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# Establish a Basis for conceptual Solutions for use in Documentation of Fire Safety in high-rise Timber Buildings

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Abstract:
Research conducted by *The Intergovernmental Panel on Climate Change* (IPCC) on the human impact on climate change is acknowledged worldwide. This has caused an increased interest for environmentally friendly materials. In this thesis problems associated with fire safety when timber is implemented in high-rise buildings have been addressed. It has been found that the pre-accepted solutions presented by the Norwegian technical regulations guideline in many cases cannot be used. As a result of this, approved calculation methods or performance based alternative design needs to be utilized for documenting fire safety in these buildings.

The factors effecting the burning of timber are many; temperature exposure/heat flux, oxygen concentration and opening factor have been evaluated in this report. In addition to this an analysis was carried out to determine the effect of varying opening factor on fire development.

To be able to establish conceptual solutions for use in documentation of fire safety in high-rise timber buildings more research is needed.

Keywords:

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| 1. High-rise timber buildings |
| 2. Documentation of fire safety |
| 3. Factors influencing fire development |
| 4. Simulating fire using computer programs |

Hege Njerve Stusvik
(Sign.)

# Preface

This report is the result of a Master thesis done in the field of Civil and Environmental Engineering at the Norwegian University of Science and Technology in Trondheim. The report is the final part of a Masters degree in Fire Safety Engineering in Buildings.

Using timber for load-bearing structures in high-rise buildings is getting more common every day. In Norway this choice in material cannot be done without deviations from the Norwegian technical regulation occurring. This Master thesis addresses the problem. This thesis has identified factors that require more research for it to be possible to establish a basis for conceptual solutions for use in documentation of fire safety in high-rise timber buildings and examined them accordingly.

Information was gathered from previous research, and PyroSim in combination with Fire Dynamics Simulator (FDS) have been used to further examine the effect variation in opening factor have on fire development in compartments where exposed cross-laminated timber is used as surface material.

The analysis presented in this report is based on a case, a newly planned student accommodation building in Trondheim (Moholt 50|50). The construction phase of the building is initiated, and the project consists of five nine-storey timber buildings.

## Acknowledgements

I want to thank my main supervisor Harald Landrø in the Department of Civil and Transport Engineering for guidance. I would also like to thank Jon Ivar Knarud for his remarkable patience and help with the analysis conducted as part of this thesis.

For presenting a relevant case, help concerning the case and inspiration through letting me observe when a full-scale fire test was carried out for the case building, I want to thank Dag Denstad and Rambøll Norge AS.

Last but not least, a major thanks goes to all the wonderful people surrounding me and helping me through the writing process. You have motivated me, and inspired me to get this done!

## Summary

Research conducted by *The Intergovernmental Panel on Climate Change* (IPCC) on the human impact on climate change is acknowledged worldwide. As a result of this the focus on using environmentally friendly materials as wood, has increased. With new technologies and different ways of treating and handling wood, the application area of the material is still growing. One of the many effects of this is the increasing interest of implementing it in high-rise buildings.

The following topics have been addressed in this thesis:

1 In what areas do high-rise timber buildings deviate from the pre-accepted solutions given for a fire class 3, or higher classified construction in the Norwegian technical regulations guideline? What are the causes of these deviations?
2 How does the use of cross-laminated timber in the construction of high-rise buildings affect fire development and documentation of fire safety?
3 What factors affect the development and spread of fire, and what can be done to enhance the fire safety when timber is implemented in the load- bearing construction of high-rise buildings?
4 Are computer programs developed for fire simulating a trustworthy method for estimating fire development, and should it be used to document fire safety in high-rise timber buildings?

A literature study was used to find the information needed to discuss the topics of interest. The reliability of sources has been considered before their implementation in the report, to ensure that the quality of the provided information is academically satisfying. In addition to this, an analysis was conducted to test the effect of varying opening factor in a compartment fire. This was carried out using PyroSim and Fire Dynamics Simulator (FDS).

For the analysis, and some mathematical examples, a case building has been utilized. Moholt 50|50 is a project that involves five nine storey/high-rise residential timber buildings, which suits this thesis perfectly.

Based on the gathered information and the carried out analyses the following conclusions and recommendations have been drawn,

1 Deviations occur for a relatively big number of pre-accepted solutions presented in the Norwegian technical regulation guideline when timber is implemented in the load-bearing structure of high-rise buildings. All the deviations are caused by timbers reaction to fire, as it is a combustible material (D-s2, d0) and the pre-accepted solutions originally were made for incombustible materials like steel and concrete.

   This problem can be avoided by establishing conceptual solutions that can be used for documentation of fire safety in high-rise timber buildings, or implementing fire protection claddings or active fire protection systems.

2 It is clear from calculations using the method presented in NS-EN 1995-1-2 Annex A that the contribution to the fire load from cross-laminated timber, when this is used for a big amount of the surface area in a compartment, is very high.

   The limitation of the application area of the method is exceeded very fast. Researchers have previously proposed expanding the limits of this method, and suggest doing it through conducting more experiments for an extended range of heating rates and fire loads. This would improve the calculation method, and this research should definitely be conducted. However, to achieve a satisfying level of fire safety in timber buildings at the moment, fire protective claddings or extensive active fire protection systems are inevitable

3 A lot of factors influence the fire development and spread. They can be divided into material and external factors. This report focuses on the external ones which are; thermal exposure/heat flux, oxygen concentration and opening factor. A lot of research has been carried out on these, but to be able to establish conceptual solutions for documenting fire safety in high-rise timber buildings, more is needed. The reason is mainly an effect of the factors influencing each other. By varying one, the others will be affected, which makes predicting fire development extremely challenging.

4 The computer programs developed for simulating fires are a very effective way of getting an overall picture of a potential fire. However, because of the uncertainties associated with factors implemented in the model, extra care needs to be taken when utilized. A fire simulation provides *a priori* data, which means that the results cannot be validated until an actual fire occurs. Experiments to establish an *a posteriori* point of view have been conducted, showing that the results of a simulated fire rarely correlate with the real fire.

At the moment using these simulation tools are a very time-consuming process, and the results is not as reliable as desired. To make better programs more knowledge is needed for the input data, to reduce the need of assumptions.

The development of better and faster computers will also increase the possibilities when it comes to using these types of programs, as the simulations will take less time. This would result in an easier method of correcting errors. This offers a faster technique to adjust assumptions based on results obtained and run new simulations.

# Sammendrag


Forskning utført av *FNs klimapanel* vedrørende menneskeskapte klimaendringer er anerkjent verden over. Et resultat av dette er et økt fokus på bruk av miljøvennlige materialer, både blant privatpersoner og bedrifter. Ny teknologi og alternative måter å behandle tre på har gjort at materialets bruksområde har økt betraktelig de siste årene. En av mange følger av dette er økt interesse for å implementere materialet i høye bygninger.

Følgende tema har blitt tatt for seg i denne oppgaven:

1. Ved hvilke paragrafer vil det for et høyhus i tre oppstå avvik fra de pre-aksepterte løsningene presentert for bygg i brannklasse 3, eller høyere i Veiledningen om tekniske krav til byggverk i Norge? Hva er grunnen til at disse avvikene oppstår?
2. Hvordan påvirkes brannutvikling og dokumentasjon av brannsikkerhet ved bruk av krysslaminert tre i høyhus?
3. Hvilke faktorer påvirker brannutvikling og brannspredning, og hva kan gjøres for å øke brannsikkerheten når tre er implementert i bæresystemet i høyhus?
4. Er bruk av dataprogrammer utviklet for å simulere brann en pålitelig måte å estimere brannutvikling på, og bør denne metoden benyttes for dokumentasjon av brannsikkerhet i høyhus av tre?

For å samle informasjon nødvendig for diskusjon av problemstillingene er det gjennomført en litteraturstudie. Kildenes pålitelighet har blitt nøye vurdert før de er inkludert i oppgaven, dette for å forsikre at den presenterte informasjonen er akademisk tilfredsstillende. I tillegg til dette er en analyse utført for å teste hvilken effekt variasjon av åpningsfaktor har for en brann i en branncelle. Analysen er gjennomført ved bruk av PyroSim og Fire Dynamics Simulator (FDS).

I analysen, og noen matematiske eksempler, har en case-bygning blitt benyttet. Moholt 50|50 er et prosjekt som består av fem boligblokker (høyhus) på ni etasjer - noe som passer denne oppgaven veldig bra.

Basert på innsamlet informasjon og den utførte analysen, har følgende konklusjoner og anbefalinger blitt utarbeidet,

1. Det oppstår relativt mange avvik fra de pre-aksepterte løsningene presentert i Forskrift om tekniske krav til byggverk når tre blir brukt som materiale i bærende konstruksjoner i høyhus. Alle avvikene er forårsaket av treets egenskaper ved brannpåvirkning, ettersom det er et brennbart materiale (D-s2, d0) og de pre-aksepterte løsningene originalt er laget for ubrennbare materialer som stål og betong.

   Dette problemet kan bli unngått ved å etablere konseptuelle løsninger til bruk ved dokumentasjon av brannsikkerhet i høyhus av tre.

2. Beregninger utført ved bruk av metoden presentert i NS-EN 1995-1-2 Annex A viser at store overflatearealer med krysslaminert tre vil øke brannlasten betraktelig.

   Avgrensningen av bruksområdet til metoden blir raskt oversteget. Forskere har tidligere foreslått en utvidelse av avgrensningene til metoden. Det er foreslått at dette blir gjort ved å utføre en større mengde eksperimenter for forskjellige oppvarmingshastigheter og brannlaster. Dette er imidlertid ikke gjort enda, så for å oppnå en tilfredsstillende brannsikkerhet i høyhus av tre for øyeblikket er brannhemmende kledninger eller omfattende aktive brannsikringstiltak uunngåelig.

