

Fire safe use of bio-based building products



**Guidance document –  
Fire design of CLT including best practise  
(N223-07)**

Version 2018

FP1404 WG2 TG1

Editors: M. Klippel, A. Just



# Guidance on Fire design of CLT including best practise

COST Action FP 1404

“Fire Safe Use of Bio-Based Building Products”

N223-07

This publication is the result of work carried out within COST Action FP1404 “Fire Safe Use of Bio-Based Building Products”, supported by COST (European Cooperation in Science and Technology). COST is a funding agency for research and innovation networks. The Actions help connect research initiatives across Europe and enable scientists to grow their ideas by sharing them with their peers. This boosts their research career and innovation. More information available at [www.cost.eu](http://www.cost.eu).



This guidance document may be cited as:

*Klippel, M, Just, A (eds) Guidance on Fire design of CLT including best practise, COST Action FP1404, Zürich, Switzerland, 2018.*

DOI 10.3929/ethz-b-000319542p

Version 1 (2018)

Updates and corrections: <http://www.costfp1404.ethz.ch/publications>.

This publication was created in WG 2 and can be considered as state of the art document. The information in the book was carefully selected-by experts from general technical knowledge, standards, most recent research results and building practice. The author(s), the editor(s) and publisher disclaim any liability in connection with the use of this information.

Neither the COST Association nor any person acting on its behalf is responsible for the use of the information contained in this publication. The COST Association is not responsible for the external websites or other references referred to in this publication.

No permission to reproduce or utilise the contents of this publication by any means is necessary, other than in case of images, diagrams or other material from the copyright holders. In such cases, permission of the copyright holder(s) is required.

# Table of Contents

1. COST FP1404.....	8
2. Introduction.....	10
3. The Component Additive Method for the separating function.....	11
3.1 Protection time.....	13
3.2 Insulation time .....	20
3.3 Position coefficients.....	22
3.4 Joint factors .....	24
3.5 Correction times .....	24
3.6 Implementation of new materials.....	28
4. Design model for the load-bearing capacity .....	39
4.1 Effective Cross-Section Method .....	39
4.2 Charring of CLT members .....	40
Important note:.....	48
4.3 Gaps widths between narrow faces of CLT laminations .....	49
Introduction .....	49
Literature review .....	50
Measurement of gap width.....	51
Data analysis .....	52
Conclusions .....	54
4.4 Protected members .....	55

Fall-off time of wood-based boards .....	56
Fall-off times of Gypsum boards.....	56
4.5 Zero-strength layers .....	58
5. Adhesive testing for the use in CLT .....	61
Europe .....	61
North America .....	64
Japan .....	66
Australia and New Zealand .....	67
International Organisation for Standardisation (ISO) .....	67
6. Reaction to fire .....	74
This chapter was published in Östman et al. (2018).....	74
Harmonisation of classification systems for Reaction to fire performance of building products .....	74
Reaction to fire performance of wood products.....	76
Fire retardant treatments for wood products .....	76
7. Fire stops and penetration – best practise and detailing .....	78
General .....	78
Field of application .....	78
Penetrations.....	79
Electrical installations.....	82
In plane joints.....	84
Corner connections of.....	85
8. Contribution to fire development.....	88
9. References .....	93



# 1. COST FP1404

Bio-based building products have a very long history, e.g. as timber structural members. However, due to its combustibility and several large fires in cities with timber buildings timber as a structural material was banned for many years. When performance-based design (PBD) was introduced and implemented in many building regulations, the market for timber structures opened again; and with it came the development of other bio-based building products. Large differences between regulations in various countries exist, and the use of combustible building products is still very 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 building 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 has to 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 techniques 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 vary, this has been confirmed in many projects, also European.

The 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. The Task Group TG1 deals with fire design of cross-laminated timber. This document was created with the help of TG1 members and contains nowadays state-of-the-art knowledge on the fire design of cross-laminated timber in Europe.

Contributions to this guidance document were provided by both industry representatives and universities. The following persons provided considerable input to this document (alphabetical order): Bas Boellard, Daniel Brandon, Ronny Bredesen, Reto Fahrni, Andreas Golger, Ulrich Hübner, Alar Just, Michael Klippel (leader of TG1), Harald Krenn, Katrin Nele Mäger, Joachim Schmid, Tim Sleik, Gernot Standfest, Gordian Stapf, Mattia Tiso, Norman Werther, .

## 2. Introduction

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(2004) was published in 2004 and is now under revision. Fire design of CLT structures is not included in the current version of EN 1995-1-2 (2004).

In 2010, the European technical guideline *Fire Safety in Timber Buildings* (Östman et al, 2010) was published. The guideline consists of new and updated design models for the separating elements and effective cross-section design for timber construction in fire including cross laminated timber.

This guidance document provides the outcome of the research performed within the WG2 of the COST action FP1404, including specific guidelines for the fire design of cross laminated timber 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**

Chapter 3 was written by Katrin Nele Mäger (TU Tallinn) and Alar Just (TU Tallinn).

The Component Additive Method (CAM), as developed by Schleifer (2009), 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 (EN 13501-2), 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, K<sub>1</sub>10 and K<sub>2</sub>10, according to EN 13501-2, 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 ).

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

where

$\sum t_{prot,i}$  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 formulas for 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.

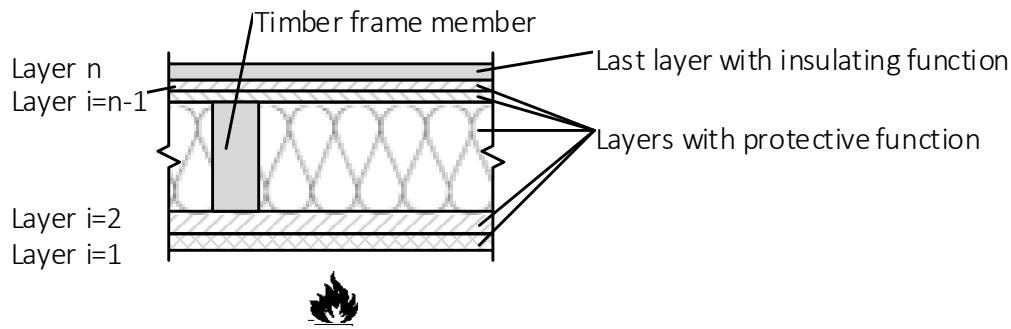


Figure 1 – Numbering and function of the layers in a timber frame assembly

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  $\Delta t$  (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 Table 2. Position coefficients for the exposed side

Material	Position coefficient $k_{pos,exp,i}$	
Cladding (gypsum, timber)*	$1 - 0,6 \cdot \frac{\sum t_{prot,i-1}}{t_{prot,0,i}}$	for $\sum t_{prot,i-1} \leq \frac{t_{prot,0,i}}{2}$
Stone wool insulation	$0,5 \cdot \sqrt{\frac{t_{prot,0,i}}{\sum t_{prot,i-1}}}$	for $\sum t_{prot,i-1} > \frac{t_{prot,0,i}}{2}$
Wood fibre cavity insulation	$1 - 0,9 \cdot \frac{\sum t_{prot,i-1}}{t_{prot,0,i}}$ $0,2 \cdot \frac{t_{prot,0,i}}{\sum t_{prot,i-1}} - 0,03 \cdot \frac{\sum t_{prot,i-1}}{t_{prot,0,i}} + 0,2$	for $\sum t_{prot,i-1} \leq \frac{t_{prot,0,i}}{2}$ for $\sum t_{prot,i-1} > \frac{t_{prot,0,i}}{2}$
Wood fibre insulation boards	$1 - \frac{\sum t_{prot,i-1}}{t_{prot,0,i}}$ $0,28 \cdot \left[ \frac{t_{prot,0,i}}{\sum t_{prot,i-1}} \right]^{0,9}$	for $\sum t_{prot,i-1} \leq \frac{t_{prot,0,i}}{2}$ for $\sum t_{prot,i-1} > \frac{t_{prot,0,i}}{2}$
Cellulose fibre insulation	$1 - \frac{\sum t_{prot,i-1}}{t_{prot,0,i}}$ $0,27 \cdot \left[ \frac{t_{prot,0,i}}{\sum t_{prot,i-1}} \right]^{1,1}$	for $\sum t_{prot,i-1} \leq \frac{t_{prot,0,i}}{2}$ for $\sum t_{prot,i-1} > \frac{t_{prot,0,i}}{2}$

Glass wool insulation	$1 - 0,8 \cdot \frac{\sum t_{\text{prot},i-1}}{t_{\text{prot},0,i}}$	for $\sum t_{\text{prot},i-1} \leq \frac{t_{\text{prot},0,i}}{4}$
for $h_i \geq 40$ mm	$(0,001 \cdot \rho_i + 0,27) \cdot \left[ \frac{t_{\text{prot},0,i}}{\sum t_{\text{prot},i-1}} \right]^{(0,75 - 0,002 \cdot \rho_i)}$	for $\sum t_{\text{prot},i-1} > \frac{t_{\text{prot},0,i}}{4}$

Where  $\rho_i$ : Density of the considered layer [kg/m<sup>3</sup>]

\*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.

);

$k_{\text{pos,unexp},i}$  is the position coefficient that takes into account the influence of layers backing the layer considered (see Table 3);

$\Delta t_i$  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 3. For joint coefficients see Table 4. Correction times are presented in clause 3.5.

Some specific rules apply to wood-based claddings and insulation materials as described in the following.

#### *Wood-based claddings*

The basic protection times of wood-based claddings should be compared with the corrected charring rates  $\beta_{0,\rho,h}$ , 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

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

$$k_h = \max \left\{ \sqrt{\frac{20}{h_p}}, 1 \right\} \quad (6)$$

where

$\beta_{0,p,h}$  is the corrected charring rate [mm/min];

$\beta_0$  is the one-dimensional charring rate [mm/min];

$k_p$  is the density coefficient [-];

$k_h$  is the panel thickness coefficient [-];

$\rho_k$  is the characteristic density [kg/m<sup>3</sup>];

$h_p$  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.

If there is no risk for fall-off of charred layer due to bondline failure, then the whole CLT cross-section should be considered as 1 layer in the calculations.

$$t_{\text{prot},i} \leq \frac{h_i}{\beta_n} \quad (7)$$

where

$\beta_n$  is the notional charring rate [mm/min];

$h_i$  is the thickness of the CLT layer  $i$  [mm].

For  $\beta_n$  see Chapter 4.



If there is a risk for fall-off of charred layer due to bondline failure then each lamella in the CLT cross-section should be considered as a separate layer in the calculations.

Separating function of the CLT element without the risk of fall-off of charred layer due to bondline failure should be calculated as one solid layer. Separating function of the CLT element with the risk of fall-off of charred layer due to bondline failure should be calculated summarizing protection times of each lamella.

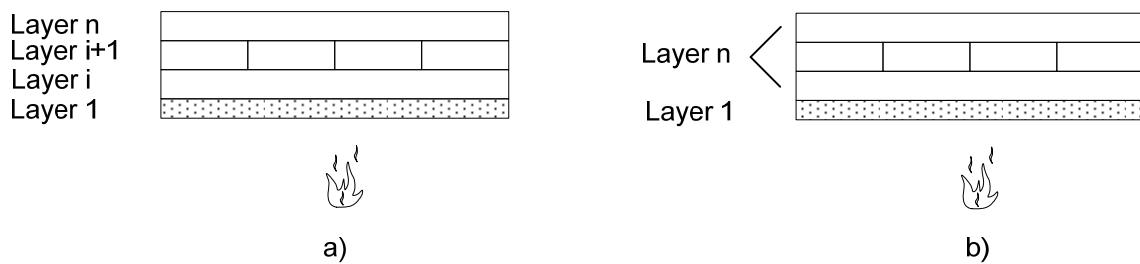


Figure 2 – Layers considered when calculating separating function of CLT with a) with risk of fall-off of charred layer due to bondline failure; b) without risk of fall-off of charred layer due to bondline failure

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 $40 \leq h_i \leq 240 \text{ mm}$ : $0,56h_i - 22$
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]  
 $\rho_i$ : Density of the considered layer [ $\text{kg/m}^3$ ]  
 $\beta_0$ : One-dimensional charring rate [mm/min]  
 $\beta_{0,p,h}$ : 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 (Tiso, 2017).

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 ( 8 ) or ( 9 ).

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

or

$$\sum_{k=1}^i t_{\text{prot},k} \leq \frac{h_i}{0,11 \cdot \sum t_{\text{prot},i-1} + 1,3} + \sum t_{\text{prot},i-1} \text{ if } \sum t_{\text{prot},i-1} > t_f \quad (9)$$

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 ( 10 ) or ( 11 ).

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

or

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

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 or FRC system [min] (See Clause 4.4);  
 $v_{\text{rec}}$  is the recession speed of the insulation [mm/min];  
 $\sum t_{\text{prot},i-1}$  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 ( 12 ).

$$t_{\text{prot},i}=0 \quad ( 12 )$$

### 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 ( 13 ).

$$t_{ins,n} = (t_{ins,0,n} \cdot k_{pos,exp,n} + \Delta t_n) \cdot k_{j,n} \quad ( 13 )$$

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;

$\Delta t_n$  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 layers. Generic values of the basic insulation times are given in Table 1, for position coefficients see Table 2. Position coefficients for the exposed side*

Material	Position coefficient $k_{pos,exp,i}$	
Cladding (gypsum, timber)*	$1 - 0,6 \cdot \frac{\sum t_{prot,i-1}}{t_{prot,0,i}}$	for $\sum t_{prot,i-1} \leq \frac{t_{prot,0,i}}{2}$
Stone wool insulation	$0,5 \cdot \sqrt{\frac{t_{prot,0,i}}{\sum t_{prot,i-1}}}$	for $\sum t_{prot,i-1} > \frac{t_{prot,0,i}}{2}$

Wood fibre cavity insulation	$1 - 0,9 \cdot \frac{\sum t_{\text{prot},i-1}}{t_{\text{prot},0,i}}$ $0,2 \cdot \frac{t_{\text{prot},0,i}}{\sum t_{\text{prot},i-1}} - 0,03 \cdot \frac{\sum t_{\text{prot},i-1}}{t_{\text{prot},0,i}} + 0,2$	for $\sum t_{\text{prot},i-1} \leq \frac{t_{\text{prot},0,i}}{2}$ for $\sum t_{\text{prot},i-1} > \frac{t_{\text{prot},0,i}}{2}$
Wood fibre insulation boards	$1 - \frac{\sum t_{\text{prot},i-1}}{t_{\text{prot},0,i}}$ $0,28 \cdot \left[ \frac{t_{\text{prot},0,i}}{\sum t_{\text{prot},i-1}} \right]^{0,9}$	for $\sum t_{\text{prot},i-1} \leq \frac{t_{\text{prot},0,i}}{2}$ for $\sum t_{\text{prot},i-1} > \frac{t_{\text{prot},0,i}}{2}$
Cellulose fibre insulation	$1 - \frac{\sum t_{\text{prot},i-1}}{t_{\text{prot},0,i}}$ $0,27 \cdot \left[ \frac{t_{\text{prot},0,i}}{\sum t_{\text{prot},i-1}} \right]^{1,1}$	for $\sum t_{\text{prot},i-1} \leq \frac{t_{\text{prot},0,i}}{2}$ for $\sum t_{\text{prot},i-1} > \frac{t_{\text{prot},0,i}}{2}$
Glass wool insulation  for $h_i \geq 40$ mm	$1 - 0,8 \cdot \frac{\sum t_{\text{prot},i-1}}{t_{\text{prot},0,i}}$ $(0,001 \cdot \rho_i + 0,27) \cdot \left[ \frac{t_{\text{prot},0,i}}{\sum t_{\text{prot},i-1}} \right]^{(0,75 - 0,002 \cdot \rho_i)}$	for $\sum t_{\text{prot},i-1} \leq \frac{t_{\text{prot},0,i}}{4}$ for $\sum t_{\text{prot},i-1} > \frac{t_{\text{prot},0,i}}{4}$

Where  $\rho_i$ : Density of the considered layer [kg/m<sup>3</sup>]

\*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.

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)*	$1 - 0,6 \cdot \frac{\sum t_{\text{prot},i-1}}{t_{\text{prot},0,i}}$	for	$\sum t_{\text{prot},i-1} \leq \frac{t_{\text{prot},0,i}}{2}$
Stone wool insulation	$0,5 \cdot \sqrt{\frac{t_{\text{prot},0,i}}{\sum t_{\text{prot},i-1}}}$	for	$\sum t_{\text{prot},i-1} > \frac{t_{\text{prot},0,i}}{2}$
Wood fibre cavity insulation	$1 - 0,9 \cdot \frac{\sum t_{\text{prot},i-1}}{t_{\text{prot},0,i}}$ $0,2 \cdot \frac{t_{\text{prot},0,i}}{\sum t_{\text{prot},i-1}} - 0,03 \cdot \frac{\sum t_{\text{prot},i-1}}{t_{\text{prot},0,i}} + 0,2$	for	$\sum t_{\text{prot},i-1} \leq \frac{t_{\text{prot},0,i}}{2}$ for
Wood fibre insulation boards	$1 - \frac{\sum t_{\text{prot},i-1}}{t_{\text{prot},0,i}}$ $0,28 \cdot \left[ \frac{t_{\text{prot},0,i}}{\sum t_{\text{prot},i-1}} \right]^{0,9}$	for	$\sum t_{\text{prot},i-1} \leq \frac{t_{\text{prot},0,i}}{2}$ for
Cellulose fibre insulation	$1 - \frac{\sum t_{\text{prot},i-1}}{t_{\text{prot},0,i}}$ $0,27 \cdot \left[ \frac{t_{\text{prot},0,i}}{\sum t_{\text{prot},i-1}} \right]^{1,1}$	for	$\sum t_{\text{prot},i-1} \leq \frac{t_{\text{prot},0,i}}{2}$ for

Glass wool insulation	$1 - 0,8 \cdot \frac{\sum t_{\text{prot},i-1}}{t_{\text{prot},0,i}}$	for $\sum t_{\text{prot},i-1} \leq \frac{t_{\text{prot},0,i}}{4}$
for $h_i \geq 40$ mm	$(0,001 \cdot \rho_i + 0,27) \cdot \left[ \frac{t_{\text{prot},0,i}}{\sum t_{\text{prot},i-1}} \right]^{(0,75 - 0,002 \cdot \rho_i)}$	for $\sum t_{\text{prot},i-1} > \frac{t_{\text{prot},0,i}}{4}$

Where  $\rho_i$ : Density of the considered layer [kg/m<sup>3</sup>]

\*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.

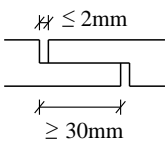
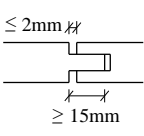
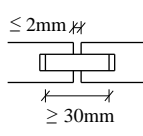
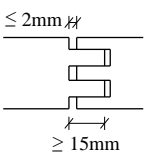
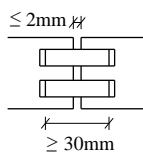
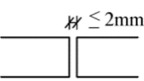
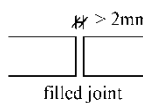
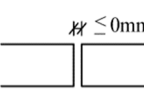
**Table 3. Position coefficients for the unexposed side**

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]  
 $\rho_i$ : Density of the considered layer [kg/m<sup>3</sup>]

### 3.4 Joint factors

Table 4. Joint factors

Material	Joint type	$k_{j,i}$	
		Layer backed by a void cavity ( $\geq 45$ 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  $\Delta t$  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 4.4. 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 ( 14 ):

$$t_{prot,max,i} = \frac{t_{prot,0,i}}{k_2} \quad ( 14 )$$

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 3 and is described by equations ( 15 ) to ( 20 ).

