



**Improved fire design models for Timber
Frame Assemblies -
Guidance document
WG2 TG4, TG5
(N 217-07)**

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Improved fire design models for Timber Frame Assemblies - Guidance document

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N217-07

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1. COST FP1404

Bio-based building products have a very long history, e.g. as timber structural members. However, due to its combustibility and contribution to several large fires in cities timber as a structural material was banned for many years. When Performance Based Design (PBD) was introduced and implemented in the building regulations in many countries in the 1990s, the market for timber structures opened again. And with it came the development of other bio-based building products. Significant differences between regulations in various countries exist, and the use of combustible building products is still limited in many of the countries. This is mainly due to the lack of knowledge on the properties of the materials, especially how the materials will influence the fire safety in buildings.

Modern living offers attractive, flexible buildings, and aims for cost efficient construction techniques. In addition, the sustainability and environmental footprint of building products has become a very important issue. Consumers demand environmentally friendly and renewable products. At the same time, the fire safety of the end-product must remain on a high level.

Fire Safety Engineering (FSE) has achieved large acceptance in the recent years. FSE allows a PBD with customized building solutions and novel materials. However, the available methods and knowledge are often limited to non-combustible materials.

During the last decade, the portfolio of building products made from bio-based materials has increased enormously. The material properties that might affect a fire development may vary significantly, as has been demonstrated in numerous (research) projects, in Europe and globally.

COST Action is a European co-operation for science and technology supported by the EU. COST Action FP1404 is created for building network on Fire Safety of Bio-Based Building Materials.

COST Action FP1404 aims at creating a platform for networking, exchange and collection of performance data, experiences, authority- and climate requirements which affect the design with respect to the Fire Safe Use of Bio-based Building Products. By systematically organizing knowledge, this area will advance at a significantly higher

rate. The Action will Exchange researchers, organize Workshop and create comprehensive dissemination material. Working Group 2 – Structural Elements made of bio-based building materials and detailing – aims to provide guidance for the use and design of structural elements made from bio-based building products. Task Groups TG4 and TG5 under Working Group 2 are dealing with the design of timber frame assemblies in fire.

2. Introduction

Models for calculating the fire separating properties and reduced cross-section of light timber frame assemblies are presented in EN 1995-1-2 [1] and the handbook Fire safety in timber buildings [2].

EN 1995-1-2 is the European design standard for the design of timber structures exposed to fire. The current version of EN 1995-1-2 was published in 2004 and is now under revision.

In 2010, the European technical guideline *Fire Safety in Timber Buildings* was published. The guideline consists of new and updated design models for fire separating building elements and models for the reduced cross-section design for timber construction in fire.

However, these models exhibit several short-comings and improvements are needed. These design models are therefore further improved within the COST Action FP1404 and are presented in this guidance document.

This guidance document provides the outcome of the research performed within the WG2 of the COST action FP1404, including specific guidelines for the design of load-bearing and non-load-bearing floors and walls. The guidance document will form part of the background documentation for the revision of EN 1995-1-2.

3. The Component Additive Method for the separating function

The Component Additive Method (CAM), as developed by Schleifer [3], is based on the contributions of each layer of the wall or floor construction to the fire separating ability of the whole assembly, considering different heat transfer paths. This method is applicable to timber frame assemblies consisting of an unlimited number of layers of claddings, wood-based materials, insulations and their combinations. The CAM can be used to calculate the protection time of a combination of layers in the construction, and the total insulation time of the complete wall or floor, i.e. the insulation (I) in the fire separating property EI. However, separating elements also have to maintain their integrity (E) throughout the fire resistance time. This has to be ensured by the design of the details, e.g. the joints of boards, the joints between walls, and the joints between wall-floor and wall-ceiling.

Fire separating walls and floors must limit the temperature increase on the unexposed side of the building element to a maximum of 140K on average over the whole surface, or 180K in a single point [4], throughout the required fire resistance time. Generally, the starting (ambient) temperature is 20°C, therefore the temperature criteria become 160°C on average and 200°C in a single point.

The temperature increase on the unexposed side of the building element can be determined using the model below, and each layer on the element (cladding, insulation) will contribute to the fire resistance. Each layer protects the layer behind from elevated temperatures that might cause charring or decomposition. For these layers, with a protecting function, the protection time is determined through the model. While the last layer, on the unexposed side of the element, has an insulating function (must prevent critical temperatures on the unexposed side of the element), and the insulation time is determined. As the assembly consists of multiple layers that fulfil different functions, different names and symbols are used, as shown in Figure 1.

In analogy to the classification of fire protective claddings, K₁10 and K₂10, according to EN 13501-2 [4], the protection time (t_{prot}) is the time until the temperature rise behind the considered layer is 250 K on average or 270 K at any point. Ambient conditions are usually 20°C, hence the temperature criteria become 270°C and 290°C,

respectively. These criteria are approximations to account for the failure (or fall-off) of thermally degraded material layers. They are also related to the charring temperature of timber (300°C). Therefore, the sum of protection times of the layers covering or protecting the timber elements may be used as a slightly conservative starting time of charring as shown in (1).

$$\sum t_{\text{prot}} = t_{\text{ch}} \tag{ 1 }$$

where

$\sum t_{\text{prot},i}$ is the sum of the protection times of the layers preceding the timber element [min];

t_{ch} is the start time of charring of the timber element [min].

The insulation time (t_{ins}) of the last material layer is the time until the temperature rise on the unexposed side is 140 K on average over the whole area and 180 K at any point. The same temperature criteria are used for the fire resistance (insulation time) of the whole separating element. Because the temperature limit is lower for this layer, the formulas are different from the previous layers.

In summary, the layers covering the timber structure delays the onset of charring of the structure, and the last layer of the separating element ensures habitable conditions on the unexposed side of the floor or wall.

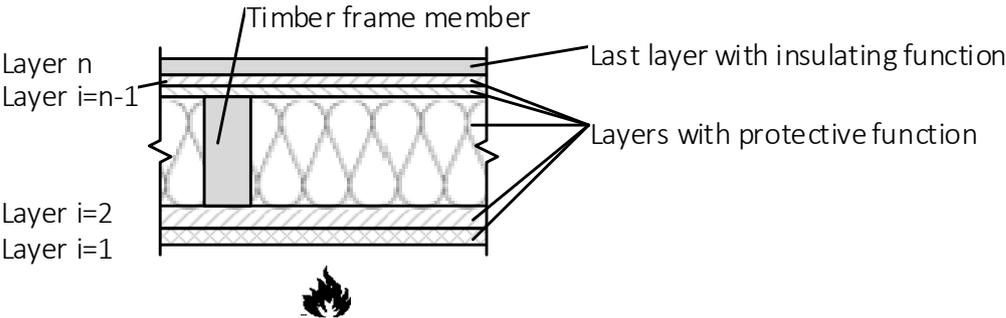


Figure 1 – Numbering and function of the layers in a timber frame assembly

The total fire resistance time for the insulation criterion, I, of the whole assembly is calculated as shown in equation (2).

$$t_{ins} = \sum_{i=1}^{i=n-1} t_{prot,i} + t_{ins,n} \quad (2)$$

where

t_{ins} is the total insulation time of the assembly [min];

$t_{prot,i}$ is the protection time of each layer in the direction of the heat flux [min], see 3.1;

$t_{ins,n}$ is the insulation time of the last layer of the assembly on the unexposed side [min], see 3.2.

3.1 Protection time

The protection times of layers before the last layer can be calculated taking into account the basic protection values of the layers ($t_{prot,0}$), the position coefficients ($k_{pos,exp}$ and $k_{pos,unexp}$) and joint coefficients (k_j) by equation (3). The protection value for layers behind a fire rated cladding, for example fire rated gypsum boards, can also be increased by Δt (see 3.5).

$$t_{prot,i} = (t_{prot,0,i} \cdot k_{pos,exp,i} \cdot k_{pos,unexp,i} + \Delta t_i) \cdot k_{j,i} \quad (3)$$

where

$t_{prot,i}$ is the protection time of the considered layer i [min];

$t_{prot,0,i}$ is the basic protection value of the considered layer i [min];

$k_{pos,exp,i}$ is the position coefficient that takes into account the influence of layers preceding the layer considered (see 3.3);

$k_{pos,unexp,i}$ is the position coefficient that takes into account the influence of layers backing the layer considered (see 3.3);

Δt_i is the correction time for considered layer i protected by a fire rated cladding [min], (see 3.5);

$k_{j,i}$ is the joint coefficient for layer i , (see 3.4).

