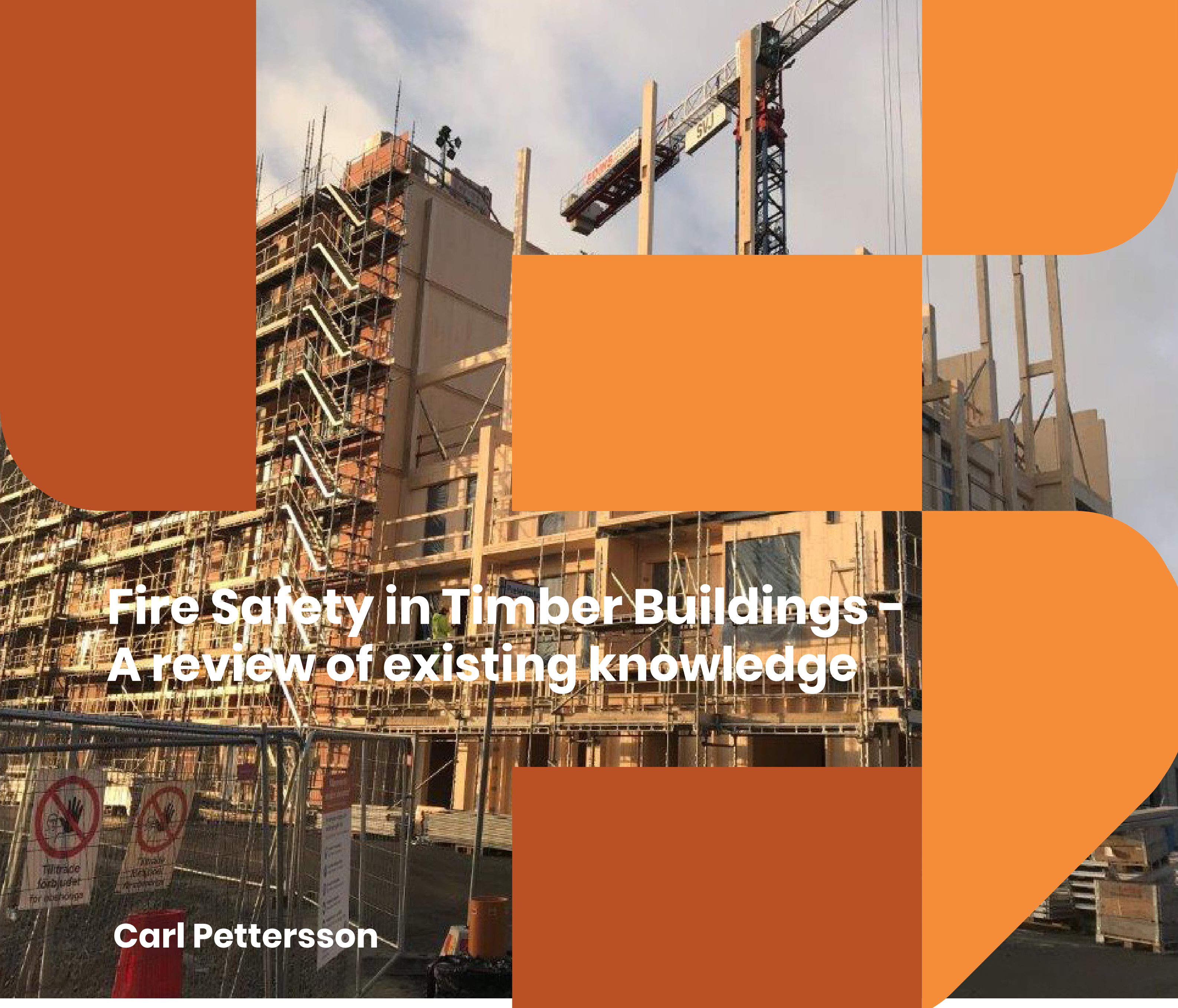

Fire Safety in Timber Buildings - A review of existing knowledge

Carl Pettersson

Brandforsk 2020:10

Frontpage.
Photo 1, Martin Sparre
Foto 2, Toby Wong (Unplash)

Foreword

The grey zone between common knowledge and the yet unknown is often characterised by opinions and little read scientific reports. 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 to 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 2020

Preface

This report is written by Carl Pettersson fire safety engineer at Brandforsk, the Swedish Fire Research Foundation. This work has been done with the financial support of Brandforsk's yearly funding for 2019 and 2020, and we are grateful to all the supporting organisations. A list of all the supporting organisations can be found on the back page of the report. This work has been done with the support of Birgit Östman, Mattias Delin, Robert Jönsson and Thomas Järphag. The work has also benefitted from scientific input from Alar Just, Amanda Kimball, Daniel Brandon, Luke Bisby and Robert McNamee and practical input from Martin Sparre.

A history of report updates is summarised below:

Version	Published date:	By:	Comments:
1	2020-11-23	Carl Pettersson	
2	2020-12-10	Carl Pettersson	Minor updates and corrections to references

Introduction to the report

This report focuses on fire safety in timber buildings where the main structure of the building uses timber based products. This can either be light-timber frame construction, premanufactured volume elements or mass timber construction using engineered timber products such as glued laminated timber (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 buildings constructed with timber, 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 for a particular building.

This report is based on a literature survey gathering knowledge across a range of different topics that relate to fire safety in timber buildings. The knowledge compiled has been divided into five different categories (chapters 3-7): *building codes and standards*, *fire dynamics*, *structural fire design*, *fire safety design* and *timber building construction*. Available research results found in the literature study from different parts of the world have been studied and summarised in this report with references to further reading.

Technical details related to fire safety in timber buildings are presented in sub-chapters “sections” (4.1, 4.2 etc.) under the main category chapters of this report and appear in alphabetical order. The sections present information about the technical topic and how it is important to the fire safety of a building. Relevant literature that contains further information about the topic is captured in tables at the end of each section. Cross-references to different sections are made where relevant, but each section can be read as a standalone technical topic. This provides the reader with easy access to detailed information about a technical topic and the possibility of gaining a holistic understanding of how these affect fire safety in timber buildings.

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

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

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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 in buildings that are constructed using it. 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 were 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 about these challenges so that they can easier be addressed. It is important to acknowledge that the purpose is to promote safe timber buildings that will be sustainable in relation to fire safety.

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 (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 three 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 gluelam 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. The Fire Protection Research Foundation (FPRF) in the US has completed two literature reviews as part of the "*Fire Safety Challenges of Tall Timber Buildings – Phase 1* [1] and *Phase 2: Task 1*" [2]. These reports give the reader a comprehensive understanding of fire safety aspects for timber buildings but with the limitation of focusing on the construction and research of CLT compartments only. Additional literature reviews of fire safety in timber buildings available. See [3] and [4].

During a period of rapid development and the emergence of new construction technology, 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 gathers facts and has the aim of reducing any confusion as well as helping the reader to get a clearer view of what knowledge has been validated and what the potential limitations might be. 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, fire fighters or property in the event of a fire in a building.

1.2 Goal

The goal of this report is to present the available knowledge in fire safety in timber buildings to support its implementation and assist the development of further knowledge. The focus is on large and tall timber buildings where engineered timber products are being utilised. However, the key fire safety aspects presented are applicable for all types of timber buildings and should be considered in relation to the specific fire safety design goal for a particular building.

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 for developers of new solutions fire safety in 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 reader will find several topics that have been considered important, an introduction to them and why they are of importance, together with a list of references and suggested literature as a guide to the reader to further relevant information. 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 survey has been undertaken of relevant literature presented at technical conferences, in technical papers and from scientific research. References to relevant literature are included in order to provide further information for the reader.

Input from researchers has allowed information to be included in the report regarding current or proposed research projects.

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 well aware of clearly defined design goals, as well as understanding the limitation 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.

Examples of risks in timber buildings that are to be considered as part of structural modelling are presented in [5] and reproduced here:

- Expected temperatures in fully developed fires
- Charring rate as a function of fire exposure
- Temperature and moisture dependent thermal and mechanical properties of heated timber
- Self-extinguishment properties of charred timber and 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
- Fire performance of connections between structural timber elements

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 these hazards might not be limiting for a particular design:

1. Fuel load provided by timber construction
    a. Reliability and redundancy from encapsulation or partial encapsulation with a protective covering
    b. Fire growth speed
    c. Duration of potential fire scenarios
2. Duration of the fire i.e. self-extinguishment and burnout of the fire
    a. Char layer fall-off
    b. Glue-line integrity maintained
    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. Safety for the fire service
   a. Resilience of safety measures specific for the fire service as well as the greater context of the buildings fire safety

Relevant literature

The following tables present references and additional literature with more details about fire safety strategy.

Table 1 Reference list

[5] Östman B., Brandon D., Frantzich H. (2017) *Fire safety engineering in timber buildings*. In: Fire Safety Journal 91 2017, pp. 11–20. issn: 0379-7112. doi: 10.1016/j.firesaf.2017.05.002. url: http ://www. sciencedirect .com/science/article/pii/S0379711217302977.

Table 2 Additional literature list

- Andersson B., Broberg L. Hultquist J., Evers B., Eriksson Lantz C., Nystedt F. (2018) *Tillämpningsstöd vid brandteknisk dimensionering av höga Br0-byggnader med förnyelsebara material (trä).* SBUF ID – 13371 (In Swedish).
- Frantzich H. (2018) *Brandskyddsvärdering av flerbostadshus BSV-FB Utveckling av metod för säkerhetsindex.* Rapport 3216. ISSN: 1402-3504. Sweden: Brandteknik, Lunds Tekniska Högskola, Lunds Universitet, 2018. Brandforsk report 2018:2:5 (In Swedish)
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3. Building codes and standards

3.1 Introduction

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 to find available information on how to design for fire safety in timber buildings.

The regulatory building codes adopted around the world (IBC[1], NCC[2], Approved Document B[3], BBR[4], etc.) all use prescriptive rules 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 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 rules. 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.

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.

3.2 History of research and regulation for timber buildings

A timeline of some important technological advances and the introduction of regulations that address fire safety in timber buildings are presented in Figure 2 below. As can be seen, much of the research and new standardised approaches to fire safety in timber buildings have been presented in the last ten years.