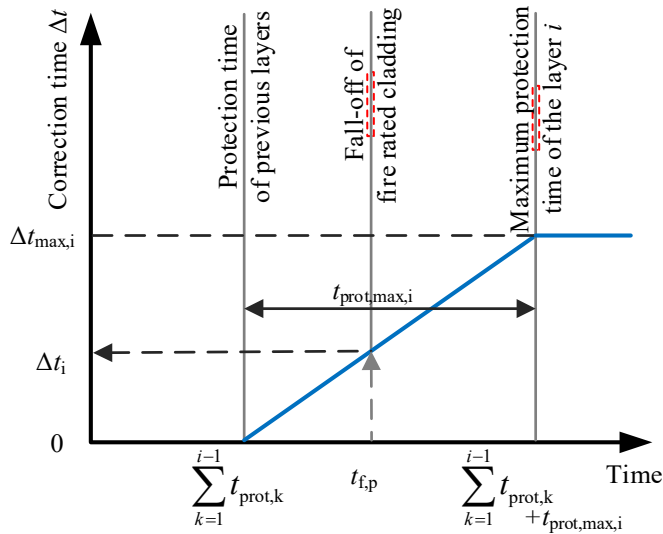


Figure 3 – Limits of the correction time

The indices used in Figure 3 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 3):

- When the fall-off time of the cladding or cladding system  $t_{f,p}$  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.

$$t_{f,p} \leq \sum_{k=1}^{i-1} t_{prot,k}, \quad \Delta t_i = 0 \quad (15)$$

or

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

- 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  $t_{prot,p}$ ) and the maximum protection time of the investigated layer  $i$ , then the maximum correction time for layer  $i$  is applied.

$$t_{f,p} \geq \sum_{k=1}^{i-1} t_{\text{prot},k} + t_{\text{prot,max},i}, \Delta t_i = \Delta t_{\text{max},i} \quad (16)$$

or

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

The maximum correction time that can be considered is expressed as

$$\Delta t_{\text{max},i} = t_{\text{prot,max},i} - t_{p,i} \quad (17)$$

or

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

where

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

$t_{p,n}$  is the insulation time of the investigated layer without correction time (equation ( 19 )) [min].

$$t_{p,i} = t_{\text{prot},0,i} \cdot k_{\text{pos,exp},i} \cdot k_{\text{pos,unexp},i} \cdot k_{j,i} \quad (18)$$

$$t_{p,n} = t_{\text{ins},0,n} \cdot k_{\text{pos,exp},n} \cdot k_{j,n} \quad (19)$$

- 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 ( 20 ).

$$\sum_{k=1}^{i-1} t_{\text{prot},k} < t_{f,p} < \sum_{k=1}^{i-1} t_{\text{prot},k} + t_{\text{prot,max},i}, \Delta t_i = \frac{(t_{f,p} - \sum_{k=1}^{i-1} t_{\text{prot},k}) \cdot \Delta t_{\text{max},i}}{t_{\text{prot,max},i}} \quad (20)$$

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  $\Delta t$  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,  $\Delta t$ , 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.

### **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 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 detail by Mäger et al (207) and in COST Guidance Document N-228-07.

### 3.7 Worked example for wall elements

Example calculations of the fire separating function of typical protected and unprotected CLT wall structures according to the component additive method

Example structures

1. 3-layer CLT 20+20+20
  - a. Unprotected
  - b. Protected by 12.5mm type A gypsum plasterboard
  - c. Protected by 15mm type F gypsum plasterboard
2. 3-layer CLT 40+40+40
  - a. Unprotected
  - b. Protected by 12.5mm type A gypsum plasterboard
  - c. Protected by 15mm type F gypsum plasterboard
3. 5-layer CLT 40+20+40+20+40
  - a. Unprotected
  - b. Protected by 12.5mm type A gypsum plasterboard
  - c. Protected by 15mm type F gypsum plasterboard

Calculation examples

#### **1.a. Unprotected 3-layer CLT 20+20+20**

Layer i=1: Solid wood

Basic protection time is dependent on the material and thickness of the considered layer:

$$t_{prot,0,1} = 30 \cdot \left(\frac{h_1}{20}\right)^{1,1} = 30 \cdot \left(\frac{20}{20}\right)^{1,1} = 30 \text{ min} \leq \frac{h_1}{\beta_0} = \frac{20}{0,65} = 30,8$$

Position coefficient for effect of exposed side depends on the protection ability of the preceding layers. Currently the considered layer is the first layer, therefore, the position coefficient is equal to 1:

$$k_{pos,exp,1} = 1$$

Position coefficient for effect of unexposed side depends on the type of material on the unexposed side of the considered layer. Two types are identified – solid (cladding,

boards, timber, gypsum) and insulation (stone or glass wool). If the backing material is a solid, the position coefficient for the unexposed side equals 1:

$$k_{pos,unexp,1} = 1$$

Correction time  $\Delta t_i = 0$  because no fire rated claddings are applied.

Joint coefficient

$$k_{j,1} = 1$$

Protection time of layer 1

$$t_{prot,1} = (t_{prot,0,1} \cdot k_{pos,exp,1} \cdot k_{pos,unexp,1} + \Delta t_1) \cdot k_{j,1} = 30 \text{ min}$$

Layer i=2: Solid wood

Basic protection time

$$t_{prot,0,2} = 30 \cdot \left(\frac{h_2}{20}\right)^{1,1} = 30 \text{ min} \leq \frac{h_2}{\beta_0}$$

Position coefficient for effect of exposed side (dependent on the preceding layers)

$$k_{pos,exp,2} = 0,5 \cdot \sqrt{\frac{t_{prot,0,2}}{t_{prot,1}}} = 0,5 \cdot \sqrt{\frac{30}{30}} = 0,5$$

Position coefficient for effect of unexposed side

$$k_{pos,unexp,2} = 1$$

Joint coefficient

$$k_{j,2} = 1$$

Protection time of layer 2

$$t_{prot,2} = (t_{prot,0,2} \cdot k_{pos,exp,2} \cdot k_{pos,unexp,2} + \Delta t_2) \cdot k_{j,2} = 15 \text{ min}$$

Sum of protection times

$$\sum t_{prot,2} = 45 \text{ min}$$

Layer n=3: Solid wood

The last layer has an insulating function, meaning the insulation criteria apply to it.

Basic insulation time

$$t_{ins,0,3} = 19 \cdot \left(\frac{h_3}{20}\right)^{1,4} = 19 \text{ min}$$

Position coefficient for effect of exposed side (dependent on the preceding layers)

$$k_{pos,exp,3} = 0,5 \cdot \sqrt{\frac{t_{ins,0,3}}{\sum t_{prot,i-1}}} = 0,5 \cdot \sqrt{\frac{19}{45}} = 0,32$$

Joint coefficient

$$k_{j,3} = 1$$

Insulation time of layer 3

$$t_{ins,3} = (t_{ins,0,3} \cdot k_{pos,exp,3} + \Delta t_3) \cdot k_{j,3} = 6,2 \text{ min}$$

Total insulation time of the structure

$$t_{ins} = \sum t_{prot,2} + t_{ins,3} = 51,2 \text{ min}$$

**1.b. Protected by GtA 12,5mm, 3-layer CLT 20+20+20**

Material	Layer, thickness	$t_{prot,0,i}$	$k_{pos,exp,i}$	$k_{pos,unexp,i}$	$\Delta t_i$	$k_{j,i}$	$t_{prot,i}$	$\sum t_{prot}$
----------	---------------------	----------------	-----------------	-------------------	--------------	-----------	--------------	-----------------

		$t_{ins,0,n}$	$k_{pos,exp,n}$		$\Delta t_n$	$k_{j,i}$	$t_{ins,n}$	$t_{ins}$
	[mm]	[min]	[-]	[-]	[min]	[-]	[min]	[min]
GtA	12,5	24,1	1	1	0	1	24,1	24,1
Solid wood	20	30	0,56	1	0	1	16,7	40,8
Solid wood	20	30	0,43	1	0	1	12,9	53,7
Solid wood	20	19	0,34		0	1	6,5	60,2

### **1.c. Protected by GtF 15mm, 3-layer CLT 20+20+20**

Material	Layer, thickness	$t_{prot,0,i}$	$k_{pos,exp,i}$	$k_{pos,unexp,i}$	$\Delta t_i$	$k_{j,i}$	$t_{prot,i}$	$\sum t_{prot}$
		$t_{ins,0,n}$	$k_{pos,exp,n}$		$\Delta t_n$	$k_{j,i}$	$t_{ins,n}$	$t_{ins}$
	[mm]	[min]	[-]	[-]	[min]	[-]	[min]	[min]
GtF	15	30	1	1	0	1	30	30
Solid wood	20	30	0,5	1	8,6	1	23,6	53,6
Solid wood	20	30	0,37	1	0	1	11,2	64,8
Solid wood	20	19	0,3		0	1	5,7	70,5



Layer 2 is protected by a fire rated cladding (FRC), therefore, a correction time must be added to the protection time of layer 2 to consider the additional protection offered by the FRC.

For gypsum plasterboards type F used in one layer, the protection coefficient is:

$$k_2 = 1 - 0,018 \cdot h_p = 0,73$$

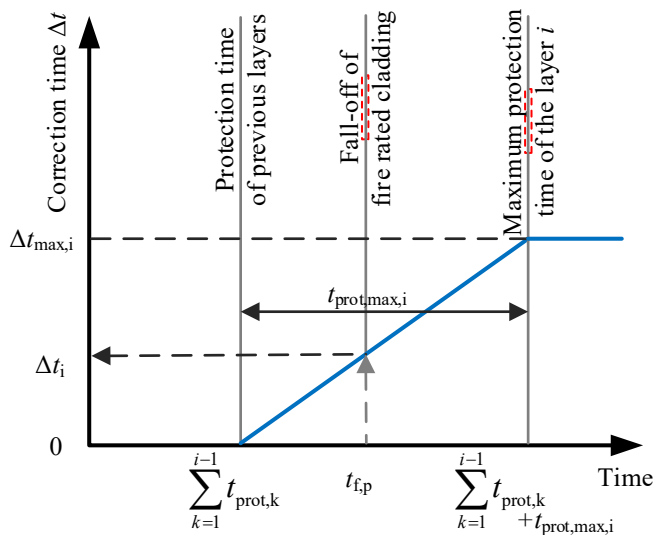
Maximum protection time of layer 2 depends on the basic protection time of the considered layer and the protection coefficient of the FRC.

$$t_{prot,max,2} = \frac{t_{prot,0,2}}{k_2} = \frac{30}{0,73} = 41,1 \text{ min}$$

Fall-off time of the FRC is taken according to FSITB:

$$t_{f,p} = 4,5 \cdot h_p - 24 = 43,5 \text{ min}$$

The fall-off time is in the linear interpolation range:



$$t_{f,p} = 43,5 < \sum_{k=1}^1 t_{prot,k} + t_{prot,max,i} = 71,1$$

Maximum correction time of layer 2

$$\Delta t_{max,2} = t_{prot,max,2} - t_{prot,0,2} \cdot k_{pos,exp,2} \cdot k_{pos,unexp,2} \cdot k_{j,2} = 26,1 \text{ min}$$

Therefore, the correction time is equal to:

$$\Delta t_2 = \frac{(t_{f,p} - \sum_{k=1}^1 t_{prot,k}) \cdot \Delta t_{max,2}}{t_{prot,max,2}} = \frac{(43,5 - 30) \cdot 26,1}{41,1} = 8,6 \text{ min}$$

### **2.a. Unprotected 3-layer CLT 40+40+40**

Material	Layer, thickness	$t_{prot,0,i}$	$k_{pos,exp,i}$	$k_{pos,unexp,i}$	$\Delta t_i$	$k_{j,i}$	$t_{prot,i}$	$\sum t_{prot}$
		$t_{ins,0,n}$	$k_{pos,exp,n}$		$\Delta t_n$	$k_{j,i}$	$t_{ins,n}$	$t_{ins}$
	[mm]	[min]	[-]	[-]	[min]	[-]	[min]	[min]
Solid wood	40	61,5	1	1	0	1	61,5	61,5
Solid wood	40	61,5	0,5	1	0	1	30,8	92,3
Solid wood	40	50,1	0,37		0	1	18,5	110,8

### **2.b. Protected by GtA 12,5mm, 3-layer CLT 40+40+40**

Material	Layer, thickness	$t_{prot,0,i}$	$k_{pos,exp,i}$	$k_{pos,unexp,i}$	$\Delta t_i$	$k_{j,i}$	$t_{prot,i}$	$\sum t_{prot}$
		$t_{ins,0,n}$	$k_{pos,exp,n}$		$\Delta t_n$	$k_{j,i}$	$t_{ins,n}$	$t_{ins}$

	[mm]	[min]	[-]	[-]	[min]	[-]	[min]	[min]
GtA	12,5	24,1	1	1	0	1	24,1	24,1
Solid wood	40	61,5	0,76	1	0	1	47,1	71,2
Solid wood	40	61,5	0,46	1	0	1	28,6	99,8
Solid wood	40	50,1	0,42		0	1	21,0	120,8

### **2.c. Protected by GtF 15mm, 3-layer CLT 40+40+40**

Material	Layer, thickness	$t_{prot,0,i}$	$k_{pos,exp,i}$	$k_{pos,unexp,i}$	$\Delta t_i$	$k_{j,i}$	$t_{prot,i}$	$\sum t_{prot}$
		$t_{ins,0,n}$	$k_{pos,exp,n}$		$\Delta t_n$	$k_{j,i}$	$t_{ins,n}$	$t_{ins}$
	[mm]	[min]	[-]	[-]	[min]	[-]	[min]	[min]
GtF	15	30	1	1	0	1	30	30
Solid wood	40	61,5	0,71	1	6,5	1	50,1	80,1
Solid wood	40	61,5	0,44	1	0	1	27,0	107,0
Solid wood	40	50,1	0,40		0	1	19,8	126,9

### **3.a. Unprotected 5-layer CLT 40+20+40+20+40**

Material	Layer, thickness	$t_{prot,0,i}$	$k_{pos,exp,i}$	$k_{pos,unexp,i}$	$\Delta t_i$	$k_{j,i}$	$t_{prot,i}$	$\Sigma t_{prot}$
		$t_{ins,0,n}$	$k_{pos,exp,n}$		$\Delta t_n$	$k_{j,i}$	$t_{ins,n}$	$t_{ins}$
	[mm]	[min]	[-]	[-]	[min]	[-]	[min]	[min]
Solid wood	40	61,5	1	1	0	1	61,5	61,5
Solid wood	20	30	0,35	1	0	1	10,5	72,0
Solid wood	40	61,5	0,46	1	0	1	28,4	100,5
Solid wood	20	30	0,27	1	0	1	8,2	108,7
Solid wood	40	50,1	0,34		0	1	17,0	125,7

### **3.b. Protected by GtA 12,5mm, 5-layer CLT 40+20+40+20+40**

Material	Layer, thickness	$t_{prot,0,i}$	$k_{pos,exp,i}$	$k_{pos,unexp,i}$	$\Delta t_i$	$k_{j,i}$	$t_{prot,i}$	$\Sigma t_{prot}$
		$t_{ins,0,n}$	$k_{pos,exp,n}$		$\Delta t_n$	$k_{j,i}$	$t_{ins,n}$	$t_{ins}$
	[mm]	[min]	[-]	[-]	[min]	[-]	[min]	[min]
GtA	12,5	24,1	1	1	0	1	24,1	24,1

Solid wood	40	61,5	0,76	1	0	1	47,1	71,2
Solid wood	20	30	0,32	1	0	1	9,7	80,9
Solid wood	40	61,5	0,44	1	0	1	26,8	107,8
Solid wood	20	30	0,26	1	0	1	7,9	115,7
Solid wood	40	50,1	0,33		0	1	16,5	132,2

### **3.c. Protected by GtF 15mm, 5-layer CLT 40+20+40+20+40**

Material	Layer, thickness	$t_{prot,0,i}$	$k_{pos,exp,i}$	$k_{pos,unexp,i}$	$\Delta t_i$	$k_{j,i}$	$t_{prot,i}$	$\sum t_{prot}$
		$t_{ins,0,n}$	$k_{pos,exp,n}$		$\Delta t_n$	$k_{j,i}$	$t_{ins,n}$	$t_{ins}$
	[mm]	[min]	[-]	[-]	[min]	[-]	[min]	[min]
GtF	15	30	1	1	0	1	30	30
Solid wood	40	61,5	0,71	1	6,5	1	50,1	80,1
Solid wood	20	30	0,31	1	0	1	9,2	89,2
Solid wood	40	61,5	0,42	1	0	1	25,6	114,8

Solid wood	20	30	0,26	1	0	1	7,7	122,5
Solid wood	40	50,1	0,32		0	1	16,0	138,5

## 4. Design model for the load-bearing capacity

Chapter 4 was written by Michael Klippel (ETH Zürich), Alar Just (TU Tallinn), if not differently indicated.

### 4.1 Effective Cross-Section Method

The effective cross-section method is used for the design of load-bearing structures.

The CLT cross-section is reduced by the effective charring depth and will not need a further reduction of strength.

The effective charring depth shall be calculated as

$$d_{\text{ef}} = d_{\text{char}} + d_0 \quad (21)$$

where

$d_{\text{ef}}$  is the effective charring depth [mm];

$d_{\text{char}}$  is the charring depth [mm];

$d_0$  is the zero-strength layer [mm].

Figure 4 shows the concept of the effective cross-section method for CLT. In general, the border of the residual cross-section can either end up in a transversal or in a longitudinal layer. This fact has to be considered in the fire design of such elements.