The basic values and coefficients are dependent on the material of the considered layer and the preceding and backing layers. Generic values of the basic protection times and basic insulation times for different materials are given in Table 1, for position

coefficients see Table 2 and Table 3, for joint coefficients see Table 4. Correction times are presented in clause 3.5.

Wood-based claddings

The basic protection times of wood-based claddings should be compared with the corrected charring rates $\beta_{0,p,h}$, based on the material, density and thickness of the wood-based boards.

$$\beta_{0,p,h} = \beta_0 \cdot k_p \cdot k_h \quad (4)$$

with

$$k_p = \sqrt{\frac{450}{\rho_k}} \quad (5)$$

$$k_h = \max \left\{ \begin{array}{l} \sqrt{\frac{20}{h_p}} \\ 1 \end{array} \right. \quad (6)$$

where

- $\beta_{0,p,h}$ is the corrected charring rate [mm/min];
- β_0 is the one-dimensional charring rate [mm/min];
- k_p is the density coefficient [-];
- k_h is the panel thickness coefficient [-];
- ρ_k is the characteristic density [kg/m³];
- h_p is the panel thickness [mm].

The protection times of cross-laminated timber (CLT) layers should be compared to the relevant charring scenario, whereas the protection time must be less than or equal to the time it takes for the CLT layer to char completely. There is more guidance given in the Guidance Document N221-07. Fire design of CLT incl. best practice.

Table 1. Basic insulation and protection times

Material	Basic insulation time $t_{ins,0,n}$ [min]	Basic protection time $t_{prot,0,i}$ [min]
Gypsum plasterboard, gypsum fibre board	$24 \cdot \left(\frac{h_i}{15}\right)^{1,4}$	$30 \cdot \left(\frac{h_i}{15}\right)^{1,2}$
Solid timber, cross-laminated timber, LVL	$19 \cdot \left(\frac{h_i}{20}\right)^{1,4}$	$30 \cdot \left(\frac{h_i}{20}\right)^{1,1} \leq \frac{h_i}{\beta_0}$
Particleboard, fibreboard	$22 \cdot \left(\frac{h_i}{20}\right)^{1,4}$	$33 \cdot \left(\frac{h_i}{20}\right)^{1,1} \leq \frac{h_i}{\beta_{0,\rho,h}}$
OSB, plywood	$16 \cdot \left(\frac{h_i}{20}\right)^{1,4}$	$23 \cdot \left(\frac{h_i}{20}\right)^{1,1} \leq \frac{h_i}{\beta_{0,\rho,h}}$
Stone wool insulation with $\rho \geq 26 \text{ kg/m}^3$	0	$0,3 \cdot h_i^{(0,75 \cdot \log(\rho_i) - \frac{\rho_i}{400})}$
Glass wool insulation with $\rho \geq 15 \text{ kg/m}^3$	0	for $h_i \leq 40 \text{ mm}$: 0 for $h_i \geq 40 \text{ mm}$: $(0,0007 \cdot \rho_i + 0,046) \cdot h_i + 13 \leq 30$
Wood fibre cavity insulation	0	for $h_i \leq 40 \text{ mm}$: 0 for $40 \leq h_i \leq 240 \text{ mm}$: $0,56 \cdot h_i - 22$
Wood fibre insulation boards	$0,47 \cdot h_i^{1,1}$	for $h_i \leq 40 \text{ mm}$: 0 for $40 \leq h_i \leq 240 \text{ mm}$: $0,93 \cdot h_i^{0,96}$
Cellulose fibre insulation	0	for $h_i \leq 40 \text{ mm}$: 0 for $40 \leq h_i \leq 240 \text{ mm}$: $19 \cdot \left(\frac{h_i}{60}\right)^{0,98}$

Where h_i : Thickness of the considered layer [mm]
 ρ_i : Density of the considered layer [kg/m^3]
 β_0 : One-dimensional charring rate [mm/min]
 $\beta_{0,\rho,h}$: One-dimensional charring rate corrected by the effect of density and thickness [mm/min]

Insulation materials

The limits of contribution of insulation depend on the protection level of the insulation material (according to [5]).

For insulation materials qualified as protection level 1, the sum of the protection times of the layers preceding the insulation layer and the insulation layer is limited as shown by equation (7) or (8).

$$\sum_{k=1}^i t_{\text{prot},k} \leq \frac{h_i}{0,11 \cdot t_f + 1,3} + t_f \quad (7)$$

or

$$\sum_{k=1}^i t_{\text{prot},k} \leq \frac{h_i}{0,11 \cdot \sum t_{\text{prot},i-1} + 1,3} + \sum t_{\text{prot},i-1} \quad \text{if } \sum t_{\text{prot},i-1} > t_f \quad (8)$$

where

$\sum_{k=1}^i t_{\text{prot},k}$ is the sum of the protection times of the layers preceding the insulation layer and the insulation layer [min];

h_i is the thickness of the insulation layer [mm];

t_f is the fall-off time of the FRC [min];

$\sum t_{\text{prot},i-1}$ is the sum of the protection times of the layers preceding the insulation layer [min].

For insulation materials qualified as protection level 2, the sum of the protection times of the layers preceding the insulation layer and the insulation layer is limited as shown by equation (9) or (10).

$$\sum_{k=1}^i t_{\text{prot},k} \leq \frac{h_i}{v_{\text{rec}}} + t_f \quad (9)$$

or

$$\sum_{k=1}^i t_{\text{prot},k} \leq \frac{h_i}{v_{\text{rec}}} + \sum t_{\text{prot},i-1} \quad \text{if } \sum t_{\text{prot},i-1} > t_f \quad (10)$$

where

$\sum_{k=1}^i t_{\text{prot},k}$ is the sum of the protection times of the layers preceding the insulation layer and the insulation layer [min];

h_i is the thickness of the insulation layer [mm];

t_f is the fall-off time of the Fire Rated Cladding (FRC) or FRC system [min]
 (See Chapter 4);
 v_{rec} is the recession speed of the insulation [mm/min];
 $\sum t_{prot,i-1}$ is the sum of the protection times of the layers preceding the insulation
 layer [min].

No protection by insulation materials qualified as protection level 3 can be considered as these materials melt or otherwise degrade and lose their protective ability before the fall-off of the cladding, see Equation (11).

$$t_{prot,i}=0 \quad (11)$$

3.2 Insulation time

The insulation time of the last layer can be calculated taking into account the basic insulation value of the layer ($t_{ins,0}$), the position coefficient ($k_{pos,exp}$) and the joint coefficient (k_j) by equation (12).

$$t_{ins,n}=(t_{ins,0,n} \cdot k_{pos,exp,n} + \Delta t_n) \cdot k_{j,n} \quad (12)$$

where

$t_{ins,n}$ is the insulation time of the last layer n [min];
 $t_{ins,0,n}$ is the basic insulation value of the last layer n [min];
 $k_{pos,exp,n}$ is the position coefficient that takes into account the influence of layers preceding the layer considered;
 Δt_n is the correction time for the last layer n protected by FRC [min];
 $k_{j,n}$ is the joint coefficient for layer n .

The coefficients and basic values are dependent on the material of the considered layer and the preceding and backing layers. Generic values of the basic protection times and basic insulation times are given in Table 1, for position coefficients see Table 2 and Table 3, for joint coefficients see Table 4. Correction times are presented in clause 3.5.

