Master Thesis

An approach to integrated fire safety design of mass timber apartment buildings

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by

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Cover: Cross laminated timber (downloaded from: https://architextures.org/textures/1823)

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TU Delft

Preface

Buildings, both structurally and architecturally, have captured my interest ever since I can remember. The human experience involves shelters in one form or another since the dawn of mankind. Practicality, beauty, materialisation and safety of these structures affect us more than many think. The degree to which such design aspects are considered, can be as a mirror held up to society.

When I first encountered timber structures during a lecture by Geert, I knew that it was going to be what I want to graduate in. The combination of qualities of timber makes it a unique material with an undeniable charm. In a designated fire safety course, I soon learned about the fire safety challenges in buildings too. Here a sobering video was shown, which made it clear how a small flame can cause a room to be engulfed by flames within minutes (flash-over). Also as part of this course, Pascal gave a guest lecture (online because of covid) which interested me, during which I remember thinking: 'I want to work for him if possible'. A few months later I started my thesis with Geert and Pascal as supervisors on the topic of fire safety in mass timber buildings.

I want to thank Pascal Steenbakkers, who guided my through the process of learning about fire safety. He showed me which documents to read, which researchers and engineers to approach with specific questions and reinforced in me that I was the writer of the thesis, therefore I was allowed to set the tone for it. This advice came in useful many times, when I felt bogged down in small details. In such moments it allowed me to think more high level and ask more relevant questions each time my knowledge on the topic increased. Daniel Brandon provided support in using his modeling technique. I could also call him any time with questions, which I did quite often. I am grateful to Daniel giving me so much knowledge without hesitation and being a great conversational partner. Around the half of the thesis, due to illness, Geert stopped being an active supervisor. Roel Schipper kindly took Geert's place of principal supervisor at TU Delft and helped me with all questions I had about writing an academic thesis. Roel also helped me out in organisational aspects, chief among which was finding a graduation committee for which I am grateful. Finally, I want to thank Jan-Willem for his enthusiasm and encouraging words during the the final presentation and taking on the role of the chair of the evaluation committee.

Sándor Seuntjens
Delft, October 2024

Executive summary

Based on previous studies, the Dutch Building Regulation (BBL) is inadequately equipped to address fire safety in timber-structured buildings, particularly when the timber is exposed and in the context of tall buildings. Fire compartments containing large volumes of structural timber suffer from additional fire safety risks compared to traditional buildings without a combustible structure. These extra risks include: a longer fire duration, unpredictable fire scenario, potential second flash-over, failure of timber members due to heat wave-penetration, larger protruding flames from openings and increased smoke production (Brandon et al., 2022). This master thesis focuses on studying fire safety of CLT (Cross Laminated Timber) compartments with properties typical for apartment buildings.

The master thesis contains a literature study, divided into material level, structural component level, compartment level and building level. This literature study can be helpful for people who want to understand the fundamentals of fire safety in contemporary CLT timber buildings and want to understand the further master thesis with more ease.

In this master thesis we used three fire behaviour models to analyse compartment fires previously tested in full scale by Brandon et al. (2021a). The outcomes of simulations done with these models were compared to full-scale compartment fire test data (for a compartment of 48 square meters) to get an understanding of the accuracy, and strengths and weaknesses of the models. The study suggests that the ZHM and Brandon models are able to simulate the average char depth in the ceiling. For compartments that have percentage of exposed mass timber and an opening factor equal to that in test 1 of Brandon et al. (2021a), the outcomes of the Brandon and the ZHM models give conservative results for the the maximum char depth in the ceiling. There is a discrepancy between the simulation results and the maximum char depth in the walls when amount of exposed timber and opening factor were increased beyond the values used in test 1 of Brandon et al. (2021a). Suggestions for correction factors based on linear interpolation are given to arrive at a better approximation for the maximum char depth. It is advised to use CFD and/or compartment fire tests for any compartments that differ from tests 1-5 in Brandon et al. (2021a). Targeted design measures were listed to protect the critical areas where maximum char depth is expected.

In order to get a better understanding of the fire behavior models for CLT compartments, I simulated 24 different realistic compartments, with differing sizes, shapes, amounts of exposed timber and opening factors. The parameters were chosen in such a way, that the variations encompass a range of typical CLT apartment buildings. I performed this analysis using three different fire behaviour models. The models calculate the charring depth into the CLT cross-section. We then added the zero strength layer (timber without any structural resistance due to the heat-wave) to the modelled charring depth, resulting in the effective char depth. The larger the effective char depth, the more of the cross-section's initial resistance is lost. Over the three models, the largest correlation was found to be between opening factor and effective depth. The second largest correlation was found to be between amount of exposed timber and effective depth. Using the results of the models, without any correction for maximum char depth, none of the simulated compartments suffer failure of the ceiling panel according to calculation.

Between the three models, the zone model (Brandon et al., 2021b), is best capable of simulating protection for a finite number of minutes, as the exact number and thickness of the protection can be input in the model.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
CLT	Cross Laminated Timber
BBL	Besluit Bouwwerken Leefomgeving
ISO	International Organization for Standardization

Symbols

Symbol	Name	Unit
d_n	Nominal charring depth	$[mm]$
d_0	Zero strenght layer	$[mm]$
d_{ef}	Effective charring depth	$[mm]$
h_{ef}	Effective height of the cross section	$[mm]$
O	Opening factor	$[mm^{1/2}]$

1 Introduction

1.1. Problem background

In recent years, there has been a notable increase in the structure of buildings made completely or partially out of 'bio-based' materials, reflecting a growing awareness of sustainable practices in the building industry (van der Lugt and Harsta, 2021). This trend is underpinned by substantial technological advancements in 'bio-based' materials over the last two decades, contributing to a shift towards eco-friendly and renewable construction. Wood construction, e.g. Cross-Laminated Timber (CLT), offers sustainability, accelerated building timelines, efficient modular construction , good earthquake resistance and promotes overall healthier indoor environments. Architects seem to be increasingly favoring the incorporation of exposed CLT ceilings, and occasionally that of exposed Glued Laminated Timber (glulam) columns and beams. Furthermore, there is a growing enthusiasm for the application of CLT in high-rise buildings, not least thanks to mass timber's high strength-to-weight ratio and superior sustainability score compared to traditional building materials (Abed et al., 2022).

1.2. Problem statement

The consequences associated with fire incidents in timber construction, particularly in high-rise structures, are significant. The complexity of a fire in a building with a timber structure is found in factors such as the parametric fire load contribution of the structure, the risk of delamination, the potential for a secondary flashover, smoldering, heat penetration into structure during the cooling phase, increased smoke production, larger protruding flames, the interaction between burning building components, etc. The parametric fire load contribution refers to the fact that the contribution of timber structure to fire load is dependant on parameters, such as magnitude of exposed timber surface, how large the window openings are compared to the size of the compartment, geometry of compartment, active fire safety measures used and on the moment of onset of the decay phase. The Dutch building decree set out in the 'Besluit Bouwwerken Leefomgeving' or 'BBL' (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2024) falls short in adequately addressing the specific demands of timber construction, as the current operative requirements lack a direct relation with the additional fire safety risks of mass timber buildings (Brandon et al., 2021c). A comprehensive understanding of both the functional requirements outlined by BBL and the requirements set by insurers is crucial to make building in CLT safe and feasible. Fire safety engineering mitigation measures in CLT buildings are likely necessary to ensure the main fire safety goals in existing timber buildings and buildings to be built in the future. The main fire safety goals are defined as 1. Safety of people including firefighters, and 2. No fire spread to neighboring properties.

The problem we focus on in this master thesis, is that of understanding strengths and weaknesses of fire behaviour models for timber compartments, how various outcomes of these models can be interpreted and amended.

1.3. Importance of study

The building decree, as previously mentioned, doesn't address the unique needs of mass timber buildings with exposed structures. This means that the level of life safety found in buildings with combustible structures isn't automatically ensured. It is important to understand that fire safety is a constantly evolving concern that needs constantly evolving solutions.

1.4. Objectives

In order to address the problem stated above, the following objectives are set for this M.Sc. research.

1. Understand the main objectives of the building regulations and fire safety design
2. Understand how timber structures and buildings behave in a fire scenario
3. Validate fire development models by comparing them with test data
4. Analyse the fire progression and char depth for a set of realistic fire compartments in order to find relevant trends and correlations
5. Perform simulations on various degrees of protection

From these objectives follows the main research objective:

MAIN OBJECTIVE: Compare outcomes of fire development simulations with test data from Brandon et al. (2021a).

1.5. Research questions

In order to meet the above mentioned objectives, the following questions are further investigated:

1. What regulatory requirements are relevant for a CLT apartment building?
2. What are extra fire risks due to timber structure?
3. In what degree do fire development and charring models agree with test data of a 48 square meter compartment?
4. What are trends and correlations between design choices and charring depth
5. What is the fire development like for various degrees of protection ?
6. In what form can the result of this thesis best be used by the practicing professional?

From these questions follows the main research question:

MAIN QUESTION: What are the strengths and weaknesses of existing fire development models, what can be done to get more accurate results?

1.6. Structure of master thesis

Chapter 2: 'Literature study' gives a literature review on best (inter)national practice and research concerning fire safety in mass timber buildings.

Chapter 3: 'Methodology' introduces the scope and limitations of the research. This chapter also introduces the models used for obtaining the research data.

Chapter 4: 'Verification of fire behaviour models' shows the verification of fire behaviour models with the help of fire compartment test data and introduces formulas for getting better approximations of maximum char depth.

Chapter 5: 'Simulation of 24 CLT compartments' gives the results for all 24 fire compartments designs and describes the observed trends.

Chapter 6: 'Simulation of degrees of protection' Analyses behaviour of various degrees of protection.

Chapter 7: 'Conclusions' summarises the findings.

Chapter 8: 'Recommendations' gives recommendations to engineers, regulatory bodies and fire fighters. It also gives recommendations for further research for follow-up researchers.

2
Literature study

This chapter addresses the following objective of the thesis:

1. Understand the main objectives of the building regulations and fire safety design
2. Understand how timber structures and buildings behave in a fire scenario

This chapter answers the following research questions:

1. What regulatory requirements are relevant for a CLT apartment building?
2. What are extra risks due to timber structure?

This chapter gives a literature review on general fire safety, best (inter)national practice and research concerning fire safety in CLT buildings.

2.1. Fire behavior of timber material

In order to better understand the behaviour of timber as a construction material in a fire scenario, the following section briefly explains the reaction of timber to fire (at what temperatures do the reactions happen?) and the resistance of timmber to fire (how does the structural behaviour change when timber is exposed to fire and high heat?). This section also addresses some additional concepts related to timber as a material in fire, such as heat propagation into the cross-section, kinds of adhesives, bond-line integrity, charring and the zero-strength layer.

2.1.1. Reaction of timber to fire

At temperatures surpassing 100 degrees Celsius, the following processes begin in a timber structure: evaporation, dehydration, oxidation, combustion and pyrolysis. From 100 degrees Celsius on, water in the wood boils and evaporates. This eventually dries out the wood called dehydration. As water is evaporated, the hemicellulose starts decomposing at around 200 degrees Celsius producing carbon dioxide, carbon monoxide and other gasses. From 280 degrees Celsius on, the cellulose starts decomposing and combustible gasses such as methane and methanol are released which combust by reacting with oxygen (oxidation) at exposed surfaces. As the combustion is imperfect (not clean) it leads to charring and the release of tar and volatile compounds such as fine particulate matter. Also ash is produced, which comprises of the incombustible molecules in the wood. The wood continues to decompose undeath the char (in absence of oxygen), this is called pyrolysis. As the temperature rises above 320 degrees Celsius, lignin starts decomposing rapidly, this leads to smoke and flames. According to Barber et al. (2024) charring is directly proportional to received heat flux and period of heating.

2.1.2. Resistance to fire

Char has no structural strength or stiffness. This means that the effective cross-section of the structural component decreases as charring occurs, which in turn leads to a decrease in strength and stiffness.

At elevated temperatures the mechanical properties and thus the structural performance of heated unburned timber is reduced. To account for this loss of strength through heating, the 'zero-strength layer'is used. The polymers cellulose, hemicellulose, and lignin have different degradation temperatures.

2.1.3. Continued heat propagation into cross section

The insulating property of char, which initially slows down the heating of the timber cross-section during a fire, also has an adverse effect during the cooling phase after the flames are extinguished. Smoldering char continues to spread heat into the cross-section for hours even after the flames have stopped. However, the char layer prevents this heat from escaping into the surrounding air. This phenomenon poses a significant concern because it can lead to structural failure even after the fire appears to be over. This generally happens in compartments with temperatures under 600 deg Celsius (Barber et al., 2024). Such unexpected collapse risks can endanger lives when a building is considered safe to enter.

Gernay (2021) conducted research on loaded columns and discovered a significant strength reduction during the cooling phase. Columns are more susceptible to this effect than than other members due to their higher sensitivity to slenderness and suffer predominantly compression loading rather than tension or bending. Kotsovinos et al. (2023) finds that exposed timber columns pose structural hazards during fires, as they can weaken and potentially collapse under prolonged exposure to high temperatures.

2.1.4. Adhesives

While Polyurethane (PUR) adhesives provide good bonding strength initially, their susceptibility to debonding under prolonged heat exposure should be considered in CLT applications. PUR adhesives are more prone to causing debonding of char during heating compared to Melamine Formaldehyde (MF) and Melamine Urea Formaldehyde (MUF) resin adhesives. It is important to note that even for panels made with glue with improved bond line integrity, extreme heat can weaken their bond strength too over time. CEN (2023) advises on how to design and test for bond line integrity. The LOCTITE® HB X by Henkel adhesives claims to maintain bond line integrity during (most) fire events by providing over 60 minutes of fire resistance (Henkel, 2023).

2.1.5. Bond-line integrity

Delamination occurs when the adhesive between CLT (cross-laminated timber) layers loses strength under increased temperatures. Ceilings are particularly susceptible. This phenomenon leads to unpredictable fire conditions as due to delamination, fresh pre-heated timber is exposed to he fire, which can cause a sudden increase in temperature or even a second flashover.

Notably, stricter requirements for adhesive performance in fire-related delamination exist in the United States and Canada, as outlined in ANSI/APA (2019).

2.1.6. Char rate

According to Borgström and Fröbel (2019) if a CLT panel is not susceptible to debonding, the average char rate during fire exposure remains around 0.7 mm/min (if the gap between CLT panels at connections is less than the 2 mm tolerance). This increases to 0.8 mm/min if the gaps between the panels are greater than 2 mm. However, if the panel is prone to debonding, the average char rate increases to 0.8-0.9 mm/min.

Borgström and Fröbel (2019) give a more detailed expression for the increased charring after delamination:

$$\begin{cases} d_{char,0} = \beta_0 * t, & \text{if} \quad d_{char} \leq t_{lam} \\ d_{char,0} = 2 * \beta_0 * t, & \text{if} \quad t_{lam} \leq d_{char} \leq t_{lam} + 25mm \end{cases} \tag{2.1}$$

β_0 — Nominal charring rate $[mm/min]$
t_{lam} — Thickness of CLT lamella $[mm]$
t — Time $[min]$

A 25 mm thickness is chosen as the heat affected zone. In this zone the char rate is faster due to the heat already inside the timber. According to this model the char rate in heat affected timber is doubled.

CEN (2023) gives a value for charring rate for CLT panels of 6.5 mm/min.

2.1.7. Thickness of zero-strength layer

The zero-strength layer, is a layer of timber that is not charred (yet), but is heated to such a degree, that in calculations it is assumed to have no strength. This layer is to be taken as 7 mm thick according to the prEN 1995-1-2:2023 (CEN, 2023). The thickness of the zero-strength layer will be updated in the final draft of the next Eurocode revision. This thickness of the zero-strength layer is thought to be constant after 20 minutes of fire heating. Eurocode prEN 1995-1-2:2023 gives various other methods for calculating the zero-strength layer for different construction methods. One of these methods is for a CLT structure.

2.1.8. Relevant regulations within the BBL

The dutch law refers to the building decree set out in the Besluit Bouwwerken Leefomgeving (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2024), which outlines several performance requirements that can be categorized at the material level. These requirements become relevant when comparing fire safety in timber buildings to that in 'traditional' structures made of concrete, steel, or brick. The key requirements are summarized as follows:

- Article 4.38 specifies the necessary fire resistance for materials located at and near a hearth.
- Article 4.39 defines the required fire resistance for materials used in the inner lining of shafts adjacent to two or more subcompartments.
- Article 4.40 addresses the fire resistance needed for smoke extraction ducts.
- Article 4.43 outlines the fire resistance and smoke classification requirements for structural components in contact with indoor air.
- Article 4.44 sets forth the fire resistance and smoke classification criteria for structural components in contact with outdoor air.
- Article 4.45 details the fire resistance and smoke classification necessary for floors, stairs, or ramps.
- Article 4.47 specifies the fire resistance and smoke classification requirements for roof surfaces.

For the exact description of the requirements see Besluit Bouwwerken Leefomgeving (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2024).

2.2. CLT construction method in relation to fire safety

CLT is a mass timber construction method, which means that massive timber panels are used to construct walls, floors, roofs, stairs and balconies. It is possible to build high-rise buildings with CLT.

Firstly, the structure of the buildings is made of combustibel material. CLT structures also often have cavities through which piping can be led. Fire can spread easily through these cavities, sometimes leading to fires in the attic, from where it can spread to the whole building.

2.2.1. Fully encapsulated CLT compartment

Here follow insights from studies on compartments with fully encapsulated CLT panels:

- Passive fire protection with fire resistant boarding plays a crucial role in fire protection, particularly when it comes to safeguarding timber from charring. However, its effectiveness depends on several key factors.
- The board needs to be securely fastened to provide its full fire-resistant benefits (Just and Brandon, 2019).

- When designing a compartment that's intended to burn out completely, the gypsum board itself needs to be specifically designed to withstand those extended periods of high temperatures. Gypsum boards dry out and crack due to heat exposure and this can lead to falling off. The board's orientation also matters. Horizontally installed boards (on ceilings) are more susceptible to falling away (due to gravity) compared to vertically oriented boards (on walls).
- The timber behind the gypsum board doesn't generally char, yet it's important to consider the "zero-strength layer" principle. High temperatures can still weaken the timber to the point where part of the cross-section loses structural capacity. Timber can also start charring behind panels, in this case it is important for fire-fighters to use thermal cameras to spot the areas where this is happening.

2.2.2. Single exposed surface

Here follow insights from studies on compartments with a single exposed CLT surface:

- Half of the experiments of Medina-Hevia (2014) showed no regrowth once fire was fully developed and started to decay.
- The USFS experiments (Zelinka et al., 2018) showed no regrowth due to large ventilation openings which allowed heat to readily escape.
- In one NFPA experiment (Su et al., 2018) showed small cyclical regrowth following the initial decay due to debonding of CLT and thus fresh timber being exposed; also visible flaming was seen on the newly exposed timber walls.
- In two NFPA experiments a fire-regrowth following the initial decay caused a secondary flashover.
- If adhesive that is not prone to char debonding is used , fire decay is much more likely. Crielaard et al. (2019) highlights the importance of preventing fall-off of charred layers.

2.2.3. Multiple exposed surfaces

Studies conducted on compartments with multiple exposed CLT surfaces have given some interesting insight, a summary of these folows:

- Char debonding and re-growth was observed in 5/16 experiments.
- A steady-state burning following flashover was observed in 4/16 experiments
- Self-extinguishment highly unlikely, however 3/4 experiments of RISE (Brandon et al., 2021a) showed natural decay before being manually extinguished
- Re-radiation is possible when more than one CLT surface is exposed. This, however, is more likely to impact smaller compartments as the combusting surfaces are in closer proximity by the nature of the smaller compartment size.

2.3. Compartment fire

The following section introduces the concept of fire compartments and explains the behaviour of compartment fires for buildings with timber structures.

2.3.1. Compartmentalising

In order to avoid large fires, which can lead to total burnout of a building, it is paramount to limit fire spread. A relation developed by Baldwin (1970) shows the importance of limiting fire spread.

$$P_L = 1.23 * {P_s}^{3.2} \tag{2.2}$$

Where P_L is the probablility of a large fire and P_s the probability of fire spread beyond the room of origin. When the likelihood of fire spreading beyond the room of origin is decreased slightly, the likelihood of a large fire scenario is decreased significantly.

As Law (1990) puts it: "Fire spread can be opposed by barriers, either partitions or compartment walls and floors." Fire compartments are sections within a building that function as barriers to withstand the spread of fire. In smaller buildings, like terraced houses, one house can be a fire compartment. In larger buildings, more than one compartments can be present in a single building. In tall buildings, each floor is usually a fire compartment.

2.3.2. Natural compartment fire versus standard fire

Natural fires are the real world fires that happen in actual compartments. These can be wildly unpredictable (especially in compartments with exposed timber), some burn hot and fast while others smolder for extended periods. These variations in intensity and duration make it difficult to assess their impact on building components.

Large compartments are generally fuel controlled, as there is relatively low variable fire load and permanent fire load (exposed timber structure) compared to the amount of available ventilation. Fuel bed controlled fires, where the ventilation openings are relatively large, tend to be shorter and hotter, there is enough oxygen at all time and the heat can escape better compared to poorly ventilated compartments.

Smaller compartments with small ventilation openings are generally ventilation controlled, leading to longer but cooler fires. Low ventilation potential in combination with much exposed timber (permanent fire load) decays slowly, or not at all.

Standard fire tests are conducted in controlled environments. Building materials are exposed to a standardized fire curve as described in ISO 834 (ISO, 1999).

Fire severity time-equivalence bridges the gap between these two scenarios. This is especially important for buildings constructed with combustible materials like Cross-Laminated Timber (CLT). It translates the impact of a real-world fire into the equivalent duration of exposure to a standard fire test. This concept is critical for ensuring the safety of CLT structures. Knowing the equivalent fire duration allows engineers to predict how long a CLT element can withstand a real fire before failing structurally. Also, building codes mandate specific fire resistance ratings for various structural elements based on the building's purpose and occupancy. Understanding the fire severity in a CLT building helps engineers choose the right thicknesses for walls and floors. Fire severity time-equivalence acts as a translator. It takes the complex and unpredictable nature of a natural fire and converts its impact into the language of building codes.

2.3.3. Behavior of natural compartment fire after peak

There are three of behaviors that a natural fire can show after it has reached full development and all fixtures and furnishings are consumed. These follow now:

If the fire within a compartment starts to decay, the burning process (pyrolysis) in the exposed timber will slow down as well. However, there's still a chance for smoldering to occur, even in areas where the exposed mass timber is limited. This smoldering, however, typically won't worsen the situation beyond the initial fire resistance expectations for the CLT structure. In some situations, however, it could lead to collapse as the heat from the smoldering char propagates deep into the cross-section weakening it to the point of failure (see 2.1.3).

Another behavior is the secondary regrowth. During this stage, after a period of decay, the fire can reignite, often rapidly. This is commonly caused by a failure in the timber encapsulating the burnt timber, or by the layers themselves debonding (separating). When secondary regrowth happens, the timber can fuel the fire for a much longer duration than originally anticipated, potentially exceeding the fire resistance expectations set for the CLT structure.