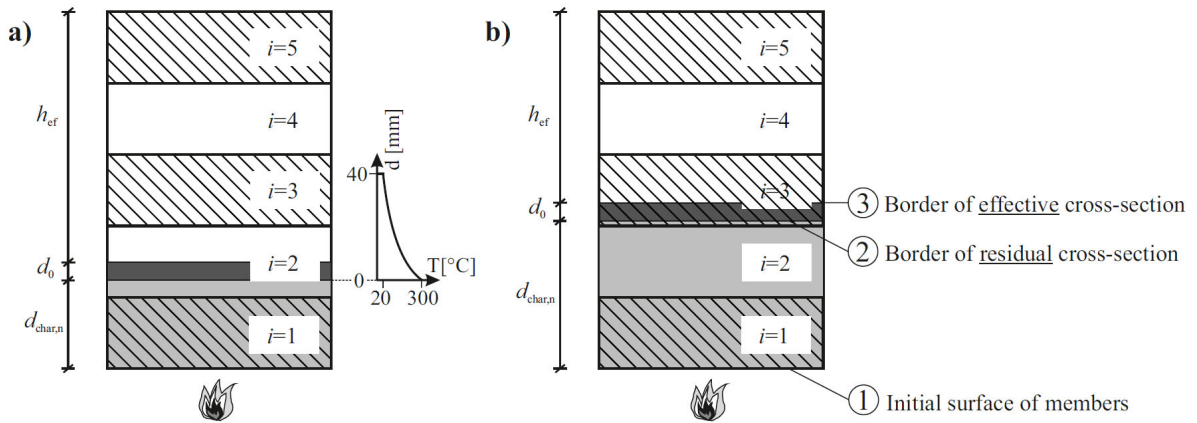


Figure 4 – Definition of residual cross-section and effective cross-section: layers with uneven numbers are load-bearing layers. (a):  $d_0$  layer is in cross-layer and thus non-load-bearing layer, (b):  $d_0$  is in load-bearing layer (according to Klippel and Schmid (2017))

### 4.2 Charring of CLT members

Charring depth is determined as

$$d_{char} = \sum \beta_n t_i \tag{22}$$

where

$\beta_n$  is the charring rate of the lamella or part of the lamella, see Figure 5 and

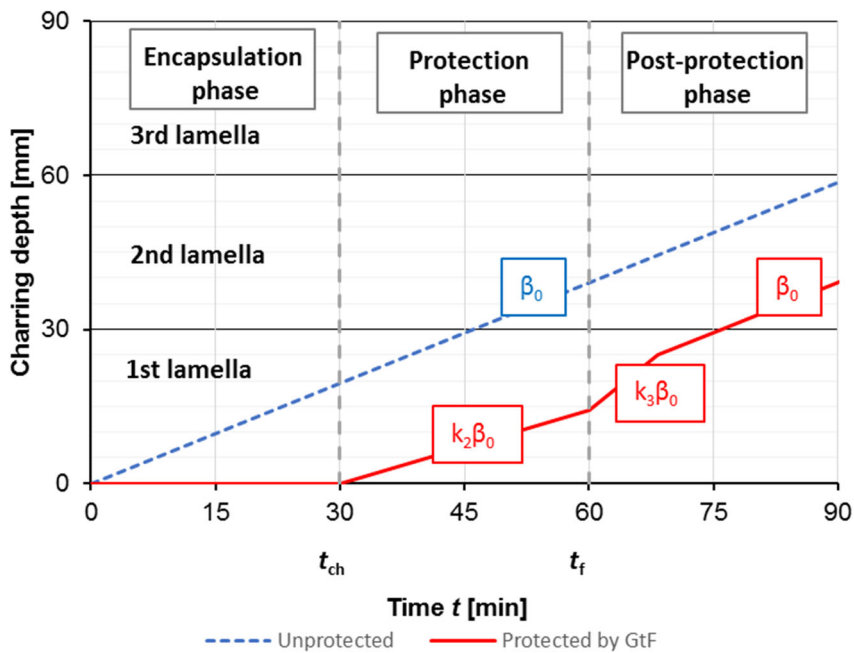




Figure 6;

$t_i$  is the charring time of the lamella or part of the lamella, see Figure 5 and Figure 6.

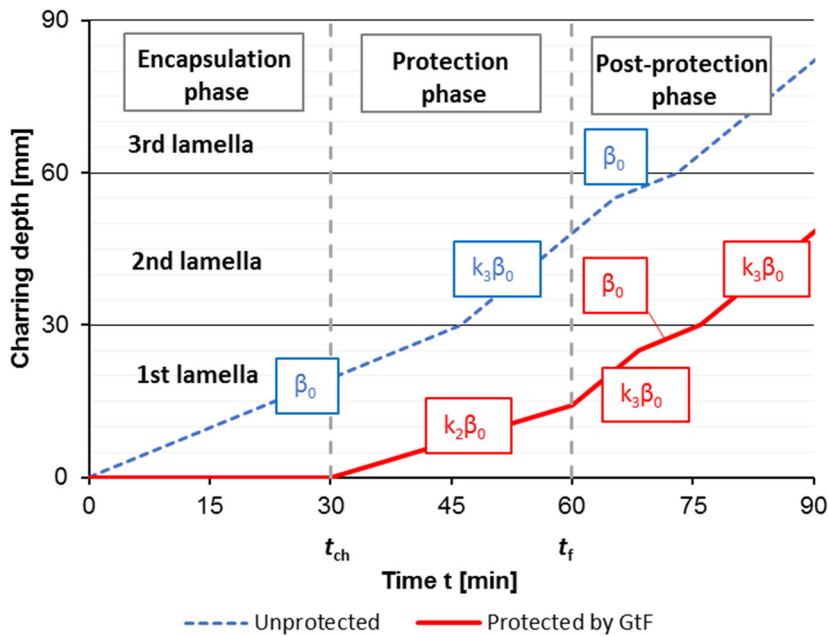


Figure 5 – Examples of charring scenarios for the protected and unprotected CLT members with risk of fall-off of charring layer.

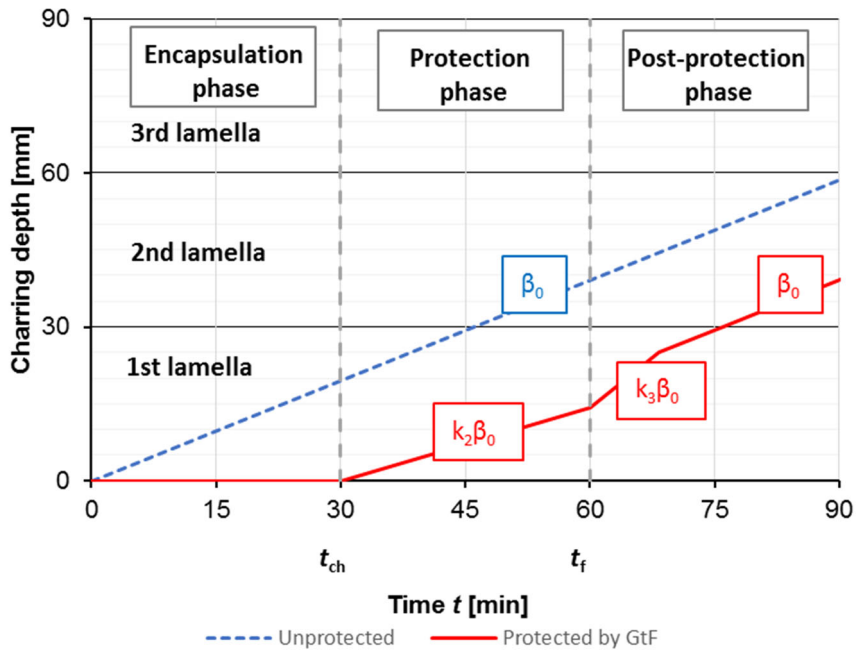


Figure 6 – Examples of charring scenarios for the protected and unprotected CLT members without risk of fall-off of charring layer.

The charring behaviour of CLT is different to charring of homogenous timber panels due to the layered, glued composition and joints between the timber boards that can lead locally to increased charring.

An enormous amount of fire tests on single CLT wall and floor elements have been performed in recent years. In these tests, the layer thickness, the number of plies, the type of adhesive, the type of encapsulation, and the support conditions have been investigated among other factors. Further, full-scale compartment fire tests and ad-hoc testing with a radiant heat panel have been performed to analyse protected and unprotected CLT elements. Based on the performed experimental investigations, the following conclusions can be drawn for the charring behaviour of CLT elements:

To determine the thickness of the char layer of floor elements, the following two boundary situations should be considered:

- If the individual charred layers of the CLT panel do not fall off (also referred to stickability, see standard series EN 13381, the forming charcoal layer protects the remaining CLT cross-section against heat. In this case, the CLT panel has a similar fire behaviour as solid wood.
- If local falling off of the char layer occurs (also referred to loss of stickability), the fire protective function of the charcoal is lost. After the charred layers have fallen off, an increased charring is expected due to the exposure of uncharred timber directly to the fire environment. This phenomenon is similar to the increased charring observed for protected timber surfaces after failure of the fire protective cladding, see Clause 4.4, and can be considered using a double charring rate for the second layer (and the subsequent layers) for the first 25 mm of depth when falling off of the first layer occurs.

Currently available fire resistance tests tend to show either of the two boundary conditions described above. Engineers in practise should be aware of the fire performance of the CLT product used.

For wall elements, the effect of falling off of charred layers was observed less pronounced in corresponding tests. However, load-bearing and unprotected wall elements should be carried out with at least five-layer CLT elements to ensure a robust solution (when the outer load-bearing layer is completely burned, there are still two load-bearing layers left in a cross-wise oriented CLT panel). Further, a minimum residual thickness of layers in span direction of 3 mm should be achieved. With regard to the fire resistance, a thicker outer layer (> 30 mm) is generally beneficial so that burn-through or a possible local falling off of charred layers occurs after about 45-60 minutes exposure to fire.

An increased charring due to the layered composition of CLT can be considered by using a greater notional charring rate  $\beta_n$  than the basic charring rate  $\beta_0$  for one-dimensional charring. The European technical guideline *Fire Safety in Timber Buildings* (Östman et al 2010) defines the relation between the basic design charring rate  $\beta_0$  and the notional charring rate  $\beta_n$  using coefficients  $k$ .

This basic design charring rate  $\beta_0$  differs for different products according to EN 1995-1-2. Increased charring due to corner roundings or gaps can be considered by multiplying the basic design charring rate with coefficients  $k_i$  that are greater than 1,0 to determine the notional charring rate  $\beta_n$ . Recently, a general charring model was proposed by Klippel et al (2016), which is very flexible and can easily be adapted and extended to calculate the char depth of any timber member exposed to fire. The description of this general charring model is shown in Equation ( 23 ).

$$\beta_n = \prod_{k_i} k_i \cdot \beta_0 \quad (23)$$

where

$\beta_n$  is the notional charring rate [mm/min];

$k_i$  are the coefficients influencing the charring rate [-], see ;

$\beta_0$  is the one-dimensional charring rate [mm/min].

**Table 5. Coefficients  $k$  to determine the notional charring rate  $\beta_n$**

Coefficient	Description	Explanation	Reference
$k_{pr}$	Protection coefficient	Coefficient addresses the behavior of protected timber surfaces, for which different charring rates should be applied during different phases of fire exposure.  $k_2$ is the protection coefficient for protection phase, $k_3$ is the protection factor for post-protection phase. See Figure 5 and Figure 6	Frangi and König (2005)
$k_n$	Corner rounding	Since charring is greater near <i>cross-section corners, gaps</i> and <i>fissures</i> , notional charring rates $\beta_n$ should be used to transform the irregular shape of residual cross-sections into	Olis (1968), König (1995)
$k_g$	Gaps between boards	simple rectangular cross-sections, or cross-sections composed of several rectangular parts.	Fornater et al. (2001)
$k_{cr}$	Cracks and char fissures		
$k_j$	Joint coefficient	Considers the influence of joints in panels not backed by battens or structural members or panels and their influence on the protection and insulation time of these layers. Usually, $k_j = 1.0$ for ultimate limit state design.	König and Walleij (1999)
$k_{co}$	Connection coefficient	Considers increased charring for connections with metal fasteners, which conduct heat into the core of the cross-section.	Erchinger (2009)

Equation ( 23 ) is a general expression to describe the notional charring rate  $\beta_n$  for a large range of timber products. This approach is based on a design charring rate  $\beta_0$  determined in fire resistance tests and specified in EN 1995-1-2. For a specific product most of the coefficients  $k_i$  are equal to 1,0, e.g. for CLT only four coefficients are used. In the design model deterministic values are used.

In case a CLT layer consists of boards bonded together along their edges or the gap width between two boards is not greater than 2 mm, the basic design charring rate  $\beta_0$

can be applied, meaning that the coefficient  $k_g = 1,0$ . In case the gap is between 2 mm and 6 mm wide, the basic design charring rate  $\beta_0$  should be multiplied by a coefficient  $k_g = 1,2$  to determine the notional charring rate. In case the gap width is greater than 6 mm, a fire exposure from three sides should be regarded in the calculation. It should also be noted that a load-bearing layer most likely has no gaps and thus  $k_g = 1,0$ .

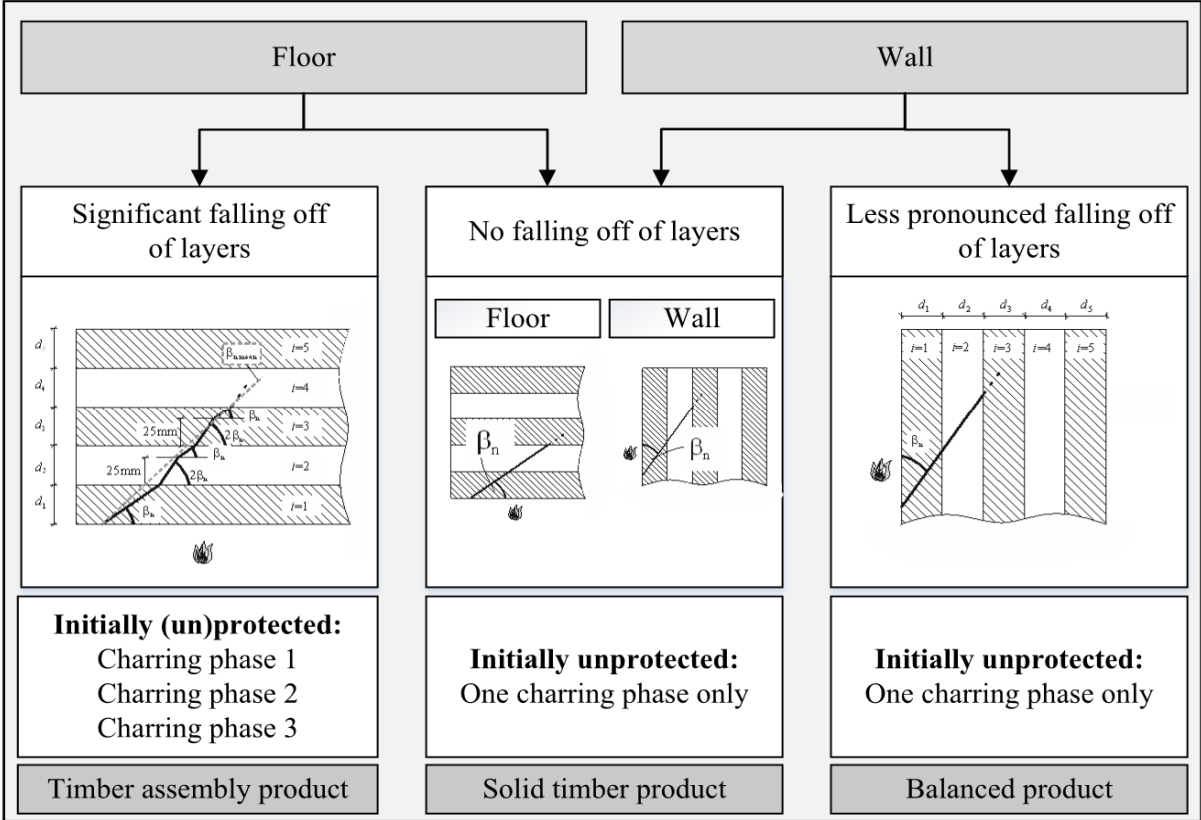


Figure 7. Charring rates for different CLT applications (without any fire protection layer) (according to Klippel and Schmid (2017))

The approach given the design guideline *Fire Safety in Timber Buildings* in Europe (Östman et al 2010) should further be extended in the future, as described in Equation ( 23 ). The determination of the notional charring rate  $\beta_n$  for a typical CLT product needs to consider the following two coefficients (the other coefficient  $k$  given in Table 5 are set to 1,0 for typical CLT products)

Whether falling off of charred layers occurs, depends on the adhesive in the glueline between the boards and the composition of the CLT element (number and thickness

of layers). For a fire resistance of 30 minutes there will be no influence of falling off of charred layers when the outer layer has a minimum depth of 25 mm, as only the first layer will be charred. For a fire rating of 60 and more minutes a clear difference in the residual cross-section is expected. However, it has to be noted that the fire resistance of a CLT element is not linearly related to the charring rate, as the charring of a perpendicular layer with low stiffness and strength properties, has nearly no effect on the overall load-carrying capacity.

Further, it should also be noted that examples for fire design of CLT floor elements used in practice showed that falling off of charred layers for common CLT panels and typical fire design situations has no influence on the design of the panel configuration (see Klippel et al. 2014). As a consequence, the fire design should not govern the design of a CLT element and thus no change of the layered structure is expected (regardless of the adhesive). The thickness and number of layers is rather given by the design at normal temperature, such as vibration, deflection, etc. and thus by the serviceability limit state (SLS).

When wood is exposed to real fires or exposed to controlled conditions represented by fire resistance tests, charring is subject to a variation. Charring models expect that the mean value is reported to assess the basic charring rate  $\beta_0$ . However, the determined values are rarely specified (Lange et al. 2015). In the following, the variation of this important value is investigated as CLT as a plane element offers an ideal possibility to investigate the distribution of charring as overlapping heat flow effects at edges of beams or columns do not exist.

In general, charring may be reported as a result measured after the fire test, here the time between termination and extinguishing of the fire has to be reduced to a minimum to minimize effects of uncontrolled charring in an undefined environment. Another possibility is to measure charring by means of thermocouples during the test and assess the charring rate by means of the 300°C isotherm. In many test reports, a mean value based on thermocouple readings is given. It should be highlighted that the arrangement of the wires or tubes to measure the temperature is crucial for the validity

of these measurements. As temperature measurements in low conductive material like wood are done with conductive metal temperature sensors, these shall be orientated parallel to the isotherms. Deviation may risk falsification of the temperature measurements.

Since the charring behaviour of CLT floor and wall elements is different if charring layer fall off, it is important to define limits for inclined elements. The Swiss Fire Safety regulations distinguish between floor and wall elements with a different in angle of 10°, as shown in Figure 8. The company KLH uses their charring model for floor elements for CLT elements with a slope between 0° and 75°.

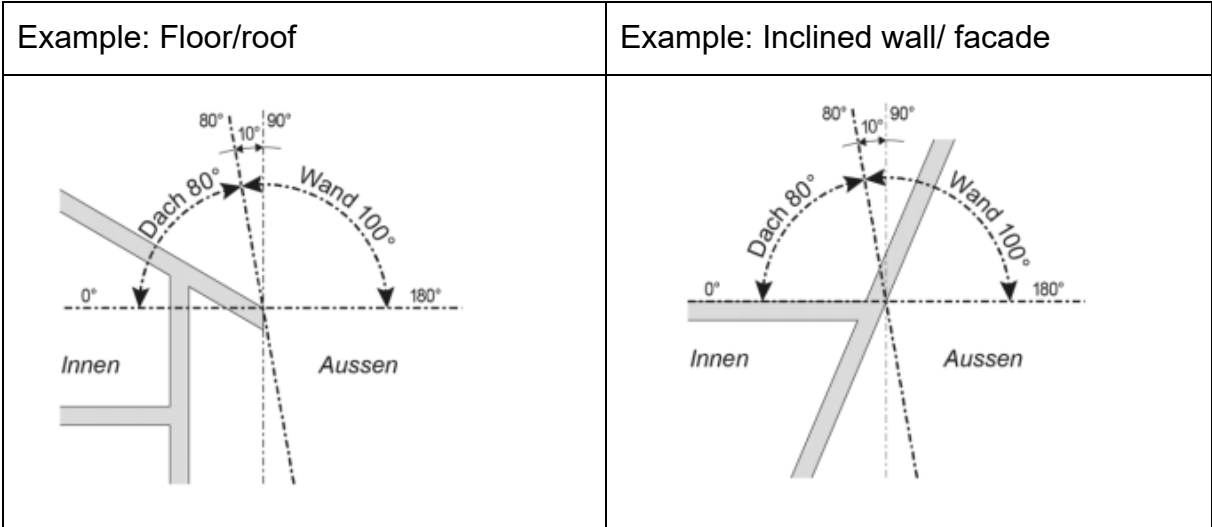


Figure 8 Definition of floor and wall elements according to Swiss fire safety regulations (use of materials, 14-15).