3.3 Position coefficients

Table 2. Position coefficients for the exposed side

Material	Position coefficient $k_{\text{pos,exp},i}$
Cladding (gypsum, timber)*	$1 - 0,6 \cdot \frac{\sum t_{\text{prot},i-1}}{t_{\text{prot},0,i}} \quad \text{for } \sum t_{\text{prot},i-1} \leq \frac{t_{\text{prot},0,i}}{2}$
Stone wool insulation	$0,5 \cdot \sqrt{\frac{t_{\text{prot},0,i}}{\sum t_{\text{prot},i-1}}} \quad \text{for } \sum t_{\text{prot},i-1} > \frac{t_{\text{prot},0,i}}{2}$
Wood fibre cavity insulation	$1 - 0,9 \cdot \frac{\sum t_{\text{prot},i-1}}{t_{\text{prot},0,i}} \quad \text{for } \sum t_{\text{prot},i-1} \leq \frac{t_{\text{prot},0,i}}{2}$ $0,2 \cdot \frac{t_{\text{prot},0,i}}{\sum t_{\text{prot},i-1}} - 0,03 \cdot \frac{\sum t_{\text{prot},i-1}}{t_{\text{prot},0,i}} + 0,2 \quad \text{for } \sum t_{\text{prot},i-1} > \frac{t_{\text{prot},0,i}}{2}$
Wood fibre insulation boards	$1 - \frac{\sum t_{\text{prot},i-1}}{t_{\text{prot},0,i}} \quad \text{for } \sum t_{\text{prot},i-1} \leq \frac{t_{\text{prot},0,i}}{2}$ $0,28 \cdot \left[\frac{t_{\text{prot},0,i}}{\sum t_{\text{prot},i-1}} \right]^{0,9} \quad \text{for } \sum t_{\text{prot},i-1} > \frac{t_{\text{prot},0,i}}{2}$
Cellulose fibre insulation	$1 - \frac{\sum t_{\text{prot},i-1}}{t_{\text{prot},0,i}} \quad \text{for } \sum t_{\text{prot},i-1} \leq \frac{t_{\text{prot},0,i}}{2}$ $0,27 \cdot \left[\frac{t_{\text{prot},0,i}}{\sum t_{\text{prot},i-1}} \right]^{1,1} \quad \text{for } \sum t_{\text{prot},i-1} > \frac{t_{\text{prot},0,i}}{2}$
Glass wool insulation	$1 - 0,8 \cdot \frac{\sum t_{\text{prot},i-1}}{t_{\text{prot},0,i}} \quad \text{for } \sum t_{\text{prot},i-1} \leq \frac{t_{\text{prot},0,i}}{4}$
for $h_i \geq 40$ mm	$(0,001 \cdot \rho_i + 0,27) \cdot \left[\frac{t_{\text{prot},0,i}}{\sum t_{\text{prot},i-1}} \right]^{(0,75 - 0,002 \cdot \rho_i)} \quad \text{for } \sum t_{\text{prot},i-1} > \frac{t_{\text{prot},0,i}}{4}$

Where ρ_i : Density of the considered layer [kg/m³]

*For the last layer use $t_{\text{ins},0,n}$ instead of $t_{\text{prot},0,i}$

For the layer directly behind a void, the position coefficient $k_{\text{pos,exp},i}$ shall be multiplied by 1,6.

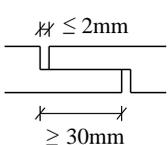
Table 3. Position coefficients for the unexposed side

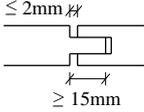
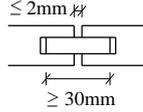
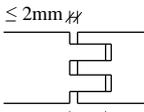
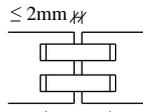
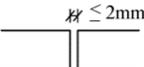
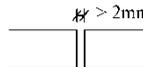
Material of the considered layer	$k_{\text{pos,unexp},i}$ for layers backed by cladding made of gypsum or timber	$k_{\text{pos,unexp},i}$ for layers backed by insulation or void cavity (thicker than 45 mm)
Gypsum plasterboard, gypsum fibre board	1,0	$0,5 \cdot h_i^{0,15}$
Solid timber, cross-laminated timber, LVL		$0,35 \cdot h_i^{0,21}$
Particleboard, fibreboard		$0,41 \cdot h_i^{0,18}$
OSB, plywood		$0,5 \cdot h_i^{0,15}$
Stone wool insulation		$0,18 \cdot h_i^{(0,001 \cdot \rho_i + 0,08)}$
Wood fibre cavity insulation		$0,97 \cdot h_i^{-0,077}$
Wood fibre insulation boards		$0,52 \cdot h_i^{0,125}$
Cellulose fibre insulation		$0,53 \cdot h_i^{0,08}$
Glass wool insulation		$0,01 \cdot h_i - \frac{h_i^2}{30000} + \rho_i^{0,09} - 1,3$

Where h_i : Thickness of the considered layer [mm]
 ρ_i : Density of the considered layer [kg/m³]

3.4 Joint coefficients

Table 4. Joint coefficients

Material	Joint type	$k_{j,i}$	
		Layer backed by a void cavity (≥ 45 mm) $k_{j,n}$ for the last layer	Layer backed by battens or panels or structural members or insulation
Cladding (timber)		0,3	1,0

	 	0,4	1,0
	 	0,6	1,0
	no joint	1,0	1,0
Gypsum plasterboard, gypsum fibre board	 	0,8	1,0
	no joint	1,0	1,0
Insulation (mineral wool insulation)		0,8	1,0
	no joint	1,0	1,0

3.5 Correction times

Fire rated cladding or fire rated cladding system is characterised by the ability to stay in place longer than the protection time which is described by the fall-off time t_f .

This effect is taken into account by adding a correction time Δt_i to the protection time of layer(s) behind the FRC. The calculations include the fall-off time (t_f) and the protection coefficient (k_2) of the fire rated cladding or cladding system. This approach is summarised, extended and clarified in the following.

Generic values of the fall-off times of some fire rated claddings and cladding systems ($t_{f,p}$) can be found in Clause 0. The index p refers to the FRC in the following equations.

The protection time of the FRC ($t_{prot,p}$) should also be calculated. Then, the maximum protection time ($t_{prot,max}$) of the layer i when the cladding stays in place is determined according to equation (13):

$$t_{prot,max,i} = \frac{t_{prot,0,i}}{k_2} \quad (13)$$

or

$$t_{ins,max,n} = \frac{t_{ins,0,n}}{k_2}$$

where

k_2 is protection coefficient of the fire rated cladding or cladding system [-].

The determination of correction time to be added to the investigated layer follows the limits shown in Figure 2 and is described by equations (14) to (19).

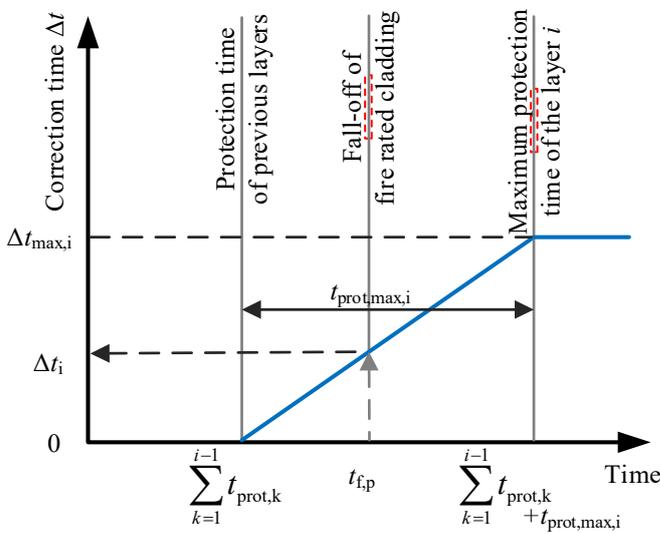


Figure 2 – Limits of the correction time

The indices used in Figure 2 and in the following equations:

i investigated layer (may be the first or any next layer after the FRC);

p fire rated cladding (FRC) or FRC system.

The limits for the correction times are defined as follows (see Figure 2):

- When the fall-off time of the cladding $t_{f,p}$ is less than or equal to the sum of protection times of the preceding layers (including the protection time of the fire rated cladding $t_{prot,p}$), then no correction time is applied.

$$t_{f,p} \leq \sum_{k=1}^{i-1} t_{prot,k} , \Delta t_i = 0 \quad (14)$$

or

$$t_{f,p} \leq \sum_{k=1}^{n-1} t_{\text{prot},k}, \Delta t_n = 0$$

- When the fall-off time of the cladding $t_{f,p}$ is greater than the sum of protection times of the preceding layers (including the protection time of the fire rated cladding $t_{\text{prot},p}$) and the maximum protection time of the investigated layer i , then the maximum correction time for layer i is applied.

$$t_{f,p} \geq \sum_{k=1}^{i-1} t_{\text{prot},k} + t_{\text{prot},\text{max},i}, \Delta t_i = \Delta t_{\text{max},i} \quad (15)$$

or

$$t_{f,p} \geq \sum_{k=1}^{n-1} t_{\text{prot},k} + t_{\text{prot},\text{max},n}, \Delta t_n = \Delta t_{\text{max},n}$$

The maximum correction time that can be considered is expressed as

$$\Delta t_{\text{max},i} = t_{\text{prot},\text{max},i} - t_{p,i} \quad (16)$$

or

$$\Delta t_{\text{max},n} = t_{\text{prot},\text{max},n} - t_{p,n}$$

where

$t_{p,i}$ is the protection time of the investigated layer without correction time (equation (17)) [min].

