Fire Safety in Timber Buildings
A review of existing knowledge

Carl Pettersson

BRANDFORSK
2023:6

BRAND FORSK

Brandforsk republishes the project report from RED Fire Engineers Sweden, that is published on their website www.ltu.se for reference

”Fire Safety in Timber Buildings - Update”

www.redfireengineers.se

BRANDFORSK
2023:6

Foto omslaget: Martin Sparre

Foreword

The grey zone between common knowledge and the yet unknown is often characterised by opinions. Brandforsk, the Swedish Fire Safety Research Foundation, works towards narrowing that area and the area of unknown by gaining new knowledge from the unknown and communicating scientific results.

This report aims to help practitioners find facts to use in their work and, within the area of research and development, to facilitate the process of identifying areas in which new knowledge and solutions are required.

I wish you all interesting reading and fire safe sustainable timber buildings in the future.

Mattias Delin
Research Director
Brandforsk
November 2023

Preface

This report constitutes a comprehensive update to the initial publication from 2020, authored by Carl Pettersson, a fire safety engineer affiliated with RED Fire Engineers Sweden AB. The revision has been made possible through the financial backing of Brandforsk's annual funding for the years 2019, 2020, and 2023, and appreciation is given to the various supporting organisations, whose comprehensive list is available on the last page of the report.

Gratitude is hereby expressed to the following contributors for their substantive input into the first version of this report: Birgit Östman, Mattias Delin, Robert Jönsson, Thomas Järphag, Alar Just, Amanda Kimball, Daniel Brandon, Luke Bisby, and Martin Sparre.

Additionally, the author acknowledges the instrumental contributions of individuals who reviewed and provided constructive feedback on the third version of this report. Special thanks are extended to Birgit Östman, Ian Pope, Antonela Čolić, Robert McNamee, Konrad Wilkens, Axel Mossberg, and Lucia Ortega for their review and insightful commentary.

The report has been published in the following versions:

Version:	Published date:	By:	Comments:
1	2020-11-23	Carl Pettersson	
2	2020-12-10	Carl Pettersson	Minor update and corrections to references.
3	2023-11-20	Carl Pettersson	Significant revision incorporating the latest research findings.

Introduction to the report

This report focuses on fire safety in timber buildings where timber products are the main structure in the building. This can either be light-timber frame construction, premanufactured volume elements (modular construction) or mass timber construction using engineered timber products such as glued-laminated timber (GLT/glulam), laminated veneer lumber (LVL), nail-laminated timber (NLT) and cross-laminated timber (CLT). Most of the information presented in this report is relevant to larger or taller timber buildings, but it is also applicable to other types of timber buildings. The applicability of the technical considerations presented in this report should be adopted in relation to the specific fire safety design goals that apply to a particular building.

This report is based on a literature review of published scholarly articles, technical papers, guidelines and design standards on the topic of fire safety in timber buildings. The findings in this report are presented in five different categories (chapters 3-7): *Overview of research and regulation, fire dynamics, structural fire design, passive and active fire protection* and *timber buildings during construction and use*.

Sub-chapters "sections" (4.1, 4.2 etc.) provide more details on different subjects within each main chapter. Cross-references to different sections are made where relevant, but each section can be read as standalone. This provides the reader with easy access to detailed information about a specific technical topic as well as the possibility of gaining a holistic understanding of key fire safety aspects that are important to consider for timber buildings.

Keywords: fire safety; timber buildings; CLT; timber façade; timber construction

Nyckelord: brandsäkerhet; träbyggnader; KL-trä; träfasad; träkonstruktion

Table of contents

1. Introduction

Timber is a building material that in recent decades has evolved into new engineered timber products. This has allowed building construction to embrace the use of timber to a greater extent with new architectural possibilities together with the environmental benefits of using a natural and renewable material.

Timber is a combustible material which offers challenges relating to fire safety. This is especially true for buildings with fire safety strategies that rely on limited fire growth, safeguarding fire separations and structural stability. Many of the challenges that relate to occupant safety in timber buildings can be accounted for and mitigated by using available building codes, standards and guidelines. For larger or taller buildings where the fire safety strategy for occupant safety is more complicated and where internal firefighting is necessary, a combustible structure can cause higher consequences. This report focuses on presenting available knowledge related to these challenges to make them easier to consider in building design, maintenance and in the event of a fire. It is important to acknowledge that the purpose of this report is to promote fire safe and sustainable timber buildings.

1.1 Background

There is a wide range of different timber products available and used in the construction of buildings today. The light timber frame construction is traditionally and widely applied to houses and low-rise buildings. For taller buildings, mass timber products (engineered timber products) such as glued-laminated timber (GLT/glulam), laminated veneer lumber (LVL) and cross-laminated timber (CLT), have become the norm in timber construction. They consist of smaller pieces of timber, laminated together to create larger structural elements. Depending on the composition of the products, different structural attributes can be achieved. CLT is one of the more modern engineered timber products and was first introduced to the building construction industry in the 1990s. By cross laminating layers (using adhesives) of timber planks (usually 22 mm to 55 mm thick in five or seven layers), large timber panels capable of holding loads in two dimensions are created. A similar product that is not as common is nail-laminated timber (NLT) which is laminated using nails instead of adhesives. CLT and NLT are suitable for many structural applications and can also be cut into bespoke shapes or sizes during the manufacturing process, making the product ideal for use in modular construction. See pictures of mass timber being used together with glulam columns and beams to construct an office building in Figure 1.

Figure 1: Example of mass timber building under construction using CLT slab construction (Photo: Carl Pettersson)

There have previously been literature reviews completed regarding fire safety in timber buildings summarising different large-scale fire testing results, different aspects of fire safety challenges and available design methodologies. Jönsson et al. 1985 [1] present a review of the existing state of knowledge and research requirements for timber structures and fires. Babrouskas 2002 [2] provides a review encompassing the available practical and experimental data on the ignition of solid wood. More recently the Fire Protection Research Foundation (FPRF) in the US completed two literature reviews as part of the "*Fire Safety Challenges of Tall Wood Buildings, Phase 1"* by Gerard and Barber 2013 [3] and "*Phase 2: Task 1*" by Brandon and Östman 2016 [4]. Liu and Fischer 2022 [5] have since published a comprehensive review of recent large-scale CLT compartment fire tests.

There are several guidelines for the fire safe use of wood. In 2010 the "*Fire safety in timber buildings: technical guideline for Europe*" [6] edited by Östman was published. Gowing from this guideline 2022 the global network Fire Safe Use of Wood (FSUW) published the "*Fire Safe Use of Wood in Buildings: Global Design Guide"* [7] which provides a comprehensive global guidance on fire safety in timber buildings.

During the recent period of rapid development and the emergence of new construction technologies, information and validation to support the use in construction may be varied, interpreted, and used by different parties, creating the potential for confusion. This report aims to consolidate factual information, alleviating potential confusion.

Amidst the recent surge in development and introduction of novel construction technologies for timber buildings, information crucial for design and construction has become diverse and is subject to interpretation. As there is an urgent need for the evolution of sustainable building technologies, fire safety designs must adapt to meet the needs of sustainability in Agenda 2030 without compromising the safety of occupants, firefighters or property in the event of a fire in a building. This report aims to consolidate factual information, alleviating potential confusion. It strives to provide readers with an understanding of validated facts while clarifying potential design limitations for fire safety in timber buildings.

1.2 Goal

The goal of this report share existing knowledge about fire safety in timber buildings, aiding its practical application and contributing to ongoing learning and further research. The focus is on large or tall timber buildings. Nevertheless, the key fire safety aspects presented apply to all types of timber buildings taking the specific fire safety design goal for a particular building into account.

1.3 Guide for the reader

This report is aimed at professional fire safety engineers and other professional engineers with an understanding of the fundamental basis of fire safety building design, fire dynamics and structural fire safety design. It may also be of interest to academic researchers investigating fire safety in timber buildings and to developers constructing timber buildings.

The report can be read as a summarised overview with literature references for further reading. This report also helps to detect where more research and development is needed. The report can be seen as a "travel guide", providing information about important fire safety considerations and where to find relevant knowledge, but leaving the rest to the reader.

1.4 Methodology

A literature review has been undertaken of relevant literature presented at technical conferences, scholarly articles and technical papers.

Input from the reference group has also made sure relevant and recent research findings are included in the report.

1.5 Responsibility

Brandforsk, the Swedish Fire Research Foundation, has gathered information to make it available for the reader. The reader is responsible for the use of the information. Brandforsk takes no responsibility for any misuse of the information or any incorrect information in the report.

Please contact *info@brandforsk.se* for suggestions of information to be included or any corrections.

2. Fire safety strategy

A fire safety strategy is a program for which a fire safety design is adopted for a building in order to meet design goals. Design goals can be based on building code regulations, insurance requirements, sustainability goals etc. Different buildings will have different design goals relating to fire safety performance in the building. When a building's fire safety is "good enough" (i.e. the design goals are met) in relation to the risks associated with fires, is very much debatable and is influenced by the interest of different stakeholders. Generally, the benchmark to determine design goals for the fire safety performance will be the applicable building code regulations, which vary between countries. It is of great importance that all stakeholders involved in constructing a building are aware of clearly defined design goals, as well as understand the limitations of these. This report will not address the determination of appropriate design goals or fire safety strategy as this will have to be determined on a case-by-case basis.

The fundamental hazard associated with the use of engineered timber is that timber burns. The degree to which this results in other hazards is dependent on the overall fire safety strategy and how the timber forms part of the building. This means that the key fire hazards in a timber building can vary on a case-by-case basis and may combine in a way that threatens the design goals of the fire safety strategy. It is therefore imperative to control these hazards, usually by separation (separation of hazards), with a fire safety strategy that creates barriers resilient to negative chain reactions concerning safety measures.

The following categories can help to identify relevant hazards in a timber building. However, each building design is unique and a particular design may not be applicable for or limited to these hazards:

1. Fuel load provided by timber construction
    a. Reliability and redundancy from encapsulation or partial encapsulation with a protective covering
    b. Fire growth rate
    c. Duration of potential fire scenarios
2. Duration of the fire
    a. Char fall-off
    b. Glueline integrity (i.e. Heat-induced delamination)
    c. Secondary flashover scenarios
3. Internal fire spread
    a. Fire spread through concealed spaces
    b. Cavities and connections
    c. Construction joints or penetration sealing systems
    d. Combustible materials within egress paths
    e. Combustible materials within concealed spaces
4. External fire spread
    a. Combustible external walls, façades or façade systems
    b. The potential for fire spread between combustible building elements and combustible façades
    c. Combustible materials in balcony areas that may have unprotected penetrations through the floor (e.g. downpipes and floor wastes) and significant ignition sources (e.g. gas, electric, timber or coal barbecues)
    d. Separation of windows

5. Structural stability
    a. Fire and heat exposure to the structure over time
    b. Construction joints
    c. Post-fire degradation of load-bearing capacity
6. Construction
    a. Combustible building elements exposed during construction
    b. Fire separating compartmentations not in place
    c. Egress provisions unavailable
    d. Conditions for fire service intervention
7. The fire service
    a. Safety measures specific for the fire service as well as the greater context of the building's fire safety
    b. Increased firefighting water demands
    c. Hidden fire spread in voids, smouldering fires, hot spots
    d. Structural capacity during firefighting operations

3. Overview of research and regulation

The regulatory frameworks, e.g. building codes and standards, are used as the main support to establish design goals in relation to fire safety in buildings. To meet the design goals, design and implementation of knowledge are needed, and one purpose of this report is to help designers find available information on how to design for fire safety in timber buildings.

The regulatory building codes adopted around the world (IBC [8], NCC [9], Approved Document B [10], BBR [11], etc.) all use prescriptive guidance to direct the design of a building towards certain levels of fire safety. Depending on the size of the building, the size of the largest fire compartment in the building, the number and type of occupancy in the building or the height of the building (number of storeys), the prescriptive requirements may be different with the intention of meeting a similar level of fire safety in different types of buildings. By following prescriptive requirements on how fire safety is to be achieved, the design process is made implicit. Allowing the fire solutions to be simpler to implement across the building industry, but with a reduction in flexibility for a design that does not fit in easily with the prescriptive guidance. To allow for more flexibility and the use of new technologies, the performance-based design is often utilised as a route of compliance with the regulatory framework. A combination of prescriptive requirements and performance-based design is usually applied to timber buildings that do not fall into the general solution prescriptive approach.

The fire safety strategy in a building will depend on fire growth as a driving process of how fire safety measures will influence reactive events such as egress and structural behaviour. Understanding the burning behaviour and fire growth in a building is fundamental for any fire safety design. As prescriptive design guidance uses knowledge of fire dynamics and empirical data to bind the fire growth for the specific conditions of the implied scenarios [12], it is important that the designer understands the limitations of using predetermined design parameters. Especially when designing timber buildings with combustible structural materials which will significantly impact the fire behaviour and the fire dynamics. "*Given that there are unavoidable and significant differences between the buildings, there is a risk of extrapolating codes and standards outside its range of applicability*" [12] p.45.

Since many of the products used in modern timber buildings are still relatively new, with limited prescriptive solutions available, the performance-based design is heavily relied upon. In order to apply performance-based design, more knowledge of the fundamental basis to which a fire safety strategy will meet the appropriate design goals is needed. Some of the fundamental understanding of fire safety in buildings is not directly applicable to timber buildings, which introduces unique challenges to fire safety performance. A timeline of some of the large-scale fire testing research, publication of international guidelines and building codes with requirements to timber buildings is presented in Figure 2 and Figure 3. As can be seen, much research has been presented in the last ten years.

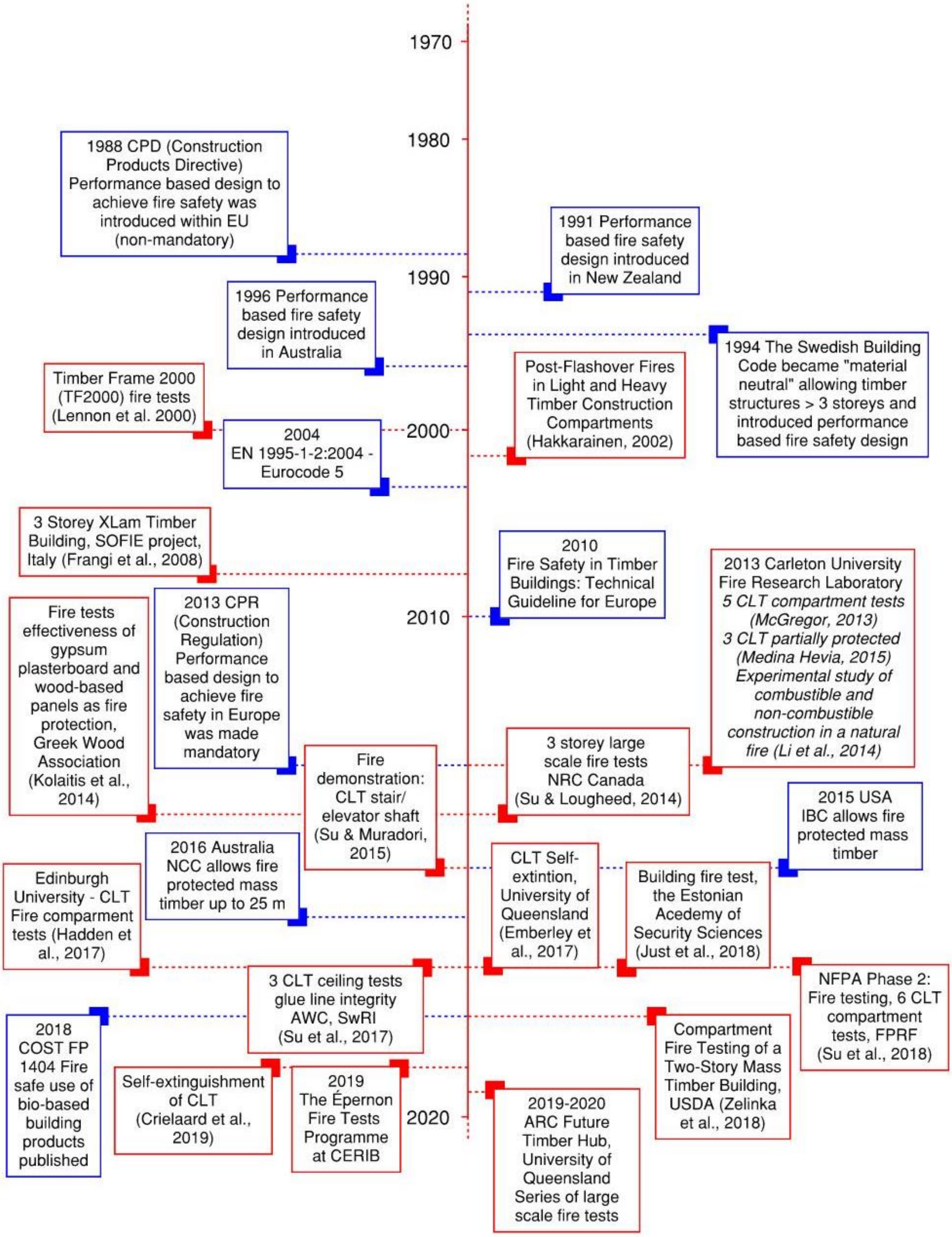


Figure 2: Timeline 1970-2020 of fire testing research and publication of guidelines and building codes.

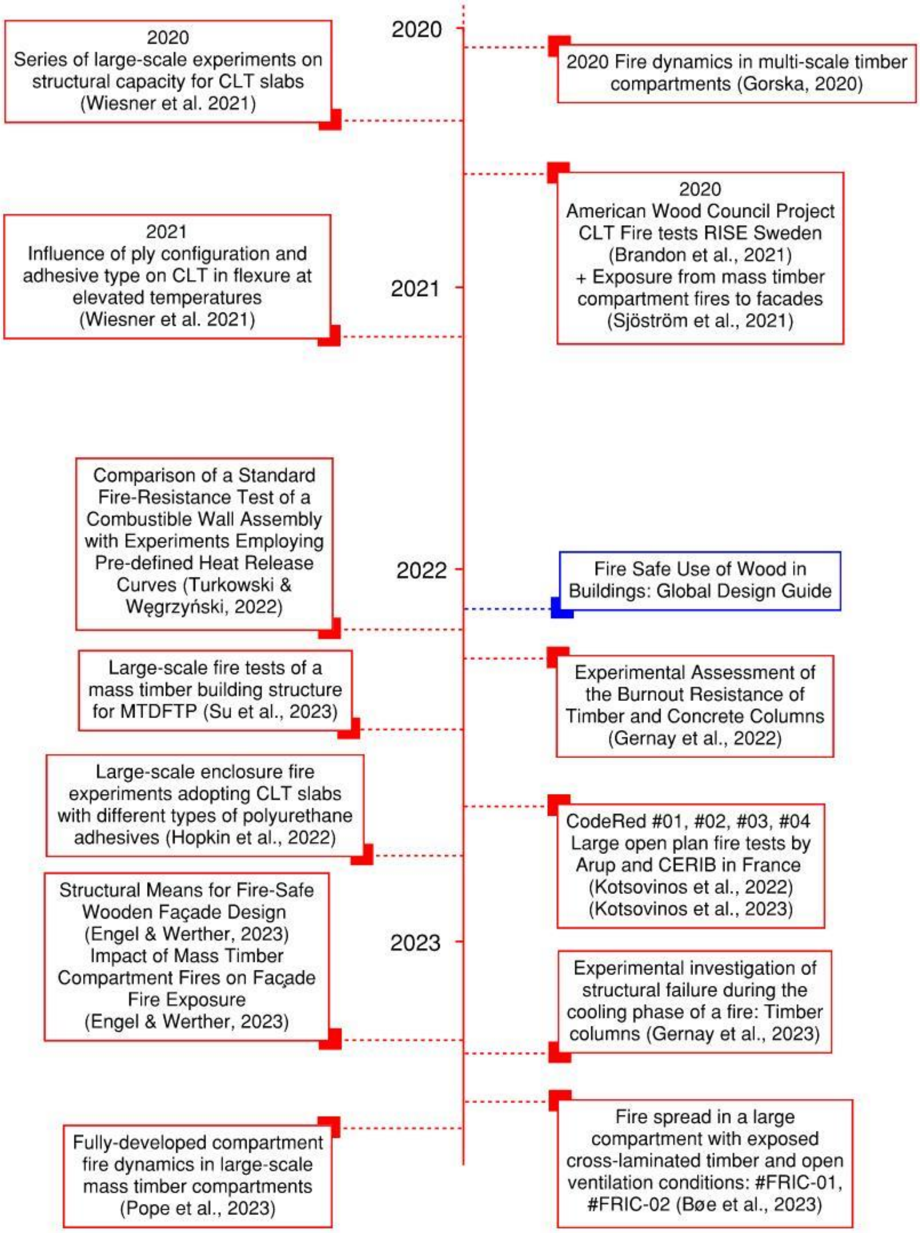


Figure 3: Timeline 2020-2023 of fire testing research and publication of guidelines and building codes.

4. Fire dynamics

4.1 Burning behaviour of timber

During initial heating, the material will degrade as free water inside the timber evaporates and creates pressure. Vapour travels both towards and away from the heat source due to diffusion and permeability. Hence, it may flow to the heated side of the material but the bigger part of the vapour is pushed to the cooler side due to the larger pressure differences, where it again condenses and leads to the increase in the moister content in the colder zones of the wood, known as a moisture front [13]. Passed the latent heat of water, the material continues to be heated and it will decompose and pyrolyse as part of the combustion. The following decomposition events and different temperature ranges have been proposed in the literature [13–18]:

- Evaporation of free water > 100 °C,
- Hemicellulose and other polymers start to decompose (volatiles formed are not combustible) 160-200 °C,
- Dehydration and slow pyrolysis (produced gases are not sufficient to create a flammable mixture) below 200-220 °C,
- The onset of pyrolysis (flaming combustion possible with the aid of piloted ignition) 225-275 °C
- Rapid pyrolysis above 300 °C, and
- Char continuous to smoulder and oxidise > 350 °C.

The processes behind pyrolysis, ignition, combustion, and extinction are generally well understood [14] and there is a good agreement in the fire science literature about the burning behaviour of timber.

The main aspects that impact the burning behaviour and pyrolysis of timber have been summarised in [14] to be:

- Heating scenario
- Oxygen concentration
- Protection
- Moisture content
- Density of the timber
- Timber species
- Grain direction
- Permeability
- Sample orientation
- Sample size

Heating

Timber has relatively low thermal conductivity and relatively high specific heat capacity [14]. This means that the material has good insulating properties against heat transfer. Once heated, timber is decomposed and volatiles are created and mixed with the surrounding air above the surface. With a sufficient mass flux of volatiles produced, once the mixture is within the flammability limits, timber is ready to ignite. With the addition of the heat source, this will occur at the lower heat fluxes.