**Important note:**

It should be noted that the charring rate is the most important design variable for the verification of the fire resistance of timber members. The design charring rate is a property of the building material wood. This design charring rate is considered to be equal for all wood products when European wood species are used for construction products (typically made from softwood). In ETAs, the fire resistance of many CLT products is specified referring to a charring rate and a reference to EN 1995-1-2 (2004).



1. Some ETAs base on ad-hoc fire tests with CLT where the charring rate has been assessed based on the char depth measured after a time limited fire resistance test. Hereby, the charring depth in some cases did not reached the bondline and any failure of the bondline was not observed or excluded (e.g. only 30min fire tests have been performed with CLT members with exposed layer depth of > 20 mm). For the ETA, the results have been extrapolated to any time larger than tested. This error may lead to significant underestimated charring rates and may further prevent burn-out of the compartment.
2. The charring rate specified in ETAs appears often to be general and is misinterpreted as universal value, valid for (i) one dimensional charring and (ii) notional charring, i.e. also for initially protected members in the post-protection phase.

During the work of this TG, it was shown that some ETAs do have a significant limitation and can be considered as flawed, inconsistent ETAs. In general, it can be said that only one fire test is not sufficient to define a charring rate for the ETA of each CLT manufacturer. A customer based charring rate or charring model for the European market should not be applied since production and quality assurance is of such a high level that the charring performance should be similar. In the future EN 1995-1-2, it is expected that a design using certain components from other sources will be prohibited when Eurocode models should be applied. In the future, charring rates and models should be independent on the CLT manufacturer.

#### **4.3 Gaps widths between narrow faces of CLT laminations**

Author of this section: U. Hübner (Association of the Austrian Wood Industries)

##### **Introduction**

The gaps in CLT between narrow faces of laminations and the grooves influence the mechanical characteristics of CLT regarding shear strength but also the mechanical resistance of dowel type fasteners. Gaps are also important for building physics, e.g. air tightness, moisture transport and the charring of the layers in case of fire. ETAs for CLT and EN 16351 (2015) state different maximum gap widths of 3 to 6 mm but very

seldom how often a certain gap width below this upper limit will be exceeded. To enlighten the distribution of gap widths between narrow faces of laminations a measurement campaign was initiated whose results are presented in this section. The task group Fire behavior of CLT within COST Action FP1404 discussed new structural fire design models for unprotected walls and floors made of CLT and the basic design charring rate  $\beta_0$ . The results for gap width distribution will also support the discussion of structural fire design of CLT in the next Eurocode generation.

### **Literature review**

Blaß and Uibel (2006) published the mean, maximum and 95th percentile of 942 measurements of gap widths between adjacent laminations in four different layups (17-17-17-17, 19-22-19, 34-13-34-13-34, 9,5-6,8-9,5-6,8-9,5) from four CLT producers. The outermost layers showed smaller gap widths than the inner layers. The mean values varied between 0,5 ... 2,0 mm for inner and 0,0 ... 0,6 mm for outermost layers. The produced volume of CLT grew by the factor of five between 2006 and 2018 (Jauk and Ebner 2017) and most new production lines allow side pressure for longitudinal and transversal layers during bonding and decreased gap widths between adjacent laminations. On the other hand, layups with thickness of layers of 40 mm are usual today and up to 60 mm possible for middle layers according to EN 16351 (2015).

EN 16351 (2015) limits the maximum width of gaps between adjacent laminations within a timber layer to  $b_{\text{gap,max}} = 6$  mm. The current final draft of prEN 16351 (2018) defines CLT as a material with a mean gap width of  $b_{\text{gap,mean}} \leq 0,6$  mm and a 90th percentile of the gap of  $b_{\text{gap,90}} \leq 2$  mm.

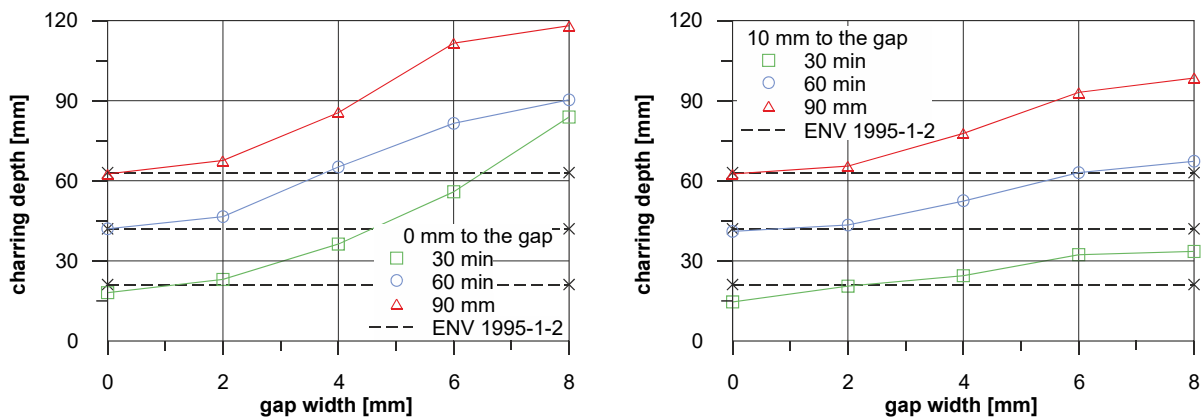


Figure 9. Charring of GLT for different gap widths: left direct next to the gap and right 10 mm beside the gap (Fornather et al. 2001)

Fornather et al. (2001) evaluated the influence of different gap widths (0, 2, 4, 6, 8, 12 and 22 mm) in 20 GLT specimens BS11 160×460×460 mm<sup>3</sup> exposed to the standard temperature-time curve according to ISO 834 after 30, 60 and 90 minutes. The bondlines between the laminations were horizontally and the gaps vertically orientated in the furnace. Large gaps allow hot gasses to heat the faces of the gap or groove and can lead to a faster charring of the layer. Figure 1 shows the charring for the different gap widths. The charring next to a gap with 2 mm width is similar to 0 mm but for gap widths equal to 4 mm and above the charring depth increases.

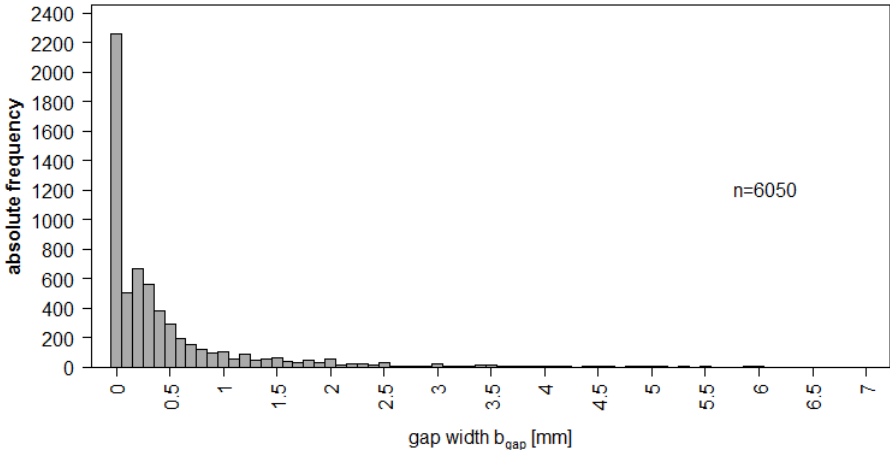
### Measurement of gap width

The Association of the Austrian Wood Industries asked European CLT producers to participate in a measurement campaign of gap widths between narrow faces of laminations. The goal was for every producer to take about 400 measurements to represent its different surface qualities, inner and outermost layers and some weeks of production. Eleven companies from Austria, France, Germany and Switzerland returned 6050 measurements in total. These are representative for 89 % of CLT production in Germany, Austria, Switzerland, the Czech Republic and Italy in 2016 (Jauk and Ebner 2017). In the header of the prepared measuring record there was a choice between three different surface qualities, inner and outermost layers. The company name, measurement device, week of production, name of the responsible

and date was noted. The measurement of each gap width was taken along a straight line with a magnifying glass (1/10 mm), a ruler or a sliding caliper.

**Data analysis**

The histogram (Figure 10) summarizes the measurements for each gap width step of 0,1 mm. 37 % of the gaps are closed and almost 88 % are smaller or equal to 1,0 mm. Statistically one gap within 5,1 m is equal or larger than 2 mm based on a mean board width of 192 mm which was calculated for one year of production of an Austrian CLT producer.



*Figure 10. Histogram for all measured gap widths*

The cumulative relative frequencies of all 6050 gap width measurements are shown in Figure 11 as a solid black line. The best quality outermost layers for visible apartment surfaces have thinner gaps due to thinner outermost layers and/or smaller widths of laminations (light gray). The inner layers have slightly wider gaps (dark gray).

The median of the gap width for all measurements is below 0,2 mm and the 90th percentile is equal to 1,2 mm for all measurements. The median of all inner layers is below 0,3 mm and the 90th percentile is equal to 1,5 mm for all inner layers. The mean gap width for all measurements is  $b_{gap,mean} = 0,43$  mm.

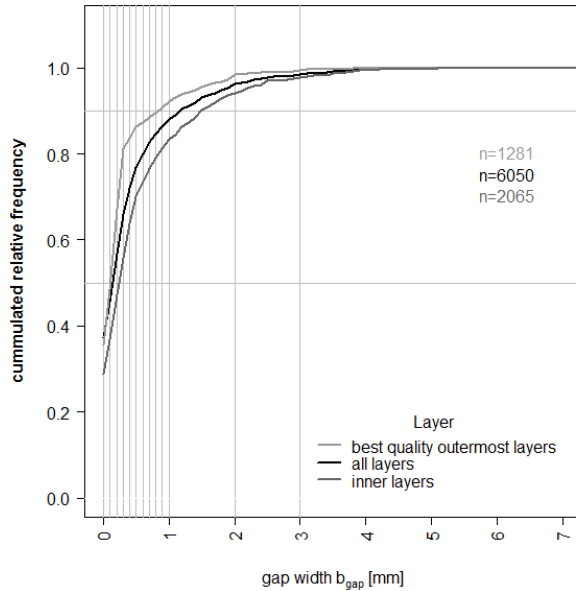
*Table 6: Number of measurements for each producer, surface quality and inner or outermost layer*

#	Producer	measuring record	Surface			Layer		Number of measurements
			superior	medium	industry	outermost	inner	

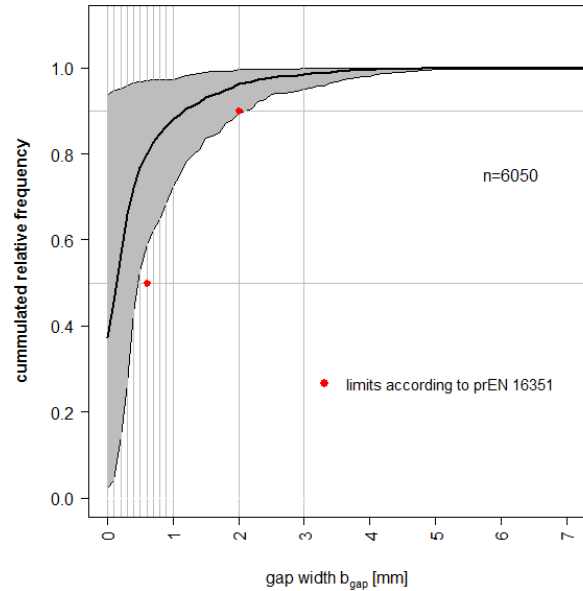
1	1	1						60
2	1	2	x	x		x	x	101
3	1	3			x	x		105
4	1	4	x			x		107
5	1	5	x			x		14
6	1	6	x			x		10
7	1	7			x	x		33
8	2	1	x				x	200
9	2	2	x			x		200
10	3	1			x	x		202
11	3	2	x			x		197
12	3	3			x	x		268
13	3	4			x		x	231
14	4	1	x			x		139
15	4	2		x		x		112
16	4	3			x		x	154
17	4	4			x	x		247
18	5	1			x	x		24
19	5	2			x		x	24
20	5	3			x	x		26
21	5	4			x		x	23
22	5	5			x	x		25
23	5	6			x		x	29
24	5	7			x	x		19
25	5	8			x		x	25
26	5	9			x	x		26
27	5	10			x		x	25
28	5	11			x	x		29
29	5	12			x		x	21
30	5	13			x	x		30
31	5	14			x		x	20
32	5	15			x	x		23
33	5	16			x		x	24
34	5	17		x		x		25
35	5	18		x			x	25
36	5	19		x		x		25
37	5	20		x			x	25
38	5	21		x		x		25
39	5	22		x			x	25
40	5	23		x		x		25
41	5	24		x			x	25
42	5	25		x		x		26
43	5	26		x			x	25
44	5	27		x		x		28
45	5	28		x			x	21
46	5	29		x		x		25
47	5	30		x			x	25
48	5	31		x		x		33
49	5	32		x			x	17
50	6	1			x	x		221
51	6	2			x		x	247
52	7	1			x	x		351
53	7	2					x	370
54	8	1						434
55	9	1		x		x		208
56	9	2			x	x		208
57	10	1	x	x	x	x	x	667
58	11	1			x	x		115
59	11	2			x		x	56

The different production methods lead to a range of cumulative relative frequencies of different producers. The gray surface in Figure 4 fills the space between minimum and

maximum cumulative relative frequency for each gap width. The median gap width for the lower bound of the grey surface is below 0,5 mm and the 90th percentile is equal to 2,0 mm. The red dots visualize the mean gap width equal to 0,6 mm and the 90th per-centile equal to 2,0 mm according to prEN 16351 (2018).



*Figure 11. Cumulative relative frequencies of all gap widths, best quality outermost layers and inner layers*



*Figure 12. Range of gap widths of different producers*

In 2017, the CLT production grew by 14 % in the region of Germany, Austria and Switzerland and new European production facilities are under development (Jauk and Ebner 2017, Jauk 2017). The modern hydraulic presses allow side pressure to reduce the gaps between laminations of longitudinal and transvers layers. The CLT production based on single layered solid wood panels leads to a high percentage of closed and very small gaps between adjacent laminations.

## Conclusions

The maximum gap width of 6 mm according to EN 16351 (2015) does not represent the measurements as well as a limit for the median gap width of  $b_{\text{gap,med}} = 0,6$  mm and a limit for the 90th percentile of  $b_{\text{gap,90}} = 2$  mm. These values lead to much more

realistic expectations of architects, engineers and customers. The measurements show that the design with the normal charring rate is reasonable and no elevated charring rate due to gaps should be applied. The results could also improve the statistical models for dowel type fasteners in CLT if they were combined with distributions for widths and thicknesses of laminations to describe the embedment of the fasteners even more realistically.

#### 4.4 Protected members

Charring of initially protected members is divided into 3 protection 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.

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 sum of protection times of cladding layers according to the component additive method;

$$t_{ch} = \sum t_{prot} \quad ( 24 )$$

For protection phase 2, when  $t_{ch} \leq t \leq t_f$ , the basic design charring rates  $\beta_0$  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  $k_3$ .

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, Type F the protection coefficient  $k_2$  should be taken as

$$k_2 = 1 - 0,018h_p \quad (25)$$

For clay claddings the protection coefficient  $k_2$  should be taken as

$$k_2 = 1 - 0,01 h_p \quad (26)$$

where  $h_p$  is the thickness of the clay cladding [mm].

For stone wool claddings the protection coefficient  $k_2$  should be taken as

$$k_2 = 1 \text{ for thickness } h_p = 20 \text{ mm} \quad (27)$$

or

$$k_2 = 0,6 \text{ for thickness } h_p \geq 45 \text{ mm}$$

For thicknesses between 20 and 45 mm the coefficient  $k_2$  could be interpolated.

The post-protection factor  $k_3 = 2$  according to EN 1995-1-2.

### ***Fall-off time of wood-based boards***

Protection by wood-based boards is considered by calculating the charring of the boards. Fall-off time of the wooden board occurs when the charring of whole thickness is reached.

### ***Fall-off times of Gypsum boards***

Fall-off of gypsum claddings in fire can be caused by thermal degradation of the boards or by pull-out of fasteners. The minimum of the two has to be taken as design value.



Fall-off time caused by pull-out of fasteners can be calculated as

$$t_f = t_{ch} + (l_f - l_{a,min} - h_p) / (k_s k_2 k_n k_j \beta_0) \quad (28)$$

where

$l_f$  is the length of fastener

$l_{a,min} = 10$  mm is the minimum anchorage length in the uncharred wood

$h_p$  is the thickness of the cladding

$k_i$  are the relevant charring coefficients for protection phase

$\beta_0$  is the basic design charring rate

Generic expressions for fall-off times of gypsum plasterboards backed by CLT and caused by thermal degradation are given in Table 7.

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 7. Fall-off times of gypsum plasterboards  $t_f$  in minutes with board thickness  $h_p$  and total board thickness  $h_{p,tot}$  in millimetres when backed by CLT.**

Cladding	Walls		Floors	
Type F, one layer	$5,9h_p-36$	$9 \text{ mm} \leq h_p \leq 18 \text{ mm}$	$1,9h_p+3,6$	$12,5 \text{ mm} \leq h_p \leq 16 \text{ mm}$
Type F, two layers	$1,9h_{p,tot}+22$	$25 \text{ mm} \leq h_{p,tot} \leq 31 \text{ mm}$	$2,3h_p-1,8$	$25 \text{ mm} \leq h_{p,tot} \leq 31 \text{ mm}$
Type A, two layers	$t_f=47,4$	$h_{p,tot}=25 \text{ mm}$	<sup>a</sup>	
<sup>a</sup> No data available.				

Fall-off times of the other claddings should be determined according to EN 13381-7.

## 4.5 Zero-strength layers

Authors of this section: J. Schmid (ETH Zürich), M. Klippel (ETH Zürich)

Below the zero strength layer thicknesses for different layups are presented, which are also suggested for standardisation. For optimization of products it is recommended to use advanced methods, simulations above the use of the simplified models presented in the following sections.

### 4.5.1 Tabulated data

Effective ZSLs are provided as tabulated data for CLT floor elements for 30, 60 and 90 min fire exposure. Generally, Maximum values were found to be 7, 10, and 12 mm, respectively. The three values could be proposed as a further simplification of tabulated data given in the following. The individual effective ZSL for the preferred CLT layups are given in Table 8.