$t_{p,n}$ is the insulation time of the investigated layer without correction time (equation (18)) [min].

$$t_{p,i} = t_{\text{prot},0,i} \cdot k_{\text{pos},\text{exp},i} \cdot k_{\text{pos},\text{unexp},i} \cdot k_{j,i} \quad (17)$$

$$t_{p,n} = t_{\text{ins},0,n} \cdot k_{\text{pos},\text{exp},n} \cdot k_{j,n} \quad (18)$$

- When the fall-off time of the fire rated cladding is greater than the sum of protection times of all layers preceding the investigated layer but less than the sum of protection times of the preceding layers and the maximum possible protection time of the layer i , then linear interpolation is possible, see (19).

$$\sum_{k=1}^{i-1} t_{\text{prot},k} < t_{f,p} < \sum_{k=1}^{i-1} t_{\text{prot},k} + t_{\text{prot},\text{max},i}, \Delta t_i = \frac{(t_{f,p} - \sum_{k=1}^{i-1} t_{\text{prot},k}) \cdot \Delta t_{\text{max},i}}{t_{\text{prot},\text{max},i}} \quad (19)$$

or

$$\sum_{k=1}^{n-1} t_{\text{prot},k} < t_{f,p} < \sum_{k=1}^{n-1} t_{\text{prot},k} + t_{\text{ins,max},n}, \Delta t_n = \frac{(t_{f,p} - \sum_{k=1}^{n-1} t_{\text{prot},k}) \cdot \Delta t_{\text{max},n}}{t_{\text{ins,max},n}}$$

where

$t_{f,p}$ is the fall-off time of the cladding (system) [min].

Correction time Δt can be applied for the next layer(s) after the fire rated cladding system which can consist of single or multiple layers. The correction time, Δt , is added to all layers after the fire rated cladding, if the sum of the protection times of the preceding layers is less than the fall-off time of the fire rated cladding.

The fall-off time $t_{f,p}$ and the coefficient k_2 may be found in EN 1995-1-2 or determined with fire tests according to EN 13381-7 [6].

A schematic example is shown in Figure 3. The continuous line in the figure shows the sum of protection times after each layer of the assembly. The dashed lines show the resulting protection times if no correction times are added (or if correction time is added only to layer 3 which is directly protected by the FRC).

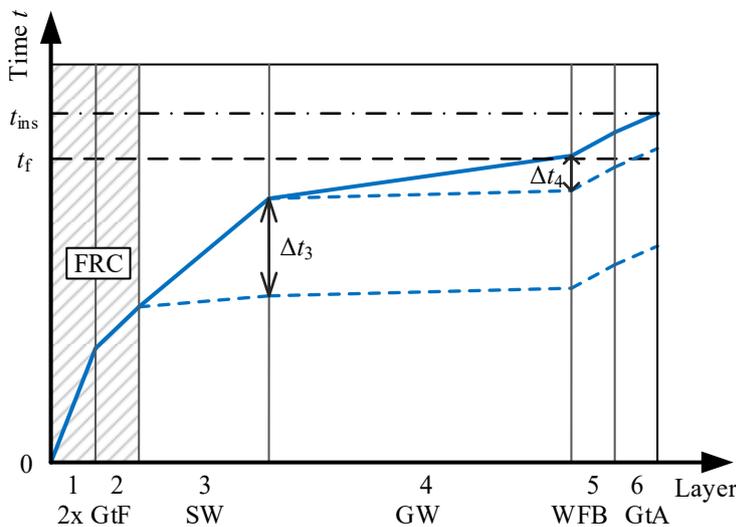


Figure 3 – Example calculation of insulation time for a 6-layer structure

3.6 Implementation of new materials

The addition of new materials and products to the improved component additive method requires the determination of basic protection and insulation times, position

coefficients and correction times. The procedure is described in detail in [7], but the general steps to be taken are in the following order:

1. Estimation of initial thermal properties at elevated temperatures, e.g. using thermo-gravimetric analysis (TGA), differential scanning calorimetry (DSC) and transient plane source (TPS) methods.
2. Fire tests (in model or full-scale)
3. Thermal simulations with initial properties and comparison with model-scale fire test data
4. Determination of the effective thermal properties
5. Thermal simulations and comparison with model-scale fire test data
6. Step-by-step thermal simulations for developing design equations
7. Validation of equations with full-scale tests

The aforementioned steps are mostly taken one after the other. Therefore, care shall be taken to obtain results as accurate as possible in each step. Otherwise the cumulative error increases. The procedure is described in COST Guidance Document N248-07.

4. Effective Cross-section Method for the load-bearing capacity

The Effective Cross-Section Method (ECSM) is an analytical design model which enable to evaluate the load-bearing capacity of timber member under fire conditions. The ECSM considers

- a reduction of a timber cross-section by charring
- a reduction of strength and stiffness by an additional zero-strength layer d_0 .

The original cross-section reduced by the notional charring depth $d_{char,n}$ and the zero-strength layer d_0 is defined as the effective cross-section. See Figure 4. The effective charring depth is given as (20).

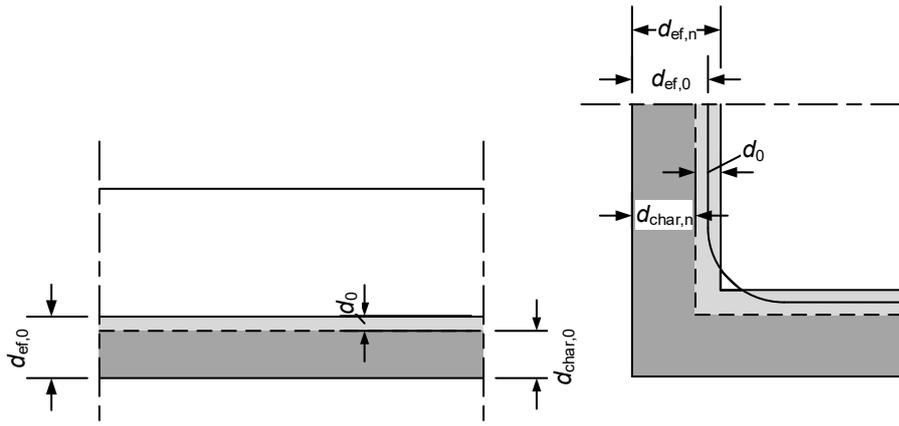
$$d_{ef} = d_{char,n} + d_0 \quad (20)$$

where

- d_{ef} is the effective charring depth [mm];
 $d_{char,n}$ is the notional charring depth [mm];
 d_0 is the zero-strength layer depth [mm].

Zero-strength layer d_0 is a fictive layer compensating for the reduction of strength and stiffness properties of the uncharred timber at elevated temperatures.

The load-bearing capacity of timber members under fire conditions can be predicted by using effective cross-section with the strength and stiffness properties as at ambient temperature.



a) One-dimensional charring, b) two-dimensional charring.

Figure 4 - Determination of effective cross-section for linear members

According to EN 1995-1-2:2004 the characteristic strength in fire shall be calculated as shown in (21).

$$f_{k,fi} = k_{fi} \cdot f_k \quad (21)$$

where

$f_{k,fi}$ is the characteristic strength of a timber member under fire conditions;

k_{fi} is the modification factor for the strength in fire condition;

f_k is the characteristic strength of a timber member at ambient temperature as given in the EN 1995-1-2:2004 [8]

The modification factor k_{fi} is defined in in the current EN1995-1-2.

The design strength value of a timber member in fire conditions shall be calculated as:

$$f_{d,fi} = \frac{f_{k,fi}}{\gamma_{M,fi}} \quad (22)$$

where

$f_{d,fi}$ is the design strength in fire of a timber member in fire conditions;

$f_{k,fi}$ is the characteristic strength in fire of a timber member in fire conditions;

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

The partial safety factor of timber in fire $\gamma_{M,fi}$ is defined in National Annexes of EN 1995-1-2.