Ignition

A reasonable agreement across the literature is that the critical heat flux for pilot ignition is 12 kW/m^2 and 28 kW/m^2 for spontaneous ignition. The critical surface temperature for pilot ignition is 350 ℃ and for spontaneous ignition 600 ℃. Both temperatures are determined in the conditions of radiant heating [14]. These values will vary depending on oxygen concentration [19], moisture content and wood species [14], and longer duration of irradiation exposure can lower the critical heat flux for ignition [20].

Pyrolisis

Pyrolysis is a thermal decomposition by which the chemical composition and physical phase are irreversibly changed. In structural fire safety design (see section 5.6) traditionally much emphasis is on the charring behaviour of timber and the indicative temperature of 300 ℃ has become widely accepted for the onset of charring [13]. The created char has high thermal conductivity, but it is porous and inhomogeneous and thereby decreases conductive heat transfer [21]. As the char layer of timber grows thicker, it serves as the protective layer, slowing down the heat transfer to the virgin timber behind. However, although its creation is beneficial for the element itself, one should consider the system as a whole due to the energy released through char oxidation which contributes to the reradiation and heating of the elements in the surroundings. During the burning char oxidation releases energy and the effect will be more significant with increased gas velocity [22] but also influenced by temperature and oxygen concentration. In a research paper by MacLeod, Law and Hadden 2023 [16] it is concluded that in longer fire scenarios, char oxidation contributes significantly to the heat release of burning timber:

"*While in design it is common to attribute the char layer as a protective layer for the virgin timber, it is clear that when it oxidises it is releasing energy into the system and contributing to the continued burning of timber*." [16] p.9

Energy contribution from timber

The heat of combustion for timber is in the order of 17.5 MJ/kg ± 2.5 MJ/kg [14]. The char layer will limit the heat transfer into the timber but this heat transfer is heavily dependent on organic impurities and cracking in the timber, as cracks will allow for radiative heat transfer as well as convective heat transfer [14]. Cracks will also allow pyrolysis gases to transfer past the char layer and fuel the fire.

The energy content of combustible material can be quantified through its heat of combustion, defined as the heat produced when a unit mass of the material is oxidized [23]. It can be defined as a net or effective heat of combustion. The net is obtained through the bomb calorimetry and it reflects the amount of energy that can be produced when the material is heated at 100 % oxygen. However, in reality, this is not the case, and the completeness of the combustion depends on the heating and air flow conditions, where heating conditions change depending on the number of surfaces exposed and airflow conditions change based on the compartment geometry and size of the openings.

Crielaard et al. 2019 [24] found in small-scale compartment fire experiments with exposed CLT walls and ceilings, where the compartments did not self-extinguish (explained in section 4.2 Burnout), that the CLT contributed significantly to the fire with a fuel load (up to 412 MJ/m^2). An increase of approximately 400 % from the moveable fire load. In the experiment where the

CLT did extinguish, the contribution of the CLT remained limited to an additional fuel load of 242 MJ/m^2. The lowest contribution was in the compartment with no char layer fall-off, which had an additional fuel load contribution from the timber of 142 MJ/m^2. Note that these values were obtained under the specific conditions of the experiments, with many CLT surfaces exposed in relation to the floor area [24]. From the "*Fire Safety Challenges of Tall Timber Buildings – Phase 2: Task 3"* [25] six different large-scale fire compartment tests were conducted with different amounts of CLT being protected with gypsum plasterboard. The moveable fuel load introduced to these tests was in the order of 550 MJ/m^2 and the effective fuel load measured in the different tests was; 1090 MJ/m^2 in Test 1-3 (one exposed wall); 1450 MJ/m^2 in Test 1-4 (ceiling exposed); 2550 MJ/m^2 in Test 1-5 (one wall exposed, same as Test 1-3 but smaller opening); and 3300 MJ/m^2 in Test 1-6 (one wall and ceiling exposed) [25]. The effective fuel load contribution from the timber was found to be at least double that of the moveable fuel load.

It is not only during the flaming combustion that an increase in heat release of burning timber will occur. The oxidation of char during smouldering combustion also provides a significant contribution to the total heat release during long durations of a fire [16].

4.2 Fire spread

The combustible nature of timber construction allows for different scenarios where fire spread between fire compartments can occur. Brandon et al. 2018 [26], present several consequences of fire spread in timber construction that have been identified and are to be limited as part of the fire safety strategy. These are presented below together with Figure 4:

"1. Limitation of fire spread directly from compartment to compartment:
  a. Limitation of spread through walls, floors or ceilings;
  b. Limitation of fire and smoke spread through connections between two wall slabs or a ceiling/floor and wall slab; and
  c. Limitation of fire and smoke spread through wall and ceiling penetrations.

2. Limitation of fire spread through cavities of the building:
  a. Limitation of fire spread via the cavities between compartments; and
  b. Limitation of fire spread via the cavity of the façade.

3. Limitation of fire spread via the outside of the building:
  a. Limitation of fire spread via the façade surface;
  b. Limitation of fire spread through windows; and
  c. Limitation of fire spread through ventilation openings (such as ventilation openings of attics)." [26] p.13

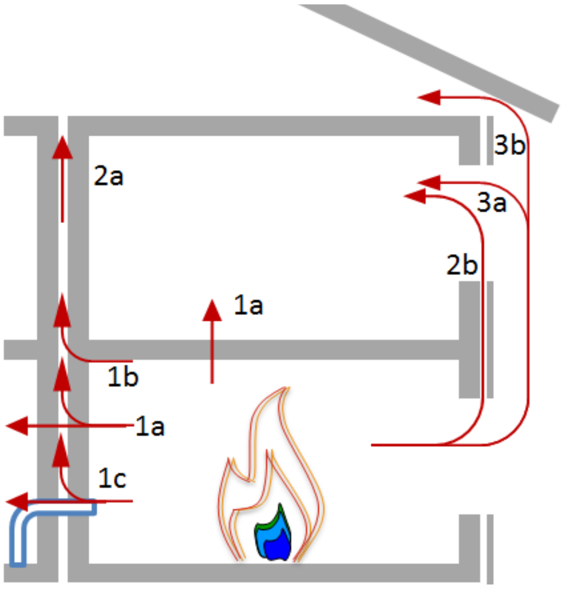


Figure 4: Potential paths of fire and smoke spread out of the compartment considered for the building design [26].

As can be seen in Figure 4 there are several paths of fire and smoke spread in a timber construction building to consider. These might not be unique to a timber construction building, however, in a timber building, there is more complexity to be considered compared to non-combustible construction. The different paths of fire spread as indicated in Figure 4 are presented below in more detail, following the same numbering.

1. Limitation of fire spread directly from compartment to compartment

In the event of a compartment fire there are some typical paths for fire spread that must be considered within the design and construction process as presented in [7]:

- Fire spread through failure of separating elements;
- Fire spread through joints;
- Fire spread through junctions;
- Fire spread through building services; and
- Fire spread through concealed construction cavities.

The risk of fire spread through joints and junctions typically occurs between floor slabs and loadbearing walls and fire spread through these to concealed cavities and voids in internal or external walls can be critical. Corner connections to other building parts or joints around service installations and penetrations have the potential to create weak spots that allow for fire spread in a fully developed fire [27]. Creeping and natural movement of timber elements in a building (e.g. due to the changes in the environmental conditions) will over time have the potential to increase the extent of gaps and joints. Gaps have the potential to allow the spread of hot gases and smoke during overpressure conditions under fire exposure and reduce the fire separating performance of the entire structure [28].

"The following general design principles for light timber frames and mass timber assemblies should be considered to guarantee the required fire resistance rating of the separating element:

- *Panel joints must be tightly jointed or be filled with fire-resistant material*
- *Joints in multilayered panels should be staggered*
- *All joints, penetrations and openings should be appropriately fire stopped*
- *Void cavities should be filled with insulation material*
- *Convective flow paths should be excluded or minimised*
- *The load-bearing function of an element supporting a separating element has to be fulfilled*
- *The end use conditions need to be considered, to avoid unexpected gaps or cracks due to shrinkage*." [7] p.321

Required cabling or other services such as plumbing, connectors, switches and sockets may be routed directly inside the separating element. Service installations embedded within the building elements will reduce the fire separating performance and need to be considered [7]. Finally, it is also important to consider the penetration position and the stress distribution in the elements in that case [29].

2. Limitation of fire spread through cavities in a building

Cavities that are built in between timber elements or behind the weather protection of external walls have the potential to spread smoke, flames or smouldering fire with significant consequences. It is of great importance that risks associated with fire spread through cavities are considered.

Non-combustible materials that are soft and compressible, such as low density insulation material, are suitable to be installed and fill cavities. This will reduce the risk of rapid fire spread through cavities, however, not necessarily limit the possibility of smouldering fire spread. In [26] mineral wool products (glass wool, stone wool and high temperature extruded mineral wool) that have a compressed density of 50 kg/m^3 after installation are recommended.

However, not only the density is a characteristic, but also the quality of the product, the thickness and how it is installed are important factors to consider. For example, normal glass wool typically has a lower melting point and will not remain in place as well as stone wool when exposed to high temperature. Products with plastic covering should be avoided as they have the potential to cause small air channels that allow hot air to flow into the cavity and they may melt and form droplets [26].

It has been suggested that timber can be used as a fire stop in open cavities [26], provided that the minimum height of a fire stop is calculated using a one-dimensional charring rate in accordance with Eurocode 5 [30]. This has the possibility to delay the fire spread, but the use of combustible material inside cavities can eventually fail if the combustion is allowed to continue. Fighting cavity fires are found to be very difficult and the possibility of cavity fires must be avoided, particularly in relation to property protection. See section 7.2 for more information about firefighting in timber buildings.

3. Limitation of fire spread via the outside of the building

The fire safety strategy for a tall building generally relies upon fire compartments maintaining their fire separation for a complete burnout of a fire. See more information about burnout in section 4.2. It is therefore important that the fire separation is not compromised by fire spread via the external façade or cavities behind the external façade. If combustible materials are used in or around cavities behind the external façade, or if the external façade is combustible, the risk of external fire spread can increase. The external wall must also mitigate the risk of falling debris causing fire spread or damage to people and firefighters [26]. The risk of fire spread to neighbouring buildings may also increase with a combustible facade.

Building codes typically present requirements on the materials used in external walls to mitigate the risk of external fire spread. In the UK there is a current ban in place that no building over 18 m should be constructed with any combustible components as part of the external wall. This restricts the possibility of using a load-bearing timber structure that forms part of the external walls. In other national building codes, combustible materials can be used as part of the external wall system if they have passed a large-scale façade test (e.g. SP Fire 105 [31], Lepir II [32], BS 8414 [33], ISO 13785 [34], NFPA 285 [35], AS 5113 [36]). This allows the use of combustible timber facades that have been treated with fire retardant products and successfully passed the relevant test. See section 6.1 for more information about fire retardant products. However, the durability of most fire retardant products applied to timber facades reduces significantly due to weathering within a few years [26,37], which is not typically addressed in building code requirements.

It should also be noted that the large-scale façade tests use a limited fire exposure, both in relation to heat release rate, temperature and the time of exposure. The façade tests are designed to represent fully developed compartment fires for a limited period of time. In a timber building, the fire scenarios can be more severe due to the increased fuel load which will lead to long fire scenarios and more extensive external flaming, compared to exposure in the façade fire tests. This has been confirmed in many large-scale fire tests [26,38–40]. Sjöström et al. 2023 [40] present the comparison between different façade fire test standards and large-scale experiments with exposed CLT. The comparison shows that the SP Fire 105 [31] and Lepir II [32] test methods produce significantly less severe plumes but that the British BS 8414 [33] façade fire testing method and a newly proposed method for the EU are the most representative of the tested fire scenarios [40].

Outdoor areas next to the façade, such as balconies or terraces also pose a risk of fire spread, especially if constructed in timber. See an example of a floor slab extension with exposed timber above a balcony in a residential timber building with a wooden façade in Figure 5.

Figure 5: Picture of a floor slab extension with exposed timber above a balcony in a residential building with a wooden façade. (Photo Carl Pettersson)

Additional considerations to fire spread in timber buildings

A fire separating measure may fail due to it not performing as intended when exposed to a real fire scenario that is different from the fire test scenario, or as a result of not being installed correctly. This is a problem in all types of buildings, not only timber construction buildings. However, the potential consequence of a failure in a fire safety measure protecting against fire spread in a timber building, where the structural elements are combustible can be far greater.

Fire stopping products are tested to achieve fire resistance when exposed to the standard temperature curve in a furnace test and should be tested in the building element they are to be installed. More information about furnace testing can be found in section 5.4. Even if the product has been tested in a mass timber wall or floor configuration the performance in a real fire in a timber building can expose the product for longer durations of heating compared to the standard test if additional fuel to the fire is provided by the timber structure.

Movements in timber structures over time or during structural stress in a fire scenario can also cause the fire protection measure to fail. If this is not accounted for with robust installation techniques that account for movement, the measure may not protect against fire spread. Using a robust design, the loss of a fire protection barrier can be avoided, even if the primary fixation method (using glue, fasteners or clamping) fails [26].

4.3 Heat-induced delamination and protection fall-off

Heat-induced delamination

Heat-induced delamination can relate to several different behaviours. In this report, it is defined as the stochastic phenomena of heat-induced delamination of timber lamellas. Protective encapsulation fall-off will give a similar effect with sudden exposure of virgin timber adding more fuel to the fire and is therefore also included in this section.

In relation to laminated timber products, heat-induced delamination may in the literature be presented in the terms of "delamination", "bond line failure", "glueline failure", "debonding", "loss of stickability" or "char fall-off". Čolić 2021 [41] describes the three different mechanisms of heat-induced delamination ("debonding") between the two lamellae: *"(1) the failure within the timber (lamellae), (2) through the loss of cohesion within the adhesive, and (3) loss of adhesion between the timber and adhesive at the bonding interphase."* [41] p.19. It differs from char fall-off because it can occur at temperatures that are lower than those inducing timber pyrolysis, and it leads to premature failure of the composite action within the element. In many different large-scale fire experiments, it has been found that the event of heat-induced delamination of CLT timber lamellas is hard to predict [42,43]. The reason for this is the interaction of moisture movement, thermal penetration and hence degradation of both timber and adhesive but also the mechanical stresses induced in the bond line region.

Char fall-off

While the heat-induced delamination will result in the detachment of pieces of lamella which are not completely charred, char fall-off is considered to be the only detachment of the charred pieces. This can occur due to loss of connectivity between the char and its substrate away from the glueline [44] but also in a way that completely charred lamella falls, leading to the exposure of the following virgin lamella.

Protection fall-off

Encapsulation failure of protective layers has been witnessed in large-scale fire compartment tests. The protective layer, being fire rated plasterboard, has after a period of fire exposure fallen off, exposing the unprotected timber surface behind. This was observed in a large-scale compartment test presented in [45], where two CLT walls were encapsulated with two layers of 12.7 mm thick Type X gypsum board and two walls were left exposed together with the CLT ceiling. The CLT used were *"second generation CLT panels"* with an adhesive that maintained the glueline integrity sufficiently to prevent heat-induced delamination throughout the test. However, despite no heat-induced delamination, the fire did not self-extinguish. The prolonged fire was sustained with continuous flaming, fuelled by pyrolysis gases passing through cracks and gaps in the gypsum plasterboards, indicating insulation failure. At 100 minutes the initial fully developed fire had decreased but continuous flaming was recorded from the cracks, which maintained the average temperature in the room above 500 °C. After 220 minutes, flames were also observed from the bottom of the two exposed CLT walls, which increased and eventually led to a secondary flashover (see section 4.4 for more information about secondary flashover) in the compartment with the loss of protective covering as a result. The fire test had to be manually extinguished.

The consequence of protection layer fall-off will be similar to the char fall-off, as virgin timber surfaces will be exposed to the fire, usually at a later stage of the fire. This increases the charring rate [46] because the elements are exposed to later (potentially more severe) stages of the developed fire, which prevents the combustion from self-extinguish and prolongs the time until burnout (see section 4.2 for more information about burnout) if ever achieved. See more information about encapsulation and protective layers in section 6.2.

Implications and relationship between the three phenomena

The energy contribution from timber in a fire is substantial. In large-scale compartment fire experiments, glueline failure has been witnessed during a fully developed compartment fire but also during the decay phase of fires [25,42]. If delamination occurs during the fully developed fire, the introduction of new fuel will maintain the high heat release rate and the fully developed fire until there is no timber left [25]. In the event of heat-induced delamination in the decay phase, or char falling off right before the bond line interphase, new virgin fuel will be introduced to the fire, increasing the heat release rate and creating a secondary flashover scenario. See section 4.4 for more information about secondary flashover. Moreover, the continuous char oxidation from fallen char on the compartment floor leads to radiative feedback to the elements. This process has the potential to stop or to continue until there is no more timber in the structural element left to burn. Heat-induced delamination of timber layers, char fall-off at the adhesive line, or protective layer fall-off, all have the potential to cause secondary flashover scenarios or continuous fully developed fires with the potential of great consequences for a building, such as structural collapse.

However, while the three phenomena, heat-induced delamination, char fall-off, and protection fall-off might have similar implications on fire dynamics, heat-induced delamination not only occurs at lower temperatures but leads to progressive and premature loss of structural capacity because the part of the uncharred lamella is also lost.

Factors influencing heat-induced delamination

Glued massed timber products with large lamellas such as CLT are more prone to this behaviour, heat-induced lamination can occur for any laminated timber product. From fire testing, it has been found that ceilings are more prone to heat-induced delamination [7] possibly due to the influence of gravity, however, it has been also observed on the walls [47] which is detrimental to the load distribution and load bearing capacity of compressive elements due to the initiation of secondary moments, as studied by Wiesner et al. 2022 [48].

Different chemical compositions of the same type of adhesives used to laminate timber layers in CLT have proven to perform very differently when exposed to higher temperatures in experiments [43,49]. It has been found that the critical temperature for the adhesives used in the most common CLT products will experience glue line failure at temperatures in the glue line as low as 90-125 °C [15]. In the experiments as part of the "*Fire Safety Challenges of Tall Timber Buildings – Phase 2 Task 5*" [43] critical bond line temperatures resulting in glue line failure were recorded at a range between 200 °C and 900 °C. However, critical temperatures between 200 °C and 400 °C were significantly more frequent. The temperature at which heat-induced delamination occurs is also dependent on the duration of the heating process [43]. This could be a reason why it has been found in large-scale CLT compartment fire tests that the second layer experienced glue line failure at lower temperatures compared to the first layer.

There are several different adhesive products used for laminated timber products, the most commonly used have a standard polyurethane (PUR) base. There are also phenol resorcinol formaldehyde (PRF), emulsion polymer isocyanate (EPI) and melamine urea-formaldehyde (MUF) based adhesives [43]. According to [43], the MUF adhesive has proven to perform better in higher temperatures but the performance varies between different products formulated from the same components. Modified 1-component-PUR has been found to offer enhanced performance over standard 1-component-PUR [44]. The laminating process of the timber product, such as mechanical or vacuum compression, can also influence the performance of the adhesive in higher temperatures [50].

The first requirement regarding the performance of adhesives in fire conditions for CLT was introduced in the USA and Canada in 2018, as part of the updated ANSI/APA PRG 320 testing regime [51]. This requires a CLT ceiling to be subject to a compartment fire test protocol. This testing protocol originates from the temperature exposure experienced in the "*Fire Safety Challenges of Tall Timber Buildings – Phase 2 Task 3*" [25] compartment fire test 1-4. An additional small-scale delamination fire test is now mandatory as part of the ANSI/APA PRG 320 standard. A CLT product that has been approved through this test regime is generally referred to as "*second-generation CLT panels*" [45].

Outside of the USA and Canada, there are currently no requirements for CLT or other timber products to be subject to a standardised testing regime representing real fire exposure. The structural performance testing of timber products tends to not expose the product to temperatures over 70 ℃ in Australia and New Zealand, 90 ℃ in Europe and 150 ℃ in Japan [37]. Subsequently, all CLT may experience heat-induced delamination if exposed to a fully developed real fire scenario where the temperature in the glue line is increased to its critical value.

In Europe, a collaborating project between RISE, ETH Zurich and 16 industrial partners, is tasked with the development of a standard fire testing methodology and classification method of the glue line integrity in fire (GLIF). As part of this project, Brandon et al. 2021 [52] present studies of the suitability of a furnace test for determining whether products exhibit glue line integrity failure or not. The proposed updated Eurocode 5 [53] will contain this new method and be applicable to CLT and comparable engineered mass timber materials.

The heat-induced delamination of laminated timber products is not only affected by the characteristic of the adhesive but also the layup of the laminated product as a system. A thicker outer timber layer in the CLT has been found to perform better against both char fall-off and heat-induced delamination [24,46]. Other properties that will also influence this behaviour, the following have been identified by Čolić 2021 [41]:

- Adhesive properties
- Bond line thickness
- Moisture content in the timber
- Species of timber
- Manufacturing technique
- Edge-bonding
- Induced structural load

4.4 Secondary flashover

A secondary flashover scenario can occur when an enclosed fire has started to decay and new fuel is introduced from timber surfaces due to heat-induced delamination or protection fall-off. Secondary flashover scenarios have been observed in several large-scale fire compartment experiments with exposed CLT elements [42,54–56]. These experiments, which involved heat-induced delamination of the outer CLT layer (typically after 120 minutes) followed by a secondary flashover, were manually extinguished before the potential third and continuous flashover occurred. However, it can be expected that the char layer would build up again leading to a new decay phase, followed by potential additional fire re-growth [42] and potential collapse [47].

If the protective encapsulation around timber structures is provided but is not able to withstand the burnout of the fuel introduced to the fire, a secondary flashover scenario can occur once the protective encapsulation starts to fall-off. This has been witnessed in fire tests presented in [45].

Factors that may contribute to the possibility of secondary flashover scenarios are presented below:

- The amount of exposed timber in the compartment
- Heat-induced delamination or failure of protective encapsulation
- How much heat the timber is being exposed to (i.e. re-radiation feedback)
- Duration of fire
- Location of the exposed timber

In the event of a secondary flashover scenario, the structure and separating elements will be exposed to a scenario it has not usually been designed for. Fire spread and structural failure are potential consequences following the event of secondary flashover scenarios.

Encapsulation of the timber can be used as a fire safety measure to protect against secondary flashover scenarios. To achieve a robust design with this measure it is important to account for the potential alterations and future use of the building that may alter the robustness of this protection. Modifications, new installations, penetrations, fit-outs and other configurations could potentially reduce the effectiveness of the protection’s possibility to withstand a burnout scenario in a fire. More information about burnout can be found in section 4.2.