The third type of behavior is the quasi steady-state burning. Unlike a typical fire where fuel sources eventually run out, here, the exposed mass timber keeps burning even after ething else has been consumed. Experiments haven't shown any signs of decay in this burning phase (Barber et al., 2024). Re-radiation can happen when multiple exposed surfaces are facing eachother or are close to each other in a corner. This can happen by design or due to falling off of protective layers. When this occurs, the heat radiates back and forth between the surfaces, essentially creating a self-feeding furnace. This intense heat can then lead to failure of compartment separation within the building, or even cause the entire structure to collapse. As with secondary regrowth, the burning duration far exceeds expectations, making quasi steady-state burning a critical fire safety concern for CLT structures.

2.3.4. Self-extinguishment of compartment fire

In a decaying fire, the flaming combustion is followed by smouldering combustion. Self-extinguishment means that the smouldering stops without fire fighting action. According to Crielaard et al. (2019) smouldering CLT self-extinguishes if the externally applied flux is below 5-6 kW/m^2. And also airflow plays a role: while an airflow speed of 0.5 m/s resulted in self-extinguishment at a flux of 6 kW/m^2, and airflow of 1.0 m/s resulted in sustained smouldering at the same heat flux. Crielaard et al. (2019) also state that delamination of CLT can cause smoldering combustion to escalate to flaming combustion on the newly exposed surface. An increased thickness of the top (outer) lamella of the CLT could be a measure for a more likely self-extinguishment, as the charring front would extinguish before it reaches the PUR adhesive, and so the ply does not delaminate.

2.3.5. Automatic suppression systems

Research such as Kotsovinos et al. (2022), Zelinka et al. (2018) and Frangi and Fontana (2015) found that automatic suppression systems can effectively suppress fire development, potentially preventing catastrophic outcomes like complete building burnout. Garis and Clare (2015) conducted research that concluded that automatic suppression systems can significantly reduce fire spread in CLT buildings. This finding reinforces the potential benefits of automatic suppression systems in mitigating fire risks also in CLT structures. In an ideal scenario, an activated Automatic suppression system system successfully intervenes, halting fire progression and minimizing damage. This would allow for a controlled fire scenario, preventing flashover (flames engulfing the entire room).

However, the reliability of automatic suppression systems remains a subject of debate. Automatic suppression systems are not infallible. In cases where the automatic suppression system system fails to function as intended, the consequences for CLT structures can be severe. This is why it's crucial to carefully consider the potential impact of a sprinkler malfunction in (CLT) building design. The effects of sprinklers can be evaluated using a deterministic approach. However, a more nuanced statistical approach can provide a more accurate assessment of sprinkler performance. The statistical reliability of sprinklers varies from country to country as failure thresholds are defined differently. The publicised values of the sprinkler reliability varies between 70% and 99.5% according to Frank et al. (2013). For instance according to McGree et al. (2024) ”... sprinkler systems operated and were effective in 89 percent of the fires considered large enough to activate them.”

This risk is further amplified when exposed timber is present as this increases the speed of fire development. Garis and Clare (2015) states that sprinklers provide a significant increase in life safety in wooden buildings. Garis and Clare (2013) states that in buildings up to 4 floors without sprinklers, there is a significantly higher mortality rate in buildings with combustible construction.

Both the European (EC) and British (BS) Standards recognize the potential benefits of sprinklers, allowing in buildings with a steel structure for a reduction factor of 0.61 for the fire load when sprinklers are present. In countries like the United States, Canada and Australia sprinklers are mandatory in CLT buildings in most cases (see IBC, NBC and NCC). This highlights the importance and trust placed on sprinkler systems as a fire safety measure in these countries.

While water damage from sprinklers can be a concern, research suggests that the financial losses associated with uncontrolled fire spread in CLT buildings far exceed the costs of sprinkler-related water damage. A study by Brandon et al. (2021c) supports this notion.

2.3.6. Compartment areas in CLT apartment buildings

Research from Brandon et al. (2021a) provides insight in the opening factor distribution and compartment area of CLT buildings compared to that of non-combustible buildings.

Figure 2.1 shows the distribution of compartment area from a sample of 185 mass timber residential buildings and that from a sample of 513 non-combustible residential buildings. It is clear that the most frequently occurring area for residential buildings is 50-55. Anything under 35 m^2 or above 100m^2 does not occur frequently.

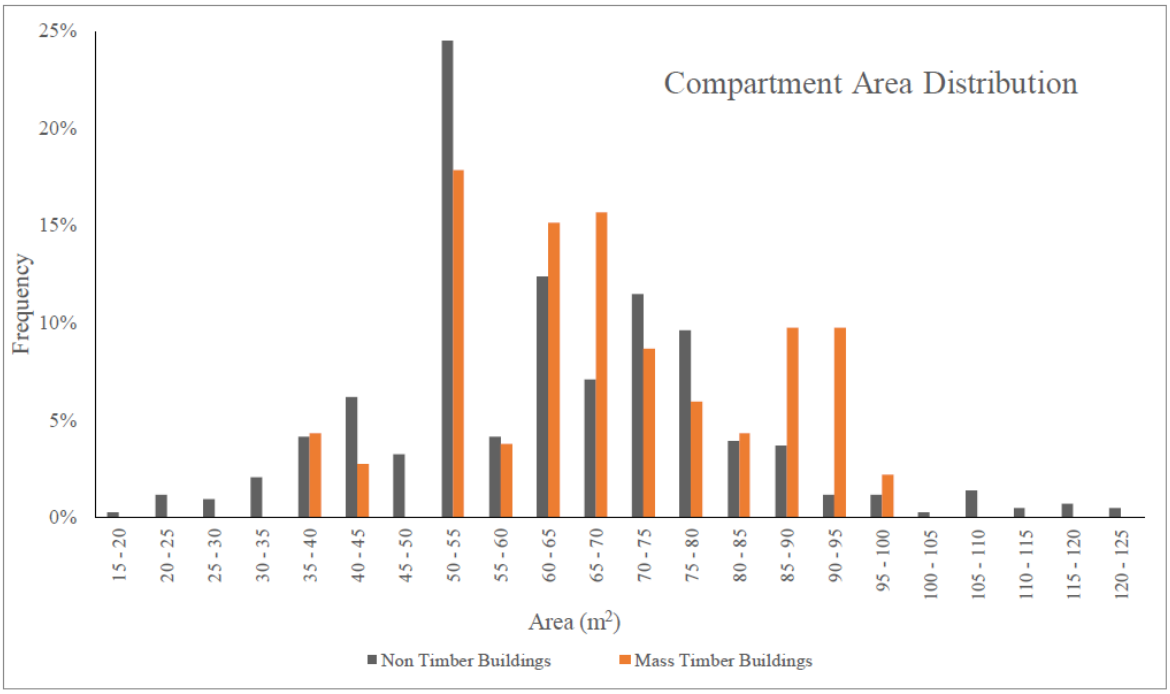


Figure 2.1: Compartment area frequencies of residential buildings (n=513 fir bib-timber buildings and n=185 for mass timber buildings) (Brandon et al., 2021a)

2.3.7. Opening factors in CLT apartment buildings

According to Brandon et al. (2021a) the opening factor O is given by:

$$O = A_0 * \sqrt{H_0}/A_t \tag{2.3}$$

$$H_0 = \sum (A_i h_i)/A_0 \tag{2.4}$$

A_i — area of each opening
A_0 — sum of all opening areas
A_t — total enclosing area (including openings)
h_i — height of each opening

In figure 2.2 it is visible that the opening factors of office buildings are, as expected, generally higher than that of residential buildings. When comparing combustible and non-combustible residential buildings, a slight shift is observed: combustible residential building compartments tend on average to have slightly larger opening factors. Brandon et al. (2021a) p erformed simulations, assuming a 49 m^2 compartment, 560 MJ/m^2 variable fuel load and exposed mass timber ceiling. For a CLT apartment buildings an opening factor of $O = 0.062m^{1/2}$ is conservative to use as a basis in calculations for this type of buildings and is smaller than 75 % of the opening factors for similar buildings in the survey.

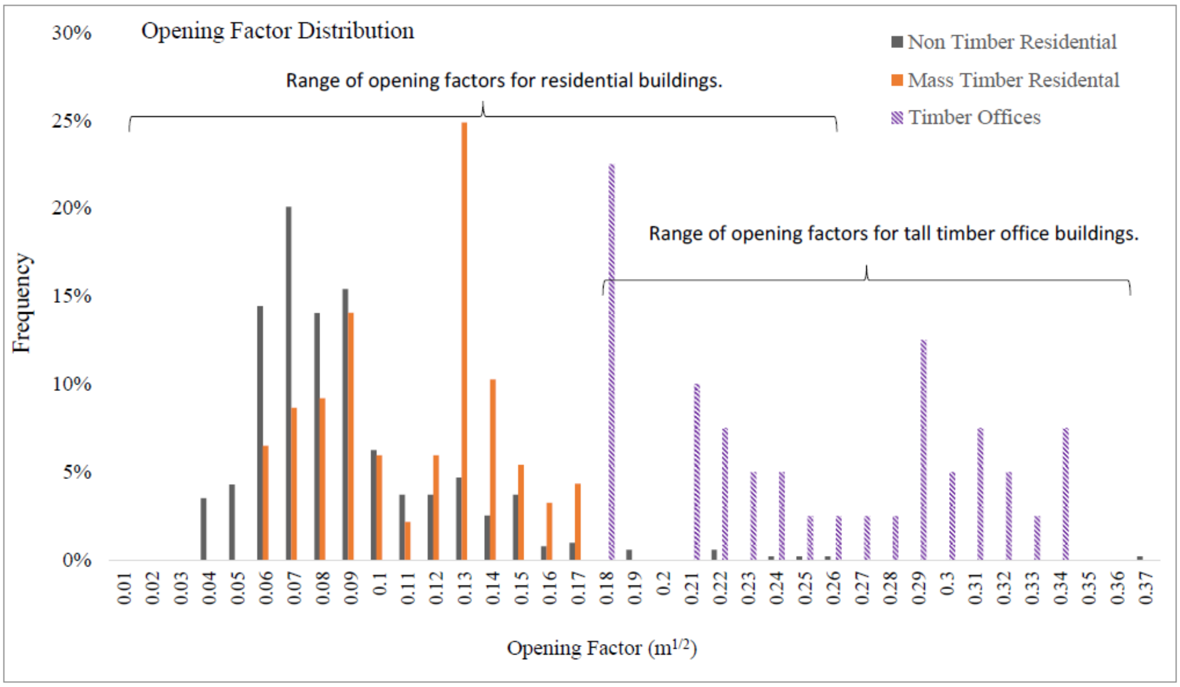


Figure 2.2: Opening factor frequencies for residential and office buildings. Note that the statistical basis for the office buildings is only 31 compartments, and 698 compartments for the residential buildings(Brandon et al., 2021a)

2.3.8. Predicting fire behavior in a compartment

Fire modeling utilizes various approaches to simulate fire behavior in buildings. Fire curves, introduced by researchers such as Brandon et al. (2018) among others, offer a simplified method by incorporating the energy contribution of wood through an iterative process. Two-zone models, such as the models discribed by Hopkin et al. (2017) and Wade (2019) which enhanced the existing B-RISK model, divide the compartment into separate zones for hot gas and smoke, accounting for heat transfer through wood but neglecting smoldering or re-radiation between nearby exposed CLT elements.

A standardized approach exists with the modified fire curve defined in prEN 1995-1-2. This method simplifies fire simulations while capturing key fire behavior aspects. Zone models provide a more comprehensive approach, treating the compartment as interconnected zones and considering factors like smoldering and interaction between exposed elements. However, they might not fully capture the complexities of natural fires.

Assessing standard fires can be done using the reduced cross-section method, which simplifies calculations for the load-bearing capacity of timber elements exposed to fire. Natural fires, on the other hand, require a variable char rate approach due to their dynamic charring behavior influenced by factors like fuel availability, ventilation, and the enclosure's thermal properties.

Several factors influence natural fires within compartments. The available fuel quantity and type significantly impact the fire's intensity and duration. Ventilation openings and airflow play a crucial role in determining the fire's oxygen supply and consequently the combustion rate and heat release. The thermal conductivity and heat capacity of the compartment's walls, ceiling, and floor affect the heat transfer rate and overall temperature distribution.

The failure of protective layers like plaster or paint, or the debonding of char from the timber surface, can expose fresh fuel and accelerate combustion. The location of exposed timber relative to fire radiation significantly impacts its charring rate and fire spread. The timber species, density, and moisture content also influence its susceptibility to charring and ignition. Finally, the presence of timber can affect the fire's decay behavior, potentially leading to regrowth or smoldering after the initial fire subsides.

In conclusion, the choice of fire modeling approach depends on the specific application and desired level of detail. Zone models offer a more comprehensive approach for simulating fire dynamics in compartments, especially for natural fires. When assessing natural fires, it's crucial to consider the various factors influencing their behavior, such as fuel availability, ventilation, enclosure properties, and the characteristics of the exposed timber.

2.3.9. Relevant regulations within the BBL

The dutch law refers to the building decree called Besluit Bouwwerken Leefomgeving (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2024) outlines a number of performance requirements categorized at the compartment level. These requirements are particularly relevant when comparing fire safety in timber buildings to traditional constructions (concrete, steel, brick). Here's a summary of key articles:

- Article 4.50: Defines the spaces that must be contained within a single fire compartment.
- Article 4.51: Specifies the maximum allowable size of a fire compartment.
- Articles 4.53 & 4.60: Set the fire resistance time required for compartment walls and facades to prevent fire spread.
- Article 4.57: Introduces the concept of a "sub-fire compartment."
- Article 4.58: Defines a "protected sub-fire compartment."
- Articles 4.61 & 4.62: Establish the smoke resistance time requirements for compartment perimeters.

For the exact description of the requirements see Besluit Bouwwerken Leefomgeving (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2024).

2.4. Building as a whole

The following sections introduces a number of aspects of importance when considering fire safety on the level of a building (which sometimes contains more than one fire compartment).

2.4.1. Goals of fire safety in a building

In terms of public law, the primary objectives of fire safety encompass ensuring the personal safety of building occupants and emergency responders, as well as safeguarding the properties of neighboring plots.

Common goals from the perspective of private bodies are minimizing damage and mitigating any disruptions to business continuity.

2.4.2. Structural safety

Analysis of documented fire-induced disproportionate collapse incidents reveals a consistent pattern: such collapses have exclusively occurred in cases where the fire had spread across multiple floors.

The scarcity of identified collapse incidents in high-rise buildings due to fire suggests that current practices and regulations are effective in preventing collapses in medium- and high-rise structures.

Preventing "burnout" scenarios, where a fire engulfs the entire building, is often mandated for buildings requiring interior firefighting interventions (typically those exceeding six floors).

In lower-rise buildings with high-risk consequences, such as hospitals, prisons, or structures relying on columns as the primary load-bearing elements, preventing burnout becomes an essential safety measure.

These findings underscore the importance of effective fire compartmentation and fire protection strategies in mitigating the risk of disproportionate collapse in various building types.

2.4.3. Height of building

As building heights increase, fire safety considerations become increasingly critical. Here's a breakdown of key challenges and corresponding fire safety goals based on building height:

Tall buildings bring high risks due to factors such as:

- More people inside building
- Longer required evacuation times (longer distance, queuing, etc.)
- Complex firefighting (internal operations required)
- Longer search and rescue times
- Building collapse poses greater danger for surrounding buildings, infrastructure, public and firefighters

In figure 2.3 the general fire safety characteristics for different 'building height categories' are given. Note, that for buildings taller than 70 m the 'handreiking SBR - Brandveiligheid in hoge gebouwen' needs to be used. This guide can be used for buildings up to 200 m.
Table A.4 shows the requirements by the BBL for these heights (Appendix A).

2.4.4. Occupancy types

The different use functions of the building stock comes with different occupancy types. Residences and hotels are assumed to have sleeping people inside. Hospitals, kindergardens and care homes are assumed to have people inside that need more time and assistance to evacuate in a fire scenario. These differences in characteristics are summarised in figure A.5 (Appendix A).

Residential buildings pose a higher risk, compared to buildings with other uses. This is because residential buildings do not require the same level of fire alarm systems as 'brandmeldinstallatie' (BMI) or 'ontruimingsalarminstallatie' (OAI), nor do they require a 'bedrijfshulpverlening' (BHV). Firefighters often need to alarm people personally from door to door. This is time consuming and risky.

2.4.5. Evacuation strategies

As buildings can vary significantly in size, and in number and mobility of occupants, there exist different kinds of evacuation strategies. These strategies also vary in different countries. Below follows a list of common evacuation strategies as found in Barber et al. (2024).

- Simultaneous (whole premise is single evacuation zone, all parts of premise evacuate at once)
- Phased (premise is divided into zones separated by fire compartmentation; zones are evacuated in controlled sequence of phases, with high risk zones evacuated first)
- Stay put (e.g. in residential apartments in some countries; occupants of dwelling of fire origin are alerted to evacuate, but occupants of all other dwellings are intended to safely remain in their dwellings unless directly affected by heat and smoke)
- Progressive horizontal evacuation (e.g. in hospitals, care homes; patients are moved into adjoining fire compartments or sub-compartments where they are protected from immediate threat; from there further evacuation can be done)

Concerns were also after the Grenfell disaster in 2017 about the use of a stay-put strategy in buildings that may not be resistant to a full fire. Timber buildings, can potentially be built in such a way (if the protective measures are not sufficient) that they may not be resistant to a full fire.

2.4.6. Life safety

The following aspects of timber buildings have (negative) impact on life safety:

- Time to flash-over may be shortened by exposed wood (particularly important in large compartments, compartments with only one exit, and compartments with health or cell functions).
- Fire development (especially via the ceiling) with exposed wood may be significantly faster than assumed in EC 1 (particularly important in large compartments).
- Available time for safe evacuation will be limited by an increase in smoke due to wood.

2.4.7. Limiting the spread area of fire within the building and to other buildings

The following aspects of timber buildings have (negative) impact on limiting fire spread withing the building:

- Fire propagation between two fire compartments in timber constructions mainly occurs due to improperly designed connections or installations.
- A select number of paths of fire spread account for the majority of propagation:
  - Along the façade, transitioning to the roof and attic
  - Through connected voids containing combustible materials, often extending to the attic
  - Through the attic, spreading fire to other parts of the building
- In tall buildings, spread typically occurs via the façade
- Flames drawn through cavities can be 5-10 times higher than the external fire plume (Colwell et al., 2007)
- In a fire test of a fully protected construction, the external flames (comming from window openings) abruptly enlarge when gypsum is removed or delamination occurs
- In compartments with exposed wood, window glass failed after only 7.5 minutes compared to 40 minutes in a non-combustible construction and cladding
- The significance of the influence of exposed wood on the external flame depends on the size of ventilation openings
- Depending on the façade system, the CLT construction behind the façade may or may not become involved in the external fire
- Fire often spreads through corner connections, especially if they do not fit perfectly
- Fire often spreads through voids, especially in classical or modular timber frame construction or solid wood modules with voids in between; fire stops in the voids can help
- Fire stops at the eaves can prevent fire spread through the attic
- Sprinklers can prevent fire spread and prevent significant financial damage (despite water damage)
- Even a gap of (tolerated) 1-2 mm can lead to combustion compared to a perfect connection
- Applying construction tape (for air tightness) on the cold side can solve problem of gaps
- Sjostrom et al. (2021) conclude that at a distance of 4.8 m, the maximum heat radiation in several tests was slightly higher than the permitted radiation in Sweden (15 kW/m2); at a distance of 8 m, it meets the criteria of Sweden, UK, and US (12.5 kW/m2)

2.4.8. Limiting smoke spread within the building

In terms of limiting smoke spread within a building, it's observed statistically that fires in buildings with timber construction tend to exhibit greater smoke spread compared to those with different construction materials Brandon et al. (2022). Enhancing the air tightness of connections between timber elements presents an effective measure for constraining the spread of smoke. Naturally increasing smoke resistance, by placing R200

2.4.9. Fighting fires

Fighting fires can be a complicated task, since all buildings are different. Here follow a few rules of thumb that can be consulted for general cases. 2.3 shows how building height can affect the attack and outcome of a fire scenario.

Attack

Firefighters are more and more concerned about their own safety at work. A primary goal for the foreman is to bring all firefighters home safely. If the situation is dangerous and the chance of saving a person or the building asset is low, a hard but crucial choice must be made, weighing the potential costs and benefits of entering.

Some steps of firefighting:

1. Outdoor exploration ('buitenverkenning')

	Firefighting aspect	Attribute
Low-rise H < 12 m	RSET	Short
	Assisted evacuation	Most people can evacuate unassisted
	Internal firefighting	Not preferred
	External firefighting	External firefighting possible
	Rescue	Internal firefighting provisions limited to protection in egress stairs
	Structure	Minimal structural fire resistance given fast evacuation times and external firefighting
	Survivability of structure	Expected that structure will not survive fully developed fire
Medium-rise 12 m < H < 25 m	RSET	Relatively short
	Assisted evacuation	Some people will need assisted evacuation
	Internal firefighting	Not preferred
	External firefighting	External firefighting possible
	Rescue	Internal firefighting provisions limited to protection in egress stairs and interior fire mains (often dry)
	Structure	Structural fire resistance will allow for whole building to evacuate and time for reasonable firefighting
	Survivability of structure	Structure may not survive fully developed fire
High-rise 25 m < H < 35 m	RSET	Relatively long
	Assisted evacuation	Some people will need assisted evacuation
	Internal firefighting	Might be necessary if not accessible externally
	External firefighting	External firefighting constrained by accessibility of ladder truck
	Rescue	Dedicated firefighting lifts typically provided as well as interior fire mains
	Structure	Structural fire resistance allows for safe evacuation and internal firefighting
	Survivability of structure	Structural fire resistance likely prevents building collapse for worst-case fire scenario
Very high-rise 35 m < H < 50 m	RSET	Relatively long
	Assisted evacuation	Some people will need assisted evacuation
	Internal firefighting	Necessary if fire is on higher floors
	External firefighting	external firefighting generally ineffective for upper floors, reliance on
	Rescue	Firefighting lift provided as well as interior fire mains
	Structure	Structural fire resistance allows for safe evacuation and internal firefighting
	Survivability of structure	Structural fire resistnace to prevent building collapse for worst case scenario
Super high-rise 50 m < H	RSET	Relatively long; total building evacuation may not be instigated
	Assisted evacuation	Some people will need assisted evacuation
	Internal firefighting	Necessary if fire is on higher floors
	External firefighting	External firefighting generally ineffective for upper floors
	Rescue	Firefighting lift provided as well as interior fire mains
	Structure	Structural fire resistance allows for safe evacuation and internal firefighting
	Survivability of structure	Structural fire resistance to prevent building collapse for worst case scenario

Figure 2.3: Influence of building height on firefighting

2. Making attack strategy
3. Exterior fire attack ('buitenaanval) as preferable first approach:
   - Handline ('handstraal') until 2-3 stories (this is possible if building perimeter is free and there are fire hydrants in close proximity)
   - From firefighter designated spot ('opstelplaats') with ladder truck or cherry picker truck until 6-7 stories (approximately 20 meters)
4. Interior attack necessary (if deemed acceptably safe depending on factors such as escalation level of fire, wind direction or available cooling power) if:
   - If there are still possibly people inside the building
   - If building is taller than 20 meters

In case of a defensive interior attack, the fire is attacked from an neighboring fire compartment. This is only possible if the integrity of the fire walls and the structure are adequate. To do this the firefighters need to be able to adequately estimate the integrity of the structure during a repressive attack. In timber buildings this is challenging or impossible; new ways of estimating this integrity are needed to ensure enough confidence in the structure.

