Engineering methods for structural fire design of wood buildings– structural integrity during a full natural fire

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Preface

This report discusses a new analytical design approach for tall timber buildings which includes calculation methods that were recently developed in parallel projects funded by Formas and Brandforsk in Sweden Additionally a method developed during a project by FPRF (Fire Protection Research Foundation), NFPA (National Fire Protection Association) in the USA is used as the base of the approach. The reports resulting from that study are cited throughout this report and are published on:

https://www.nfpa.org/News-and-Research/Fire-statistics-and-reports/Research-reports/Building-and-life-safety

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- Brandforsk
- Swedish wood

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1 Introduction

Structural collapse as a result of fire is rare, but it can, especially in case of high rise buildings, lead to high property loss. For buildings with a risk of high financial damages, such as tall buildings, there may be a need to show that the building can withstand a complete natural fire without structural collapse, by e.g. using simulation and calculation methods. Such methods and guidance on how to use these are available for structures made of concrete and steel. Hereby, the structure is assessed against design fire exposures which are expected in a potential fire of the specific building or building design. However, such methods and guidance on how to use them is lacking for tall timber buildings.

The risk of collapse is dependent on the fire exposure and properties of the structure. When timber is the structural material, the structure can have an influence on the fire exposure as timber can contribute to the fire as fuel. Therefore, successful structural design methods should include the contribution of timber to the fuel of the fire.

This report presents a design strategy and guide lines to limit the risk of progressive collapse. The strategy includes a number of methods that were developed in recent projects. The scope of this work is limited to fires during the utilization phase of buildings and, therefore, it excludes fires that occur during the construction phase. An overview of the strategy is given in Annex B.

2 Background

Timber buildings are generally designed using prescriptive regulations for fire safety. Based on the function and the height of the building, there are certain prescriptive requirements regarding exposed material's reaction to fire and the fire resistance of structural and compartment separating elements. The fire resistance is defined as the time in minutes in which a structure can withstand the conditions of a standard fire test. As prescriptive regulations are mostly based on experience, these regulations may not be sufficient for unconventional buildings (such as tall timber buildings). In Swedish regulations it is mandatory to use analytical design methods to demonstrate that an acceptable level of fire safety is achieved, for buildings over 16 stories (BBR 25). Structural integrity is designed according to EKS (BFS 2015:6; 2015) which in turn relies on the Eurocodes (EN 1995-1-2, 2004). There are, however, no specified performance requirements regarding the structural behaviour of this type of buildings. In contrast, in Denmark and Norway it is required to design certain types of buildings, so that the building can withstand a full natural fire without collapse and without the interference of the fire brigade or sprinklers. The design of concrete and steel structures to meet these requirements is possible using existing engineering methods. However, there are no widely accepted engineering tools available for the design of timber structures.

Generally, timber structures can be divided into light timber frame structures and mass timber structures. Light timber frame structures generally are made of structural timber elements with their smallest dimension under 80mm (Buchanan, 2000). These elements on their own do not have a significant structural resistance in fire and have to

be encapsulated if to be applied in buildings with fire safety requirements. Mass timber structures are made with larger timber elements, such as glued laminated beams and cross-laminated timber slabs. These elements keep their structural integrity for longer time periods than timber elements of light timber frame structures because of their size. If timber elements are exposed to fire, a char layer is formed on the exposed surface. The char layer is thermally insulating and protects the wood deeper inside the timber element. Dependent on the size of the members, un-encapsulated mass timber elements achieve fire resistances that are required for tall buildings in most countries. Exposed mass timber, however, has an influence on the fire development if it becomes involved in a fire. Therefore, a suitable engineering design method should include the contribution of exposed timber for the structural assessment of exposed timber structures.

This report provides a strategy for structural design to limit the risk of structural collapse and refers to recently developed engineering methods that correspond to the strategy. Predictions for structures with and without exposed timber are discussed separately.

3 Relevant studies

The strategy presented herein uses a combination of methods presented in recent studies. The studies of which the methods are used are shown in Table 1.

Table 1: Overview of included studies

Project name	References	Supporting research council
Fire Safety Challenges of Tall Wood Buildings Phase 2 Task 4: Engineering Methods	Daniel Brandon (2018) Fire Safety Challenges of Tall Wood Buildings Phase 2 Task 4: Engineering Methods Joseph Su, Pier-Simon Lafrance, Matthew Hoehler, Matthew Bundy (2018), Cross Laminated Timber Compartment Fire Tests for Research on Fire Safety Challenges of Tall Wood Buildings, Phase 2. Daniel Brandon, Birgit Östman (2016) Fire Safety Challenges of Tall Wood Buildings Phase 2 Task 1: Literature Review	FPRF (*Fire Protection Research Foundation*) / NFPA (*National Fire Protection Agency*)
Fire Safety Challenges of Tall Wood Buildings Phase 2 Task 5: CLT tests	Daniel Brandon and Christian Dagenais (2018) Fire Safety Challenges of Tall Wood Buildings Phase 2 Task 5: Experimental Study of Delamination of Cross-Laminated Timber (CLT) in Fire	FPRF (*Fire Protection Research Foundation*) / NFPA (*National Fire Protection Agency*)

Project name	References	Supporting research council
Natural Fire Design	Daniel Brandon, David Lange, Alar Just, Mattia Tiso (2017) Parametric Fire Design. *In:* INTER International Network on Timber Engineering Research Proceedings. August 2017, Kyoto, Japan. ISSN 2199-9740. Daniel Brandon, David Lange, Ulf Wickström, Joachim Schmid (2018) Material Property reduction method. Submitted to Fire Technology	Formas
The influence of parametric fire scenarios on structural timber performance and reliability	David Lange, Lars Boström, Joachim Schmid, Joakim Albrektsson (2014) The influence of parametric fire scenarios on structural timber performance and reliability. SP Report 2014: 35, SP Technical Research Institute of Sweden, Borås	Brandforsk

4 Analysis of progressive collapse multi-storey buildings caused by fire

Collapse within multi-storey buildings as a consequence of fire is rare. However, especially when the collapse is progressive, the event can lead to high risks of loss of life and to high financial consequences. In case of progressive collapse, failure of one structural element leads to the failure of one or more other structural elements. Therefore, progressive collapse often involves the destruction of multiple floors and sometimes the entire building.

An international overview of collapse of structures as a result of fires in buildings that exceed 3 floors is given by Beitel and Iwankiw (2008). Their overview included also collapse that was not progressive. Table 2 provides overview of fires that lead to progressive collapse and excludes fires that occurred during the construction phase of a building. In addition to the overview given by Beitel and Iwankiw, the table includes some more recent fires and an indication of the number of floors that were directly exposed to the fire and the time it took to extinguish the fires. It should be noted that the validity of the references may vary, as information is obtained from different media and news articles. The amount of floors that were directly exposed to the fire is estimated using photographs from the referenced articles.

Table 2 shows that all, except for one, cases of progressive collapses in buildings exceeding 3 floors caused by fires involved fire spread over more than two storeys. In the single case that the fire did not spread beyond two stories, a structural error was identified by Vahey (1972). This correlation indicates that limiting fire spread within the fire compartment of origin can lead to reduced risk of progressive collapse and that limiting fire spread should be included in a strategy to prevent progressive collapse.

Table 2: Overview of fires that lead to progressive collapse (data from Beitel and Iwankiw, 2008 unless stated otherwise)

Building name	Location	Year of incident	Main structural material	Number of floors	Time until collapse (h)	Fire spread >2 floors	Reference for additional information (in red)
Unknown (Residential)	St. Petersb., Russia	2002	Concrete	9	1	yes	Beitel and Iwankiw (2008)
WTC 7	New York, NY, USA	2001	Steel frame	47	7	yes	Beitel and Iwankiw (2008)
WTC 2	New York, NY, USA	2001	Steel frame	110	1	yes	Beitel and Iwankiw (2008)
WTC 1	New York, NY, USA	2001	Steel frame	110	1.5	yes	Beitel and Iwankiw (2008)
WTC 5	New York, NY, USA	2001	Steel frame	9	8	yes	Beitel and Iwankiw (2008)
Pentagon	Washington DC, USA	2001	Concrete	5	2	yes	Beitel and Iwankiw (2008)
Textile factory	Alexandria, Egypt [1]	2000	Concrete	6	9	Unkn.	Beitel and Iwankiw (2008)
Faces Nightclub and Memories Lounge Bar	Motherwell, Lanarkshire UK	2001	Unknown	4	2	Unkn.	Beitel and Iwankiw (2008)
Apartment van der grift	Pittsburgh, PA, USA	2000	Timber	6	Unkn.	Unkn.	
Katrantzos Sport Department Store	Athene, Greece	1980	Concrete	8	<3	Yes	Papaioannou (1986)
Apartments, Brooke	Bronx, NY, USA	1994	Masonry	5	Unkn.	Unkn.	
Central Square Apt. Massachusetts Ave. And Douglas St.	Cambridge, MA, USA	1993	Masonry	8	Unkn.	Unkn.	
CESP Building 2	Sao Paulo, Brazil	1987	Concrete	21	2	Unkn.	Beitel and Iwankiw (2008)
Hotel Vendome	Boston, MU, USA	1972	Masonry with cast iron	5	3	No (2 stories) **	Vahey (1972)
Delft University	Delft, the Netherlands	2008	Concrete & steel frame	13	8	yes	Engelhardt et al. (2013)
Plasco	Tehran, Iran	2017	Steel frame	17	3.5	yes *	ABC news (2018)
Wilton Paes de Almeida Building	Sao Paulo	2018	Steel frame & concrete slabs	24	1.5	yes *	Wikipedia (2018)

* Indicated by photographic evidence found in the reference

** Accident report by Vahey (1972) indicated a structural error which has led to failure during the increased load by water

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The duration of the fire is also directly related to the risk of collapse, because the strength of structural materials is reduced during heating and the risk that the structural capacity is insufficient to bear the loads increases.