3. Veldig mange faktorer påvirker brannutvikling og brannspredning. Disse kan deles inn i materielle og eksterne faktorer. I denne rapporten har fokuset vært på de eksterne, som er; termisk eksponering/varmefluks, oksygenkonsentrasjon og åpningsfaktor. Mye forskning er utført for disse faktorene, men for å muliggjøre etablering av konseptuelle løsninger for dokumentasjon av brannsikkerhet i høyhus av tre kreves enda mer. Grunnen til dette er hovedsakelig effekten av at faktorene påvirker hverandre. Ved å variere én faktor vil de andre bli berørt av dette, noe som gjør det å forutsi hvordan en brannutvikling vil oppføre seg veldig vanskelig.

4. Dataprogrammene utviklet for simulering av brann er en svært effektiv måte å skaffe et samlet bilde av en potensiell brann på. Det er imidlertid veldig mange usikkerheter knyttet til faktorene som implementeres i modellene. Et resultat av dette er at økt

forsiktighet må knyttes til utførelsen av simuleringer. En brannsimulering genererer *a priori* data, noe som betyr at resultatet ikke kan verifiseres før en faktisk brann oppstår. Eksperimenter har blitt utført for å generere et *a posteriori* syn på metoden, med resultater som viser at data kalkulert ved simuleringer sjeldent stemmer overens med virkeligheten.

For øyeblikket er bruk av simuleringsverktøy en svært tidkrevende prosess, uten at resultatene er så pålitelige som en skulle ønske. For å kunne utvikle bedre programmer er det behov for mer kunnskap om dataene som blir implementert i modellen, dette for å redusere antagelser som gjøres.

Utviklingen av bedre og raskere datamaskiner vil også øke mulighetene for bruk av denne typen programvarer, da det vil redusere behovet for tid til utførelse. En kortere simuleringstid vil gjøre det lettere å rette feil, justere antakelser basert på resultatene, for så å kjøre nye og bedre simuleringer.

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# 1 Introduction

The introduction addresses the background of the conducted work, problems identified, objectives and limitations of the report. The background information is divided into two subsections. The first section presents the background information, and the second briefly introduces the supporting theory. Chapter 3, 4 and 5 will expand on this theory.

## 1.1 Background

Research conducted by *The Intergovernmental Panel on Climate Change* (IPCC) on the human impact on climate change is acknowledged worldwide. The focus on this topic, has led to a new way of thinking making environmentally friendly materials more important than ever before.

When looking to implement environmentally friendly materials to a construction, timber offers a myriad of benefits. The material has been a favoured construction material from the beginning of civilization because of its abundance, high stiffness and strength-to-weight ratios and the relative simplicity with which it can be adapted to use (Östman et al., 2010). Timber is also a renewable resource, and research shows that use of wood instead of a traditional building material like concrete, is an effective way of reducing fossil fuel use and net $CO_2$ emission (Gustavsson and Sathre, 2006).

In addition to all these benefits of the material itself, an important reason why the use of timber is increasing is also the new engineered timber products. The potential economic benefit of prefabricated timber and timber composite systems are high.

With new technologies and different ways of treating and handling wood, the application area of the material is still increasing. The positive attributes of timber are numerous, but there are still areas that require more research.

Fire safety has always been a concern when it comes to using timber as a building material. In 1997 the Norwegian government made a change to the technical regulation, which for the first time legalized use of timber in the load-bearing system of buildings exceeding three stories. Table 1-1 presents a timeline and information about the maximum amount of floors that was/is allowed to build using wood in the different Scandinavian countries.

**Table 1-1 Changes over the years in allowed number of floors when using timber in the grid system of buildings (Halvorsen, 2014)**

| Year / Country | 1993 | 1994 | 1997 | 1999 | 2004 | 2007 | 2010 |
|---|---|---|---|---|---|---|---|
| **Norway** | 3 | 3 | ∞ | ∞ | ∞ | ∞ | ∞ |
| **Sweden** | 2 | ∞ | ∞ | ∞ | ∞ | ∞ | ∞ |
| **Finland** | 2 | 2 | 4[1)] | 4[1)] | 4[1)] | 4[1)] | 4[1)] |
| **Denmark** | 2 | 2 | 2 | 4 | ∞ | ∞ | ∞ |

[1)] Requires total sprinkling

Although use of timber in the load-bearing structure of high-rise buildings is now legalized, the pre-accepted solutions given in the Norwegian technical regulations guideline are not adjusted for use of this material. This means that the fire safety has to be thoroughly documented when timber is chosen, which result in a more time-consuming and expensive design phase.

To further enhance the use of timber in high-rise buildings the Norwegian technical regulations guideline needs to be adjusted to the material. The occurring deviations need to be evaluated, and the importance of the different parts of the guideline determined.

The first step in the right direction is to establish a basis for conceptual solutions for use in documentation of fire safety in these types of constructions. The aim of this Master thesis is to locate the occurring deviations in the Norwegian technical regulations guideline, and determine how different factors will influence the fire development and spread in compartment fires of high-rise timber buildings. In addition, the current methods available for documenting fire safety in timber buildings have been evaluated.

## 1.2 Theoretical background

The theoretical background for this project work is mainly based on the deviations from the Norwegian laws and regulations, which are addressed in Chapter 3 – Basic literature. The pre-accepted solutions for fire safety engineering in fire class 3, or higher classified buildings given in the Norwegian technical regulations guideline, are based on the use of incombustible materials. Timber is a combustible material, thus creating problems.

In December 2014 SP Fire Research, with SiT Trondheim as the contracting authority, conducted an experiment on cross-laminated timber (Hox, 2015). The experiment was carried out as part of the design phase of Moholt 50|50, five new nine storey timber buildings meant for student accommodation.

A full-scale model of one of the compartments in the buildings was constructed and Rambøll Norge AS (the consulting company responsible for the fire safety engineering of Moholt 50|50) estimated the variable fire load. The experiment was carried out to see how cross-laminated timber behaves in a natural fire and what charring rates occur. Other important questions of interest were: the duration of a fire in this type of compartment/building, if the fire would self extinguish, the temperature development, when the window would break and if the fire would spread to nearby rooms.

The results answered some questions, and showed some areas that need more research. Some of these research areas of interest are:

- Fire load. How does the exposed cross-laminated timber contribute to the fire? And how to estimate the contribution to the fire load from the load-bearing system?
- Opening factor. How does the window size affect the fire development?

## 1.3 Problems to be addressed

The background information in 1.1 and 1.2 presents some different problems in connection to using timber in fire class 3, or higher classified high-rise buildings. In this report it will be focused on:

1. In what areas do high-rise timber buildings deviate from the pre-accepted solutions given for a fire class 3, or higher classified construction in the Norwegian technical regulations guideline? What are the causes of these deviations?

2 How does the use of cross-laminated timber in the construction of high-rise buildings affect fire development and the documentation of fire safety?
3 What factors affect the development and spread of fire, and what can be done to enhance the fire safety when timber is implemented in the load- bearing construction of high-rise buildings?
4 Are computer programs developed for fire simulating a trustworthy method for estimating fire development, and should it be used to document fire safety in high-rise timber buildings?

## 1.4 Objectives

### 1.4.1 Result oriented goal

The goal of this thesis is to identify deviations in the Norwegian technical regulations guideline, when timber is implemented in the load-bearing structure of high-rise buildings. To gather information about the different factors affecting fire development and spread in these buildings, and to determine the credibility of methods and software programs developed for estimating fire safety.

### 1.4.2 Effect oriented goal

To present information that can be of use to improve the current technical regulations guideline regarding implementation of timber in high-rise buildings.

### 1.4.3 Success criteria

1 Finding that data and literature needed to be able to thoroughly discuss the problems to be addressed
2 Conduct a fire simulation that provides suitable data that can be used as a basis for discussion of the effect for varying opening factors in compartment fires

## 1.5 Limitations of the report

The topic addressed in this report can include a lot of very different fields. Limitation of the report is therefore necessary.

This reports main focus have been limited to include factors affecting fire spread and rate of fire development in compartments, that are part of high-rise residential buildings with timber used for the main load-bearing structures. As an example on this kind of building the Moholt 50|50 project have been used as a reference building. Where analyses have been conducted, measurements and numbers have been taken from this project.

When evaluating properties that influence fire development, the main focus has been placed on external factors. A fire safety engineer can adjust these factors in the design phase, which makes them interesting when discussing what can be done to improve fire safety.

## 1.6 Structure of the report

The report is directed towards people that work with fire safety on a daily basis. This includes construction engineers, architects, entrepreneurs, building owners etc. The terms and expressions used should be easily understood by the target group, and possible to understand for other people as well.

The report is divided into four main parts:

| | | |
|---|---|---|
| 1 | Chapter 1 & 2: | Introduction to the carried out work. |
| 2 | Chapter 3, 4 & 5: | Literature. |
| 3 | Chapter 6 & 7: | The conducted analysis and results. |
| 4 | Chapter 8,9 & 10: | Discussion and recommendations, conclusions and proposals for future work based on the gathered information. |

## 1.7 Definitions

Words unfamiliar to laypersons will be defined upon use.