4.1 Charring phases

The charring of timber members in wall and floor assemblies exposed to fire is influenced by the protective properties of the claddings and cavity insulation materials. A primary protection for a timber member is achieved by the cladding on the fire exposed side. The charring phase prior to fall-off (failure) of protective claddings is defined as the protection phase. After the fall-off of the cladding, a secondary protection of the timber member might be provided by cavity insulation materials. The charring phase after the fall-off of protective cladding is defined as the post-protection phase.

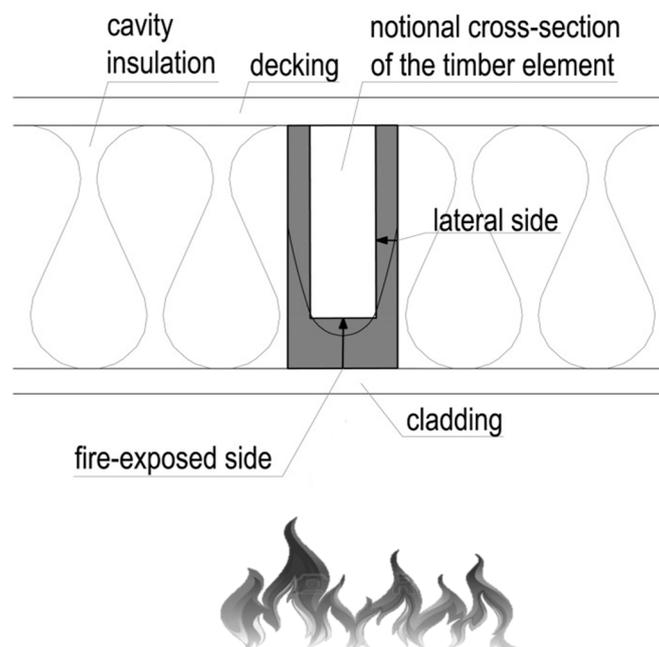


Figure 5 – Cross-section of a timber frame assembly.

Charring of the timber cross-section can occur on the fire exposed side and on the lateral side (see Figure 5) depending on the protective ability of the claddings and cavity insulations.

Charring of initially protected members is divided into three phases.

Encapsulation phase (Phase 1) is the phase when no charring of the timber member occurs.

Protection phase (Phase 2) is the phase when charring occurs behind the protective cladding while the cladding is still in place.

Post-protection phase (Phase 3) is the phase when the protective cladding has fallen off.

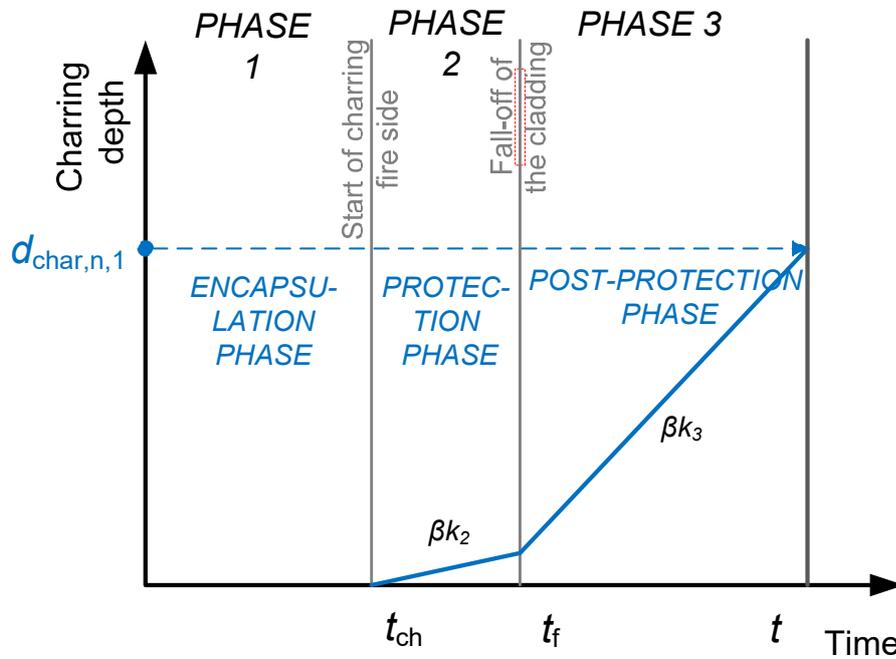


Figure 6 – Charring phases for the Effective Cross-Section Method

Start time of charring of timber members can be delayed using protective claddings on the fire side of the members.

The start time of charring is determined using the improved component additive method by summarizing the protection times of the cladding system (all layers preceding the timber member);

$$t_{ch} = \sum t_{prot} \quad (23)$$

For protection phase 2, when $t_{ch} \leq t \leq t_f$, the basic design charring rates β_0 of the timber member given in EN 1995-1-2 should be multiplied by protection factor k_2 . After the fall-off of the cladding the charring rates should be multiplied by the post-protection factor k_3 . During protection and post-protection phase the basic design charring rate has to be also corrected by the cross-section factor $k_{s,n}$.

The notional charring rates should be taken as

$$\beta_n = k_2 \cdot k_{s,n} \cdot \beta_0 \quad (24)$$

$$\beta_n = k_3 \cdot k_{s,n} \cdot \beta_0 \quad (25)$$

where

β_n is the notional charring rate [mm/min];

k_2 is the protection factor;

$k_{s,n}$ is the cross-section factor,

k_3 is the post-protection factor;

β_0 is the basic design charring rate of timber [mm/min].

Basic design charring rates of timber are given in EN 1995-1-2. [9]

The protection coefficient k_2 for different gypsum boards and stone wool claddings are published in EN 1995-1-2:2004. For other cladding materials the coefficients can be determined according to EN 13381-7.

For gypsum plasterboards the protection factor k_2 should be taken as

$$k_2 = 1.05 - 0.0073 h_p \quad (26)$$

where

h_p is the thickness of the gypsum plasterboard [mm]

For clay claddings the protection factor k_2 should be taken as

$$k_2 = 1 - 0,01 h_p \quad (27)$$

where

h_p is the thickness of the clay cladding [mm];

For stone wool claddings with minimal density of 26kg/m³ the protection coefficient k_2 should be taken as

$$k_2 = 1 \text{ for thickness } 20 \text{ mm}$$

$$k_2 = 0,6 \text{ for thickness } 45 \text{ mm and more.} \quad (28)$$

For stone wool claddings with thicknesses between 20 and 45 mm the factor k_2 can be interpolated.

4.2 Fall-off time of wood-based boards

Protection by wood-based boards is considered by calculating the charring of the boards taking into account the appropriate coefficients for thickness and density according to equation (4). Fall-off time of the wooden board occurs when the charring of the whole thickness is reached.

4.3 Fall-off time of Gypsum boards

Generic expressions for fall-off times of gypsum plasterboards are given in Table 5.

Since the values given in the tables are conservative, producers may wish to determine values for their products and applications according to EN 13381-7 to be used by designers.

Table 5. Failure times of gypsum plasterboards t_f in minutes with board thickness h_p and total board thickness $h_{p,tot}$ in millimetres.

Cladding	Walls		Floors	
Type F, one layer	$4,9h_p-30$	$9 \text{ mm} \leq h_p \leq 18 \text{ mm}$	$1,6h_p+3$	$12,5 \text{ mm} \leq h_p \leq 16 \text{ mm}$
	58	$h_p > 18 \text{ mm}$	29	$h_p > 16 \text{ mm}$
Type F, two layers	$1,6h_{p,tot}+18$	$25 \text{ mm} \leq h_{p,tot} \leq 31 \text{ mm}$	$1,9h_p-1,5$	$25 \text{ mm} \leq h_{p,tot} \leq 31 \text{ mm}$
	68	$h_{p,tot} \geq 31 \text{ mm}$	57	$h_{p,tot} \geq 31 \text{ mm}$

4.4 Protection provided by Clay plaster systems

Clay plaster is a surface finish material for interior walls and ceilings. A dry mixture of clay plaster consists of clay, sand and some form of natural fibre. Product standard DIN 18947 [10] determines the terms, requirements and test methods for clay plaster. It does not apply to stabilised plasters and applies only to clay plaster with a thickness over 3 mm. Recently, clay plaster has been incorporated into the superior standards of application - DIN 18550-2 where it is implemented alongside other conventional plasters. Since 2016, clay plaster is also described in the European standard for interior plasters - EN 13914-2 [11].