*Table 8. Layup of preferred CLT floor elements with layup specification and total thickness in mm.*

Layup specification	20 mm ( $d_{char}$ )	39 mm ( $d_{char}$ )	59 mm ( $d_{char}$ )
	(R 30 min)	(R 60 min)	(R 90 min)
20+20+20	2,0	7,0	n.a.
40+40+40	8,0	4,0	n.a.
20+20+20+20+20	3,0	9,5	5,0
40+20+20+20+40	6,0	5,0	8,0
40+20+40+20+40	5,0	6,0	9,0
40+30+40+30+40	5,0	5,0	3,0
40+40+40+40+40	5,0	5,0	2,0

It should be noted that the data given in Table 8 were developed for 30, 60 and 90 min using the char line assessed by the 300°C isotherm, i.e. a simulated charring rate. To allow for limited deviations, it is recommended to use the charring depths in the top row of Table 8 for further use. Values are not valid when individual charring rates

determined by testing are used or charring layer fall-off occurs. Charring layer fall-off is defined by the loss of stickability of laminate products which undergo charring and tend to show failure of the bond line when exposed to fire.

#### 4.5.2 The simplified design model “twelve and two” for CLT floor elements

Aim of the simplified rule is to increase the application range exceeding the preferred layups. A large range of CLT layups was simulated and analysed systematically with respect to available products. Simulations were performed with three- and five layer CLT. The outcome is a simple design methodology which can be applied using the original definition of  $d_0$  since the transversal layers are taken into account explicitly as shown in the flow chart in Figure 13. To execute the resulting rule, the designer has to check whether the residual cross-section starts (i.e. the depth at the char front) in a longitudinal layer.

- $d_0$  of 12 mm has to be deducted from the residual cross section unless the residual cross section comprises parts of the first layer, then  $d_0 = 7$  mm applies.
- When the calculated cross section starts in a transversal layer, the effective depth of the following longitudinal has to be reduced by 2 mm.

#### 4.5.3 The simplified design model for CLT wall elements

The simplified design model for CLT wall elements will be implemented into this document in a next iteration.

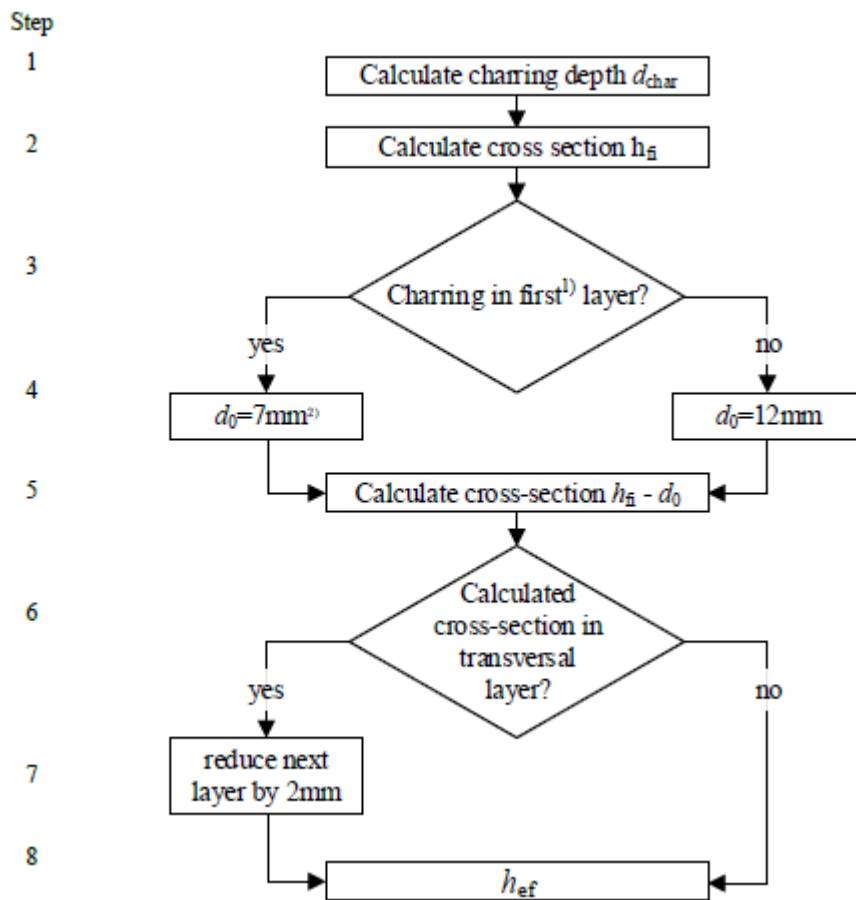


Figure 13 – Determination of “twelve and two” simplified design of CLT. The eight-step procedure to determine the effective cross-section for CLT floor elements.

#### 4.6 Worked example for floor elements

Worked examples for CLT floor elements will be included in a next iteration of this document

#### 4.7 Worked example for wall elements (buckling analysis)

Worked examples for CLT wall elements will be included in a next iteration of this document

## **5. Adhesive testing for the use in CLT**

Authors of this section: Gordian Stapf (Henkel), Gernot Standfest (Dynea)

### **5.1 Overview of test standards to assess the adhesive performance in fire exposed CLT**

Adhesives used in load-bearing timber structures need to pass different standards tests. These tests vary from continent to continent. The following overview summarises current adhesive testing standards related to tests at elevated temperature and fire. The following text is based on the PhD thesis of Michael Klippel and updated and adapted to CLT.

#### **Europe**

In Europe, the performance requirements for adhesives used in load-bearing timber structures must comply with performance requirements classified according to the type of the adhesive:

- Phenolic and aminoplastic adhesives (EN 301:2018)
- One-component polyurethane (1C PUR) adhesives (EN 15425:2017)
- Emulsion-polymer-isocyanates (EPI) adhesives (EN 16254:2013)

Currently, CLT can only be certified on a European level according to EAD 130005-00-0304 “Solid Wood Slab Element to be Used as a Structural Element in Buildings”. However, the European standard EN 16351 “Timber structures – Cross laminated timber – Requirements” is in preparation and will be harmonized in the next one to three years. While EAD 130005-00-0304 only allows for aminoplastic and 1C PUR adhesives according to EN 301 and 15425, EN 16351 will presumably allow the use of EPI adhesives according to EN 16254 adhesives as well.

The respective adhesive standards define several classes, from which the General Purpose (GP) adhesives of the adhesive class I are suitable for the face bonding of CLT.

#### Aminoplastic and phenolic adhesives

Melamine-Urea-Formaldehyde (MUF) and Phenol-Resorcinol-Formaldehyde (PRF) adhesives that are classified according to EN 301 (adhesive type I) and tested according to EN 302 are applicable for the manufacture of CLT. According to EN 302 “Adhesives for load-bearing timber structures - Test methods” (Parts 1-8), different test parts as listed below need to be tested:

- EN 302-1: Determination of longitudinal tensile shear strength (with glue line thicknesses of 0.1 mm and 1.0 mm)
- EN 302-2: Determination of resistance to delamination (with a glue line thickness of 0.1 mm)
- EN 302-3: Determination of the effect of acid damage to wood fibres by temperature and humidity cycling on the transverse tensile strength (with glue line thicknesses of 0.1 mm and 0.5 mm)
- EN 302-4: Determination of the effects of wood shrinkage on the shear strength (with a glue line thickness of 0.5 mm)
- EN 302-5: Determination of maximum assembly time under referenced conditions
- EN 302-8: Static load test of multiple bond line specimens in compression shear delamination (with a glue line thickness of 0.1 mm)

#### Moisture curing one-component polyurethane adhesives (PUR)

For PUR adhesives the requirements of EN 15425 (adhesive type I) needs to be fulfilled. Different test parts as listed below need to be tested:

- EN 302-1: Determination of longitudinal tensile shear strength (with glue line thicknesses of 0.1 mm and 0.5 mm)

- EN 302-2: Determination of resistance to delamination (with a glue line thickness of 0.1 mm)
- EN 302-3: Determination of the effect of acid damage to wood fibres by temperature and humidity cycling on the transverse tensile strength (with a glue line thickness of 0.5 mm)
- EN 302-4: Determination of the effects of wood shrinkage on the shear strength (with a glue line thickness of 0.5 mm)
- EN 302-8: Static load test of multiple bond line specimens in compression shear delamination (with a glue line thickness of 0.1 mm)
- EN 15416-1, Adhesives for load bearing timber structures other than phenolic and aminoplastic – Test methods – Part 1: Long-term tension load test perpendicular to the bond line at varying climate conditions with specimens perpendicular to the glue line (Glass house test) (with a glue line thickness of 0.3 mm)
- EN 15416-3, Adhesives for load bearing timber structures other than phenolic and aminoplastic – Test methods – Part 3: Creep deformation test at cyclic climate conditions with specimens loaded in bending shear strength (with glue line thicknesses of 0.1 mm and 0.5 mm)

Regarding the performance at elevated temperature, the highest temperature in the tests according to these standards is 70°C or 90°C, according to the adhesive class of adhesive type I. The temperature is

- applied over 72h without load and the specimens are then tested in a short term test (Designation A7 / A8 of EN 302-1) or
- held over two weeks under constant loading of the specimens (EN 302-8:2017)

Those methods cover the situation of short- or long-term high temperature exposure (e.g. caused by the impact of sustained sunlight) for glued timber members and was developed in dependence on ASTM D 3535.

The current European standards do not provide any further information about the performance of adhesives at elevated temperature or in a fire situation. Load-bearing

timber elements can be tested in full-scale fire resistance tests according to EN 1365-2:2015 or analysed and designed according to the fire part of Eurocode 5 (EN 1995-1-2:2004). Regarding the performance of adhesives, a note in Eurocode 5 states that for some adhesives the softening temperature is considerably below the charring temperature of the wood.

Other European standards test the performance of adhesives at temperatures above room temperature. For example, EN 14292:2005 determines the time to rupture at a constant temperature rate of 50°C per hour under constant loading of EN 302-1 specimens. For non-load bearing adhesives, EN 14257:2006, also known as the “Watt’91” test, evaluates the bond strength of adhesives at temperatures of about 80°C. However, those tests

- are not integrated in the certification of load bearing adhesives and
- might not be relevant for the situation in a bondline of, for example, glued-laminated timber exposed to fire.

In 2009, a working group (CEN TC 193/SC1/WG13) was formed in Europe to address the adhesive performance at elevated temperatures and in fire situations. This effort resulted in prEN 17224:2018 “Determination of compressive shear strength of wood adhesives at elevated temperatures” which will most likely be published in a final version with only little changes quite soon. prEN 17224 is basically a copy of ASTM D 7247 (see the following section about North American Standards) but does – in contrast to its North American counterpart – not define test temperatures.

## **North America**

CLT is standardized within the International Building Code (IBC) according to PRG 320. The current version IBC 2018 references ANSI/APA PRG 320-2017 “Standard for Performance-Rated Cross-Laminated Timber”. According to PRG 320, the used adhesives need to comply with ANSI 405 “Standard for Adhesives for Use in Structural Glued Laminated Timber”. ANSI 405 includes and ASTM D 2559 that itself references ASTM D 3535, which is similar to EN 302-8 and tests the resistance to creep under



static loading and exterior exposure conditions for structural adhesives. The specimens are exposed to a defined climate under loading. Requirements for the total deformation shall be met. The highest temperature tested in this standards is 80°C, which captures a long-term heating scenario, different to the fire situation with typically steep temperature gradients in timber cross-sections (Mikkola et al. 1990).

In response to concerns about the fire performance of non-phenolic-resorcinol adhesives in finger-jointed lumber ANSI 405 includes also ASTM D 7247-17 "Standard Test Method for Evaluating the Shear Strength of Adhesive Bonds in Laminated Wood Products at Elevated Temperatures", which was first published in 2006. ASTM D 7247 defines short-time block shear tests on a shear area with the size of 45 mm x 51 mm. The requirement defined in ANSI 405 is to achieve a ratio of the mean residual shear strength between the target temperature 21°C (70°F) and 220°C (428°F) for the bonded specimen is equal to or higher than the lower 95% confidence interval on the ratio of the mean residual shear strength for the solid wood control specimens. The objective of this standard is to evaluate the adhesive performance at elevated temperatures near wood ignition (Yeh and Brooks 2006). The specimens and testing machine are described in detail in ASTM D 905. It is worth noticing that no link between these tests according to ASTM D 7247 and the performance in fire has been demonstrated (König et al. 2008). Further, the test temperature near wood ignition is not relevant for structural glued-laminated timber beams, as found by Klippel (20xx).

Due to this reason, PRG 320-2017 requires (in contrary to the first version of the standard from 2012) an additional small-scale fire test according to section 6.1.3.4 "Heat performance test" of NIST DOC PS 1 "Voluntary Product Standard Structural Plywood". This test requires that a piece of plywood subjected to a Bunsen burner flame for 10 Minutes or until a charred area appears on the back side shows no delamination of the veneers. Since this test was made for plywood and the outcome is very dependent on the veneer (or in case of CLT layer) thickness, the test was superseded in the follow-up version of PRG 320 that was published 2018, by an adapted method of CSA O177-06 "Qualification code for manufacturers of structural glued-laminated timber.", A2 "Small-scale flame test". The test is rigorous method to

evaluate the fire performance of adhesives by exposing a CLT-specimen to flames from a Bunsen burner parallel to the fiber. However, due to poor correlation with full compartment tests and problems to obtain the required wood qualities, the test might not end up in the next version of PRG 320 and will perhaps never be mandatory. Additional to the CSA O177-test, PRG 320-2018 requires a full compartment test, where a loaded, unprotected CLT floor-ceiling slab with the dimensions of 8 ft x 15 ft (2.4 m x 4.6 m) must sustain a 240-minute fire without the fall-off of char layers.

(Note: For the fire behaviour of finger-jointed timber members, two closely related standards were developed: The standards ASTM D 7374 and ASTM D 7470. Both standards refer to the Glued Lumber Policy, which groups the adhesives in “Heat Resistant Adhesives (HRA)” and “Non-Heat Resistance Adhesive (Non-HRA)”. HRA adhesives must pass a one-hour fire resistance according to ASTM D 7374 and ASTM D 7470. Following these standards, a full-scale fire test according to ASTM E 119 on a wall assembly made with end-jointed lumber is required. The wall assembly shall sustain the applied load for at least 60 minutes. Adhesives passing this test can be used in jointed lumber interchangeably with solid-sawn members of the same species and grade in fire-rated applications.)

## **Japan**

The Japanese CLT product standards is JAS MAFF motif No. 3079 (2013). According to this standard, an adhesive, according to Condition A, B or C must be used.

The temperature dependence of adhesive bonds for Conditions A, B or C is determined according to JIS K 6831 (2003). A block shear test specimen according to JIS K 6852 (1994) is tested at different temperatures. The maximum temperature is 150°C (Condition A) according to a Japanese guideline (NTI 2009). At this temperature, a minimum strength of 66% of the strength at normal temperature is required for the approval of the adhesive. Before testing, the specimen is first preconditioned for 168 hours according to JIS K 6848-1 (1999) and subsequently heated to the target temperature for 24 hours. The same procedure is applied to a compressive shear test at 100°C (Condition B and C), for which a minimum of 75% of the dry strength is

required. Further, a creep test according to ASTM D 2559 (2012a) and ASTM D 3535 (2007a) at a maximum temperature of 71°C for 7 days is required.

Full-scale fire tests under loading according to a Japanese guideline (NTI 2009) must be performed for adhesive approvals. Two glued-laminated timber beams with specified dimensions and height of lamella are to be tested in a fire test using the standard ISO-fire curve according to ISO 834 (1999) (three-sided fire exposure) and 4-point loading. Requirements are specified regarding the grade of the lamellas and the position of the finger joints. The fire test is stopped after 45 minutes of fire exposure. It is required that no fracture occurs during this period and the charring depth should be smaller than 35 mm, which corresponds to a charring rate of 0.8 mm/min.

### **Australia and New Zealand**

In Australia and New Zealand, there is currently no standard for the production of CLT. Adhesives must meet the requirements according to AS/NZS 4364:2010 “Timber—Bond performance of structural adhesives”. Two test methods are introduced, which should be chosen depending on the application of the adhesive. Method A is based on CSA O112.9 (2004). A block-shear creep test is performed at a maximum temperature of 70°C for a period of seven days. For method B, a tensile shear test according to EN 302-1 and a creep-shear-test according to EN 15416-2:2007 (superseded by EN 302-8:2017) are required based on European test methods. Thus, the highest temperature tested are usually 70°C.

### **International Organisation for Standardisation (ISO)**

There is no current ISO CLT standard but ISO/FDIS 16696-1 “Timber structures -- Cross laminated timber -- Part 1: Component performance and production requirements” is under development.

With regard to the adhesive performance, the draft standard from January 2018 refers to ISO 20152:2011 “Timber structures -- Bond performance of adhesives”. In case “local building regulations require heat durability testing”, the adhesive must meet the requirements of ISO 20152-2:2011 for high temperature strength of bondlines in

structural wood products. Herein, a lap shear test at 220°C or higher is required to test the adhesive for a high temperature strength (based on ASTM D 7247-2007 requirements). ISO 20152-2:2011 also contains a creep test of bondlines at 180°C or higher, based on CSA O112.9-2004. The overall creep should thereby not exceed 0.6 mm and the maximum average creep displacement at any single bonded cross-section for each specimen shall not exceed 2.9 mm after the loading period. ISO 20152-2:2011 further notes that a creep test at temperatures in the range of 180°C to 220°C is generally appropriate to assess the adhesive performance in small cross-section members in fire-protected assemblies.

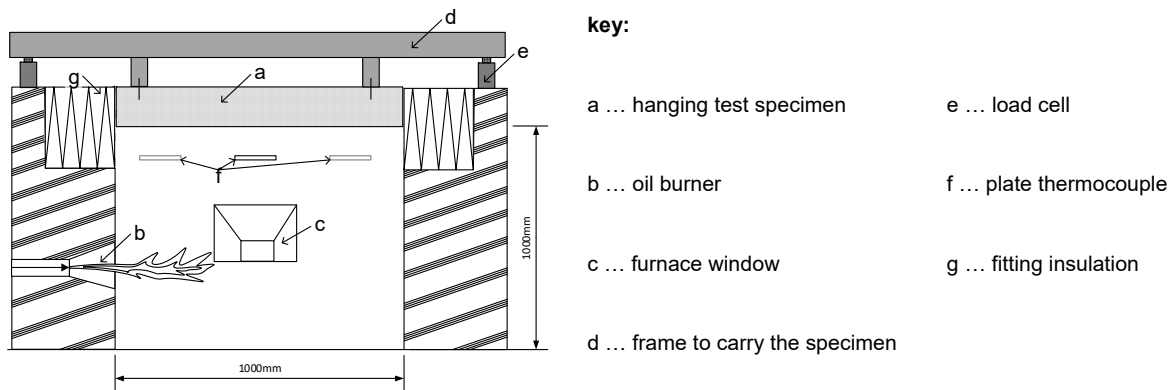
The international standard ISO 19212:2006 “Adhesives - Determination of temperature dependence of shear strength” describes a method to determine the temperature dependent shear strength of adhesives or adhesive bonds in adhesively bonded products. Adhesives used to glue engineered wood products are tested in a block shear test under compressive loading according to ISO 6238:2018 “Adhesives - Wood-to-wood adhesive bonds - Determination of shear strength by compressive loading.” After pre-conditioning, the test specimens are tested at selected temperatures ranging in 20°C intervals up to a maximum temperature of 180°C. For each temperature, a minimum number of 12 specimens shall be tested. For each test, the failure patterns are to be classified in accordance with ISO 10365:1992. ISO 19212:2006 classifies the adhesives by their temperature dependence in four different groups. Thereby, the adhesive strength at an elevated temperature, expressed as a percentage of the adhesive strength at 23°C, forms the criterion for the sorting into the four groups. The ISO standard, however, does not give a specific temperature at which adhesives should be tested for the application in engineered wood products. The standard ISO 19212:2006 can be stated as similar to the Japanese standard JIS K 6831 (2003) to test the temperature dependence of adhesive bonds.