## 1.8 Acronyms

| | |
|---|---|
| E | Integrity (Fire resistance criteria) |
| FDS | Fire Dynamics Simulator |
| FIGRA | Fire Growth Ratio |
| HRR | Heat Release Rate |
| HRRPUA | Heat Release Rate Per Unit Area |
| I | Insulation (Fire resistance criteria) |
| M | Mechanical action (Fire resistance criteria) |
| R | Stability (Fire resistance criteria) |
| SBI | Single Burning item (Fire testing procedure) |

## 1.9 Symbols

| | | |
|---|---|---|
| $A$ | Surface area | $[m^2]$ |
| $A_f$ | Floor area of the fire compartment | $[m^2]$ |
| $A_{fuel}$ | Exposed surface are of burning fuel | $[m^2]$ |
| $A_h$ | Area of horizontal openings | $[m^2]$ |
| $A_i$ | Surface area of window i | $[m^2]$ |
| $A_j$ | Area of enclosure surface j, openings not included | $[m^2]$ |
| $A_t$ | Total area of enclosure (walls, ceiling and floor, including openings) | $[m^2]$ |
| $A_V$ | Window/Ventialtion opening, Total area of vertical openings on all walls | $[m^2]$ |
| $D$ | Diameter | $[m]$ |
| $D_H$ | Hydraulic diameter | $[m]$ |
| $E$ | Total fuel load | $[MJ]$ |
| $H_u$ | Net calorific value including moisture | $[MJ/kg]$ |
| $H_{u0}$ | Net calorific value of dry material | $[MJ/kg]$ |
| $H_{ui}$ | Net calorific value of material i | $[MJ/kg]$ |
| $H_V$ | Height of window opening | $[m]$ |
| $HRRPUA$ | Heat release rate per unit surface area $A_{fuel}$ | $[kW/m^2]$ |
| $L_V$ | Heat of gasification | $[kJ/g\,; MJ/kg]$ |

| | | |
|---|---|---|
| $M_{k,i}$ | Amount of combustible material i | $[kg]$ |
| $M_{k,i,t}$ | Amount of combustible material related to the surface area $A_t$ | $[kg/m^2]$ |
| $O$ | Opening factor of fire compartment | $[m^{1/2}]$ |
| $O_{ekv}$ | Equivalent opening factor of fire compartment | $[m^{1/2}]$ |
| $P$ | Perimeter of opening | $[m]$ |
| $Q_{fi,k}$ | Characteristic fire load | $[MJ]$ |
| $Q_{fuel}$ | Rate of heat release for fuel controlled fire | $[MW]$ |
| $Q_{vent}$ | Rate of heat release for ventilation controlled fire | $[MW]$ |
| $\dot{Q}_E''$ | Heat flux to surface from external radiant heater | $[kW/m^2]$ |
| $\dot{Q}_F''$ | Heat flux to surface from flame | $[kW/m^2]$ |
| $\dot{Q}_L''$ | Heat flux from surface (heat loss) | $[kW/m^2]$ |
| $T$ | Temperature | $[°C; K]$ |
| $T_{exposed\ side}$ | Temperature on the side of a material exposed to fire | $[°C]$ |
| $T_{ig}$ | Ignition temperature | $[°C]$ |
| $T_{middle}$ | Average temperature in a material | $[°C]$ |
| $T_{unexposed\ side}$ | Temperature on the side of a material not exposed to fire | $[°C]$ |
| $V$ | Volume | $[m^3]$ |
| $b$ | Width of cross-section; Thermal absorptivity for the total enclosure | $[mm; J/m^2 s^{1/2} K]$ |
| $b_j$ | Thermal absorptivity of one enclosure surface i | $[J/m^2 s^{1/2} K]$ |
| $b_{min}$ | Original minimum width of cross-section for one-dimensional charring | $[mm]$ |
| $c$ | Specific heat | $[J/kgK]$ |
| $d_0$ | Depth of layer with assumed zero strength and stiffness | $[mm]$ |
| $d_{char,0}$ | Charring depth for one-dimensional charring | $[mm]$ |
| $d_{char,n}$ | Notional charring depth | $[mm]$ |
| $d_{ef}$ | Effective charring depth | $[mm]$ |
| $f_k$ | Coefficient for estimating equivalent opening factor | $[-]$ |
| $h$ | Depth of cross-section; Convective heat transfer coefficient, The distance between the geometrical points of gravity for vertical and horizontal openings | $[mm;\ kW/m^2K\ ; m$ |

| | | |
|---|---|---|
| $h_{eq}$ | Weighted average of heights of all vertical openings in the fire compartment | $[m]$ |
| $h_i$ | Height of window i | $[m]$ |
| $k$ | Thermal conductivity | $[W/mK]$ |
| $k_0$ | Factor depending on the protection of the timber surface | $[-]$ |
| $m$ | Mass; Combustion factor | $[kg; -]$ |
| $m_f$ | Mass of fuel available for combustion | $[kg]$ |
| $\dot{m}$ | Rate of mass loss/burning | $[kg/s]$ |
| $\dot{m}''$ | Rate of mass loss per unit area | $[kg/m^2s]$ |
| $t$ | Time; Time of fire exposure | $[min; h]$ |
| $t_0$ | Time period with a constant charring rate | $[min]$ |
| $t_b$ | Duration of burning | $[min]$ |
| $t_{lim}$ | Time for maximum gas temperature in case of fuel controlled fire | $[h]$ |
| $t_{max}$ | Time for maximum gas temperature | $[h]$ |
| $u$ | Moisture content | $[\%]$ |
| $q_f$ | Fire load | $[MJ]$ |
| $q_{f,d}$ | Design fire load density related to the surface area $A_f$ | $[MJ/m^2]$ |
| $q_{f,k}$ | Characteristic fire load density related to the surface area $A_f$ | $[MJ/m^2]$ |
| $q_{t,d}$ | Design fire load density related to the surface area $A_t$ | $[MJ/m^2]$ |
| $q_{t,k}$ | Characteristic fire load density related to the surface area $A_t$ | $[MJ/m^2]$ |
| $\dot{q}_B$ | Rate of heat storage in the gas volume of a compartment | $[kW]$ |
| $\dot{q}_C$ | Rate of heat release due to combustion | $[kW]$ |
| $\dot{q}_L$ | Rate of heat loss due to replacement of hot gases by cold | $[kW]$ |
| $\dot{q}_R$ | Rate of heat loss through openings | $[kW]$ |
| $\dot{q}_W$ | Rate of heat loss through walls, ceiling and floor | $[kW]$ |
| $\dot{q}''$ | Heat flux | $[kW/m^2]$ |
| $\dot{q}_i''$ | Incident radiation reaching the fuel surface | $[MW/m^2]$ |
| $\Gamma$ | Time factor function of the opening factor $O$ and the thermal absorptivity $b$ | $[-]$ |

| | | |
|---|---|---|
| $\Theta_g$ | Gas temperature in the fire compartment | [°C] |
| $\Theta_{max}$ | Maximum temperature | [°C] |
| $\Psi_i$ | Protected fire load factor | $[-]$ |
| $\beta_0$ | Design charring rate for one-dimensional charring under standard fire exposure | $[mm/min]$ |
| $\beta_n$ | Design notional charring rate under standard fire exposure | $[mm/min]$ |
| $\beta_{par}$ | Design charring rate during heating phase of parametric fire curve | $[mm/min]$ |
| $\delta_{ni}$ | Factor accounting for the existence of a specific fire fighting measure i | $[-]$ |
| $\delta_{q1}$ | Factor taking into account the fire activation risk due to the size of the compartment | $[-]$ |
| $\delta_{q2}$ | Factor taking into account the fire activation risk due to the type of occupancy | $[-]$ |
| $\Delta H_c$ | Heat of combustion | $[kJ/g\,; MJ/kg]$ |
| $\varepsilon$ | Emissivity | $[-]$ |
| $\lambda$ | Thermal conductivity | $[W/mK]$ |
| $\rho$ | Density | $[kg/m^3]$ |
| $\sigma$ | Stefan-Boltzmann constant | $[W/m^2K^4]$ |
| $\phi$ | Configuration factor | $[-]$ |

# 2 Methods

This chapter contains information about the methods implemented in this Master thesis. The main part of the report is based on a literature study. Supplementing the theory is an analysis carried out to look at the effect of varying opening factors on fire development. The computer program/method used for this analysis is briefly presented here.

## 2.1 Literature study

This report has primarily been based on Norwegian laws and regulations. The literature below has been used as it demonstrates accurate and essential information needed for documentation of fire safety,

- Plan and building act
- The Norwegian technical regulation
- The Norwegian technical regulations guideline
- NS-EN 1991: Actions on structures
  Part 1-2: General actions – Actions on structures exposed to fire
- NS-EN 1995: Design of timber structures
  Part 1-2: General – Structural fire design
- Well known handbooks and books on the field of study:
  - Fire safety in timber buildings – Technical guideline for Europe

Based on the different laws and regulations data relevant for fire design of high-rise timber buildings have been gathered. This has been done through carrying out a literature study. This method was chosen, as it is a very efficient way to identify problems, gather research previously conducted by other people, and comparing available data on the topics of interest. The following search engines were used to gather the information presented in the literature:

- BIBSYS Ask
- Google Scholar
- Google

The key words entered, when searching for information were: "timber structures", "fire safety", "solid wood", "high-rise buildings in timber", "properties wood", "burning wood", "pyrolysis wood", "opening factor", "charring rate", "mass loss rate", "ventilation controlled fire" etc.

The reliability of sources has been considered before their inclusion in this report. To ensure the quality of the provided information, articles of a high academic calibre were used. The resources used were mainly: journal articles, academic documents, international standards and published textbooks.

## 2.2 Case study

To enhance the understanding, and ease certain explanations, this thesis utilizes a case building. It has been used where an example including numbers is beneficial.

Moholt 50|50 is a high-rise timber building under construction in Trondheim, Norway. Calculations and analysis that have been carried out in this report are based on this building. More information about the building and the compartment used is presented in Section 6.1.