4.4.1 Design model

The proposed design model is limited to clay plasters that are in accordance to DIN 18947 [10] and belong to the plaster density class 1.8. Important mechanical requirements are the compressive strength 1.5 – 5 N/mm² and the linear shrinkage of drying that should be not more than 2%. The mechanical strength of clay plaster should be classified as S II with specific limits for adhesion $\geq 0,1$ N/mm² and tensile strength $\geq 0,7$ N/mm². The selection, design and application of clay plaster systems shall be in accordance with EN 13914-2 [11].

Plaster is applied directly on building boards or on the substrates. Clay plaster adheres well with ecological boards such as clay panels, hemp boards, wood fibre boards etc. Currently, a first product standard for clay panels is being developed in Germany (DIN 18948).

It is mandatory to adhere to the manufacturer's recommendations while applying clay plaster systems on timber surfaces. The substrates should be fastened on timber in accordance with the manufacturer's guidance following the minimal requirements stated below.

Design parameters are given with respect to two traditional substrates for plastering on timber surfaces:

- reed mat
- reed board

Reed mat is a plaster base consisting of ca. 6-10 mm thick reed stems with approx. 70 stems per linear metre. Reed stems are bound together by a galvanized carrier wire and a thinner binding wire. The carrier wire is fixed with staples to timber. The carrier wire presses the reed stems against timber. The distance between staples is usually 5 – 10 cm.

Reed board is a rigid building board which is made from natural reeds that are laid in parallel and tightly bound using a thin gauge galvanised wire. Reed board is fixed with screws using fastening clips on the wires. The distance between screws on the wire support should not be more than 150 mm.

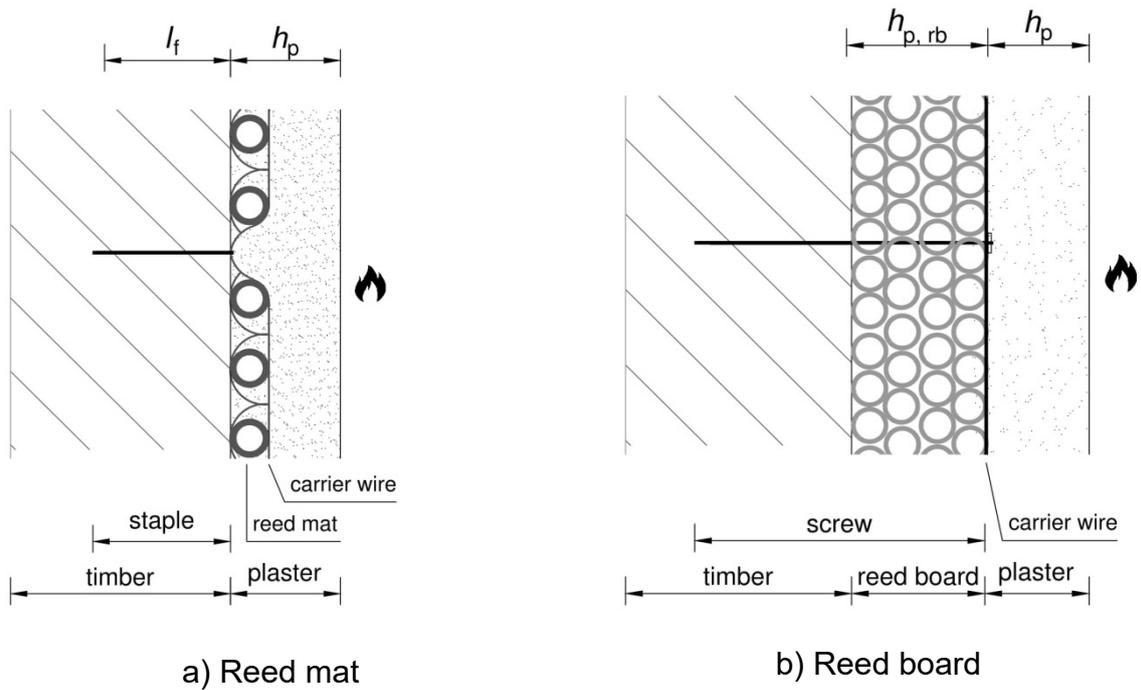
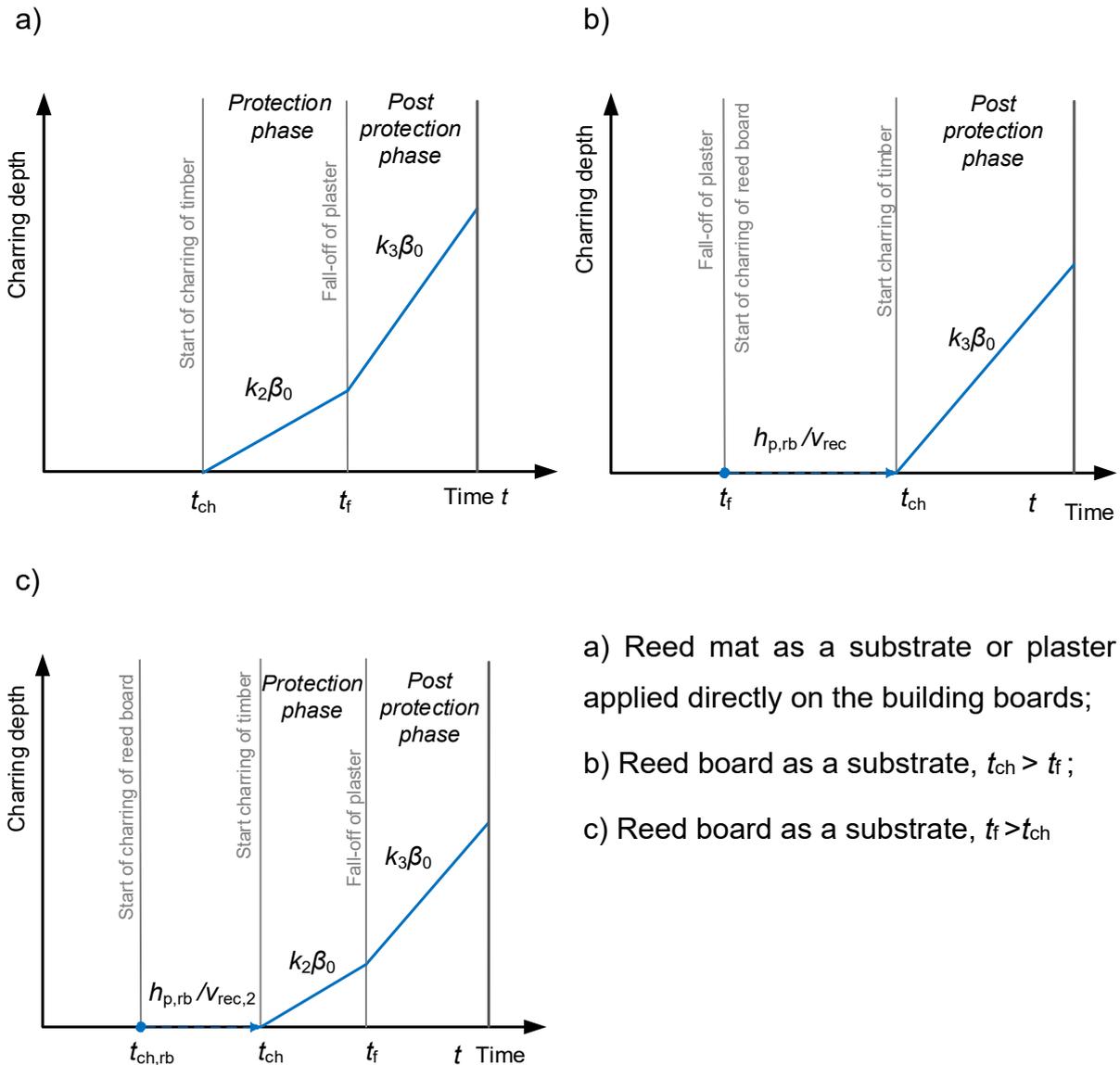


Figure 7 – Clay plaster substrates.

The following design models are presented as a result of the most recent experimental studies carried out under standard fire exposure conditions [15], [16]. Based on the conducted tests, the proposed design model is valid for clay plasters with the maximum thickness of 30 mm for walls and 17 mm for ceilings. The design models for clay plaster are illustrated in Figure 8.



- a) Reed mat as a substrate or plaster applied directly on the building boards;
- b) Reed board as a substrate, $t_{ch} > t_f$;
- c) Reed board as a substrate, $t_f > t_{ch}$

Figure 8 – Design models for clay plaster with different substrates on timber.