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[1] *International Building Code* (IBC) 2018, International Code Council (ICC) 2018. (USA)

[2] *National Construction Codes* (NCC) 2019, Volume One, Building Code of Australia (BCA). (AUS)

[3] *Approved Document B* (fire safety) Volume 2: Buildings other than dwellings, 2019 edition. (UK)

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

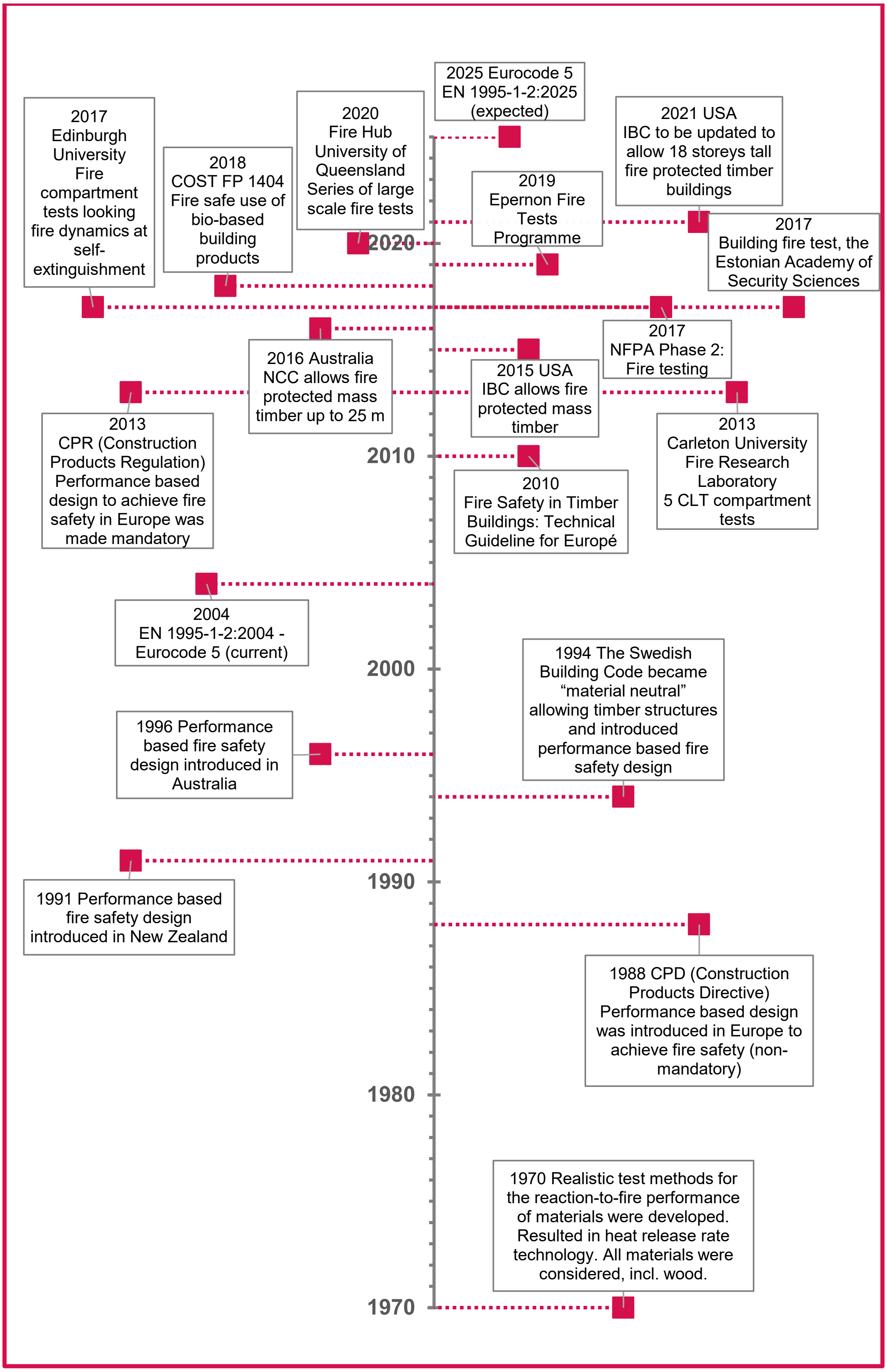

Figure 2: Timeline of some important technological advances and the introduction of regulations

3.3 The standardisation process in Europe

Construction Products Regulation (CPR)

The Construction Products Regulation (CPR) was adopted in 2011 and applied in full since July 2013, superseding the previous Construction Products Directive (CPD). It presents harmonised rules to be achieved for the marketing of construction products in the EU [6].

The CPR presents five requirements on fire safety on how the structure must be designed and built such that, in the event of fire [7]:

1. Load-bearing capacity can be assumed to be maintained for a specific period of time.
2. The generation and spread of fire and smoke are limited.
3. The spread of fire to neighbouring structures is limited.
4. Occupants can leave the building or be rescued by other means.
5. The safety of rescue teams is taken into considerations.

The CPR does not set any product requirements that construction products need to meet. Instead, it sets harmonised rules on how to express their performance in relation to their essential characteristics [6]. It ensures that reliable information is available to professionals, public authorities and consumers, so they can compare the performance of products from different manufacturers in different countries.

CEN harmonised standards

The European standardisation body, CEN, publishes the harmonised standards (hEN) and is the normal route for compliance of most products [7]. A product that is part of a harmonised standard will achieve compliance with building codes that are applicable in Europe.

Technical assessment documents

As new products and building techniques are innovated and introduced to the construction industry, there will naturally be a time before they can be approved and incorporated into harmonised standard or national requirements. In Europe, there is a pathway for products and systems to be compliant for building applications through a European Technical Assessment (ETA). This assessment will function as a temporary standard that can be referenced as support for a product. Similar certification systems are also available in Australia and New Zealand through a "certificate of conformity".

The ETAs are issued individually for a manufacturer's product under the rules laid out in a European Assessment Document (EAD). An ETA can be issued by national member bodies of the European Organisation for Technical Assessment (EOTA)[5].

The ETA is a technical assessment of a product's suitability for its intended end use [7]. It is to be noted that the ETA certification system does not require any specific technical competence as part of the approval process. As an ETA allows a product to gain compliance with national building code regulations in Europe without a harmonised standard (hEN), but with a risk of not being assessed appropriately for the intended use.

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[5] http ://www.eota.eu

There are many examples of when manufactures have misused these certifications (ETA and certificate of conformity etc.) which do not require a technical review for approval. One example is approvals for combustible façade systems that have been installed in tall buildings all over Australia and New Zealand. At the time of construction, these certificates of conformity demonstrated compliance with the applicable building codes, but without the appropriate technical support that the product was suitable for installation on the façade of tall buildings. All of these certificates have later been revoked. Subsequently making newly constructed buildings in these countries non-compliant with the fire safety performance requirements prescribed in the building regulations and consequently remediation work forced on the owner(s) of the building.

In relation to timber materials, there has been an increase in new types of building products available to the market that has not yet gone through appropriate technical review and agreement to be approved in harmonised standards. Typically, laminated products such as CLT are not yet part of a harmonised standard and their properties may vary depending on how each manufacturer produces these products. In some of the ETAs currently available, the properties specified are often based on small scale ad-hoc fire tests with extrapolated values for longer exposures than tested. If such ETAs are being used to determine charring rates for the structural design it may lead to significant underestimated structural performance [8]. From the work presented in [8], it was shown that some ETAs do have a significant limitation in their applicability and can even be considered flawed. The work further points out that, in general, it can be said that just one fire test is not sufficient to define a charring rate of a CLT product. Another type of product that has been found to use ETA assessments for the application in timber construction is different fire-retardant treatments, applied internally and externally, on timber to reduce its reaction to fire. See Section 5.1 for more information about charring rates, section 5.1 for more information about fire separating methods, section 5.3 for more information about load-bearing capacity methods and section 6.2 for fire-retardant and coating treatments.

3.4 “BBR” the Swedish Building Code

The current building code applicable for buildings in Sweden is “Boverkets ByggRegler” (BBR), the EKS and PBL.

Historically, it has not been allowed to construct buildings with a combustible structure of more than two storeys above the ground in Sweden. This can be read in previous building codes (BABS, SBN, NR) prior to 1994 when the first edition of the BBR was introduced. The previous requirement of non-combustible fire rated construction A 30, A 60, A 90 applied to buildings above two-storeys and fire rated construction using combustible materials i.e. B 30, B 60, B 90, where allowed in buildings with two-storeys or less. One exception to this was floor slabs being constructed out of timber that were allowed in buildings with a maximum of four storeys. However, if the timber floor slab or other structures were not part of the load-bearing structure, there would be no height restrictions to the building.

As the first version of the current building code adopted in Sweden was introduced in 1994, prescriptive requirements in the building code were made material neutral. The requirement for fire rated construction did no longer distinguish between combustible (B 30, B 60, B 90 etc.) and non-combustible classification (A 30, A 60, A 90 etc.). The new fire rated construction class (EI 30, EI 60, EI 90 etc.) was introduced and previous limitations to building height for timber construction were subsequently removed. Due to this, there are no limitations in the current building code for constructing the building with a combustible structure. The consequent analysis that was made as a background to the proposed changes in 1994 does not contain reasoning of why this change was considered appropriate in relation to fire safety challenges with combustible building materials. This makes it difficult to get support to specifically address fire safety risks associated with combustible materials in Sweden.

Sweden is now (2020) investigating new ways to change the regulatory framework for the construction of buildings. In relation to changes in the fire safety regulations, fire safety in timber buildings is one topic that has been identified as needing review. However, what this might result in is too early to know.

Relevant literature

The following tables present references and additional literature with more details about building codes and standards.

Table 3 Reference list

[6] Commission Staff Working Document SWD (2019) *1770 - Evaluation of Regulation (EU) No 305/2011 laying down harmonised conditions for the marketing of construction products and repealing.* Council Directive 89/106/EEC - Document date: 24/10/2019 - Created by GROW.DDG1.C.4

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Table 4 Additional literature list

- Andersson B., Broberg L., Hultquist J., Evers B., Eriksson Lantz C., Nystedt F. (2018) *Tillämpningsstöd vid brandteknisk dimensionering av höga Br0-byggnader med förnyelsebara material (trä)*. SBUF ID – 13371 (In Swedish)

4. Fire dynamics

4.1 Burning behaviour of timber

Timber is combustible, meaning that it will ignite and burn when exposed to a significant amount of heat. Timber has been described as undergoing three different stages of pyrolysis [9], [10]:

- Dehydration and very slow pyrolysis below 200 °C,
- The onset of pyrolysis up to 300 °C and
- Rapid pyrolysis above 300 °C.

The burning behaviour of timber is a very complex phenomenon. However, the processes behind pyrolysis, ignition, combustion, and extinction are generally well understood. This is described in detail in [9], which concludes that 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 [9] to be:

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

Timber has relatively low thermal conductivity and relatively high specific heat capacity [9]. This means that the material is thermally "thick" and has good insulating properties against heat transfer.

There is also reasonable agreement across the literature 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 °C and for spontaneous ignition 600 °C. Both temperatures are determined in the conditions of radiant heating [9].

A European classification system EN 13501-1 for the reaction to fire properties of building construction products was introduced by a European Commission decision in 2000. It is often called the Euroclass system and consists of two sub-systems, one for construction products excluding floorings, i.e. mainly wall and ceiling surface linings, and another similar system for floorings. The European classification system for reaction to fire performance is based on a set of EN standards for different test methods. Three test methods are used in EN 13501-1 for determining the classes of combustible building products. Both sub-systems have classes A to F of which classes A1 and A2 are non-combustible products. This European system has replaced the earlier national classification systems, which have formed obstacles to trade, and is mandatory to use in all member states [7].

Additional considerations to burning behaviour of timber

Structural timber elements such as columns, beams, walls and floors contribute with fuel to fire if they are exposed to high heat flux or high temperatures. See section 4.4 for more information about the energy contribution of timber.

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. Following prescriptive building codes, the fire growth behaviour is normally implicitly applied with a fuel load relating to the use and potential storage of fuel loads in a space. Typically, it does not account for the burning behaviour of combustible structures to impact the design parameters. Given that there are differences between building designs, there is a risk of extrapolating codes and standards outside their range of applicability [11].

Relevant literature

The following tables present references and additional literature with more details about the burning behaviour of timber products.

Table 5 Reference list

[7] Östman B., et al. (2010) *Fire safety in timber buildings - Technical guideline for Europe*. SP Technical Research Institute of Sweden. SP Report 2010:19. ISBN 978-91-86319-60-1

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

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4.2 Burnout

The definition of burnout in a fire compartment can be considered to be when all fuel inside the compartment has been consumed in a fire. It can also specifically relate to the burnout of all movable fuel loads in a compartment i.e. furniture, installations etc. that are not part of the building construction. Burnout should not be confused with the capacity to self-extinguish which may occur for other reasons than a lack of fuel to the fire. Read more about self-extinguishment in section 4.8.

Historically, burnout first becomes 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 [12], [13], [14], [15]. 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 proved successful for non-combustible construction such as fire protected steel and concrete. The burnout includes all phases of a fire scenario from the ignition to a fully developed fire and includes the decay phase (post-fire). See section 5.5 for more information about post-fire behaviour. In relation to timber buildings, the achievement of burnout is less certain, the residual fuel presented by the structural timber elements may never stop burning [16]. Even if burnout of all available fuel is not reached, the fire may still self-extinguish due to the energy feedback from a fire not being sufficient to maintain the burning. Read more about self-extinguishment in section 4.8.