## **5.2 New proposal for a standard test method to assess the adhesive performance in fire exposed CLT**

Authors of this section: Michael Klippel (ETH Zürich), Joachim Schmid (ETH Zürich), Reto Fahrni (ETH Zürich), presented at WCTE 2018

At ETH Zurich, several fire tests were performed with CLT floor elements (unloaded) in model-scale in 2017 and 2018 with an approximate timber element size of 0.8 m<sup>2</sup>. One solid timber panel (STP) and eight cross-laminated-timber panels (CLTs) made from spruce were tested exposed to EN/ISO standard fire exposure. The reason to use STP elements was that there is no risk for failure of bond lines, i.e. fall off of layers during charring, as the joints between the beams are vertically orientated (parallel to the heat flow). Further, thermocouples can be placed easily in any requested distance to the fire exposed surface before assembling the element. For CLT elements, thermocouples were inserted during the production between the layers (in-laid TCs). The CLT specimens were manufactured with four different structural adhesives, such as 1-component polyurethane (1C-PUR) and melamine urea formaldehyde (MUF) type of adhesives.

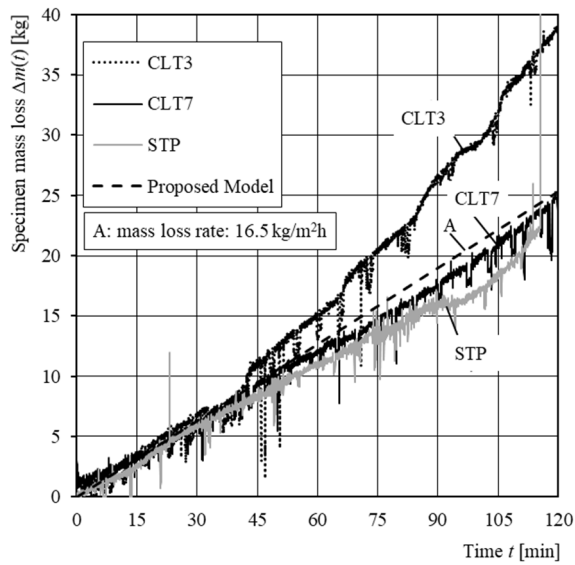
The furnace was controlled with plate thermometers and tests lasted between 60 and 120 min. Type K thermocouples (wire inlaid) were used to measure the development of the charring temperature. Figure 6 bases on the measurements with the following thermocouple setup: K-w-e-0.5/2.2/in-pa, see Fahrni et al. (2018). Elements were tested at approximate 12% equilibrium moisture content. In addition to standard fire resistance tests, the mass loss of the specimens was recorded continuously with load cells during these tests, see Figure 14. Further, the specimen was weighed before and right after the fire test to check measurements of the load-cells. Measuring the mass allows the calculation of the total mass loss due to charring and fall off of charring layers.



**Figure 14:** End elevation of the model scale furnace showing the hanging test specimen (details up scaled).

Results of these tests are, among others, the mass loss of the timber specimens, the temperature development in the cross-section and the residual cross-sections (total depth including the char layer and depth of virgin wood) after the test. The development of the mass loss is shown in Figure 15 exemplary for three different tests.

In the test with specimen CLT 3, fall off of charring layers was observed leading to a considerable mass loss in comparison to fire test with specimen CLT 7. The loss of significant parts of the charring layers can be observed due to the change of the graphs' slope at approximately 42 min, 65 min, 82 min and 100 min. The specimen CLT 7 was manufactured with a novel type of one-component polyurethane (1C-PUR) adhesive and showed almost the same mass loss as with a solid timber deck plate (STP), which is used as benchmark.



*Figure 15: Specimen mass loss continuously measured over time of fire exposure using load cells for selected tests with CLT and STP (solid timber panel).*

It should be noted that specimen CLT 6 was produced with a MUF adhesive resulting in approximate the same mass loss rate as observed for the solid timber deck specimen STP, see Table 9. The mean density of the specimens tested was 453 kg/m<sup>3</sup> with only a small deviation from this value ( $\pm 20$  kg/m<sup>3</sup>), which means that the density should have no influence on the results and interpretations presented here.

Table 9: Mass loss overview (\* benchmark)

Specimen name	Adhesive <sup>1</sup>	Layer thickness [mm]	Density [kg/m <sup>3</sup> ]	Fire time [h]	Total mass loss [kg]	Mass loss rate [kg/(m <sup>2</sup> h)]	[-]
CLT 1	PUR 1	10	463.5	1	14.4	18.8	1.22
CLT 2	PUR 1	25	471.4	2	27.6	18.0	1.17
CLT 3	PUR 2	25	447.5	2	40.7	26.5	1.73
CLT 4	PUR 1	25	438.7	2	28.4	18.5	1.21
CLT 5	PUR 1	20	471.0	1.5	22.6	19.6	1.28
CLT 6	MUF	25	448.7	2	23.7	15.5	1.01
CLT 7	PUR 1	35	456.8	2	25.3	16.5	1.07
CLT 21	PUR 3	25	433.0	2	33.2	21.6	1.40
Solid timber deck STP	-	-	454.0	2	22.4	15.4	<b>1.00*</b>

<sup>1</sup> PUR: One-component polyurethane; PUR1 passes compartment test acc. to PRG 320-2018.

MUF: Melamine-urea-formaldehyde; certified according to EN 301:2017 for structural timber

Specimen CLT 7 (PUR1, lamella thickness 35mm) and CLT 2 (PUR1, lamella thickness 25mm) showed similar charring behaviour as given in Eurocode 5 (see Figure 16) and thus a charring rate of 0.65 mm/min over 120 minutes of standard fire exposure. However, although glued with the same adhesive PUR1, the observed mass loss rate was higher for specimen CLT 2 with 25mm thick lamellas than for specimen CLT 7 with 35mm thick lamellas. A possible reason could be the macroscopic shrinkage effect of char pieces (approx. mean length 40 mm) which leads to bending of the char pieces and subsequently to tension perpendicular to the bond lines. Thus,



it can be concluded that the behaviour of fall off is not solitary a characteristic of the adhesive used but the adhesive and the layup of the CLT.

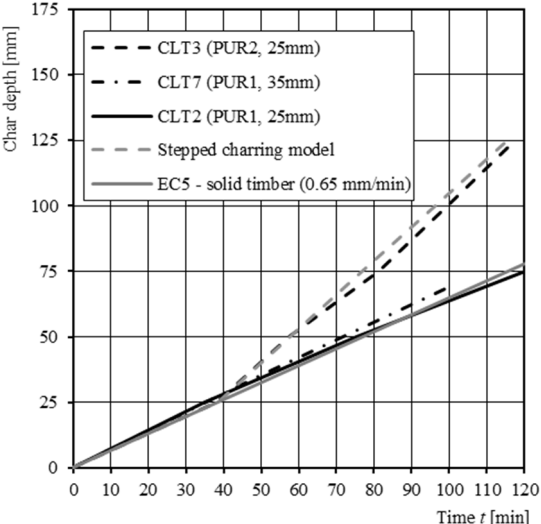


Figure 16: Development of char depth with time of fire exposure, calculated on the basis of wire in-laid thermocouple. Very good agreement between model and tests.

## 6. Reaction to fire

This chapter was published in Östman et al. (2018)

### **Harmonisation of classification systems for Reaction to fire performance of building products**

Reaction to fire involves the response from materials to an initial fire attack and includes properties like time to ignition, flame spread, heat release rate and smoke production.

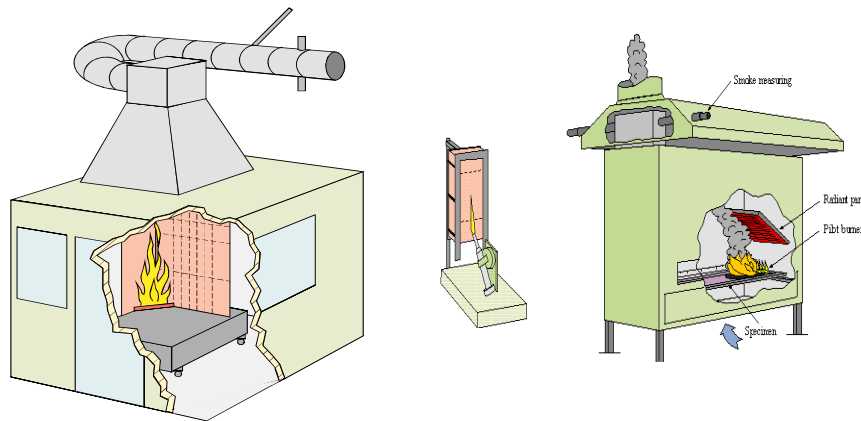
A European classification system (EN 13501-1) for the reaction to fire properties of building construction products was introduced in 2000. The system is often referred to as the Euroclass system and consists of two sub systems: one for construction products excluding floorings, i.e. mainly wall and ceiling surface linings, see Table 10; and another similar system for floorings. Both sub systems have classes A to F of which classes A1 and A2 are for non-combustible products. Additional classes are defined for smoke, s1-s3, and burning droplets, d<sub>0-d2</sub>. This European system has replaced the earlier national classification systems, aiming to decrease the number of obstacles for international trading of products and services.

The European classification system for reaction to fire performance is based on a set of EN standards for different test methods. Three test methods are used for determining the classes of combustible building products, see Figure 17. For non-combustible products, additional fire test methods are used.

**Table 10: Overview of the European reaction to fire classes for building products used as wall and ceiling linings.**

Euro class	Smoke class	Burning droplets class	Requirements according to			FIGRA W/s	Typical products
			Non comb	SBI	Small flame		
A1	–	–	x	–	–	–	Stone, concrete
A2	s1, s2 or s3	d0, d1 or d2	x	x	–	≤ 120	Gypsum boards (thin paper), mineral wool
B	s1, s2 or s3	d0, d1 or d2	–	x	x	≤ 120	Gypsum boards (thick paper), fire retardant wood
C	s1, s2 or s3	d0, d1 or d2	–	x	x	≤ 250	Coverings on gypsum boards
D	s1, s2 or s3	d0, d1 or d2	–	x	x	≤ 750	Wood and wood-based panels
E	–	- or d2	–	–	x	–	Some synthetic polymers
F	–	–	–	–	–	–	Fails to fulfil class E criteria

SBI = Single Burning Item, main test for the reaction to fire classes for building products, EN 13823;  
 FIGRA = Fire Growth Rate, main parameter for the main fire class according to the SBI test.



**Figure 17 Three main test methods for the reaction-to-fire performance relevant for wood products: the SBI Test (Single Burning Item Test), EN 13823, Small Flame Test, EN ISO 11925-2 and the Radiant Panel Test for floorings, EN ISO 9239-1, see Östman et al. (2018)**

## **Reaction to fire performance of wood products**

Products with known and stable performance may be classified as groups according to an initiative from the European Commission (Construct 2004). This is a possibility for wood products that have a fairly predictive fire performance. Properties such as density, thickness, joints and type of end use application may influence the classification. The procedure is called CWFT, Classification without further testing, and is a list of generic products, not a list of proprietary products (Östman and Mikkola 2010).

The CWFT approach has recently been applied also to CLT (Commission delegated regulation 2017) which is classified as D-s2,d0 or D<sub>fl-s1</sub> (for floorings) for thicknesses and densities over certain limits. These data have been approved by the European Commission and will be published in their Official Journal.

## **Fire retardant treatments for wood products**

It is relatively easy to obtain an improved fire performance of wood products. Most existing fire retardants are effective in reducing different reaction-to-fire parameters. The highest European and national fire classifications for combustible products can be reached (Östman et al 2010). But for the fully developed fire, the influence is minor (Nussbaum 1988). One exception is intumescent paints that may delay the time for start of charring and thus increase the fire resistance of timber structures. In any case, fire retardants cannot make wood non-combustible.

However, the excellent fire performance of the virgin fire retardant (FR) wood products may degrade over time, especially in outdoor applications. When exposed to high humidity, the FR chemicals may migrate in the wood towards the surface and may ultimately be leached out. This problem has been known for a long time in the US and the UK, but is not so well known in the rest of Europe. A literature review (Östman et al 2001) and studies on exterior exposure during up to ten years (LeVan and Holmes 1986; Östman and Tsantaridis 2017) have been published.

A European system with Durability of Reaction to Fire performance, DRF, classes has been developed in order to guide the potential users to find suitable FRT wood products (EN 16755 2017). The system is based on a North American system and a previous Nordic system. It consists of a classification system for the properties over time of FRT wood and suitable test procedures.

## **7. Fire stops and penetration – best practise and detailing**

Author of this chapter: Norman Werther (TUM)

### **General**

This section describes the relevance of detailing for the fire safety of CLT structural elements and the compartmentation of structures. The evaluation of the fire resistance for building elements is based in general on standardised fire tests, like the EN 1365 series, tabulated construction setups, like in DIN 4102-4 and ÖNORM B 1995-1-2 or on calculation methods, like EN 1995-1-2. These methods usually only consider individual elements and do not, or just to a low extent, take into account any joints and junctions to neighbouring elements, mounting parts or typical penetrations of service installations. However, these points are unavoidable for real structures and influence the fire safety of the plane undisturbed elements. Therefore, the general fire safety requirements must be guaranteed also at these points. General solutions and principles are provided in this section in order to achieve compartmentation under consideration of joints, junctions and penetrations as provided by the structural element. This solution may be used as a guidance within the design process, describing the state of research and practice. For the execution and installation of fire stops for service penetrations and joints companies provide highly specialized products certified by ETAs for particular building designs, which provide more efficient realization than the solutions provided here. Deformation and tolerances of the structural elements and between structural elements should be considered when designing fire stops and penetrations.

### **Field of application**

This section covers the design of (A) penetrations of service installations and openings including (1) ducting, (2) pipes, (3) electrical cables and (4) doors/windows and (B)

joints in and to neighbouring elements of CLT structures. Typical flame spread paths resulting from penetrations and joints are exemplarily shown in following Figure 18.

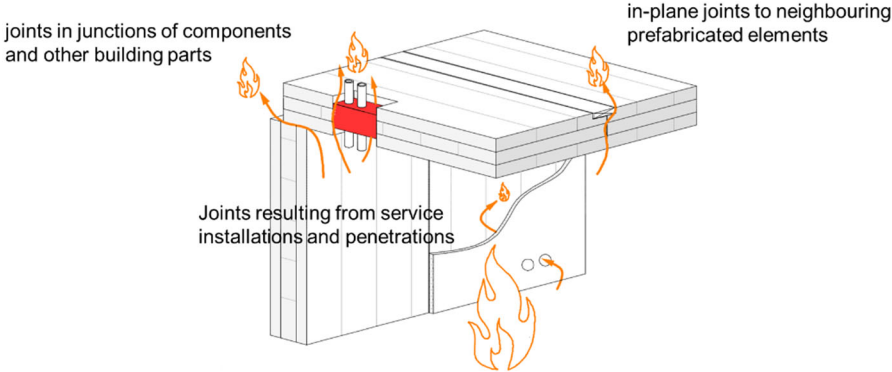
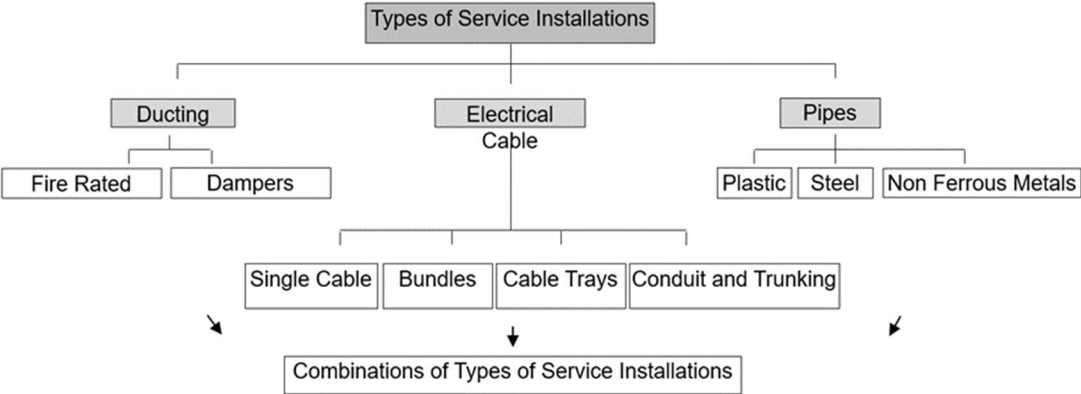


Figure 18: system- and element specific joints for CLT structures

**Penetrations**

In principle, penetration through fire rated assemblies should be reduced as much as possible, by considering service installations from the beginning of the design process. If they are essential for the use of a building, certified systems to maintain the assembly’s fire rating must be used. Fire tests and technical approvals show that every type of service installation passing through fire separating elements has its own specific characteristic, level of performance and therefore, range of application. Hence, there is no single solution or product that can be used for all services and protects all elements in the same manner to avoid early fire spread. The variety of types of service installations is shown in Figure 19.

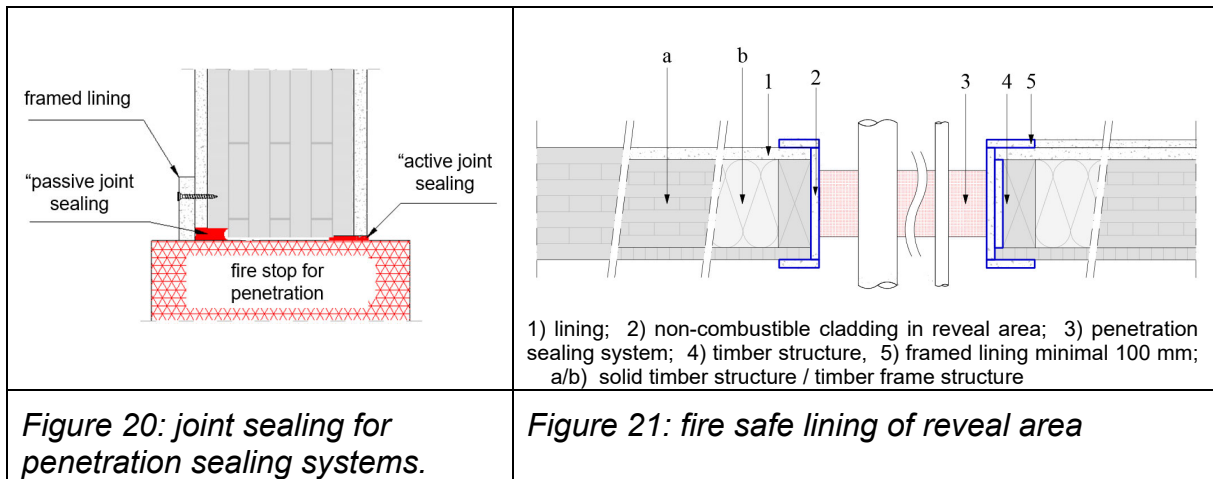


*Figure 19: types of service installations and penetrations*

As main influencing factor to guarantee the fire safety for timber elements with service installation penetrations, the interface between the timber structure and the service installation can be identified. Continuous joints, where hot gasses can pass and contribute to an early fire spread must be excluded by appropriate detailing.