4.5 Burnout

Burnout can be defined as "*the ability for flaming and smouldering combustion to stop without intervention*" [7] p.433. In other words, the combustion will "self-extinguish" (auto-extinguish) which is defined as a verb in the international standard ISO 13953 Fire Safety – Vocabulary meaning *"cease combustion without being affected by any external agent*" [57]. The term "self-extinguishment" (or auto-extinction) however, is not well-defined and has been used to describe the end of flaming combustion, the end of the decay stage, or the end of smouldering combustion. Due to the term is it not well-defined it is strongly discouraged in the Fire Safe Use of Wood in Buildings: Global Design Guide [7].

Historically, burnout first became relevant as part of the fire severity tests performed by Simon Ingberg in the 1920s. By investigating fire severity (i.e. the time period of how long the fire of known fuel loads continued burning) Ingberg related the fuel load in his fire experiments to the standard temperature fire curve exposure. This later became the basis of standardised fire resistance testing [58–62]. See section 5.4 for more information about fire resistance testing.

The fire resistance concept of maintaining a fire inside the compartment of fire origin has since been incorporated into the fire safety strategy for tall building designs around the world. This has historically been proven successful for non-combustible construction such as fire protected steel and concrete.

"*The fire resistance ratings in contemporary design codes were created with the intention that a structure would maintain its loadbearing capacity for as long as a fire could burn, until all the fuel in the compartment was consumed – this is design for burnout."* [63] p.1

In relation to timber buildings, where also the structure provides fuel load, the achievement of burnout is less certain and the residual fuel presented by the structural timber elements may never stop burning [64]. This can eventually lead to structural collapse if the fire is not manually extinguished. However, the fire may still self-extinguish due to insufficient energy feedback from the burning composition in the compartment.

Several large-scale and medium-scale experiments have proven that a mass timber compartment fire can self-extinguish [25,42,65] but many are found to not self-extinguish. In the experiments conducted by Hadden et al. 2017 [42] the same configuration of a test (Beta-1 and Beta-2), had two opposite walls being exposed mass timber and other walls and ceilings protected with encapsulation. In the Beta-2 test, char layer fall-off occurred followed by a secondary flashover scenario, whilst in the Beta-1 test, the char layer was maintained and the flaming fire eventually self-extinguished. From this, it can be concluded that it is difficult to predict if the fire will self-extinguish in a compartment with exposed CLT elements. It also demonstrates that when comparing fire compartment tests, it is important to acknowledge the many variables and uncertainties that will influence the results.

From a review of completed compartment tests, it was found in [4] that only one of the 41 compartment tests achieved completely self-extinguished. The other tests had been extinguished manually before this could be confirmed. In the "*Fire Safety Challenges of Tall Timber Buildings – Phase 2: Task 2 & 3*" test series [25] it was found that char layer fall-off prevented self-extinguishment in test "1-5", where one CLT wall was exposed and a secondary flashover occurred. In test "1-6", which had an exposed CLT ceiling and wall, continuous char layer fall-off from the ceiling maintained a fully developed fire throughout the test, preventing the fire from self-extinguish.

There are many factors that will impact the potential for a fire scenario to self-extinguish. In the literature the following aspects have been found to influence the potential for a fire scenario to self-extinguish [24,54,55,59,66–72]:

- Configuration of the compartment
- Compartment size and ventilation
- Location of mass timber elements
- Movable fuel loads introduced to the fire
- Heat-induced delamination and char fall-off of timber layers and failure of protective layers in the fire

If a fire is not providing enough heat back to combustible materials or if there is not enough oxygen, the combustion cannot be maintained, and the fire will eventually self-extinguish.

Work has been carried out by Emberley et al. 2017 [59], to understand the critical mass loss rate and the critical heat flux when flaming combustion will cease in timber. Tests were conducted using a small-scale cone heater with a steady-state condition in order to quantify the worst-case scenario for the critical heat flux for flame extinction.

Bartlett et al. 2017 [71] undertook bench-scale flammability studies to explore the conditions under which self-extinction (auto-extinction) will occur. They found that mass loss rate is a better criterion compared to critical heat flux. Using their findings in the bench-scale experiments they found that the critical mass loss rate was valid for application to full-scape compartment fire experiments.

Cuevas et al. 2023 [68] investigated the influence that oxygen concentrations near the burning surfaces of timber have in the occurrence of self-extinction, considering a range of heat exposures and oxygen concentrations. They used FM-Global’s Fire Propagation Apparatus (FPA) and concluded that lower oxygen concentrations result in an increase of the critical mass loss rate leading to self-extinction and an increase of the minimum incident heat flux leading to self-extinction.

Cuevas and Maluk 2023 [73] also used FM-Global’s FPA to investigate the impact of moisture content (7 %, 11 %, and 14 %) on the burning behaviour of timber. They found that the time-to-ignition was observed to be directly proportional to the moisture content of timber and that the critical mass-loss rate required to sustain burning or achieve flame extinction increased with higher moisture content in the samples [73].

In relation to a fire in a building, smouldering combustion can still pose a hazard to the structural integrity and may transition into flaming combustion [74]. An important factor that will influence the smouldering combustion is airflow which can occur naturally within a compartment, especially in small gaps, and re-radiation of smouldering surfaces will maintain the combustion and depend on the complex design of the timber buildings [66]. The provision of a rise in oxygen for the smouldering combustion can lead to flaming combustion under the right conditions. Smouldering also poses a risk of fire spread in a building, especially through concealed spaces. Another important factor that will influence the combustion is the feedback, such as in a corner, which can lead to a runaway temperature rise that will raise the production of pyrolysis gases to a point that will create a flammable mixture [75].

In most large-scale fire tests with CLT compartments, the fire has been extinguished manually with water before complete burnout i.e. the cessation of smouldering combustion has been witnessed [25,42,59,65,67,74,75]. In a recent large-scale test series presented by Su et al. 2023

[76] conducted by the National Research Council of Canada. The tests were terminated manually after approx. 4 hours, but it was found that deeper charring near the connections and junctions of the beams, columns and ceiling with some deep-seated hidden hot spots and smouldering remained after the tests. This required firefighting operations and for one test it was necessary to remove exterior walls and roof covering to directly attack the hidden flames and hot spots in the joints and junctions [76].

A different approach was taken in the large compartment fire test series "*CodeRed"* [66] and *"The Epernon Fire Tests Programme"* [77]. In the "*CodeRed"* tests smouldering behaviour was allowed to continue without manual extinction and smouldering combustion was observed in hotspots for more than 48 h (even 22 days in the *CodeRed #04* test [66]) since the flaming ceased. It was found that smouldering hotspots can lead to stress concentrations increasing the likelihood of structural failure and smouldering in a reappearance of flames, hence posing a risk of fire spread [66]. As smouldering spreads at a greater rate when subject to higher airflow, small gaps between timber connections where airflow exists were identified as having an enhanced risk of maintaining the combustion [66]. In the paper by Wiesner et al. 2021 [77] an analysis of selected observations and measurements from *"The Epernon Fire Tests Programme"* is presented. Comparing the results from three similar 'natural' fire scenarios with variations in opening geometry gave considerably different results. Scenarios 1 and 2 had more ventilation from openings to the compartment compared to scenario 3, which resulted in faster fire growth and faster decay phase in these scenarios. Continued localised smouldering was observed in scenario 2, which structurally survived fire exposure and decay phases but collapsed after 29 hours due to unseen smouldering [77]. Scenario 3 with the least ventilation had the longest burning duration but also slower decay. Resulting in a longer thermal attack leading to a deeper char depth and enhanced thermal penetration, which after 108 minutes resulted in structure failure during the decay phase [77]. In relation to the longer thermal attack which led to deeper char depth for scenario 3 the following is stated:

"This is potentially important because it means that, for CLT (and other forms of mass timber such as glued laminated timber), the duration of a fire is likely to be more critical for its load bearing capacity than the peak temperatures in the enclosure (for the likely ranges of temperatures)." [77] *p.306*

In a compartment fire, where all movable fuels are consumed and all timber surfaces are burning without any heat-induced delamination of timber layers, it is possible to theoretically quantify when the flaming combustion in the compartment will self-extinguish. However, as mentioned above, this is influenced by many factors such as oxygen concentration, moisture content and heat feedback. Furthermore, as identified by Mitchell et al. 2023 [66] the potential of smouldering combustion in hotspots makes it practically challenging to predict when the fire will self-extinguish and further studies on smouldering in complex timber design elements are necessary to determine the hazard that smouldering may pose.

Although smouldering may stop in large parts of the structures, it may continue in small gaps or enclosed locations. Hindering complete burnout in a building requires firefighting intervention to extinguish smouldering fires [78].

4.6 The effects of geometry

The size and geometry of a compartment will have a great influence on the fire behaviour and the fire dynamics.

The enclosure fire dynamics and burning behaviour of timber will be influenced by the geometry in the compartment and the location of timber surfaces. An enclosure fire can be divided into three stages; the growth stage, the fully developed (or postflashover) stage and the decay stage [15,79]. A recent study by Lucherini and Torero 2023 [80] also separates decay and cooling into separate phases, highlighting their difference in thermal boundary conditions which is important for structural fire design. The transition period between the growth stage and the fully developed stage is referred to as "flashover". However, in a large enclosure these stages may not strictly be true and what is described as travelling fire may occur instead (see section 4.6).

Early research has shown a distinction between two regimes, a ventilated-controlled regime and a momentum-controlled (fuel-surface controlled) regime [81–83]. Most models developed to predict enclosure fire dynamics have been based on experimental data from fire tests in the ventilated-controlled regime with non-combustible compartment linings. These models are applicable for smaller compartments with more homogeneous temperatures and less complicated fire behaviour in the compartment. In the momentum-controlled regime, typically represented by fires with greater ventilation, common in larger open-plan compartments, it is more difficult to predict the fire scenario and the enclosure fire dynamics. See section 4.6 for more information about the effects of geometry in a compartment.

Pope et al. 2023 [84] present results from a series of large-scale experiments with a compartment constructed out of CLT, with variations of the amount of exposed timber in the different tests. The compartments studied were of a geometry and opening factor that would conventionally define them as a ventilation-controlled regime. The results showed significant variations were seen in the fire dynamics. The results show that the surface area of exposed timber alters the flow fields both inside the compartment and at the doorway and Pope et al. [84] make the following conclusion:

"Typical simplifications of the momentum equation in zone models, which are commonly used to define thermal boundary conditions in under-ventilated compartments, are not valid in mass timber compartments. The thermal boundary conditions in the fully-developed phase dictate the level of structural damage and can induce localised failures, such as char fall-off or encapsulation failure, which can inhibit self-extinction. Therefore, these simplified solutions should be used in a conservative manner that accounts for the range of thermal conditions observed in large-scale experiments." [84] p.15

In larger compartments, a flashover scenario may not occur and the fire might travel or migrate, and no longer be a local fire but a spreading fire (often referred to as a travelling fire) [83,85–87]. The fire behaviour in a larger compartment plan can be divided into three distinct modes of behaviour: a fully-developed fire, a growing fire, and a travelling (steadily moving) [87]. The concept of travelling fires depends on the initial point of ignition, heat sources, available fuel to the fire, geometry, ventilation and the direction of fire spread. A fire in a large compartment can result in highly non-uniform temperature distribution within the enclosure [88,89]. One definition of a travelling fire is a fire that moves across floor plates as flames spread, burning over a limited area at any one time [89,90].

In a travelling fire, the structure experiences pre-heating at relatively low temperatures (far-field) and is only exposed to high temperatures when the flames arrive (near-field). After the flame front passes, the structure receives far-field heating again, which can lead to longer durations of burning compared with post-flashover fires. As a result, travelling fires can have a more detrimental thermal impact on a complete building structure [88,89,91].

The effects of a travelling fire are difficult to quantify, but the Travelling Fires Methodology (TFM) [90], the improved Travelling Fires Methodology (iTFM) [92] and the Extended Travelling Fire Methodology (ETFM) [93] provide travelling fire models to predict thermal exposure in non-uniform temperature distributions in large-space building fires. A large review of the state-of-the-art experimental research of large compartment fires from the past three decades has been conducted and presented by Gupta et al. 2021 [87]. Comparing the heat fluxes obtained from this analysis of the available experimental data with the current travelling fire methodologies. They found that the underlying assumptions for travelling fire methods are overly conservative and do not adequately capture the physics of travelling fires and that they should be revisited.

Structural fire design methods that are applicable for timber construction are generally based on the post-flashover assumption, that the temperature in the compartment will be homogenous for a limited period of time and therefore not applicable for travelling fires [7]. Richter et al. 2021 [94] point out that due to the longer pre-heating in a travelling fire, the structural strength may decay ahead of the charred front in a timber structure. Rackauskaite et al. 2021 [95] provide a review of key parameters of the general concepts and principles of most published travelling fire methodologies, which will be influenced by mass timber structures. They conclude that it is necessary to investigate many of these key parameters with additional experimental and numerical research, to make the travelling fires methodology fit for purpose when relying on it in design safety.

Nothard et al. 2022 [96] have conducted a series investigating the influence of an exposed timber ceiling and ceiling intrusions on the fire dynamics in a reduced scale open plan compartment. They found that the ceiling intrusions had a stalling effect on the momentum-driven flow, which increased the residence time of the pyrolyzates from the CLT. This contributed to a faster transition from a travelling fire (Mode 3) to a growing fire (Mode 2) and then to fully a developed fire (Mode 1) as the conditions created earlier ignition of the CLT ceiling. Although the reduced scale of the tests and subsequently relatively thin smoke layer may impact these results, it was found that the ceiling intrusions had an influence on the fire behaviour [96].

The recent experimental series "*CodeRed"* investigated travelling fire behaviour in mass timber compartments. CodeRed #01 was built with a fully exposed CLT ceiling, two glulam columns and a protected steel column to evaluate their performance during and after a fire [97]. CodeRed#02 had the same setup but with reduced available ventilation [98]. The CodeRed #04 had the identical setup as CodeRed #01 but with plasterboard encapsulation consisting of three layers of 12,5 mm plasterboard, equivalent to $K_2$60/A2-s1,d0 protection [99]. With a floor area of 352 m^2, these are the largest compartment fire experiments with exposed (and encapsulated) CLT performed to date [39]. In the experiments with exposed CLT, the flames spread quickly across the ceiling with an average spread rate of approximately 9 m/min, which significantly exceeded the flame spread rates found in 48 different compartment experiments without exposed combustible surfaces (≤ 1 m/min) [39]. The rapid flame spread in the experiments with exposed CLT was representative of typical flashover behaviour, although comparative experiments with non-combustible materials “x-ONE” [100] and “x-TWO” [101], did create a travelling fire behaviour. In the #FRIC-01 [39] fire experiment (95 m^2) with an exposed CLT ceiling, with large ventilation openings concentrated along one side of the compartment. In the test flashing waves were observed as the fire travelled back and forth in the compartment. However, the flame spread was not as significant as observed in the CodeRed #01 and #02 experiments, which used another setup of wood crib fuel. Indicating that the type of fuel and whether the flames from the fuel bed are impinging the exposed CLT ceiling greatly impact the flame spread rate [39].

For timber buildings with larger floor areas and volumes, such as office or atrium spaces, see Figure 6, exposed timber in walls and ceiling elements can provide conditions for fast developing travelling fires. In the design of a building, the possibility of a travelling fire in larger compartments may be important to consider in relation to the fire safety strategy of the building.

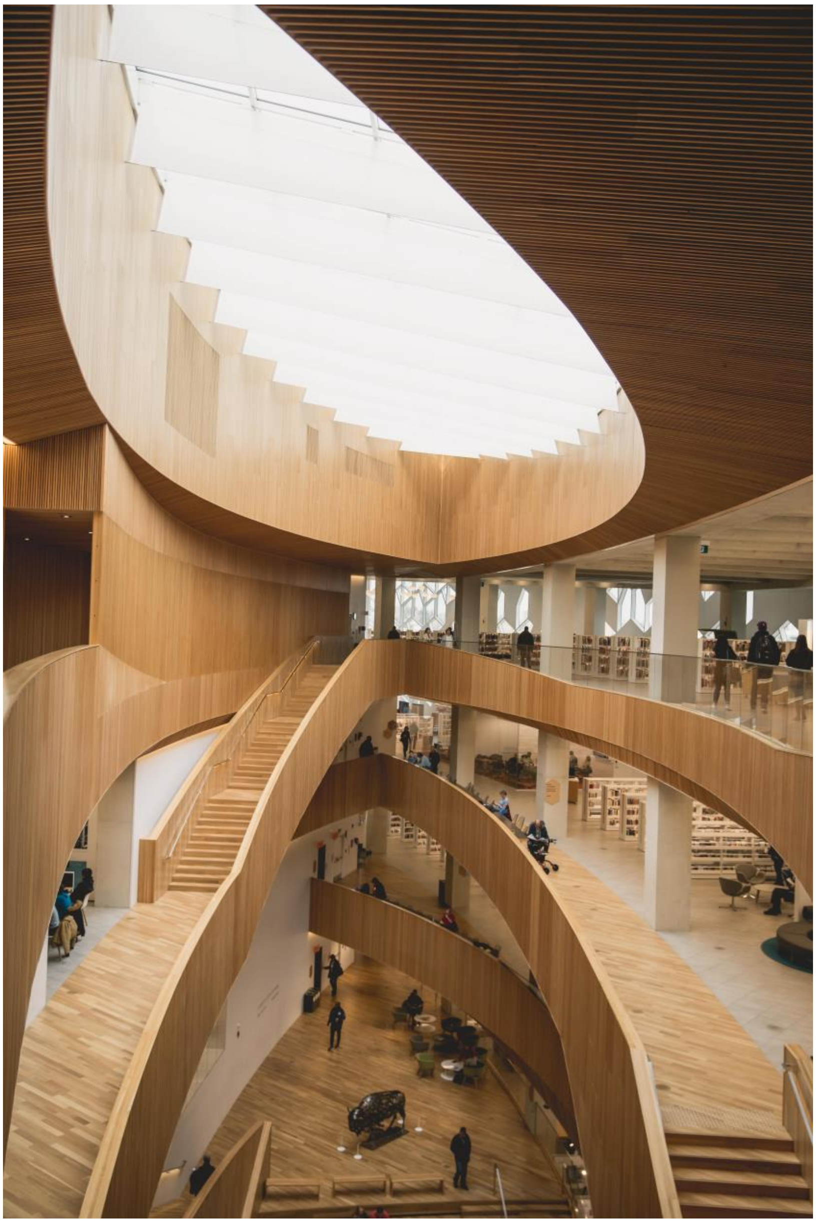


Figure 6: An atrium design with an open floor plan and many decorative exposed timber surfaces.

5. Structural fire design

5.1 Charring rate

Char is a carbonaceous residue resulting from pyrolysis or incomplete combustion. Charring used in structural design is usually derived from standard fire exposure and is a simplification of the complicated pyrolysis of timber [14]. The theory of the pyrolysis process has been well described in detail by Bartlett et al. 2019 [14]. The charring rate in timber depends on the density, moisture content, heat flux exposing the timber and the local oxygen concentrations [14,15,91]. Considering charring rates established by furnace testing, it is found that the low oxygen content in a furnace may present different charring rates compared to real fire scenarios [102].

Charring rates are commonly applied in structural fire engineering models to estimate the residual "healthy" timber cross-section and from there the fire resistance rating for separating structures and load-bearing structures.

There are several methods on how to calculate the charring rate. The methods available are based on testing correlated to the standard fire exposure in order to be related to fire resistance ratings in furnace testing. See section 5.4 for more information about fire resistance testing. The most conventional calculation method for the charring rate was presented in 2004 in the current Eurocode 5 [30]. Eurocode 5 is only valid for the ISO 834 standard fire exposure and does not account for the decay phase [94].

Guidelines [14,27] include methods to account for increased charring rating following char fall off in CLT, a similar methodology is suggested to be included in the proposed updated Eurocode 5 [53], named "European Charring Model" [7]. Since the method is based on the charring rate and assumes that the lamella has completely charred once it falls (i.e. char fall-off at the adhesive line), it does not assign for the heat-induced delamination which can occur at lower temperatures than 300 °C, which is usually taken as the charring isotherm.

There are also fire models that use zone models applicable for smaller compartments, up to 100 m^2, with exposed timber, to predict the fire conditions inside a compartment. Some of these models include assumptions for the charring rate where heat-induced delamination of CLT layers occurs [7].

The use of charring rates in structural design

The available charring rates that are commonly used and prescribed in different standards, only relate to temperature exposure in standard fire testing and the conditions the furnace testing provides. This does not consider real fire behaviour [91]. Research has found that the commonly used charring rate calculation method in the Eurocode 5 [30] generally leads to unsafe predictions, especially in consideration of the cooling phase [48,77,103–106] and subsequently, some updates are suggested in the proposed updated Eurocode 5 [7]. Lucherini et al. 2023 [103] present a numerical study on the reduction of the effective cross-section of timber elements from the effect of the heating (following the ISO 834 standard fire curve) and different cooling phases. They found that the cooling-phase, which is not considered in cross-section methods (see section 5.3), will have an impact on the char depth but also reduce the load-bearing capacity significantly. Similar findings have been presented previously by Gernay 2021 [104] using numerical finite element modelling of timber columns to consider the cooling phase of natural fire exposure. See more information about load-bearing capacity methods in section 5.3 and the post-fire phase in section 5.5.

For laminated products such as CLT (which is not included in the current Eurocode 5), an increased charring rate can be expected as the timber layers fall-off [46]. The "*Fire safety in timber buildings*" [6] guideline presents an improvement of the calculation methods to the Eurocode 5 [30] charring rate calculations. For CLT, using an increased charring rate is recommended in case of the aforementioned effect of char fall-off at the adhesive line.

Charring rates prescribed in some European Test Assessments (ETAs) are often based only on ad-hoc small-scale fire tests and even extrapolated values for longer exposure than tested. This error may lead to significantly underestimated charring rates and may further prevent burnout of the compartment [37]. The charring rate specified in ETAs appears often to be general and is misinterpreted as a universal value [37].

5.2 Fire separating function methods

The most common methods of theoretically predicting the fire separating fire resistance for a wall or floor system are the simplified calculation methods; the Component Additive Method (CAM) used in the US and Canada, and the Separating Function Method (SFM) in Europe [7].

"*These methods determine the fire resistance of a layered construction by adding the contribution of each layer to obtain the fire resistance. Here, the integrity criterion is deemed to be satisfied if the insulation criterion is met. It needs to be noted that the individual contribution of each layer of material is definitely not the same as the fire resistance of that layer of material when tested individually.*" [7] p.205

The method presented in Eurocode 5 [30], has been further developed by Schleifer [107] in 2009. The improved SFM is published in the "*Fire safety in timber buildings*"[6] guideline and is suggested to be included in the proposed updated Eurocode 5 [7,108]. The procedure for implementing new materials to the component additive method is presented in [108].