Additional considerations to burnout in timber buildings

If a tall building fails to withstand a complete burnout, there is a risk that the structure of the building will eventually fail and cause a structural collapse. Traditional fire calculation models and fire resistance testing assuming temperatures representing fully developed fires, do not consider the additional fuel contributed by the timber structure [10], [17].

In recent years, significant effort has been put into determining if burnout can be achieved in a timber fire compartment. The following three design objectives are presented in [18] which will make burnout in a timber building possible:

1. Protected surfaces around the timber that remain for the entire fire duration, or at least until the fire temperatures are low enough to avoid ignition of suddenly exposed surfaces.

2. Cold timber surfaces are not suddenly exposed to the fire i.e. no delamination of charring layer during the fire.
3. The combustion of the burning timber is not sufficient to maintain the fully developed stage of the fire and the structural capacity remains sufficient for the entire duration of the fire.

The traditional fire safety strategies for building design tend to rely on a fire starting in one place only so that it is contained within the compartment of fire origin and will burnout. If the fire spreads (see section 4.5 for more information about fire spread) to other compartments, or there are multiple fires in a building, the fire safety strategy of the building can fail if sufficiently redundant measures are not in place to deal with this scenario. If the fire safety strategy does not consider the impacts of using combustible structural elements allowing the fire to spread and not burnout, there is a potential that the building will collapse.

Relevant literature

The following tables present references and additional literature with more details about burnout.

Table 7 Reference list

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4.3 Delamination or protection fall-off

Delamination can relate to several different behaviours. In this section, it relates to the stochastic phenomena of delamination of timber lamellas but also the fall-off of protective encapsulation around the timber. The common effect of delamination in the event of a fire is the introduction of more fuel to the fire, as the protective char layer or the protective encapsulation falls off.

Char fall-off

In relation to laminated timber products, delamination may relate to glue line failure, debonding or char fall-off. In many different large scale fire experiments it has been found that the event of delamination of CLT timber lamellas is very hard to predict [19], [20].

Char fall-off is mainly a consequence experienced for larger timber element products such as CLT but can also occur with other laminated timber products. Notwithstanding the above, glulam and other laminated timber products, which consist of smaller parts of timber laminated together with the timber grains in the same direction, have been found in large scale fire tests summarised in [10] to perform in a similar way to solid timber when exposed to fire.

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 [20], [21]). 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 [10]. In the experiments as part of the "*Fire Safety Challenges of Tall Timber Buildings – Phase 2 Task 4*" [20] critical temperatures for the 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 delamination occurs is also dependent on the duration of the heating process [20]. 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 a number of different adhesive products used for laminated timber products, the most commonly used are polyurethane (PUR) based. There are also phenol resorcinol formaldehyde (PRF), emulsion polymer isocyanate (EPI) and melamine urea-formaldehyde (MUF) based adhesives [20]. According to [20], the MUF adhesive has proven to perform better in higher temperatures but the performance varies between different products formulated from the same components. The laminating process of the timber product, such as mechanical or vacuum compression, can also influence the performance of the adhesive in higher temperatures.

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 [22]. 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*" [23] 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*" [24]. Given the scale of the compartment fire test required under this current standard, the testing regime is expensive and only two different adhesives applied in three different CLT products are currently known to have been tested and to have passed this test.

Outside of the USA and Canada, there are 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 75 °C in Australia and New Zealand, 90 °C in Europe and 107 °C in Japan [8]. Subsequently, all CLT (with exception of the ANSI/APA PRG 320 approved CLT products) can be expected to delaminate if exposed to a fully developed real fire scenario where the temperature in the glue line is increased to its critical value.

The delamination of laminated timber products is not only affected by the characteristic of the adhesive but the layup of the laminated product as a system. A thicker outer timber layer in the CLT has been found to perform better against fire induced delamination [25].

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 large scale compartment test presented in [24], 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 was *"second generation CLT panel"* with an adhesive that maintained the glue-line integrity sufficiently to prevent glue line failure induced delamination in the test. It was found that no delamination of the CLT elements occurred, but 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. 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 lead to a secondary flashover (see section 4.7 for more information about secondary flashover) in the compartment with the loss of protective covering as result. The fire test had to be manually extinguished.

Eurocode 5 [26] presents a method to calculate the reduced cross-section of a timber structure when exposed to the standard temperature curve, taking protective layers into account.

The consequence of protection layer fall-off will be similar to the glue line failure and char layer fall-off, as timber surfaces will be exposed to the fire, usually at a later stage of the fire. This increases the charring rate [25], prevents self-extinguishment (see section 4.8 for more information about self-extinguishment) 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 6.1.

Additional considerations to delamination or protection fall-off

The energy contribution from timber in a fire is substantial. See section 4.4 for more information about the energy contribution. In the event of delamination, new fuel will be introduced to the fire. This process has the potential to stop or continue until there is no more timber to burn. Delamination of timber layers or protective layers has the potential to cause secondary flashover scenarios or continuous fully developed fires with the potential of great consequences for a building, such as the potential of leading to a complete collapse.

In large scale compartment fire experiments, glue line failure has been witnessed during a fully developed compartment fire but also during the decay phase of fires [19], [23]. If the fire reaches the decay phase, at which point delamination is experienced, the newly introduced fuel has the potential of increasing the heat release rate and creating a secondary flashover scenario. See section 4.7 for more information about secondary flashover. 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 [23]. From fire testing, it has been found that ceilings are more prone to delamination, which also relates to delamination of protective encapsulation.

Relevant literature

The following tables present references and additional literature with more details about delamination.

Table 9 Reference list

[8] Klippel M., Just A., (2018) *Guidance on Fire design of CLT including best practise*. COST FP 1404 Fire Safe Use of Bio-Based Building Products. N223-07.

[10] Wade C.A. (2019) *A theoretical model of fully developed fire in mass timber enclosures*. Doctor of Philosophy Thesis. Department of Civil and Natural Resources Engineering University of Canterbury Christchurch, New Zealand. 2019

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

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Relevant research currently in progress

Research is currently being undertaken to develop more affordable testing regimes to assess glue integrity failure induced delamination. A new research project with a focus on the European market called "FIRENTIMBER" with tests done in early 2020. In this project, test specimens will be glued with eleven different adhesive products using timber with similar and known properties. Tests will be performed under a cone heater, in models, in full scale furnaces and chambers with elevated temperatures.

There is also a collaborating project to develop a standard fire testing methodology and a classification method of the glue line integrity of CLT and comparable engineered mass timber materials. The project is called GLIF (Glue Line Integrity in Fire) and the goal is to find an affordable testing method to quantify the performance of different adhesives in relation to heat-induced laminated fall-off.

4.4 Energy contribution from a timber structure

The heat of combustion for timber is in the order of 17.5 MJ/kg ± 2.5 MJ/kg [9] making it a good energy source. When solid timber burns a layer of char is created and there is strong agreement that temperatures around 300 °C represent the onset of rapid pyrolysis and char formation [9]. 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 [9]. Cracks will also allow pyrolizate of the timber 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 [27]. It is important to acknowledge that the amount of energy that can be released from a combustible material depends on how complete and effective the combustion in the fire is. If the fire is extinguished in the early stages of a fire before the fire grows and involves the fuel provided by the timber structure, either by an automatic sprinkler system or manual fire fighting intervening, the consequences of fuel contribution from the timber will be reduced.

In compartment fires, experiments with exposed CLT walls and ceilings have been carried out by [13]. In the tests where the compartments did not self-extinguish the CLT contributed significantly with fuel to the fire with a fuel load of up to 412 MJ/m^2, an increase of approximately 400 % from the moveable fire load. In the experiment were 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 [13]. From the "*Fire Safety Challenges of Tall Timber Buildings – Phase 2: Task 3*" [23] 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) [23]. The effective fuel load contribution from the timber was found to be at least double that of the moveable fuel load.

Additional considerations to the energy contribution of timber

The fuel load provided from structural timber has the potential to:

- Never stop burning, leading to failure in fire separations or structural collapse.
- Substantial flame spread outside of the compartment as the excess energy is combusted outside of the compartment when mixed with oxygen [28].

The consequences of a fire will increase if more timber is exposed or can become exposed during a fire. This is something that must be considered in the fire safety strategy. In the Epernon Fire test series in France, standard furnace tests of concrete walls and CLT walls were compared [29]. The article concludes that a fire safety design with structural timber must account for and quantify the increased fuel load contribution, as well as the in-depth temperatures that impact the structural strength of the timber.

Relevant literature

The following table presents references with more details about the energy contribution from a timber structure.

Table 11 Reference list

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Relevant research currently in progress

The "*Epernon Fire Tests Programme*" is seeking to understand the links between normative fire resistance ratings and real fire performance in buildings. The project has several objectives, such as quantification of the energy participation of combustible materials in standard furnace tests, the influence of combustible surfaces and ventilation factors on the dynamics of compartment fires (including external flaming), and the thermomechanical behaviour of structures under standard and natural fires.

The test programme was completed in 2019 and includes three standard fire resistance tests and six natural fire experiments. As all conclusions from the testing will be published 2020 this is still considered current research in progress. The outcomes of the project expect to shed light on several issues which should be considered when assessing a building using a fire safety engineering approach to provide an adequate level of safety.

More information and updates regarding future publications of the work are available at *http://www.epernon-fire-tests.eu/*

4.5 Fire engineering models in timber compartments

There are several different fire engineering models available to predict fire conditions in compartments using timber construction and their impact on the timber structure. Information about available models is presented in this section.

SP-TimFire was created in 2016 by Daniel Brandon and is a one-zone model used to predict temperatures and heat release rates of fires in compartments with exposed timber [30]. 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 delamination of CLT and its influence on the heat release and the fire temperature in a compartment. Comparisons with three existing test results were used to evaluate the model. In order to account for 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 is found to be more staggered. If the model can be updated to account for delamination occurring over a time period instead of delamination occurring simultaneously, more accurate but less conservative values can be expected [30].

A one-zone model has been developed in 2017 [31]. The material properties are based on Eurocode 5 [26]. The rate of charring is assumed to be constant irrespective of surface orientation or location, but with variation in the char layer conductivity depending upon heating rate. The zone model simply 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, i.e. as is the case for most exposed CLT structures. This introduces an immediate source of error at the outset of the analysis [31]. 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 delamination, improved thermo-mechanical material properties and inclusion of radiation between exposed walls [31].

Using the pyrolysis functionality within the computational fluid dynamics program Fire Dynamics Simulator (FDS)[6], [32] presented a model to determine the response of a mass timber structure in 2018. The method was validated using the results from five full-scale compartment fire tests with exposed CLT. However, the FDS model was not able to account for inconsistent pyrolysis or delamination. The computational time to undertake pyrolysis modelling was found to be extensive and the simulation run times may be considered too long to be used as a viable design tool.

By using the two-zone fire model B-RISK[7], [10] presented two timber pyrolysis submodels in 2019 (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

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[6] Fire Dynamic Simulator, developed and maintained by the Building and Fire Research Laboratory (BFRL) at National Institute for Standards and Technology (NIST), Gaithersburg.

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allows fire dynamics in small mass timber enclosures to be predicted. The kinetic submodel is capable of taking 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 limitations that come with the models are well described in [10] and further development is proposed.

Applicability of fire engineering models in timber compartments

All the fire models that have been reviewed have different limitations and all are based on enclosure fire behaviours and generic material properties. The user is required to understand and take these limitations into account in order to gain results from the models that can be applied for design. As pointed out in [10] fire models of this type are likely to be more useful for forensic applications rather than for fire safety design because the exact nature and arrangement inside an enclosed compartment are usually not known at the design stage of buildings.

It is particularly difficult to account for the delamination of CLT layers accurately and the models are only developed for small compartments, less than 100 m^2, with validation to full-scale tests that are much smaller. The kinetic submodel presented in [10] used in the two-zone program B-RISK, is found to be the more accurate model and has the most validation to full-scale fire tests. The reviewed models have all presented suggestions to be further developed.