When a fire is not quickly extinguished soon after the start of the fire, it is likely not possible to extinguish it anymore. In this case the strategy of the firefighters is to let the fire burn out in a controlled way. In timber buildings, letting the compartment burn out in a controlled manner is arguably not an option. This is because the (initially or due to gypsum boards fall-off) exposed structural timber will contribute to the fire, and will in turn compromise the fire wall integrity as well as the structural integrity.

Firefighters in The Netherlands have more or less 10 MW of cooling power when using a low pressure hose system. This power is approximately enough to fight a developing fire in a 40 m2 residential compartment. Another way to look at this, is that the resources allocated for firefighting operations are primarily focused on containing a fire within a fire compartment for approximately 60 minutes. This is in line with the principles described in the 'IFV Basisprincipe van Brandbestrijding 2020'. If the developing fire takes place in a fire compartment larger than 40 m2, the possibility of an internal attack are limited, due to a lack of cooling power.

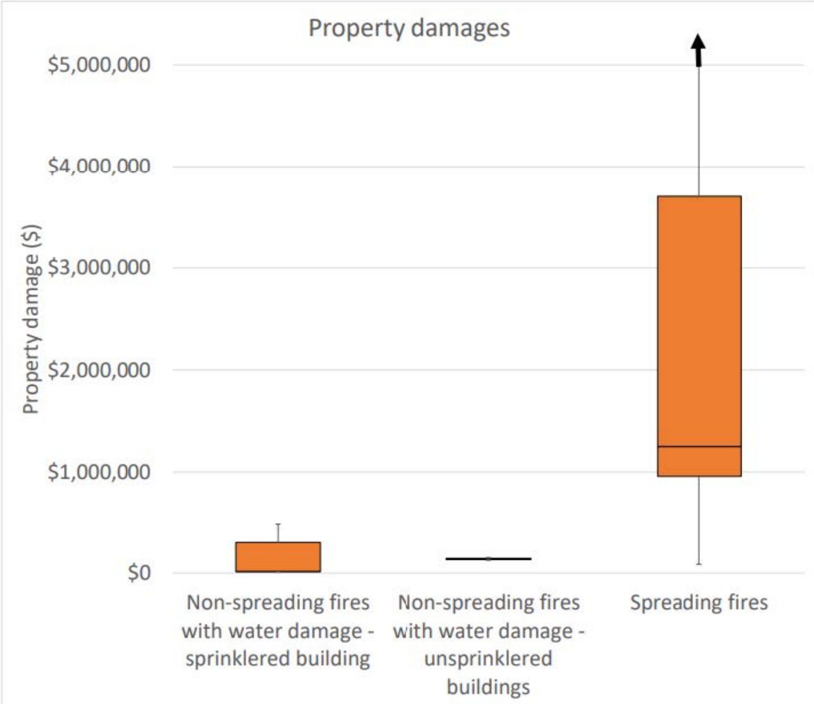


Figure 2.4: Diagram showing property damage comparing buildings with sprinklers and buildings withoug sprinklers where fire does not spread, and where fire does spread (diagram borowed from Brandon et al. (2021c)

Detection

A challenging and labor intensive part of firefighting is the scouting for fire and smoke spreading.

A smoldering fire might not extinguish by itself behind gypsum boards. The same is true in hollow spaces and in connections. To properly assess if smouldering is still present in these hard-to-see places, and to localize the hotspots, infrared thermal cameras can be used by firefighters. (Vylund en Palmkvist 2017)

Late stage smoldering and progressive heating up of the timber structure can cause structural failure post-flaming. This is extremely dangerous for firefighters scouting the building after fire has been tamed.

Water damage

Water for extinguishing (from firefighting hoses or sprinklers) can cause significant damage to timber buildings, this damage however needs to be weighed with the damage caused by the fire if no water is used. Brandon et al. (2021c) conducted a study on comparing the damage done by these phenomena, see Figure 2.4.

According to Hox en Saeter Boe (2017) an approach using thermal cameras and a 'cobra coldcut' cutting extinguisher (which spews water mist) causes least amount of water damage

Increased risk for firefighters in timber framed structure

The structure doesn't provide any warning signs to firefighters prior to a sudden collapse. Firefighters must have the capability to evaluate the condition of the structure and rely on its stability. Extinguishing the fire can become laborious and time-consuming since it's often unclear how much of the wall needs to be demolished to access the smoldering areas within the cavities. During this time the structure (or part of it) could still collapse and cause injury or death.

Increased risk for firefighters in CLT structure

Because fire spreads more rapidly when exposed timber is involved, it's probable that the fire is fully developed by the time firefighters arrive. In such cases, the intensity of the fire likely surpasses the cooling capacity of firefighting equipment, rendering an offensive interior attack impractical. Additionally, the off-gassing of burning timber heightens the risk of smoke explosions and backdrafts upon opening doors. This, coupled with an increased amount of smoke and its spread, further complicates firefighting efforts. The risk of a second flashover, triggered by delamination or gypsum board detachment, also presents an elevated hazard for firefighters engaged in interior attacks. There's also uncertainty regarding the extent to which the structure needs to be dismantled to ascertain if smoldering has ceased.

2.4.10. Fire safety during construction

Research by Martin and Klippel (2018) reveals that arson is the primary cause of fires during construction. There is significantly heightened risk of large-scale fire spread during construction in buildings with a combustible structure compared to buildings with non-combustible structure. There's a strong emphasis on promptly installing fire protection measures. Additionally, pre-gluing gypsum during CLT production is recommended to enhance fire resistance during building phase. Notable examples underscoring the importance of fire safety measures include incidents at Notre Dame and the Copenhagen Stock Exchange building each having a fire start in a timber part of the building.

2.4.11. Damage mitigation and restoration after fire event

Fire spread through voids and via the façade or balconies are significant contributors to major damage incidents. Repairing CLT construction after charring is potentially feasible, as suggested by Gales (2021) and Brandon et al. (2021c), although the available studies on this topic are quite limited.

2.4.12. Circular approach to fire safety in CLT buildings

An interesting research by Qvist (2022), compares the total costs to society of a number of CLT buidling designs. The environmental costs in terms of material use as well as the environmental costs of fire damage are taken into account. Qvist (2022) sums up her findings relating to protective boards and sprinklers in the following two paragraphs:

For smaller compartments she writes: "For a building with a compartment area of 48 m2 a fully exposed CLT compartment results in the lowest material impact up to 15 building storeys (41m). However, this solution does not result in the functional requirement for residential buildings stating that the compartment beyond the neighbouring compartment may not be lost. Therefore, it is proposed that only up to 3 building storeys a residential building should be fully exposed.For buildings higher than 3 building storeys, but lower than 8 building storeys, it is suggested to apply 2 layers of fire rated encapsulation for 70% of the compartment surface. Above this height, a sprinkler becomes preferred over the use of encapsulation."

For larger compartment she writes: "Similar results are obtained for a compartment with a GFA of 140 m2. From these results follows that a fully exposed CLT compartment is preferred up to a building with 4 building storeys, after which a sprinkler is preferred. Again, considering the requirements it is proposed to construct residential buildings up to 3 storeys without additional fire safety measures. For 4-storey buildings, encapsulation is suggested. For a building higher than 4 building storeys, a sprinkler is preferred over the use of encapsulation"

2.4.13. Regulation related to external flaming

prEN 1995-1-2:2023 Annex E
NEN 6068

2.4.14. Regulation related to separating function

prEN 1995-1-2:2023 Annex A clause (2)

2.4.15. Relevant regulations within the BBL

The dutch law refers to the building decree called Besluit Bouwwerken Leefomgeving (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2024), which states a number of performance requirements that could be categorized in the building level. The requirements that are relevant when comparing fire safety in timber buildings to that in 'traditional' (concrete, steel, brick) buildings are summarized below.

- Article 4.65 describes the general requirements for escape route.
- Article 4.66 describes the egress from inside a 'subbrandcompartiment' to the exit of this 'subbrandcompartiment.'
- Article 4.69 gives the requirements for an 'extra beschermde vluchtroute.'
- Article 4.71 gives the requirements for a second escape route.
- Article 4.77 gives the case when a 'rooksluis' (smoke lock) needs to be used, along with its requirements.
- Article 4.84 gives requirements concerning a firefighting lift.
- Article 4.85 gives requirements concerning the walking distance for firefighters.
- Article 4.89 refers to requirements in 'SBRCURnet Handreiking – Brandveiligheid in hoge gebouwen' for buildings with usable floorspace higher than 70 meters.
- Articles 4.91–4.96 describe the requirements of building components adjacent to a 'branvoorschriftengebied' or 'explosievoorschriftengebied' (areas and roads where dangerous compounds are transported).
- Articles 4.208–4.211 describe if and what type of fire and smoke detection systems are required.
- Article 4.212 describes if and what type of evacuation alarm system is required.
- Article 4.228 states that if a building has a usable floor space higher than 20 meters, there needs to be a firefighting lift.
- Article 6.14 describes the fire safety requirements concerning 'aankleding' (which refers to curtains, ornaments, and other items that are not part of the construction or furnishing).

For the exact description of the requirements see Besluit Bouwwerken Leefomgeving (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2024).

3 Methodology

Methodology introduces the scope and limitations of the research. This chapter also introduces the models used for obtaining the research data.

3.1. General scope and limitations

This thesis focuses on **CLT buildings**. The range of opening factors and compartment sizes simulated (see section 3.4) in this thesis are in line with those found in CLT apartment buildings (see sections 2.3.6 and 2.3.7).

The **Dutch context** is chosen. According to Brandon et al. (2022) the fire safety in mass timber buildings described by the functional requirements in the Netherlands is likely not sufficiently covered by current performance requirements in the regulations. The BBL provides qualitative functional requirements (high level requirements providing fire safety). And in order to specify each of these, it also provides quantitative performance requirements (explicit rules for building) which must be met. Note, however, that these current performance requirements will likely not guarantee that the functional requirements are met in timber buildings.

As an alternative to strictly adhering to the prescriptive requirements, the Dutch Building Code allows for an equivalent solution. This alternative solution should demonstrate compliance with the functional requirements through a performance-based or risk-base approach. The key is to achieve an equivalent level of fire safety as specified by the building code. In practice, such an equivalent solution needs approval from local authorities and the fire brigade.

In this thesis we verify fire behaviour models on the basis of CLT compartment fire tests by Brandon et al. (2021a). We also simulate an array of realistic compartment designs with the models, to get a general understanding of the trends and correlations of the design choices and the fire behaviour. We also check these designs for structural fire safety. Finally we simulate various degrees of protection.

3.2. Fire behavior models used in compartment analysis

This master thesis involves simulations with three fire behaviour models. These models simulate the fire development and the charring. The three models are further outlined bellow.

3.2.1. Eurocode model adapted for CLT compartment (EC)

Frederik Mollen Poulsen and Javor Panev created a tool that calculates a fire curve adapted specifically for timber buildings. It also calculates the char depth. This tool is usable in a python IDE (Integrated Development Environment). The parametric fire curve in the Eurocode, specifically outlined in EN 1991-1-2, Annex A, is a method used to model the temperature development in a fire compartment over time. This curve accounts for various factors such as the fire load, ventilation conditions, and the thermal properties of the compartment boundaries. It provides a more realistic representation of fire behavior compared to the standard fire curve by including phases of fire growth, fully developed fire, and decay. This approach helps in designing structures to withstand real fire scenarios more effectively.

Frederik Mollen Poulsen adapted this model by adding an iterative process of charring to calculate the char depth in timber structures.

3.2.2. Zehfuss Hosser modified decay phase model (ZHM)

In Zehfuss and Hosser (2006) the iBMB model (origins of name: Institute of Building Materials, Concrete Structures and Fire Protection, Braunschweig University of Technology) is presented. It considers fire load, ventilation conditions, geometry and thermal properties of the compartment. The authors derived the parametric fire curves using heat balance simulations. According to Zehfuss and Hosser (2006) ”Contrary to the Eurocode 1 parametric temperature–time curves, the iBMB parametric fire curves are directly derived from the rate of heat release defining the design fire”. The authors claim that this model is most suited for steel structures. The model uses three mathematical formulas to describe three sections of the parametric fire curve. Section three represents the cool down phase.

Frederik Mollen Poulsen adapted this model by adding an iterative process of charring to calculate the char depth in timber structures. He also altered (extended) the leg of the cool down phase, that is more suited for simulating timber compartments.

3.2.3. Zone model (Brandon)

Daniel Brandon’s single-zone model (introduced in Brandon (2016) and Brandon and Anderson (2018) and update introduced in Brandon et al. (2021b)) for timber compartments is designed to predict fire behavior in mass timber structures, such as those made from Cross-Laminated Timber (CLT) and glulam. The model operates on the principle of energy equilibrium, calculating gas and surface temperatures within the compartment. A key aspect of the model is its ability to predict the charring rate of timber, which is essential for understanding how the structure will behave during a fire. This is achieved by incorporating the energy contribution from the charring process into the overall energy balance. The model also includes through-depth temperature calculations of the timber members, which help determine the combustion rate and provide data for structural integrity assessments.

3.3. Verification of fire development models with existing CLT compartment fire tests

The tests 1-5 as described in Brandon et al. (2021a) are modeled with fire behaviour models (EC, ZHM and Brandon) described above. These test were validated in Brandon et al. (2021b), where the Zone model was adjusted. Now simulations are done with all three models and the results are then compared with the obtained results from the physical tests. The aim is to find similarities in the fire behaviour and the charring depth with all models, and if necessary strategies for amending the results are suggested.

3.4. Simulation of realistic CLT fire compartments

We simulate 24 realistic CLT fire compartments with the three fire behaviour models described in section 3.2. We do this to calculate the fire curve and the resulting char depth for several compartments designs to be able to observe trends and correlations in the results. Below we describe the variations in compartment size, shape amount of exposed timber and opening factors used in order to test a spread of compartments typical for CLT apartment buildings. We also check the structural fire safety of the ceiling panel.

3.4.1. Compartment size and shape

A ceiling height of 2.74 m is considered in all compartments. The following are the **apartment areas considered**:

- (Ss) Studio apartment (area = 6 * 6 = 36 m^2)
- (Sr) Studio apartment (area = 12 * 3 = 36 m^2)
- (Ms) Three bedroom apartment (area = 10 * 10 = 100 m^2)

- (Mr) Three bedroom apartment (area = 20 * 5 = 100 m^2)

These values are chosen according to the low and high extremes from the CLT compartment size study of Brandon et al. (2021a). These are realistic compartment sizes in the Netherlands, as student housing studios and three bedroom apartments are commonly built at the moment of writing. For both sizes a square geometry and a rectangular geometry are chosen. The models take compartment geometry into account: narrower geometry generally exaggerates the fire behavior. The naming structure is as such: e.g. the compartment 'Mr' stands for **m**edium size, **r**ectangular compartment.

3.4.2. Amount of exposed timber

Four different exposed timber areas are considered:

- (1) 30 % of enclosing area (∼exposed ceiling)
- (2) 40 % of enclosing area (∼ exposed ceiling and one wall)
- (3) 70 % of enclosing area (∼ all walls and ceiling exposed)

The 30 % option is a good 'compromise' which allows for the CLT to be 'showed off aesthetically', however, it contributes a relatively low amount to the fire if ensured that the exposed timber surfaces are never facing each other: removing the risk of re-radiation (see section 2.3.3); only exposing the timber in the ceilings is a good choice in this case, as potential failure of a floor is also less likely to cause progressive collapse than the failure of a wall (or column) and re-radiation between initially exposed surfaces is not possible.

3.4.3. Opening factors

Three opening factors are considered taking into account the distribution of opening factors described in Brandon et al. (2021a). $O = 0.062\ m^{1/2}$ represents the 85th percentile of damage to the exposed timber surface. $O = 0.17\ m^{1/2}$ represents the highest opening factor recorded for mass timber residential buildings (Brandon et al., 2021a).

- (i) Opening factor $O = 0.062\ m^{1/2}$ (Brandon et al., 2021a)
- (ii) Opening factor $O = 0.17\ m^{1/2}$

3.4.4. Naming convention of compartments

24 combinations are formed when cycling through these parameters. The naming system of the combinations is according to the symbols that are given in the lists above. E.g. the combination with the name: Mr3i, represents a 100 m^2, rectangular apartment with timber exposed in 70 % of the total encapsulating area, and has an opening factor of $O = 0.062m^{1/2}$.

3.4.5. Structural analysis

In this master thesis we focus on the load bearing capacity (R) of the CLT floor plate of the compartment above the compartment with a fire. This is done, to be able to give an indication, and is not a full structural analysis. Such an exhaustive analysis would require more time than allowable in the master thesis. Another reason why we analysed floor plates, is because ceilings are often the surfaces that are chosen to be left exposed in contemporary designs. They also allow for a general calculation method as this does not change respective of the building height. Floor plates are loaded in bending, which is also more favorable than walls as they are typically loaded in compression and the timber strength in compression is diminished at lower temperatures than that in bending, causing the effective cross-section in compression to be smaller than that in bending. For these reasons we assume that walls will not be left unprotected in tall buildings for now. A follow up study could also look at the structural resistance in walls for these compartments.

3.5. Analysis of degrees of protection

In this analysis we model various degrees of protection. Five degrees of protection are used to define how much timber is visible and what requirements the protection has to adhere to. The results for each simulation (charring depths and fire behaviours) are then shown and compared with each other.

4

Verification of fire behaviour models

This chapter addresses the following objective of the thesis:

3. Validate fire development models by comparing them with test data

This chapter answers the following research questions:

3. In what degree do fire development and charring models agree with test data of a 48 square meter compartment?

In this chapter, we simulate the 5 CLT fire compartment tests as described in Brandon et al. (2021a) with fire behaviour models (EC, ZHM and Brandon). In Brandon et al. (2021b) the Brandon model is already compared with the 5 full scale compartment tests and updated accordingly. We will use the results from the 5 tests now to compare them to all three of the fire behaviour models described in section 3.2 (EC, ZHM and Brandon). The Brandon model we use is this thesis is described in Brandon et al. (2021b), which is the updated version of the zone model introduced in Brandon and Anderson (2018) and Brandon (2016). For further info on the Brandon model see section 3.2.3.

Brandon et al. (2021a) states: ”The dimensions of the compartment, size of the openings and fuel load density were determined from a probabilistic analysis aiming to test a severe fire scenario that is based on the designs of real buildings ...”. In the tests, there is no glazing in the window openings, this is also how the simulations are modelled. It is important to note, that these tests show a scenarioY where there is no fire-fighting intervention, except for test 3 where intervention was needed to prevent a revitalisation of flaming and temperature increase. In the other tests the smoldering and hot sports were manually extinguished after 4 hours. The boundary conditions for the 5 tests are shown in Table 4.1. The glue used in the test is the HB X Purbond by Henkel, which demonstrates adhesive performance in fire. This means that they can withstand a long duration compartment fire without delamination occurring.

Name	Test 1	Test 2	Test 3	Test 4	Test 5
Opening factor [$m^{1/2}$]	0.062	0.062	0.062	0.25	0.062
Floor area [m^2]	48	48	48	48	48
Wall length A [m]	7.0	7.0	7.0	7.0	7.0
Wall length B [m]	6.85	6.85	6.85	6.85	6.85
Height of ceiling [m]	2.73	2.73	2.73	2.73	2.73
Variable fire load [MJ/m^2]	560	560	560	560	560
Exposed mass timber surfaces [m^2]	53.8	91.2	96.2	77.9	97.2
Perc. of exp. mass timb. surf. [%]	31	53	56	45	57
Layers of 15.9 mm type X fire resistant gypsum board	2	3	3	2	3

Table 4.1: Design choices for the 5 tests in Brandon et al. (2021a)

4.1. Analysis

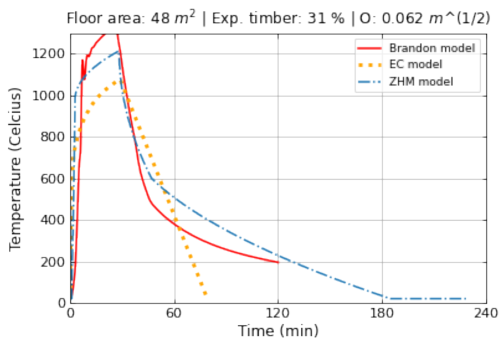
In this section the gas temperature of the simulations is plotted against the gas temperature measured in the tests. Also the charring depth of the simulations is plotted against that of the tests in bar plots.

4.1.1. Test 1

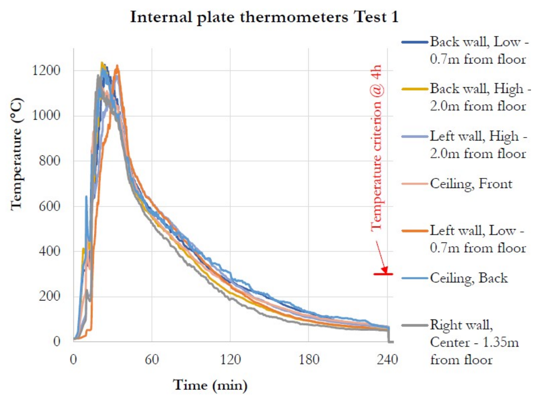
Figure 4.1 shows plots of the temperature vs time curves of the simulation based on test 1 (gathered from Brandon et al. (2021a)) and the two plots superimposed. Accounting for the fact that the simulations reach flash-over 10 minutes earlier than the timeline of the test, sub-figure d shows a plot where the flash-over times are adjusted to be synchronised.

The EC model underestimates the peak temperature and underestimates the temperature in the decay phase. The ZHM model predicts the peak temperature and the decay phase temperature closely. The Brandon model overestimates the peak temperature and underestimates the temperature in the decay phase.

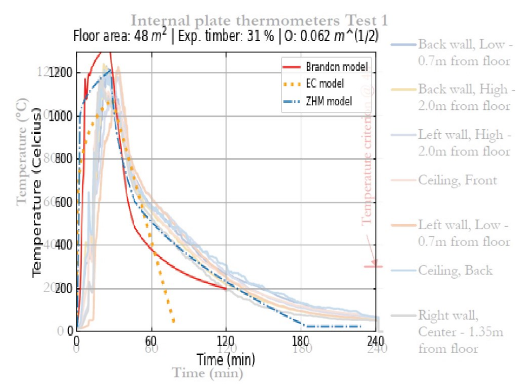
Figure 4.2 shows the charring depth measured in the test 1 by Brandon et al. (2021a). According to this figure the maximum char depth measured in the test (only ceiling exposed) is 45 mm. This suggests that the EC model (char depth of 38 mm) is not conservative for this compartment (see table 4.1). The ZHM seems to be more suitable for this compartment, given that its simulated charring depth is equal to the maximum charring depth seen in the test (45 mm). The Brandon model gives a conservative estimate for the charring depth (52 mm) that is greater than the measured charring depth.