## 2.3 Analysis using Fire Dynamics Simulator (FDS) and PyroSim

To illustrate and study the effect of varying opening factors in a compartment containing surfaces with exposed cross-laminated timber, simulations have been carried out in Fire Dynamics Simulator (FDS). FDS is a computer program for simulating fire development. The program is well recognized, and is often used when fire safety design of buildings is to be documented. To get the most realistic result possible from the simulations carried out, knowledge about fire development, and factors affecting it, is essential.

The model used in FDS was designed in PyroSim, which is a program developed by Thunderhead Engineering in USA. PyroSim is used to make graphical representations of constructions. When the model is finished, a text file is generated by the program, which reflects the graphics. This text file can then be used in FDS.

In this report PyroSim is used to draw a graphical model of a compartment that is part of a high-rise timber building. Moholt 50|50 have been utilized as a case building. Measurements and materials included in the model have been taken from the architects drawings of the building and the report from the experiment conducted on the same compartment in December 2014 (Hox, 2015).

# 3 Basic literature

This chapter provides the basic literature necessary to address the identified problems. The literature is a combination of; classification methods, the deviations from the Norwegian technical regulations guideline that occur when timber is implemented in high-rise residential buildings, fire design, and timber as a construction material and the effect high temperatures have on it.

As the most common way to protect timber in fire situations is by use of gypsum, some details about this material have been included. Detailed information about fire protection systems is however not given, as passive fire protection is the focus area of this report. Parts of the presented information may seem unnecessary, but is incorporated to better show the bigger picture.

## 3.1 Active vs. passive fire protection

When designing a building there are many things that need to be taken into consideration. This report will only focus on one out of the two ways to increase the fire safety of a construction, passive fire protection.

The second method, active fire protection, complements the passive. It is used to increase the fire safety in buildings to a higher level than is possible with passive fire protection alone. In some cases it can also be used as a way to achieve a satisfying level of fire safety where passive fire protection alone, is not enough to meet the criteria given by laws and regulations.

### 3.1.1 Passive fire protection

Passive fire protection measures include (Östman et al., 2010):

- Adequate compartmentation to inhibit the spread of heat, smoke and gases
- Limitation of fire compartment size
- Control of flammability/combustibility of wall linings – particularly on escape routes
- Control of the spread of smoke
- Provision of protected escape routes
- Provision of adequate thermal insulation, stability and structural performance
- Fire stopping

To make sure the passive fire protection is adequate the criteria given in laws and regulations need to be met. There is alternative ways of doing this, which will be discussed further in the following subsections.

Before doing this, the classification methods used by the Norwegian technical regulations guideline are presented. The reason for this is to make it easier to address the deviations from the guideline occurring, when timber is implemented in the load-bearing structure of high-rise buildings.

## 3.2 Classification methods

Using the Norwegian technical regulations guideline is a way of reducing the time needed for fire safety engineering in the design phase. The guideline presents pre-accepted solutions that can be used, these solutions, however cannot be used in all cases. Before presenting the deviations that occur when timber is implemented in high-rise buildings. This chapter will present the classification methods that are used to evaluate materials. The classification of a material gives information about its application area.

The Norwegian technical regulations guideline uses two different types of classification methods to determine if a certain material fulfils the requirements given in the Norwegian laws and regulations. The two methods are; fire resistance and reaction to fire.

### 3.2.1 Fire resistance

This method classifies a structure, a part of a structure or a members capability to withstand fire. The object of interest is evaluated based on its ability to fulfil its required functions for a specified load level, fire exposure and period of time. NS-EN 1991-1-2 describes the three main criteria for fire resistance as follows (Norsk Standard, 2008):

*Stability (R):*

> Ability of a structure or a member to sustain specified actions during the relevant fire, according to defined criteria

*Integrity (E):*

> Ability of a separating element of building construction, when exposed to fire on one side, to prevent the passage through it of flames and hot gases and to prevent the occurrence of flames on the unexposed side

*Insulation (I):*

> Ability of a separating element of building construction when exposed to fire on one side, to restrict the temperature rise of the unexposed face below specified levels

Table 3-1 shows the construction elements that are affected by the different failure criteria.

**Table 3-1 Failure criteria for construction elements (Buchanan, 2002)**

| Construction element | Stability (R) | Integrity (E) | Insulation (I) |
|---|---|---|---|
| Partition | | X | X |
| Door | | X | X |
| Load-bearing wall | X | X | X |
| Floor/ceiling | X | X | X |
| Beam | X | | |
| Column | X | | |
| Fire-resistant glazing | | X | |

For some separating structural elements the mechanical action (M) has to be considered in addition to the three main criteria already mentioned. The mechanical action is the ability of the structural element to withstand impact, representing the case where structural failure of another component in a fire causes an impact on the element concerned. The test for this is carried out immediately after the building element has been tested during a certain time for another classification (R, E and/or I) (Norsk Standard, 2009b).

In addition to the most common classification criteria (R, E, I and M), the object is given a number when classified. The number range from 10 to 360 (Norsk Standard, 2009b), and gives information about how many minutes the object can fulfil its required function during a fire. For instance, a load-bearing wall classified “REI90” should maintain its stability, integrity and insulation requirements for 90 minutes.

### 3.2.2 Reaction to fire

The second method used to classify a building material/element is conducted by evaluating the objects contribution to development and spread of fire. All new materials are tested, after which they are given a classification depending on the result. The different classes, with test methods, test criteria and examples of materials, are presented in Table 3-2.

**Table 3-2 Classification of reaction to fire (ROCKWOOL Firesafe Insulation)**

| Euroclass | Test method(s) | Test criteria | Example |
|---|---|---|---|
| A1 | Non-combustibility | Temperature rise<br>Mass loss<br>Sustained flaming | Stone, glass |
| | AND<br>Calorific content | Total energy in product<br>Energy per internal and external component | |
| A2 | Non-combustibility OR Calorific content | As above | Gypsum boards (thin paper), mineral wool |
| | AND<br>Single Burning Item (SBI) | Fire growth rate<br>Lateral flame spread and total heat release in 600s | |
| B | SBI | As SBI above | Gypsum boards (thick paper), fire retardant wood |
| | AND<br>Small flame test for 30s | Lateral flame spread in 60s | |
| C | SBI | As SBI above | Coverings on gypsum boards, fire retardant wood |
| | AND<br>Small flame test for 30s | Lateral flame spread in 60s | |
| D | SBI | As SBI above | Wood, wood-based panels |
| | AND<br>Small flame test for 30s | Lateral flame spread in 60s | |
| E | Small flame test for 15s | Lateral flame spread in 20s | Some synthetic polymers |
| F | No performance determined | | |

The tests presented in Table 3-2 are all small/medium-size fire tests. To get a better understanding of how construction products will react in ‘real fires’, the test data from Table 3-2 needs to correlate with larger scale test results. A Room Corner Test can be conducted as a reference test to find this correlation.

The Room Corner test is a standardized test carried out in a relatively big room. Walls and ceiling are lined with the product that is being tested, and then exposed to a small gas flame in one corner. The result is found by measuring the heat release rate (HRR) over a period of time, as illustrated in Figure 3-1. The slope of the plot conducted from the measurements indicates the fire growth ratio (FIGRA index). The material is classified based on the measured FIGRA index, as shown in Table 3-3.

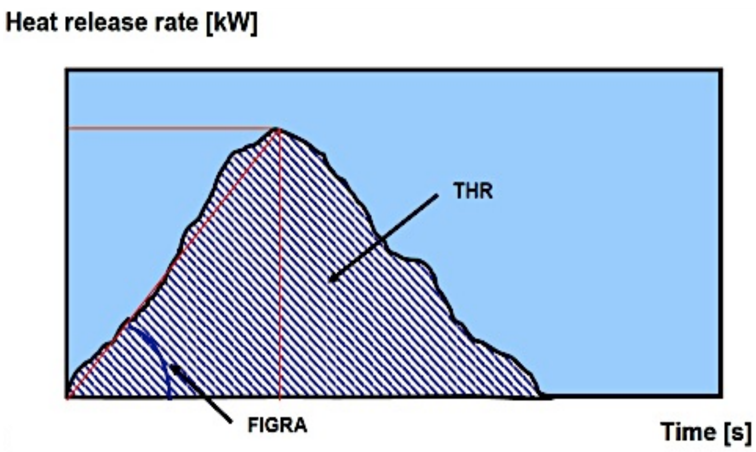



**Figure 3-1 Heat release rate and FIGRA index. Used to classify a materials reaction to fire.**

**Table 3-3 Classification of reaction to fire with use of the FIGRA index (ROCKWOOL Firesafe Insulation)**

| Euroclass [in reference test] | FIGRA index [KW/s] | Time to flashover |
|---|---|---|
| A1 | Less than 0.15 | No flashover |
| A2 | Less than 0.15 | No flashover |
| B | Less than 0.5 | No flashover |
| C | Less than 1.5 | Flashover after 10 minutes |
| D | Less than 7.5 | Flashover 2 – 10 minutes |
| E | More than 7.5 | Flashover before 2 minutes |
| F | No performance determined | |

In addition to this, smoke production and flaming droplets/particles are also a part of the classification of materials reaction to fire. The different classes are presented in Table 3-4 and Table 3-5.