Relevant literature

The following table presents references with more details about fire engineering models in timber compartments.

Table 12 Reference list

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4.6 Fire spread

The combustible nature of timber construction allows for different scenarios where fire spread between fire compartments and different floors can occur. In the report [33] presented in 2018, several consequences of fire spread in timber construction have been identified and are to be limited as part of the fire safety strategy. These are presented below:

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).

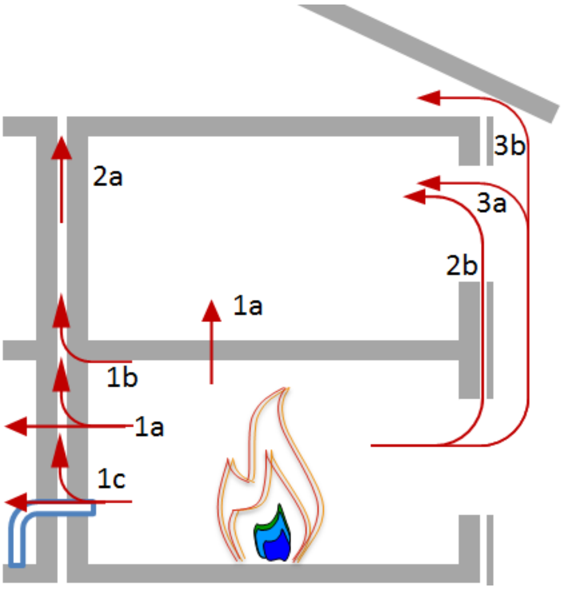

Figure 3: Potential paths of fire and smoke spread out of the compartment considered for the building design [33].

As can be seen in Figure 3 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 3 are presented below in more detail, following the same numbering.

1. Limitation of fire spread directly from compartment to compartment

The fire spread internally in a building can occur through inappropriate penetrations, connections and joints with other materials. It can create weak spots and allow for fire spread. Fire resistance tests are generally performed on a perfectly flat ceiling or wall assembly without penetrations, damages, connections etc. In practice, many of these assemblies have full or partial penetrations, for example, electrical switches, lamps, wires, water pipes and ventilation shafts [33].

Joints or gaps can be expected to be more frequent in construction where prefabricated plane elements (typically CLT construction) are being installed. Corner connections to other building parts or joints around service installations and penetrations have the potential of creating weak spots that allow for fire spread in a fully developed fire [34]. Creeping and movement of timber elements in a building will over time have the potential to increase the extent of gaps and joints.

Fabrication inaccuracy or construction tolerances between CLT elements can create gaps that allow hot gases and smoke to pass through during overpressure conditions under fire exposure and reduce the fire separating performance of the entire structure [35].

CLT floor panels are commonly connected to the shear walls below using long self-tapping screws and connections between CLT floor panels typically use spline joints [22]. The spline joints are prone to moisture damage but also have lower performance when exposed to fire, hence, the detailing of spline joint connection requires proper field installation. Inadequate field installation may result in potential gaps at the butt joints between the splines (or splines not being installed at all). The potential gaps between butt joints could be minimised if tongue-and-groove or scarf joints are used between splines [22]. CLT panel-to-panel joints must be sealed, a fire-resistant sealant can prevent smoke leakage [22]. However, it is not clear if these sealants can maintain the performance of the fire separation for long periods of time when exposed to real fire conditions. The performance of timber connections which become exposed to a real fire is not easy to quantify due to the influence of numerous parameters, such as fastener type, the geometry of the connection, different failure modes, as well as differences in the thermal conductivity properties of steel, timber, and char layer components [22]. In this context, butt-connections should be avoided. To improve the separating performance and smoke tightness, the use of elastic joint sealants on both sides of timber elements or the implementation of a flexible mineral wool stripe is recommended in [34].

CLT elements or other mass timber elements can effectively be connected to any other building material, such as light timber frame, steel or concrete [22]. However, the connections between these different types of building materials and structural elements must be carefully considered as the connection introduces a potential risk of failure, in relation to expected theoretical fire resistance, and even more so the performance when exposed to real fire scenarios.

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 of allowing smoke spread, flaming fire spread or smouldering fire spread.

Non-combustible materials that are soft and compressible, such as low density insulation material, are suitable for cavities. In [33] 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 is recommended. Not only the density is a characteristic that guarantees the performance when exposed to a fire, the quality of the product, the thickness and how it is installed are important factors to consider. Note that 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 of causing small air channels that allow hot air to flow into the cavity and they may melt and form droplets [33].

It has been suggested that timber can be used as a fire stop in cavities [33], provided that the minimum height of a fire stop is calculated using a one-dimensional charring rate in accordance with Eurocode 5 [26]. This has the possibility to delay the fire spread, but the use of combustible material inside cavities to stop fire spread will eventually fail if the fire is allowed to burn for long enough. 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 7.3 for more information about fire fighting 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, the risk of external fire spread can increase. For a timber building where the load-bearing structure is combustible timber, this is something that has to be accounted for. The external wall must also mitigate the risk of falling debris causing fire spread or damage to people and fire fighters [33].

Generally, this results in strict requirements to which any of the components in an external wall should be non-combustible. 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 (SP 105[8], BS 8414[9], ISO 13785[10], NFPA 285[11], AS 5113[12]). This allows the use of combustible timber facades that have been treated with fire-retardant products and successfully passed the relevant test. See section 6.2 for more information about fire-retardant products. The effectiveness of most fire-retardant products applied to timber facades reduces significantly due to weathering within a few years [8], [33].

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 the order of 10 min). In a timber building, the fire scenarios can be more severe than expected in the façade fire test due to the increased fuel load which will lead to long fire scenarios and extensive external flaming. This has been confirmed in many large scale fire tests [28]. See section 4.4 for more information about the energy contribution from timber. The location of openings (windows, ventilation etc.) in an external wall system have a great impact on the possibility for external fire spread if not designed appropriately [33]. Even if the external façade is non-

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[8] 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

[9] 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.

[10] ISO 13785-2:2002 *Reaction-to-fire tests for façades* – Part 2: Large-scale test. International Organization for Standardization.

[11] NFPA 285 *Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Wall Assemblies Containing Combustible Components,* 2019 edition

[12] AS 5113:2016 *Fire propagation testing and classification of external walls of buildings,* published 2016

combustible or does not contribute to the fire spread, the extensive external flaming from openings in the fire compartment with additional fuel from the timber construction may lead to an increased risk of fire spread compared to non-combustible construction. 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 wooden façade in Figure 4.

Figure 4: Picture of a floor slab extension with exposed timber above a balcony in a residential building with 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 from 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 a fire resistance when exposed to the standard temperature curve in a furnace test. More information about furnace testing can be found in section 5.4. These products have generally only been tested in non-combustible elements and are not often tested in a combustible timber wall or floor system. It is therefore common that qualitative statements by professionals or ETAs are established for a product to allow it to be used in timber structures without support from any testing in such configuration. More information about ETAs can be found in section 3.3. Even if the product has been tested in a 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 provide protection against fire spread. Using a robust design, loss of a fire protection barrier can be avoided, even if the primary fixation method (using glue, fasteners or by clamping) fails [33].

Relevant literature

The following tables present references and additional literature with more details about fire spread in timber buildings.

Table 13 Reference list

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[26] CEN. *EN 1995 Eurocode 5 Design of timber structures Part 1-1: General - Common rules and rules for buildings*. European Standard. Brussels: European Committee for Standardization, 2004.

[28] McNamee R., Zehfuss J., Bartlett A.I., Heidari M., Robert F., Bisby L.A. (2019) *Enclosure fire dynamics with a combustible ceiling*. Interflam, 1-3 July 2019, UK

[33] Brandon D., Just A., Andersson P., Östman B. (2018) *Mitigation of fire damages in multi-storey timber buildings – statistical analysis and guidelines for design*. RISE Rapport 2018:43. ISBN: 978-91-88695-82-6. Sweden: RISE Research Institutes of Sweden, 2018. Brandforsk report 2018:2:2

[34] Östman B., Schmid J., Klippel M., Just A., Brandon D. (2018) *Fire Design of CLT in Europe*. Timber and Fiber Science, 50 (Special Issue), 2018, pp. 68-82

[35] McGregor C.J. (2013) *Contribution of cross laminated timber panels to room fires*. Master of Applied Science Thesis. Ottawa, Canada: Carleton University, 2013.

Table 14 Additional literature list

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- Werther N., Denzler J.K., Stein R. Winter S. (2016) *Detailing of CLT with Respect to Fire Resistance*. In: Proceedings of the Joint Conference of COST Actions FP1402 & FP1404: Cross-Laminated Timber - A competitive timber product for visionary and fire safe buildings, KTH Royal Institute of Technology, Stockholm (Sweden), 2016.

4.7 Secondary flashover

A secondary flashover scenario can be found to occur when an enclosed fire has started to decay after being a fully developed fire and due to delamination (of timber layers or protective encapsulation) new fuel is introduced to the fire which leads to a new flashover in the compartment. Secondary flashover scenarios have been observed in many fire compartment tests with exposed CLT elements [19], [36]). As all the movable fuel in the compartment is consumed, as well as any exposed timber surfaces, the fire will start to decay. In the tests where delamination of the outer CLT layer was witnessed (typically after 120 minutes), more fuel was introduced to the compartment fire as the char layer fell off. This spikes the heat release rate in the compartment creating a second fully developed fire, i.e. a secondary flashover scenario. None of the tests allowed the fire to continue past this point and they were manually extinguished. However, it can be expected that the char layer would build up again and a new decay phase would occur followed by potential additional flashover scenarios [19].

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 [24].

There are a few factors that can be expected to contribute to the possibility of secondary flashover scenarios, or scenarios without self-extinguishment in general. These are presented below:

- The amount of exposed timber in the compartment
- Delamination of laminated layers or protective encapsulation
- How much energy the timber is being exposed to
- Location of the exposed timber

Additional considerations to secondary flashover scenarios

In the event of a secondary flashover scenario, the structure and separating elements in the building can experience a fire exposure which would not have 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.

Relevant literature

The following table presents references with more details about secondary flashover scenarios.

Table 15 Reference list

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

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4.8 Self-extinguishment (auto-extinction)

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 (auto-extinguish). The definition of self-extinguishment depends on many factors. Typically, self-extinguishment is considered to have occurred at the time when flaming fires are transitioning into smouldering fires [13]. However, in the event of a fully developed fire that decreases into a smouldering fire, it is not certain that the fire will self-extinguish as a smouldering fire can transition into a flaming fire again [37]. The provision of a rise in oxygen flow into a compartment will increase the pyrolysis of a smouldering fire in timber, which can lead to flaming fires under the right conditions. Hence, the definition of when a fire self-extinguish occurs is difficult to determine. Self-extinguishment is different from the phenomena of "burnout", which is defined as the point at which all fuel available to the fire has been consumed leading to the extinguishment of the fire. Read more about burnout in section 4.2.

In many of the full-scale fire compartment tests with CLT construction, where delamination did not occur, the heat release rate of the fire will decay after being fully developed and finally turn into a smouldering fire. Research has been done to determine at which heat release rate the transition from a flaming fire to a smouldering fire can be expected to occur [13]. In most self-extinguishment tests in CLT compartments, the fire has been extinguished manually with water before complete self-extinguishment of the smouldering fire has been witnessed [13], [19], [23], [37], [38].