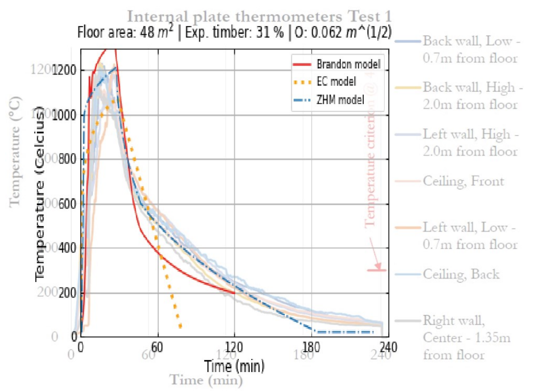
(a) Simulation



(b) Physical test Brandon et al. (2021a)

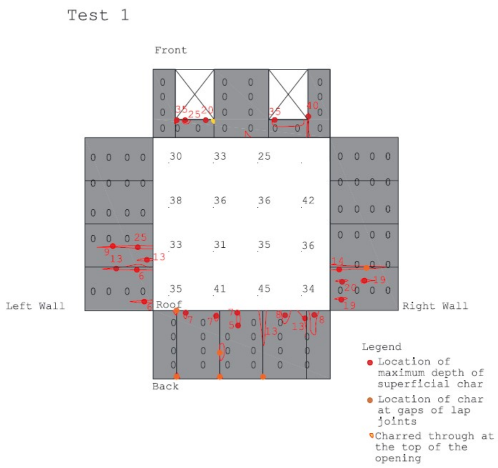


(c) Simulation and physical test data in one graph

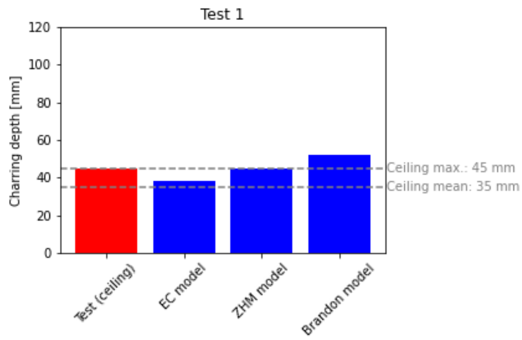


(d) Simulation and physical test data in one graph and adjusted for timing of flash-over

Figure 4.1: Fire behaviour in physical test 1, in the simulation and the two superimposed



(a) Charring depth measured in test 1 by Brandon et al. (2021a); protected surfaces are visualized in grey



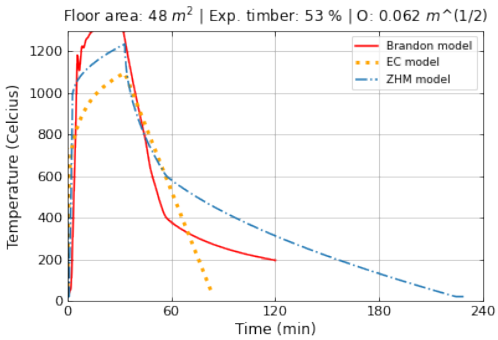
(b) Comparison of charring depth between test results and simulation results

Figure 4.2: Charring depth

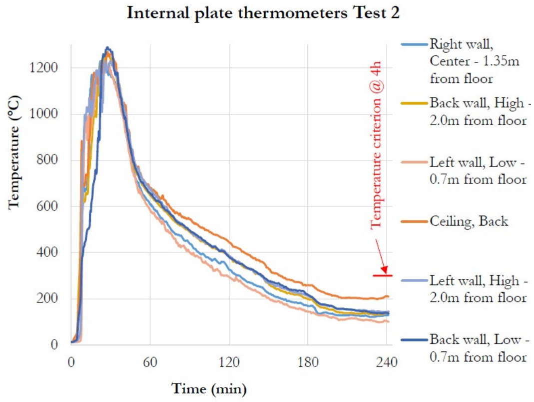
4.1.2. Test 2

Figure 4.3 shows plots of the temperature vs time curves of the simulation based on test 2 (gathered from Brandon et al. (2021a)) and the two plots superimposed. In this example it seems that the peak of the fire scenario of the ZHM model is most aligned with the test data. The EC model does not reach the peak temperature by a difference of 60 degrees Celsius. The ZHM model follows the gas temperature curve accurately both in the peak (underestimating with 50 K) and in the decay phase (slight underestimation for most of decay). The Brandon model overestimates the peak temperature and underestimates the temperature in the decay phase.

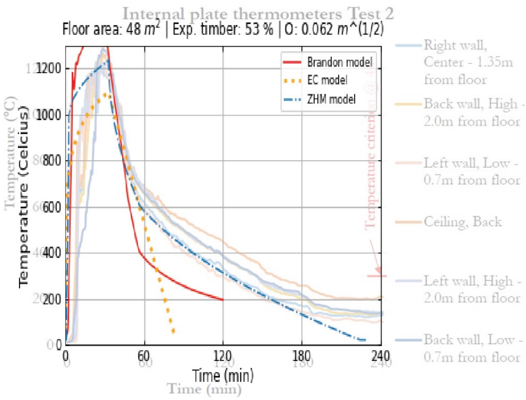
The simulation with the EC model gives a charring depth of 42 mm, the ZHM gives 53 mm and Brandon model gives 62 mm. Figure 4.4 shows the charring depth measured in the test 2 by Brandon et al. (2021a). According to this figure the maximum char depth measured in the test ceiling is 57 mm and in walls is 86 mm. The ZHM model underestimates the maximum charring depth found in the test in the ceiling by 4 mm and in the wall by 33 mm. This suggests, that in similar compartments the ZHM model will result in more non-conservative charring depth estimation. The prediction of the Brandon model is conservative for the maximum charring depth in the ceiling.



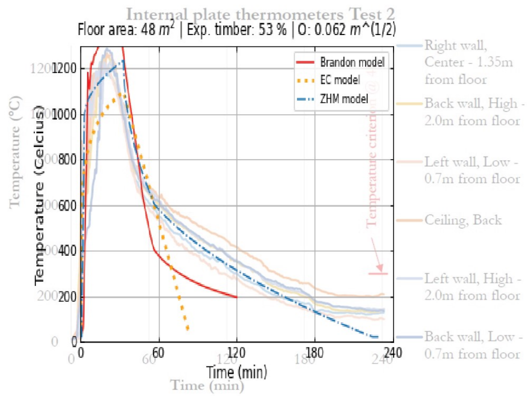
(a) Simulation



(b) Physical test Brandon et al. (2021a)

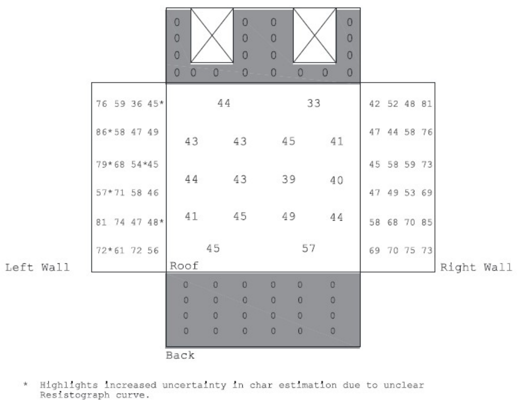


(c) Simulation and physical test data in one graph

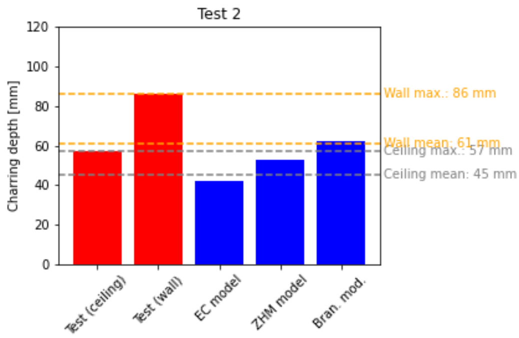


(d) Simulation and physical test data in one graph and adjusted for timing of flash-over

Figure 4.3: Fire behaviour in physical test 2, in the simulation and the two superimposed



(a) Charring depth measured in test 2 by Brandon et al. (2021a); protected surfaces are visualized in grey



(b) Comparison of charring depth between test results and simulation results

Figure 4.4: Charring depth

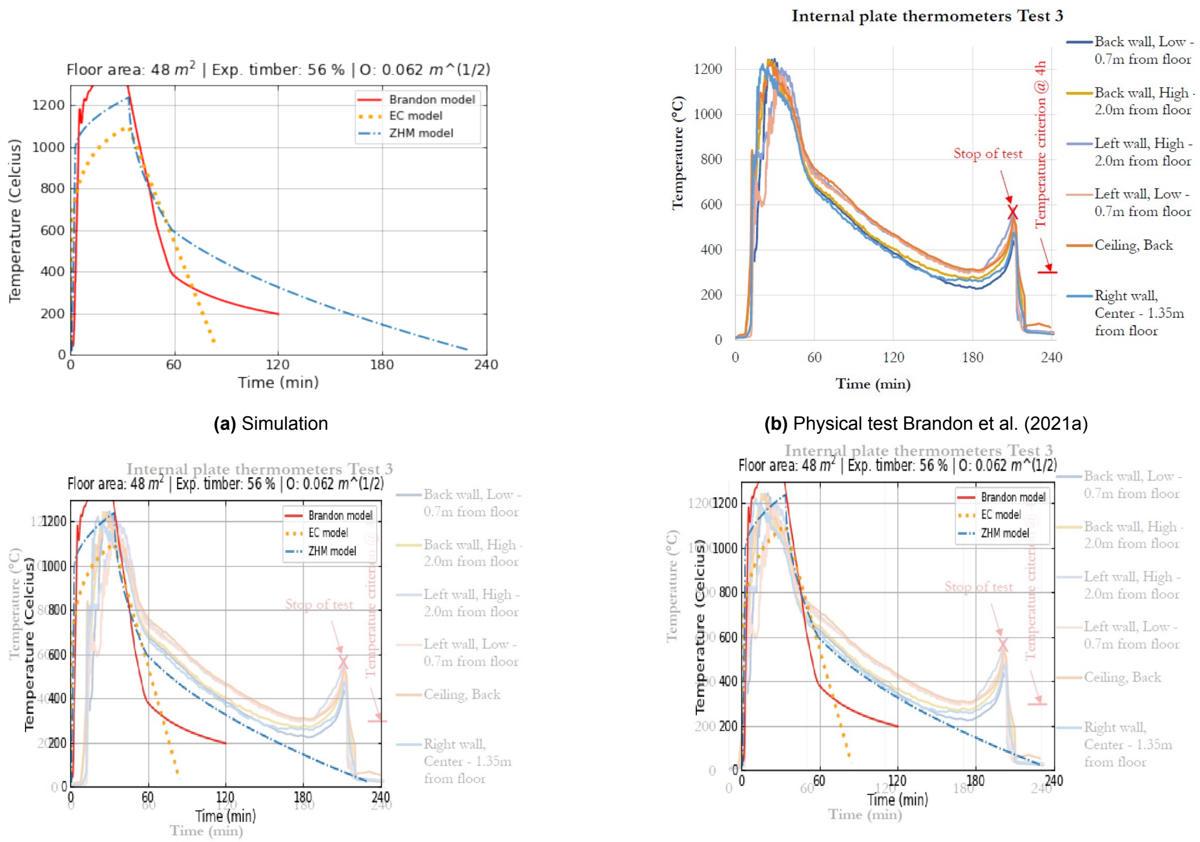
4.1.3. Test 3

In the setup, there are places where two exposed timber walls meet in a corner. Test 3 was prematurely ended, when the temperature started rising again rapidly. This was done at around 210 minutes after the ignition of the fire. This means that the results of the physical test cannot be compared one-to-one to the other tests, because the fire was extinguished manually as the flaming did not stop by its self.

Figure 4.5 shows plots of the temperature vs time curves of the simulation based on test 3 (gathered from Brandon et al. (2021a)) and the two plots superimposed. The ZHM model captures the temperature in the peak of the fire scenario closely, whereas the EC model is lower by 60 degrees Celsius. The ZHM folows the decaying curve, but shows a constantly a lower temperature (100 k). The Brandon model overestimates the peak temperature and underestimates the temperature in the decay phase. The test shows a revitalization of the fire, that could have potentially lead to a second flash-over if the scientists conducting the test did not stop the test. The simulation models do not show such behaviour, because bond-line integrity and delamination are not included in these models.

The simulation with the EC model gives a charring depth of 42 mm and the ZHM gives a charring depth of 55 mm. Figure 4.6 shows the charring depth measured in the test 3 by Brandon et al. (2021a). According to this figure the maximum char depth measured in the test is 58 mm in the ceiling and 104 mm in the wall. This suggests that the EC model is not conservative for this compartment (see table 4.1. The ZHM model seems to simulate the charring depth of the ceiling with a difference of 3 mm, the charring depth of the walls are much higher than the simulated charring depth. ZHM underestimates the charring depth in the wall with 49 mm. The Brandon model manages to predict the maximum charring depth in the ceiling and underestimates the maximum charring depth in the walls.

The largest charring depth is seen in the lower quarter of the walls as smoldering ash laying on the ground continues to heat the wall at this height. Also the proximity to the windows increases the charring depth, as here there is ample oxygen to provide for the smoldering, as opposed to other parts of the compartment that have become ventilation-controlled. This is exaggerated on lower parts of the wall close to the window as the cooler air comes into the compartment through the lower part of the window, as the upper part of the window is where the hotter air leaves. The places where two walls meet in an 90 degrees angle is also a place of increased charring depth as re-radiation between the walls takes place, in addition to re-radiation with ash on the ground surface.



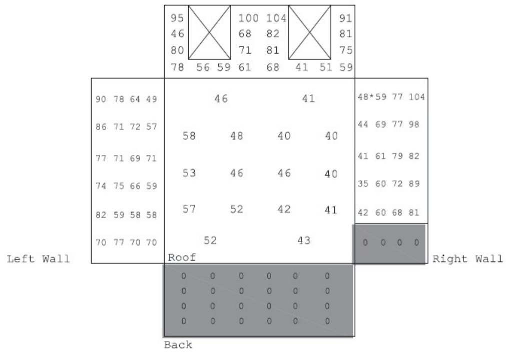
(a) Simulation

(b) Physical test Brandon et al. (2021a)

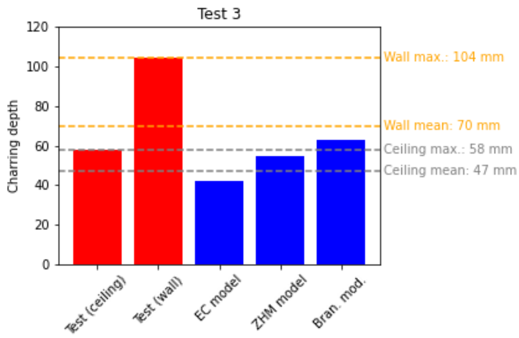
(c) Simulation and physical test data in one graph

(d) Simulation and physical test data in one graph and adjusted for timing of flash-over

Figure 4.5: Fire behaviour in physical test 3, in the simulation and the two superimposed



(a) Charring depth measured in test 3 by Brandon et al. (2021a); protected surfaces are visualized in grey



(b) Comparison of charring depth between test results and simulation results

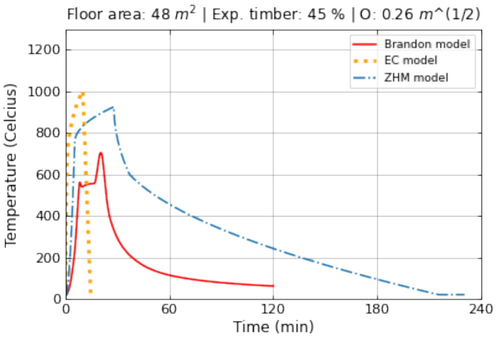
Figure 4.6: Charring depth

4.1.4. Test 4

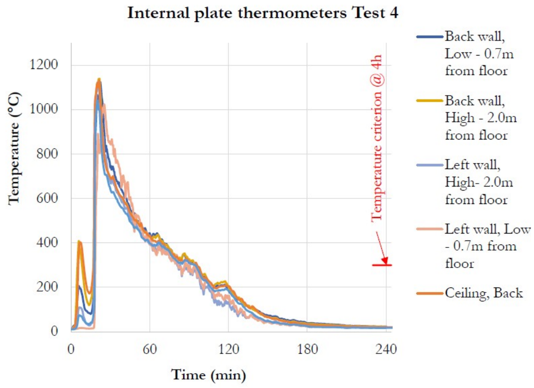
In test 4, the opening factor is increased to $O = 0.25\ m^{1/2}$ and in the setup, there are places where two exposed timber walls meet in a corner. The ratio of exposed surfaces vs the total encapsulating area is less than in test 2,3 or 5, (due to the large window openings where there is no exposed timber).

Figure 4.7 shows plots of the temperature vs time curves of the simulation based on test 4 (gathered from Brandon et al. (2021a)) and the two plots superimposed. Neither simulations EC or ZHM reach the maximum temperature at peak of fire in the test data. EC underestimates the test peak by 200 degrees Celsius and ZHM underestimates the peak temperature by 230 degrees Celsius. The ZHM method is conservative in the decay phase as it constantly models higher temperatures than that measured in the test. The Brandon model underestimates the peak gas temperature with 400 K and underestimates the gas temperature in the decay phase.

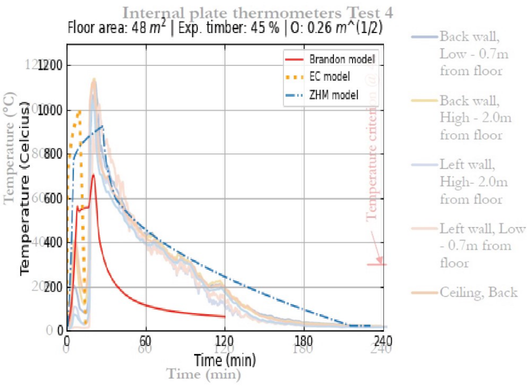
The simulation with the EC model gives a charring depth of 12 mm and the ZHM gives a charring depth of 28 mm. Figure 4.8 shows the charring depth measured in the test 1 by Brandon et al. (2021a). According to this figure the maximum char depth measured in the test is 45 mm in the ceiling and 104 mm in the walls. The ZHM model underestimates the maximum charring in the ceiling by 17 mm and in the walls by 96 mm. The Brandon model also underestimates both the maximum char depth in the ceiling and in the walls.



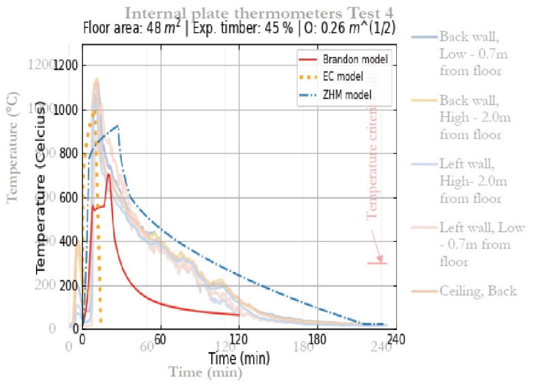
(a) Simulation



(b) Physical test Brandon et al. (2021a)

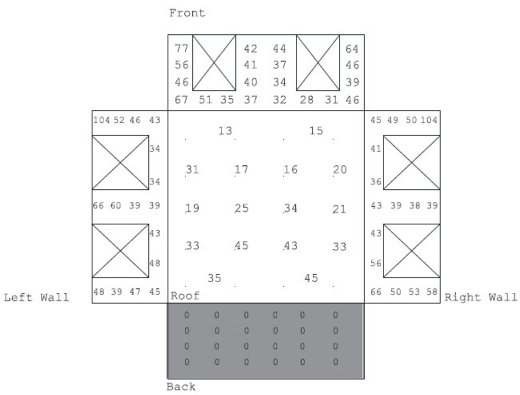


(c) Simulation and physical test data in one graph

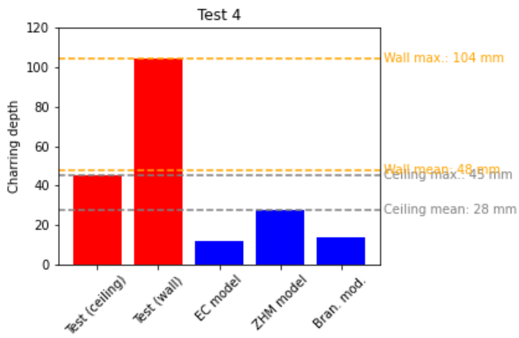


(d) Simulation and physical test data in one graph and adjusted for timing of flash-over

Figure 4.7: Fire behaviour in physical test 4, in the simulation and the two superimposed



(a) Charring depth measured in test 4 by Brandon et al. (2021a); protected surfaces are visualized in grey



(b) Comparison of charring depth between test results and simulation results

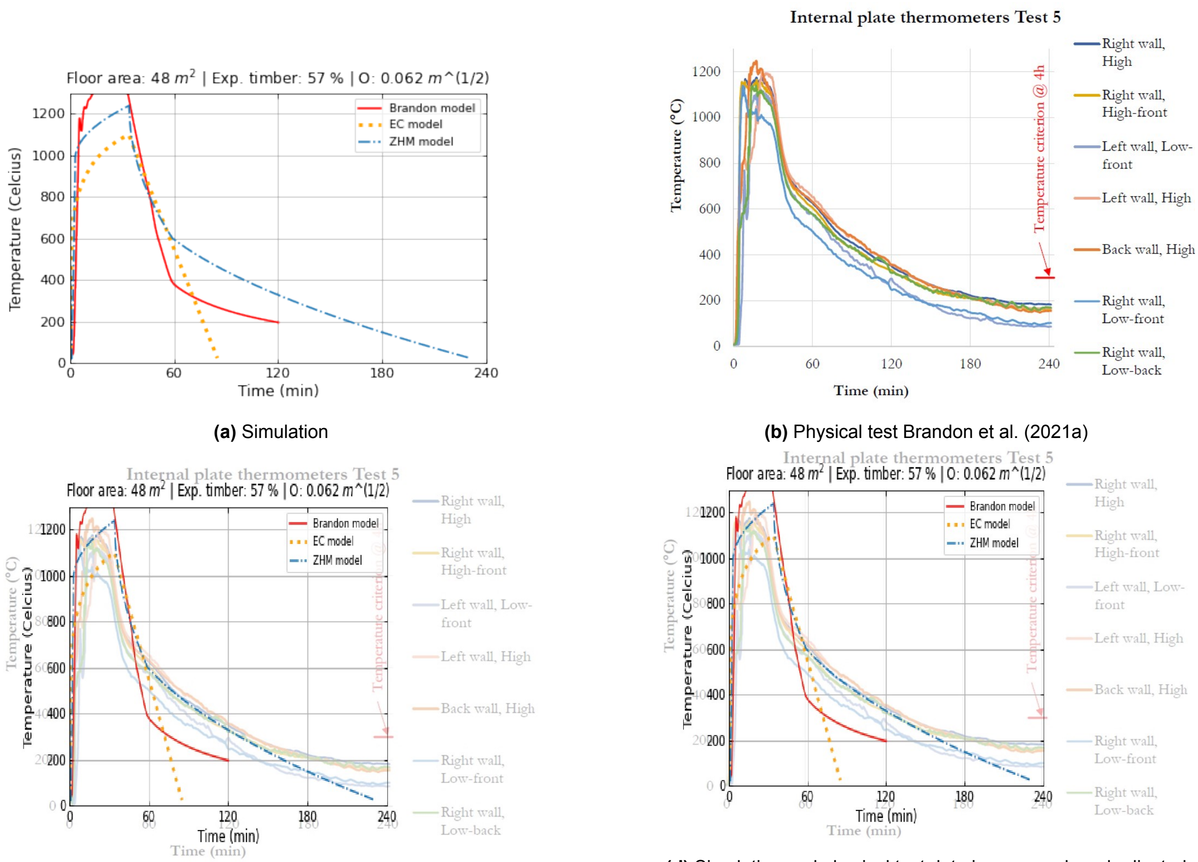
Figure 4.8: Charring depth

4.1.5. Test 5

Test 5 again uses the lower opening factor of $O = 0.062\ m^{1/2}$ and the same ratio of exposed timber as Test 3. In the setup of test 5 however there are no two exposed timber walls meeting in a corner like there is in Test 3. Additionally, test 3 was ended prematurely because of the revitalisation of the fire. In contrast, test 5 auto-extinguished. Therefore, the results of Test 5 cannot be compared one-to-one with those of Test 3.