The overview in Table 2 only includes one building with timber as the main structural materials. However, multiple studies (Medina Hevia, 2014; Hadden et al. 2017; Su et al., 2018) have shown that fires in compartments with exposed timber or insufficiently protected timber are potentially continuous, which means that they would lead to collapse if the fire service and sprinkler activation is not sufficient or not present. In reality, there is a risk that sprinkler systems do not activate or are not sufficient to extinguish a fire (approximately 12% of the cases in USA, NFPA, 2017). Additionally, fire service interference is increasingly challenging for fires in increasingly tall buildings. In order to reduce the risk of collapse it could, therefore, be necessary to design compartments so, that a fully developed fire which could occur, would involve a decay phase and potentially would extinguish automatically. If methods are available structures can be designed so that fires involve a decay phase and extinguish automatically and that there is no structural collapse for the entire duration of the fire.

5 Methods

Based on the analysis discussed in the previous chapter a strategy to prevent progressive collapse should include the following aspects:

- Robust separations between fire compartments, involving all elements in the compartment boundaries, such as walls, ceilings, connections and electricity and ventilation channels;
- Conditions that lead to a decay phase and self-extinguishment of a fire, even if effective sprinkler activation and fire service interference are lacking;
- A structure that withstands the full natural fire until self-extinguishment is achieved.

These aspects concern the performance of the structure in natural fires which are depending on the design of the building. As it is not possible to test the performance in a full natural fire this needs to be assessed through numerical simulations. In Sweden analytical design is required for buildings of building class BR0 (which includes buildings exceeding 16 stories). This involves an evaluation of the design against performance criteria using severe design fires that are approximations of natural fires expected in the compartment. These design fires should be dependent on relevant parameters, such as the dimensions, ventilation conditions (dimensions of ventilation openings), thermal properties of lining materials and the quantity of the fuel load (combustibles).

Analytical design is increasingly used for the design of concrete and steel structures. However, due to a lack of engineering methods, analytical structural design is in practice not implemented for timber buildings.

This report presents a strategy involving analytical design methods developed in recent and parallel projects (Lange et al, 2015; Brandon et al., 2017; Brandon, 2018).

For this a distinction is made for:

- Mass timber structures, which comprise of timber members with a smallest dimension exceeding 80mm.
- Light timber frame structures, which comprise of smaller timber members that require sufficient encapsulation in order to achieve fire resistances relevant for tall buildings.

Common engineered timber products used in mass timber structures are *cross-laminated timber* (CLT) and *glued laminated timber*. Large (mass) timber members keep their structural integrity for a longer time period than small timber members and are, therefore, sometimes applied without encapsulation. Recent studies have, however, shown that there is a limit of amount of surface area that can be exposed in natural fires as exposed timber contributes to a fire as fuel. Light timber frame structures should be protected against fire using encapsulation, by for example fire rated gypsum plaster boards, in order to obtain sufficient fire resistance. If the integrity of the protection is compromised, the timber frame can still contribute to the fire. Methods to design mass timber and light timber frame structures for self-extinguishment are taken from recent research projects and summarized in this report.

5.1 Parametric design fires (background)

Parametric design fires are used for analytical fire design of structures against post-flashover fires. Different parametric fires were proposed previously (Wickström, 1986; Lie 1974; Petterson and Magnusson, 1974; Mehaffey, 1999; Ma and Makelainen, 2000, Barnett, 2002 and Franssen, 1999). These design fires prescribe the fire temperature development based on design parameters of the building.

Parametric design fires involve a fully developed phase and a decay phase. These design fires do not take a possible second flashover into account, which could occur in the decay phase. From the literature review by Brandon and Östman (2016) two causes of a second flashover were identified:

- Integrity failure of engineered timber elements, such as heat delamination of CLT lamellas, during the fire;
- Failure of gypsum boards (or other fire protective boards), causing initially protected CLT or timber surfaces to become exposed.

Parametric design fires can, therefore, only be valid if these causes for a second flashover are avoided.

Delamination of CLT can be avoided by:

1. using non-delaminating adhesives, as shown by Brandon and Dagenais (2018) and Janssens (2017);
2. designing the apartment so that the delamination temperatures of the bond line are not reached.

Examples of compartment fires in which the critical bond line temperature was not reached during the full duration of a flashover fire are the compartment fire tests

recently performed at the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF). Also tests by Medina Hevia (2014), Hadden et al. (2017) and Emberley et al. (2017) involved exposed CLT, without occurrence of heat delamination.

Failure of the gypsum board protection can be avoided, by using the right type and a sufficient amount of fire rated gypsum board layers. Additionally, it is important the gypsum boards are attached with sufficient amount of fasteners, with a sufficient penetration depth into the timber and limited screw distances.

Parametric fires, provided by Eurocode 1 (EN1991-1-2, 2002), describe the development of the compartment fire temperature based on:

- the opening factor of a compartment (suitable for vertical ventilation openings only)
- the thermal inertia of compartment linings
- the fuel load density relative to the surface area of the compartment boundaries

It can be noted that the fuel load of the fire should be known, which includes the contribution of timber. As the contribution of timber is dependent on the fire development, it is not possible to directly obtain a suitable temperature development with the equations for parametric fires. In this report a method is discussed to include the contribution of timber to the fuel load. A successful model results in conservative predictions of the damaged timber after the fire.

The parametric fire curves assume that the fire temperature is independent of the location in the compartment. According to Eurocode 1 this assumption is suitable for compartments with a floor area up to 500m².

5.2 Generating parametric design fires

The relationship between the fire temperature, Θ, and the time, t, given by Eurocode 1 (EN 1995-1-2, 2004) of parametric fires is:

$$\Theta = 20 + 1325(1 - 0.324e^{-0.2t\Gamma} - 0.204e^{-1.7t\Gamma} - 0.472e^{-19t\Gamma}) \tag{1}$$

where Γ is a factor that changes the heating rate corresponding to the thermal inertia of the compartment boundaries and the opening factor, O, of a compartment:

$$\Gamma = (O/\sqrt{pc\lambda})^2 / (0.04/1160)^2 \tag{2}$$

$$O = \frac{A_v}{A_t}\sqrt{h_v} \tag{3}$$

Where, p is the density in kg/m³, c is the specific heat J/kgK and λ is the thermal conductivity in W/mK of the compartment's boundary, A_v is the total area of the ventilation openings (m²), A_t is the total area of floors walls and ceilings of the compartment (m²), h_v is the height of the opening or the weighted average of the height of multiple openings (m).

The duration of the heating phase t_{max} (h) is related to the fuel load within the compartment:

$$t_{max} = \max\left[(0.2 \cdot 10^{-3} q_{t,d}/O); t_{lim}\right] \tag{4}$$

Where: $q_{t,d}$ is the fuel load divided by the total surface area of the compartment boundaries (including walls and ceiling) in MJ/m²; t_{lim} is the lower limit of the duration of the heating phase, which is 0:15h, 0:20h or 0:25h for fast, medium and slow fire growth, respectively. After the start of the cooling phase at t_{max}, the temperature decreases linearly until it reaches 20°C according to one of the following expressions:

$$\Theta = \Theta_{max} - 625(t \cdot \Gamma - t_{max} \cdot \Gamma \cdot x) \qquad\qquad \text{if} \qquad\qquad t_{max} \cdot \Gamma \leq 0.5 \quad (5)$$

$$\Theta = \Theta_{max} - 250(3 - t_{max} \cdot \Gamma)(t \cdot \Gamma - t_{max} \cdot \Gamma \cdot x) \qquad \text{if} \qquad 0.5 < t_{max} \cdot \Gamma < 2 \quad (6)$$

$$\Theta = \Theta_{max} - 250(t \cdot \Gamma - t_{max} \cdot \Gamma \cdot x) \qquad\qquad \text{if} \qquad\qquad t_{max} \cdot \Gamma \geq 2 \quad (7)$$

$$x = 1.0 \text{ if } t_{max} > t_{lim} \text{ or } x = t_{lim}\Gamma/t_{max}\Gamma \text{ if } t_{max} = t_{lim}$$

5.3 Charring of timber in parametric fires

Two models exist that describe charring rates of timber in parametric fires (Hadvig, 1981 and Brandon et al., 2018). Both are discussed and compared in this section.