The SFM can be used to calculate the fire resistance protection time before failure and is given by a combination of layers in the construction, and the total insulation time of the complete wall or floor system [37]. Similarly, the classification of fire protective claddings (K_1(10, 30, 60) and K_2(10, 30, 60)) according to EN 13501-2 can be used for estimating the protection time achieved for a protective layer in the method.

The SFM presented in the "*Fire safety in timber buildings*"[6] guideline has been updated in [109] with correction factors for different types of materials. In [37] suggestions are presented on how to use this method for CLT elements. It is suggested that heat-induced delamination can be considered using a double charring rate for the second layer (and the subsequent layers) for the first 25 mm of depth when heat-induced delamination of the first layer occurs [37].

Additional considerations to the fire separating function methods

The available fire separating function methods exhibit several shortcomings and improvements are needed as pointed out in [109]. The methods are not able to cover the entire fire scenario and only relate to the expected fire resistance when exposed to the standard temperature curve. The calculation methods according to Eurocode 5 [30] were derived empirically from fire tests [110]. There are therefore very few possible combinations of layers, and their application range is extremely limited [107]. The charring rates for timber panelling and timber-based panels as given in Eurocode 5 [30] do not take into account the fact that the panels or timber panelling burn through much more quickly around joints [6]. Hence, the more recent updates and correction factors presented in the literature are necessary to consider.

The fire separating function methods are based on mean values of basic charring rates determined from the standard temperature exposure on perfectly performing walls or floors. For more information about charring rates see section 5.1. In real fire scenarios, the influence of different temperature exposures, geometry in the compartment or penetrations into the timber will cause variations in the charring behaviour [37].

5.3 Load-bearing capacity methods

Methods on how to calculate the load-bearing capacity of timber elements are standardised in different countries [7]. An example of calculating the fire resistance of a glulam beam protected with 15 mm fire-rated gypsum plasterboards in "*Fire Safe Use of Wood in Buildings: Global Design Guide*" [7] using the European, Canadian and US approaches. For this example it is found that the design for fire resistance will provide similar results, however, the design assumptions must be consistent with the respective design standard [7].

The European approach is presented in the Eurocode 5 [30] published in 2004. The principle of this approach is based on a predetermined constant charring rate which is applied to a timber element over a period of time, representing the time in a furnace test to standard temperature exposure. For more information about the charring rate see section 5.1 and for fire resistance testing see section 5.4. In Eurocode 5 [30], there are two methods for the simplified cross-section calculations available. The first method is the Effective Cross-Section Method (ECSM) also known as the Reduced Cross-Section Method (RCSM) which uses a fictive zero-strength layer [111]. The other method is the Reduced Properties Method (RPM) which differs from the ECSM as it uses modification factors for elasticity and the bending, tensile, and compressive strength of timber in the overall structural calculations.

The zero-strength layer in the ECSM is usually referred to as an added sacrificial layer in structural design [112]. This method has been further developed and updated in the "*Fire safety in timber buildings"* [6] guideline published in 2010. In the *"Fire safety in timber buildings"* [6] guideline a simplified method for the load-bearing capacity of CLT by accounting for the char layer plus a compensating layer for the thermal penetration depth into the uncharred portion of the cross-section. Allowing input to consider a number of CLT layers, the thickness, stress orientation of the fire exposed side and thermal penetration temperature gradient. However, the method does not account for heat-induced delamination of the CLT.

The ECSM accounts for lost mechanical properties of the heated timber that have not yet combusted and charred [113]. In the current Eurocode 5, the zero-strength layer is assumed to have a fixed depth of 7 mm. The justification for the 7 mm thickness originated from the work presented in 1967 by Schaffer [114]. However, the 7 mm zero-strength layer has been concluded as non-conservative [77,56,94,103,105,115–123], particularly in relation to non-standard heating or exposed CLT. As part of the update to the proposed updated Eurocode 5 [53] this value will be increased to 10 mm (for bending or tension) and 14 mm (linear timber members) [7]. The use of the zero-strength layer in the current Eurocode 5 requires homogeneous material characteristics within the section, which is not the case for CLT where the strength transversal layers are incorporated in the layup [117]. In the proposed updated Eurocode 5 [53] a new calculation methodology will be available to determine the applicable zero-strength layer depending on lamella thicknesses.

The RPM originates from the German standard DIN 4102 and gives values of a modification factor for fire taking into account the reduction in strength and stiffness properties at elevated temperatures for compressive, tensile and bending strengths as well as the elasticity of timber frame members [110]. The method is derived from curves fitted to test results on small solid timber frame members in bending, making it unreliable for larger members and the method cannot be used for timber slabs [110]. Other drawbacks of the RPM are the gradual increase of strength reduction during the first 20 min or until the start of charring of protected members, which is not taken into account. No reduction is given for shear strength and the section factor depends on whether notional or one-dimensional charring rates are used. Although the method seems more complex than the ECSM, it does not give any better accuracy [110] and might give unconservative results [7]. The only simplified method in the proposed updated Eurocode 5 [53] is the ECSM.

There is also an easy-to-use program "*SPFiT*" [124], developed by RISE to calculate fire resistance of the load-bearing capacity in slabs, timber frames, columns and beams using the load-bearing capacity methods presented in Eurocode 5 [30] and with updates in the "*Fire safety in timber buildings"* [6] guideline.

Additional considerations to the load-bearing capacity methods

The current Eurocode 5 [30], which presents both methods, is not applicable for CLT or materials that will delaminate [37]. These methods normally do not consider joints and junctions to neighbouring elements or the influence of mounting parts and penetrations of service installations [27]. They do not solve the issue of continuous burning or the potential failure of a timber element post-fire. However, the ECSM is the most used design method to determine a structural fire resistance rating in any type of timber building.

It is stated in the "*Fire safety in timber buildings"* [6] guideline that the simplified method for load-bearing capacity should not be applied for more than two hours. If these methods are being used to determine the load-bearing capacity in buildings, the limitations of the methods will require burnout (including the post-fire phase) to be achieved within two hours. It should also be noted that heat-induced delamination is not accounted for in this method. For more information about burnout see section 4.2 and for the post-fire phase see section 5.5.

The methods have many limitations on how well they are able to estimate structural capacity in real fires and they do not cover the entire fire scenario. It is pointed out in [77,109,118,120,121], that the load-bearing capacity methods presented above exhibit several shortcomings and improvements are needed. Improvements are suggested for the proposed updated Eurocode 5 [53] although the standard is yet not established [7].

5.4 Fire resistance testing

Depending on the type of building, the structure of the building is required by building codes to meet a certain level of performance when exposed to a fire. To set a benchmark for the fire performance required for fire separating and load-bearing functions in a building "fire resistance" has been adopted in building code requirements around the world. Fire resistance refers to the ability of a building element to maintain enough integrity, insulation and structural stability (if load-bearing) when exposed to a standard temperature curve inside a furnace, measured in minutes. It is important to understand that this does not necessarily transfer to the actual performance of the building element in real fires. The ISO 834 temperature-time curve is used in many fire resistance standards and is presented in Figure 7.

The fire resistance ratings in contemporary design codes were created with the intention that a structure would maintain its load-bearing capacity until all the fuel in the compartment was consumed, at least for ratings of 60 minutes and above. This is referred to as "design for burnout" [60]. See section 4.2 for more information about burnout. However, as stated in [104]: "*A design approach based on a sacrificial charring depth under prescribed standard fire is inadequate to demonstrate burnout resistance*." [104] p.10

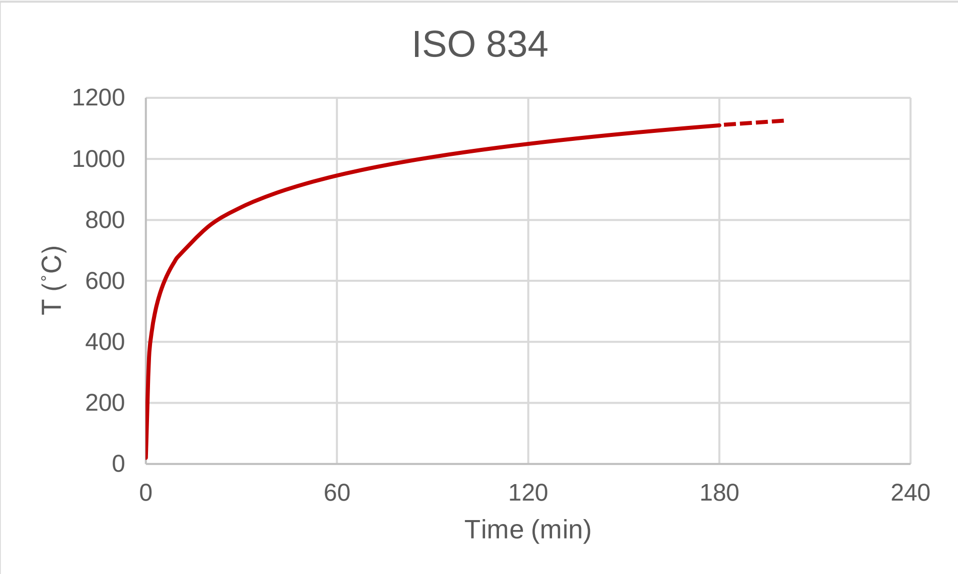


Figure 7: The standard temperature curve as per ISO 834.

Applicability of fire resistance testing

The standard temperature curve has been the main fire test to quantify the performance of materials in a fire for the last hundred years and research laboratories around the world have invested in equipment to determine the fire resistance of materials through this type of test. The approach of measuring fire resistance performance is adopted in all building codes around the world, and it has become ingrained in the building industry.

Generally, building codes are based on the fundamental principle that the fire resistance required in the building relates to the fuel load inside the fire compartments. This originated from the early fire severity work by Ingberg in the 1920s [58,59]. In order to follow this principle of fire safety strategy in the building codes, the increased fuel load contributed by a combustible timber structure could be expected to be considered when determining the required fire resistance ratings.

When combustible elements or structures are tested in a furnace which follows a predetermined standard temperature curve, the energy released from the timber will increase the temperature in the furnace. To account for the increased heating due to the combustion of timber, the heaters in the furnace may need to be adjusted in order to follow the predetermined temperature curve. Bartlett et al. 2020 [125] investigated the performance of timber versus non-combustible structural elements, subjected to the standard temperature curve, has been compared. During the first 120 minutes of these experiments, the major difference in how much more energy had to be provided into the furnace through gas burners was approximately 350 % for the non-combustible concrete compartment compared to the CLT compartment [125]. This gives an indication of how much energy exposed CLT contributes to a standard furnace test. A similar detailed comparison between the fire dynamics in a furnace with combustible versus non-combustible elements subjected to the standard temperature curve was researched by Lange et al. 2020 [126]. As shown in [126], the difference between exposed timber in a furnace test and concrete is partly due to the extra fuel from the timber, but also partly from the lower conductivity of wood compared to concrete. A concrete sample will absorb much more energy, therefore requiring more energy input to the furnace to meet the same temperature curve. It is stated in [125] that:

"It might be the case that different types of structures should be required to meet different fire resistance benchmarks when designs are justified on the basis of standard furnace testing, or indeed that application of the 'fire resistance' framework should be abandoned in favour of a more rational, risk-based fire engineering design approach intended to deliver the requisite (agreed) level of safety.". [125] p.5

In [105] the standard fire resistance framework application for combustible elements or structures is also being reviewed with the following conclusion:

"The conventional fire resistance framework, where structural safety in case of fire is provided essentially as a relative measure, cannot provide suitable means by which to optimise innovative laminated timber products, and also hinders the application of structural fire safety engineering as part of a holistic fire safety design approach in tall, engineered mass timber buildings." [105] p.294

Research has been done to investigate if a radiant heat source test, exposing a timber element to radiant heat, is a possible testing method alternative for fire resistance of combustible elements instead of the standard furnace test. The idea is that these tests will be more cost-effective compared to furnace testing or large-scale compartment fire experiments [46]. However, the unlimited supply of oxygen makes it very different from real fire behaviour in a compartment or a furnace.

5.5 Post-fire phase

The post-fire phase (decay and cooling phase) is not typically considered explicitly within prescriptive building codes and standards. In the post-fire phase, in-depth temperatures of a structural element will continue to increase long after the fire exposure is halted [48,77,105,106]. From a fully developed fire, the core of a concrete element will rarely exceed the 300–500 °C required to induce significant structural damage to the material. However, timber is more vulnerable to relatively low temperatures, losing approximately 75 % of its compressive strength and 65 % stiffness parallel to the grain at 100 °C. In timber, all strength and stiffness are lost at 300 °C [105]. "*This susceptibility to failure during the cooling phase is due to the combined effect of delayed heating and loss of mechanical properties at relatively low temperatures.* " [104] p.9

In the experimental tests conducted by [54], it has been found that even after a compartment fire self-extinguished, the 200 °C isotherm continued to increase for an additional 10 minutes before cooling dominated. The 100 °C isotherm continued into the element for 30 minutes after burnout. This thermal lag may result in temperatures in the un-charred timber increasing during and after the decay phase of a fire. Cracks in the char layer or openings in connections can also allow heat to impinge deeper behind the char layer and at a faster rate.

In [105] heat transfer calculations in timber that are based on calculation methods presented in Eurocode 5 [30] were applied to a glued laminated timber column to determine the structural capacity for the post-fire phase. The glued laminated timber column had been tested in a standard fire resistance test for 90 minutes and "survived" with 45 % of its original crushing capacity. By calculating the strength based on measured heat impingement in the column after it had been removed from the furnace, it was demonstrated that it retained less than 13 % of its crushing capacity 2–3 hours after the end of the heating in the furnace.

In timber compartments with significant amounts of exposed timber structural elements. The results presented in [105], and the accompanying theoretical considerations for the reduction in structural capacity, suggest that the fire dynamics and the thermal and structural response are closely interlinked and cannot be considered separately. Which is explicitly done within the traditional fire resistance design framework [105].

As found in [16] char oxidation provides a significant heat release rate in the post-fire phase prolonging the temperature exposure for a timber structure. In a compartment with many exposed timber surfaces the contribution of char oxidation will impact the structural capacity and should therefore be accounted for.

Fire resistance and burnout resistance have been investigated by Gernay 2021 [104] adopting a data set of 49 standard fire tests. From this data, it was found that the heat wave continued penetrating the timber column section for hours after the end of the fire, giving a severe reduction in strength properties at relatively low temperatures [104].

Gernay et al. 2022 [127] present a new experimental method for evaluating the load-bearing capacity function of structural elements until fire burnout is presented. The method adopts the Duration of Heating Phase (DHP) indicator, which is presented in more detail in [104,128,129], for assessing the burnout resistance of full-scale loaded columns (concrete and timber) in standard furnaces. The timber columns were designed to achieve a target fire resistance of R 60 according to the current Eurocode 5 [30] with consideration of the revised value of the zero-strength layer proposed for the updated Eurocode 5 [53]. The experiments with timber columns were conducted at Braunschweig during the spring and summer of 2021, with details of the tests presented in [106]. It was found that columns exposed to 15 minutes of ISO 834 heating followed by a linear cooling phase at a rate of -10.4 K/min (from the Eurocode parametric fire model) structurally failed in the late decay phase under constant load. During the decay phase, the temperature continued to increase inside the timber section. It was concluded that flame extinction was not an indicator of whether the timber column would survive to full burnout, however, flame extinction is a pre-requisite for this [127]. It is further concluded:

"*The findings from the experiments demonstrate that delayed thermal-mechanical effects can jeopardize structural stability in real fires, and they provide a framework to measure these effects in tests. Research is ongoing to further study the effects of different cooling rates, including in natural compartment fire experiments. Moving beyond fire resistance to quantify the response until burnout will support designs for safety of occupants and firefighters throughout the fire and promote repairability and resilience.*" [127] p.12

More recently, conclusions have been made from a test series with glued-laminated timber (GLT) columns subject to seven different natural fire scenarios, presented in a paper by Gernay et al. 2023 [130] stating:

"These tests confirm the conclusion of previous numerical and experimental studies that a timber column can fail in a fire long after the fire temperatures started to decrease, and the fact that the structural element displays some "self-extinction" does not mean that its stability is ensured." [130]

5.6 Structural fire engineering of timber

Structural fire engineering covers many technical aspects, but the objective is to obtain a robust structure that can withstand the stress posed by fire. *"When undertaking the structural design of a building, it is necessary to determine the thermal effects of a fire occurring within or near the building. This is often referred to as the structural fire severity."* [131] p.138

Structural analysis in fire requires an understanding of the complete fire exposure, including the decay phase of a fire. Different fire design methods have been developed for compartments with mass timber elements.

Advanced structural fire engineering modelling of timber structures must include both thermal and structural modelling, integrated as far as possible, and the modelling is dependent on an accurate design fire model [132]. The relevant parameters to consider for structural fire engineering modelling are presented in detail in [132,133] and are illustrated in the flow chart below, see Figure 8.

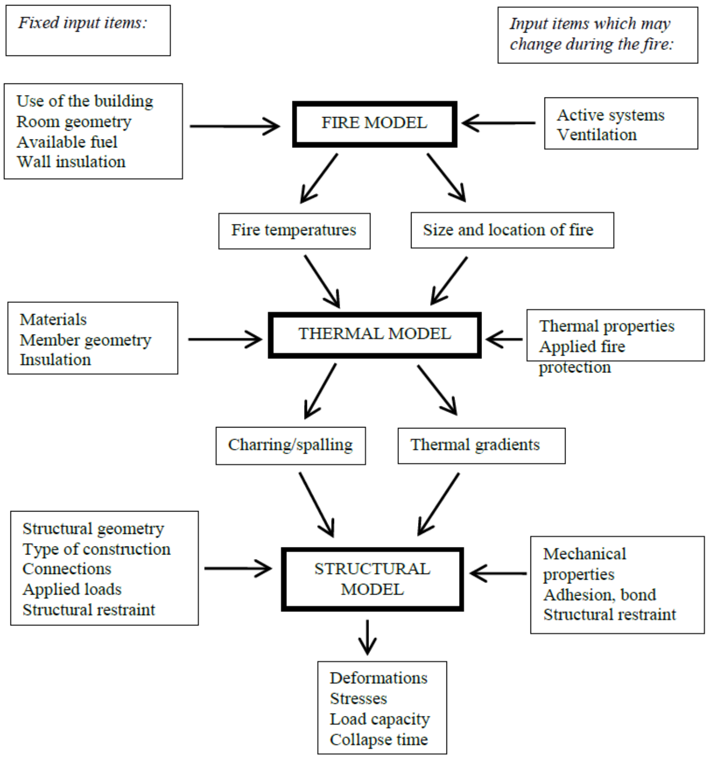


Figure 8: Flow chart for predicting structural fire performance [133].

In order to achieve a holistic fire safety strategy in timber buildings, there are some elements that are to be understood as part of the structural fire engineering modelling of realistic fire scenarios.

Examples of risks in timber buildings that are to be considered as part of structural modelling are presented in [132] and reproduced here:

- Expected incident heat flux in fully developed fires;
- Thermal penetration as a function of fire exposure;
- Temperature and moisture dependent thermal and mechanical properties of heated timber;

- End of combustion when the structure self-extinguish;
- Critical heat flux or mass loss rate for continuous burning;
- Predicting the fire performance and fall-off times of protective systems (e.g. gypsum plasterboards);
- Storey to storey fire spread via combustible façade cladding;
- Effectiveness of details to prevent internal fire spread; and
- Fire performance of connections between structural timber elements.

Further, is the following comment made in relation to the construction of timber buildings:

“There are also a lot more short term challenges to overcome. The most important issues are to ensure:

- *Quality of construction workmanship and inspection and fire safety during construction, since proper detailing is the main challenge to reach fire safety*
- *Develop strategies to reach property loss prevention in relation to other types of buildings*
- *Control of the main strategies to avoid a collapse of the building in case a fire is not extinguished by an automatic active system or by the fire services.”* [132] p.17

The task of calculating the fire exposure (“fire model” in Figure 8) can be complex, simple calculation methods have been developed and one such method is the “time-equivalence method” [134].

Time-equivalence methods background

The first parametric fire curves were introduced in 1970 and the more commonly used curves are the “Swedish fire curves” by Magnusson and Thelandersson [135]. These fire curves have then been linked to the expected performance of elements or structures in standardised furnace testing, i.e. time equivalence calculations [136]. Given the limited size of the compartment tests used for the correlation of these fire curves, time equivalence calculations are not validated for compartments with floor areas of more than 100 m².

The time equivalence concept is used to relate the expected real fire exposure to the standardised furnace testing, allowing estimates of required fire resistance ratings given a compartment design [136]. A detailed background of the state of the art time equivalence methods is presented in [134] together with 16 different time-equivalence methods. There are generally three different models that are widely used, the CIB W14 [137], and the Eurocode 1 [138] which is configured from the CIB W14 and Law [61]. These are empirical formulae developed by regression analysis using the results of a selected number of tests or calculations making them crude methods of comparing real fire exposure with standard test fires [136]. The models are limited by the experimental data and are not applicable for compartments containing structural timber or any other combustible structural materials that hinder the potential for complete burnout [38]. After tests on large-scale compartments with timber cribs, it has been suggested that the Eurocode 1 [138] model and the CIB W14 model underestimate the fire severity [136]. Furthermore, the Eurocode 1 model is claimed to be valid for compartments with floor areas up to 500 m² and 4 m in height, however, it is not known how these areas have been validated as most of the experimental data comes from much smaller compartments (less than 100 m²).

Parametric methods for compartments with exposed timber

A parametric fire curve is a collective name for the adaption of mathematical models for the temperature exposure inside a compartment with natural fire behaviour, including pre-flashover, flashover and post-flashover [139]. Parametric fire curves have been modified to develop calculation methods for compartments with exposed timber, which need to consider the following.

"*To determine the time-equivalence for timber, the complete char depth must be determined, which includes the charring during the decay phase and, any charring that occurs with smouldering, i.e. complete char depth through to full consumption of the calculated fuel load and any impact due to smouldering and thermal penetration. Thus, to determine time-equivalence for a mass timber structure, the HRR decay phase is critical. This differs from the assessment that occurs for a steel structure, where peak temperature is important.*" [140] p.823

The following presented parametric methods for compartments with exposed timber, are subject to many generalised assumptions and awareness must be taken of the limitations of the methods' applicability in relation to compartment sizes, ventilation factors, fuel loads, exposed areas etc.

Barber et al. 2016 [141] present a method that follows two steps, using approximations by hand calculations based on work by Crielaard 2015 [74]. A critical lamella thickness to avoid heat-induced delamination of CLT is to be determined based on a calculated char depth in the parametric fire conditions. The parametric fire exposure from Eurocode 1 [138] is used to determine the charring rate and calculated following the guidance in Eurocode 5 [30]. Additional fuel load is added to the fuel load energy density (FLED), based on the charring depth assumed in the calculation of the parametric fire. This requires iteration to ensure that the depth of char calculated and the FLED assumed are consistent. Secondly, to check for smouldering extinction of CLT, a calculation of the incident radiant heat flux on the timber surface is done using a value of 5-6 kW/m^2 taken from [74].

