = 26 kg/m^3

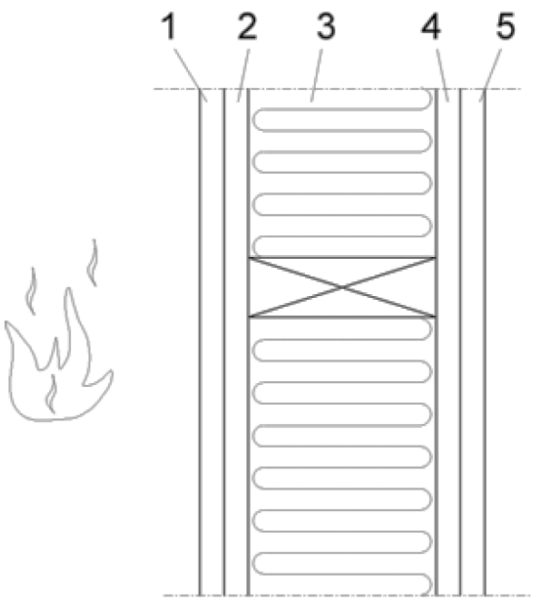
Layer 4: Plywood, 12 mm

Layer 5: Gypsum plasterboard type A, 12.5 mm



Separating function: Worked example

2. Wall – Fire resistance EI 60, Basic value of layers



Layer 1: Gypsum plasterboard type A, 12.5 mm

$$t_{ins,0} = 1.4 \cdot h_p = 1.4 \cdot 1.5 = 17.5 \text{ min}$$

Layer 2: Plywood, 12 mm

$$t_{ins,0} = 0.95 \cdot h_p = 0.95 \cdot h_p = 11 \text{ min}$$

Layer 3: Rock fibre batts, 80 mm; ρ = 26 kg/m³

$$t_{ins,0,i} = 0.2 \cdot h_{ins} \cdot k_{dens} = 0.2 \cdot 80 \cdot 1.0 = 16 \text{ min}$$

Layer 4: Plywood, 12 mm

$$t_{ins,0} = 0.95 \cdot h_p = 0.95 \cdot h_p = 11 \text{ min}$$

Layer 5: Gypsum plasterboard type A, 12.5 mm

$$t_{ins,0} = 1.4 \cdot h_p = 1.4 \cdot 1.5 = 17.5 \text{ min}$$

Separating function: Worked example

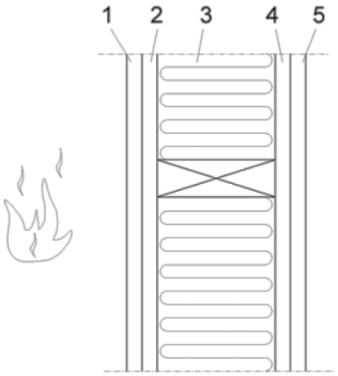
3. Wall – Fire resistance EI 60, Position coefficients

Table E5 — Position coefficients k_{pos} for walls with double layered panels

Construction: Layer number and material		Layer number 1	2	3	4	5
1, 2, 4, 5 3	Wood-based panel Void	0,7	0,9	1,0	0,5	0,7
1, 2, 4, 5 3	Gypsum plasterboard type A or H Void	1,0	0,8	1,0	0,8	0,7
1, 5 2, 4 3	Gypsum plasterboard type A or H Wood-based panel Void	1,0	0,8	1,0	0,8	0,7
1, 5 2, 4 3	Wood-based panel Gypsum plasterboard type A or H Void	1,0	0,6	1,0	0,8	0,7
1, 2, 4, 5 3	Wood-based panel Rock fibre batts	0,7	0,6	1,0	1,0	1,5
1, 2, 4, 5 3	Gypsum plasterboard type A or H Rock fibre batts	1,0	0,6	1,0	0,9	1,5
1, 5 2, 4 3	Gypsum plasterboard type A or H Wood-based panel Rock fibre batts	1,0	0,8	1,0	1,0	1,2
1, 5 2, 4 3	Wood-based panel Gypsum plasterboard type A or H Rock fibre batts	1,0	0,6	1,0	1,0	1,5

Separating function: Worked example

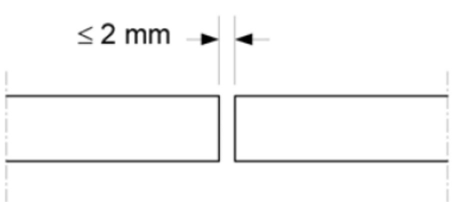
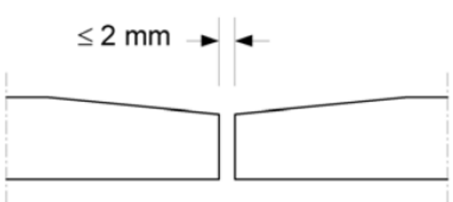
4. Wall – Fire resistance EI 60, Joint coefficients



Layer 1 to 4: k_j = 1.0 (layer backed by other layer)

Layer 5: k_j = 1.0 (filled joints)

Table E7 — Joint coefficient k_j to account for the effect of joints in panels of gypsum plasterboard which are not backed by battens

	Joint type	Type	k_j	
			Filled joints	Unfilled joints
a		A, H, F	1,0	0,2
b		A, H,F	1,0	0,15