Hadvig (1981) developed an empirical model to predict charring depths from a large number of parametric fire tests in a furnace. The model is discussed in this section. The initial charring rate β_{par} is dependent on the heating rate factor, Γ, mentioned in the previous section.

$$\beta_{par} = 1.5\beta \frac{0.2\sqrt{\Gamma} - 0.04}{0.16\sqrt{\Gamma} + 0.08} \tag{8}$$

where, β is the charring rate (mm/min) corresponding to standard fire resistance tests following ISO 834, which is applicable according to Eurocode 5. This charring rate is either the one-dimensional (β_0) or the notional charring rate (β_n) as described in Eurocode 5 (EN 1995-1-2, 2004) dependent on the geometry of the timber member and the presence of exposed corners of the members. The one-dimensional charring rate corresponding to soft wood is 0.65mm/min according to Eurocode 5.

Brandon et al. (2018) re-evaluated the equation with fire tests in modern furnaces, in which the exposure is controlled using plate thermometers:

$$\beta_{par} = \beta\Gamma^{0,25} \tag{9}$$

It should be noted that the one dimensional charring rate corresponding to fire resistance tests found by Brandon et al. was β_0=0.67mm/min.

Figure 1 shows initial charring rates of three different studies in furnaces of different scales. Additionally, the charring rates given by eq.8 (Hadvig, 1981) and eq.9 (Brandon et al., 2018) are included in the figure. Eq.9 (solid line) is more conservative than eq.8 and corresponds better with recent fire tests.
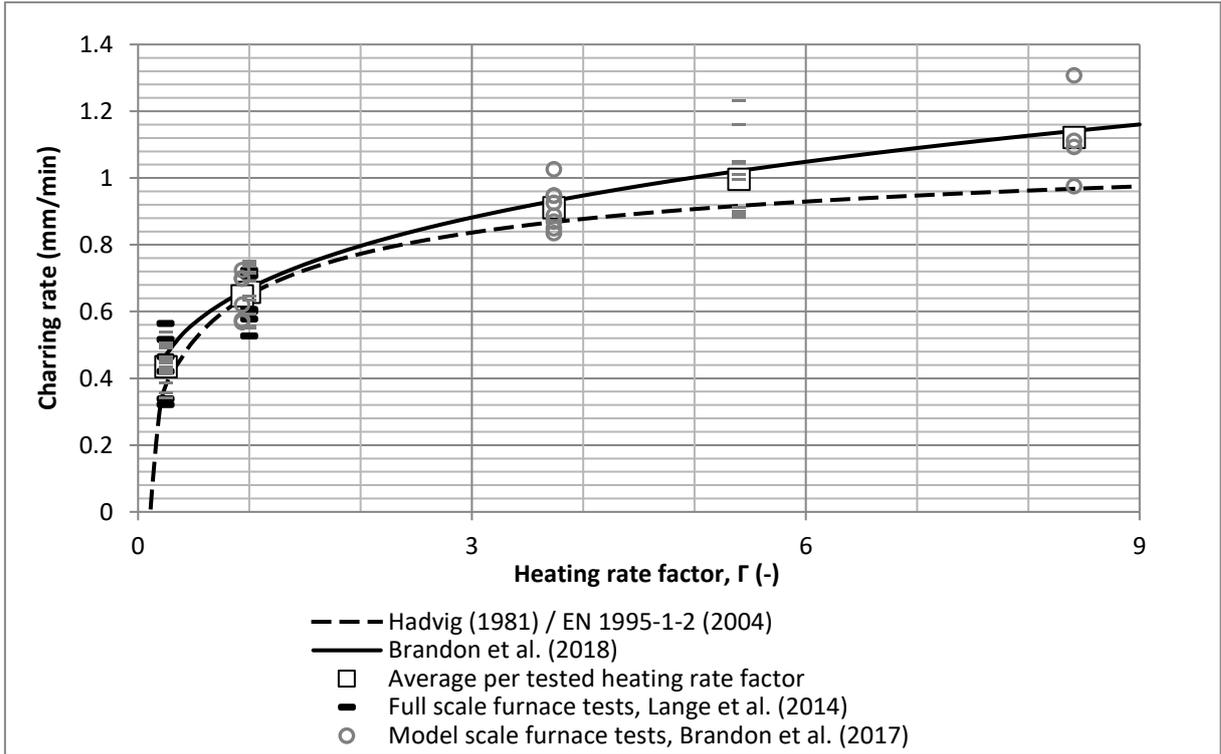
Figure 1: Charring rates during the fully developed stage of parametric fires

Hadvig (1981) and Brandon et al. (2018) used the same approach to describe the reduction of the charring rate in the decay phase. At time $t=t_o$ the charring starts to reduce linearly until it completely stops at time $t = 3 t_o$:

$$t_o = 0.009 \frac{q_{t,d}}{O} \tag{10}$$

The charring depth at any moment can be calculated using:

$$d_{char} = \beta_{par} t \qquad \text{for } t \leq t_o \tag{11}$$

$$d_{char} = \beta_{par} \left(1.5t - \frac{t^2}{4t_o} - \frac{t_o}{4} \right) \qquad \text{for } t_o < t < 3t_o \tag{12}$$

$$d_{char;end} = 2\beta_{par} t_o \qquad \text{for } t \geq 3t_o \tag{13}$$

6 Parametric fire design for light timber frame structures and mass timber structures with full gypsum encapsulation

Parametric fires can only be applied if sudden contribution of encapsulated timber is avoided. Therefore, it is required that there is a sufficient amount of gypsum board layers protecting the timber.

Recently, a method was developed within a project led by the NFPA on fire safety challenges of tall wood buildings (Brandon, 2018) to predict the fall-off of gypsum boards in natural fires. For the validation of the model, all relevant data that were available of compartment fire tests with encapsulation were analysed. From a study of compartment tests, performed for the same study (Su et al., 2018), it was observed that fall-off of the exposed gypsum layer from the ceiling occurred when the temperature behind the first gypsum board was between 300°C and 500°C. Therefore, the proposed method by Brandon (2018) conservatively assumed that gypsum fall-off occurs when and if the temperature on its unexposed side reaches 300°C. To implement gypsum fall off, all elements representing the falling layer should be removed from the model after the temperature on the unexposed side of the layer has reached 300°C.

The model is limited to be used for type F (in Europe), type X and type C (in North-America) gypsum boards only. Using parametric design fires from Eurocode 1, a homogeneous fire temperature is assumed in the entire compartment, making the model only suitable for compartments with floor areas smaller than 500m² according to Eurocode 1.

The method requires finite element temperature calculations. One-dimensional heat transfer calculations are sufficient for walls and floors with a homogeneous build-up such as encapsulated or unprotected CLT. For timber frame assemblies (with studs) the heat transfer will not be one-dimensional and require more extensive two-dimensional or three-dimensional heat calculations.

An example of a calculation in accordance with the method is discussed in Annex A. According to the proposed model, the following steps should be modelled:

> **Step 1)** Calculation of the temperatures of the assembly protected with type F or type X gypsum board(s) (1, 2 or 3-dimensional). The used fire temperature is defined by the parametric fire that corresponds specifically with the compartment design. The convective and radiative heat transfer to the exposed surface of the assembly should be in accordance with Eurocode 1 and can be expressed as follows:
>
> $$q_n = h_c(T_f - T_s) + \sigma\varepsilon(T_f^4 - T_s^4) \tag{14}$$
>
> where q_n is the net heat flux through the surface, h_c is a convection coefficient, σ is the Stefan Boltzmann constant, ε is the effective emissivity, T_f is the fire

temperature and T_s is the surface temperature. In accordance with Eurocode 5, on the exposed side, a convection coefficient of 25 W/m²K and an emissivity of 0.8 should be used. On the unexposed side, the same emissivity and a lower convection coefficient should be implemented (9 W/m²K).

Effective thermal properties of wood showed in Table 3 (from Brandon et al. 2018). In order to allow predictions of temperatures in a range of parametric fires corresponding to heating rates from Γ=0.25 to Γ=9.0 in accordance with eq. (2), the thermal conductivity is scaled using a factor α:

$$\alpha = 1.54\Gamma^{-0.244} \qquad (15)$$

Furthermore, effective thermal properties of gypsum showed in Figure 2 and Table 4 should be used as material properties (Tiso, 2014). The thermal properties can be determined for every temperature between 20 and 1200°C from the tables by linear interpolation.

Table 3: Effective thermal properties for parametric fire exposure

Temperature (°C)	Thermal conductivity (W/mK)	Specific heat (J/kgK)	Density (kg/m³)
20	0.12	1530	495
98	0.133	1770	495
99	0.265	13600	495
120	0.272	13500	495
121	0.137	2120	495
200	0.15	2000	495
250	0.136 x α*	3337	460
300	0.106 x α*	1463	257
350	0.077 x α*	1751	188
400	0.084 x α*	2060	163
500	0.099 x α*	2472	155
600	0.194 x α*	2884	139
800	0.385 x α*	3399	129
1200	1.65 x α*	3399	0

*α to be determined using eq. (15)

Figure 2: Effective thermal properties for temperature calculations of gypsum board.