**Table 3-4 Explanation of the different classes of smoke production (Paroc Group, 2015a)**

| Class | Explanation |
|---|---|
| s1 | The structural element may emit a very limited amount of combustion gases |
| s2 | The structural element may emit a limited amount of combustion gases |
| s3 | No requirement for restricted production of combustion gases |

**Table 3-5 Explanation of the different classes of production of burning droplets/particles (Paroc Group, 2015a)**

| Class | Explanation |
|---|---|
| d0 | Burning droplets or particles must not be emitted from the structural element |
| d1 | Burning droplets or particles may be released in limited quantities |
| d2 | No requirement for restriction of burning droplets and particles |

### 3.2.3 Classification of timber

Timber that have not been treated in any specific way is classified **D-s2, d0**. This means that it is combustible, produces some smoke and no burning droplets/particles. Because timber is combustible, deviations from the Norwegian technical regulations guideline occurs when it is implemented in the load-bearing structure of high-rise buildings or used as surface material in some specified rooms.

## 3.3 Norwegian laws and regulations

As stated in 1.1, up until 1997 the highest amount of stories that were allowed to build in Norway using timber, was three. This limit is now gone, as the Norwegian technical regulation now, is performance-based instead of prescriptive.

The laws and regulations are not as conservative as they once were, but the pre-accepted solutions given in the Norwegian technical regulations guideline are still not adjusted to the use of timber in high-rise buildings. The guideline is based on the load-bearing materials being incombustible, which introduces problems when timber is implemented.

This subsection presents the Norwegian hierarchy of laws and regulations and the effect of the changes made to the regulations in 1997. It also pinpoints the paragraphs in the Norwegian technical regulations guideline that has to be addressed with special care when using timber.

### 3.3.1 Hierarchy

The legal hierarchy concerning construction works in Norway are shown in Figure 3-2.

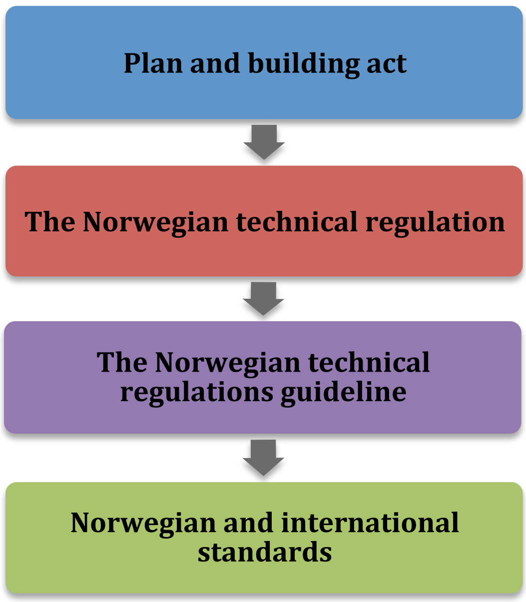



**Figure 3-2 The hierarchy of Norwegian laws and regulations**

The main purpose of the Plan and building act is to promote sustainable development for the benefit of individuals, the society and future generations (Kommunal- og moderniseringsdepartementet, 2010). To concretise the law and make it easier to follow, a technical regulation with guidelines has been instituted to give a more detailed explanation and specific requirements.

The regulation, and its guidelines, is created to make sure that measures are planned, designed and constructed in a way that ensures good visual quality and universal design, and that security, safety, health and energy demands are met (Kommunal- og moderniseringsdepartementet, 2010). One must comply with the Norwegian technical regulation in order to obey the plan and building act. While both the laws and regulations are more general and performance-based, the regulations guideline gives specified pre-accepted solutions that can be used to meet the criteria given by the laws and regulations.

If the building that is being designed does not fit the pre-accepted solutions, the project designers have to document that the construction meets the criteria presented in the laws and regulations in alternative ways. The different Norwegian and international standards show ways of completing calculations for approval of the design. The documentation can also be done by use of simulations, advanced analysis etc. The standards present many of the different methods, and how to use them.

### 3.3.2 Performance based vs. prescriptive technical regulation

> "In general terms, a prescriptive code states how a building is to be constructed whereas a performance based code states how a building is to perform under a wide range of conditions" (Custer and Meacham, 1997).

In 1997 the Norwegian technical regulation changed from being prescriptive (Kommunal- og arbeidsdepartementet og Miljøverndepartementet, 1987) to being performance based (Kommunal- og arbeidsdepartementet og Miljøverndepartementet, 1997). The main effect of this change is the fire engineers increasing opportunity for finding new and alternative solutions. While the old regulation presented specific ways to meet the criteria given in the law, the new one gives information about how the construction should perform in given situations, and the fire engineer himself can find the best suited way of meeting these criteria.

There are positive and negative attributes with both alternatives. Some of these are presented in Table 3-6.

**Table 3-6 Pros and cons of prescriptive and performance based technical regulation**

| | Pros | Cons |
|---|---|---|
| Prescriptive | ▪ No need for additional documentation<br>▪ Saves time and money in design phase | ▪ Alternative solutions and materials are neglected<br>▪ No room for creative thinking |
| Performance based | ▪ Alternative methods can be used<br>▪ Opens for creative and new solutions, innovation | ▪ Can be difficult to document the fire safety in a satisfying way<br>▪ Can cause higher costs and a more time-consuming design phase<br>▪ Requires a higher skill-level amongst engineers |

Even though the Norwegian technical regulation is changed to being performance based, it is important to remember that its guideline still have a prescriptive format. In the Norwegian technical regulations guideline pre-accepted solutions are presented, and if these fit the project being designed there is no reason not to choose them. If however they do not fit, the performance based regulations opens for using standards to find approved calculation methods, or performance based alternative design can be used.

This means that the prescriptive part in some ways are still available, and by taking the Norwegian technical regulations guideline into use a fire engineer can save both money and time. However, when deviations from the pre-accepted solutions occur there are still alternative ways to document the fire safety of the construction.

Figure 3-3 illustrates the hierarchical relationship for performance based design.

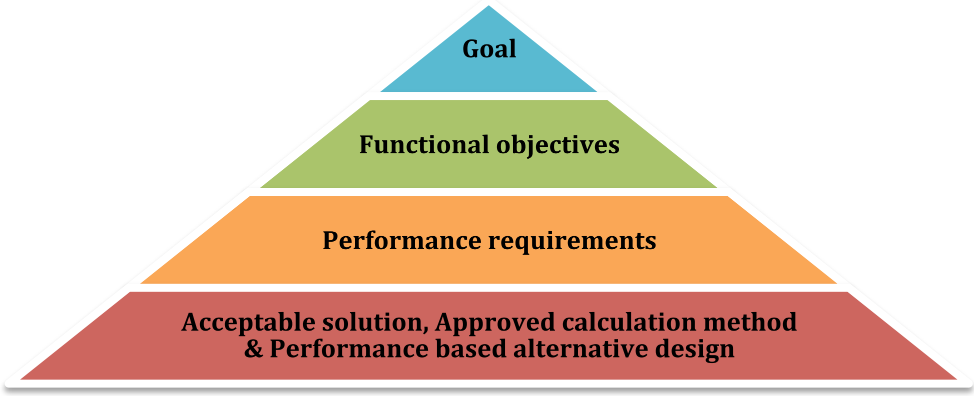



**Figure 3-3 Hierarchical relationship for performance based design (Buchanan, 2002)**

A prime example of the benefits of the performance based regulation is the ability to use timber in high-rise buildings. The next subsection presents the occurring deviations from the Norwegian technical regulations guideline when glue-laminated and cross-laminated timber is used. The deviations create challenges and a more time-consuming design phase, but because the Norwegian technical regulation now is performance based, alternative documentation can be used to document fire safety.

### 3.3.3 Deviations occurring from the pre-accepted solutions in the Norwegian technical regulations guideline, caused by use of timber in the load-bearing system

When timber is used for the load-bearing construction in high-rise buildings deviations from the pre-accepted solutions occur. These are caused by the fact that timber is a combustible material. Some of the deviations are questionable, but because it is difficult to determine if timber satisfies the given requirements or not, they are included in the list below.

#### *3.3.3.1 § 11-3 Fire class*

It is difficult to determine the extent of the contributing fire energy caused by the combustible load-bearing system. If the contributing fire energy from the building itself exceeds $400\,MJ/m^2$ a residential building should be categorized as a fire class 4 building. When this is the case analysis is required to document the fire safety, and pre-accepted solutions cannot be used for the building.

#### *3.3.3.2 § 11-4 Loadbearing capacity and stability*

Assuming the contributing fire energy from the construction is less than $400\,MJ/m^2$ and the high-rise building is classified as a fire class 3 construction.

For a normal fire class 3 construction the pre-accepted solutions presented in Table 3-7 can be applied. If the load-bearing system is designed in accordance with Table 3-7, no further documentation is needed for this part of the construction.

**Table 3-7 Capacity criteria of different constructions parts in a fire class 3 of the construction (Direktoratet for byggkvalitet, 2010)**

| Part of construction | Fire class 3 Criteria |
|---|---|
| Main load bearing system | R 90 A2-s1, d0 |
| Secondary load bearing construction parts, floors and roof constructions that are not part of the main load bearing system or stabilizing parts | R 60 A2-s1, d0 |
| Stairwell | R 30 A2-s1, d0 |
| Loadbearing construction parts localized beneath the first basement floor | R 120 A2-s1, d0 |
| Outdoor stairwell, protected against the effect of flames and radiation | A2-s1, d0 |

For a fire class 3 construction where timber is used for the load-bearing structure, the pre-accepted solutions cannot be used. The reason for this is timbers reaction to fire. As the material is combustible, **D-s2, d0**, it does not satisfy the fire class 3 criteria given by the pre-accepted solutions.

### 3.3.4 Deviations occurring from the pre-accepted solutions in the Norwegian technical regulations guideline, caused by use of timber in separating elements

High-rise timber buildings often use modules of cross-laminated timber. This decreases the construction time, and the attributes of using wood in this way are many. When it comes to fire safety, it introduces some challenges. Without use of gypsum or other fire retardant materials or methods, the cross-laminated timber does not satisfy all the criteria given in the pre-accepted solutions. This means that once again documentation of the fire safety has to be done in alternative ways. The occurring deviations are listed below.