Design parameters for clay plaster

The start time of charring of timber depends on the plaster thickness and substrate.

For clay plaster applied directly on wood-based surfaces using a reed mat the start time of charring of timber t_{ch} [min] should be taken as

$$t_{ch} = h_p - 7 \tag{29}$$

where

t_{ch} is the start time of charring of timber [min];

h_p is the thickness of clay plaster on timber [mm].

For clay plaster applied on a reed board, the start time of charring of timber t_{ch} should be taken as a combination of the following:

- the start time of charring of the reed board $t_{ch,rb}$
- the fall-off time of plaster t_f
- the recession speed of the reed board v_{rec} (see Figure 8b and Figure 8c)

When the fall-off time of plaster occurs after the start time of charring of timber, the start time of charring of timber can be estimated using equation (30).

$$t_{ch} = t_{ch,rb} + \frac{h_{p,rb}}{v_{rec,2}} \quad (30)$$

where

$t_{ch,rb}$ is calculated according to Equation (29), $t_{ch,rb} = t_{ch}$, [min];

$h_{p,rb}$ is the thickness of the reed board [mm];

$v_{rec,2}$ is the recession speed of the reed board and is multiplied by the protection factor k_2 according to Equation (27), $v_{rec,2} = k_2 \cdot v_{rec}$ [mm/min].

When the fall-off time of plaster occurs before the start time of charring of timber (see Figure 8b), the start time of charring of timber should be estimated using equation (31).

$$t_{ch} = t_f + \frac{h_{p,rb}}{v_{rec}} \quad (31)$$

where

t_f is the fall-off time of plaster [min];

$h_{p,rb}$ is the thickness of the reed board [mm];

v_{rec} is the recession speed of the reed board [mm/min].

When $t_{ch,rb} < t_f < t_{ch}$ an interpolation between the values provided by Equations (30) and (31) could be performed.

Fall-off time of plaster

For clay plaster with reed mat as a substrate the fall-off time of plaster can be calculated using equation (22)

$$t_f = t_{ch} + \frac{l_f - 10}{k_2 \beta_0} \quad (32)$$

where

l_f is the length of the fastener [mm]

For k_2 see Equation (27).

Equation (32) applies to clay plaster with a thickness up to 17 mm for horizontal positioning and up to 30 mm for vertical positioning. The extension of these limits has to be verified by furnace tests.

For clay plaster with a reed board as a substrate the fall-off time of plaster is recommended to be taken as

$$t_f = t_{ch,rb} \quad (33)$$

where

$t_{ch,rb}$ is the start time of charring of reed board [min].

If the fall-off time of plaster is not determined, then Equation (33) should be used. Otherwise, the design scenario in Figure 8c should be followed.

4.5 Protection provided by cavity insulations

The charring scenario of the timber member applied in frame assemblies can be described by means of a notional charring depth from the fire exposed side only or from both fire-exposed side and lateral sides (see Figure 5) depending on the ability of the cavity insulation to protect timber against the charring.

To clearly distinguish the different abilities of the cavity insulation product to protect timber against the charring, the three protection levels for cavity insulations have been introduced [5], [17], [18]. Protection level 3 (PL3) indicates the weakest protection level and Protection Level 1 (PL1) indicates the strongest protection level. The protection level is evaluated by means of a standard test set-up [20] .

An improved design model where the charring of the timber element can be considered to occur from only the fire exposed side of the timber member or from three sides, depending on the protection level of the cavity insulation has been further presented [17]–[19].

Stone wool products, can be in general, qualified as PL1, glass wool and cellulose fibre products, in general, can be qualified as PL2 and polyurethane products are qualified as PL3.

Performance of specific products can be evaluated by means of a standard test set-up.

Design model for Protection Level 1

For timber frame assemblies with applied cavity insulations qualified as PL1, the notional charring depth on the timber member is regarded from the fire exposed side only (the fire exposed side and lateral sides of cross-section are defined in Figure 5).

The PL 1 assigned to generic insulation products, limits charring scenario from a fire-exposed side only to a post-protection phase not longer than 15 minutes.

To extend the application to post-protection phase longer than 15 minutes, the PL 1 has to be assigned by means of fire tests. In case of specific insulation products evaluated by means of fire tests, it is possible to assign to the cavity insulation a PL 1–

X_{post} , where X_{post} is the maximum length of the post-protection phase on which a one-side charring behavior can be considered.

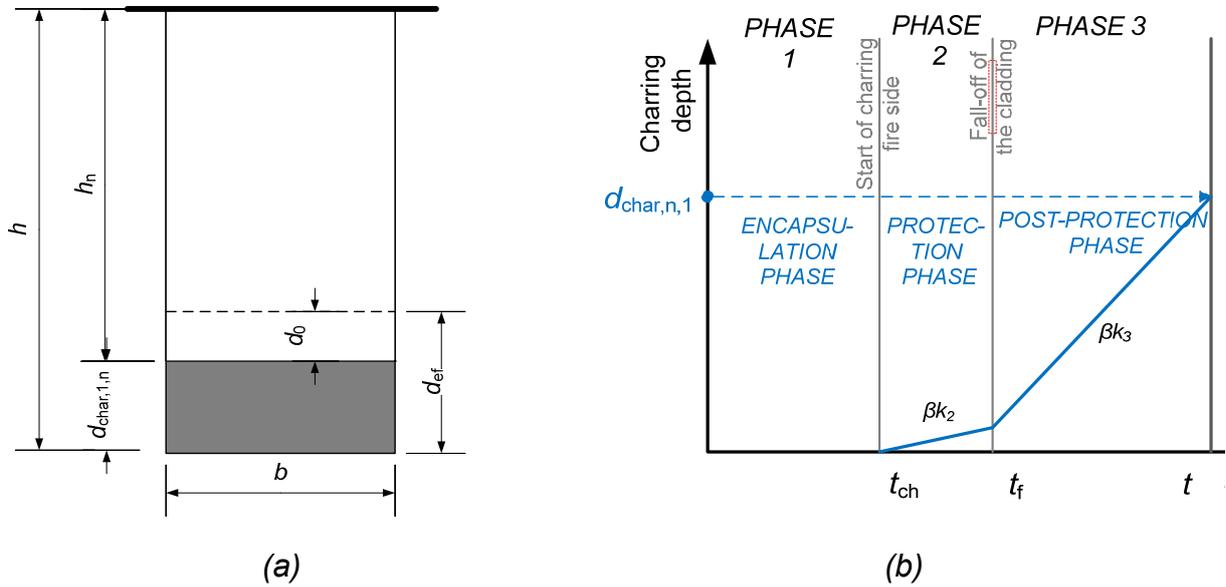


Figure 9 – Improved design model for timber frame assemblies with PL1 insulation; (a) determination of the effective cross-section; (b) different charring phases of the design model.

The nominal char depth along the fire exposed side ($d_{\text{char},1,n}$) is calculated as:

$$d_{\text{char},1,n} = \beta_0 \cdot k_{s,n} \cdot k_2 \cdot (t_f - t_{\text{ch}}) + \beta_0 \cdot k_{s,n} \cdot k_{3,1} \cdot (t - t_f) \quad (34)$$

where

- $k_{s,n}$ is the cross-section factor considering the notional charring rate [-];
- k_2 is the protection factor of the protective cladding or cladding system [-];
- $k_{3,1}$ is the post-protection factor for the fire exposed side [-].

Coefficient $k_{s,n}$ is determined by:

$$\begin{aligned} k_{s,n} &= 0,00025 \cdot b^2 - 0,044 \cdot b + 3,41 && \text{for } b \leq 90 \text{ mm} \\ k_{s,n} &= 1,5 && \text{for } b > 90 \text{ mm} \end{aligned} \quad (35)$$

where

- b is the width of the timber cross-section [mm].

Coefficient $k_{3,1}$ can be evaluated as:

$$k_{3,1} = 0,022 \cdot t_f + 1 \quad \text{for cavity insulations of stone wool} \quad (36)$$

$$k_{3,1} = 0,0173 \cdot t_f + 1 \quad \text{for cavity insulations of HTE mineral wool} \quad (37)$$

where

t_f is the fall-off time of the cladding (system) [min].

The post-protection factor $k_{3,1}$ for other specific products can be evaluated according to the methodology published in [18].