Table 4: Effective thermal properties for temperature calculations of gypsum boards

Temperature (°C)	Thermal conductivity (W/mK)	Specific heat (J/kgK)	Density (kg/m3)
20	0.25	1500	680
78	0.25	1842	680
85	0.25	2769	642
90	0.25	5234	615
97	0.2045	8684	577
110	0.12	15096	577
124	0.12	22000	577
139	0.12	2006	577
148	0.12	1001	577
373	0.12	714	577
430	0.12	715	577
571	0.12	571	577
600	0.12	606.9	577
609	0.128	618	577
662	0.176	3000	577
670	0.183	3070	577

Temperature (°C)	Thermal conductivity (W/mK)	Specific heat (J/kgK)	Density (kg/m3)
685	0.197	571	577
800	0.3	571	577
1000	0.6	571	577
1200	1.4	571	577

Step 2) Determine the time at which the temperature on the unexposed side of the exposed gypsum board reaches 300°C and remove elements corresponding to this gypsum board at the determined time. Continue the temperature calculation without the elements of the fallen gypsum boards. The surface of the layer on the unexposed side of the fallen gypsum board should become the exposed surface in the continued calculation. This step should be repeated, either, until the temperature in the unexposed side of the base layer of gypsum board reaches 300°C or until the end of the parametric fire at time $t = 3t_0$.

If the temperature on the unexposed side of the base layer of gypsum remains under 300°C the model indicates that the fire would decay without charring of protected timber. If this is not the case and if timber becomes exposed to the fire, the model indicates that the fire could re-intensify and could be continuous until collapse. Multiple tests have shown that fall-off of the base layer of gypsum boards can lead to continuous fully developed fires (Hakkarainen, 2002, McGregor, 2014; Su et al, 2018). Although it may be possible that the fire self-extinguishes after fall-off of the base layer at a late stage of the fire, it is conservative to require that gypsum boards remain in place for the entire duration of the fire to meet the performance criterion of withstanding complete burnout without collapse.

For validation Brandon (2018) compared predictions of fall-off with recorded occurrences of fall-off during compartment fire tests. Figure 3 shows the time between flashover and fall-off recorded for the first layer of gypsum plaster board from ceilings in compartment tests summarised by Brandon (2018). In this figure only fire rated gypsum boards (type-X in North America and type-F in Europe) of 16mm or thinner that fell from the ceiling during the fully developed phase are included. Also for an additional test in which gypsum board fall-off did not occur during the fully developed phase, the duration of the fully developed phase is plotted (see grey data point). By using parametric fires to describe the post-flashover phase of ventilation controlled natural fires, the dataset is extended with data corresponding to standard fire tests published by Just et al. (2015). As the standard ISO 834 temperature curve corresponds to the heating phase of a specific parametric fire, the corresponding opening factor for standard fire tests can be determined (assuming solely gypsum linings). Predictions of fall-off of the first layer using the finite element model, described above, are included in Figure 3. From the correlation between the predictions and the results it was concluded that the predictions of time to fall-off of the exposed gypsum layer are within the range of test results.

Further it was shown by Brandon (2018) that the model predicted the occurrence of gypsum fall-off of the exposed layer correctly for all (20 out of 20) relevant compartment tests of which data were available. The predictions of fall-off of the second layer of gypsum plaster boards could be conservative for compartments with opening factors less than $0.04m^{1/2}$, but seemed to be correct in all cases with higher opening factors.

The method presented by Brandon (2018) was shown to be accurate or conservative in all comparisons with real scale compartment fire tests. To meet the performance criterion of withstanding a complete natural fire without collapse, the required amount of fire rated gypsum board layers to withstand burnout can be calculated using the model discussed in this section.
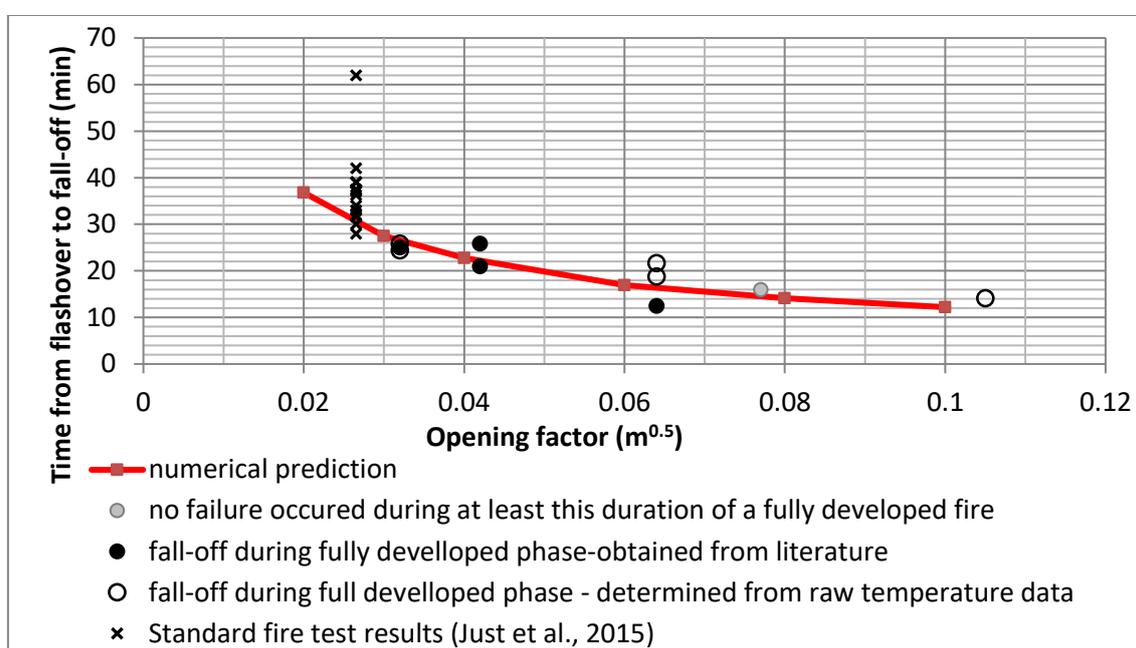
Figure 3: Time from flashover to gypsum fall-off (only fall-off in the fully developed phase is considered)

7 Parametric fire design for mass timber structures with exposed wooden surfaces

In the previous section a method was discussed which can be used to avoid the contribution of protected timber for the entire duration of the fire. In practice it is, however, desired to implement timber structures with exposed wood. A number of real scale compartment tests (Medina Hevia 2014; Emberley et al., 2017; Hadden et al., 2017; Janssens, 2017; Su et al 2018) have shown that it is possible for structures with exposed wood to withstand burn-out if:

1. protected surfaces remain protected for the entire fire duration, or at least until the fire temperatures are low enough to avoid ignition of suddenly exposed surfaces.
2. cold timber surfaces should not suddenly be exposed to the fire (For example: CLT should not delaminate during the fire).
3. the combustion of the burning timber is not sufficient to maintain the fully developed stage of the fire and the structural capacity remains sufficient for the entire duration of the fire.

Point 1 of the above can be achieved using the method discussed in the previous section to calculate the amount of gypsum board layers needed to keep protected surfaces protected for the entire duration of the fire. However, it should be noted that the contribution of exposed timber changes the fire development and requires a new design fire as discussed further in this section. Additionally, it is needed to install the gypsum boards correctly with a sufficient penetration depth of fasteners and a maximum fastener distance. A robust way to maintain the integrity of the exposed mass timber members (point 2) is by using adhesives and fasteners that do not allow fire induced delamination failure during a fire. For example, it was shown that delamination of CLT elements can be avoided by using suitable adhesives (Janssens, 2017; Brandon, 2018).

A model including the contribution of timber, which predicts whether point 3 is met, is discussed in this section. This method was proposed by Brandon (2018), in which the contribution of timber is included iteratively using the following expression:

$$q_{td}^{i+1} = q_{mfl} + \frac{A_{CLT} \cdot \alpha_1 \cdot (d_{char;end}^i - 0.7 \cdot \beta_{par} \cdot t_{max}^1)}{A_c}$$

(16)

Where q_{mfl} is the fuel load corresponding to the moveable fuel divided by the total surface area of the compartment boundaries (including walls and ceiling) in MJ/m² ($q_{mfl} = q_{td}$ for compartments with non-combustible linings). A_{CLT} is the surface area of exposed CLT given in m², α_1 is the ratio between heat release and char depth ($\alpha_1 = 5.39$ MJ/m²mm according to Schmid et al 2017) $d_{char,end}$ is the final char depth in mm, β_{par} is the charring rate in mm/min and t_{max}^1 in min. A_c is the total surface area of the compartment boundaries (including walls and ceiling) in m². The superscripted letter i denotes the number of the iteration, meaning that the char depth from the first calculation is used to calculate the fuel load density used for the second calculation (iteration) and so forth. From analysis by Brandon (2018), it was concluded that approximately 70% of the contribution of the timber combusts outside for at least the duration of the fully developed phase of a similar compartment without combustible linings (t_{max}^1). It should be noted that this is not valid if the moveable fuel load alone would not be sufficient to reach a fully developed state.