Brandon 2018 [54] presents a method with the proposed change of the so-called "advanced calculation method" described in Annex B of the Eurocode 5 [30]. The method requires finite element or finite difference calculations of the temperatures in elements throughout the structural member. The parametric fire equations are used in conjunction with an iterative procedure, adjusting the fuel density at each iteration, to estimate the char depth based on calculated temperatures. The mechanical properties at these locations are adjusted based on local temperatures which allow for the calculation of the load-bearing capacity of the structural element during the fire. The method is suitable for CLT but is not able to capture the effects of heat-induced delamination and other limitations of the parametric fire equations apply.

Brandon and Anderson 2018 [142] present a single zone model for compartments with exposed wood that has been updated in Brandon et al. 2021 [143] to make it more suitable for use in practice. The model uses input from movable fuel load to predict a parametric heat release fire curve, assuming well mixed conditions within the compartment. Then includes the charring and heat release rates from exposed timber, established experimentally in [22], adding this heat release to the movable fuel. The model finally approximates the heat release from energy stored in the char during the oxidation process when flaming combustion stops. The steps are repeated until the char depth converges to a stable value between iterations. This model does not take into account hot spots of continuous smouldering in the decay phase and is not applicable for heat-induced delamination, char fall-off, or protective layer fall-off. An engineering design tool for use in Sweden to predict the structural capacity of mass timber in compartments with exposed timber has been developed [144]. The design tool is based on the results from many calculations adopting the single zone model presented in [143]. The results have been tabulated, allowing the designer to estimate a total charring depth based variable input consisting of the opening factor, and fuel load (movable and permanent) in the compartment. It also gives the designer fire performance requirements for the protective encapsulation of non-exposed timber surfaces in the compartment. The tool is only applicable if the user can determine that heat-induced delamination will not occur.

Pyrolysis models for compartments with exposed timber

Models to predict the pyrolysis rate of wood range from simple approximate analytical equations to more complicated detailed numerical solutions using the Fire Dynamic Simulator (FDS) [145]. Often these numerical solutions adopt test data from a Cone Calorimeter (or similar) to estimate the kinetic parameters for the thermal degradation reactions, apparent thermal properties of the material and its char and other model parameters [7]. The user of these models must be aware of and consider the limitations of these if used for structural design.

Barber et al. 2018 [146] present a methodology using the computational fluid dynamics program FDS to determine the response of mass timber structures. The methodology takes into account variations in heat flux, heat release rate and additional fire load from exposed timber. The pyrolysis functionality was calibrated against measured data from cone calibration tests. The method was validated using the results from five full-scale experiments with exposed CLT. Limitations in the method include not accounting for inconsistent pyrolysis of the CLT within FDS models, heat-induced delamination or encapsulation fall-off. It was found that to undertake pyrolysis modelling the computational time was extensive.

The B-RISK [147] zone model presented by Wade 2019 [15] accounts for the burning surfaces of timber and recalculates the energy contribution. The model provides two timber pyrolysis submodels (an equivalence ratio pyrolysis submodel and a kinetic timber pyrolysis submodel) that have been developed to estimate charring rates in a compartment. The two-zone model B-RISK allows fire dynamics in small mass timber enclosures to be predicted. The kinetic submodel is capable of taking heat-induced delamination of CLT layers into account. The model predictions for heat release rate, gas temperatures and/or char depths are compared with data from 19 full-scale fire experiments. The model has been updated by Wade et al. 2020 [148] with an additional flame heat flux term for the burning timber surfaces that accounts for the oxygen mass fraction of the enclosure gases along with a critical mass loss rate for flaming combustion. The updates allow the model to better describe the thermal boundary conditions during the decay phase, especially as the enclosure oxygen levels return to their ambient value.

Schmid and Frangi 2021 [149] present the Timber Charring and Heat Storage (TiCHS) model to estimate the contributions from structural timber to a fire. It accounts for the fully developed and decay phases of the fire until burnout, using the energy stored in the char layer as a key characteristic. An iterative process is applied to estimate the temperature and gas characteristics in the compartment. The model does not consider the potential of heat-induced delamination and is currently only validated for gas velocities occurring in compartments with openings on one side.

SP-TimFire was created by Brandon 2016 [150] and is a one-zone model used to predict temperatures and heat release rates of fires in compartments with exposed timber. This model calculates the heat release rate contribution from timber surfaces in a compartment by assuming a linear relationship with charring depth of 5.39 MJ/m^2 per mm of char depth. The model also includes an approach to account for heat-induced delamination of CLT and its influence on the heat release and the fire temperature in a compartment. The heat release rate curve in the model is updated in an iterative process. The model has been validated with the comparison of three experimental results from large-scale testing. In order to account for heat-induced delamination, the *SP-TimFire* model assumes that all CLT surfaces in the compartment delaminate simultaneously. This has been shown to overestimate the heat release rate compared to real fire tests, as the delamination in these is found to be more staggered. If the model can be updated to account for heat-induced delamination occurring over a time period instead of heat-induced delamination occurring simultaneously, more accurate but less conservative values can be expected [150].

Hopkin et al. 2017 [151] present a one-zone model with material properties based on Eurocode 5 [30]. The charring rate is assumed to be constant, irrespective of surface orientation or location, but with variation in the char layer conductivity depending upon the heating rate. The zone model resolves energy inputs and losses, leading to a temperature variance within the gas control volume. The properties in the model require the user to pre-empt the fire load density, which is practically not possible when the structure may be a significant part of the fuel load, as is the case for most exposed CLT structures. This introduces an immediate source of error at the outset of the analysis [151]. The zone model was validated using four experiments involving partially or fully exposed CLT. The presented model assumes homogeneity of gas temperatures within the compartment, which would result in increasingly large errors for increasingly larger compartments. Future development of the model is proposed to include the effects of heat-induced delamination, improved thermo-mechanical material properties and inclusion of radiation between exposed walls [151].

The heat-mass-pyrolysis model PYCIF by Pečenko et al. 2023 [152] is an updated version of the model by Pečenko et al. 2021 [153]. The model predicts charring in case of natural fire exposure and the updated version calibration of the most influential kinetic parameters for the charring development. The model is proposed to be further developed to account for fires with forced convection where the phenomena of oxidative pyrolysis of smouldering wood.

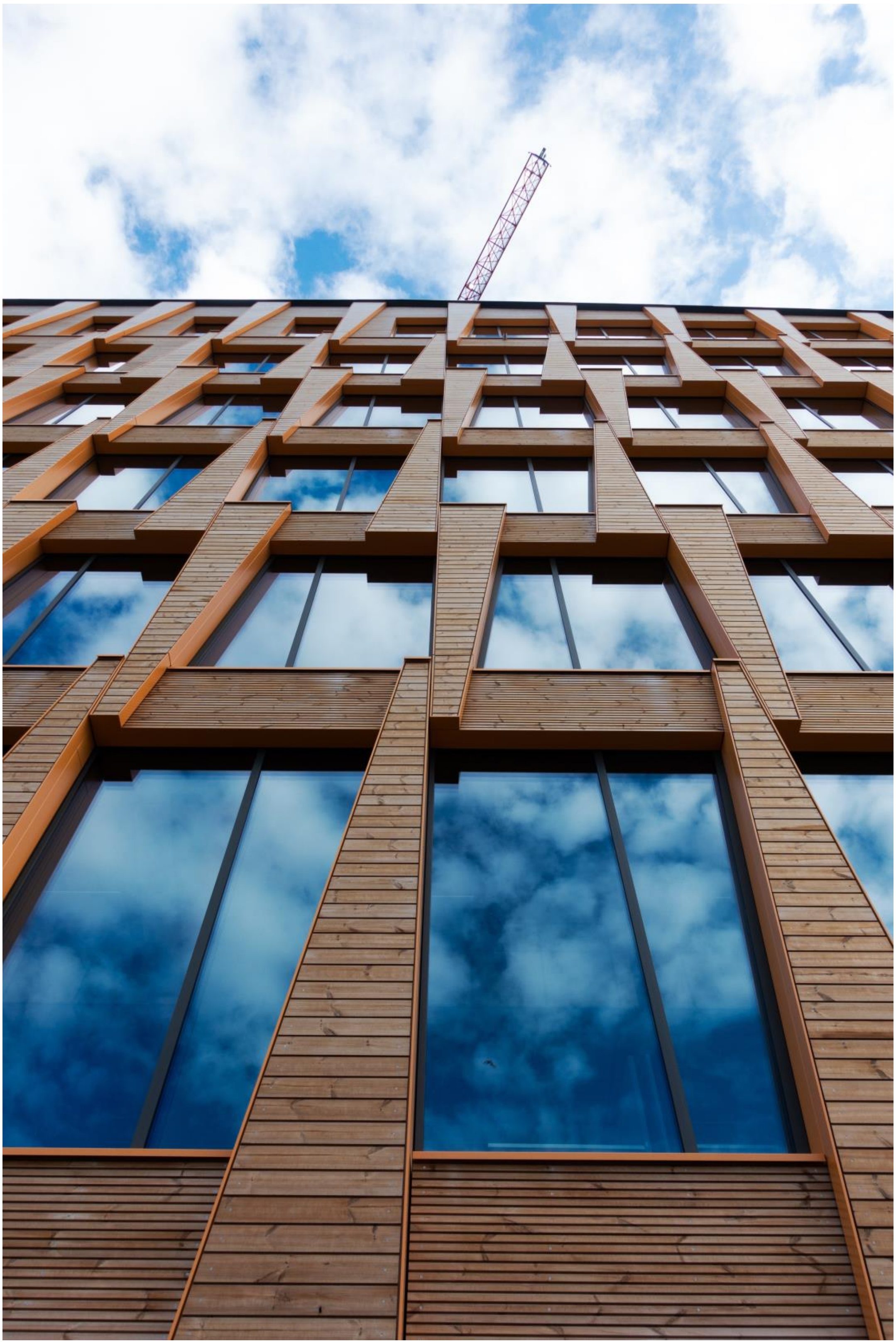
Considerations relating to structural fire engineering of timber

Structural fire engineering models considering fire behaviour are based on approximations and have limitations in their applicability. It is therefore important that the designer understands and takes these limitations into account in order to gain applicable design output.

It is noted in [7] that the application of structural fire calculation methods for timber compartments has many limitations. They are applicable for compartments that reach flashover and fully developed fire, but may not be applicable for open-plan well-ventilated compartments where travelling fires may occur [7].

In relation to the fire safety strategy for a timber building, it may be necessary to demonstrate that the fire safety design goals are met without the support of active fire suppression systems. In this case, the design must achieve an appropriate level of structural robustness and fire separation with passive fire safety measures, particularly in areas that are critical for occupant egress and fire brigade intervention [154]. As pointed out by Buchanan 2017 [64] for tall timber buildings, it may be necessary to demonstrate that the structural design can withstand a burnout of all the fuel inside a fire compartment. For more information about burnout see section 4.2.

6. Passive and active fire protection



6.1 Fire retardant treatments and surface coatings

Fire retardant treatment products are available that can enhance the performance of timber when exposed to fire by delaying the time to ignition, reducing the heat release rate and lowering the flame spread rate [37]. There is a vast variety of chemical compositions and treatment processes for fire retardants, but they can be classified as additive or reactive [155].

"*Additive retardants are applied to the wood by dip, spray, vacuum or brush application, but do not react with the wood and therefore are more likely to migrate out of the material in service. Reactive fire retardants are more expensive because they have the chemical functionality to react with the wood, but they are less likely to be lost during the service lifetime of the material.*" [155] p.9053

The durability of the fire retardant products is an important consideration, especially for outdoor applications. Exposure to high relative humidity will elevate the moisture content and migration of the fire retardant chemicals within the timber product, causing salt crystallisation on the product surface and resulting in a loss of fire performance [7]. The fire performance may also decrease due to a loss of the fire retardant chemicals by leaching or other mechanisms [7,37,156].

In the report by Östman and Tsantaridis 2017 [156], several long-term studies using natural field exposure of timber panels treated with fire retardant products have been presented. The testing was conducted in the Stockholm area of Sweden and the panels were facing south, both at vertical (90°) and 45° slope. Results have been presented for exposures over 1, 2, 3, 5 and 10 years. The timber products tested were all timber panelling products (mainly spruce) with vacuum pressure impregnated with different fire retardant chemicals. Untreated timber panelling was used as a reference in the study. It was found that many of the treatments lost most of their fire retardant properties after the first 2 years of field exposure. However, the samples that had paint systems applied, such as alkyd or linseed oil paints, in addition to the fire retardant treatment, showed a considerable contribution to weather protection and reduced the mass loss of the treatment during weathering. The study concludes that paint systems are essentially needed to maintain the reaction to fire performance on exterior applications. From the natural field tests, it was also found that higher retainment levels maintained fire performance for longer [156]. It should be noted that no products have been proven to maintain the initial level of protection for longer than 5 years. However, longer performance has been claimed by manufacturers.

Lin et al. 2023 [157] present recent research into new methods of impregnating wood followed by thermal treatment has demonstrated the potential for better durability. Post-heat treatment of black pine wood has also been found to improve the durability of fire retardment impregnation [158]. However, others have shown the opposite, that thermally treated wood indicates a higher burn rate [159].

A European system "Durability of Reaction to Fire" (DRF), has been developed to guide potential users to find suitable fire retardant products for timber. The standard EN 16755:2017 use this system to class fire retardant treated timber products in interior and exterior applications. The system is mainly based on the Nordtest standard NT Fire 054, which was based on earlier North American standards (D2898-94). It consists of a classification system for the properties over time of fire retardant timber and suitable test procedures [37]. From the natural field tests presented in [156], it is found that the accelerated durability test represents an equivalent to a maximum of 5 years of neutral field exposure. The standard EN 16755:2017 has been discredited in a recent report from the Danish Institute of Fire and Security Technology (DBI) showed that the current acceptance criteria used in this standard are not valid methods to show the effects of fire retardant durability [160]. This is in relation to the use of a cone calorimeter (ISO 5660-1) as an alternative method to the SBI method (EN 13823) to measure the effectiveness of the fire retardant after accelerated weathering exposure. The EN 16755:2017 standard is currently under review and until the new standard is available the Research Institutes of Sweden (RISE) has chosen to not offer this alternative to the testing method until further notice [161].

Passive protection does not have intrinsic fire resistance but they offer a contribution to fire resistance. Intumescent paints and varnishes can offer either reduced ignitability (i) fire class EN Class B (BS Class 0/1) for the first 20 minutes or increased fire resistance (ii) for 30 to 60 minutes. The number of applied coatings defines the performance.

Lucherini et al. 2023 [162] presents research proving that intumescent paint coatings can delay the onset of charring of the timber. However, it has been noted in some fire resistance testing that an intumescent paint product applied to CLT elements experienced a faster time to failure compared to similar unprotected CLT elements [163]. Furthermore, Hartl et al. [164] compared the performance of fire rated plasterboard and intumescent coating with small-scale CLT timber samples (90*90 mm) when exposed to radiant panels at 50 and 200 kW/m^2. They measured the temperatures behind the plasterboard and under the coating. Plasterboard was shown to be less dependent on the increase of heat conditions than intumescent paint. Moreover, as noted by some of the manufacturers, these products are not recommended for use in areas with high humidity, constantly increased heat sources, and where physical impact is likely. For example, for intumescent paints, if the sprinkler acts directly on the product while the foam is forming, the reaction stops, and the protective product does not work as intended.

In the preliminary study by Johnson et al. 2023 [165] the authors used cone calorimetry with radiant heat flux of 35 and 60 kW/m^2 to study the performance of three commercially available transparent intumescent passive fire protective coatings for wood. One of the coatings, the only one advertised as a product to upgrade fire resistance of existing wood panelling, did not intumesce in the tests. They conclude from the tests that these products have the potential to improve the reaction-to-fire performance, but that more research is necessary to justify any performance that reduces the char rate of timber.

Additional considerations to fire retardant treatments and coatings

When a surface coating is applied during construction, there are usually several steps of application that must be applied as specified by the manufacturer following the appropriate standards. In Europe, the European Assessment Document EAD 350865-00-1106 (previously ETAG 028) is applicable for fire retardant products.

The right conditions must also be assured during future maintenance and re-application of coatings, something that will result in significant maintenance within ten years. If painted coatings are applied as the last layer on a timber surface, these may first have to be removed before re-application of fire retardant treatment can be done. If the coating is being applied to timber with too high humidity levels, the fire retardant chemical may leach out of the timber.

If the fire retardant treatments are not applied correctly, under the right conditions or not maintained appropriately, there is no guarantee that the product will perform as expected.

Fire retardant treatments cannot make timber non-combustible, only limiting the flame spread rate, making it a common solution for internal timber surfaces. Building codes around the world generally restrict the use of combustible materials in the external façade of buildings over a certain height in order to reduce the risk of fire spread. However, it is possible to use standardised large-scale façade fire test standards (e.g. SP Fire 105 [31], Lepir II [32], BS 8414 [33], ISO 13785 [34], NFPA 285 [35], AS 5113 [36]) as an alternative pathway to demonstrate compliance with the prescriptive requirements. Fire retardant treatments can be applied to timber products that are part of façade systems, helping them to pass these types of external façade fire tests.

It is important to acknowledge that these types of façade fire testing standards have limitations on how well they address the risk of fire spread. Passing a test is not a guarantee that the façade system will perform as well against fire spread when applied in different configurations on a real building or other fire scenarios that are more challenging than the tested scenario, such as a scenario where timber is contributing with fuel to the fire. Read more about the limitations of the large-scale façade tests and the potential of increased risk of fire spread via openings in section 4.2. As an example, the SP 105 test accepts fire spread inside of the façade system and on the façade surface up to the lower edge of the window two floors above the level of the fire room [166].

6.2 Fire separation

One key fire safety measure for most buildings is to compartmentalise a fire, in order to reduce the consequences of a fire, to protect occupants and firefighters. It also allows the fire safety strategy to assume that only one fire in one location is to be considered. In certain buildings where structural failure or fire spread will cause great consequences, for example, tall buildings, designing to withstand burnout is essential. In non-combustible buildings designers often assume prescriptive fire separation requirements are sufficient to withstand burnout [7]. In compartments with exposed timber construction, longer fire scenarios can be expected (as the structure is contributing with fuel), and the fire separation will be exposed to a more severe scenario compared to a compartment with only non-combustible building materials. Adequate fire separation of walls, floors and ceilings of fire compartments is important for the building design to be able to withstand burnout. The performance of the fire separation is dependent on the composition of these elements but also on installations and connections.

Fire protective covering and encapsulation of timber

The easiest way to mitigate the fire hazards presented by timber is to prevent it from being involved in the fire. Encapsulating the timber using protective layers, such as gypsum plasterboard, capable of protecting the timber from reaching 200 °C until burnout of the fire is a recognised approach used to mitigate the hazard [1]. This can be achieved using different methods and Schmid et al. 2021 [78] define the term "timber protection" as "*a combination of boards, or wraps, or cladding or coverings that provide structural fire protection and work as a system of components, together with their fixings for a particular substrate*". [78]

If the design goal for the building can allow encapsulation around timber structures to fail, as part of the fire safety strategy, the encapsulation will only delay the impact of a fire on the structural timber. This does not prevent feedback between the structure and the fire and does not achieve the objective of a complete encapsulation strategy as described by Buchanan et al. 2014 [133].

The ability of a protective layer to maintain protection from the increased temperature on the non-fire side is part of current standards for gypsum plasterboard and other protective claddings. In the classification of fire protective claddings K_1(10, 30, 60) and K_2(10, 30, 60), according to EN 13501-2, the protection time (t_{prot}) is the time until the temperature rise, behind the considered layer, has increased 250 K on average or 270 K at any point. Ambient conditions are usually 20 °C, hence the temperature criteria are 270 °C and 290 °C, respectively. These criteria are approximations to account for the failure (or fall-off) of thermally degraded material layers [37]. Note that this test is not specifically adapted for combustible structures and it follows the standard temperature curve and that a critical temperature for when timber starts to pyrolyse is typically 200 °C [1].

If the encapsulation falls off in a fire, preheating of the timber behind the protective layer, will result in an increased charring rate [46]. The accelerated combustion of the timber has the potential to contribute to secondary flashover scenarios or prolonged burning should the encapsulation not withstand the burnout of the fire, as seen in large-scale experiments [45]. See section 4.4 for more information about secondary flashover.

Charring calculation methods are available to determine fire resistance ratings that adopt higher charring rates once the partial encapsulation falls off. However, these methods do not address the complete burnout of fire and do not take into account the fundamental issue that timber is combustible and contributes fuel to a fire.

From the testing series performed and presented in [45], it has been concluded that the redundancy of how long a protective layer can stay in place is a very important factor to consider for the fire safety design. The amount of protection (i.e. type of protection, thickness and number of layers) and the type of mechanical fixing that is used must be considered carefully. The penetration depth of fasteners and the maximum fastener distance are important factors in relation to the performance of the encapsulation [139]. Future alterations and maintenance work in a building, also pose the risk of the encapsulation being compromised and not performing as expected.

Penetrations, connections and fixings

Penetrations and installations through fire separating or structural elements can allow fire and smoke to spread or weaken the structural element in the event of a fire where passive fire protection is not performing adequately.

There are many fire stopping products available on the market to seal penetrations in fire separations. In most cases, the type of product for fire protection chosen depends on the size and configuration of the opening or aperture to be fire protected, the construction type and the type of services (if any) that penetrate the construction.

A fire stopping product tested for non-combustible construction may perform equally as well when used in timber construction in relation to fire resistance testing. However, this does not imply that the product will achieve the same performance in a real fire. Long fire scenarios and different fire exposures due to the increase of fuel load, can be expected to challenge the fire stopping in a timber building more compared to a non-combustible structure. Movements in a timber structure may also be more significant compared to other types of construction, something that will potentially impact the performance of fire stopping products.

Common defects in fire compartmentation as a result of inaccurate installation e.g. wrong products used or poor workmanship are found to be in the order of 43-54 % of all installations inspected in a research project presented in [6]. Future changes to the installations in a building, but also wear and tear, are other aspects that can cause defects in the fire separating performance.

Penetrations of building service systems through fire separations may not be avoidable in a building but the concept design should strive to eliminate any unnecessary penetrations. The consequence of fire spread via a penetration, fixing or connection is dependent on where a fire will spread to if the fire separation fails. The "*Fire safety in timber buildings*" [6] guideline presents three different types of design concepts to deal with building services penetrations: installation shaft with penetration sealing; fire sealing in each fire separating element; and encasing of each installation line. As recommended in [7] it is beneficial in multi-storey buildings to congregate services via dedicated central shafts. This design will allow for fewer penetrations through fire separations, simplify the coordination process and reduce the possibility of incorrect installations or unnecessary penetrations [7]. As part of the design of service penetrations, consideration must also be taken for acoustic, moisture and thermal performance, as well as accessibility for maintenance and service [6,7].