There are many factors that will impact the potential for a fire scenario to self-extinguish. Some of them are presented below as given in [36]:

- Configuration of the compartment
- Movable fuel loads
- Compartment size and ventilation
- The number, size and orientation of exposed timber surfaces
- Delamination of timber layers and fall-off of protective layers in the fire

In a compartment fire, where all movable fuels are consumed and all timber surfaces are burning without any delamination of timber layers, it is possible to theoretically quantify when the compartment will self-extinguish. Timber will only stop burning if the pyrolysis rate drops below the critical value required to sustain flaming combustion. Understanding and quantifying the heat feedback processes between the compartment fire and the burning timber require close examination of the energy balance for a compartment fire. For extinction of the timber to occur, the overall losses from the compartment must be greater than the energy generated due to the combustion of the timber [13], [19]. Self-extinguishment is not the same as burnout of all the fuel in the compartment, which relates to the time when all the fuel in the compartment has been consumed and subsequently extinguishing the fire. Read more about burnout in section 4.2.

Determining conditions for self-extinguishment

Work has been carried out and presented in [13], to understand the critical mass loss rate and the critical heat flux that defines the self-extinction of flaming fires in timber. Tests were conducted with a steady-state condition in order to quantify the worst-case scenario for the critical heat flux for extinction. From the testing in [13], it was found that the critical mass loss rate for extinction is in the order of 3.93 ± 0.45 g/m^{2}s and the critical heat flux value for self-extinction of flaming fires is in the order of 43.6 ± 4.7 kW/m^2. These results are only valid for timber that does not delaminate. In the tests presented in [13], delamination of the CLT layers prevented the compartment from reaching self-extinction and it was concluded that self-extinction did not show any systematic dependency on the density of the timber, while ignition has previously been shown to be a function of density [13]. This demonstrates the necessity for individual testing of the timber used in specific designs as well as any new timber species entering the market. Testing is required to quantify specific self-extinction properties.

Several large-scale and medium-scale experiments have proven that self-extinguishment of flaming fires can be achieved [19], [23], [38] but many are found to not self-extinguish. In the tests presented in [19] the same configuration of a test (Beta-1 and Beta-2), had two opposite walls being exposed and other walls and ceiling 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 very difficult to predict if self-extinguishment will occur in a compartment with exposed CLT elements. It also demonstrates that when fire compartment tests are compared, it is important to acknowledge the many variables and uncertainties will influence the results.

From a review of completed compartment tests, it was found in [2] that only one of the 41 compartment tests achieved complete self-extinguishment. The other tests had been extinguished manually before this could be confirmed. In the ”*Fire Safety Challenges of Tall Timber Buildings – Phase 2: Task 3*” test series [23] 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 self-extinguishment.

If the timber starts to pyrolyze and burn, the key question that designers must answer is whether the timber compartment will self-extinguish (auto-extinction), before the loss of structural stability or fire compartmentation is breached. There are many limitations to how well fire behaviour can be predicted in a compartment. Consequently, determining that a fire in a specific compartment, with a specific fuel load and a specific structural timber product, will decay and self-extinguish is difficult. See section 4.2 for more information about burnout, section 4.3

about delamination, section 4.4 about energy contribution and section 4.7 about secondary flashover.

Relevant literature

The following tables present references and additional literature with more details about self-extinguishment.

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Relevant research currently in progress

The ARC Future Timber Hub Project "*Exploring the self-extinguishment mechanism of engineered timber in full-scale compartment fires*". The large-scale tests programme is expected to be completed in 2020. The different stages of the project include:

- Stage 0 (baseline tests): 2 tests completed in 2019.
- Stage 1 (char fall-off study): 1 test completed in November 2019. 1 test to be tested in January 2020.
- Stage 2 (increased exposed surface of timber study): to be completed in 2020.
- Stage 3 (encapsulation failure study): to be completed in 2020.

More information can be found at *https://futuretimberhub.org/news/increasing-awareness-engineered-timber-fire-testing*

4.9 Travelling fires or local fires

A local fire refers to a fire that is burning in a limited area which is not sufficient to heat the compartment to temperatures needed for spontaneous conditions that would create a flashover and a fully developed fire. If the fire starts to spread, it will no longer be a local fire but a spreading fire (often referred to as a travelling fire).

The concept of travelling fires depends on the initial point of ignition, heat sources, available fuel to the fire, geometry and the direction of fire spread. This is different from a local fire as the fire can spread and travel in the compartment without the conditions required for flashover and a fully developed fire to occur, resulting in a highly non-uniform temperature distribution within the enclosure [39], [40]. 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 [40], [41].

A travelling fire grows to a certain size and then moves through the area, ahead of the flames. 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 [39], [40], [42]. Structural fire design methods are generally based on the assumption that the temperature in the compartment will be homogenous. It is important to note that none of the methods or models used to predict fire behaviour in a post-flashover fire with homogeneous conditions is applicable for travelling fires.

The effects of a travelling fire are difficult to predict. Experiments on travelling fires are very costly due to the size of the test needed and research within this field is limited. No research has been found which focuses specifically on travelling fires in timber buildings. However, the mechanisms governing flame spread and burnout have recently been investigated using four full-scale enclosure fire experiments with high porosity wood cribs with similar enclosure geometries [43]. The experiments had varying ventilation conditions and locations of the fuel (similar fuel conditions). In the experiments, the fuel was located either on the floor (wood cribs), floor (wood cribs) and walls (cork) or floor (wood cribs) and ceiling (cork). It was concluded that if sudden increases of the flame or external heat flux are obtained, e.g. by changing the ventilation or by an additional heat source such as a flaming ceiling, a transient rapid flame spread takes place. It was found that when the solid fuel is close to the fire and being pre-heated to the ignition temperature, the travelling fire will have a greater magnitude of fire spread. It was demonstrated that flame spread and burnout within an enclosure are controlled by the energy balance at the fuel surface. The more fuel surfaces that are introduced close to the fire, the faster the fire spread.

For timber buildings with larger floor areas and volumes, such as an office or atrium spaces, see Figure 5, exposed timber in walls and ceiling elements can provide conditions for fast-developing travelling fires. The consequences of this type of scenario in a timber building need to be investigated further. In the design of a building, the potential consequences of a travelling fire in larger compartments are important to consider in relation to the fire safety strategy of the building.

Figure 5: An atrium design with open floor plan and many decorative exposed timber surfaces.

Relevant literature

The following tables present references and additional literature with more details about travelling fires.

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Relevant research currently in progress

A potential new research project in Australia by XLam together with the University of Queensland plans to commence a large scale open plan fire test (approx. 12 m x 18 m) representing a typical office layout with exposed CLT ceiling and typical curtain wall window systems. The project is currently in the early planning stages and is called “INFERNO”. It is planned to be completed in 2021. Considering the size of the test, results will be helpful to gain more understanding of travelling fires in timber buildings.

5. Structural fire design

5.1 Charring rate

Char is carbonaceous residue resulting from pyrolysis or incomplete combustion. Charring is a simplified structural application for the pyrolysis of timber and is a very complicated process. Refer to [9] for more details. The charring rate in timber depends on the density, moisture content, heat flux exposing the timber and the local oxygen concentrations [9], [10], [42].

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 [26]. The background is presented in [44]. There are no standards available to determine an expected charring rate for laminated products that delaminate, such as CLT. All methods available in the current standards assume that the laminated products will behave in the same way as solid timber i.e. with no delamination. Guidelines) [8], [34] include methods to account for delamination and these will be included in the next version of Eurocode 5. See section 4.3 for more information about delamination. To obtain charring rates for CLT, large scale furnace testing to the standard temperature curve or large scale fire compartment tests are generally being used.

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 including assumptions for the charring rate where delamination of CLT layers occurs. See more information about these models in section 4.5.

Charring rates are commonly applied in structural fire engineering models to estimate the fire resistance rating for separating structures and load-bearing structures. See more about structural engineering methods in section 5.1 and 5.3.

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. This only represents a fully developed fire and does not consider real fire behaviour [42]. Research has found that the commonly used charring rate calculation method in the Eurocode 5 generally leads to unsafe predictions, indicating that the method should be updated in the next version of Eurocode 5 [45].

For laminated products such as CLT (which is not included in the current Eurocode 5), and increased charring rate can be expected as the timber layers delaminate [25].

The "*Fire safety in timber buildings*" [7] guideline presents an improvement of the calculation methods in the Eurocode 5 charring rate calculations. For CLT, using an increased charring-rate is recommended in case of the aforementioned effect of delamination. See more information about these methods in sections 5.1 and 5.3.

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 burn-out of the compartment [8]. The charring rate specified in ETAs appears often to be general and is misinterpreted as a universal value [8]. See section 3.3 for more information about ETAs.

Relevant literature

The following tables present references and additional literature with more details about charring rates in timber products.

Table 20 Reference list

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- Brandon D., Hopkin D., Anastasov S. (2017) *Reviewing the veracity of a zone-model-based-approach for the assessment of enclosures formed of exposed CLT*. Conference Paper. DOI: 10.1201/9781315107202-18
- Friquin K.L. (2011) *Material properties and external factors influencing the charring rate of solid timber and glue-laminated timber*. Fire Mater 35(5), Pages 303–327
- Mindeguia, J., Cueff G., Dréan V., Auguin G. (2018) *Simulation of charring depth of timber structures when exposed to non-standard fire curves*. Journal of Structural Fire Engineering, Vol. 9 No. 1, pp. 63-76. https://doi.org/10.1108/JSFE-01-2017-0011
- Richter F., Rein G. (2017) *Pyrolysis kinetics and multi-objective inverse modelling of cellulose at the microscale*. Fire Safety Journal Volume 91, July 2017, Pages 191-199
- Schmid J., Santomaso A., Brandon D., Wickström U., Frangi A. (2017) *Timber under real fire conditions – the influence of oxygen content and gas velocity on the charring behavior.* In: Journal of Structural Fire Engineering Sept. 2017. issn: 2040-2317. doi: 10.1108/JSFE-01-2017-0013.

Relevant research currently in progress

Development of the submodels presented in [10] for theoretical charring rates using B-RISK zone models in timber construction.

Research is also ongoing in cooperation between Estonia, Germany, Sweden and Switzerland.

5.2 Fire separating function methods

There are different ways to account for the expected fire resistance in a fire separating function constructed out of timber. One way is to have the wall or floor system tested in a furnace test, according to applicable fire resistance test standards. For more information about fire resistance testing see section 5.4. The most common method of theoretically predicting the fire separating fire resistance for a wall or floor system is the Component Additive Method (CAM), or additive component method, which is given in Eurocode 5 [26] and was then further developed by Schleifer [46] in 2009.

The CAM presents different calculations on how the fire separating functions can be estimated for lightweight timber frame structures. The CAM 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 [8]. Similarly to 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 layer in the method.

The method has been updated in [47] with correction factors for different types of materials and further updated in [8] to be applicable for CLT elements. However, for the laminated product, the method is not applicable in the event of delamination [8]. See section 4.3 for more information on delamination.

It is suggested in [8] that 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 delamination of the first layer occurs.

In the "*Fire safety in timber buildings*" [7] guidelines, an improved design method for separating function of timber constructions is presented, which is based on the additive component method given in Eurocode 5 [26]. In [7] experiments and finite element analysis have been carried out to provide an improved additive method that considers an unlimited number of layers. However, for laminated timber products, the additive method is not applicable in the event of delamination. This will be implemented in the next version of Eurocode 5.

There is also an easy-to-use program "*SPFiT*"[13], developed by the RISE to calculate fire separating functions of timber using the additive method presented in Eurocode 5 [26] and with updates in the "*Fire safety in timber buildings*" [7] guideline.

Additional considerations to the fire separating function methods

The available fire separating function methods exhibit several short-comings and improvements are needed as pointed out in [47]. The methods are not able to cover the entire fire scenario and

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[13] 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*

only relate to the expected fire resistance when exposed to the standard temperature curve. The calculation methods according to Eurocode 5 [26] were derived empirically from fire tests [44]. There are therefore very few possible combinations of layers, and their application range is extremely limited [46]. The charring rates for timber panelling and timber-based panels as given in Eurocode 5 [26] do not take into account the fact that the panels or timber panelling burn through much more quickly around joints [7].