#### *3.3.4.1 § 11-7 Fire sectioning*

As presented in Table 3-8, the pre-accepted solutions for fire sectioning walls require incombustible materials. This means that unprotected cross-laminated timber cannot be used for these walls, as the materials reaction to fire is classified **D-s2, d0**.

**Table 3-8 Fire resistance of sectioning wall (Direktoratet for byggkvalitet, 2010)**

| The construction fire class | The fire resistance of the sectioning wall depending on the specific energy of the fire[1)] $[MJ/m^2]$ | | |
|---|---|---|---|
| | Under 400 | 400-600 | 600-800 |
| 2 and 3 | REI 120-M A2-s1, d0 | REI 180-M A2-s1, d0 | REI 240-M A2-s1, d0 |

[1)] The specific energy of fire is given as energy per $m^2$ enclosure surface area

#### *3.3.4.2 § 11-8 Fire cells*

Walls dividing a fire class 3 or higher classified building into fire cells need to be incombustible to satisfy the given pre-accepted solutions. This cannot be achieved when cross-laminated timber is used, without additional fire safety measures being applied.

### *3.3.4.3 § 11-9 Material properties in a fire situation*

The materials used in a building can affect the potential fire development. While the indoor surfaces influence ignition, heat release and smoke development, the outside surfaces can be crucial to fire spreading to nearby buildings. The pre-accepted solutions for surface materials in a fire class 3 construction are presented in Table 3-9.

**Table 3-9 Lower limit for material properties in fire class 3 and hazard class 4 (Direktoratet for byggkvalitet, 2010)**

| Surfaces and claddings | Fire class 3 |
|---|---|
| **Surfaces in fire cells that are not part of escape routes** | |
| Surface of walls and ceiling in a fire cell not exceeding 200 $m^2$ | D-s2, d0 |
| Surface of walls and ceiling in a fire cell exceeding 200 $m^2$ | B-s1, d0 |
| Surface in shafts and hollow spaces | B-s1, d0 |
| **Surfaces in fire cells that are escape routes** | |
| Surface of walls and ceiling | B-s1, d0 |
| Surface of floor | $D_{fl}$-s1 |
| **Exterior surfaces** | |
| Surface of exterior cladding | B-s3, d0 |
| **Claddings** | |
| Cladding in fire cell not exceeding 200 $m^2$, that are not part of escape route | $K_2$10 D-s2, d0 |
| Cladding in fire cell exceeding 200 $m^2$, that are not part of escape route | $K_2$10 B-s1, d0 |
| Cladding in fire cell that are part of escape route | $K_2$10 A2-s1, d0 |
| Cladding in shafts and hollow spaces | $K_2$10 A2-s1, d0 |

Whether or not timber should be used as a surface material in the compartments of a high-rise residential building needs to be evaluated. As timber contributes to the fire, other materials might be preferable. For areas that are part of an escape route, untreated timber once again does not meet the criteria given in the pre-accepted solutions.

### 3.3.5 Comments to the deviations

It is clear that including timber in high-rise buildings creates some challenges. Because of the performance-based technical regulation, these can however be dealt with. As the pre-accepted solutions cannot be used for some parts of the construction, alternative methods need to be carried out to ensure that the fire safety design of the building is acceptable.

The first step towards documenting the fire safety of high-rise timber buildings is by looking deeper into fire design. How a potential fire will develop and spread in a fire compartment is important knowledge to be able to determine the fire safety level of the building. The next subsection summarizes some of the main things to consider when looking into fire design.

## 3.4 Fire Design

The main principles forming the basis for fire safety regulations in most European countries are (Östman et al., 2010):

- Occupants shall be able to leave the buildings or be rescued
- The safety of rescue teams shall be taken into account
- Load-bearing structures shall resist fire for the required minimum duration of time
- The generation and spread of fire and smoke shall be limited
- The spread of fire to neighbouring buildings shall be limited

When designing and constructing a building, these bullet points are what we aim to achieve when it comes to fire safety. As mentioned earlier, with the current Norwegian technical regulation and its guidelines, there are three different ways of achieving this:

- Acceptable solution,
- Approved calculation method,
- Performance based alternative design

Timber introduces some challenges in the design phase because of the occurring deviations from the pre-accepted solutions. As a result of this, special care needs to be shown to these types of buildings. A good way to determine the risks associated with a specific building is by performing a risk assessment. This should be done according to NS 3901. The next subsections present a brief introduction to the two possible risk analyses that can be carried out, and some of the main parts of the analysis.

## 3.5 Risk assessment

When the pre-accepted solutions do not fit the construction being designed, or the complexity of the construction is too comprehensive, analysis and modelling is required. According to NS 3901 there are two different ways of determining the risks associated with the fire safety of a building (Norsk Standard, 2013):

*Risk analysis:*

> When conducting a risk analysis initiating events, consequences and associated probabilities is identified and compiled for the construction of interest.

*Comparative analysis:*

> When conducting a comparative analysis a comparison of the fire safety in the construction being analysed and a corresponding reference construction is performed.

The planning phase of a risk assessment is almost the same for both types of analysis. The difference occurs when the method is chosen and the analysis is carried out. Figure 3-4 is retrieved from NS 3901, and shows the steps of a risk assessment.

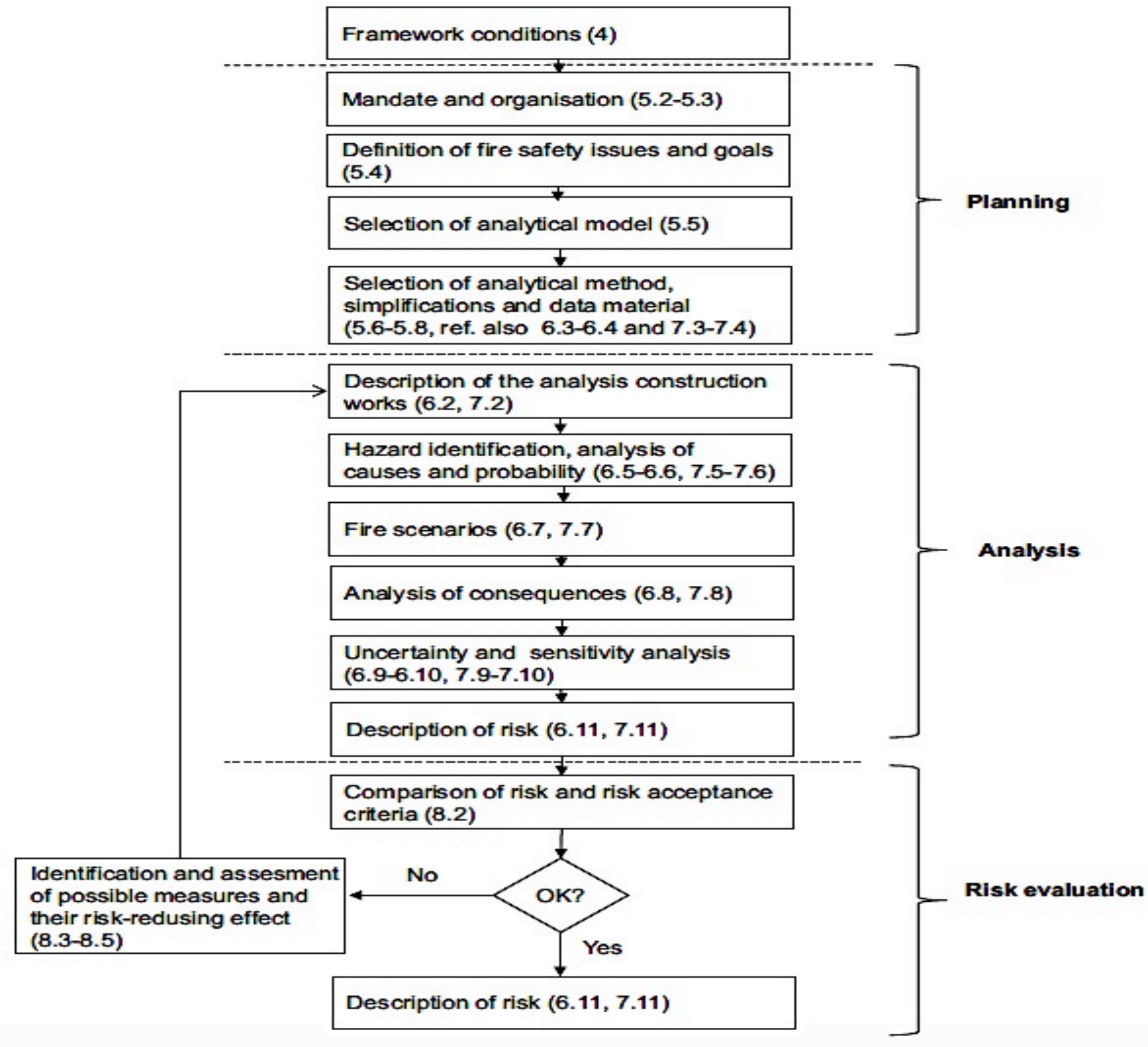



**Figure 3-4 Flow diagram for risk assessments of fire in construction works (Norsk Standard, 2013)**

Regardless of what type of analysis is chosen to be carried out, a couple of things need to be established. Amongst these are possible fire scenarios.

## 3.6 Fire scenarios

To be able to analyse a building it is important to have information about how a potential fire will develop and spread. This subsection presents the most essential information about fire development, and some of the different ways to estimate the growth of a potential fire.