Separating function: Worked example

5. Wall – Fire resistance EI 60

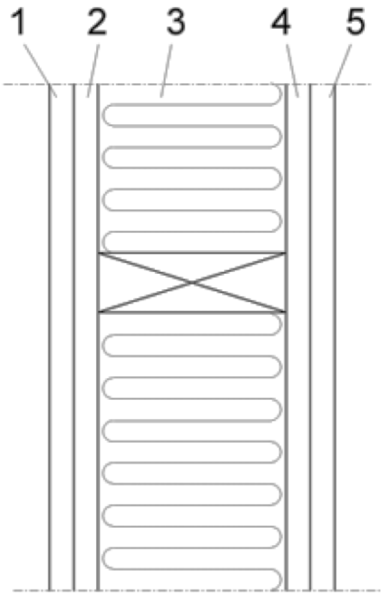
Layer 1: Gypsum plasterboard type A, 12.5 mm

Layer 2: Plywood, 12 mm

Layer 3: Rock fibre batts, 80 mm; $\rho = 26$ kg/m^3

Layer 4: Plywood, 12 mm

Layer 5: Gypsum plasterboard type A, 12.5 mm



$$t_{ins} = \sum_{i} t_{ins,0,i}\, k_{pos}\, k_j$$

$$t_{ins} = 17.5 \cdot 1.0 + 11 \cdot 0.8 + 16 \cdot 1.0 + 11 \cdot 1.0 + 17.5 \cdot 1.2 = 74\,\text{min}$$ ☺


Zürich, 7 storeys (Switzerland)

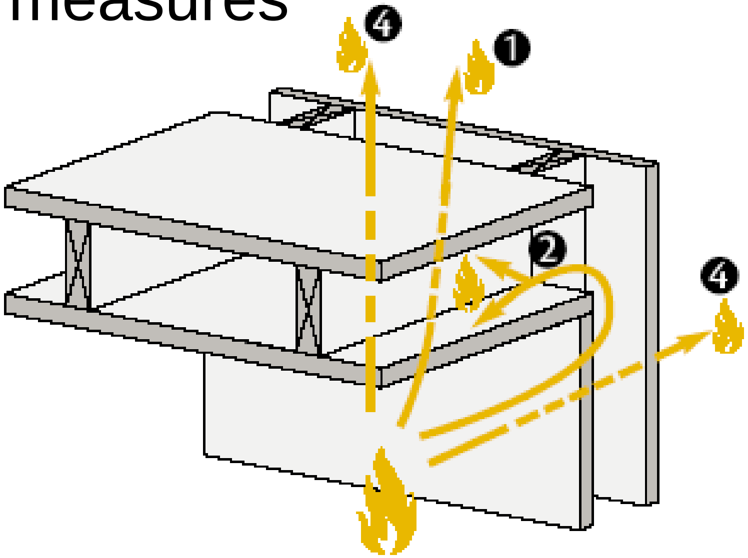

Steinhausen, 6 storeys (Switzerland)


Lugano, 6 storeys (Switzerland)


Baar, 5 storeys (Switzerland)

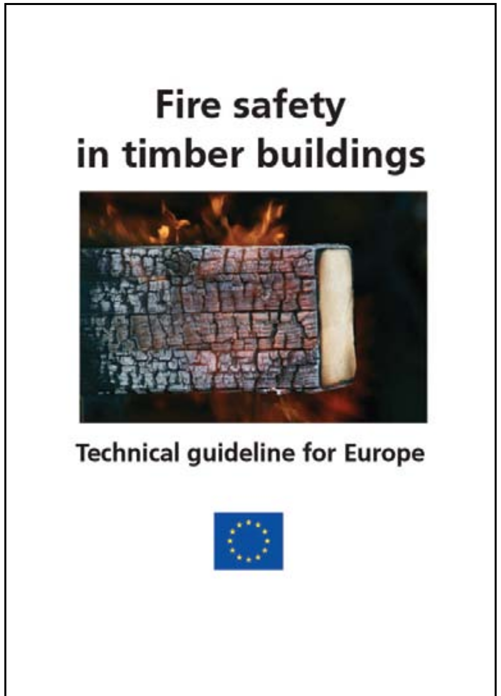
Quality of construction

- 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



Concluding remarks

- EN 1995-1-2 has filled many gaps in the knowledge of structural timber design in fire
- However, some problems are still to be solved, hopefully before the next generation of Eurocodes will be published
- Further knowledge in
  "Fire safety in Timber Buildings"
  Technical guideline for Europe
  SP Report 2010



Future evolution EN 1995-1-2

- **Evolution group: D. Dhima, A. Frangi (Chair), A. Just, P. Kuklik, J. Schmid, N. Werther**
- **Simplification ("only one design principle shall be available")**
- **Harmonisation (Annexes should be moved to the main part; other parts and other ENs)**
- **Improvement / extension**
  - Cross-laminated timber panel (new rules)
  - Timber-concrete-composite elements (new rules)
  - Connections (Improved rules)
  - Failure of claddings (Improved rules)
  - Separating function (Improved rules)

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1995-1-2

November 2004

ICS 91.010.30; 13.220.50; 91.080.20

Incorporating corrigenda June 2006 and March 2009
Supersedes ENV 1995-1-2:1994

English version

Eurocode 5: Design of timber structures - Part 1-2: General - Structural fire design

Eurocode 5: Conception et Calcul des structures en bois - Part 1-2: Généralités - Calcul des structures au feu

Eurocode 5: Entwurf, Berechnung und Bemessung von Holzbauten - Teil 1-2: Allgemeine Regeln - Bemessung für den Brandfall

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