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 to the charring behaviour [8]. It is also pointed out in [8] that in order to gain correct temperature measurements with conductive metal temperature sensors in a low conductive material like timber, they must be orientated parallel to the isotherms. It is therefore important to understand how the temperature measurements are conducted if results from a fire test are being used to justify a design.

Relevant literature

The following table presents references with more details about the fire separating function methods.

Table 22 Reference list

[7] Östman B., et al. (2010) *Fire safety in timber buildings - Technical guideline for Europe*. SP Technical Research Institute of Sweden. SP Report 2010:19. ISBN 978-91-86319-60-1

[8] Klippel M., Just A., (2018) *Guidance on Fire design of CLT including best practise*. COST FP 1404 Fire Safe Use of Bio-Based Building Products. N223-07.

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

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[47] Just A., Schmid J. (2018) *Improved fire design models for Timber Frame Assemblies*. COST FP 1404 Fire Safe Use of Bio-Based Building Products. N217-07.

5.3 Load-bearing capacity methods

Methods on how to calculate the load-bearing capacity of timber elements were first standardised for applications to solid timber frames in the Eurocode 5 [26] published in 2004. The principle for these methods 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 charring rate see section 5.1 and for fire resistance testing see section 5.4. It is assumed that the char layer and part of the heated timber will have "zero" structural strength. If the residual timber element has enough unaffected structure to maintain the required structural loads as per an applied structural design, the method assumes that the element will achieve a fire resistance rating representing the time period it has been calculated for. This zero strength layer is usually referred to as an added sacrificial layer in structural design [48]. This method has been furthered developed and updated in the "*Fire safety in timber buildings"* [7] guideline published in 2010.

In Eurocode 5 [26], there are two methods for the simplified cross section calculations available. The first method is the effective cross section method (ECSM) or the so-called reduced cross-section method (RCSM) which uses zero-strength layers. 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 ECSM accounts for lost mechanical properties of the heated timber that have not yet combusted and charred [49]. The zero-strength layer is assumed to a fixed depth of 7 mm. The justification for the 7 mm thickness originated from the work presented in 1967 by Schaffer [50]. If the structural member protection, such as gypsum board falls off, the charring rate doubles as per the ECSM, until the char layer re-increases to 25 mm [48]. The ECSM does not account for the degradation of strength and stiffness properties with increased temperature and the adoption of the zero-strength layer for beams and columns normally gives non-conservative results [51]. The method is based on testing of small timber samples at constant temperatures which poorly reflect the behaviour of larger sections where mass transfer (migration and re-condensation of water vapour) influences the load-bearing capacity [52].

The use of the zero-strength layer requires homogeneous material characteristics within the section, this is not the case for CLT where the strength transversal layers are incorporated in the layup [52].

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 [44]. 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 [44]. 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 [44].

In the *"Fire safety in timber buildings"* [7] guideline a simplified method for the load-bearing capacity of CLT, based on the methods given in Eurocode 5 [26], is presented. The simplified method uses recommended accounts 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 overall thickness, stress orientation of fire-exposed side and thermal penetration temperature gradient. However, the method does not account for delamination of the CLT. See section 4.3 for more information about delamination.

There is also an easy-to-use program "*SPFiT*"[14], developed by the 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 [26] and with updates in the "*Fire safety in timber buildings"* [7] guideline.

Additional considerations to the load-bearing capacity methods

The current Eurocode 5 [26], which presents both methods, is strictly not applicable for CLT or materials that will delaminate [8]. These methods normally do not, or just to a low extent, consider joints and junctions to neighbouring elements or the influence of mounting parts and penetrations of service installations [34]. 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.

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 [47], that the load-bearing capacity methods presented above exhibit several short-comings and improvements are needed.

It is stated in the "*Fire safety in timber buildings"* [7] 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 post-fire phase) to be achieved within the two hours. It should also be noted that 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 5.6.

Relevant literature

The following table presents references with more details about load-bearing capacity methods.

Table 23 Reference list

[7]	Östman B., et al. (2010) *Fire safety in timber buildings - Technical guideline for Europe*. SP Technical Research Institute of Sweden. SP Report 2010:19. ISBN 978-91-86319-60-1
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[14] 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*

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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 to 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 6.

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. This is referred to as “design for burnout” [14]. See section 4.2 for more information about burnout.

For a non-combustible structure, there is a possibility that this can be achieved, but when structural timber contributes with fuel to the fire much longer fire scenarios can be expected.

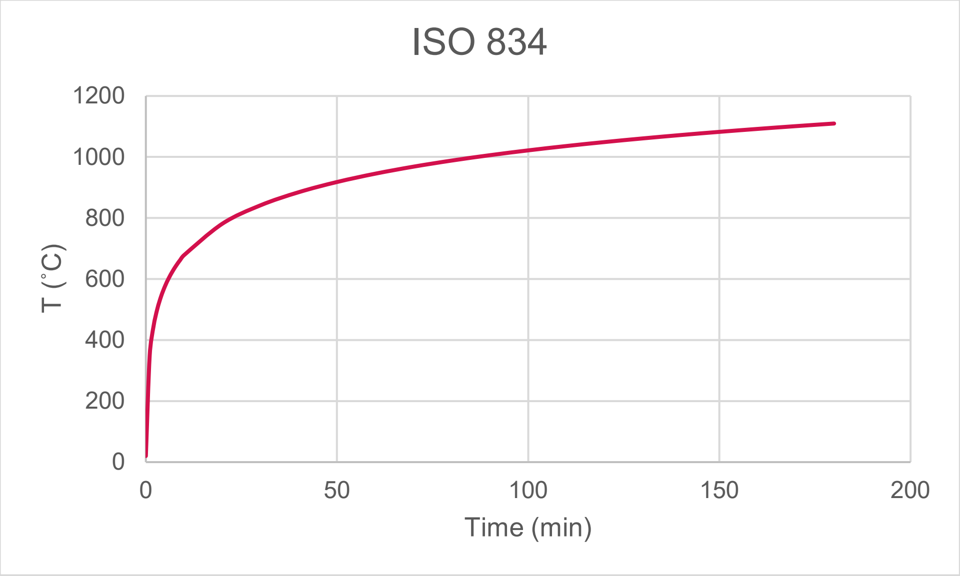

Figure 6: The standard temperature curve as per ISO 834.

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 engrained 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 [12], [13]. This originated from the early fire severity work by Ingberg in the 1920s [12], [13]. In order to follow this fundamental 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. Unfortunately, this is currently not practised in the industry and the consequences of additional fuel loads are not being addressed by professional engineers and are not accounted for in the fire safety strategy of the building. When combustible materials 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 standard heaters in the furnace may need to be adjusted in order to follow the predetermined temperature curve. In [29] 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 is approximately 350 % for the non-combustible concrete compartment compared to the CLT compartment [29]. 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 [53]. The results agree with [29] and it is concluded the fire resistance approach alone is not an appropriate benchmark to assure a level of fire safety in a timber building. Fire dynamics considering the potential for self-extinguishment and account for the quantity of exposed timber in the compartment, the ventilation conditions, as well as the quantity of ‘‘additional’’ fuel in the compartment amongst other things.

In [54] the standard fire resistance framework application for combustible materials is also being reviewed and the following statement is made:

"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."

This indicates that it does not seem to be an easy answer to what the best approach for fire testing of combustible timber elements is. Methods to quantify the fire resistant performance of timber needs to be researched further.

It is also discussed in [29] that different types of structures should be required to meet different fire resistance benchmarks when designs are being justified on the basis of standard furnace testing. The 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 [29]. Similar arguments are presented in [55] but in a response to this article [56], the use of fire resistance testing as a standardised method of testing building materials, combustible or non-combustible is being justified. Concluding that temperatures in a compartment in under-ventilated fires will not be governed by the energy contribution of fuel loads but the availability of oxygen to the fire. The fuel load from a combustible structure does not influence the rate of temperature increase but only the fire duration [56]. It is pointed out that fire resistance is one of the very few methods where calculations based on physical material properties can predict the test results.

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. However, the unlimited supply of oxygen makes it very different from real fire behaviour in a compartment. The idea is that these tests will be more cost-effective compared to furnace testing or large scale compartment fire experiments [25].

Relevant literature

The following tables present references and additional literature with more details about fire resistance testing.

Table 24 Reference list

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Table 25 Additional literature list

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Relevant research currently in progress

The “*Epernon Fire Tests Programme*” is seeking to understand the links between normative fire resistance ratings and real fire performance in buildings. The project has several objectives, such as quantification of the energy contribution of combustible materials in standard furnace tests, the influence of combustible surfaces and ventilation factors on the dynamics of compartment fires (including external flaming), and the thermomechanical behaviour of structures under standard and natural fires.

The test programme was completed in 2019 and includes three standard fire resistance tests and six natural fire experiments. As all conclusions from the testing will be published in 2020 this is still considered current research in progress. The outcomes of the project are expected to shed light on several issues which should be considered when assessing a building using a fire safety engineering approach to provide an adequate level of safety.

More information and updates regarding future publications of the work are available at *http://www.epernon-fire-tests.eu/*

5.5 Parametric fire curve models

Structural analysis in fire requires an understanding of the complete fire exposure, including the decay phase of a fire. A parametric fire curve is a collective name for adaption of mathematical models for the temperature exposure inside a compartment with natural fire behaviour, including pre-flashover, flashover and post-flashover [18].

The first parametric fire curves were introduced in 1970 and the more commonly used curves are the “Swedish fire curves” by Magnusson and Thelandersson [57]. These fire curves have then been linked to the expected performance of materials in standardised furnace testing, i.e. time equivalence calculations [17]. 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 [17]. There are generally three different models that are widely used, the CIB W14 [58], [59], the Eurocode 1 [60] which is configured from the CIB W14 and Law [15]. 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 [17]. The models are limited by the experimental data and not applicable for compartments containing structural timber or any other combustible structural materials that hinder the potential for complete burnout [28]. After tests on large scale compartments with timber cribs, it has been suggested that the Eurocode 1 [60] model and the CIB W14 model underestimate the fire severity [17]. 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).

More recently, parametric fire curves have been applied to compartments with exposed timber, the following methods use parametric fire curve models.

The methods presented in [61] and [45] account for the reduction of the load-bearing capacity during a fire by subtracting a non-linear char layer and a constant zero strength layer. The parametric fire exposure from Eurocode 1 [60] is used to determine the charring rate and calculated following the guidance in Eurocode 5 [26]. The methods are only applicable for solid timber and glued laminated timber, not CLT or products that may delaminate [18].

The method presented in [62] follows two steps and the same principles as the method presented in [37]. A critical lamella thickness to avoid 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 [60] is used to determine the charring rate and calculated following the guidance in Eurocode 5 [26]. 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/m² taken from [37].

The method presented in [18], includes a proposed change of the so-called “advanced calculation method” described in Annex B of the Eurocode 5 [26]. 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 explain how the effects of delamination and other limitations of the parametric fire equations apply.

Additional consideration relating to parametric fire curve models

Parametric fire curves are equation-based which makes them easy to use and suitable for spreadsheet calculations. However, they lack the flexibility of models that solve the mass and energy conservation governing equations for an enclosure [10].

Parametric fire curves used to correlate a "time equivalence" exposure to the structure as tested in standardised furnace testing, are limited to non-combustible structures in compartments with known moveable fuel loads [10].

The contribution of energy from timber surfaces to a fully developed enclosure fire is coupled to the design fire. As such, timber charring rates determined from standard fire resistance tests or parametric time-temperature relationships may not be applicable. This is particularly important when the structural fire performance of load-bearing structures is to be justified. The methods presented above are bound by these limitations and further research is needed.

Relevant literature

The following tables present references and additional literature with more details about parametric fire curve models.

Table 26 Reference list

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5.6 Post-fire phase

The post-fire phase (or decay 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 [54]. 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 “warm” 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 [54].

In the experimental tests conducted by [36], 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. Eurocode 5 [26] and other methods that use the standard time-temperature curve does not extend to account for the delayed heating in timber and loss of strength.