Figure 4.9 shows plots of the temperature vs time curves of the simulation based on test 5 (gathered from Brandon et al. (2021a)) and the two plots superimposed. The EC model does not reach the peak temperature measured in the test. The ZHM model reaches the peak temperature and follows the temperature development measured in the test during the fire decay phase. The Brandon model underestimates the peak gas temperature and the gas temperature in the decay phase.

The simulation with the EC model gives a charring depth of 43 mm and the ZHM gives a charring depth of 55 mm. Figure 4.10 shows the charring depth measured in the test 1 by Brandon et al. (2021a). According to this figure the maximum char depth measured in the test is 73 mm in the ceiling and 95 mm in the walls. This suggests that the EC model underestimates the measured maximum charring depth with 52 mm. The ZHM model underestimates the charring in the ceiling by 18 mm and in the walls by 40 mm. The Brandon model gives a higher charring depth, which is still not as high as the measured charring depth in the ceiling or in the wall and is therefore non-conservative.



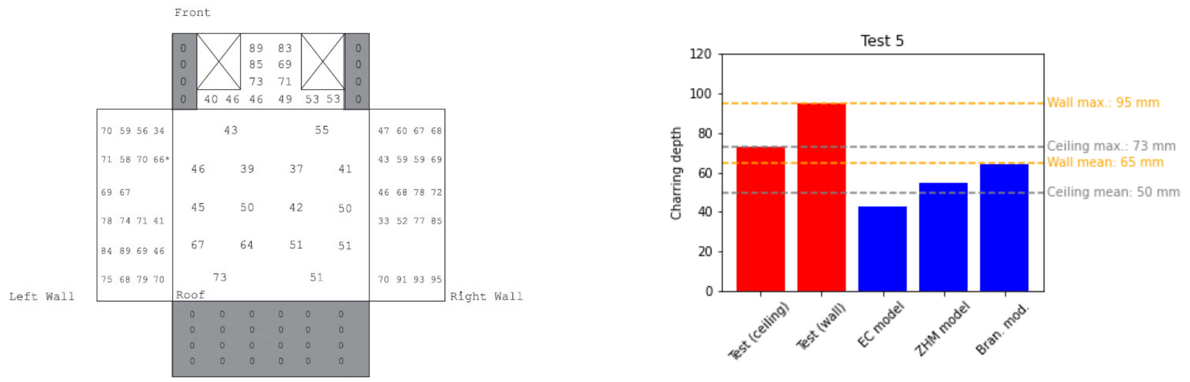
(a) Simulation

(b) Physical test Brandon et al. (2021a)

(c) Simulation and physical test data in one graph

(d) Simulation and physical test data in one graph and adjusted for timing of flash-over

Figure 4.9: Fire behaviour in physical test 5, in the simulation and the two superimposed



(a) Charring depth measured in test 5 by Brandon et al. (2021a); protected surfaces are visualized in grey

(b) Comparison of charring depth between test results and simulation results

Figure 4.10: Charring depth

4.2. Discussion

In this section, the data obtained above is discussed and placed in the context of design. The EC model is non-conservative in all the following tests and so is omitted in the further discussion.

4.2.1. Opening factor

Only test 4 has a larger opening factor of $O = 0.25\ m^{1/2}$ compared to $O = 0.062\ m^{1/2}$ in tests 1,2,3 and 5. Inline with expectations, in test 4 we observe a shorter fire with a lower peak gas temperature, compared to the other tests. Heat can dissipate quicker through the large openings, and since the fire will in most places have enough oxygen, which allows the fuel to burn at a faster rate.

4.2.2. Exposed timber and orientation of walls

As expected we see an increase in fire duration and char depth in the tests with more exposed timber. Tests 3 and 4 also have corners where two exposed CLT walls meet. In these cases the charring depth in the test result is significantly increased in the lower part of these wall corners Brandon et al. (2021a). The simulations showed an increase in char depth as exposed surfaces increased, but as it is not possible to model which walls are exposed, the effect of orientation of walls was not modelled (see similarity between simulation results of test 3 and 5).

4.2.3. Implications for design

As the test results suggest, the maximum charring depth in a ceiling is typically found close to the back wall (furthest away from the window openings). In case of the walls, the maximum charring depth are typically found in the strip close to the floor (lowest quarter of the wall), and/or close to the window openings.

The study suggests that the ZHM and Brandon models are able to simulate the average char depth in the ceiling. For compartments that have percentage of exposed mass timber and an opening factor equal to that in test 1 of Brandon et al. (2021a), the outcomes of the Brandon and the ZHM models give conservative results for the the maximum char depth in the ceiling. There is a discrepancy between the simulation results and the maximum char depth in the walls when amount of exposed timber and opening factor were increased beyond the values used in test 1 of Brandon et al. (2021a). Suggestions for correction factors based on linear interpolation are given to arrive at a better approximation for the maximum char depth. It is advised to use CFD and/or compartment fire tests for any compartments that differ from tests 1-5 in Brandon et al. (2021a). Targeted design measures were listed to protect the critical areas where maximum char depth is expected.

Consequences of failure or partial failure of the structural component at the extreme charring location is to be reviewed case-by-case. When designing columns, the risk caused by the extremes in charring depth are higher, because of the increased risk of collapse or progressive collapse when a column fails. It is advised to account for the discrepancy between the predictions and the maximum charring depth by using extra measures. Suggestions for extra measures include the following, to be used separately or in combination: extra 'sacrificial' layer of CLT around columns or structurally 'important' walls, the use of a protective plinth around columns or along walls, to protect lower quarter of walls and extra 'sacrificial' layer for ceiling panel.

I propose two correction factors based on linear interpolation that account for the opening factor and on the amount of exposed timber. Use of bi-linear interpolation (taking into account the two variables simultaneously) is also a possibility. This however takes an extra step of interpolation, and will give less conservative results and so is omitted.

$$d_{char,ceiling,op,ZHM} = 15 * \frac{O - 0.062}{0.188} \tag{4.1}$$

or

$$d_{char,ceiling,op,Brandon} = 25 * \frac{O - 0.062}{0.188} \tag{4.2}$$

And for the walls:

$$d_{char,wall,op,ZHM} = 70 * \frac{O - 0.062}{0.188} \tag{4.3}$$

or

$$d_{char,wall,op,Brandon} = 80 * \frac{O - 0.062}{0.188} \tag{4.4}$$

The O in the formula representing the opening factor in the given compartment.

To address the uncertainty introduced by the amount of exposed timber, we advise the use of the following formula for the ceiling:

$$d_{char,ceiling,ex,ZHM} = 15 * \frac{A_{ex} - 30}{25} \tag{4.5}$$

or

$$d_{char,ceiling,ex,Brandon} = 10 * \frac{A_{ex} - 30}{25} \tag{4.6}$$

And for the walls:

$$d_{char,wall,ex,ZHM} = 35 * \frac{A_{ex} - 30}{25} \tag{4.7}$$

or

$$d_{char,wall,ex,Brandon} = 30 * \frac{A_{ex} - 30}{25} \tag{4.8}$$

The A_{ex} in the formula representing the percentage of exposed timber of the encapsulating area in the given compartment.

Or more elegantly:

For the ceiling:

$$d_{char,ceiling,ZHM,pen} = 15 * \frac{O - 0.062}{0.188} + 15 * \frac{A_{ex} - 30}{25} \tag{4.9}$$

or

$$d_{char,ceiling,Brandon,pen} = 25 * \frac{O - 0.062}{0.188} + 10 * \frac{A_{ex} - 30}{25} \tag{4.10}$$

And for the walls:

$$d_{char,wall,ZHM,pen} = 70 * \frac{O - 0.062}{0.188} + 35 * \frac{A_{ex} - 30}{25} \tag{4.11}$$

or

$$d_{char,wall,Brandon,pen} = 80 * \frac{O - 0.062}{0.188} + 30 * \frac{A_{ex} - 30}{25} \tag{4.12}$$

Advised maximum charring depth would be as follows:

Max. char depth estimation = Simulated char depth + Total correction

It is advised to use CFD and/or compartment fire tests for any compartments that differ from tests 1-5 in Brandon et al. (2021a).

5

Simulation of 24 CLT compartments

This chapter addresses the following objective of the thesis:

4. Analyse the fire progression and char depth for a set of realistic fire compartments in order to find relevant trends and correlations

This chapter answers the following research questions:

4. What are trends and correlations between design choices and charring depth

In this chapter we simulate 24 fire compartments with the 3 fire behaviour models (EC, ZHM and Brandon). We used research data from Annex C of Brandon et al. (2021a) to design 24 compartments in such a way, that they envelop the range of realistic fire compartments in existing CLT apartment buildings. The floor sizes, shapes, opening factors and amount of exposed timber chosen for each compartment are described in section 3.4.

5.1. Pilot study

First a pilot study is done to show on one example compartment the step-by-step calculations that are later done on all 24 compartments.

5.1.1. Example compartment

As mentioned in the methodology, 24 different compartments will be analysed in this master thesis. In this pilot study chapter, we pick one compartment and use it to demonstrate the procedure of data collection. The compartment we pick is Ms1ii (medium sized, square shaped, 30 % of surrounding area is visible timber, opening factor is $O = 0.17m^{1/2}$)

Some more details of this compartment are as follows: the wall height is chosen as 2.74 meters. The compartment is square shaped with walls each with a length 10 meters. The compartment has 13 openings with dimensions 1.68 x 1.8 meters, which results in an opening factor of $O = 0.17\ m^{1/2}$. The variable fire load is chosen to be $180MJ/m^2$ per total-encapsulating-area (floor + ceiling + walls) which is equivalent to approximately $570\ MJ/m^2$ per floor area. This value is chosen for the variable load because it is equal to the fire load provided by $30\ kg/m^2$ of spruce wood as defined in NEN 6081. In terms of fire load provided by the structure: $93m^2$ which is approximately 30% of the total-encapsulating-area is left as unprotected CLT. The rest of the CLT surface is modelled in such a way, that the protection cannot fall off and so there cannot be charring behind the protection. And it is assumed that all window glass breaks, resulting that all the openings are free for gasses to flow through.

5.1.2. Charring depth and temperature time curves

We use the EC and ZHM fire curve tool developed by Javor Panev and Frederik Poulsen described in more detail in 3 and the zone model created by Brandon et al. (2021b).

The models EC and ZHM are run by inputting the compartment details in a python script (see A). The zone model was run by Daniel Brandon using a batch file we provided.

The resulting char depths are printed in Table 5.1. A graph showing the fire behaviour of the models is shown in Figure 5.1.

	EC model	ZHM model	Brandon model
Char depth (mm)	20	37	27

Table 5.1: Calculated char depths of EC and ZHM models and zone model for compartment Ms2ii

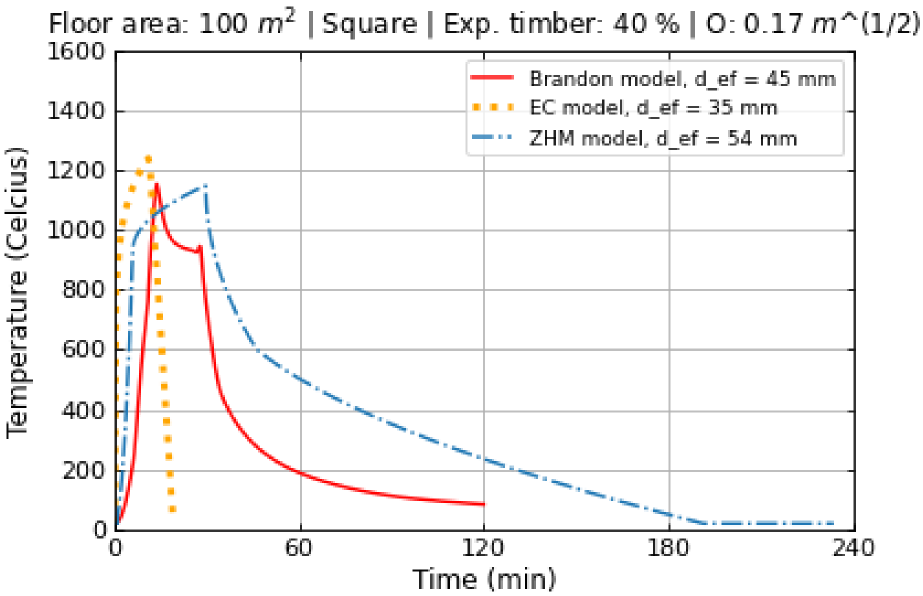


Figure 5.1: Temperature-time curves of EC and ZHM models and the zone model for compartment Ms2ii for reference the standard fire curve is included

5.1.3. Structural fire safety

We use the char depths obtained to assess whether the structure fails or not. We use the method described in the eurocodes (the load combinations from EN 1990, the magnitudes for loads from EN 1991-1-1 and the verification calculations from prEN 1995-1-1:2023 and prEN 1995-1-2:2023).

As discussed in chapter 3.4.5, we analyse a CLT floor plate.
We chose a generic floor structure made of a CLT plate simply supported on CLT walls. We picked a floor plate using KLH (2019). For a summary of all the assumptions made for the structure see Table 5.2

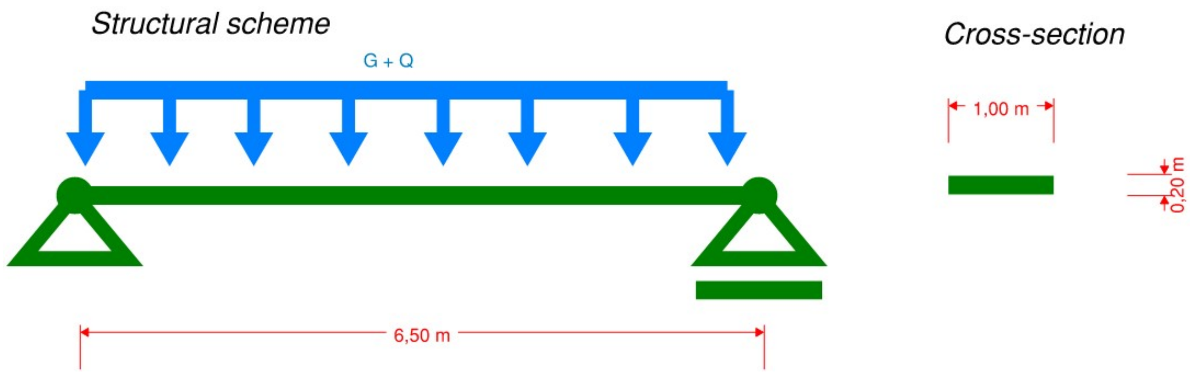


Figure 5.2: Structural scheme and cross-section of CLT plate

Building type	Apartment building with CLT structure
Consequence class of building	CC2
Structural system	Simply supported floors on walls
Horizontal system	Not relevant
Length of simply supported floor	$L = 6.5\ m$
Thickness of floor panel	$h = 200\ mm$
Number of layers	$n_{layers} = 5$
Thickness of a layer	$t_{layer} = 40\ mm$
Width of analysed 'beam-strip'	$b = 1000\ mm$
Characteristic strength of material (prEN 1995-1-2:2023 section 4.5)	$f_k = 24\ N/mm^2$
Approximated self weight of floor panel	$G_{k,self} = 1.0\ kN/m^2$
Permanent load on floors (e.g. screed, installations, architectural walls)	$G_{k,perm} = 1.5\ kN/m^2$
Variable load (residential)	$Q_{k,resid} = 1.75\ kN/m^2$

Table 5.2: Assumptions about building and structural system

Fundamental combination

Partial factor for material	$\gamma_M = 1.25$
Strength modification factor for the effect of load duration and moisture content	$k_{mod} = 0.8$
Partial factor related to permanent load	$\gamma_G = 1.35$
	$\xi = 0.89$
Partial factor related to variable load	$\gamma_Q = 1.5$

Table 5.3: Parameters needed for calculation of fundamental load combination

We calculate the material strength:

$$f_d = k_{mod}\frac{f_k}{\gamma_M} = 15.36\ N/mm^2$$

We calculate the load effect:

$$E_d = \gamma_G(G_{k,perm}G_{k,self}) + \gamma_Q Q_{k,resid} = 5.38\ kN/m^2$$

We now convert this into a line load per one meter of width and use Newtons and millimeters:

$$q_d = 5.38\ N/mm$$

We now calculate the stress in the outer fibers of the cross-section:

$$W = 1/6bh^2 = 6.67 * 10^6\ mm^3$$
$$M_d = 1/8q_dL^2 = 2.84 * 10^7\ Nmm$$
$$\sigma_d = \frac{M_d}{W} = 4.46\ N/mm^2$$

We perform a unity check:

$$U.C. = \sigma_d/f_d = 0.28$$

Zero-strength layer using Lange et al. (2014)
When calculating the zero-strength layer, we use the interpolated value from table 7.1 from Lange et al. (2014), with a minimal value of $d_0 = 7\ mm$.

Modification factor for timber in fire scenario (prEN 1995-1-2:2023 table 4.1)	$k_{fi} = 1.15$
Partial factor in fire scenario (prEN 1995-1-2:2023 section 4.5)	$\gamma_{M,fi} = 1.0$
Modification factor in fire scenario (prEN 1995-1-2:2023 section 4.5)	$k_{mod,fi} = 1.0$
Psi factor for accidental load case	$\psi_2 = 0.3$
zero-strength layer (prEN 1995-1-2:2023 table 7.4)	$d_0 = 7\ mm$

Table 5.4: Parameters needed for calculation of accidental (fire scenario) load combination

We calculate the material strength:

$$f_{20} = k_{fi}f_k = 30.0\ N/mm^2$$
$$f_{dfi} = k_{mod,fi}\frac{f_{20}}{\gamma_{M,fi}} = 30.0\ N/mm^2$$

We calculate the load effect:

$$E_{d,fi} = (G_{k,perm}G_{k,self}) + \psi_2 Q_{k,resid} = 3.03\ kN/m^2$$

We now convert this into a line load per one meter of width and use Newtons and millimeters:

$$q_{d,fi} = 3.03\ N/mm$$

We now calculate the total effective cross-section:

$$d_{ef} = d_{char} + d_0$$

$$d_{ef,EC} = 27\ mm$$
$$d_{ef,ZHM} = 44\ mm$$
$$d_{ef,zone} = 34\ mm$$

$$h_{ef,EC} = h - d_{ef,EC} = 173\ mm$$
$$h_{ef,ZHM} = h - d_{ef,ZHM} = 156\ mm$$
$$h_{ef,zone} = h - d_{ef,zone} = 166\ mm$$

We now calculate the stress in the outer fibers of the cross-section:

$$W_{ef,EC} = 1/6bh_{ef}^2 = 4.99 * 10^6\ mm^3$$
$$W_{ef,ZHM} = 1/6bh_{ef}^2 = 4.06 * 10^6\ mm^3$$
$$W_{ef,zone} = 1/6bh_{ef}^2 = 4.60 * 10^6\ mm^3$$

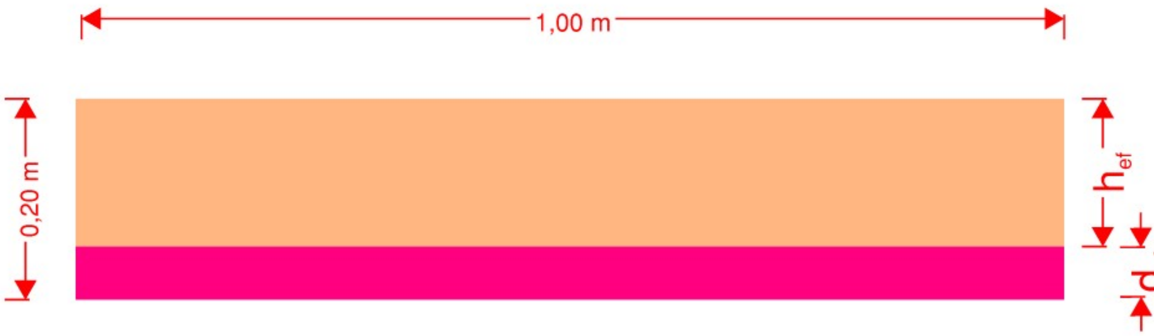


Figure 5.3: Effective charring depth and the resultant effective height of the cross-section

$$M_d = 1/8 q_{d,fi} L^2 = 1.60 * 10^7\ Nmm$$

$$\sigma_{d,fi,EC} = \frac{M_d}{W} = 3.20\ N/mm^2$$

$$\sigma_{d,fi,ZHM} = \frac{M_d}{W} = 3.94\ N/mm^2$$

$$\sigma_{d,fi,zone} = \frac{M_d}{W} = 3.48\ N/mm^2$$

We perform the unity checks:

$$U.C._{1,EC} = \sigma_{d,fi}/f_d = 0.21$$

$$U.C._{1,ZHM} = \sigma_{d,fi}/f_d = 0.26$$

$$U.C._{1,zone} = \sigma_{d,fi}/f_d = 0.23$$

zero-strength layer using CEN (2023)

In this calculation we use the zero-strength layer as defined by section 7.2.3 Design of plane timber members of CEN (2023). This method is officially only to be used with timber members subjected to standard fires, however, it is a useful additional check.