At each iteration the total fuel load, q_{td}^{i+1} obtained from eq. 16, is substituted in eq. 4 to calculate the start time of the decay phase. The final charring depth, needed to calculate the total fuel load for the next iteration, can be determined using eq. 13. The number of iterations needed depends on whether the charring depth converges to a certain value. It was shown previously that the iterative calculations could be stopped when the change of calculated charring depth in subsequent calculations is less than 0.1% or if the time of the fully developed phase is so long that it can be considered continuous.

Fires that have a continuous fully developed phase according to the calculations will never converge, as the fire duration will be extended with every iteration.

In the calculation, the contribution of timber to the fuel of the fire increases the duration of the fully developed phase, which can be calculated using eq. 4 with the iterated total fuel load. The temperatures of the parametric fire can subsequently be calculated using eq. 1, 5, 6 and 7 using the total fuel load obtained by the iterated total fuel load. As shown before, the fire temperatures are dependent on the properties of the lining materials. In case of exposed timber, the material is combusting and is a source of heat. The complexity related to surface flaming, significant change of mass, mass transfer, evaporation of moisture, potential condensation of moisture deeper in the timber and pyrolysis complicates the calculation procedure. However, Brandon (2018) showed that the fire temperatures of compartments with large and small surfaces of exposed CLT, had the similar fire temperatures during the fully developed phase, than compartments with only gypsum linings. This indicates that the thermal inertia of gypsum boards can effectively be used instead of the thermal inertia of wood to calculate the parametric fire temperature (using eq.2).

To evaluate the method Brandon (2018) compared maximum char depths measured in compartments after complete flashover fire tests with exposed timber with predicted charring depths. Figure 4 shows that predictions of the damage / char depth are generally conservative in comparison with experiments. This indicates that parametric fires can be conservatively implemented to predict the structural damage and potential structural collapse as a consequence of flashover fires. Annex A provides a calculation example in which the method of this chapter is used.
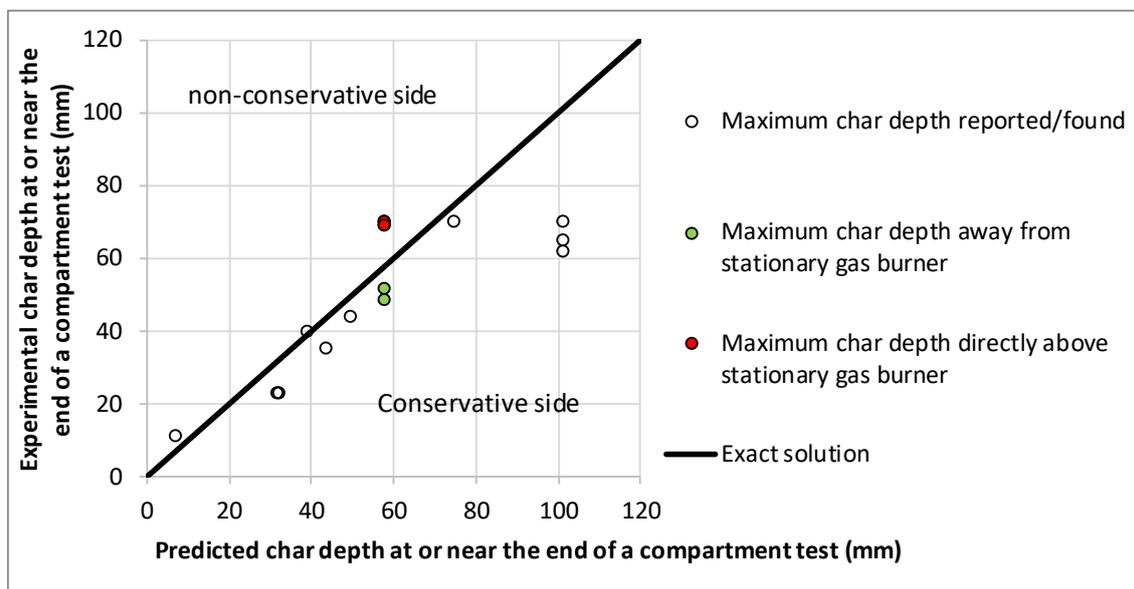
Figure 4: Maximum charring depths reported/found in compartment tests versus predicted charring rates (using the charring rate of eq.8)

8 Structural analysis

Once the parametric fire curve is determined the structural analysis can be performed. Three methods have been proposed in previous and parallel projects (Lange et al.,

2015; Brandon et al., 2017; Brandon et al., 2018). Two of these three methods account for the reduction of the load bearing capacity during a fire by reducing the load bearing cross-section of structural elements. The other method accounts for the reduction of load bearing capacity by reducing the mechanical properties throughout the structural element based on temperature calculations. Only the last mentioned is suitable for structural members with an inhomogeneous built up, such as CLT members. All three methods are discussed here. Table 5 gives an overview of the methods.

Table 5: Overview of structural calculation methods for timber subjected to parametric design fires

Name	Reference	Description	Glued laminated timber	Cross laminated timber
Method 1	Lange et al. (2015)	Reducing the load bearing cross section of structural elements by subtracting a non-linear char layer and a constant zero-strength-layer.	Suitable	Not suitable
Method 2	Brandon et al. (2017)	Reducing the load bearing cross section of structural elements by subtracting a non-linear char layer and a non-linear zero-strength layer.	Suitable	Not suitable
Method 3	Brandon et al. (2018)	Reducing local mechanical properties throughout structural elements based on calculated temperatures	Suitable	Suitable

8.1 Method 1, Lange (2015)

Method 1 involves reducing the cross-section of the load bearing member from exposed sides and was published by Lange (2015). According to this method, a char layer and a, so called, zero-strength-layer should be subtracted from the initial cross-section of the timber member (Figure 5). The load bearing capacity of the element throughout the fire can then be calculated as the load bearing capacity of the effective cross section with unchanged mechanical properties.
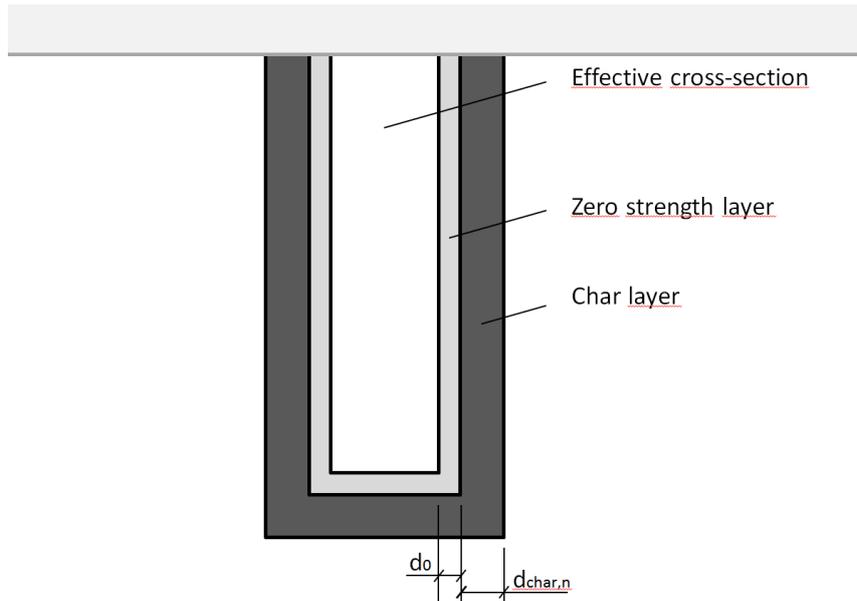
Figure 5: Effective cross-section of a beam in accordance with the reduced cross-section method

Lange proposed to calculate the char depths in accordance with Hadvig (1981), which can be calculated using eq.8, 11, 12 and 13, as previously discussed. Based on a series of fire tests, Lange determined that the zero-strength layer was 15mm thick for the long cool fires of the test series and 8mm thick for the short hot fires of the test series. To be conservative it was, therefore, chosen to implement a zero-strength-layer of 15mm for the calculations.

For, for example, a beam with a rectangular cross-section exposed from three sides (Figure 5) subjected to parametric design fires, the bending capacity can be calculated for the duration of the fire, by solving the following equations to M_{ult}:

$$d_{inef} = d_o + d_{char} \tag{17}$$

$$W_{ef} = \frac{(b - 2d_{inef})(h - d_{inef})^2}{6} = \frac{M_{ult}}{f_b} \tag{18}$$

Where: d_{inef} is the ineffective layer (*Note: the ineffective layer denoted as d_{ef} in Eurocode 5*); d_o is the zero strength layer according to Lange (2015) of 15mm; d_{char} is the char depth at a specified time according to eq. 11, 12 or 13; b is the width of the cross-section; h is the height of the cross-section; f_b is the bending strength of the beam.

The application of the zero-strength layer is based on an assumption that the mechanical properties within the cross-section are homogeneous. Therefore, the reduced cross-section method as it is presented here cannot be implemented to determine the fire resistance and the structural capacity of CLT in fires.