Fire stopping is also of great importance to mitigate fire spread via cavities and gaps, examples of a gap in a timber floor slab and between the floor and curtain wall system are presented in Figure 9. As can be seen, these gaps have the potential for fire spread should they not be appropriately sealed.

Figure 9: Example of gaps in floor slab (left) and curtain wall system (right) in a timber building during construction. (Photo Carl Pettersson)

The properties of timber will vary depending on moisture content and over loadbearing elements may move, which can cause cracks and openings around penetration seals. Fire stopping products that are not flexible or do not have appropriate properties to expand and adapt to movements in the timber construction may not seal sufficiently or even fall out.

In timber construction, it is important to account for differential movements and settlements of the connections to the shaft over time. Flexible spacers or movable connectors must be used between connections to walls and floors as well as for penetrations for pipes cables and ducts [6]. A CLT product with its orthogonal arrangement of layers that are bonded with structural adhesive, is more prone to time-dependent deformations under load (creep) than other engineered timber products, such as glued-laminated timber [51]. This is not only important from a structural point of view but also in relation to how fire stoppings around penetrations, joints, fixings and connections, are performing over time.

Joints may be the first points of fire spread and negatively influence the smoke tightness of a wall or floor. Gaps between elements can allow hot gases and smoke to pass through due to overpressure in the compartment under fire conditions. Butt connections, in particular, should be prevented or at least be protected with an additional measure to protect against fire spread [27].

Penetrations through fire compartment walls and floors for ventilation, pipes and other building services can provide paths for the spread of fire and smoke. Attention to detailing and quality control is required during the construction or maintenance of a building. Insufficient detailing of the fire separation may have larger consequences in timber buildings compared to non-combustible construction [133].

An example is a fire that occurred in 2013 in a five-storey residential timber building in Sweden that caused severe damage to all apartments. The fire started in a small kitchen on the top floor and managed to spread to the attic and down vertical voids between apartments. There are two main reasons for the high consequence of this fire. One was the kitchen ventilation allowing the fire to spread, the other was insufficient fire stops in the multi-storey vertical voids between the fire compartments [132,133].

6.3 Automatic water suppression system

There is a wide variety of active fire protection systems available. Some systems are required to be installed as part of building code requirements for certain types of buildings. As part of a performance-based design automatic water suppression systems can be used to increase fire safety and provide a more flexible fire safety design [7]. Operating successfully, an automatic suppression system will reduce the rate of growth of a fire or extinguish the fire [167].

In timber buildings, automatic sprinkler systems may be the automatic water suppression system of greatest use [7]. Automatic water mist systems, high-pressure or low-pressure, traditionally developed to suppress fires in ship engine rooms, are also an alternative for mass timber buildings. A water-mist system uses less water and can be expected to minimize the potential water damage in the building [168]. Kotsovinos et al. 2022 [169] present a full-scale experiment with a low-pressure water mist system installed in a large open-plan compartment with an exposed CLT ceilings. The automatic suppression system was activated prior to the ignition of the exposed CLT ceiling and controlled the fire growth [169]. Other experiments with exposed CLT corners (walls and ceiling) in a large compartment have investigated the effectiveness of automatic sprinklers, and low- and high-pressure water mist systems [168]. They found that, in the experiment set-up, all systems successfully maintained tenable conditions in the room, except for smoke obscuration.

"*Currently, the NFPA 750 and EN 14972 standards are available for design and installations, and further standardisation work is ongoing. Users of water mist fire suppression systems are very much dependent on information and data produced by the manufacturers. Consequently, the design and installation of a successful water mist system must take into account the probable type and location of fire, the fuel and the immediate environment*." [7] p.352

The water supply capacity and robustness together with spacing between sprinkler heads and types of sprinkler heads used in a particular building or part of a building are normally standardised depending on the expected fire hazards associated with its use. Building codes and standards are available for different types of design criteria, and specifications, with requirements of installation and maintenance. Fire hazards introduced by the provision of combustible timber structures and timber surfaces in a building must be appropriately accounted for when applicable system specifications are determined. The type of occupancy in the building alone may not account for the fire hazards introduced by timber.

In fire safety design, the ignition of fire is considered as having a probability of unity (1-100 %). Thus, a fire will be assumed to ignite and progress depending on expected growth rates appropriate to the building's use and design [154]. Automatic water sprinkler systems have a long and successful history and are recognised to reduce the probability of a fire event reaching unwanted conditions with the generalised reliability of successful operation [7]. Nevertheless, they do not eliminate all probability of not operating successfully. Hence, an automatic suppression system provides supplemental protection in the building but does not supersede other elements of the fire safety strategy [170].

The regard to the effectiveness of automatic sprinkler protection there are many features to consider. Frank et al. 2013 [171] present a review of the effectiveness of general fire sprinkler systems, and based on the available data estimate that a range of sprinkler system effectiveness from a minimum of 70 % to a maximum of 99.5 % may be possible. A more recent study by Arnstein and Kumar 2019 [172] provides more information on how to read statistical data on the effectiveness of sprinkler systems. In compartments with exposed CLT surfaces, large-scale fire testing suggests that appropriately installed automatic suppression systems with good coverage are an effective measure to suppress the fire [65].

The failure mode for an active fire suppression system differs from failure modes for most passive systems, a condition that is neglected in many analyses [132]. A failure in an active fire suppression system results in no protection at all, a failure in a passive system often provides some degree of protection.

If the fire safety design goal for a building is to maintain structural capacity in the event of a fire, an appropriate fire safety strategy must manage the potential large consequences of a fire in a timber building. Hence, the fire safety strategy should not focus only on the reduction of probability. For this reason, active fire suppression systems are to be deemed as a robustness measure, only reducing the probability of larger consequences of a fire. For structural fire safety analysis, scenarios where the active fire suppression system fails i.e. higher consequence from a fire, are to be accounted for [154].

In all buildings, active fire suppression systems will help to reduce the fire hazard. They are especially recommended in tall timber buildings [133] since they create the possibility of a fire being extinguished or controlled well before the timber structure becomes at risk of being involved in the fire.

"*Very tall buildings shall be designed in such a way that there is a very low probability of fire spread to upper floors and a very low probability of structural collapse, at any time during a fire regardless of whether or not the fire can be controlled by fire-fighting services and/or suppression systems."* [133] p.7

The great benefit of active fire suppression systems comes in the early stages of a fire and its proven ability to save lives and contain a fire before the fire brigade's arrival is recognised in many building codes. The logic that fully developed fire scenarios are eliminated in buildings with an automatic sprinkler system, as presented in [6], is the reason why active fire suppression systems allow for trade-offs with other types of protection measures in some building codes [133]. This can lead to confusion on how these relaxations, particularly relaxation to fire safety measures related to protection against fire spread and fully developed fire scenarios, will impact the fire safety strategy for the building and how to achieve the design goals. If implicit relaxations are applied to timber buildings without further consideration the consequence of a automatic suppression system failure in the event of a fire may be greater than compared with a non-combustible building. A probabilistic approach, considering robustness, is more appropriate than a comparison with reference buildings based on implicit requirements to show cause for a suggested fire safety design of timber buildings.

It is also important to acknowledge the increased risk of fire spread via cavities in a timber building and the potential consequence of such fire spread making the benefits of active fire suppression systems less effective.

7. Timber buildings during construction and in use

7.1 Fire safety during construction

The construction period is the time when timber buildings are most susceptible to risks associated with fire because most active and passive fire safety measures are not yet in place [51]. Several guidelines on building execution and control have been published around the world as mentioned in [7]. Appropriate mitigating measures are to be considered during the design stage and appropriately implemented before construction, to ensure the safety of workers and firefighters attending a construction site. The fire service should be consulted during the design, in order for them to be aware of the risks associated with the construction and be made familiar with the site, which will improve their ability to fight fires safely should they be called [51].

"*To provide the best fire safety during the construction of a building, the following measures must be addressed:*

1. *Appoint a person responsible for managing construction fire safety, both at the design stage and the construction phase*
2. *Take preventive measures to prevent any fire from starting*
3. *As far as possible, provide adequate fire detection and suppression if a fire starts*
4. *Provision of a comprehensive fire safety plan for the construction site*
5. *Implement a risk assessment and resultant actions to stop any fire spread to neighbouring buildings."* [7] p.413

Engineered mass timber elements, such as CLT, provide new innovative design opportunities. They are suitable for spans in floors, walls and roofs and have the potential for a high degree of off-site pre-installation of exterior and interior finishes. The ability to be used as either a panelled or a modular system makes these products suitable for extensions with new floors and additions to existing buildings [51]. Construction work incorporating existing buildings will pose new risks to the existing building parts, such as high temporary fuel loads and temporary fire hazards, which can allow fire spread to several fire compartments. See the example of a construction site providing additional levels to an existing building using prefabricated CLT elements in Figure 10.

Figure 10: Example of mass timber construction being used to construct a ten-storey hotel on top of an existing building. (Photo Carl Pettersson)

The installation of an automatic fire suppression system should be planned to achieve installation and operation as soon as possible to reduce the risk of a fire on the construction site [173]. Another possible way of reducing the fire risk is to install a temporary automatic fire suppression system that will operate during the construction. In [173] it is recommended that during the construction of multi-storey timber buildings, installation of the system should be prioritised for stairways and fire hazardous areas (areas with high fuel loads, high risk of ignition or rapid flame spread).

All hydrants and boosters for the use of the fire service connections must be fully operational for the building during construction as soon as reasonably practicable. The hydrants should be progressively brought into service on each floor level [173].

The construction work of buildings requires many disciplines to work together under short timeframes and cost restraints. All these factors combined are a recipe for possible mistakes. In the report by Boverket [174], a review of faults, defects and damages to buildings in Sweden concluded in 2018, that the costs associated with these are major (in the order of 1,000 million SEK per year). The main contributing factors are considered to be a lack of competency within the construction industry. The report also identifies tall timber buildings, among other construction areas, as having an increased risk of construction and design defects. In regards to the proper installation of fire stops and cavity barriers, the following is pointed out in [7].

"Common modes of failures are as follows:

- *Fire stopping missing around penetrations and building services*
- *Cavity barriers missing around voids through which a service penetration passes*
- *Lack of an effective cavity barrier to close off voids around an external wall opening or internal compartment wall*
- *Fire stopping missing at compartment envelope junctions where the internal dry lining (internal cladding) is absent*
- *Incorrect or change of specification of fire stopping or cavity barrier"* [7] p.410

Many possible mistakes can occur during construction. Preventing fire spread between compartments is therefore of great importance [175]. Incomplete fire compartmentation and protection around fire stairs and exits can expose workers and firefighters to very dangerous conditions during construction. Strategies on how safe evacuation routes will be maintained during the construction process are essential. There may be few if any, fire barriers to hinder fire from spreading in the building during construction. Lack of fire compartmentation may cause the intensity of a potential fire to be very high and pose a significant risk of fire spread to neighbouring buildings [173]. Consideration should be given to how fire compartmentation can be introduced early in the construction process. One strategy could be to complete a set number of floors with complete passive and active fire safety measures in place before progressing [51]. On a construction site, having emergency exits in place that are kept clear and fire separated from the rest of the building is not an easy task.

To reduce the consequences, fire protection around exposed timber and combustible insulation materials is to be provided at the earliest opportunity. It may also be necessary to protect windows and door openings temporarily before the fire separating construction is provided if these are not required as means of escape during construction time. This approach also provides significant security benefits [176].

Hot work, heaters on-site or careless fire safety practices (such as the improper disposal of cigarettes) are typical fire hazards. Removing some of these hazards can be straightforward, such as eliminating hot work and enacting strictly no-smoking policies on-site. The majority of fire incidents are however incendiary (arson) and 24-hour security provisions to the site are therefore very important [51].

Management of the construction process is key and all construction sites require formalised fire safety management systems, including auditing of contractors and subcontractors [7].

7.2 Firefighting in timber buildings

There are unique hazards for fighting fires in timber buildings. Smolka and Kempna 2018 [177] present the following hazards identified for buildings constructed in bio-based materials:

- Faster fire growth and shorter time to flashover
- Possibility of secondary flashover
- Increased total heat release rate
- Longer burning duration
- Increased severity of external flaming
- Charring and consequently cracking of timber allows smoke and heat to spread in structures
- Increased possibility of intensive fire development – backdraft, flashover
- Hidden fire spread in structures (walls, cladding, attics, etc.)
- Fire reignition after extinguishing
- Fire spreading in void spaces and attics – higher possibility of backdraft occurrence
- Cracking of structure allows smoke spread
- Increased production of volatiles and smoke
- Premature structural collapse
- Hydrophobic properties of fire insulation materials complicate fire extinguishing
- Late fire observation – hidden development and spread of fire in structures
- Increased fire hazard during construction and maintenance
- Sprinkler failure can cause serious damage – e.g. delay of the water mist extinguishing system can postpone flashover
- The presence of materials with higher flammability and hazardous materials can cause serious damage to the structure
- Wrong design or building procedures can cause serious damage and malfunction of fire protection

It is important for firefighters to understand these different hazards and the potential fire behaviour of structures with combustible building materials, and the following is pointed out in the "*Fire Safe Use of Wood in Buildings: Global Design Guide*" [7]:

"*Understanding the scope of structural fire resistance of timber buildings during the later stages of the fire duration is especially important given that the design concepts of burnout in traditional buildings may not apply to timber construction.*" [7] p.433

It is likely that the initial approach to firefighting in large timber buildings will be similar to other buildings [7], and it may not be obvious to the first responders on the scene that the building is constructed out of timber. In Sweden, there is a discussion between fire brigades and authorities on how tools such as signs or information cards available on site for a building can provide firefighters with easy access to information on the construction type in the building. Fire services around the world have expressed concern about fire safety in mass timber buildings and the following is highlighted in [7].

"*Specific concerns expressed by firefighters include the following:*

- *Faster fire growth and greater total heat release rates*
- *Earlier flashover, including the possibility of multiple flashovers*
- *Increase in fuel load producing longer duration fires*

- *Increased firefighting water demands*
- *Greater requirements for resources inside the building, including access above the fire floor*
- *Hidden fire spread in voids and ongoing combustion behind encapsulation*
- *Increased severity of external flaming from windows and openings*
- *Increased chance of fire spread to adjacent buildings*
- *Greater reliance on fixed fire protection systems*
- *Increased production of carbon monoxide due to ongoing smouldering combustion*
- *Increased influence of wind-driven fires*" [7] p.435

In taller timber buildings the provision of concrete stairwells and lift shafts in the core of the building can provide greater confidence to firefighters in the robustness and resilience of this type of constriction [7].

With a combustible structure, smouldering fires may continue for a long period and are hard to identify and locate. The fire spread within cavities, where combustible materials are present, is a hazard that is introduced with timber construction, but combustible materials in cavities and shafts may also be present in other building construction designs. The increased pressure in a compartment due to higher temperatures from a fire or fans used by firefighters may help the fire to spread into cavities and must be accounted for. Fighting fires inside cavities is difficult and it is important to avoid openings in voids and introduce oxygen to the fire before the fire is under control [7]. The best approach is to use piercing nozzles and cutting extinguishers to get extinguishing media through small openings [7]. An alternative and more defensive tactic is to maintain the cavity fire in place by hindering further fire spread [178].

Combustible façade systems will increase the risk of fire spread between levels in the building but also to and from the building, either due to heat radiation or hot and burning particles [177]. External flaming out of openings can be more severe from a compartment with exposed timber surfaces [26,38–40], increasing the risk of fire spread between storeys even with non-combustible external walls.

In modern buildings, an important design goal is to achieve more sustainable benefits from the building. Hence, modern timber buildings are likely to be equipped with solar power systems and hubs for batteries and energy storage inside the buildings. These by themselves, cause difficulties and unique hazards for the firefighting operations.

Water is one of the most effective extinguishers and most commonly used agents for firefighting [177]. The amount of water needed to fight a fire can be correlated with how much fuel is provided to the fire. In timber buildings with the main structure constructed of timber, there is the potential for unlimited fuel for a fire, which will require a higher demand for water supply compared to non-combustible buildings. This is something that must be accounted for in the fire safety strategy of a building.

Additional considerations for firefighting in timber buildings

It is important to acknowledge that firefighting is a profession governed by health and safety regulations, which will have to adapt to the risks associated with fighting a fire in a building. There must be confidence that the firefighters will not be put at risk from unforeseen fire spread or structural collapse before committing to internal firefighting [7]. For timber buildings, the complex hazards identified above have the potential to reduce the possibility of internal firefighting.

As most modern timber buildings have been constructed over the last ten years, with an increase in development in the last few years, firefighting experience in large timber buildings is limited. The experience of fighting fires in timber buildings is primarily based on fires in historical buildings with solid timber structures. This creates a challenge with modern timber buildings which can be taller but also tend to consist of more combustible façade systems, such as timber facades or aluminium composite panels with combustible core and/or combustible insulation solutions [177].

7.3 Damages after a fire

There are several different aspects to consider in relation to fire damage to timber. As presented in [76] the type, cause and spread of the fire, as well as the thermal gradients and resistance ratings, will have an impact on the residual load-bearing capacity.

The length of a fire will have an impact on the residual load-bearing capacity. As found in [105] there is a delay in the heating of a timber structure that will impact the residual strength behind the charring layer. The length of heat exposure has a great impact on the heating inside the timber. It is not limited to the exposure to high temperatures but also smouldering combustion and the cooling period after a fire [179]. Prolonged exposure to temperatures above 65 °C has been found to result in a permanent loss in structural properties in timber [105,179,180]. The char layer itself will have no residual load-bearing capacity, but the uncharred timber will, in relation to the exposure time from the fire, have some reduced residual strength.

Timber is inherently variable and graded during manufacturing. Underlying factors of the structural strength of timber depend on density, slope of grain and presence of knots [179]. If evaluating the fire damage on the structural load-bearing capacity, information about the typical capacity of the original product is important. In [179] it is recommended that the timber structures are re-graded after the char is completely removed.

It is stated by McLain 2023 [181] that as part of a post-fire investigation facts need to be determined, such as:

- Original dimensions, species, grades, layups, and connection details of timber elements prior to fire
- Source of the fire
- Intensity and duration of the fire
- Growth pattern of the fire
- When the fire/smouldering was extinguished

During a fire, the size and configuration of a compartment will have an impact on the temperature exposure to different timber elements in the compartment. In large compartments, homogenous temperature exposure cannot always be expected for all surfaces in a fully developed fire.

Moisture content in the timber has been found to impact the load-bearing capacity. Immediately following a fire the moisture content of charred members is likely to fall below 6.5 % [179], which should be compared to the equilibrium moisture content of timber (typically assumed to be around 10–12 %) [14]. A 1 % change in moisture content can affect timber strength properties by as much as 2 to 6 % [179].

Connections and screws between timber elements are commonly made of metal, which will melt and lose load-bearing capacity quickly if exposed to high temperatures. After a fire, it may be clear if the metal has lost its capacity due to heat. However, there is also a possibility for chemical damage to metal due to the corrosive effects of fire residues [179]. Detailed inspections will be required to understand the conditions of metal connections.

Water damage after a fire may be a result of sprinkler activation or the fire services intervention. From a statistical study in [26], the data indicates that high water damage is most often caused by fire service intervention rather than sprinkler activation. This is also acknowledged in [6]. In relation to concerns about mould damage, any moisture damage associated with fire suppression (sprinkler or fire brigade) is important to be addressed after a fire event in a timber building [179]. Fire residue and its chemical impact on metallic building components is also something that can be transported with extinguishment water to non-fire affected parts of the building.

The design of the building will also have an influence on its repairability and possibility for reuse after a fire. This is a relatively new topic in research and limited information is available [7]. "*In general, it seems that a well-thought-through design-for-deconstruction approach that allows the de-installation of structural members seems to be beneficial in this context.*" [7] p.405.

One example is that modular construction may provide some benefits with the possibility of module removal and reinstallation, depending on the design of the building, location and extent of fire damage. In fire in a five-storey residential modular timber building in Uppsala, Sweden 2018. The fire spread inside cavities and between modules but most damage resulted from the fire extinguishment water and burned through water pipes. According to Brandon et al. 2021 [182] the building was repaired relatively cost-effective with a procedure of disassembling the construction modules and repairing them off site.

It is also important to consider the risks associated with repair work in a building. If not already damaged, passive fire protection such as fire compartmentation may need to be disassembled and active fire safety measures such as smoke detection and automatic fire suppression systems may need to be temporarily disconnected. If parts of a building are still occupied or in normal use, this will cause an increased risk to occupant safety.

References

[1] V. Babrauskas, Ignition of Wood: A Review of the State of the Art, Journal of Fire Protection Engineering. 12 (2002) 163–189. https://doi.org/10.1177/10423910260620482.

[2] R. Jönsson, O. Pettersson, L.J. Gruber, Timber structures and fire: a review of the existing state of knowledge and research requirements, Swedish Council for Building Research, Stockholm, 1985.

[3] R. Gerard, D. Barber, A. Wolski, Fire Safety Challenges of Wood Buildings, Phase 1, Fire Protection Research Foundation, San Francisco, CA, 2013.

[4] D. Brandon, B. Östman, Fire Safety Challenges of Tall Wood Buildings. Phase 2: Task 1 - Literature Review, Fire Protection Research Foundation, Quincy, MA, 2016. FRPF-2016-22.

[5] J. Liu, E.C. Fischer, Review of large-scale CLT compartment fire tests, Construction and Building Materials. 318 (2022) 126099. https://doi.org/10.1016/j.conbuildmat.2021.126099.

[6] B. Östman, et al., Fire safety in timber buildings: technical guideline for Europe, SP Technical Research Institute of Sweden, Stockholm, 2010.

[7] B. Andrew, B. Östman, eds., Fire Safe Use of Wood in Buildings: Global Design Guide, CRC Press, Boca Raton, 2022. https://doi.org/10.1201/9781003190318.

[8] IBC (2018) International Building Code. International Code Council, Washington DC, USA., (n.d.).

[9] NCC (2019) National Construction Codes. Volume One, Building Code of Australia (BCA), Canberra, AUS., (n.d.).

[10] Approved Document B (fire safety) Volume 2: Buildings other than dwellings (2019) HM Government (UK)., (n.d.).

[11] Building Regulations (BFS 2019:2 BBR 28) (2019) Code of Statutes of the Swedish National Board of Housing, Building and Planning (Boverket) (SWE)., (n.d.).