In [54] heat transfer calculations in timber that are based on calculation methods presented in Eurocode 5 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 [54], and the accompanying theoretical considerations for the reduction in structural capacity, suggests 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 [54].

Consequences of post-fire heating in timber structures

In [54] it has been shown that the load-bearing capacity of structural timber walls and slabs can be expected to continue to reduce, to differing degrees, during the decay phase of a fire. If the structural design of a building, especially of tall timber buildings, has not considered the post-fire behaviours, a severe fire that is not extinguished early can cause major structural failures.

There is a lack of research on the reduction in strength and elastic modulus for heated timber post-fire heating as the main focus is to structural performance during the heating under the standard time-temperature curve [54]. There is a need for more research to investigate further how to address issues with post-fire behaviours.

Relevant literature

The following table presents references with more details about the post-fire phase.

Table 28 Reference list

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5.7 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. The fire safety strategy in a tall building is often applied to meet the design goals without the support of active fire suppression systems. Meaning that the performance of buildings' structural elements can be considered as a passive fire protection system that can only rely on other passive fire protection measures, such as fire separation. The design must, therefore, achieve an appropriate level of structural redundancy, particularly in areas that are potentially critical for occupant egress and fire brigade intervention [63]. For tall buildings, it is necessary to demonstrate that the structural design can withstand a burnout of all the fuel inside a fire compartment [16]. For more information about burnout see section 4.2.

Detailing of connections and fixings between structural elements must be considered to make sure that these do not present a weakness that can cause failure in the structural system. This is particularly important for modular construction and the use or large wall and floor timber elements. A task that is not easy if the available fire testing for the structural elements has not included connection parts of the complete structural system.

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 fire model [5]. The relevant parameters to consider for a structural fire engineering modelling are presented in detail in [5], [64] and are illustrated in the flow chart below, see Figure 7.

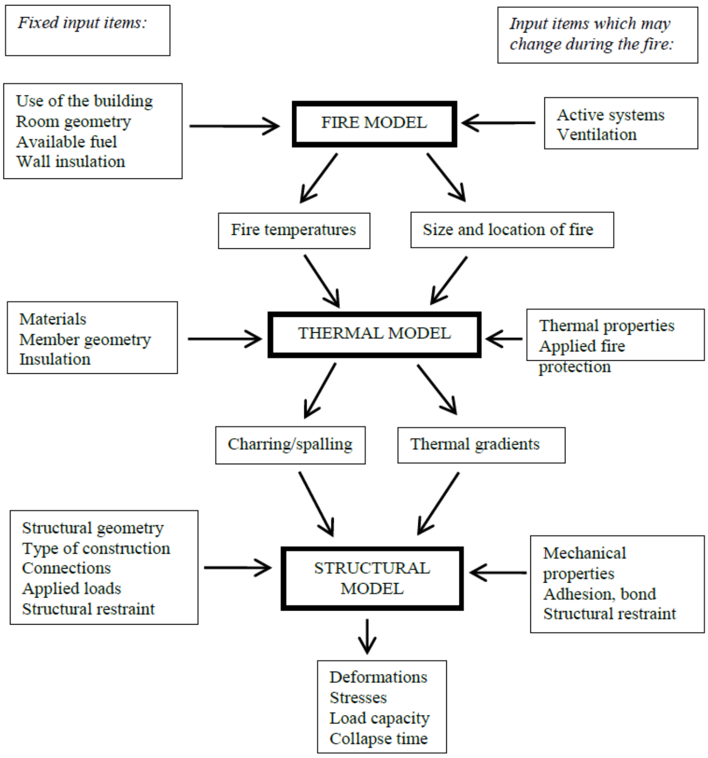

Figure 7: Flow chart for predicting structural fire performance [64].

Approaches of structural fire engineering

There are two fundamentally different approaches presented in available guidelines for the structural fire engineering design of timber buildings, which is an obvious cause of confusion. There is also a difference between designing smaller buildings or taller more complex buildings where a structural collapse due to a fire is not an acceptable scenario. The most common approach is to ignore the fact that timber is combustible and will contribute fuel to a fire. Normally this is justified by providing an automatic sprinkler system or the provision of encapsulation around the timber without further analysis. Whereas the more holistic approach is to address the fire safety challenges introduced by the combustible structure, demonstrating that a combustible building design will achieve burnout without structural collapse even in scenarios when the structure is contributing fuel to the fire.

In order to achieve a more 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. The following is presented in [5]:

1. Expected temperatures in fully developed fires.
2. Charring rate as a function of fire exposure.

3. Temperature and moisture dependent thermal and mechanical properties of heated timber.
4. Self-extinguishment properties of charred wood.
5. Predicting the fire performance and fall-off times of protective systems (e.g. gypsum plasterboards).
6. Storey to storey fire spread via combustible façade cladding.
7. Effectiveness of details to prevent internal fire spread.
8. Fire performance of connections between structural timber elements.

In [5] the following comment is 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."*

Relevant literature

The following tables present references and additional literature with more details about structural fire engineering.

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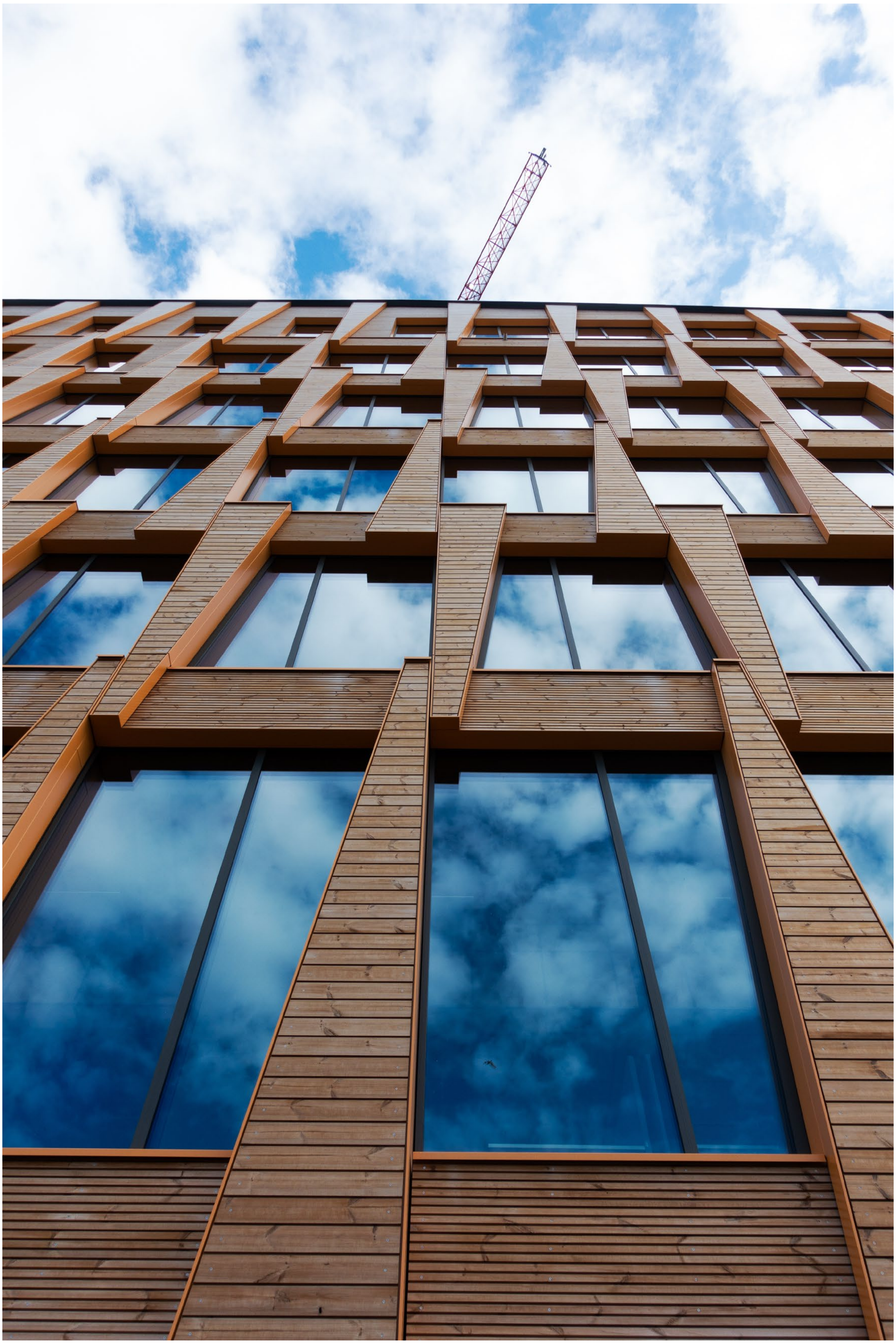
6. Fire safety design



6.1 Encapsulation of timber with protective layers

The easiest way to mitigate the fire hazards presented by timber is to prevent it from pyrolysing, which will not occur if the surface temperature of the timber does not exceed 200 °C [3]. 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.

If the design goals 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 from a fire on the structural timber. This is defined as *partial-encapsulation* and should not be confused with complete encapsulation. Partial-encapsulation does not prevent feedback between the structure and the fire and does not achieve the objective of a complete encapsulation strategy of "removing" the fire hazard presented by timber [64].

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. 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 [8]. 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 [3].

Additional considerations to the encapsulation of timber

If the encapsulation falls off in a fire, preheating of the timber behind the protective layer, will result in an increased charring rate [25]. 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 [24]. See section 4.7 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. See section 5.1 for more information. 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 [24], 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 a maximum fastener distance are important factors in relation to the performance of the encapsulation [18]. Future alterations and maintenance work in a building, also pose the risk of the encapsulation being compromised and not performing as expected.

Relevant literature

The following table presents references with more details about the encapsulation of timber.

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6.2 Fire-retardant treatments and coatings

There are fire-retardant treatment products available that can enhance the performance of timber when exposed to fire by delaying the time to ignition, reducing heat release rate and lowering the flame spread rate [8]. Surface coatings with chemicals and pressure-impregnated chemicals are the two types of fire-retardant treatments available for timber [22].

The fire performance of the fire-retardant timber products (pressure impregnated or surface coated) will degrade over time, especially in 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 results in a loss of fire performance. The fire performance may also decrease due to a loss of the fire-retardant chemicals by leaching or other mechanisms [8], [65]. The durability of the fire-retardant treatment depends on a range of different factors such as UV light, rain, salt and humidity.

In a report [65] 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) 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 of 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 [65]. 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. Re-application is therefore essential to maintain the protection of the fire-retardant treatments.

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 based on a North American system and a previous Nordic system. It consists of a classification system for the properties over time of fire-retardant timber and suitable test procedures [8]. It is found that the accelerated durability test represents an equivalent to a maximum of 5 years of neutral field exposure [65].

There is research that has proven intumescent paint coatings unset the charring of the timber [66]. However, it has been noted in some fire resistance testing that an intumescent paint product applied to CLT elements experienced faster time to failure compared to similar unprotected CLT elements [67].

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 limit 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 tests standards (SP 105[15], BS 8414[16], ISO 13785[17], NFPA 285[18], AS 5113[19]) 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 stress the risk of fire spread. A passed test is not a guarantee that the façade system will perform as well against fire spread when applied in different configurations on a

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[15] 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

[16] 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.

[17] ISO 13785-2:2002 *Reaction-to-fire tests for façades* – Part 2: Large-scale test. International Organization for Standardization.

[18] NFPA 285 *Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Wall Assemblies Containing Combustible Components,* 2019 edition

[19] AS 5113:2016 *Fire propagation testing and classification of external walls of buildings,* published 2016

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 4.6. As an example, the SP 105 test accepts the spread of fire in the façade and on the façade surface up to two floors above the fire room to the level of the lower edge of the window. This means that there may be a fire spread on the wall to another fire compartment [68].