Modification factor for timber in fire scenario (prEN 1995-1-2:2023 table 4.1)	$k_{fi} = 1.15$
Partial factor in fire scenario (prEN 1995-1-2:2023 section 4.5)	$\gamma_{M,fi} = 1.0$
Modification factor in fire scenario (prEN 1995-1-2:2023 section 4.5)	$k_{mod,fi} = 1.0$
Psi factor for accidental load case	$\psi_2 = 0.3$
zero-strength layer (prEN 1995-1-2:2023 table 7.4)	$d_0 = 7\ mm$

Table 5.5: Parameters needed for calculation of accidental (fire scenario) load combination

We calculate the material strength:

$$f_{20} = k_{fi} f_k = 30.0\ N/mm^2$$

$$f_{dfi} = k_{mod,fi} \frac{f_{20}}{\gamma_{M,fi}} = 30.0\ N/mm^2$$

We calculate the load effect:

$$E_{d,fi} = (G_{k,perm} G_{k,self}) + \psi_2 Q_{k,resid} = 3.03\ kN/m^2$$

We now convert this into a line load per one meter of width and use Newtons and millimeters:

$$q_{d,fi} = 3.03\ N/mm$$

We now calculate the total effective cross-section:

$$d_{tot} = d_{char} + d_0$$

$$d_{ef} = \begin{cases} d_{tot} & \text{if } d_{tot} < t_{layer} \\ 2 \cdot t_{layer} + 2\ mm & \text{if } t_{layer} < d_{tot} < 2 \cdot t_{layer} \\ d_{tot} & \text{if } 2 \cdot t_{layer} < d_{tot} < 3 \cdot t_{layer} \\ 4 \cdot t_{layer} + 2\ mm & \text{if } 3 \cdot t_{layer} < d_{tot} \end{cases}$$

$$d_{ef,EC} = 27\ mm$$
$$d_{ef,ZHM} = 82\ mm$$
$$d_{ef,zone} = 34\ mm$$

$$h_{ef,EC} = h - d_{ef,EC} = 173\ mm$$
$$h_{ef,ZHM} = h - d_{ef,ZHM} = 118\ mm$$
$$h_{ef,zone} = h - d_{ef,zone} = 166\ mm$$

We now calculate the stress in the outer fibers of the cross-section:

$$W_{ef,EC} = 1/6bh^2_{ef,EC} = 4.99 * 10^6\ mm^3$$
$$W_{ef,ZHM} = 1/6bh^2_{ef,ZHM} = 2.31 * 10^5\ mm^3$$
$$W_{ef,zone} = 1/6bh^2_{ef,zone} = 4.58 * 10^6\ mm^3$$

$$M_d = 1/8q_{d,fi}L^2 = 15975781.25\ Nmm$$

$$\sigma_{d,fi,EC} = \frac{M_d}{W} = 3.20\ N/mm^2$$
$$\sigma_{d,fi,ZHM} = \frac{M_d}{W} = 6.88\ N/mm^2$$
$$\sigma_{d,fi,zone} = \frac{M_d}{W} = 3.49\ N/mm^2$$

We perform the unity checks:

$$U.C._{2,EC} = \sigma_{d,fi}/f_d = 0.21$$
$$U.C._{2,ZHM} = \sigma_{d,fi}/f_d = 0.45$$
$$U.C._{2,zone} = \sigma_{d,fi}/f_d = 0.23$$

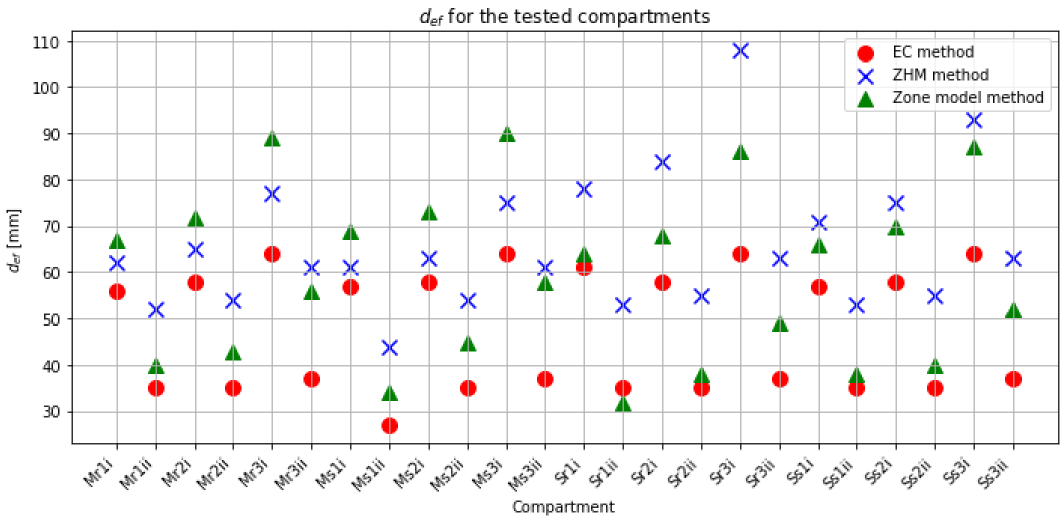


Figure 5.4: effective charring depth for each compartment per model

5.2. Data collection

In this section we will introduce the data gathered for all of the 24 compartments discussed in chapter 3. The way of analysis per compartment is described in section 5.1. From now on we will only consider the results where the zero-strength layer is found using Lange et al. (2014) as this is likely compatible with EC and ZHM fires and likely also compatible with the zone model and because the approach of finding the zero-strength layer by CEN (2023) also strongly depends on the properties of the CLT member chosen, thus being less generic.

Table A.1 (Appendix A) shows the charring depth and the unity check results for the structural analysis of the floor plate with zero-strength layer from Lange et al. (2014). A Table showing the same for the structural analysis using zero-strength layer from CEN (2023) section 7.2.3 is printed in appendix A.

Figure 5.4 gives a quick visualization of which compartments had higher effective charring depths broken down per model.

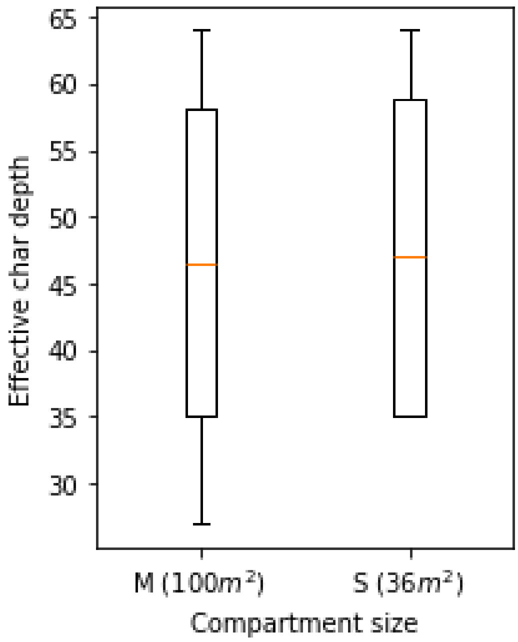
Figures 5.5 to 5.7 visualize the correlation between the effective charring depth calculated and the compartment size, compartment shape, amount of exposed timber and opening factor for all three models used. The orange horizontal line in the box plot gives the median value, and the box is bound by the 25th and 75th percentile values (the quartiles). Some plots show 'whiskers' which represent the 1.5 times the inter quartile range (the difference between the 25h and the 75th quartiles). Circles in the plot represent an outlier, such as seen in 5.5 (d). The same correlations visualized in scatter plots are printed in Appendix A

5.3. Analysis

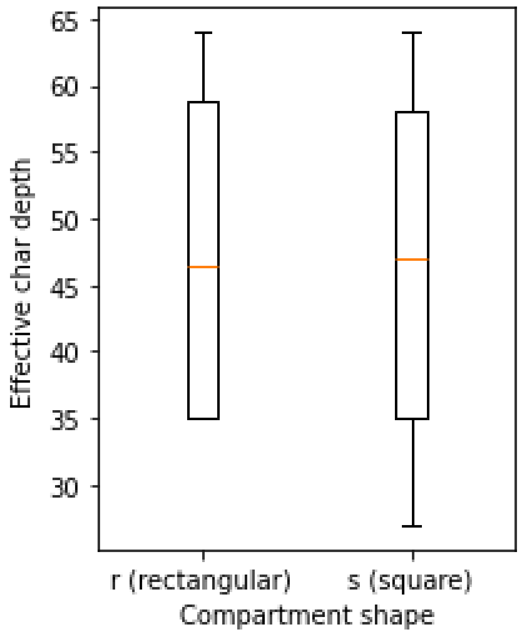
From the data gathered we now describe the observed trends, common themes, consistent values and correlations.

The causation relationship between the single model parameters and the effective charring depth are clear and can be found in the model descriptions. It is more interesting to look for effects of all parameters in action. Therefore we will look for correlations between parameters and differences between the models. From this we can extract insights that can be useful in design questions.

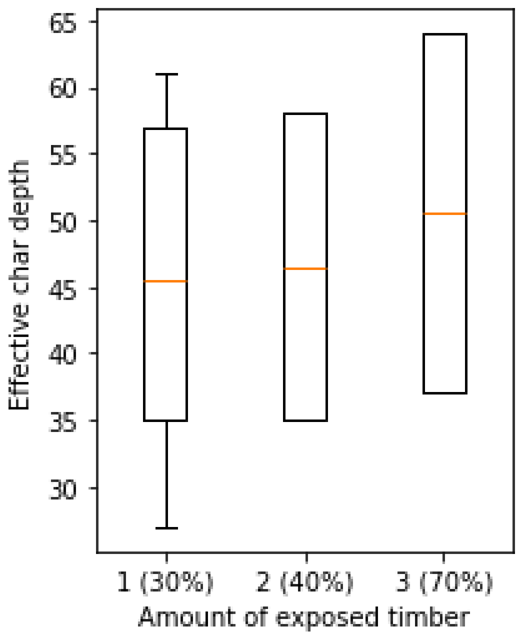
Figure 5.4 an opportunity to get a general understanding of the data at a glance. Some compartments have a clear peak, no matter what model is used. Such compartments are Sr3i and Ss3i. Averaging over all models, these compartments will have the highest value for the effective charring depth. Commonalities between these compartments are: small compartment area, 70 % of surface has exposed



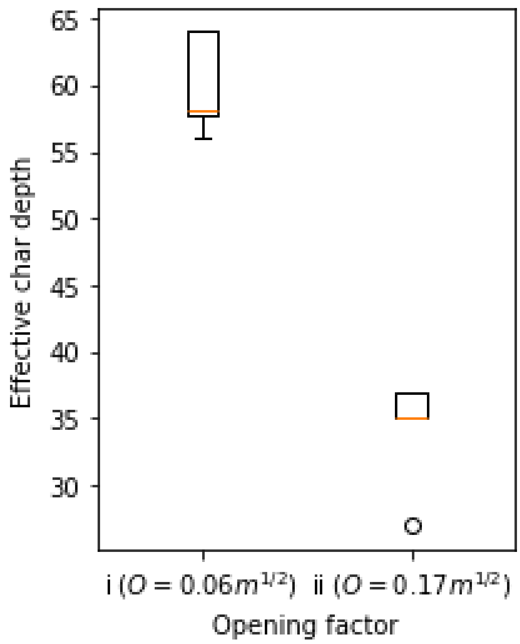
(a)



(b)



(c)



(d)

Figure 5.5: Box plot visualizing correlation between effective charring depth and parameters of the EC model

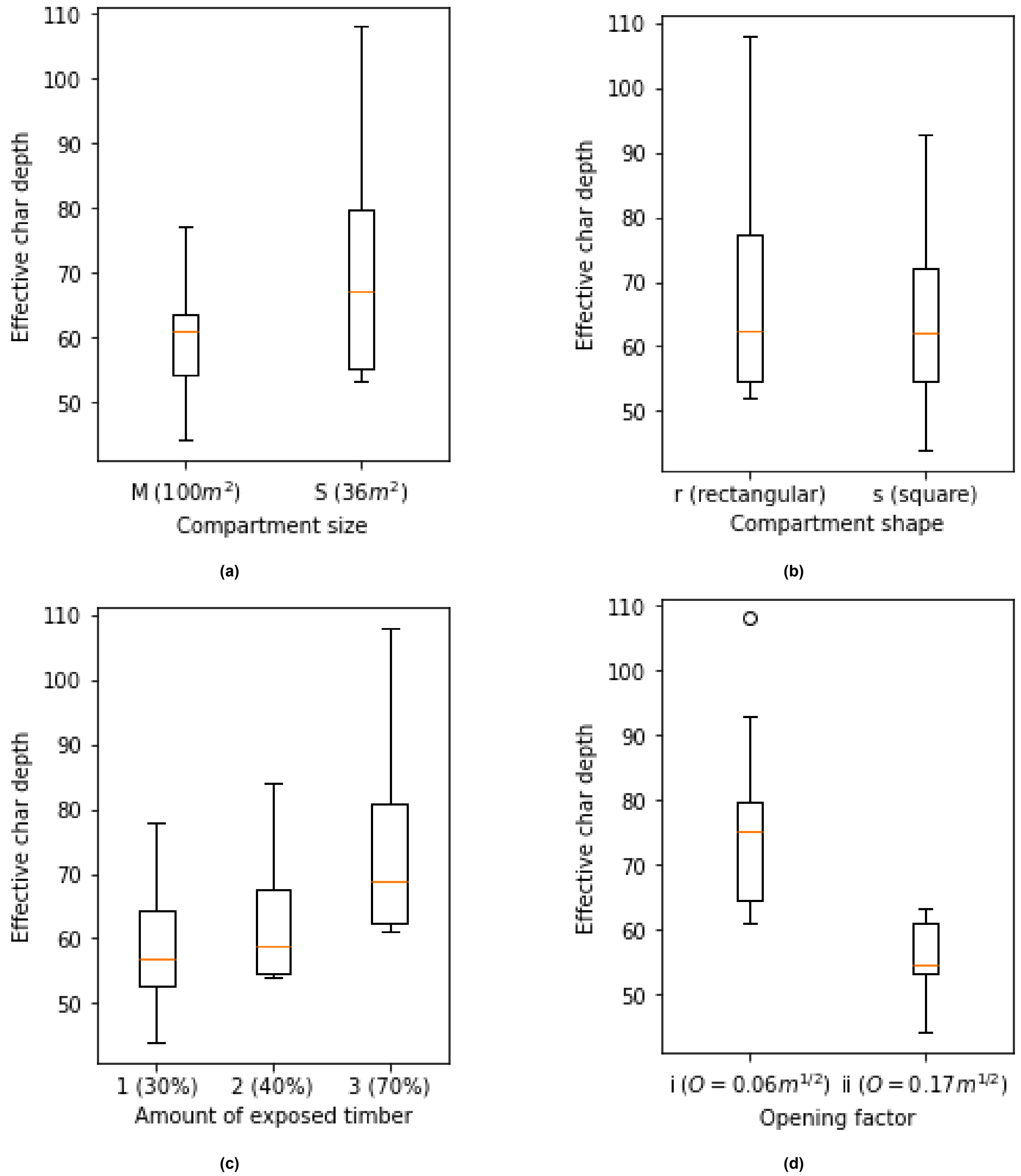


Figure 5.6: Box plot visualizing correlation between effective charring depth and parameters of the ZHM model

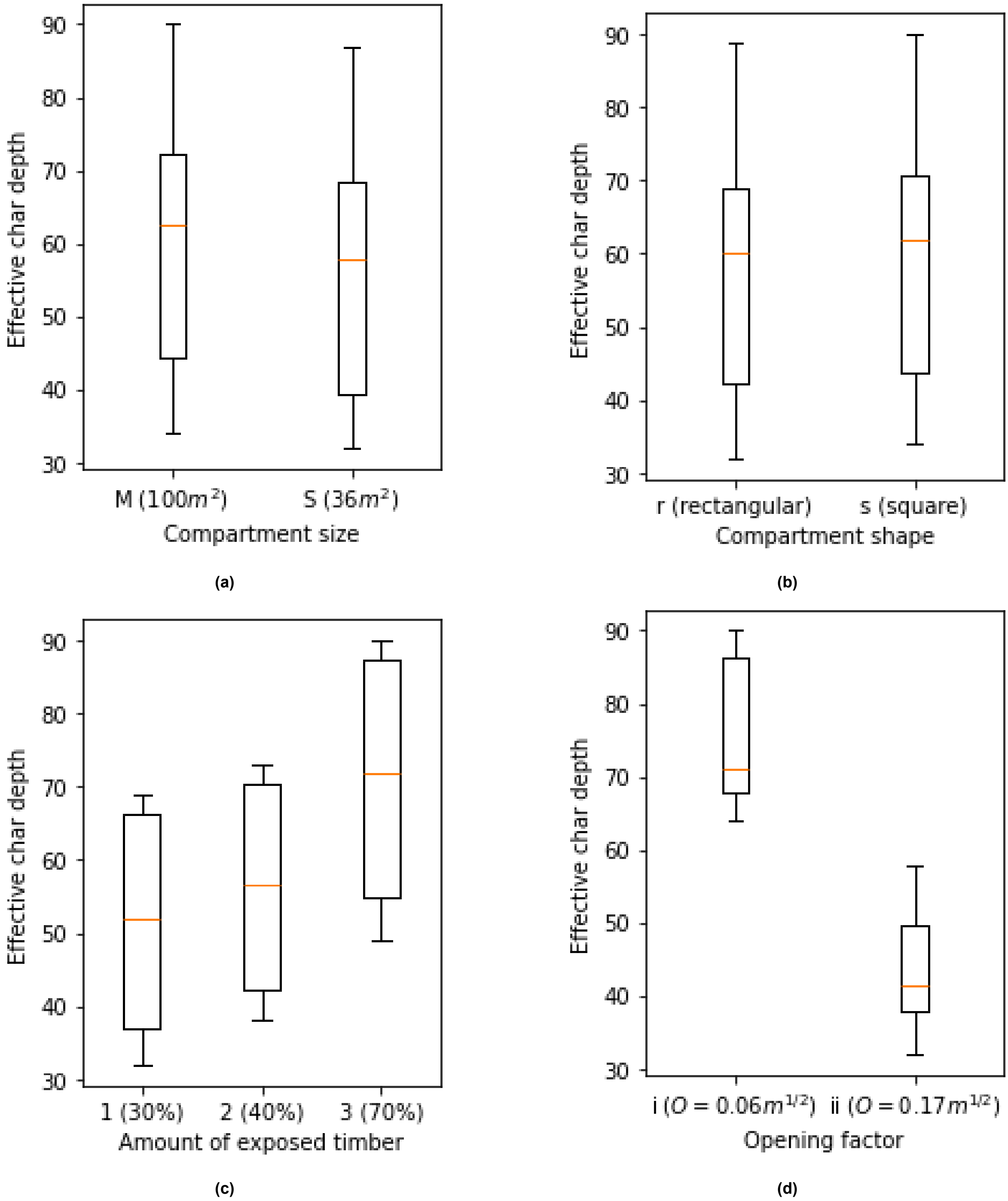


Figure 5.7: Box plot visualizing correlation between effective charring depth and parameters of the Zone model

timber and a small opening factor. These results are in line with the expectations.

5.3.1. EC model

In Figure 5.5 (a) we recognize no significant difference (4 % increase) for the effective charring depth between the medium and small sized compartment according to the EC model. The small compartments have on average a 2 mm deeper effective charring depth compared to those with a larger floor area.

In Figure 5.5 (b) we again recognize no significant difference (2 % decrease) between a rectangular or square shaped compartment according to the EC model. The rectangular compartments have on average a 1 mm deeper effective charring depth.

In Figure 5.5 (c) we can observe a slight trend of increasing effective charring depth going from 30 % to 40 % and from 40 % to 70 % exposed timber (4 % and 4 % increase). The average effective charring depth is 45 mm for 30 %, 47 mm for 40 % and 49 mm for 70 % exposed timber.

In Figure 5.5 (d) we recognize a significant difference (41 % decrease) between the smaller opening factor and the larger opening factor according to the EC model. The compartments with the smaller opening factor have on average a 25 mm deeper effective charring depth compared to those with a larger opening factor.

5.3.2. ZHM model

In Figure 5.6 (a) we recognize a significant difference (18 % decrease) between the a medium and small sized compartment according to the ZHM model. The small compartments have on average a 11 mm deeper effective charring depth compared to those with a larger effective charring depth.

In Figure 5.6 (b) we recognize a slight shift (3 % decrease). A noteworthy outlier is Sr3i. It seems that if the compartment is small, has a high percentage of exposed timber in the surfaces, and has a small opening factor, the rectangular shape of the compartment is less favourable compared to a similar compartment with a square shape. The rectangular compartments have on average a mere 2 mm deeper effective charring depth.

In Figure 5.6 (c) we can observe a trend of increasing effective charring depth going from 30 % to 40 % and from 40 % to 70 % exposed timber (5 % and 16 % increase) . The average effective charring depth is 59 mm for 30 %, 62 mm for 40 % and 72 mm for 70 % exposed timber.

In Figure 5.6 (d) we recognize a significant difference (27 % decrease) between the smaller opening factor and the larger opening factor according to the ZHM model. The compartments with the smaller opening factor have on average a 20 mm deeper effective charring depth compared to those with a larger opening factor.

5.3.3. Zone model

In Figure 5.7 (a) we recognize a slight difference (5 % decrease) between the a small and a medium sized compartment according to the ZHM model. The small compartments have on average a mere 3 mm shallower effective charring depth compared to those with a larger effective charring depth. This is surprising because both EC and ZHM models showed an opposite correlation, where the smaller compartment showed a larger effective charring depth. The difference can be attributed to the different nature of the zone model where other variables related to compartment size, such as net fuel load, might weigh more heavily.

In Figure 5.7 (b) we recognize no noteworthy shift (2 % increase). The rectangular compartments have on average a 1 mm shallower effective charring depth. This again is a correlation in the opposite direction as we have seen in the EC and ZHM models.

From Figure 5.6 (c) we can observe a clear trend of increasing effective charring depth going from 30 % to 40 % and from 40 % to 70 % exposed timber 10 % and 27 % increase). The average effective charring depth is 51 mm for 30 %, 56 mm for 40 % and 71 mm for 70 % exposed timber.

From Figure 5.6 (d) we recognize a significant difference (41 % decrease) between the smaller opening factor and the larger opening factor according to the Zone model. The compartments with the smaller opening factor have on average a 31 mm deeper effective charring depth compared to those with a larger opening factor.

5.3.4. Observations in structural calculation

None of the compartments failed according to all three models as can be seen in Table A.1. The floor plate was designed keeping in mind vibration requirements (SLS). This design turned out to be sufficiently safe based on the three models.

5.3.5. Gas temperature

The graphs provided show gas temperature in the room. It is however crucial to understand that even if the gas temperature is low, the char on the timber members will likely be much hotter for a long period of time, and thus the gas temperature is not necessarily an indication to whether or not the timber cross-sections are being heated and thus reduced in strength.

Figure 5.8shows the compartment with the shortest fire duration (Sr1ii) and the compartment with the longest fire duration (Sr3i).

5.3.6. Equivalent fire duration

By dividing the charring depth obtained with the basic design charring rate for CLT $\beta_0 = 0.65\ mm/min$ (CEN, 2023), we get the standard fire duration that would result in the same charring depth. This can give us an indication for the minimum fire separation value of the compartment walls. A.2 shows this equivalent fire duration for the three models per compartment.

If we take for example Sr1ii, here the equivalent fire duration over the three models is 57 minutes. This suggests that a fire separation value of at least 60 minutes is advisable for compartments similar to Sr1ii. Even though the BBL allows for buildings with highest usable floor space under 5 meters that has a permanent fire load < 500 MJ/m2 to have compartment separation value of 30 minutes, it is advised to use at least 60 minutes in this case.

If we take for example Sr3i, here the equivalent fire duration over the three models is 109 minutes. This suggests that a fire separation value of at least 120 minutes is advisable for compartments similar to Sr3i. The maximum requirement of the BBL for fire separation value is 60 minutes, so it might be interesting to consider a higher separation value for compartments like this because the flaming might last a lot longer than 60 minutes.