[12] J. Torero, G. Rein, Physical Parameters Affecting Fire Growth, in: C. Wilkie, A. Morgan (Eds.), Fire Retardancy of Polymeric Materials, Second Edition, CRC Press, 2009: pp. 43–73. https://doi.org/10.1201/9781420084009-c3.

[13] A. Inghelbrecht, Evaluation of the burning behaviour of wood products in the context of structural fire design, International Master of Science in Fire Safety Engineering, The University of Queensland, Ghent University, 2014. https://www.semanticscholar.org/paper/Evaluation-of-the-burning-behaviour-of-wood-in-the-Inghelbrecht/dd7fa8af485ac8bc1f4723ddc8d90a06f24ea006.

[14] A.I. Bartlett, R.M. Hadden, L.A. Bisby, A Review of Factors Affecting the Burning Behaviour of Wood for Application to Tall Timber Construction, Fire Technol. 55 (2019) 1–49. https://doi.org/10.1007/s10694-018-0787-y.

[15] C.A. Wade, A theoretical model of fully developed fire in mass timber enclosures, (2019). https://doi.org/10.26021/1936.

[16] C.E. MacLeod, A. Law, R.M. Hadden, Quantifying the heat release from char oxidation in timber, Fire Safety Journal. 138 (2023) 103793. https://doi.org/10.1016/j.firesaf.2023.103793.

[17] A. Law, R. Hadden, We need to talk about timber, The Structural Engineer. 98 (2020). https://www.istructe.org/journal/volumes/volume-98-(2020)/issue-3/we-need-to-talk-about-timber-fire-safety-design-in/.

[18] L.A. Lowden, T.R. Hull, Flammability behaviour of wood and a review of the methods for its reduction, Fire Science Reviews. 2 (2013) 4. https://doi.org/10.1186/2193-0414-2-4.

[19] F. Richter, F.X. Jervis, X. Huang, G. Rein, Effect of oxygen on the burning rate of wood, Combustion and Flame. 234 (2021) 111591. https://doi.org/10.1016/j.combustflame.2021.111591.

[20] Z. Liang, S. Lin, X. Huang, Smoldering ignition and emission dynamics of wood under low irradiation, Fire and Materials. 47 (2023) 514–524. https://doi.org/10.1002/fam.3107.

[21] D. Morrisset, R.M. Hadden, A.I. Bartlett, A. Law, R. Emberley, Time dependent contribution of char oxidation and flame heat feedback on the mass loss rate of timber, Fire Safety Journal. 120 (2021) 103058. https://doi.org/10.1016/j.firesaf.2020.103058.

[22] J. Schmid, A. Santomaso, D. Brandon, U. Wickström, A. Frangi, Timber under real fire conditions – the influence of oxygen content and gas velocity on the charring behavior, JSFE. 9 (2018) 222–236. https://doi.org/10.1108/JSFE-01-2017-0013.

[23] D. Zeinali, D.I. Kolaitis, J. Schmid, Guide for Obtaining Data from Reaction to Fire Tests, COST Action FP1404, Zürich, Switzerland, 2018.

[24] R. Crielaard, J.-W. van de Kuilen, K. Terwel, G. Ravenshorst, P. Steenbakkers, Self-extinguishment of cross-laminated timber, Fire Safety Journal. 105 (2019) 244–260. https://doi.org/10.1016/j.firesaf.2019.01.008.

[25] J. Su, P.-S. Lafrance, M. Hoehler, M. Bundy, Fire Safety Challenges of Tall Wood Buildings – Phase 2: Task 2 & 3 – Cross Laminated Timber Compartment Fire Tests, Fire Protection Research Foundation, Quincy, MA, 2018. FRPF-2018-01.

[26] D. Brandon, A. Just, P. Andersson, B. Östman, Mitigation of fire damages in multi-storey timber buildings – statistical analysis and guidelines for design, RISE Research Institutes of Sweden, Stockholm, 2018. ISBN: 978-91-88695-82-6.

[27] B. Östman, J. Schmid, M. Klippel, A. Just, N. Werther, D. Brandon, Fire Design of CLT in Europe, Wood and Fiber Science: Journal of the Society of Wood Science and Technology. 50 (2018) 68–82. https://doi.org/10.22382/wfs-2018-041.

[28] C. McGregor, Contribution of cross laminated timber panels to room fires, Master of Applied Science, Carleton University, 2013. https://doi.org/10.22215/etd/2013-06885.

[29] L. Hasburgh, K. Bourne, D. Barber, Fire performance of penetrations in glulam beams: a preliminary study, in: World Conference on Timber Engineering (WCTE 2023), World Conference on Timber Engineering (WCTE 2023), Oslo, Norway, 2023: pp. 1545–1550. https://doi.org/10.52202/069179-0209.

[30] EN 1995-1-2 Eurocode 5 – Design of timber structures, Part 1–2: General – Structural fire design. European Standard CEN, European Committee for Standardization, Brussels, (2004).

[31] SP FIRE 105 Method for fire testing of façade materials, Dnr 171-79-360 Department of Fire Technology, Swedish National Testing and Research Institute, 1994, (n.d.).

[32] LEPIR II Test. Large scale Fire Performance testing of construction systems for façade – CECMI (French committee for the evaluation and the classification of products and elements of construction as regards to fire hazard – under the French Ministry of Internal Affairs directives), 2013, (n.d.).

[33] BS 8414-1:2015 Fire performance of external cladding systems. (masonry face of a building) Amended in June 2017. BS 8414-2:2015 Fire performance of external cladding systems. (structural steel frame) Amended in June 2017., (n.d.).

[34] ISO 13785-2:2002 Reaction-to-fire tests for façades – Part 2: Large-scale test. International Organization for Standardization., (n.d.).

[35] NFPA 285 Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Wall Assemblies Containing Combustible Components, 2019 edition., (n.d.).

[36] AS 5113:2016 Fire propagation testing and classification of external walls of buildings, published 2016., (n.d.).

[37] M. Klippel, A. Just, Guidance on Fire design of CLT including best practise, COST Action FP1404, Zürich, Switzerland, 2018. DOI 10.3929/ethz-b-000319542p.

[38] R. McNamee, J. Zehfuss, A.I. Bartlett, M. Heidari, F. Robert, L.A. Bisby, Enclosure fire dynamics with a cross-laminated timber ceiling, Fire and Materials. 45 (2021) 847–857. https://doi.org/10.1002/fam.2904.

[39] A.S. Bøe, K.L. Friquin, D. Brandon, A. Steen-Hansen, I.S. Ertesvåg, Fire spread in a large compartment with exposed cross-laminated timber and open ventilation conditions: #FRIC-01 – Exposed ceiling, Fire Safety Journal. (2023) 103869. https://doi.org/10.1016/j.firesaf.2023.103869.

[40] J. Sjöström, D. Brandon, A. Temple, J. Anderson, R. McNamee, External fire plumes from mass timber compartment fires—Comparison to test methods for regulatory compliance of façades, Fire and Materials. 47 (2023) 433–444. https://doi.org/10.1002/fam.3129.

[41] A. Čolić, Study of the char fall-off phenomenon in cross-laminated timber under fire conditions, International Master of Science in Fire Safety Engineering Thesis, 2021. DOI: 10.13140/RG.2.2.10704.84480.

[42] R.M. Hadden, A.I. Bartlett, J.P. Hidalgo, S. Santamaria, F. Wiesner, L.A. Bisby, S. Deeny, B. Lane, Effects of exposed cross laminated timber on compartment fire dynamics, Fire Safety Journal. 91 (2017) 480–489. https://doi.org/10.1016/j.firesaf.2017.03.074.

[43] D. Brandon, C. Dagenais, Fire Safety Challenges of Tall Wood Buildings – Phase 2: Task 5 – Experimental Study of Delamination of Cross Laminated Timber (CLT) in Fire, Fire Protection Research Foundation, Quincy, MA, 2018. FRPF-2018-05.

[44] D. Hopkin, W. Węgrzyński, M. Spearpoint, I. Fu, H. Krenn, T. Sleik, C. Gorska, G. Stapf, Large-Scale Enclosure Fire Experiments Adopting CLT Slabs with Different Types of Polyurethane Adhesives: Genesis and Preliminary Findings, Fire. 5 (2022) 39. https://doi.org/10.3390/fire5020039.

[45] J. Su, P. Leroux, P.-S. Lafrance, R. Berzins, K. Gratton, E. Gibbs, M. Weinfurter, Fire testing of rooms with exposed wood surfaces in encapsulated mass timber construction, National Research Council of Canada. Construction, 2021. https://doi.org/10.4224/23004642.

[46] M. Klippel, J. Schmid, Guidance Document on the Verification of the Adhesive Performance in Fire, COST Action FP1404, Zürich, Switzerland, 2018. DOI 10.3929/ethz-b-000307755.

[47] S. Mohaine, A. Čolic, D. Morrisset, J.-C. Mindeguia, J.-M. Franssen, J. Zehfuss, R. McNamee, L. Bisby, F. Robert, Performance of passive protection of cross laminated timber during standard furnace tests and natural fires, in: World Conference on Timber Engineering (WCTE 2023), World Conference on Timber Engineering (WCTE 2023), Oslo, Norway, 2023: pp. 1839–1847. https://doi.org/10.52202/069179-0243.

[48] F. Wiesner, R. Hadden, S. Deeny, L. Bisby, Structural fire engineering considerations for cross-laminated timber walls, Construction and Building Materials. 323 (2022) 126605. https://doi.org/10.1016/j.conbuildmat.2022.126605.

[49] E. Johansson, A. Svenningsson, Delamination of cross-laminated timber and its impact on fire development | Focusing on different types of adhesives, Master of Science, Division of Fire Safety Engineering, Lund University, 2018.

[50] G. Stapf, S. Aicher, Einfluss des Pressdrucks - Möglichkeiten und Grenzen der Niedrigdruck-Vakuumverpressung bei der Herstellung von geklebten Holzbauteilen, 2015.

[51] E. Karacabeyli, S. Gagnon, eds., Canadian CLT Handbook, FPInnovations, Pointe-Claire, QC, 2019.

[52] D. Brandon, M. Klippel, A. Frangi, Glueline Integrity in Fire, RISE Research Institutes of Sweden, 2021. https://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-59177.

[53] prEN 1995-1-2 Eurocode 5. Final Draft. Design of Timber Structures. 1–2: General: Structural Fire Design. European Draft Standard. CEN European Committee for Standardization, Brussels., (2021).

[54] D. Brandon, Fire Safety Challenges of Tall Wood Buildings – Phase 2: Task 4 – Engineering Methods, Fire Protection Research Foundation, Quincy, MA, 2018. FPRF-2018-04.

[55] H. Mitchell, P. Kotsovinos, F. Richter, D. Thomson, D. Barber, G. Rein, Review of fire experiments in mass timber compartments: Current understanding, limitations, and research gaps, Fire and Materials. 47 (2023) 415–432. https://doi.org/10.1002/fam.3121.

[56] G. Ronquillo, D. Hopkin, M. Spearpoint, Review of large-scale fire tests on cross-laminated timber, Journal of Fire Sciences. 39 (2021) 327–369. https://doi.org/10.1177/07349041211034460.

[57] ISO 13943 Fire Safety – Vocabulary, (n.d.).

[58] S. Ingberg, Tests of the Severity of Building Fires, NFPA Quarterly Issue 22. (1928) 43–61.

[59] R. Emberley, T. Do, J. Yim, J.L. Torero, Critical heat flux and mass loss rate for extinction of flaming combustion of timber, Fire Safety Journal. 91 (2017) 252–258. https://doi.org/10.1016/j.firesaf.2017.03.008.

[60] P.H. Thomas, The fire resistance required to survive a burnout, Borehamwood: Fire Research Station, 1970.

[61] M.A. Law, Relationship Between Fire Grading and Building Design and Contents, Fire Research Note Number 877, Fire Research Station, U.K. (1971).

[62] A. Law, L. Bisby, The rise and rise of fire resistance, Fire Safety Journal. 116 (2020) 103188. https://doi.org/10.1016/j.firesaf.2020.103188.

[63] A. Law, R. Hadden, Burnout means Burnout, SFPE Europe Q1. (2017). https://www.research.ed.ac.uk/en/publications/burnout-means-burnout (accessed July 24, 2023).

[64] A. Buchanan, Fire Resistance of Multistorey Timber Buildings, in: K. Harada, K. Matsuyama, K. Himoto, Y. Nakamura, K. Wakatsuki (Eds.), Fire Science and Technology 2015, Springer, Singapore, 2017: pp. 9–16. https://doi.org/10.1007/978-981-10-0376-9_2.

[65] S.L. Zelinka, L.E. Hasburgh, K.J. Bourne, D.R. Tucholski, J.P. Ouellette, Compartment fire testing of a two-story mass timber building, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI, 2018. https://doi.org/10.2737/FPL-GTR-247.

[66] H. Mitchell, R. Amin, M. Heidari, P. Kotsovinos, G. Rein, Structural hazards of smouldering fires in timber buildings, Fire Safety Journal. (2023) 103861. https://doi.org/10.1016/j.firesaf.2023.103861.

[67] H. Xu, I. Pope, V. Gupta, J. Cadena, J. Carrascal, D. Lange, M.S. McLaggan, J. Mendez, A. Osorio, A. Solarte, D. Soriguer, J.L. Torero, F. Wiesner, A. Zaben, J.P. Hidalgo, Large-scale compartment fires to develop a self-extinction design framework for mass timber—Part 1: Literature review and methodology, Fire Safety Journal. 128 (2022) 103523. https://doi.org/10.1016/j.firesaf.2022.103523.

[68] J. Cuevas, J.L. Torero, C. Maluk, Flame extinction and burning behaviour of timber under varied oxygen concentrations, Fire Safety Journal. 120 (2021) 103087. https://doi.org/10.1016/j.firesaf.2020.103087.

[69] R. Emberley, A. Inghelbrecht, Z. Yu, J.L. Torero, Self-extinction of timber, Proceedings of the Combustion Institute. 36 (2017) 3055–3062. https://doi.org/10.1016/j.proci.2016.07.077.

[70] L. Terrei, Z. Acem, P. Lardet, P. Boulet, G. Parent, Study of wood self-extinguishment with a double sliding cone calorimeter, Fire Safety Journal. 122 (2021) 103316. https://doi.org/10.1016/j.firesaf.2021.103316.

[71] A.I. Bartlett, R.M. Hadden, J.P. Hidalgo, S. Santamaria, F. Wiesner, L.A. Bisby, S. Deeny, B. Lane, Auto-extinction of engineered timber: Application to compartment fires with exposed timber surfaces, Fire Safety Journal. 91 (2017) 407–413. https://doi.org/10.1016/j.firesaf.2017.03.050.

[72] R. Emberley, C.G. Putynska, A. Bolanos, A. Lucherini, A. Solarte, D. Soriguer, M.G. Gonzalez, K. Humphreys, J.P. Hidalgo, C. Maluk, A. Law, J.L. Torero, Description of small and large-scale cross laminated timber fire tests, Fire Safety Journal. 91 (2017) 327–335. https://doi.org/10.1016/j.firesaf.2017.03.024.

[73] J. Cuevas, C. Maluk, The role of moisture on the flame extinction potential of Cross-laminated Timber, Fire Safety Journal. 141 (2023) 103937. https://doi.org/10.1016/j.firesaf.2023.103937.

[74] R. Crielaard, Self-extinguishment of cross-laminated timber, Master of Science in Civil Engineering, Faculty of Civil Engineering and Geosciences Delft University of Technology, 2015. http://resolver.tudelft.nl/uuid:c7e7ade5-3c04-4268-b370-8e2c33e3e0ee.

[75] I. Pope, H. Xu, V. Gupta, J. Carrascal, D. Lange, M. McLaggan, J. Mendez, A. Solarte, D. Soriguer, J. Torero, F. Wiesner, J. Hidalgo, Fire dynamics in under-ventilated mass timber room compartments, 2021. https://doi.org/10.14264/7e19a8f.

[76] J. Su, E. Gibbs, M. Weinfurter, P.-S. Lafrance, K. Gratton, A. Frade, P. Leroux, Large-scale fire tests of a mass timber building structure for MTDFTP, National Research Council of Canada, 2023. https://doi.org/10.4224/40003036.

[77] F. Wiesner, A. Bartlett, S. Mohaine, F. Robert, R. McNamee, J.-C. Mindeguia, L. Bisby, Structural Capacity of One-Way Spanning Large-Scale Cross-Laminated Timber Slabs in Standard and Natural Fires, Fire Technol. 57 (2021) 291–311. https://doi.org/10.1007/s10694-020-01003-y.

[78] J. Schmid, D. Barber, D. Brandon, N. Werther, The need for common terminology for fire safe design of timber structures, in: Proceedings of the 12th Asia-Oceania Symposium on Fire Science and Technology (AOSFST 2021), The University of Queensland, Online, 2021. https://doi.org/10.14264/f60d2c9.

[79] D. Drysdale, An introduction to fire dynamics, Third edition, John Wiley & Sons, Ltd., Chichester, West Sussex, England, 2011. DOI:10.1002/9781119975465.

[80] A. Lucherini, J.L. Torero, Defining the fire decay and the cooling phase of post-flashover compartment fires, Fire Safety Journal. 141 (2023) 103965. https://doi.org/10.1016/j.firesaf.2023.103965.

[81] P.H. Thomas, A.J.M. Heselden, M.A. Law, Fully-developed compartment fires: Two kinds of behaviour, HM Stationery Office, 1967.

[82] J. Torero, A. Majdalani, C. Abecassis-Empis, A. Cowlard, Revisiting the Compartment Fire, Fire Saf. Sci. 11 (2014) 28–45. https://doi.org/10.3801/IAFSS.FSS.11-28.

[83] V. Gupta, A.F. Osorio, J.L. Torero, J.P. Hidalgo, Mechanisms of flame spread and burnout in large enclosure fires, Proceedings of the Combustion Institute. 38 (2021) 4525–4533. https://doi.org/10.1016/j.proci.2020.07.074.

[84] I. Pope, V. Gupta, H. Xu, F. Wiesner, D. Lange, J.L. Torero, J.P. Hidalgo, Fully-developed compartment fire dynamics in large-scale mass timber compartments, Fire Safety Journal. (2023) 104022. https://doi.org/10.1016/j.firesaf.2023.104022.

[85] J.P. Hidalgo, T. Goode, V. Gupta, A. Cowlard, C. Abecassis-Empis, J. Maclean, A.I. Bartlett, C. Maluk, J.M. Montalvá, A.F. Osorio, J.L. Torero, The Malveira fire test: Full-scale demonstration of fire modes in open-plan compartments, Fire Safety Journal. 108 (2019) 102827. https://doi.org/10.1016/j.firesaf.2019.102827.

[86] V. Gupta, J.P. Hidalgo, A. Cowlard, C. Abecassis-Empis, A.H. Majdalani, C. Maluk, J.L. Torero, Ventilation effects on the thermal characteristics of fire spread modes in open-plan compartment fires, Fire Safety Journal. 120 (2021) 103072. https://doi.org/10.1016/j.firesaf.2020.103072.

[87] V. Gupta, J.P. Hidalgo, D. Lange, A. Cowlard, C. Abecassis-Empis, J.L. Torero, A Review and Analysis of the Thermal Exposure in Large Compartment Fire Experiments, International Journal of High-Rise Buildings. 10 (2021) 345–364. https://doi.org/10.21022/IJHRB.2021.10.4.345.

[88] E. Rackauskaite, P. Kotsovinos, A. Jeffers, G. Rein, Structural analysis of multi-storey steel frames exposed to travelling fires and traditional design fires, Engineering Structures. 150 (2017) 271–287. https://doi.org/10.1016/j.engstruct.2017.06.055.

[89] J. Stern-Gottfried, G. Rein, Travelling fires for structural design–Part I: Literature review, Fire Safety Journal. 54 (2012) 74–85. https://doi.org/10.1016/j.firesaf.2012.06.003.

[90] J. Stern-Gottfried, G. Rein, Travelling fires for structural design-Part II: Design methodology, Fire Safety Journal. 54 (2012) 96–112. https://doi.org/10.1016/j.firesaf.2012.06.011.

[91] F. Richter, G. Rein, P. Kotsovinos, The role of chemistry and physics in the charring of timber in realistic fires, SFPE FPE Extra Issue 28. (2018). https://www.sfpe.org/page/FPEExtraIssue28?&_zs=hc01d1&_zl=rmom4 (accessed July 4, 2023).

[92] E. Rackauskaite, C. Hamel, A. Law, G. Rein, Improved Formulation of Travelling Fires and Application to Concrete and Steel Structures, Structures. 3 (2015) 250–260. https://doi.org/10.1016/j.istruc.2015.06.001.

[93] X. Dai, S. Welch, O. Vassart, K. Cábová, L. Jiang, J. Maclean, G.C. Clifton, A. Usmani, An extended travelling fire method framework for performance-based structural design, Fire and Materials. 44 (2020) 437–457. https://doi.org/10.1002/fam.2810.

[94] F. Richter, P. Kotsovinos, E. Rackauskaite, G. Rein, Thermal Response of Timber Slabs Exposed to Travelling Fires and Traditional Design Fires, Fire Technol. 57 (2021) 393–414. https://doi.org/10.1007/s10694-020-01000-1.

[95] E. Rackauskaite, P. Kotsovinos, D. Barber, Letter to the Editor: Design Fires for Open-Plan Buildings with Exposed Mass-Timber Ceiling, Fire Technol. 57 (2021) 487–495. https://doi.org/10.1007/s10694-020-01047-0.

[96] S. Nothard, D. Lange, J.P. Hidalgo, V. Gupta, M.S. McLaggan, F. Wiesner, J.L. Torero, Factors influencing the fire dynamics in open-plan compartments with an exposed timber ceiling, Fire Safety Journal. 129 (2022) 103564. https://doi.org/10.1016/j.firesaf.2022.103564.

[97] P. Kotsovinos, E. Rackauskaite, E. Christensen, A. Glew, E. O'Loughlin, H. Mitchell, R. Amin, F. Robert, M. Heidari, D. Barber, G. Rein, J. Schulz, Fire dynamics inside a large and open-plan compartment with exposed timber ceiling and columns: *CodeRed #01*, Fire and Materials. 47 (2023) 542–568. https://doi.org/10.1002/fam.3049.

[98] P. Kotsovinos, E.G. Christensen, E. Rackauskaite, A. Glew, E. O'Loughlin, H. Mitchell, R. Amin, F. Robert, M. Heidari, D. Barber, G. Rein, J. Schulz, Impact of ventilation on the fire dynamics of an open-plan compartment with exposed timber ceiling and columns: *CodeRed #02*, Fire and Materials. 47 (2023) 569–596. https://doi.org/10.1002/fam.3082.