Relevant literature

The following tables present references and additional literature with more details about fire retardant treatments and coatings.

Table 32 Reference list

[8] Klippel M., Just A. (2018) *Guidance on Fire design of CLT including best practise*. COST FP 1404 Fire Safe Use of Bio-Based Building Products. N223-07.

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- Östman B., Tsantaridis L.D. (2013) *Fire performance of multi-storey timber facades*. MATEC Web of Conferences 9:06001 DOI: 10.1051/matecconf/20130906001

6.3 Fire separation

One key fire safety measure for most buildings is to compartmentalise a fire, in order to reduce the consequences of a fire and to protect occupants as well as fire fighters. It also allows the fire safety strategy to assume that only one fire in one location is to be considered.

In construction using combustible materials such as timber, the prolonged fire scenarios that can be experienced (because the structure is contributing with fuel to the fire) may reduce the expected time a fire separating element can be maintained. For more information about fire resistance testing see section 5.4. There are methods available to calculate the expected fire resistance of separating timber elements, more information about these can be found in section 5.1.

For a CLT product with its orthogonal arrangement of layers that are bonded with structural adhesive, it is more prone to time-dependent deformations under load (creep) than other engineered timber products, such as glued-laminated timber [22]. This is not only important from a structural point of view but also in relation to how fixed fire stoppings around penetrations, joints, fixings and connections are affected over time.

Joints may lower the fire resistance and negatively influence the smoke tightness. Gaps can allow hot gases and smoke to pass through due to over-pressure 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 [34].

Additional considerations to fire separation in timber buildings

Depending on the design goals in a building, the fire separations are to be designed and constructed with significant redundancy. Penetrations through fire compartment walls and floors for ventilation, pipes and other building services can provide paths for spread of fire and smoke. Careful 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 [64].

A recent example is a fire 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 significant reasons for the high consequence of this fire. One was the inferior kitchen ventilation allowing the fire to spread, the other was insufficient fire stops in the multi-storey vertical voids between the fire compartments [5], [64].

Relevant literature

The following table presents references with more details about fire separations.

Table 34 Reference list

[5]	Östman B., Brandon D., Frantzich H. (2017) *Fire safety engineering in timber buildings.* In: Fire Safety Journal 91 2017, pp. 11–20. issn: 0379-7112. doi: 10.1016/j.firesaf.2017.05.002. url: http ://www. sciencedirect .com/science/article/pii/S0379711217302977.
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[64]	Buchanan A., Östman B., Andrea F. (2014) *Fire Resistance of Timber Structures.* Grant/Contract Reports (NISTGCR) - 15-985. https://doi.org/10.6028/NIST.GCR.15-985

6.4 Sprinkler protection

Automatic water suppression using sprinklers is a common active fire safety measure to suppress fires in buildings. The sprinkler system will reduce the rate of growth of a fire or extinguish the fire [69]. A sprinkler system consists essentially of a reliable water supply and an array of individual sprinkler heads mounted at the standardised spacing on an appropriately sized network of hydraulic pipes [7]. The water supply capacity and redundancy 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. Many codes and standards are available to cover different types of design criteria, 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 sprinkler system specifications are determined. The type of occupancy in the building alone may not account for the fire hazards introduced by timber.

The design goals for a building are very important to consider because a sprinkler system is often installed in a building to reduce the risks associated with a fire. Whilst sprinkler systems can potentially extinguish a fire, thus eliminating the problem, responsible design cannot assume, that due to the presence of sprinklers, a fire event that challenges the lives of occupants and the structure of the building will not occur. 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 buildings use and design [63]. Sprinklers are recognised to reduce the probability of a fire event reaching unwanted conditions with generalised reliability of successful operation, nevertheless, they do not eliminate all of the probability. A sprinkler system can be included as supplemental protection in the building but does not supersede other elements of the fire safety strategy [70].

The effectiveness of automatic sprinkler protection is well documented, although there are many features to consider, statistical data has been gathered all over the world and more information on how to read statistical data on the effectiveness of sprinkler systems can be found in [71]. In compartments with exposed CLT surfaces, large scale fire testing suggests that appropriately installed sprinkler systems with good spray coverage are an effective measure to suppress the fire [38].

In all buildings, active fire-safety precautions like sprinklers will help to reduce the risk of serious damage, supplemented by on-site water storage in when necessary for increased redundancy or when an alternative water supply is not available. They are especially recommended in tall timber buildings [64] 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." [64]*

Additional considerations in relation to sprinkler protection

The reliability of sprinkler systems can be greater than that of many passive fire protection systems, fire doors probably being the most obvious example. However, the failure mode for a sprinkler system differs from failure modes for most passive systems, a condition that is neglected in many analyses [5]. As failure in a sprinkler system results in no protection at all, a failure in a passive system often provides some degree of protection.

If the design goals for a building are 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, sprinklers are to be deemed as a redundancy measure, only reducing the probability of larger consequences of a fire. For structural fire safety analysis, scenarios where the sprinkler system fails i.e. higher consequence from a fire, are to be accounted for [63].

The great benefit of sprinkler protection 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. Building codes, therefore, tend to allow for relaxation regarding some prescriptive fire safety requirements if a sprinkler system is installed in a building [69]. The logic that fully developed fire scenarios are eliminated in buildings with an automatic sprinkler system, as presented in [7], is the reasoning why sprinkler systems can allow trade-offs with other types of protection measures in some building codes [64]. 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 the design goals are to be met. If implicit relaxations are applied to timber buildings without further consideration, the consequence of failure may be greater than anticipated for buildings constructed with non-combustible materials. A probabilistic approach, considering redundancy to support the fire safety strategy, is more appropriate than comparison with reference buildings based on implicit requirements to show cause for a suggested design in timber buildings.

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

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6.5 Penetrations, connections, fixings and installations

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 penetrates the construction.

A fire stopping product tested for non-combustible construction can perform equally as well when used in timber construction in relation to fire resistance. 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. Fire stopping products that are used in a timber building may never have been tested for this application and if they have been tested to demonstrate a fire resistance in the particular timber structure that is being used, information about their performance in experiments with longer fire exposure beyond the fire resistance testing is uncommon.

Common defects in fire compartmentation as a result of inaccurate installation e.g. wrong products used or poor workmanship is found to be in the order of 43-54 % of all installations inspected in a research project presented in [7]. 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*" [7] 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. Combining services into a fire separate shaft that does not have combustible surfaces and limited combustible materials will reduce the possibility of a fire spreading, should fire spread into this space. By concentrating services in shafts in a building, the design will allow for fewer penetrations through fire separations. 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 [7]. An example of penetrations during construction in a mass timber building and a connection to the curtain wall system is presented in Figure 8. As can be seen, these areas provide the potential for fire spread should they not be appropriately sealed.

Figure 8: Example of gaps in floor slab (left) and curtain wall system (right) in a timber building during construction. (Photo Carl Pettersson)

Additional considerations in relation to penetrations, connections and fixings

Timber is a natural material that will vary in moisture content over time and experience movements, which can cause cracks and openings around penetration seals. Fire stopping products that do not have appropriate properties to expand and adapt to movements in the timber construction may not seal sufficiently or even fall out.

When using shafts 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 [7].

Relevant literature

The following tables present references and additional literature with more details about penetrations, connections and fixings.

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7. Timber buildings during construction and in use

7.1 Construction work of timber buildings

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 [22]. Appropriate mitigating measures are to be considered during the design stage and appropriately implemented before construction, to ensure the safety of workers and fire fighters 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 [22].

Engineered mass timber elements, such as CLT, are building systems that are adaptable to new design opportunities. They are suitable for long 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 [22]. Construction work incorporating existing buildings will pose new risks to the existing building parts, such as high temporary fuel loads and fire exposure that 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 9.

Figure 9: 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 a sprinkler system should be planned to achieve installation and operation as soon as possible to reduce the risk of a fire on the construction site [72]. Another possible way of reducing the fire risk is to install temporary sprinkler systems that will operate during the construction. In [72] it is recommended that during the construction of multi-storey timber buildings, temporary sprinklers should as a minimum in stairways and fire hazardous areas (such as areas with a lot of combustibles, areas with a risk of highly ventilated fires, areas with a high risk of ignition).

All hydrants and booster 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 [72].

Additional considerations to the construction work of timber buildings

The construction work of buildings requires many disciplines to work together under short timeframes and cost restraints. All these factors combined is a recipe for possible mistakes. In the report by Boverket [73], a review of faults, defects and damages to buildings in Sweden has concluded 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 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.

Many possible mistakes can occur during construction. Preventing fire spread between compartments is therefore of great importance [74]. Incomplete fire compartmentation and protection around fire stairs and exits can expose workers and fire fighters to very dangerous conditions during construction. Strategies on how safe evacuation routes will be maintained during a 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 [72]. 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 [22]. 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 are 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 [75].

Hot work, heaters on-site or careless fire safety practices (such as the improper discarding of cigarettes) are typical fire hazards. Removing some of these hazards can be straight forward, such as eliminating hot work and enacting strictly no-smoking policies on-site. The majority of fire incidents are however incendiary (arson) and 24h security provisions to the site are therefore very important [22].

Relevant literature

The following tables present references and additional literature with more details about the construction work of timber buildings.

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7.2 Damages after a fire

There are several different aspects to consider in relation to fire damage of 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 [54] 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 of high temperatures but also smouldering combustion and the cooling period after a fire [76]. Prolonged exposure to temperatures above 65 °C has been found to result in a permanent loss in structural properties in timber [54], [76], [77]. 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 [76]. If evaluating the fire damage on the structural load-bearing capacity, information about the typical capacity of the original product is important. In [76] it is recommended that the timber structures are re-graded after the char is completely removed.

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 % [76], which should be compared to the equilibrium moisture content of timber (typically assumed to be around 10–12 %) [9]. A 1 % change in moisture content can affect timber strength properties by as much as 2 to 6 % [76].

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 (over 600 °C). 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 [76]. 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 [33], the data indicates that high water damage is most often caused by fire service intervention rather than sprinkler activation. This is also acknowledged in [7]. 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 [76]. 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.

Additional considerations to damages after a fire in a timber building

Repair work in a building will open up passive fire protection such as fire compartmentation, but also temporarily disconnect active fire safety measures such as smoke detection and sprinkler protection. If parts of a building are still being occupied, this will cause an increased risk of fire scenarios in an incomplete building. The same applies for partly damaged buildings that turn into construction sites where the fire safety measures are not maintained.

Relevant literature

The following tables present references and additional literature with more details about damages after a fire in timber buildings.

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7.3 Firefighting in timber buildings

There are unique hazards for fighting fires in timber buildings. In [78] the following hazards are identified to relate to 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 water mist extinguishing system can postpone flashover
- Presence of materials with higher flammability and hazardous materials can cause serious damage to structure
- Wrong design or building procedures can cause serious damage and malfunction of fire protection

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 may also be present in other building construction designs. Firefighting inside of cavities is difficult and openings made during firefighting attempts may introduce oxygen to the fire, increasing the risk of fire spread further forcing the fire fighters to chase the fire. A defensive tactic of maintaining a cavity fire in place and controlling the hazard of fire spread and structural impact from this fire may be found to be more effective [79]. The increased pressure in a compartment due to higher temperatures from a fire or fans used by fire fighters may help the fire to spread into cavities and must be accounted for.

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 [78].

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 of the buildings. These by themselves, cause difficulties and unique hazards for the firefighting operations.

Water is one of the most effective extinguisher and most commonly used agent for firefighting [78]. 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 of 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. Many fire brigades will not allow fire fighters to enter and fight a fire in a building if it is in the latter stages of a fire and there are no lives to save. 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 of 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. In [78] a good comparison between the firefighting hazards expected in legacy buildings compared to modern timber buildings is made. One of the key differences is that modern buildings are taller but also tend to use combustible façade systems, such as timber facades or aluminium composite panels with combustible core and/or combustible insulation solutions.

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