Design model for Protection Level 2

For timber frame assemblies insulated with cavity insulations qualified Protection Level 2, the charring is considered from three sides after the fall-off of the cladding. The charring on the lateral sides takes place with a different charring rate compared to the charring from the fire-exposed side. Recession speed of the insulation material (v_{rec}) is used additionally as a parameter to describe the delay of start of charring of the timber member on the lateral side ($t_{ch,2}$). The recession speed varies for different insulation materials. Where no recession speed is defined, the start of charring on the lateral sides is taken as equal to the fall-off time of the cladding.

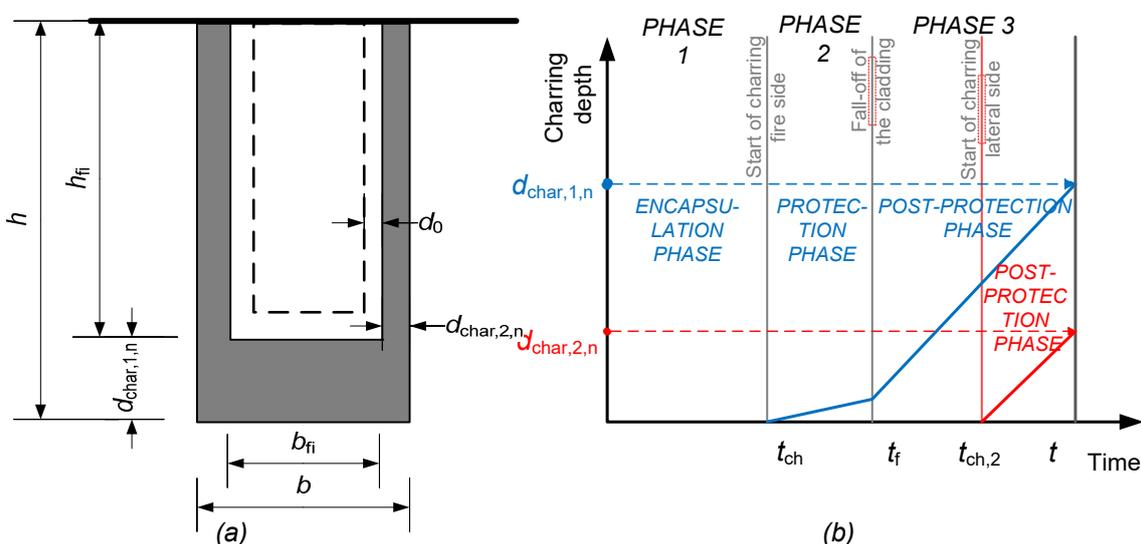


Figure 10 – (a) Evaluation of the charring depths for timber frame assemblies with cavity insulations qualified as PL2; (b) different charring phases of the design model.

The charring depth along the fire exposed side ($d_{char,1,n}$) is calculated as:

$$d_{char,1,n} = \beta_0 \cdot k_{s,n} \cdot k_2 \cdot (t_f - t_{ch}) + \beta_0 \cdot k_{s,n} \cdot k_{3,1} \cdot (t - t_f) \quad (38)$$

where

- $k_{s,n}$ is the cross-section factor considering the notional charring rate;
 k_2 is the protection factor of the protective cladding or cladding system;
 $k_{3,1}$ is the post-protection factor for the fire exposed side.

After the start of lateral charring, the charring depth on the lateral sides can be evaluated as:

$$d_{\text{char},2,n} = \beta_0 \cdot k_{s,n} \cdot k_{3,2} \cdot (t - t_{\text{ch},2}) \quad (39)$$

where

- $k_{3,2}$ is the post-protection factor for the fire exposed side.

Factor $k_{s,n}$ for the charring on the fire exposed side can be determined according to equation (35).

Coefficient $k_{s,n}$ for $d_{\text{char},2,n}$ is given by:

$$\begin{aligned} k_{s,n} &= 0,00025 \cdot h^2 - 0,044 \cdot h + 3,41 && \text{for } h \leq 90 \text{ mm} \\ k_{s,n} &= 1 && \text{for } h > 90 \text{ mm} \end{aligned} \quad (40)$$

where

- h is the height of cross-section of the timber member [mm].

Coefficient $k_{3,1}$ is determined by:

$$k_{3,1} = 0,0171 \cdot t_f + 1 \quad \text{for cavity insulations of glass wool} \quad (41)$$

$$k_{3,1} = 0,0262 \cdot t_f + 1 \quad \text{for cavity insulations of cellulose fibre} \quad (42)$$

Coefficient $k_{3,2}$ is given as:

$$k_{3,2} = 0,051 \cdot t_{\text{ch},2} \geq 1 \quad \text{for cavity insulations of glass wool} \quad (43)$$

$$k_{3,2} = 0,0138 \cdot t_{\text{ch},2} \geq 1 \quad \text{for cavity insulations of cellulose fibre} \quad (44)$$

where

- $t_{\text{ch},2}$ is the start time of charring from the lateral sides [min].

Charring on the lateral sides is assumed to start when the cladding has fallen off. For the specific insulation products, the start time of charring on the lateral side can be delayed depending on the recession speed of the insulation:

$$t_{ch,2} = t_f + \frac{2}{3} \frac{h}{v_{rec}} \quad (45)$$

where

t_f is the fall-off time of the cladding [min];

v_{rec} is the recession speed of the cavity insulation [mm/min];

h is the height of the timber member cross-section [mm].

Design model for Protection Level 3

The design procedure for Protection Level 3 considers the start time of charring on the lateral sides equal to the start time of charring on the fire-exposed side.

$$t_{ch,2} = t_{ch,1} \quad (46)$$

4.6 Effective charring depth and zero-strength layers

Behind the char layer of a timber member exposed to fire there is a heated zone where the strength and stiffness properties of the timber are reduced compared to the respective initial properties at ambient temperature. This reduction of the mechanical properties is taken into account by means of a fictive layer called zero-strength layer (d_0). The effective char depth is determined by the notional char depth plus a zero-strength layer (d_0), see Equation (20).

The effective cross section is obtained by subtracting the effective charring depth from the original cross-section. The effective cross-section enables to predict the load bearing capacity of the element under fire conditions using the strength and stiffness properties as they are at ambient temperature.

Zero-strength layer d_0 is taken into account from the beginning of fire ($t=0$).

For timber frame assemblies where the cavities are filled with PL1 insulation, charring occurs on the fire-exposed side of the cross-section and d_0 has to be subtracted from the fire exposed side (see Figure 9a) for the whole duration of the fire exposure. Different expressions are proposed according to the load conditions and the cavity

insulations. For timber frame assemblies with cavities filled with stone wool insulation, the following expressions can be used:

- bending member with the fire exposed side in tension:

$$d_0 = 9 + 0.25 h - 0.18 b \quad (47)$$

- bending member with the fire exposed side in compression:

$$d_0 = 27.9 + 0.14 h - 0.26 b \quad (48)$$

- out-of-plane buckling of compression member:

$$d_0 = 29.1 + 0.16 h - 0.26 b \quad (49)$$

- in-plane buckling of compression member:

$$d_0 = 43.6 + 0.43 h - 0.37 b \quad (50)$$

For timber frame assemblies insulated with HTE mineral wool, the following expressions can be used:

- bending member with the fire exposed side in tension:

$$d_0 = 18.6 + 0.17 h - 0.18 b \quad (51)$$

- bending member with the fire exposed side in compression:

$$d_0 = 27.9 + 0.14 h - 0.28 b \quad (52)$$

- out-of-plane buckling of compression member:

$$d_0 = 25.5 + 0.17 h - 0.26 b \quad (53)$$

- in-plane buckling of compression member:

$$d_0 = 36.4 + 0.45 h - 0.37 b \quad (54)$$

For timber frame assemblies insulated with PL2 insulations cavity insulations, d_0 has to be subtracted from three sides (see Figure 10a). The following expressions are proposed:

- bending member with the fire exposed side in tension:

$$d_0 = 2.8 + 0.02 h + 0.01 b \quad (55)$$

- bending member with the fire exposed side in compression:

$$d_0 = 3.2 + 0.03 h + 0.01 b \quad (56)$$

- out-of-plane buckling of compression member:

$$d_0 = 3.7 + 0.06 h + 0.01 b \quad (57)$$

- in-plane buckling of compression member:

$$d_0 = 3.5 + 0.03 h + 0.01 b \quad (58)$$

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