[99] P. Kotsovinos, E.G. Christensen, A. Glew, E. O'Loughlin, H. Mitchell, R. Amin, F. Robert, M. Heidari, D. Barber, G. Rein, J. Schulz, Impact of partial encapsulation on the fire dynamics of an open-plan compartment with exposed timber ceiling and columns: *CodeRed #04*, Fire and Materials. 47 (2023) 597–626. https://doi.org/10.1002/fam.3112.

[100] E. Rackauskaite, M. Bonner, F. Restuccia, N. Fernandez Anez, E.G. Christensen, N. Roenner, W. Wegrzynski, P. Turkowski, P. Tofilo, M. Heidari, P. Kotsovinos, I. Vermesi, F. Richter, Y. Hu, C. Jeanneret, R. Wadhwani, G. Rein, Fire Experiment Inside a Very Large and Open-Plan Compartment: x-ONE, Fire Technol. 58 (2022) 905–939. https://doi.org/10.1007/s10694-021-01162-6.

[101] M. Heidari, Travelling fires methodology and probabilistic design of structures, Doctor of Philosophy, Imperial College London, 2021. https://doi.org/10.25560/99999.

[102] A. Rinta-Paavola, D. Sukhomlinov, S. Hostikka, Modelling Charring and Burning of Spruce and Pine Woods During Pyrolysis, Smoldering and Flaming, Fire Technol. (2023). https://doi.org/10.1007/s10694-023-01458-9.

[103] A. Lucherini, D. Šejnová Pitelková, V. Mózer, Predicting the effective char depth in timber elements exposed to natural fires, including the cooling phase, in: World Conference on Timber Engineering (WCTE 2023), World Conference on Timber Engineering (WCTE 2023), Oslo, Norway, 2023: pp. 1681–1690. https://doi.org/10.52202/069179-0226.

[104] T. Gernay, Fire resistance and burnout resistance of timber columns, Fire Safety Journal. 122 (2021) 103350. https://doi.org/10.1016/j.firesaf.2021.103350.

[105] F. Wiesner, L.A. Bisby, A.I. Bartlett, J.P. Hidalgo, S. Santamaria, S. Deeny, R.M. Hadden, Structural capacity in fire of laminated timber elements in compartments with exposed timber surfaces, Engineering Structures. 179 (2019) 284–295. https://doi.org/10.1016/j.engstruct.2018.10.084.

[106] T. Gernay, J. Zehfuß, S. Brunkhorst, F. Robert, P. Bamonte, R. McNamee, S. Mohaine, J. Franssen, Experimental investigation of structural failure during the cooling phase of a fire: Timber columns, Fire and Materials. 47 (2023) 445–460. https://doi.org/10.1002/fam.3110.

[107] V. Schleifer, Zum Verhalten von raumabschliessenden mehrschichtigen Holzbauteilen im Brandfall, Doctoral Thesis, ETH Zurich, 2009. https://doi.org/10.3929/ethz-a-005771863.

[108] K.N. Mäger, A. Just, J. Schmid, N. Werther, M. Klippel, D. Brandon, A. Frangi, Procedure for implementing new materials to the component additive method, Fire Safety Journal. 107 (2019) 149–160. https://doi.org/10.1016/j.firesaf.2017.09.006.

[109] A. Just, J. Schmid, Improved fire design models for Timber Frame Assemblies, COST Action FP1404, Zürich, Switzerland, 2018.

[110] J. König, Structural fire design according to Eurocode 5—design rules and their background, Fire Mater. 29 (2005) 147–163. https://doi.org/10.1002/fam.873.

[111] M. Tiso, A. Just, J. Schmid, K.N. Mäger, M. Klippel, M. Izzi, M. Fragiacomo, Evaluation of zero-strength layer depths for timber members of floor assemblies with heat resistant cavity insulations, Fire Safety Journal. 107 (2019) 137–148. https://doi.org/10.1016/j.firesaf.2019.01.001.

[112] R. Emberley, J. Torero Cullen, Cross-laminated timber failure modes for fire conditions, in: Proceedings of the Second International Conference on Performance-Based and Life-Cycle Structural Engineering (PLSE 2015), School of Civil Engineering, The University of Queensland, Brisbane, QLD, Australia, 2015: pp. 1023–1030. https://doi.org/10.14264/uql.2016.403.

[113] J.-C. Mindeguia, S. Mohaine, L. Bisby, F. Robert, R. McNamee, A. Bartlett, Thermo-mechanical behaviour of cross-laminated timber slabs under standard and natural fires, Fire and Materials. 45 (2021) 866–884. https://doi.org/10.1002/fam.2938.

[114] E.L. Schaffer, Charring rate of selected timbers - transverse to grain, U.S. Department of Agriculture · Forest Service · Forest Products Laboratory, Madison, WI, 1967. https://apps.dtic.mil/sti/citations/AD0651143 (accessed July 10, 2023).

[115] D. Brandon, A. Just, D. Lange, M. Tiso, Parametric fire design – zero-strength-layers and charring rates, in: 2017. https://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-59254.

[116] S.A. Lineham, D. Thomson, A.I. Bartlett, L.A. Bisby, R.M. Hadden, Structural response of fire-exposed cross-laminated timber beams under sustained loads, Fire Safety Journal. 85 (2016) 23–34. https://doi.org/10.1016/j.firesaf.2016.08.002.

[117] J. Schmid, M. Klippel, A. Just, A. Frangi, M. Tiso, Simulation of the Fire Resistance of Cross-laminated Timber (CLT), Fire Technol. 54 (2018) 1113–1148. https://doi.org/10.1007/s10694-018-0728-9.

[118] F. Wiesner, L. Bisby, The structural capacity of laminated timber compression elements in fire: A meta-analysis, Fire Safety Journal. 107 (2019) 114–125. https://doi.org/10.1016/j.firesaf.2018.04.009.

[119] J. Schmid, M. Klippel, A. Just, A. Frangi, Review and analysis of fire resistance tests of timber members in bending, tension and compression with respect to the Reduced Cross-Section Method, Fire Safety Journal. 68 (2014) 81–99. https://doi.org/10.1016/j.firesaf.2014.05.006.

[120] F. Wiesner, F. Randmael, W. Wan, L. Bisby, R.M. Hadden, Structural response of cross-laminated timber compression elements exposed to fire, Fire Safety Journal. 91 (2017) 56–67. https://doi.org/10.1016/j.firesaf.2017.05.010.

[121] D. Lange, L. Boström, J. Schmid, J. Albrektsson, The Reduced Cross Section Method Applied to Glulam Timber Exposed to Non-standard Fire Curves, Fire Technol. 51 (2015) 1311–1340. https://doi.org/10.1007/s10694-015-0485-y.

[122] J. Schmid, A. Just, M. Klippel, M. Fragiacomo, The Reduced Cross-Section Method for Evaluation of the Fire Resistance of Timber Members: Discussion and Determination of the Zero-Strength Layer, Fire Technol. 51 (2015) 1285–1309. https://doi.org/10.1007/s10694-014-0421-6.

[123] J. Schmid, A. Menis, M. Fragiacomo, I. Clemente, G. Bochicchio, Behaviour of Loaded Cross-Laminated Timber Wall Elements in Fire Conditions, Fire Technol. 51 (2015) 1341–1370. https://doi.org/10.1007/s10694-015-0516-8.

[124] SPFiT v 2.0 (2019) User's manual, RISE, dated 2019-10-10, https://www.ri.se/en/what-we-do/expertises/fire-safety-timber-buildings, (n.d.).

[125] A.I. Bartlett, R. McNamee, F. Robert, L.A. Bisby, Comparative energy analysis from fire resistance tests on combustible versus non-combustible slabs, Fire and Materials. 44 (2020) 301–310. https://doi.org/10.1002/fam.2760.

[126] D. Lange, J. Sjöström, J. Schmid, D. Brandon, J. Hidalgo, A Comparison of the Conditions in a Fire Resistance Furnace When Testing Combustible and Non-combustible Construction, Fire Technol. 56 (2020) 1621–1654. https://doi.org/10.1007/s10694-020-00946-6.

[127] T. Gernay, J. Zehfuß, J.-M. Franssen, F. Robert, S. Brunkhorst, R. Felicetti, P. Bamonte, S. Mohaine, R. McNamee, Experimental Assessment of the Burnout Resistance of Timber and Concrete Columns, in: SiF 2022 – The 12th International Conference on Structures in FireThe Hong Kong Polytechnic University, 2022.

[128] T. Gernay, J.-M. Franssen, A performance indicator for structures under natural fire, Engineering Structures. 100 (2015) 94–103. https://doi.org/10.1016/j.engstruct.2015.06.005.

[129] T. Gernay, Fire resistance and burnout resistance of reinforced concrete columns, Fire Safety Journal. 104 (2019) 67–78. https://doi.org/10.1016/j.firesaf.2019.01.007.

[130] F. Robert, J.-M. Franssen, J. Zehfuß, S. Brunkhorst, P. Bamonte, S. Renard, R. McNamee, T. Gernay, Natural fire tests on GLT columns including the cooling down phase, in: World Conference on Timber Engineering (WCTE 2023), World Conference on Timber Engineering (WCTE 2023), Oslo, Norway, 2023: pp. 1848–1854. https://doi.org/10.52202/069179-0244.

[131] J.D. MacIntyre, A. Abu, P. Moss, D. Nilsson, C.A. Wade, A review of methods for determining structural fire severity—Part II: Analysis and review, (2021). https://doi.org/10.1002/fam.2961.

[132] B. Östman, D. Brandon, H. Frantzich, Fire safety engineering in timber buildings, Fire Safety Journal. 91 (2017) 11–20. https://doi.org/10.1016/j.firesaf.2017.05.002.

[133] A. Buchanan, B. Östman, A. Frangi, White paper on fire resistance of timber structures, National Institute of Standards and Technology, Gaithersburg, MD, 2014. https://doi.org/10.6028/NIST.GCR.15-985.

[134] J.D. MacIntyre, A. Abu, P. Moss, D. Nilsson, C.A. Wade, A review of methods for determining structural fire severity—Part I: A historical perspective, (2021). https://doi.org/10.1002/fam.2962.

[135] S.E. Magnusson, S. Thelandersson, Temperature - Time Curves of Complete Process of Fire Development, Lund Institute of Technology, 1970.

[136] G. Thomas, A. Buchanan, C. Fleischmann, Structural Fire Design: The Role Of Time Equivalence, Fire Saf. Sci. 5 (1997) 607–618. https://doi.org/10.3801/IAFSS.FSS.5-607.

[137] P.H. Thomas, Design guide: Structure fire safety CIB W14 Workshop report, Fire Safety Journal. 10 (1986) 77–137. https://doi.org/10.1016/0379-7112(86)90041-X.

[138] EN 1991-1-2 Eurocode 1: Actions on Structures: Part 1–2: General Actions - Actions on structures exposed to fire. European Standard. CEN European Committee for Standardization, Brussels., (n.d.).

[139] D. Brandon, Engineering methods for structural fire design of wood buildings: Structural integrity during a full natural fire, RISE Research Institutes of Sweden, 2018. urn:nbn:se:ri:diva-35109.

[140] D. Barber, R. Dixon, E. Rackauskaite, K. Looi, A method for determining time equivalence for compartments with exposed mass timber, using iterative parametric fire curves, in: Proceedings of the 11th International Conference on Structures in Fire (SiF2020), The University of Queensland, Online, 2020. https://doi.org/10.14264/f53607f.

[141] D. Barber, R. Crielaard, X. Li, Towards Fire Safe Design of Exposed Timber in Tall Timber Buildings, in: Proceedings of WCTE 2016 World Conference on Timber Engineering, 2016. https://research.thinkwood.com/en/permalink/catalogue1680.

[142] D. Brandon, J. Anderson, Wind effect on internal and external compartment fire exposure, RISE - Research Institutes of Sweden, 2018. https://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-36911.

[143] D. Brandon, A. Temple, J. Sjöström, Predictive method for fires in CLT and glulam structures – A priori modelling versus real scale compartment fire tests & an improved method, RISE Research Institutes of Sweden, 2021. https://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-58151.

[144] A. Mossberg, D. Brandon, A. Temple, R. McNamee, B. Gåfvels, Ramverk för hantering av brandbelastning vid projektering av trähus, SBUF ID: 14145. (2023).

[145] K.B. McGrattan, S. Hostikka, J.E. Floyd, R. McDermott, M. Vanella, E. Mueller, Fire dynamics simulator (version 6) - user’s guide, National Institute of Standards and Technology, Gaithersburg, MD, 2023. https://doi.org/10.6028/NIST.IR.6784.

[146] D. Barber, L. Sieverts, R. Dixon, J. Alston, A Methodology for Quantifying Fire Resistance of Exposed Structural Mass Timber Elements, in: A. Nadjai, F. Ali, J.-M. Franssen, O. Vassart (Eds.), Applications of Structural Fire Safety Engineering, Ulster University, Belfast, UK, 2018: p. 217.

[147] C. Wade, G. Baker, K. Frank, R. Harrison, M. Spearpoint, B-RISK 2016 user guide and technical manual, BRANZ. (2016).

[148] C. Wade, D. Hopkin, M. Spearpoint, C. Fleischmann, Calibration of a coupled post-flashover fire and pyrolysis model for determining char depth in mass timber enclosures, 2020. https://doi.org/10.14264/20b5cf6.

[149] J. Schmid, A. Frangi, Structural Timber In Compartment Fires – The Timber Charring and Heat Storage Model, Open Engineering. 11 (2021) 435–452. https://doi.org/10.1515/eng-2021-0043.

[150] D. Brandon, Practical method to determine the contribution of structural timber to the rate of heat release and fire temperature of post-flashover compartment fires, SP Technical Research Institute of Sweden, Borås, 2016. ISSN 0284-5172.

[151] D. Hopkin, S. Anastasov, D. Brandon, Reviewing the veracity of a zone-model-based-approach for the assessment of enclosures formed of exposed CLT, 2017. https://doi.org/10.1201/9781315107202-18.

[152] R. Pečenko, T. Hozjan, S. Huč, Modelling charring of timber exposed to natural fire, J Wood Sci. 69 (2023) 19. https://doi.org/10.1186/s10086-023-02091-4.

[153] R. Pečenko, T. Hozjan, A novel approach to determine charring of wood in natural fire implemented in a coupled heat-mass-pyrolysis model, Holzforschung. 75 (2021) 148–158. https://doi.org/10.1515/hf-2020-0081.

[154] AFAC, Fire Safety Principles for Massive Timber Building Systems, Australasian Fire and Emergency Service Authorities Council Limited, Melbourne, 2018.

[155] C. Hill, M. Kymäläinen, L. Rautkari, Review of the use of solid wood as an external cladding material in the built environment, J Mater Sci. 57 (2022) 9031–9076. https://doi.org/10.1007/s10853-022-07211-x.

[156] B. Östman, L.D. Tsantaridis, Durability of the reaction to fire performance of fire-retardant-treated wood products in exterior applications – a 10-year report, International Wood Products Journal. 8 (2017) 94–100. https://doi.org/10.1080/20426445.2017.1330229.

[157] C. Lin, O. Karlsson, O. Das, R.A. Mensah, G.I. Mantanis, D. Jones, O.N. Antzutkin, M. Försth, D. Sandberg, High Leach-Resistant Fire-Retardant Modified Pine Wood (*Pinus sylvestris L.*) by In Situ Phosphorylation and Carbamylation, ACS Omega. 8 (2023) 11381–11396. https://doi.org/10.1021/acsomega.3c00146.

[158] O.E. Özkan, A. Temiz, Ö. Tor, H. Vurdu, Effect of post-heat treatment on fire retardant treated wood properties, Holzforschung. 76 (2022) 645–657. https://doi.org/10.1515/hf-2021-0235.

[159] M.J. Spear, S.F. Curling, A. Dimitriou, G.A. Ormondroyd, Review of Functional Treatments for Modified Wood, Coatings. 11 (2021) 327. https://doi.org/10.3390/coatings11030327.

[160] M. Pauner, Tvivl om standard for brandimprægneret træ, (2021). https://brandogsikring.dk/nyhed/2021/undersoegelser-rejser-tvivl-om-standard-for-brandimpraegneret-trae/ (accessed August 10, 2023).

[161] L. Tsantaridis, P. Thureson, Is your old wood good enough?, (2023). https://www.ri.se/en/what-we-do/services/is-your-old-wood-good-enough (accessed November 14, 2023).

[162] A. Lucherini, Q.S. Razzaque, C. Maluk, Exploring the fire behaviour of thin intumescent coatings used on timber, Fire Safety Journal. 109 (2019) 102887. https://doi.org/10.1016/j.firesaf.2019.102887.

[163] L. Osborne, C. Dagenais, Fire-resistance test report of E1 stress grade cross-laminated timber assemblies, Service canadien des forêts., 2013. https://library.fpinnovations.ca/en/permalink/fpipub42918.

[164] A. Hartl, Q.S. Razzaque, A. Lucherini, C. Maluk, Comparative study on the fire behaviour of fire-rated gypsum plasterboards vs. thin intumescent coatings used in mass timber structures, in: The University of Queensland, 2020. https://doi.org/10.14264/4040b08.

[165] L. Johnson, D. Morrisset, A. Čolic, L. Bisby, Comparative performance of protective coatings for mass timber structures, in: World Conference on Timber Engineering (WCTE 2023), World Conference on Timber Engineering (WCTE 2023), Oslo, Norway, 2023: pp. 1788–1797. https://doi.org/10.52202/069179-0237.

[166] J. Anderson, L. Boström, R. Jansson Mcnamee, Fire Safety of Façades, 2017. https://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-33097.

[167] F. Nystedt, Verifying Fire Safety Design in Sprinklered Buildings, Lund University, Dept of Fire Safety Engineering and Systems Safety, 2011. https://portal.research.lu.se/en/publications/verifying-fire-safety-design-in-sprinklered-buildings.

[168] Y.J. Ko, N. Elsagan, Investigation of the performance of fire suppression systems in protection of mass timber residential buildings, Indoor and Built Environment. 32 (2023) 230–241. https://doi.org/10.1177/1420326X221138415.

[169] P. Kotsovinos, E.G. Christensen, J. Gale, H. Mitchell, R. Amin, F. Robert, M. Heidari, D. Barber, G. Rein, J. Schulz, The Effectiveness of a Water Mist System in an Open-plan Compartment with an Exposed Timber Ceiling: *CodeRed #03*, FPE Extra. (2022).

[170] J.L. Torero, Grenfell Tower; Phase 1 Report, TÆC, London, 2018.

[171] K. Frank, N. Gravestock, M. Spearpoint, C. Fleischmann, A review of sprinkler system effectiveness studies, Fire Sci Rev. 2 (2013) 6. https://doi.org/10.1186/2193-0414-2-6.

[172] F. Arnstein, A.K. Kumar, Reliability Data on Fire Sprinkler Systems: Collection, Analysis, Presentation, and Validation, CRC Press, Boca Raton, 2019. https://doi.org/10.1201/9780429287503.

[173] Y. Martin, M. Klippel, Fire safety of (timber) building during construction, COST Action FP1404, Zürich, Switzerland, 2018.

[174] Kartläggning av fel, brister och skador inom byggsektorn (Mapping faults, defects and damages in the construction sector), Boverket, 2018. ISBN 978-91-7563-612-2.

[175] D. Brandon, A. Just, B. Östman, Förslag för brandskydd i flervånings trähus, 2018. https://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-38515.

[176] Fire prevention on construction sites, CFPA-E No 21:2012 F, 2012.

[177] J. Smolka, K. Kempna, Guidance on Fire-fighting and Bio-Based Materials, COST FP 1404, Zürich, Switzerland, 2018.

[178] L. Vylund, K. Palmkvist, Taktik och metodik för släckning av höga trähus, RISE - Research Institutes of Sweden, Borås, Sweden, 2017. https://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-32907.

[179] B. Kukay, R.H. White, F. Woeste, Chapter 6: Fire damage of wood structures, in: In: Inspection, Testing and Monitoring of Buildings and Bridges. National Council of Structural Engineers Association. Chapter 6. ISBN: 978-1-60983-198-1, 2012: pp. 73–83.

[180] R.J. Ross, B.K. Brashaw, X. Wang, R.H. White, R.F. Pellerin, Post-fire assessment of structural wood members, in: Wood and Timber Condition Assessment Manual. Madison, WI : Forest Products Society, 2005: pp. 29–46.

[181] R. McLain, Repair of Fire-Damaged Mass Timber - A summary of assessment considerations and repair methods for post-fire conditions, WoodWorks – Wood Products Council, 2023.

[182] D. Brandon, F.V. Plathner, E. Mikkola, SAFITS - Statistical Analysis of Fires in Timber Structures, 2021. ISBN:978-91-89385-87-0.

Support organisations

This project was funded 2023 by the organizations below

Akademiska hus • Bengt Dahlgren Brand & Risk • Brand och Bygg Sverige AB
Brandkåren Attunda • Brandskyddsföreningen • Brandskyddsföreningen Gävleborg
Brandskyddsföreningen Skaraborg • Brandskyddsföreningen Södermanland
Brandskyddsföreningen Värmland • Brandskyddsföreningen Väst
Brandskyddsföreningen Västernorrland • Brandskyddslaget • Brandutredarna
Dina Gruppen • Eld & Vatten • Folksam • Försäkrings AB Göta Lejon • GellCon
Höglandets räddningstjänstförbund • If Försäkring • Kristianstads Räddningstjänst
Kommunassurans Syd Försäkrings AB • Kyrkans Försäkring • Lantmännen
MSB, myndigheten för samhällsskydd och beredskap • NBSG, Nationella Brandsäker-hetsgruppen • Nerikes Brandkår • Q-Fog i Nora AB • Region Stockholm, Trafikförvalningen
RISE, Research Instiutes of Sweden Riksantikvarieämbetet • Räddningstjänsten Boden
Räddningstjänsten Karlstadsregionen • Räddningstjänsten Kalix • Räddningstjänsten Luleå
Räddningstjänsten Storgöteborg • Räddningstjänsten Syd • Räddningstjänsten Östra Götaland Räddningstjänsten Mitt Bohuslän • Skinnskattebergs Räddningstjänst Statens fastighetsverk • Stockholms Stads Brandförsäkringskontor • Storstockholms Brandförsvar
Södertörns brandförsvarsförbund • Södra Älvsborgs Räddningstjänstförbund

The Swedish Fire Research Foundation - enables development of fire safety knowledge by research and other activities, and the spread of this knowledge to make a difference in our society.

This is possible trough raising money from all kinds of organisations with fire safety on their agenda as well as for altruistic reasons. The broad support from our society together with prosperous networks are key factors for our success.

Our mission is "A fire safe society built on knowledge"

Brandforsk
info@brandforsk.se, www.brandforsk.se

Project team

RED
FIRE ENGINEERS

Financed by Brandforsk
Brandforsk's activities are made possible by support from various organizations in the community. Read more about our support organisations at www.brandforsk.se