### 3.6.1 Fire development and fire load

When a fire occurs in a room or similar enclosure it is called a compartment fire. The dimension of the room is important when talking about this type of fire. Bigger rooms, or rooms with special shapes, needs special consideration because the fire will develop in a different way when the surface area and ventilation conditions (opening factor) changes. As illustrated in Figure 3-5, a compartment fire can be divided into three stages (Drysdale, 2011):

1 The growth or pre-flashover stage, in which the average compartment temperature is relatively low and the fire is localized in the vicinity of its origin
2 The fully developed or post-flashover fire, during which all combustible items in the compartment are involved and flames appear to fill the entire volume
3 The decay period, often identified as that stage of the fire after the average temperature has fallen to 80% of its peak value

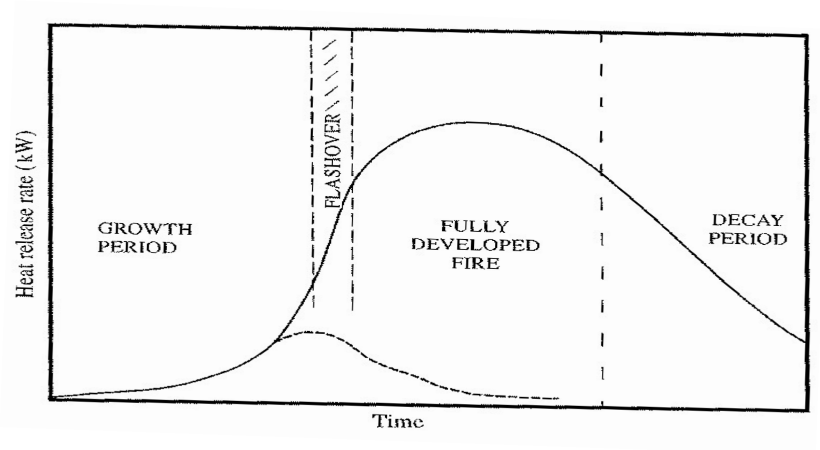



**Figure 3-5 Course of a well-ventilated compartment fire, expressed as the rate of heat release as a function of time**

Another important factor influencing the development of a fire, in addition to the shape of the room and the opening factor, is the combustible materials in the fire compartment. The type, amount and arrangement of the movable items in the room are essential to the pre-flashover stage of the fire development. The contributing energy from surrounding combustible surface materials on the other hand, has a big impact on the post-flashover fire. This, the fire load, and how to estimate it will be further discussed in Chapter 4.

The pre-flashover stage of a fire is the period of greatest importance when it comes to safety of human life. Research has shown that flashovers have played a significant role in a number of major fire disasters (Rasbash, 1991). In the event of a flashover the behaviour of the fire changes dramatically. All exposed combustible surfaces starts pyrolysis; this produces large amounts of combustible gases, which burn where there is sufficient oxygen (Buchanan, 2002). After a flashover takes place the main focus changes from human safety, to minimizing the harm to the construction. How the fire develops after a flashover is dependent on whether it is ventilation controlled or fuel controlled.

### 3.6.2 Ventilation controlled vs. fuel controlled

Most compartment fires are ventilation controlled. This means that the design of the ventilation openings in the compartment is the main factor influencing the rate of combustion. The ventilation opening determines the amount of fresh air that can get into the compartment and the amount of hot gases that can get out. By doing this it controls the fire development.

In some cases however, the fire is fuel controlled. This is often the case for larger rooms, or areas where there is an unlimited amount of oxygen available. If this is the case, the rate of combustion is mainly dependent on the surface of the burning fuel and what type of fuel it is.

More details about calculation methods and the effect of different opening factors in ventilation controlled fires will be presented in Chapter 4.

### 3.6.3 Estimations of fire scenarios

There are many different ways of estimating a fire. The two methods presented in NS-EN 1991-1-2 are nominal and parametric temperature-time curves. The amount of available information is of great importance when calculation method is chosen.

#### *3.6.3.1 Nominal curves*

Nominal temperature-time curves can be found directly in the standard. They show the relationship between the temperature of the gases in a compartment as a function of time. Figure 3-6 illustrations the different types of nominal curves given in NS-EN 1991-1-2.

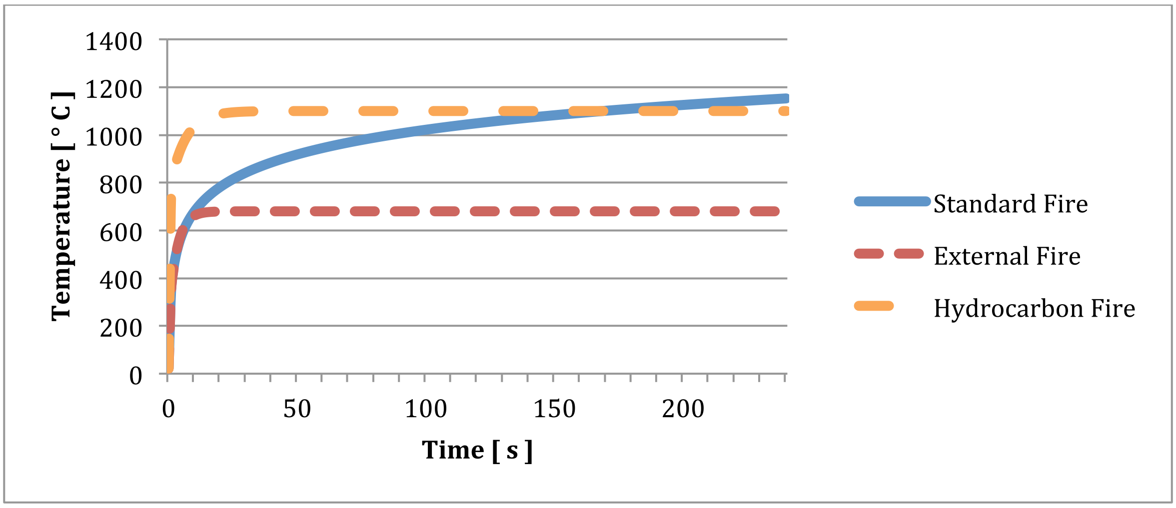



**Figure 3-6 Nominal temperature-time curves given by NS-EN 1991-1-2 (Norsk Standard, 2008)**

The curves are found using the following equations,

*Standard temperature-time curve:*

$$\Theta_g = 20 + 345 log_{10}(8t + 1) \tag{3.1}$$

*External fire curve:*

$$\Theta_g = 660(1 - 0.687e^{-0.32t} - 0.313e^{-3.8t}) + 20 \tag{3.2}$$

*Hydrocarbon curve:*

$$\Theta_g = 1080(1 - 0.325e^{-0.167t} - 0.675e^{-2.5t}) + 20 \tag{3.3}$$

where $\Theta_g[°C]$ is the gas temperature in the fire compartment and $t[min]$ is the time.

Even though these curves are used as the main exposure condition in European Standards, they do have some weaknesses. The curves represent a fully developed fire, which means that the growth and decay period of the fire is not fully accounted for using these curves.

The standard-curve is however the one used in most research concerning timber structures. This means that most of the available information about timber in fire conditions are based on this types of curves, and if other curves/models are to be used modifications of the thermal properties of timber needs to be carried out.

#### *3.6.3.2 Parametric curves*

A more accurate way of estimating a fire is by using parametric fire curves. These curves take all phases of the fire into account, not only the phase where the fire is fully developed. The model is based on simplified formulas developed for limited boundary conditions. The formulas take into account the most important factors for temperature development (Östman et al., 2010):

- The fire load (amount, type and arrangement of combustible material),
- The ventilation conditions in the room,
- The thermal properties of the enclosure, and
- The fire fighting action

The heating phase of the parametric fire curve can be calculated using the following equation,

$$\Theta_g = 20 + 1325\left(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*}\right) \qquad (3.4)$$

where $\Theta_g[°C]$ is the gas temperature in the fire compartment and $t^*[h]$ can be found using,

$$t^* = t \cdot \Gamma \qquad (3.5)$$

where $t[h]$ is the time of the fire exposure and $\Gamma$ is a time factor function of the opening factor $O\left[m^{1/2}\right]$ and the thermal absorptivity $b\left[J/m^2 s^{1/2} K\right]$.

The estimation of the cooling phase is dependent on the maximum temperature $\Theta_{max}$[°C], and can be calculated using,

$$\Theta_g = \begin{cases} \Theta_{max} - 625(t^* - t^*_{max} \cdot x) & for \quad t^*_{max} \leq 0.5 & (3.6a) \\ \Theta_{max} - 250(3 - t^*_{max})(t^* - t^*_{max} \cdot x) & for \quad 0.5 < t^*_{max} < 2 & (3.6b) \\ \Theta_{max} - 250(t^* - t^*_{max} \cdot x) & for \quad t^*_{max} \geq 2 & (3.6c) \end{cases}$$

where $t^*$ is given by Equation (3.5), $x = 1.0$ if $t_{max} > t_{lim}$, or $x = t_{lim} \cdot \Gamma / t^*_{max}$ if $t_{max} = t_{lim}$ and,

$$t^*_{max} = \left(0.2 \cdot 10^{-3} \cdot q_{t,d}/O\right)\Gamma \quad (3.7)$$

where $q_{t,d}[MJ/m^2]$ is the design value of the fire load density in the given compartment.

As stated in Section 3.6.3.1 about nominal temperature-time curves, the information available on the performance of timber structures in natural fires is limited. Unless the thermal properties of timber are modified, the properties given in the Norwegian standards are only valid for standard fire exposure.

One of the reasons why the parametric curve cannot be used directly on timber structures is the burning/charring of wooden surfaces. This factor will influence the fire load, which is included in the calculation of parametric fire curves.