8.2 Method 2, Brandon *et al.* (2017)

Brandon *et al.* (2017) developed a calculation model based on multiple test series. A numerical model was developed to calculate temperatures within exposed timber members in a wide range of parametric fires, which will be discussed in the next sub-

section. Using the numerical model it was shown that the zero-strength layer is not constant during the fire and increases in size during the cooling phase, because of heat dissipation. Therefore, Brandon et al. proposed a new effective cross-section method. The char layer has been used for calculations of the capacity of timber members exposed to standard fire conditions following ISO 834. The standard fire exposure involves solely a heating phase until the test is stopped. This heating phase corresponds to an approximately constant zero-strength layer. The charring depth has, therefore, a straight forward correlation with the capacity of the structural elements. In the cooling phase of parametric fires, the relationship between the charring rates and the reduction of the load bearing capacity is, however, not straight forward. Therefore, Brandon et al. (2017) proposed to use an effective char depth that allowed the implementation of a constant zero-strength layer after the first 20 minute of the fire. The effective char depth exceeds the real char depth in the decay phase, but is the same as the real char depth in the fully developed (heating) phase. The calculation method proposed by Brandon et al. is discussed below.

The zero-strength-layer is constant, but dependent on the heating rate, Γ (see eq.2) and can be calculated using the following expression:

$$d_0 = 8.0 + 0.02\Gamma - 0.05\Gamma^2 \tag{19}$$

According to the proposed model by Brandon et al., the effective charring rate is the same as the charring rate according to eq.9 until the start of the decay phase, t_{max}. During the decay phase the charring rate reduces linearly until the time at which the temperature of the parametric fire curve returns back to 20°C, t_{end} (as shown in :

$$t_{end} = \frac{625 t_{max} x \times \Gamma + \Theta_{max} - 20}{625 \times \Gamma} \qquad \text{if} \qquad t_{max} \times \Gamma \leq 0.5 \tag{20}$$

$$t_{end} = \frac{-250 t_{max}^2 x \times \Gamma^2 + 750 t_{max} x \times \Gamma + \Theta_{max} - 20}{250 \times \Gamma (t_{max} \times \Gamma - 3)} \qquad \text{if} \qquad 0.5 < t_{max} \times \Gamma < 2 \tag{21}$$

$$t_{end} = \frac{250 t_{max} x \times \Gamma + \Theta_{max} - 20}{250 \times \Gamma} \qquad \text{if} \qquad t_{max} \times \Gamma \geq 2 \tag{22}$$
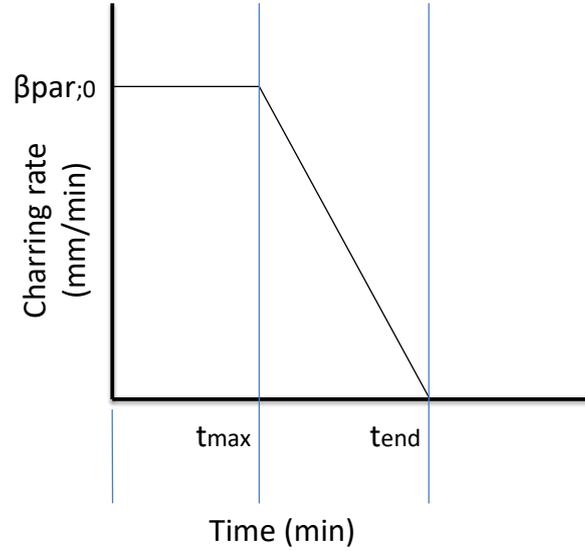
Figure 6: Proposed effective charring model

An effective charring model is proposed with significant differences from the current charring model in EN1995-1-2 (2004). In the proposed model the charring rate is constant for the entire heating phase. It should be noted that t_0 of the Eurocode 5 model is not equal to the duration of the heating phase, t_{max} (see eq.4). As mentioned before, t_{end} is the time at which the temperature of the parametric fire curve returns back to 20°C:

$$t_{end} = \frac{625 t_{max} x \times \Gamma + \Theta_{max} - 20}{625 \times \Gamma} \qquad \text{if} \qquad t_{max} \times \Gamma \leq 0.5$$

(23)

$$t_{end} = \frac{-250 t_{max}^2 x \times \Gamma^2 + 750 t_{max} x \times \Gamma + \Theta_{max} - 20}{250 \times \Gamma (t_{max} \times \Gamma - 3)} \qquad \text{if} \qquad 0.5 < t_{max} \times \Gamma < 2$$

(24)

$$t_{end} = \frac{250 t_{max} x \times \Gamma + \Theta_{max} - 20}{250 \times \Gamma} \qquad \text{if} \qquad t_{max} \times \Gamma \geq 2 \quad (25)$$

The maximum fire temperature Θ_{max} can be obtained by substituting t_{max} for t in Eq.(1). The effective charring depth, $d_{char;ef,}$ at any time can be calculated using:

$$d_{char;ef} = \beta_{par} t \qquad \text{for } t \leq t_{max} \qquad\qquad (26)$$

$$d_{char;ef} = \beta_{par} t_{max} + 0.5 * \left(\frac{-\beta_{par}}{t_{end} - t_{max}} \right) \times (t - t_{max})^2 + \beta_{par}(t_{end} - t_{max})$$

$$\text{for } t_{max} < t \leq t_{end} \qquad\qquad (27)$$

8.3 Method 3, Brandon *et al.* (2018)

Brandon et al. (2018) proposed a change of the so called *Advanced Calculation Method* described in Annex B of Eurocode 5 (EN1995-1-2:2004), so that it is suitable for structural predictions of timber members exposed to parametric fires. The method is suitable for members with complex geometries, for members protected with new insulation materials or, for members with inhomogeneous cross-sections, such as CLT members. The method requires finite element or finite difference calculations of the temperatures in elements throughout the structural member.

The calculation of temperatures has already been discussed in chapter 7. Once one or more temperatures of each element are known for the duration of the fire, the mechanical properties of the elements should be adjusted corresponding to their temperature. The reduction of tensile and compressive strength (f_t and f_c) and tensile and compressive Young's modulus (E_t and E_c) of each element is based on temperatures, as shown in Figure 7 (König and Walleij, 2000; EN 1995-1-2:2004).
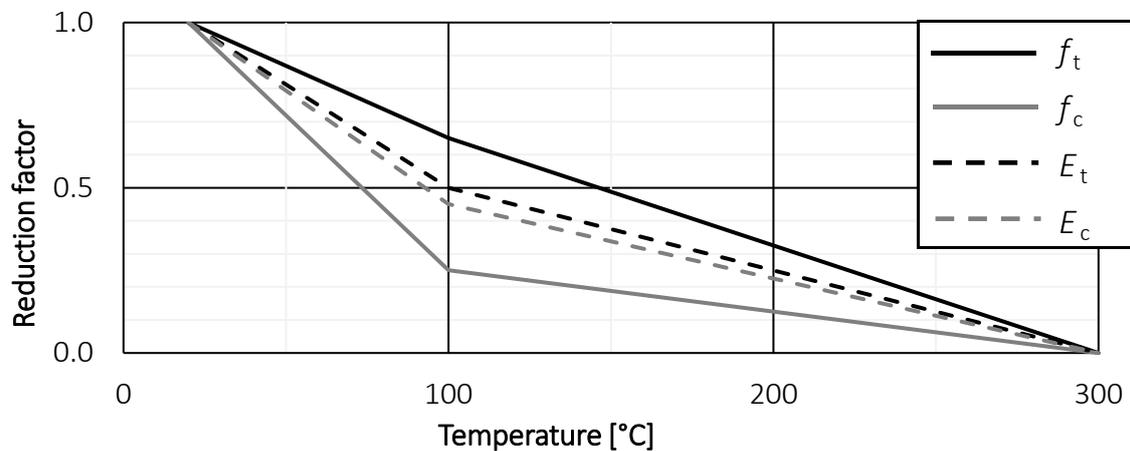
Figure 7: Temperature dependent reduction factors for strength and Young's modulus

The calculation of the load bearing capacity of the structural member with reduced mechanical properties can be performed using the same finite element model if 3-dimensional elements are used. It is, otherwise, possible to perform the temperature calculation in a 2-dimensional model and perform the structural calculation with a simpler method published by (Schmid, 2018). The method proposed by Schmid can be used for bended and compressed (buckling) elements with or without a homogeneous cross section and involves of iterative calculations of the stresses in the timber. In the analysis, the curvature of the structural member is increased with increments and the stresses in all elements are calculated for each increment using the reduced moduli of elasticity and the classical beam theory. The bending moment corresponding to the curvature of every increment can be calculated as equilibrium of forces is required. In case the normal stress in an element exceeds the reduced material strength, the elements are eliminated and the calculation is performed again without these elements. Once the increment of the curvature does not result in an increased bending moment, the moment capacity of the member has been found. Schmid's method can be performed in common software such as Microsoft excel and is also applicable for CLT elements exposed to parametric design fires.

8.4 Comparisons of the methods

For the evaluation of the three methods, results of parametric fire tests of loaded glued laminated timber beams published by Lange et al. and Brandon et al. are compared with predictions. Figure 8 shows the experimentally determined bending moment at the time of failure against predicted moment capacity at that time. The scatter of results seems typical for timber members in fires, as the coefficient of variation is in the same order of magnitude as that of previous research of beams in a standard fire (Brandon 2016). A significant part of the variation is caused by natural variation of strength properties within each timber beam and the uncertainties involved in the determination of the material strength and stiffness properties.