5.4. Discussion

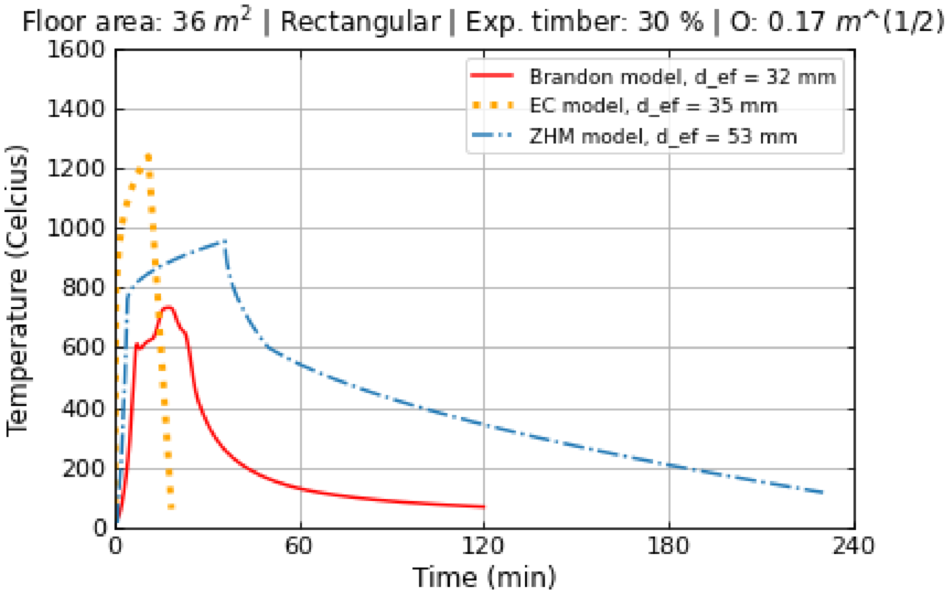
In this section we discuss the trends and correlations observed in the analysis.

5.4.1. Size of compartment

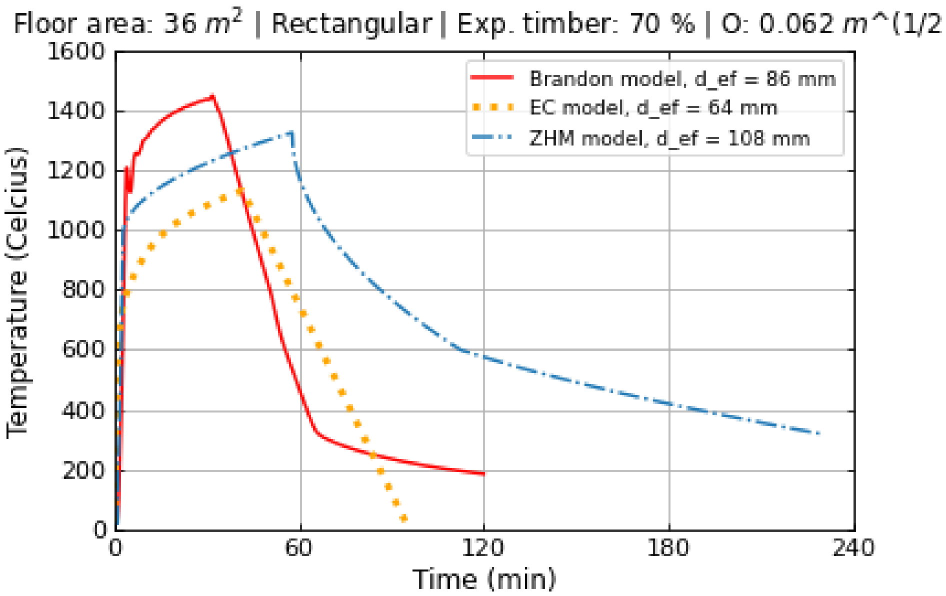
Averaged over the three models a difference of 5 mm in effective charring depth is observed between the medium sized and small compartments with the medium sized compartments having on average a lower effective charring depth.

5.4.2. Shape of compartment

Averaged over the three models, compartment shape had the smallest correlation with effective charring depth, with an average of 2 mm difference between square and rectangular shaped compartments. A noteworthy outlier is Sr3i which is a small compartment with high percentage of exposed timber surfaces and low opening factor. This compartment and its counterpart Ss3i show a large contrast of in effective charring depth in the ZHM method, suggesting that if the compartment is sufficiently small, has a large passive fire load and small opening factor, the compartment shape starts to correlate with the effective charring depth. This model suggests that in compartments with the mentioned features it is a potent passive mitigation measure to avoid longitudinal shaped compartments.



(a) Temperature vs time curve for Sr1ii



(b) Temperature vs time curve for Sr3i

Figure 5.8: Temperature vs time curves for compartment with shortest fire duration and compartment with longest fire duration

5.4.3. Percentage of exposed timber

All three models suggest a significant difference in effective charring depth between compartments with 30, 40 and 70% exposed timber surfaces. Averaged over the three models, there is a 3 mm increase in effective charring depth from 30 to 40 % and a 9 mm increase in effective charring depth from 40 to 70 % exposed timber. The Zone model suggests the most rapid increase. Limiting the amount of exposed timber surfaces is therefore a potent passive mitigation measure.

5.4.4. Opening factor

In all three models a significant correlation between opening factor and effective charring depth is observed. Averaged over the three models, a 25 mm increase in effective charring depth is seen when choosing for the opening factor of $O = 0.06\ m^{1/2}$ compared to $O = 0.17\ m^{1/2}$. Following these results, a small opening factor is the best predictor for a large effective charring depth and a long fire duration. Choosing larger opening factors is therefore a potent passive mitigation measure to consider.

5.4.5. Example

As an example we can consider the compartments with the highest effective charring depth averaged over the three models (Sr3i and Ss3i). Commonalities between these compartments are: small compartment area, 70 % of surface has exposed timber and a small opening factor. Even if one of these three aspects is changed, the effective charring depth is critically lowered. The analysis suggests that increasing the opening factor has the highest impact on the charring depth.

5.4.6. Structural strenght

Structural calculations (R) all had a unity check value smaller than one, suggesting that in all compartments, within the analysed time frame, the structure does not collapse. The smoldering effect in the cool down phase and the re-radiation between CLT panels and fallen char and other CLT panels are not considered in the models and structural calculation, and must therefore be accounted for separately, considering also that the timber cross-section can heat up for many more hours and lose structural strength to the point of failure within the time frame from the end of flaming up to 24 hours after the flaming stopped.

6

Simulation of degrees of protection

This chapter addresses the following objective of the thesis:

5. Perform simulations of protection degrees

This chapter answers the following research questions:

5. What is the fire development like when passive fire safety measures of various protection degrees are simulated

We will simulate compartments with the packages applied with the EC model, the ZHM model and the Brandon model.

For each protection degree we model in two different compartment sizes $36m^2$ and $100m^2$ as described in 3.5. We assume an opening factor of $O = 0.62m^{1/2}$ because it represents a statistically low opening factor.

6.1. Analysis

Six protection degrees are described and simulated in the following sections.

6.1.1. Protection degree A (No protection)

Here no protection is applied, and so all walls, the ceiling and the floor are left exposed.

Figures 6.1 and 6.2 show the simulations in a $100m^2$ and $36m^2$ compartment respectively. The graphs show a longer fire duration, and high peak temperature compared to the other protection degrees. Interestingly, the Brandon and EC models give a slightly larger char depth in the medium sized compartment, whereas the ZHM model gives a larger char depth in the smaller compartment.

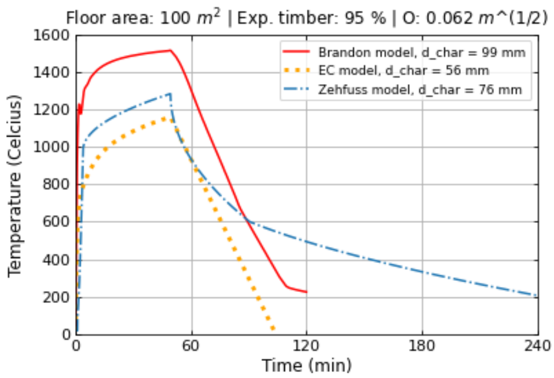


Figure 6.1: Fire curve and char depth simulation for protection degree 0 in $100m^2$ compartment

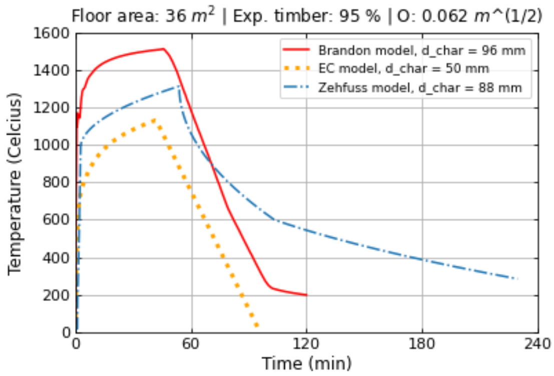


Figure 6.2: Fire curve and char depth simulation for protection degree 0 in $36m^2$ compartment

6.1.2. Protection degree B

Protection degree B protects all surfaces for 60 minutes and the area of the ceiling in unprotected. The allowed amount of exposed timber is such that the permanent fire load will not exceed $30kg - Spruce - Equivalent/m^2$. This limitation was simulated in the Brandon model, as here the amount and thickness of the protection could be chosen. This is not the case for the other two models, where protection can only be modeled as protection that cannot fail.

Figures 6.3 and 6.4 show the predicted fire development and char depth. The fire duration and char depths are longer and larger in the medium sized compartment compared to the small compartment, this first seems counter to the findings in section 5.4.1. It must however be noted that the percentage of exposed timber in the medium sized compartment is larger than that in the small compartment because of the different outcomes in the prescribed formula for allowed amount of exposed timber. For the medium sized compartment, the Brandon model shows that the char depth after 30 minutes is 59 mm and after 60 minutes is 86 mm, these are 60% and 87% of the char depth at 120 minutes respectively. These percentages are even higher for the protection degrees we will consider later.

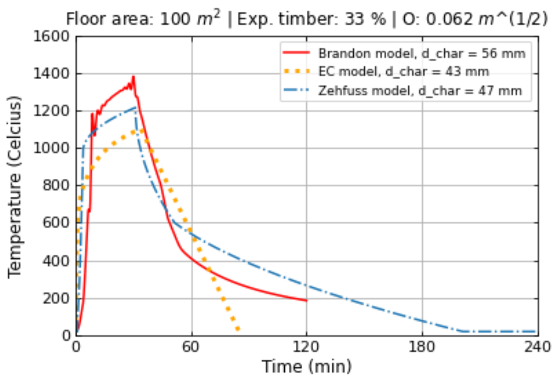


Figure 6.3: Fire curve and char depth simulation for protection degree 1 in $100m^2$ compartment

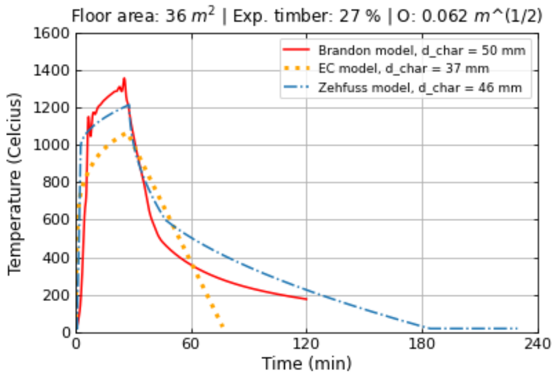


Figure 6.4: Fire curve and char depth simulation for protection degree 1 in $36m^2$ compartment

6.1.3. Protection degree C

Protection degree C further limits the amount of exposed timber.

Figures 6.5 and 6.6 show the simulations performed on compartments with protection degree 2.

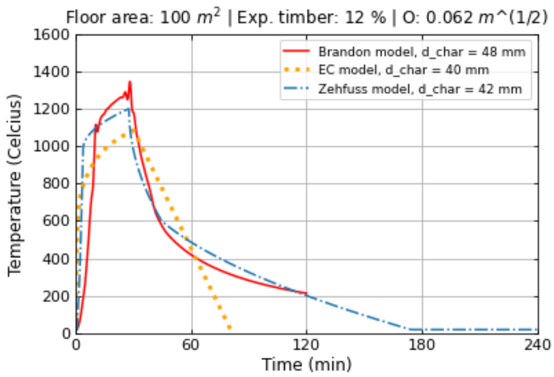


Figure 6.5: Fire curve and char depth simulation for protection degree 2 in $100m^2$ compartment

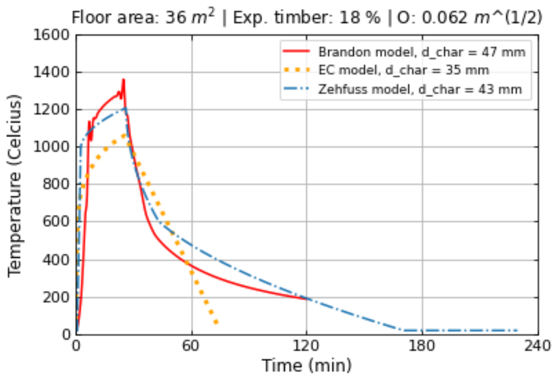


Figure 6.6: Fire curve and char depth simulation for protection degree 2 in $36m^2$ compartment

6.1.4. Protection degree D

Protection degree D limits the exposed timber to one thirds of the floor area. The simulations suggest, that the low percentage of exposed timber surfaces (8-10% in our examples) result in a marginally shorter fire duration and marginally smaller char depth, compared to protection degree C.

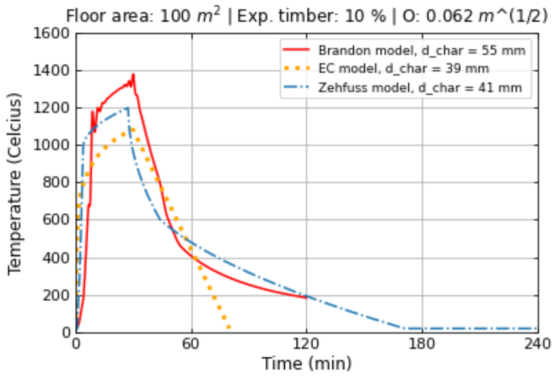


Figure 6.7: Fire curve and char depth simulation for protection degree 3 in $100m^2$ compartment

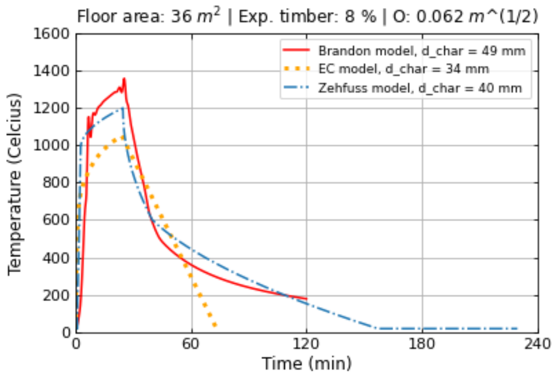


Figure 6.8: Fire curve and char depth simulation for protection degree 3 in $36m^2$ compartment

6.1.5. Protection degree E

In protection degree E requires all timber surfaces are protected for 30 minutes. The contribution of mass timber to the fire is thus delayed. The smaller compartment again gives a shorter fire duration and char depth, which in this case is attributed to the fact that the net variable fire load in total in the larger compartment is larger compartment than in the smaller compartment. Because the Brandon model is the only model able to simulate the 30 minute fire protection, it is likely the most accurate for this protection degree. The EC and ZHM models can only assume a fire protection that stays active for the whole fire duration and thus cannot properly address protection degree 4.

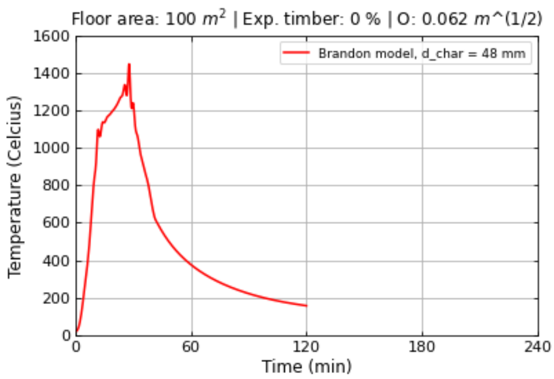


Figure 6.9: Fire curve and char depth simulation for protection degree 4 in $100m^2$ compartment

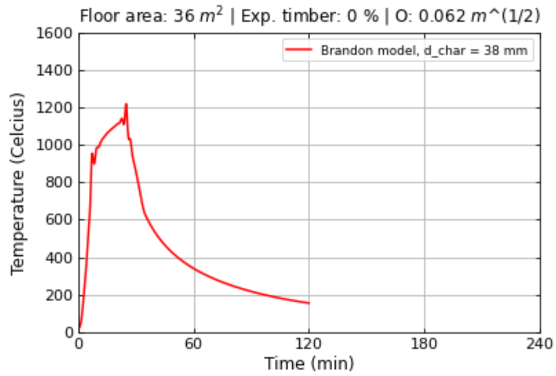


Figure 6.10: Fire curve and char depth simulation for protection degree 4 in $36m^2$ compartment

6.1.6. Protection degree F

Protection degree F is similar to degree E, but instead of having the timber surfaces protected for 30 minutes, in degree F they are protected for 60 minutes. Given that the EC and ZHM model can only model an infinite protection duration, and thus cannot properly address protection degree F. The Brandon model, however, can model the 60 minutes of protection. The graph does not show the peak at 30 minutes where the timber starts contributing in degree F. The char depth according to the Brandon model is 4 mm shallower in degree F compared to degree E.

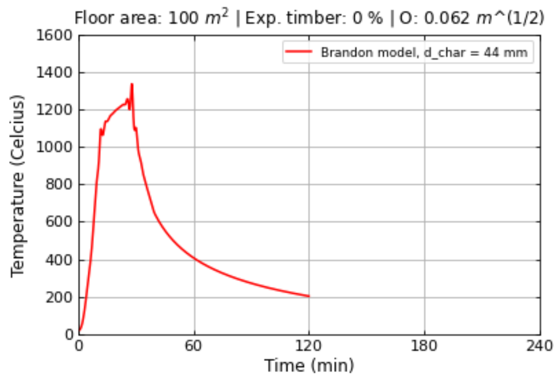


Figure 6.11: Fire curve and char depth simulation for protection degree 5 in $100m^2$ compartment

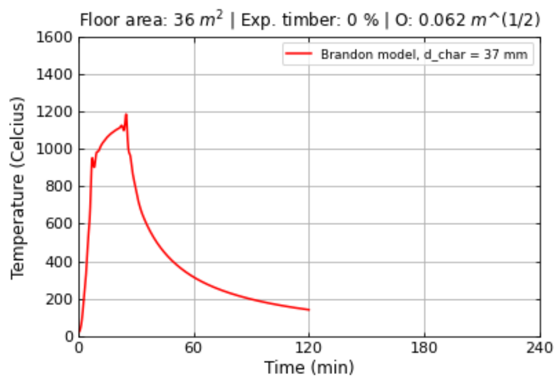


Figure 6.12: Fire curve and char depth simulation for protection degree 5 in $36m^2$ compartment

7
Conclusions

This chapter answers the following research questions:

6. In what form can the result of this thesis best be used by the practicing professional?

Comparison of the simulations of the EC, ZHM and Brandon models to the test data, suggests that for compartments of the same size and geometry as used in Brandon et al. (2021a):

- The EC model is non-conservative in all comparisons and should be omitted in favour of the ZHM or Brandon models
- When there is exposed timber only on the ceiling and the compartment size, geometry and opening factor is similar to that in 'test 1' in Brandon et al. (2021a), both ZHM and Brandon models give conservative estimates for the maximum char depth
- For other compartment sizes, opening factors and amounts of exposed timber further research with CFD (computational fluid dynamics) models and/or compartment fire tests is recommended
- The maximum char depth in the ceiling is typically found close to the wall furthest away from the window openings; this can be explained by the propensity for smouldering in areas of lower heat dissipation typically found further away from the windows
- The maximum char depth in the walls is typically found in the strip close to the floor (lowest quarter of wall) and/or close to the window openings; this can be explained by the cold oxygen-rich (necessary for pyrolysis) air entering in the lower part of the window openings, while the hot gas leaves through the upper part of the window openings
- Designing engineers can use the maximum charring depth as seen fit for mitigation of risks in a given building
- Possible measures include: extra 'sacrificial' layer of CLT around columns and 'important walls', the use of protective plinth around columns or along walls to protect lower quarter, extra 'sacrificial' layer for ceiling panel or the use of protective board in area of ceiling where maximum or critical char depth is expected

We performed simulations with EC model, ZHM model and a zone model on 24 different compartments. This compartment level analysis suggests the following correlations:

- A studio ($36m^2$) shows on average 5 mm deeper effective charring depth compared to a three bedroom apartment ($100m^2$)
- Longitudinal compartments (short wall to long wall ratio of 1:4) show on average 2 mm deeper effective charring depth compared to square shaped compartment
- Compartments with CLT on 40 % of total enclosed area left exposed show on average 3 mm deeper effective charring depth than compartments with CLT on 30 % of total enclosed area left exposed
- Compartments with CLT on 70 % of total enclosed area left exposed show on average 9 mm deeper effective charring depth than compartments with CLT on 40 % of total enclosed area left exposed

- Compartments with an opening factor of $O = 0.06\ m^{1/2}$ show on average 25 mm deeper effective charring depth compared to a compartment with an opening factor of $O = 0.17\ m^{1/2}$.

Lastly, we simulated various degrees of passive protection.

- In protection degree A (no protection), the simulated char depth and fire duration are 99 mm and more than three hours respectively; considering the char depth penalty (see section 4.2.3) that likely needs to be added to the simulated values to result in realistic maximum char depth, the structural integrity and fire and smoke separation are likely compromised if the automatic suppression system does not function
- Between EC, ZHM and Brandon models, only the Brandon model is able to simulate protection for a limited number of minutes and is therefore the advised model to use for calculations where no fire-fighting intervention is modeled and fire protection will fail after a finite number of minutes

8 Recommendations

This chapter answers the following research question:

5. In what form can the result of this thesis best be used by the practising professional?

The following chapter gives recommendations to regulatory bodies and fire fighters. It also gives recommendations for further research for follow-up researchers.

8.1. Recommendations for governing bodies

Since CLT is a relatively new (< 30 years) building material, the complex industry such that is the building industry has not yet fully adapted to the challenges of this new material in case of fire scenarios. It is advised for at least one of the fire safety specialists working for any governing institution, dealing with approval of building construction, to have read and studied relevant literature to get a basic understanding of the risks and possible extra measures of contemporary timber structures.

8.2. Recommendations for fire-fighters

Similarly as for governing bodies, the fire-fighting stations are advised to have prior knowledge of fire safety in contemporary timber buildings, by for instance assigning an expert in this subject. While some fire-fighting stations already do this, advise is for all stations to do so, especially as such timber structures are believed to become more common in the near future. Know-how of how to pinpoint smoldering timber (potentially behind protective panels) and how to extinguish it is useful and can shorten fire-fighting operations significantly as well as potentially save lives.