Systems with intumescent materials (“active systems”), see Figure 20, which expand when exposed to high temperatures, can efficiently seal the gap between the sealing system and solid timber element. For “passive”, see Figure 20, systems, without capacity to expand under fire exposure like gypsum putty a further sealant to reach air tightness should be applied on both sides of the penetrated element. To optimize these joints with respect to fire conditions an additional tight fitted non-combustible framed lining is recommended. Due to the charring of timber and potential failure of linings in contact to the fire stop the joints shall be caulked/sealed at both sides- exposed and unexposed - or continuous throughout the entire element thickness. As a main concept to install multi penetration sealing systems, such as mineral wool boards, a non-combustible lining of the reveal area (reveal lining) over the entire thickness of the separating element in combination with an external framed lining to cover continuous joints can be recommended, see Figure 21. The reveal lining must provide the same protection as the plane lining of the structural element. In alternative to a framed lining, solutions with intumescent strips or intumescent coating in the interface area between reveal lining and timber structure were tested successfully, in order to prevent convective flows when exposed to fire (Teibinger 2013). The concept to line the reveal area may also be used for the installation of fire rated doors, windows or dampers. With respect to metal pipes penetrating timber elements the heat conducted from the pipe to the unexposed side must be considered too. Despite sufficient sealing avoiding hot gasses passing the penetration, the conducted heat can ignite timber elements at unexposed side, in direct contact to the pipe. A 25.4 mm annular gap, caulked and filled with mineral wool in combination with a continuous pipe insulation (pipe shell) is recommended to ensure fire safety.





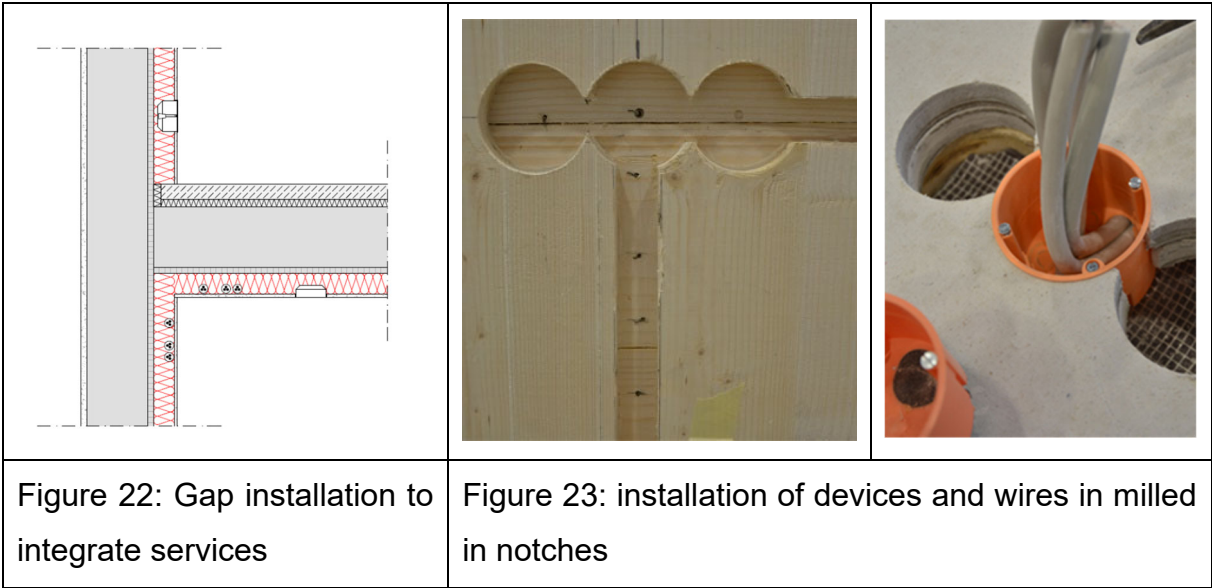
The measures to guarantee fire safe service installation for timber structures can be summarised as follows.

- The consideration of services from beginning of a project to avoid penetrations is essential for fire safe and economical structures.
- The exclusion of continuous joints by application of surface linings, intumescent materials and the covering of the reveal area are essential measures to reach fire safety.
- To eliminate convective flows, which lead to early fire spread, air tightness measures shall applied on both sides of the penetration, also in order to reduce the spread of smoke and toxic gasses.
- A sufficient embedment depth of fasteners used for the fixation of fire stops is needed.
- For metal pipes, joint filling in combination with pipe shells is essential to exclude ignition on unexposed side.
- The creation of installation conditions in timber structures (reveal linings) comparable to the boundary conditions of approved sealing systems allow the use of several existing systems.
- Guidance documents for the design phase are available in many countries, new and certified producer specific systems for solid timber constructions reaching the market.

**Electrical installations**

Due to the high amount of installations for electrical and communication purposes, CLT walls and floor elements have to provide ways to include such services into the structural elements without losing the approved performance of fire safety. In order to include sockets, switches and the corresponding wirings two potential solution can be identified i) adding of an installation gap in front of the structural CLT elements, see Figure 22 or ii) implementation of services by milled in channels which reduce the dimension of the structural elements, see Figure 23.

For CLT elements where fire resistance is fulfilled by the plane element, the arrangement of an additional service installation gap does not influence the fire performance negative.



Penetrations and openings in claddings and notches reduce the dimension of fire rated CLT elements and may influence the fire performance in a negative way compared to undisturbed elements. Beside an increased charring in the area of the openings of sockets and switches in a fire protective cladding, notches behind the cladding also may contribute to a fire spread in the element. With respect to fire resistance CLT elements producer specific technical approval documents and classification reports

may include tested setups with relevant conditions for installation and application of such services. Typical solutions to compensate the opening inside a cladding or the reduced thickness resulting from notches and recessed electrical boxes are:

- i) over dimension of the CLT element
- ii) application of fire rated sockets (e.g. intumescent material)
- iii) application of fire rated gypsum boxes or gypsum putty

With respect to sockets and recessed electrical boxes that penetrate a fire rated lining or encapsulation cladding of CLT elements Merk et al. (2014) recommend an intumescent coating, to protect the timber behind the penetrated cladding. The intumescent coating was applied not only in the recession of the CLT elements but also at its surface circular around the penetration including the notches. This procedure prevented an early ignition, burning of the timber and also smouldering, because the protective lining always arched upwards during fire exposure, see Figure 24.

Penetrations of single cables in fire rated claddings shall be caulked with gypsum putty or intumescent compounds over the entire thickness of the cladding. For penetrations of cable bundles further solutions are summarised in the fire safety in timber guideline (Östman 2010).

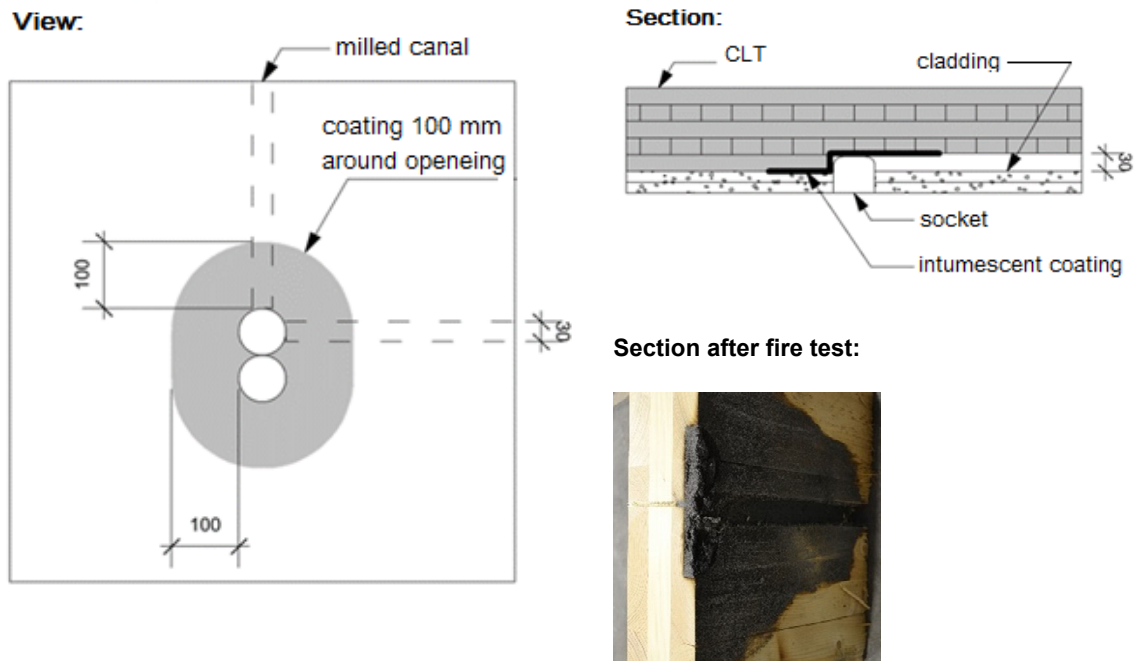


Figure 24: Application of intumescent paint in order to maintain fire resistance

### In plane joints

In plane joints in CLT elements may lower the fire resistance and influence the smoke tightness in a negative way. Gaps resulting from fabrication inaccuracy or needed construction tolerances allow hot gases and smoke to pass through in the presence of over-pressure under fire conditions. Especially butt connections should be prevented or at least need additional actions. Nowadays, CLT element joints uses exterior splines, step joints or tongue – groove connections. These joints have been tested several times in research projects and producer specific tests (Werther, 2016). Findings of such tests are generalised in the Austrian ÖNORM B 1995-1-2 and German DIN 4102-4 A1 standard, which shows that the fire safety can guaranteed if the remaining cross section covering a tongue and groove, a step joint or a joint with exterior spline is at least 2 cm, see Figure 25. To avoid hot gases passing through tight fitted joints additional joint sealing tapes, generally used for the purpose of air tightness, should be used within the joints, see Figure 25. In alternative, a lining or flooring system at the unexposed side should be used, also with respect to an improved

smoke tightness of the entire element. The Swiss guideline about detailing for fire resistant timber structures follows these principles too, however provides predefined minimal dimensions and structural measures to reach a specific fire resistance (Angehrn et al. 2018). Further designs and solutions are include in producer specific tests and classification documents.

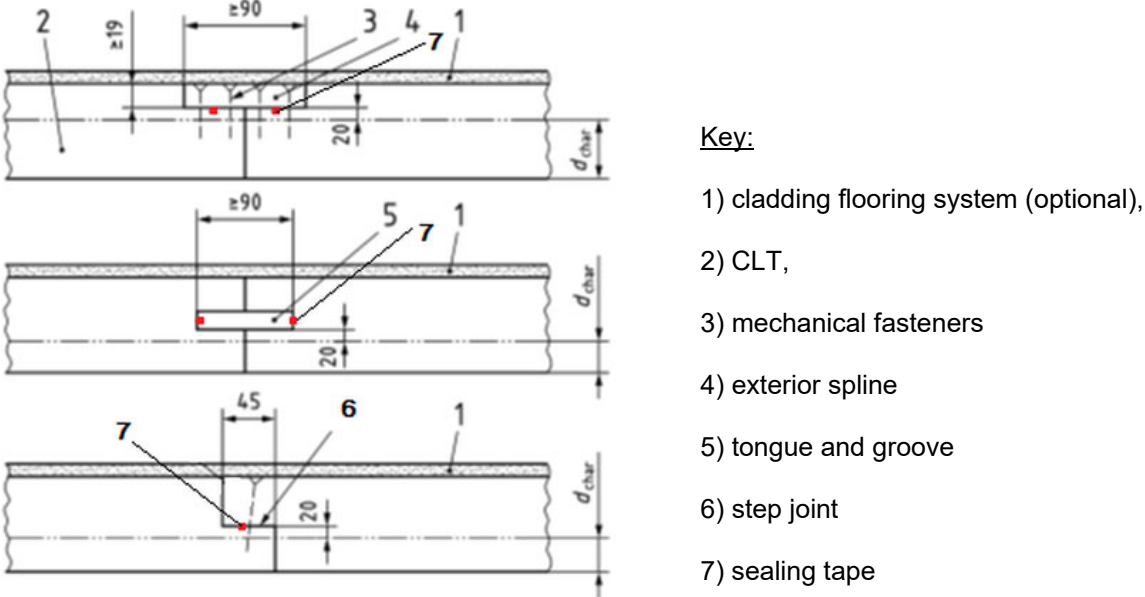


Figure 25: design recommendation for CLT element joints

In general, CLT floors consist of several elements. The corresponding element joints can be crucial for the fire resistance with respect of integrity when uneven loading, supporting or charring conditions exist and lead to different deflection between the elements. Resulting in an opening of the joints of the residual cross section. An additional flooring system such as concrete topping may reduce the risk of an early failure.

**Corner connections of**

Comparable to element joints, joints in corner connections and joints/connections to other building parts need to fulfil the equivalent fire resistance like the plane separating elements. The aim is to prevent the spread of fire and smoke to other fire compartments or an early spread of fire within the structural elements. Potential

solution, depending on the supporting conditions and structure are summarised in the Swiss guideline about detailing for fire resistant timber structures (Angehrn et al. 2018) or the German DIN 4102-4 A1 standard. Detailed drawings for various applications under consideration of all structural aspects, including fire safety are presented in the European construction catalogue – [www.dataholz.eu](http://www.dataholz.eu).

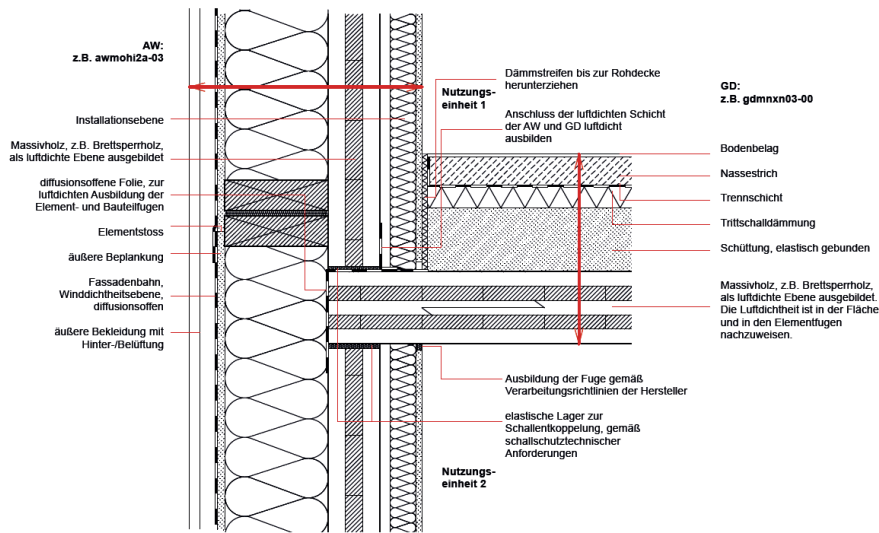


Figure 26: design recommendation for CLT element joints

Especially for multi storey timber buildings the fire detailing of such connections requires the consideration of other aspects, like building physics and statics. For instance, the assessment of the influence of elastomer vibration absorbers in the interface between wall and floor elements becomes necessary for the overall fire safety, see Figure 27. Fire tests with different elastomer absorbers showed excellent results with no additional charring within such connections up to 90 minutes and without failure of integrity or penetration of smoke, (Werther, 2016). It was shown, that despite their combustibility such absorbers do not reduce the fire safety when applied in CLT structures and covered at narrow side with linings, putty or sealant compounds. Fire tests also pointed out, that the measured charring depths within such corners were

less compared to the plane elements, which can be explained by the lower heat flux density at inside corners.



Figure 27: Fire test with elastomer vibration absorber in wall to floor junction, (Teibinger 2011, Merk 2014)

Joints between structural elements shall be tight. Compressed flexible mineral wool with melting point  $> 1000^{\circ}\text{C}$  and density  $\geq 30 \text{ kg/m}^3$  may be used to exclude continuous joints, for instance to fill joints resulting from construction tolerances. Furthermore, for lined CLT elements tight fitted or caulked joints of claddings are essential to prevent an early spread of fire. Similar to in-plane element joints the need of an air tight sealing between the elements is essential which is also required with regard to building physics like sound- and thermal insulation purposes. Such sealing's should applied on both sides of an element or placed in a thermal unexposed area of the connection or joint detail.

## 8. Contribution to fire development

Author of this chapter: Daniel Brandon (RISE)

As timber is a combustible material it can contribute to the fuel load of a fire, which can lead to continuous fires if effective fire service or sprinkler intervention is absent (Brandon and Östman, 2016). This chapter discusses methods for structural fire engineering of timber and cross-laminated timber that account for the contribution of CLT. First the relevance of such methods is discussed. Additionally, a method to account for sprinkles is discussed.

### 8.1 Relevance and recommendations

Structural fire safety and mitigation of fire spread through compartment boundaries are generally regulated using fire-resistance requirements, which indicate the number of minutes a structure should withstand conditions of a standard fire resistance test. However, due to the contribution of timber to a fire and its potential consequences for the fire duration, the fairness of using the same fire-resistance-framework for both combustible and non-combustible materials has been questioned (Law and Hadden, 2017).

A recent statistical study of data from New Zealand (Brandon et al. 2018-1) indicated that direct fire damages within modern multi-storey residential timber structures are not more extensive than fire damages within other types of multi-storey residential structures (see *Figure 28*). This indicates that the current fire-resistance-framework is sufficient to avoid increased damage due to the combustibility of the structure. However, the database used did not include any fires in timber buildings over 5 stories and conclusions of the study cannot be drawn for buildings over 5 stories. The statistical distribution of damages is dependent on numerous factors, of which a significant one is the effectiveness of the fire service. In New Zealand, as in many European countries, it is statistically improbable that the fire brigade does not effectively control local compartment fires in buildings of 3, 4 or 5 stories within an hour.



Fire service intervention of tall buildings, however, involve additional challenges for the fire brigade as a fire may be out of their reach, if they are not allowed to enter a building. In that case it is recommended to design a building to withstand potential burn-out without fire service intervention.