Data points that are positioned above the 0% error line are non-conservative and data points positioned below the 0% error line are conservative. It can be seen that method 2 and method 3 generally predict the failure behaviour more accurately and more conservatively than method 1. Method 3 results in a relatively large scatter of results. However, it is the only method discussed here that is equipped to predict the behaviour of CLT and other more complex scenarios.
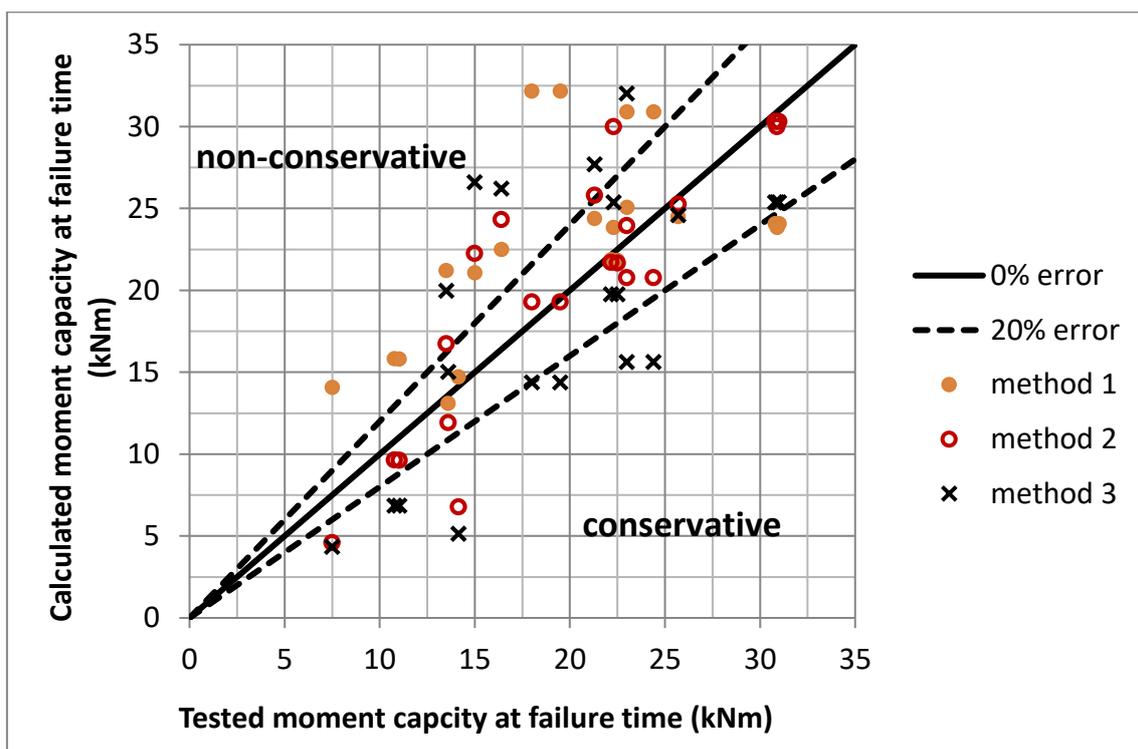
Figure 8: Predicted versus experimental moment capacity at the time of failure of glued laminated timber beams exposed to parametric fires.

9 Conclusions

This report provides analytical design methods aiming to prevent high damage collapse in tall timber buildings caused by fires, even in the scenario that the fire brigade cannot suppress the fire or sprinklers are not extinguishing the fires. Post-flashover fires can have a significant impact on the structural behaviour and can lead to collapse. Usually,

this is performed using prescribed regulations and structural fire resistance ratings obtained by standardised tests or calculations. As prescriptive regulations are mostly based on experience, these regulations may not be sufficient for unconventional buildings. In Sweden it is, therefore, required to use analytical design instead of prescriptive regulations for buildings taller than 16 stories. Analytical design is not used for the structural design of timber buildings, because there is a lack of methods available. This report summarised analytical design methods that were recently developed in parallel projects from Formas and BrandForsk in Sweden and the NFPA in the USA.

Based on statistics of previous collapses of multi-storey buildings and on the increased risk of collapse in longer fires, these aspects are important to consider in order to avoid progressive collapse:

- Limit fire spread out of the fire cell of origin
- Avoid continuous fires and achieve decaying fires
- Provide enough structural resistance throughout the fire

Due to the combustibility of timber, fire spread within timber buildings requires special attention. Another report of this project (Brandon et al, 2018) discussed robust design to avoid fire spread within timber structures..

In order to avoid continuous fires that lead to collapse, it is important that the contribution of the structure itself is not sufficient to sustain fully developed fire. This report describes methods to avoid continuous fires by:

- limiting the amount of exposed timber based on calculations using parametric design fires.
- avoiding fall-off of the base gypsum layer which protect timber members.
- avoiding fire induced delamination or other events that suddenly expose cold timber surfaces.

Parametric design fires that include the contribution of exposed timber surfaces have been published recently by the NFPA (Brandon, 2018). An increased surface area of exposed timber results in an increased contribution of the exposed timber to the fire and an increased (possibly infinite) fire duration. Comparisons with experiments showed that the method results in conservative predictions of structural damage if encapsulated timber members remain protected during a fire and if integrity failure of exposed timber members is avoided.

Using a numerical procedure using a relatively simple finite element model, predictions of gypsum board fall off can be made. Comparisons with full scale compartment fire tests showed that the predictions of the required number of gypsum boards were accurate in most cases and conservative in other cases. There was no test for which the prediction was non-conservative (unsafe).

Fire induced delamination was previously seen in fire tests of compartments with exposed CLT. This potentially leads to an increased combustion and prolongation or regrowth of the fire. A parallel project led by the NFPA (Brandon and Dagenais, 2018) showed that fire induced delamination can be avoided by using suitable adhesives.

Three models for the structural assessment of timber members under the conditions of parametric design fires were evaluated. Two of those models were based on the reduced cross-section method of Eurocode 5, which is originally not suitable for structures exposed to parametric fires. Both methods involved compartment-property dependent charring rates for the fully developed fire. The first method involves an increased zero-strength-layer, which needs to be subtracted from the loadbearing member before the structural fire calculation is performed. The second method involves an effective charring rate in the cooling phase instead of the real charring rate. The third method involves finite element analysis to calculate the temperature at many locations within the material. Using the temperature, the mechanical properties at these locations are adjusted based on local temperatures which allows calculating the load bearing capacity of the structural element during the fire. Comparisons with results of furnace tests with parametric fire temperatures showed that the second and the third method are more accurate than the first method. The first method is slightly non-conservative.

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Annex A: Worked example of determining a parametric fire curve

Note: This Annex was modified after it was first published, because a correction needed to be made to ensure that the calculated parameters corresponded with the text. As a result, values in Table A1 and A2 have changed.

In this section an example of engineering structural design to meet the performance criterion that the structure should withstand a full natural fire without the occurrence of structural collapse. For this, the natural fire should decay and a second flashover should be avoided. The example is based on a full-scale compartment fire tests performed at the ATF Fire Research Laboratory (Zelinka et al. 2018).

Scenario:

-   Compartment internal dimensions: 9.10 x 9.10 x 2.74m (width x depth x height)
-   Ventilation opening: 2 open windows of 3.66 x 2.44m positioned at the same height from the floor. The door remains closed, separating the compartment from the corridor for the entire duration of the fire.

    Note 1: Windows that are not fire rated have been failing quickly at the start of previous flashover fire tests (such as published by Hox 2015). However, a number of previous compartment tests have shown that a flashover fire can be prevented if all windows and doors are closed (Lennon, 2000; ATF, 2018; Brandon et al, 2018)

    Note 2: There are no calculation models available to estimate the fire resistance of doors in natural fires. In this example it is simply assumed that the door will avoid fire spread. In the full-scale fire test, the fire resistance rating of the door was 20 minutes, which seemed sufficient to avoid fire spread in this particular test.

-   Fire growth rate according to Eurocode 1: fast -> t_{lim}= 0:15hour
-   Fuel load density excluding CLT: 550MJ/m^2. The fuel load comprises of typical apartment furniture capable of causing a fully developed fire in a completely non-combustible compartment.
-   Composition of all walls and floor: 175 mm 5 ply CLT with a lamella thickness of 35mm for every lamella, protected by two layers of 15.9mm fire rated gypsum boards (type X).
-   Composition of Ceiling: 175 mm 5 ply CLT with a lamella thickness of 35mm for every lamella, 20% of the ceiling is exposed, the rest is protected by two layers of 15.9mm fire rated gypsum boards (type X).

Approach:

In order to use parametric fires for the calculation, it has to be made sure that the exposed CLT does not delaminate in the fire. For this example, this is done by using CLT with a suitable adhesive (Janssens, 2017; Brandon, 2018). Additionally, the base layer of gypsum board should remain in place. Whether the applied gypsum boards are sufficient, should be calculated using the method discussed in chapter 6.