8.3. Further research

Here follow valuable research topics for future students/researchers:

- Calculate more failure mechanism other than the failure of the floor plate
- Laboratory testing of resistance of columns, walls and floor plates that have been charred and have heat penetration
- Finding alternative ways to translate fire in timber compartment to equivalent standard fire duration and comparing the methods
- Perform compartment fire tests for compartment sizes that have not been tested yet; keep the amount of exposed timber at the area of the ceiling; try out a range of opening factors from $0.06 - 0.2m^{1/2}$; measure char depth on a grid of many points on compartment boundary like done in Brandon et al. (2021a);

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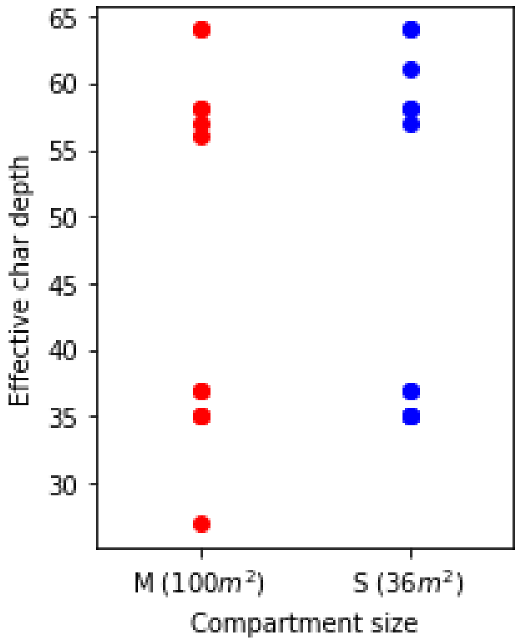
A

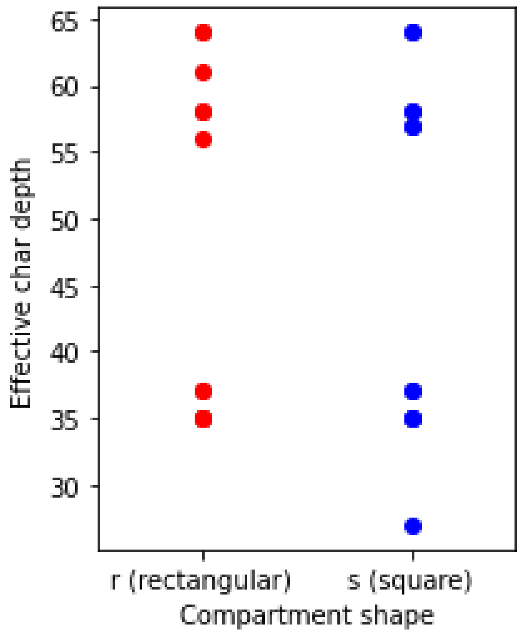
Appendix A: Large figures and Tables that are referred to in the text

	Characteristic	Cause(s)
Living function	Pre-movement times	Sleeping, intoxication
	Slower, longer compartment fires which can become quasi steady-state and so could potentially not auto-extinguish	Smaller window openings
Meeting function	Faster and hotter fire with less charring depth and less delamination	Larger window openings
	Unrational crowd behavior	crowd panic
	Unfamiliarity with building	building being public building
Health function	Slower, longer compartment fires which can become quasi steady-state and so could potentially not auto-extinguish	Smaller window openings
	Pre-movement times	Sleeping, intoxication, debilitation
	Assistance necessary for evacuation	debilitation
	Unfamiliarity with building	building being public building
Office function	Faster and hotter fire with less charring depth and less delamination	Larger window openings
Accommodation function	Unfamiliarity with building	building being a hotel or similar
	Pre-movement times	Sleeping, intoxication
Educational function	Faster and hotter fire with less charring depth and less delamination	Larger window openings
	Assistance necessary for evacuation	small children
Sports functie	Faster and hotter fire with less charring depth and less delamination	Larger window openings
	Unfamiliarity with building	building being public building
Retail function	Unrational crowd behavior	crowd panic

Figure A.5: Fire safety characteristics of different building heights categories



(a) First subfigure



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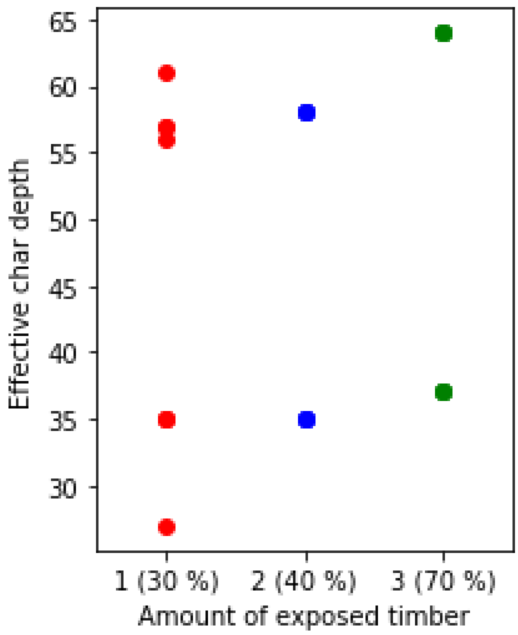

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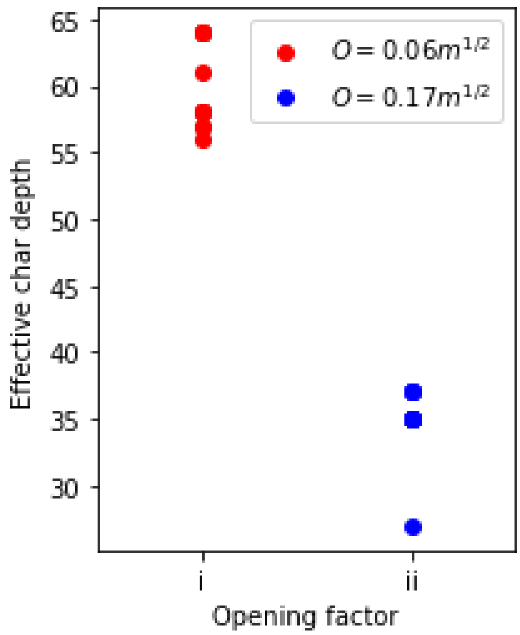
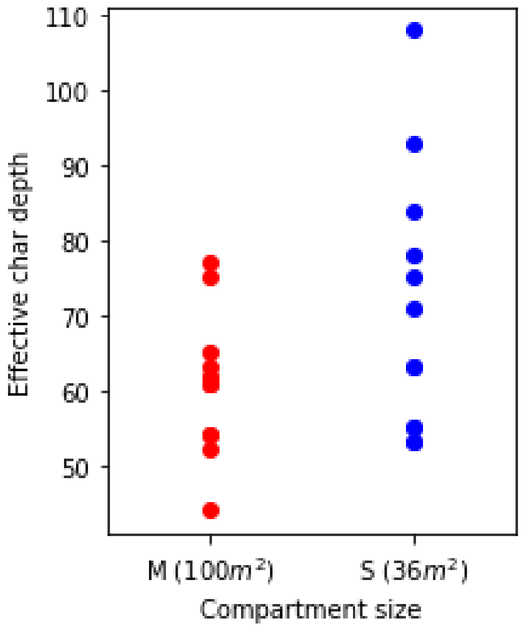
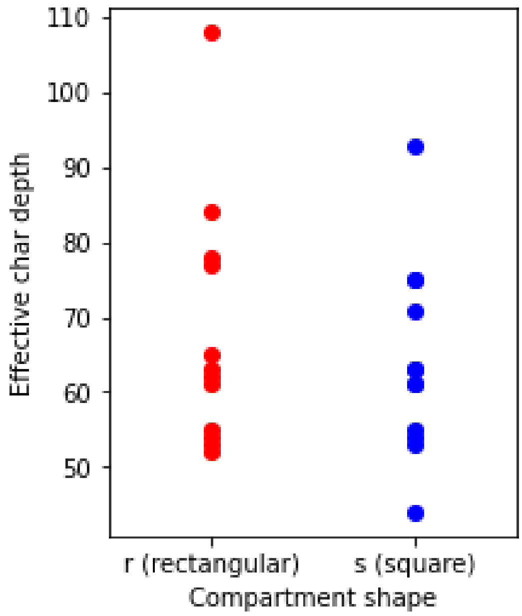


(d) Second subfigure

Figure A.1: Correlation between effective charring depth and parameters of the EC model



(a) First subfigure



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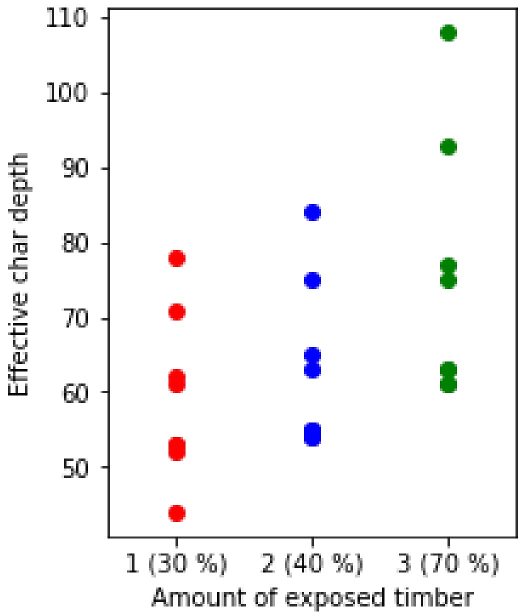

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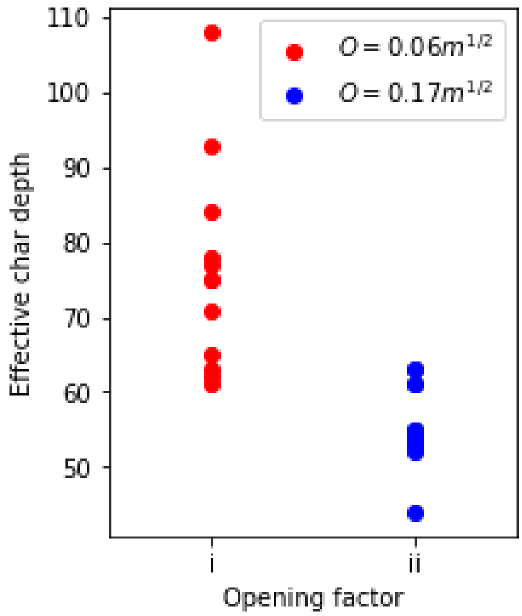
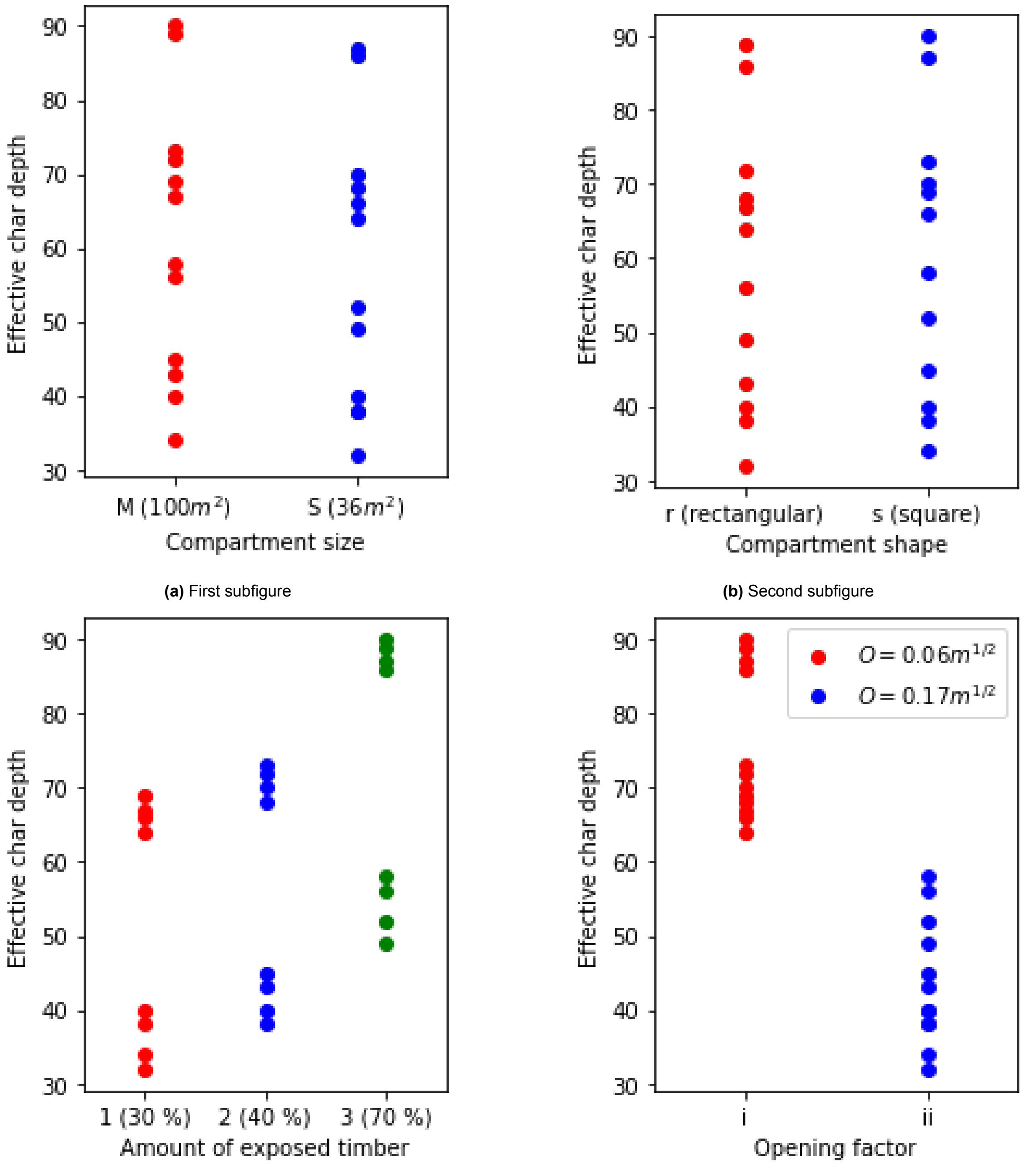


(d) Second subfigure

Figure A.2: Correlation between effective charring depth and parameters of the ZHM model



(a) First subfigure

(b) Second subfigure

(c) Second subfigure

(d) Second subfigure

Figure A.3: Correlation between effective charring depth and parameters of the Zone model

Woning										
	Art. 4.17	Art. 4.44	Art. 4.44	Art. 4.47	Art. 4.53	Art. 4.69	Art. 4.77	Art. 4.89	Art. 4.221	Art. 4.228
Vloerhoogte verblijfsgebied	Een bouwconstructie bezwijkt bij brand in een brandcompartiment waarin die bouwconstructie niet ligt, niet binnen de in tabel 4.17a aangegeven tijdsduur door het bezwijken van een bouwconstructie binnen of grenzend aan dat brandcompartiment. Voor zover dat brandcompartiment een woonfunctie is, geldt dit niet voor een bouwconstructie van een aan dat brandcompartiment grenzend subbrandcompartiment of grenzende buitenruimte. Kan worden verkort met 30 min als perm. vuurbelasting < 500	Brandklasse gevel nabij oppervlak tot 2.5 m	Het deel van een zijde van een constructieonderdeel dat grenst aan de buitenlucht en hoger ligt dan 13 m, voldoet aan brandklasse B, bepaald volgens NEN-EN 13501-1.	De bovenzijde van een dak van een bouwwerk is, bepaald volgens NEN 6063, niet brandgevaarlijk. Dit geldt niet als het bouwwerk geen voor personen bestemde vloer heeft die hoger ligt dan 5 m boven het meetniveau, en de brandgevaarlijke delen van het dak ten minste 15 m vanaf de bouwwerkperceelsgrens liggen. Als het perceel waarop het bouwwerk ligt, grenst aan een openbare weg, openbaar water, openbaar groen of een perceel dat niet is bestemd voor bebouwing of voor een speeltuin, een kampeerterrein of opslag van brandgevaarlijke stoffen of van brandbare niet-milieugevaarlijke stoffen wordt die afstand aangehouden tot het hart van die weg, dat water, dat	De weerstand tegen branddoorslag en brandoverslag van een brandcompartiment naar een ander brandcompartiment, naar een besloten ruimte waardoor een extra beschermde vluchtroute voert, naar een niet-besloten veiligheidsvluchtroute en naar een liftschacht van een brandweerlift of van een lift als bedoeld in artikel 4.189 in een woongebouw is ten minste 60 minuten. Kan worden verkort met 30 min als perm. vuurbelasting < 500 MJ/m2 én geen vloer van gebruiksgebied > 7m.	Een vluchtroute in een trappenhuis waarin een hoogteverschil van meer dan 8 m wordt overbrugd, is een extra beschermde vluchtroute.	Een besloten trappenhuis waarin een hoogteverschil van meer dan 20 m wordt overbrugd, wordt in de vluchtrichting alleen bereikt door een afzonderlijke beschermde vluchtroute met een loopafstand van ten minste 2 m.	Een bouwwerk waarin een vloer van een gebruiksgebied hoger dan 70 m boven het meetniveau ligt: a. is zo ingericht dat het bouwwerk een zelfde mate van brandveiligheid heeft als beoogd met de paragrafen 4.2.2, 4.2.6, 4.2.7, 4.2.8, 4.2.9, 4.2.10, 4.2.11 en 4.2.12; of b. voldoet aan de SBRCURnet Handreiking – Brandveiligheid in hoge gebouwen.	Een gebruiksfunctie met een vloer van een verblijfsgebied hoger gelegen dan 20 m boven het meetniveau heeft een droge blusleiding.	Een gebouw waarvan een vloer van een verblijfsgebied hoger ligt dan 20 m boven het meetniveau heeft een brandweerlift.
0-5m	30-60 min	-	-	-	30-60 min	vluchtroute	-	-	-	-
5-7m	30-60 min	Brandklasse B	-	NEN 6063	30-60 min	vluchtroute	-	-	-	-
7-8m	90 min	Brandklasse B	-	NEN 6063	60 min	vluchtroute	-	-	-	-
8-13m	90 min	Brandklasse B	-	NEN 6063	60 min	extra beschermde vluchtroute	-	-	-	-
13-20m	120 min	Brandklasse B	Brandklasse B	NEN 6063	60 min	extra beschermde vluchtroute	-	-	-	-
20-70m	120 min	Brandklasse B	Brandklasse B	NEN 6063	60 min	extra beschermde vluchtroute	Voorportaal lift	-	Ja	Ja
>70m	120 min	Brandklasse B	Brandklasse B	NEN 6063	60 min	extra beschermde vluchtroute	Voorportaal lift	Ja	Ja	Ja

Figure A.4: Requirements set by BBL that change depending on building height

Table A.1: effective charring depth (using ZSL from Lange et al. (2014)) and unity check for structural calculation of floor plate

Name	Comp. area	Shape	% exp.	Open. fact.	$d_{ef,EC}$[mm]	$U.C._{1,EC}$	$d_{ef,ZHM}$[mm]	$U.C._{1,ZHM}$	$d_{ef,zone}$[mm]	$U.C._{1,zone}$	Mean d_{ef}
Mr1i	100	Rectangular	29.67	0.063	56	0.301	62	0.328	67	0.353	62
Mr1ii	100	Rectangular	29.67	0.170	35	0.229	52	0.285	40	0.244	42
Mr2i	100	Rectangular	40.06	0.062	58	0.309	65	0.342	72	0.381	65
Mr2ii	100	Rectangular	40.06	0.171	35	0.229	54	0.293	43	0.253	44
Mr3i	100	Rectangular	69.73	0.062	64	0.337	77	0.412	89	0.506	77
Mr3ii	100	Rectangular	69.73	0.171	37	0.235	61	0.323	56	0.301	51
Ms1i	100	Square	30.04	0.062	57	0.305	61	0.323	69	0.364	62
Ms1ii	100	Square	30.00	0.170	27	0.209	44	0.256	34	0.226	35
Ms2i	100	Square	39.73	0.062	58	0.309	63	0.332	73	0.387	65
Ms2ii	100	Square	39.73	0.170	35	0.229	54	0.293	45	0.260	45
Ms3i	100	Square	69.44	0.062	64	0.337	75	0.399	90	0.516	76
Ms3ii	100	Square	69.44	0.170	37	0.235	61	0.323	58	0.309	52
Sr1i	36	Rectangular	29.83	0.055	61	0.323	78	0.419	64	0.337	68
Sr1ii	36	Rectangular	29.83	0.170	35	0.229	53	0.289	32	0.221	40
Sr2i	36	Rectangular	40.21	0.062	58	0.309	84	0.464	68	0.358	70
Sr2ii	36	Rectangular	40.21	0.170	35	0.229	55	0.297	38	0.238	43
Sr3i	36	Rectangular	70.04	0.062	64	0.337	108	0.737	86	0.480	86
Sr3ii	36	Rectangular	70.04	0.170	37	0.235	63	0.332	49	0.274	50
Ss1i	36	Square	29.76	0.062	57	0.305	71	0.375	66	0.348	65
Ss1ii	36	Square	29.76	0.170	35	0.229	53	0.289	38	0.238	42
Ss2i	36	Square	39.92	0.062	58	0.309	75	0.399	70	0.369	68
Ss2ii	36	Square	39.92	0.170	35	0.229	55	0.297	40	0.244	43
Ss3i	36	Square	69.69	0.062	64	0.337	93	0.545	87	0.489	81
Ss3ii	36	Square	69.69	0.170	37	0.235	63	0.332	52	0.285	51

Name	Comp. area	Shape	% exposed	Opening fact.	Equi. fire dur. EC	Equi. fire dur. ZHM	Equi. fire dur. Zone	Avg. equi. fire dur. [min]
Mr1i	100	Rectangular	29.67	0.063	63	72	81	72
Mr1ii	100	Rectangular	29.67	0.170	31	57	39	42
Mr2i	100	Rectangular	40.06	0.062	66	77	87	77
Mr2ii	100	Rectangular	40.06	0.171	31	60	42	44
Mr3i	100	Rectangular	69.73	0.062	75	95	114	95
Mr3ii	100	Rectangular	69.73	0.171	34	71	62	56
Ms1i	100	Square	30.04	0.062	65	71	83	73
Ms1ii	100	Square	30.00	0.170	31	57	42	43
Ms2i	100	Square	39.73	0.062	66	74	89	76
Ms2ii	100	Square	39.73	0.170	31	60	46	46
Ms3i	100	Square	69.44	0.062	75	92	116	94
Ms3ii	100	Square	69.44	0.170	34	71	67	57
Sr1i	36	Rectangular	29.83	0.055	71	97	76	81
Sr1ii	36	Rectangular	29.83	0.170	31	58	26	38
Sr2i	36	Rectangular	40.21	0.062	66	106	82	85
Sr2ii	36	Rectangular	40.21	0.170	31	62	35	43
Sr3i	36	Rectangular	70.04	0.062	75	143	109	109
Sr3ii	36	Rectangular	70.04	0.170	34	74	53	54
Ss1i	36	Square	29.76	0.062	65	86	78	76
Ss1ii	36	Square	29.76	0.170	31	58	35	41
Ss2i	36	Square	39.92	0.062	66	92	84	81
Ss2ii	36	Square	39.92	0.170	31	62	38	44
Ss3i	36	Square	69.69	0.062	75	120	110	102
Ss3ii	36	Square	69.69	0.170	34	74	56	55

Table A.2: Equivalent fire duration per compartment