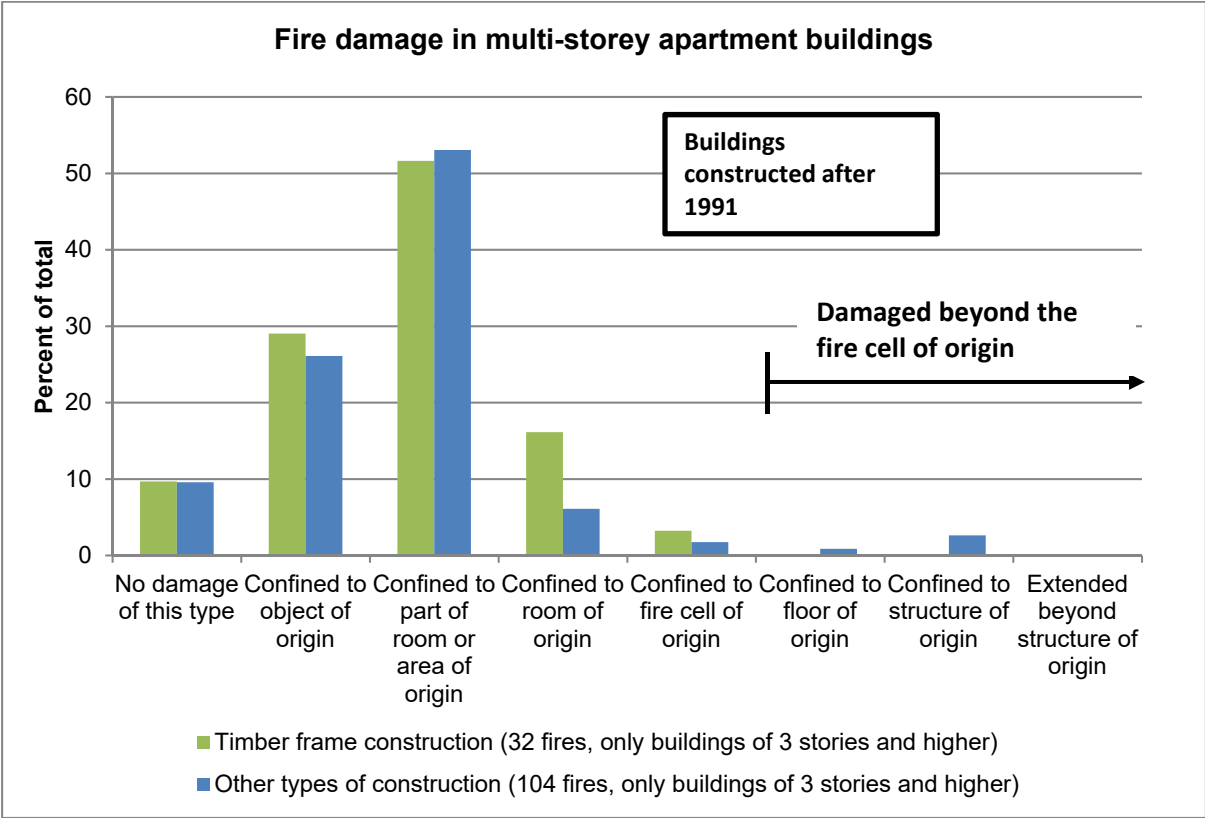
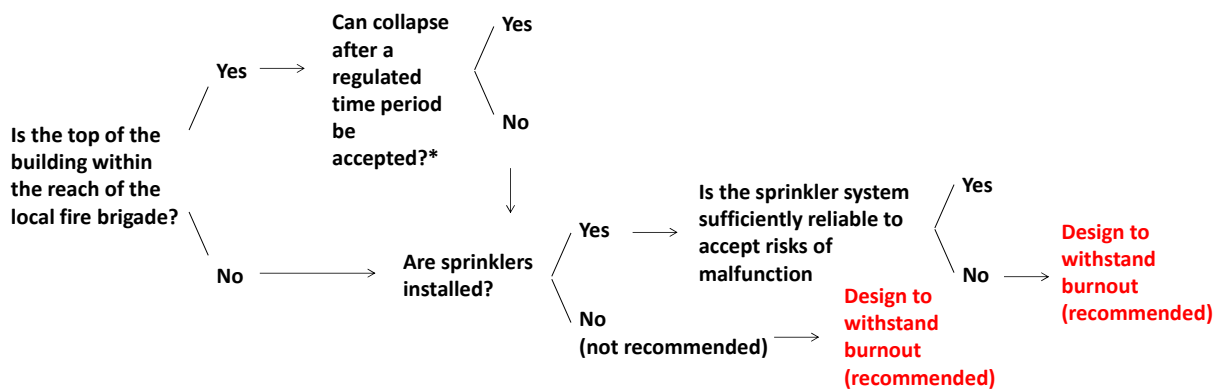


Figure 28. Distribution of damages caused by flame spread and direct radiation in residential multi-storey buildings New Zealand from 2001 to 2015.

As a result of a recent expert meeting organized by COST Action FP1404 on the fire safe use of bio-based building materials recommendations were generated. Whether it is recommended to design for burnout is dependent of the (1) height, (2) design and (3) function of the building, the (4) reach of the local fire service and the (5) presence and (6) reliability of sprinklers. A tree-diagram indicating these recommendations is shown in Figure 29.



\* examples of structures of which collapse may not be acceptable even after a certain fire duration are structures which hold multiple immobile persons such as hospitals and care houses or buildings that have only a single escape route.

Figure 29. Tree-diagram indicating scenarios for which design-for-withstanding-burnout is recommended

## 8.2 Methods

In order to design structures for withstanding burnout, the potential contribution of combustible structures to the fuel load of a fire should be taken into account. For structural analysis, structures are generally assessed for exposure to post-flashover fires, as these are arguably the most damaging to a structure. For assessment of structures in post-flashover fires, methods using single-zone models and methods using parametric design fires exist, which will be discussed in the next two sub-sections.

It should be noted that the contribution of CLT to a fire and the duration of a fire can be significantly increased due to char fall-off or fall-off of fire protection (such as gypsum boards). Both of these phenomena have led to continuous fires in multiple compartment tests (with a few exceptions), Therefore, it is recommended to avoid gypsum board fall-off and char fall-off.

Char fall-off can be postponed or avoided by having a sufficiently thick exposed lamella, which delays heating and weakening of the bond line. However, a recent case study (Brandon et al. 2018-1) indicated that this is not always sufficient in realistic scenarios. Therefore, it is recommended to use thermally resistant adhesives for CLT

which can be identified using fire tests proposed by Janssens (2017) and Brandon and Dagenais (2018).

Only one calculation method to assess fall-off of the base layer of gypsum board has been found in the literature. Brandon (2018-1) proposed to use temperature calculations and a fall-off criterion of gypsum board based on the temperature on the unexposed side of the gypsum board. Fire temperatures needed for this can be calculated using the same methods that are discussed in the following two subsections.

### **9.2.1 Parametric design fires**

All calculation methods discussed in this subsection are described in detail (including a worked example) by Brandon (2018-2).

Parametric design fires are given in Eurocode 1 (1991-1-2) and are based on Swedish fire curves (Magnusson and Thelanderson, 1970). A method to include the contribution of exposed wood for the calculation of a parametric design fire was proposed by Brandon (2018-1). It should be noted that this method can only be used if fall-off of the base layer of gypsum board and char fall-off of CLT are avoided as discussed before.

Advantages of the use of parametric design fires instead of zone models are the simplicity of the calculations and the availability of three different structural calculation methods for timber exposed to parametric design fires. Lange et al. (2015) determined values of the zero-strength-layer to be used together with charring rates by Hadvig (1981). Brandon et al. (2017), however, showed that the zero strength layer for timber exposed to parametric time-temperature curves is not constant during the fire, as it increases during the decay phase. Brandon et al. proposed an effective charring rate, which varies from the real charring rates in the decay phase, and proposed zero-strength-layer thickness values that were dependent on the heating rate of the parametric design fire. The charring models can, however, only be used for structural calculations of timber members with homogeneous cross-sections and are therefore not suitable for CLT. Brandon et al. (2018-2) proposed heating rate dependent effective

thermal properties which can be used to calculate temperatures and the capacity of timber members including CLT slabs. Temperature calculations can also be used in combination with CST-Fire by Schmid et al. (2018).

### **9.2.2 Single-zone models**

A single-zone model can be used to calculate temperatures based on an equilibrium of energy gains and energy losses. In a single zone model it is assumed that there is no spatial variation of temperature in a compartment. This assumption is, however, not accurate for large compartments and Eurocode 1 (EN 1991-1-2) limits the use of this assumption to compartments with a floor area up to 500m<sup>2</sup>.

Single-zone models have been proposed, that include the contribution of CLT using calculations of the material temperatures and charring rates (Brandon 2016, Hopkins et al. 2017). The input for these methods is the heat release rate vs time curve corresponding to a flashover fire involving only the moveable fuel load (i.e. the combustible content of the compartment). The fire temperature is calculated using a single-zone model and the temperatures throughout the CLT are calculated using a finite element or finite difference model. Using a charring temperature (generally 300°C) the charring rate can be estimated. Due to an approximately constant ratio between the charring rate and the heat release rate, the heat release rate corresponding to the combustion of timber can be estimated. In the calculation the heat release rates of the moveable fuel load and the heat release rate of the charring timber are added to obtain the total heat release rate of the fire. Brandon (2016) included the contribution of timber in multiple iterations, as the contribution of timber can prolong the fire, which leads to more contribution of timber. Hopkins et al. (2017) avoided the use of an iterative procedure by updating the timber's contribution in all time steps of the calculation. The heat release rate of the timber material can prolong the fully developed phase of the fire and can prevent a fire from decaying if too much timber is exposed.

Using results of the temperature calculations throughout the CLT (or timber) member, structural calculations could be performed by assuming temperature dependent

material properties. However, due to lack of suitable tests (i.e. compartment fire tests with relevant structural loads) such a method is difficult to validate.

### **8.3 Accounting for sprinkles**

The presence of sprinklers and uncertainties regarding sprinkler activation can be taken into account using Eurocode 1 (1991-1-2). Based on statistics, this approach involves a reduction of the moveable fuel load density (which excludes the CLT contribution) of compartment used for calculations.

## **9. References**

Angehrn C., Brühwiler I., Wiederkehr R. (2018) Lignum-Dokumentation Brandschutz 4.2 Bauteile in Holz – Anschlüsse bei Bauteilen mit Feuerwiderstand

Blaß, Hans Joachim; Uibel, Thomas: Load carrying capacity of joints with dowel type fasteners in solid wood panels. CIB Paper 39-7-5, 2006

Brandon D., Östman B. (2016) Fire Safety Challenges of Tall Wood Buildings – Phase 2: Literature Review. NFPA report: FPRF-2016-22.

Brandon D, Just A, Andersson P, Östman B (2018) Mitigation of fire spread in multi-storey timber buildings – statistical analysis and guidelines for design. RISE Report 2018:43.

Brandon D., Dagenais C. (2018) Fire Safety Challenges of Tall Wood Buildings – Phase 2: Task 5 – Experimental Study of Delamination of Cross Laminated Timber (CLT) in Fire. National Fire Protection Association. NFPA report: FPRF-2018-05.

Brandon D (2018) Fire Safety Challenges of Tall Wood Buildings – Phase 2: Task 4 - Engineering methods. National Fire Protection Association. NFPA report: FPRF-2018-04.

Brandon D (2018) Engineering methods for structural fire design of wood buildings – structural integrity during a full natural fire. RISE Rapport 2018:44, Research Institutes of Sweden, Stockholm, Sweden.

Brandon D., Just A., Lange D., Tiso M. (2017) Parametric fire design – Zero-Strength-Layers and Charring Rates.

Brandon D. Practical method to determine the contribution of structural timber to the heat release rate and fire temperature of post-flashover compartment fires. Technical Research Institute of Sweden – SP, SP Report 2016:68, Borås, Sweden; 2016.

Craft S., Barber D., Klippel M., Schmid J., Frangi A. (2018) Test Methods to Evaluate the Adhesive Performance in CLT when Exposed to Fire, World Conference on Timber Engineering WCTE 2018, 20-23 August, Seoul, Republic of Korea.

CONSTRUCT 01/491 rev 3. Classification of products of known and stable performance - Procedural aspects, 2004.

EN 13501-1:2009. Fire classification of construction products and building elements -

EN 1995-1-2. Eurocode 5 - Design of timber structures - Part 1-2 - General: Structural fire design. CEN. 2004.

EN 13501-2. Fire classification of construction products and building elements. Classification using test data from reaction to fire tests. CEN, 2007.

EN 13381-7. Test methods for determining the contribution to the fire resistance of structural members - Part 7: Applied protection to timber members. CEN, 2018.

EN 1991-1-2 (2002) Eurocode 1: Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire. CEN, Brussels.

EN 16755:2017. Durability of reaction to fire performance of FRT wood-based products in interior and exterior end-use applications. European Standard. CEN - European Part 1: Classification using test data from reaction-to-fire tests. European Standard. CEN - European committee for standardization, Brussels.

EN 13501-2:2009. Fire classification of construction products and building elements - Part 2: Classification using data from fire resistance tests, excluding ventilation services. European Standard. CEN European Committee for Standardization, Brussels.

Erchinger CD. (2009) Zum Verhalten von Mehrschnittigen Stahl-Holz-Stabdübelverbindungen im Brandfall. PhD Thesis, vdf Hochschul-Verlag, Zurich, 2009.

Fahrni R., Schmid J., Klippel M., Frangi A. (2018) Correct temperature measurements in fire exposed wood, World Conference on Timber Engineering WCTE 2018, 20-23 August, Seoul, Republic of Korea.

Fahrni, R., Schmid, J., Klippel, M, Frangi, A. (2018), Investigation of different designs and installations of temperature measurements in wood as low conductive materials, Conference Structures in Fire SIF'18, Belfast, 2018.

Fornater J, Bergmeister K, Hochreiner G. (2001) Versuchsbericht – Kleinbrandversuchsreihe 2. Teil 1 KBV 2/1 – Versuche mit Rissen. Institut für konstruktiven Ingenieurbau, Universität für Bodenkultur, Vienna, 2001.

Frangi A, König J. (2011) Effect of increased charring on the narrow side of rectangular timber cross-sections exposed to fire on three or four sides. Fire Mater. 2011; 35(8): 593–605.

Hadvig S (1981) Charring of wood in building fires. Technical University of Denmark. ISBN 87-87 245-83-3.

Hopkin D., Anastasov S., Brandon D. (2017) Reviewing the veracity of a zone-model-based approach for the assessment of enclosures formed of exposed CLT. In: Gillie. M, Wang Y. Applications of Fire Engineering.

Janssens (2017) Development of a fire performance assessment methodology for qualifying cross-laminated timber adhesives. South West Research Institute

Jauk, Günther: Triumph of CLT continues. timber-online.net, 14.11.2017

Jauk, Günther; Ebner, Gerd: BSP Special. Holzkurier 2017

Klippel M, Leyder C, Frangi A, Fontana M, Lam F, Ceccotti A. (2014) Fire tests on loaded cross-laminated timber wall and floor elements. Proceedings of the 11th International Symposium, Christchurch, 2014.

Klippel M., Schmid J. (2017) Design of Cross-Laminated Timber in Fire, Structural Engineering International, 27 (2): 224-230, International Association for Bridge and Structural Engineering, 2017.

Klippel M., Schmid J., Fahrni R., Frangi A. (2018) Assessing the Adhesive Performance in CLT Exposed to Fire, World Conference on Timber Engineering WCTE 2018, 20-23 August, Seoul, Republic of Korea.

König J. (1995) Fire resistance of timber joists and load bearing wall frames. Report I 9412071, Swedish Institute for Wood Technology Research, Stockholm, 1995.

König J, Walleij L. (1999) One-dimensional charring of timber exposed to standard and parametric fires in initially protected and non-protected fire situations. Report No. I 9908029, Trätek, Swedish Institute for Wood Technology Research, Stockholm, 1999.

Lange D., Boström L., Schmid J., Albrektsson J. (2015) The reduced cross section method applied to glulam timber exposed to non-standard fire curves. Fire Technology DOI: 10.1007/s10694-015-0485-y

Law A, Hadden R.M. (2017) Burnout means burnout. SFPE Europe Q1 2017 (5).

LeVan S, Holmes C A (1986). Effectiveness of fire-retardant treatments for shingles after 10 years of out-door weathering. Research Paper FPL 474.

Mäger, K N et al., Procedure for implementing new materials to the component additive method, Fire Safety Journal, 2017.

Magnusson S.E., Thelanderson S. (1970) Temperature-time curves of complete process of fire development. Acta Polytechnica Scandinavica, 65.



Merk M, Werther N, Grafe M, Fulle C, Leopold N, Sprinz D, Busch M, Brunn M (2014) Erarbeitung weiterführender Konstruktionsregeln/-details für mehrgeschossige Gebäude in Holzbauweise der Gebäudeflasse 4. Fraunhofer IRB Verlag, Stuttgart, Deutschland.

Ollis WJB. (1968) Standard tests and calculation of fire resistance in timber. Munic. Eng. 1968; 145: 1213.

Östman B, Mikkola E, Stein R, Frangi A, König J, Dhima D, Hakkarainen T, Bregulla J (2010). Fire safety in timber buildings – European Guideline. SP-Technical Research Institute of Sweden. SP Report 2010:19.

Östman B, Mikkola E (2010). European classes for the reaction to fire performance of wood-based panels. Fire and Materials 34:315-332.

Östman B, Tsantaridis L (2017). Durability of the reaction to fire performance of fire retardant treated wood products in exterior applications – A ten years report. International Wood Products Journal, 8:2, 94-100.

Östman et al., Fire safety in timber buildings - Technical guideline for Europe. SP Technical Research Institute of Sweden, 2010.

Östman B., Schmid J., Klippel M., Just A., Wether N., Brandon N. (2018) Fire design of CLT in Europe, Wood and Fiber Science, Vol 50 (Special Issue – CLT/Mass Timber).

Schleifer, V. Zum Verhalten von raumabschliessenden mehrschichtigen Holzbauteilen im Brandfall, PhD Thesis, ETH Zurich, 2009.

Schmid J., Klippel M., Just A., Frangi A, Tiso M. (2018) Simulation of the fire resistance of Cross-Laminated Timber (CLT). Fire Technology 54(5) pp 1113-1148.

Schmid J., Brandon D., Werther N., Klippel M. (2018), Technical note - Thermal exposure of wood in standard fire resistance tests. Fire Safety Journal. <https://doi.org/10.1016/j.firesaf.2018.02.002>.

Schmid J., Lange D., Sjöström J., Brandon D., Klippel M., Frangi A., (2018) The use of furnace tests to describe real fires of timber structures, Proceedings of 10th International Conference on Structures in Fire, Belfast, UK: Ulster University, 2018.

Teibinger M. (2011) Brandschutz im Detail. Holzbau, die neue quadriga (4), 39-43.

Teibinger M., Matzinger I, (2013) Construction with Cross-Laminated Timber in Multi-Storey Buildings – Focus on Building Physics. Wien, Österreich: Holzforschung Austria

Tiso, M. The contribution of cavity insulations to the load-bearing capacity of timber frame assemblies exposed to fire. PhD thesis, Tallinn University of Technology, Estonia. 2018

Tiso, M and Just, A. Design criteria for insulation materials applied in timber frame assemblies, Journal of Structural Fire Engineering, Nov. 2017.

Werther et al. Standardisierung der brandschutztechnischen Leistungsfähigkeit von Holztafelkonstruktionen mit biogenen Dämmstoffen. Report of TU Munich, 2018.

Werther N, Denzler K.J, Stein R, Winter S, (2016) Detailing of CLT with Respect to Fire Resistance, Proceedings of the Joint Conference of COST Actions FP1402 and FP1404, Stockholm, Sweden, 10th – 11th March 2016

# **Guidance on Fire design of CLT including best practise**

**COST Action FP 1404**

**“Fire Safe Use of Bio-Based Building Products”**

**Document N223-07**



**COST Action FP1404**

Chair of COST Action FP1404: Joachim Schmid

Vice Chair of the Action: Massimo Fragiaco