As the compartment involves exposed wood, the contribution of wood should be iteratively calculated to determine suitable fire temperatures. For the first calculation, the wood contribution is not included. In the following iterations the contribution of the wood is included until the difference between results of subsequent iterations becomes negligible.

The iterative procedure is performed by repeatedly using eq. 13 to calculate the final char depth and eq.16 to calculate the total fuel load that includes the contribution of exposed CLT. Table A1 shows the calculated char depth corresponding to each iteration. Both, the charring models of Hadvig and Brandon are implemented. It can be seen that the results converged within a few iterations in this case.

Table A1: Iteratively calculated char depth

	Charring depth at the end of the parametric fire, using eq.8 and eq.13 (mm)	Charring depth at the end of the parametric fire, using eq.9 and eq.13 (mm)
initial calculation	30,18	39,17
1st iteration	31,13	40,08
2nd iteration	31,19	40,84
3rd iteration	31,19	40,90
4th iteration	31,19	40,90
5th iteration	31,19	40,90
6th iteration	31,19	40,90
7th iteration	31,19	40,90
8th iteration	31,19	40,90
9th iteration	31,19	40,90

Table A2 summarizes the calculation steps to determine the temperatures of the fire that includes the contribution of exposed CLT, together with a reference to the equations used and the solution of the calculations. The corresponding fire temperatures are shown in Figure A1.

Table A2: Steps to calculate the fire temperatures corresponding to a non-combustible compartment

Step	Eq.	Solution
1) calculate the opening factor	2	0,105 m$^{1/2}$
2) calculate the heating rate factor	3	15,7
3) calculate the duration of the fully developed phase	4	20,2 min (corresponding to the charring rate according to eq 8);
4) determine the temperatures during the fully developed phase as a function of time	1	$\Theta = 20 + 1325(1 - 0.324e^{-0.2t \cdot 15.7} - 0.204e^{-1.7t \cdot 15.7} - 0.472e^{-19t \cdot 15.7}$ for $0 < t < t_{max}$
5) determine the temperatures during decay phase as a function of time	7	x=1; $\Theta = \Theta_{max} - 250(t \cdot 15.7 - 0.33 \cdot 15.7 \cdot 1)$
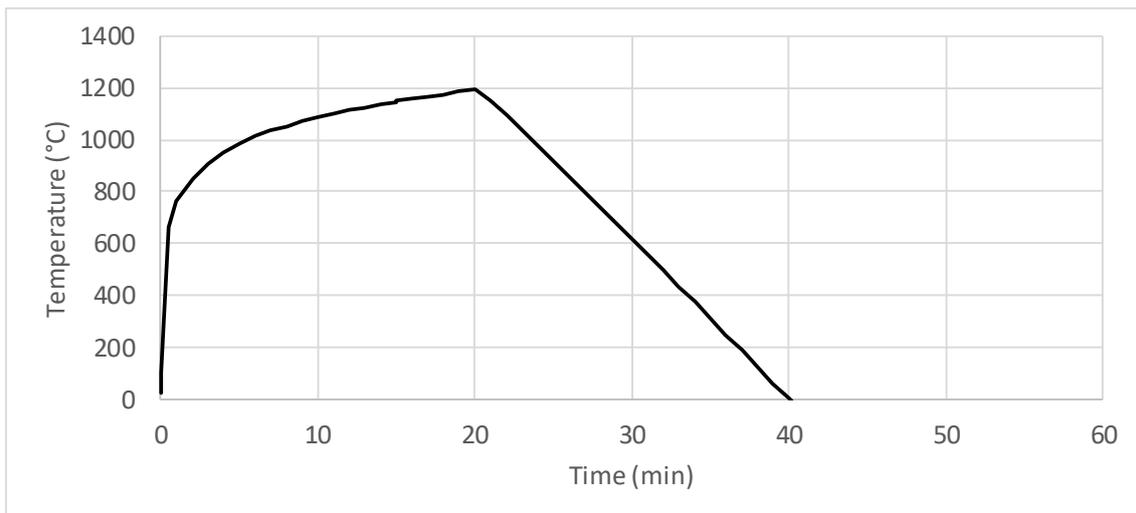
Figure A1: Predicted fire temperatures (corresponding to the charring rate according to eq.8)

In order to determine whether two layers of 15mm type X gypsum plaster boards are sufficient a numerical analysis is performed in accordance with chapter 6. Due to the built-up, one-dimensional heat transfer through the walls and ceiling is assumed. A schematic drawing of the finite element model used for one-dimensional heat transfer is shown in Figure A1. The software used is SAFIR2007. The model consists of a single

strip of two-dimensional square elements. In the figure the fire exposure is on the left side. The element size of 1 x 1mm and a time step of 2 seconds are verified by performing a mesh sensitivity analysis. As one-dimensional heat transfer was needed, there was no heat gain or heat loss implemented from the longitudinal sides. At both ends convective and radiative heat transfer are taken into account using eq.14. The implemented fire temperatures are shown in Figure A1.

The model consists of two 15mm long strips representing gypsum layers and a 175mm long strip representing the CLT panel (See Figure A2,a). The thermal properties of the materials are in accordance with Table 3 and Table 4. As mentioned in chapter 6, it is assumed that a gypsum board falls when the temperature on its unexposed side reaches 300°C. According to predictions the temperature on the unexposed side of the first layer reaches 300°C in 17 minutes. The calculation is continued without the first layer of gypsum boards, using the model shown in Figure A2,b. According to the continued calculation, the temperature behind the second layer of gypsum boards never reaches 300°C. Therefore, it is predicted that 2 layers of 15mm type X gypsum boards are sufficient to achieve a decaying fire if the gypsum boards are installed sufficiently. This can for example be done using a maximum screw distance of 400mm, with a penetration depth of 15 mm into the timber, which is in line with the compartment tests summarised by Brandon (2018). Additionally, the joints between gypsum board panels of the base layer should not be aligned with the joints between gypsum board panels in the second layer. Where there is a partitioning wall within the compartment, it is important that the gypsum boards are placed before the partitioning wall is placed to avoid that the CLT of the floor becomes exposed after failure of the partitioning wall.

a) Before fall-off of 1st gypsum board (GB) layer

Boundary
conditions:
Convection
and radiation

Boundary
conditions:
Convection
and radiation

Fire tem-
perature

GB layer 1

GB layer 2

CLT layer

Ambient
tempera-
ture

1mm

1st layer thickness

2nd layer thickness

CLT thickness

total thickness

b) After fall-off of 1st gypsum board (GB) layer

Boundary conditions:
Convection and radiation

Boundary
conditions:
Convection
and radiation

Fire tem-
perature

GB layer 2

CLT layer

Ambient
tempera-
ture

1mm

2nd layer thickness

CLT thickness

total thickness

c) After fall-off of 2nd gypsum board (GB) layer

Boundary conditions:
Convection and radiation

Boundary
conditions:
Convection
and radiation

Fire tem-
perature

CLT layer

Ambient
tempera-
ture

1mm

CLT thickness

total thickness

Figure A2: Schematic drawing a finite element model for calculations of temperatures behind gypsum boards.

Annex B: Guidelines –Requirements and engineering methods

Guidelines for robust performance based structural design of tall timber buildings

Performance criterion:

Avoid structural collapse during a full natural fire without interference by the fire service or active fire protection

	Light timber frame		Mass timber			
	Limited fire spread	Integrity of encapsulation	Limited fire spread	Integrity of encapsulation	Integrity of exposed timber	Structural integrity
Requirements	Prevent fire spread to other compartments	All timber should remain protected for the entire duration of the fire.	Prevent fire spread to other compartments	All surfaces that are initially protected should remain protected for the entire duration of the fire.	Integrity failure of exposed timber members should be avoided	Structural collapse of exposed timber members should be avoided, considering the entire duration of the fire.
References within the project for engineering methods	Mitigation of Fire Damages in Multi-storey timber buildings. Brandon et al. (2018)	Engineering methods for structural fire design of wood buildings–Structural integrity during a full natural fire. Brandon (2018) Chapter 6	Mitigation of Fire Damages in Multi-storey timber buildings. Brandon et al. (2018)	Engineering methods for structural fire design of wood buildings–Structural integrity during a full natural fire. Brandon (2018) Chapter 6	Engineering methods for structural fire design of wood buildings–Structural integrity during a full natural fire. Brandon (2018) Chapter 7	Engineering methods for structural fire design of wood buildings–Structural integrity during a full natural fire. Brandon (2018) Chapter 8
External references for engineering methods	Brandforsk project: Brandstopp: Just and Brandon (2016) Brandon et al. (2016)	NFPA project: Fire Safety Challenges of Tall Timber Buildings – Phase 2 Task 4 Brandon (2018)	Brandforsk project: Brandstopp Brandon et al. (2016) Just and Brandon (2016)	NFPA project: Fire Safety Challenges of Tall Timber Buildings – Phase 2 Task 4 Brandon (2018)	NFPA project: Fire Safety Challenges of Tall Timber Buildings – Phase 2 Task 5 Brandon and Dagenais (2018)	Brandforsk Project: The influence of parametric fire scenarios on structural timber performance and reliability Lange et al. (2014) Formas project: Natural Fire Design Brandon et al. (2017) Brandon et al. (2018)

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