One way to make it possible to utilize parametric fire curves when the construction is timber based, is by use of the method presented in NS-EN 1995-1-2 Annex A and iterations. This way a rough estimate of the timbers contribution to the fire load can be calculated. More information about this and charring of timber is presented in Chapter 4.

#### *3.6.3.3 Experimental studies on temperatures of post-flashover fires*

Several experimental studies have measured temperature in post-flashover fires. Butcher *et al.* measured the correlation between temperature and time in real rooms with door or window openings and well-distributed fuel load (Butscher et al., 1966). Thomas and Heselden measured the maximum temperature during the steady burning period for a large number of wood crib fires in small-scale compartments. There is however considerable scatter between the results of different studies (Buchanan, 2002).

A conceptually simple model for estimating temperatures in fire compartments was developed by Magnusson and Thelandersson (Magnusson and Thelandersson, 1970). These are the most referenced temperature-time curves, and normally referred to as the *Swedish curves*. They have later been used by Pettersson *et al*. to develop a method for calculating "fire resistance requirements" (Pettersson et al., 1976), and was a basis when the parametric fire curves presented in the Eurocode was derived (Buchanan, 2002).

The model is based on Kawagoe's equation for the burning rate of ventilation controlled fires,

$$\dot{m} = 0.092 A_V \sqrt{H_V} \tag{3.8}$$

where $\dot{m}[kg/s]$ is the rate of mass loss, $A_V[m^2]$ is the area of the window opening and $H_V[m]$ is the height of the window opening. The consequence of assuming that a fire is ventilation controlled when it actually is fuel controlled is an overestimate of the burning rate, and an underestimate of the duration of the fire. This is an uncertainty that needs to be considered when utilizing this model.

When using this model the temperature is found by solving Equation (3.9),

$$\dot{q}_c = \dot{q}_L + \dot{q}_W + \dot{q}_R + \dot{q}_B \tag{3.9}$$

where $\dot{q}_c$ is the rate of heat release due to combustion, $\dot{q}_L$ is rate of heat loss due to replacement of hot gases by cold, $\dot{q}_W$ is the rate of heat loss through walls, ceiling and floors, $\dot{q}_R$ is the rate of heat loss through openings and $\dot{q}_B$ is the rate of heat storage in the gas volume (which is neglected). The model can be illustrated as in Figure 3-7.

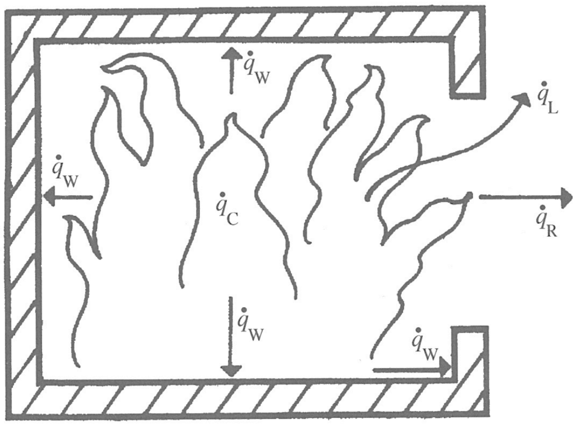



**Figure 3-7 Illustration of heat losses during a fully developed compartment fire (Drysdale, 2011; Pettersson et al., 1976)**

The model is based on the following assumptions (Drysdale, 2011):

- Combustion is complete and takes place entirely within the confines of the compartment
- The temperature is uniform within the compartment at all times
- A single surface heat transfer coefficient may be used for the entire inner surface of the compartment
- The heat flow to and through the compartment boundaries is unidimensional i.e., corners and edges are ignored and the boundaries are assumed to be "infinite slabs".

Originally the model calculates the heat release rate using the following equation,

$$\dot{q}_c = 0.09 A_V \sqrt{H_V} \cdot \Delta H_c \tag{3.10}$$

where $\Delta H_c [kJ/kg]$ is the heat of combustion of wood $(18.8\, kJ/kg)$. However, based on wood equivalents the following can be used too,

$$\dot{q}_c = \dot{m}_{air} \cdot \Delta H_{c,air} \tag{3.11}$$

Which gives,

$$\dot{q}_c = 1560 A_V \sqrt{H_V} \tag{3.12}$$

Note that there is a small deviation between Equation (3.10) and (3.12). The curves obtained from this method are presented in Figure 3-8. They are temperature-time curves based on the effect of different ventilation factors and fuel load.

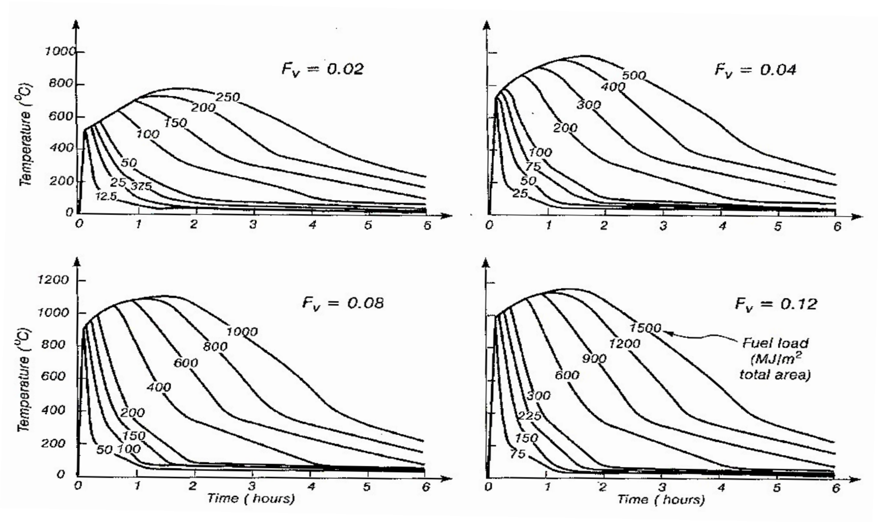



**Figure 3-8 Temperature-time curves for different ventilation factors and fuel loads (MJ/m2 of total surface area), Swedish curves (Buchanan, 2002)**

## 3.7 Timber

Timber differs from other common materials in many ways, some of the most significant are (Buchanan, 2002):

- Timber strength is very variable, both within boards and between boards
- Mechanical properties are different in different directions (parallel and perpendicular to the grain)
- Strength and ductility are very different in tension and compression
- Failure stresses depend on the size of the test specimen
- The strength reduces under long duration loads

Creating different timber products can modify the properties of the material. When building high-rise buildings in timber, three main timber products are normally used:

*Solid wood:*

When lumber has been sawn and adjusted to fit standardized measures the remaining part is called solid wood (or dimensional lumber). The solid wood is put into different categories depending on the strength of the timber. The sorting can be done in two different ways, mechanically or visually. Solid wood is most commonly used in framework and joists, but it is also the main component in glue-laminated timber and cross-laminated timber.

*Glue-laminated timber (Glulam):*

When producing glulam individual wood laminations (dimensional lumber) are specifically selected. Based on their performance characteristics the timber laminations are positioned, with the grain of each individual dimension lumber parallel to the length of the member, and glued together using durable and moisture-resistant glue. Glulam is usually used for beams and columns (reThink Wood, 2014b).

*Cross-laminated timber (CLT):*

CLT is mainly used for floors, walls and roofs; this is because of its structural properties and dimensional stability. The cross-laminated timber usually consists of three, five or seven layers of dimension lumber. Unlike the glue-laminated timber, the cross-laminated is made by orienting the dimension lumber so that the direction of the grain in each layer is perpendicular to the layers next to it (reThink Wood, 2014a).

## 3.8 Material properties of timber at elevated temperatures

Wood differs from other common building materials like concrete and steel, due to its combustibility. When a layer of char has been formed, the burning continues at a slow and steady rate. The wood will continue to burn if the necessary requirements are being met (enough oxygen and fuel). As it continues to burn, the size of the cross-section will be reduced.

With this taken into consideration, the risk of using timber is often looked upon as higher than the benefits obtained. However, this is not necessarily true. Although timber burns and char is formed, the mechanical properties of the remaining wood underneath the char will be approximately the same. This subsection will discuss how wood burns and how specific heat, thermal conductivity and the strength of wood is affected by fire.

### 3.8.1 The pyrolysis of wood

There are four different stages in the burning/charring of timber. These four zones occur during pyrolysis, and are parallel to the exposed surface (as shown in Figure 3-9). They can be characterized as follows (Friquin, 2011):

*Zone A: Temperatures lower than 200°C*

- 100°C – The chemically unbound water in the wooden cells starts to evaporate
- 160-180°C – The wood slowly starts to decompose
- No combustible gases are formed in this stage

*Zone B: Temperatures from 200 to 280°C*

- The pyrolysis is still slow
- Most of the gases are non-combustible
- 225-275°C – Possible to ignite the wood with a pilot flame

*Zone C: Temperatures from 280 to 500°C*

- Temperature exceeding 300°C – Physical structures in the wood starts to brake down and char is rapidly formed
- At first the gases that are released from this zone contain too much carbon dioxide and water vapour to spontaneous ignition to take place
- When the pyrolysis starts going faster the products will be CO, $CH_4$ etc., which are largely combustible
- 350-360°C – Ignition will occur even in the presence of only a spark
- When released gases are mixed with oxygen outside the char layer, combustion takes place (with a flame temperature at approximately 1100°C)

- Because of the insulating effect of the char layer, the temperature rise in the remaining cross-section will be very slow.

*Zone D: Temperatures higher than 450–500◦C*

- Temperature above 450-500°C – The production of volatiles is complete
- Smouldering and oxidation of char form $CO_2$, CO and $H_2O$, which causes further mass loss

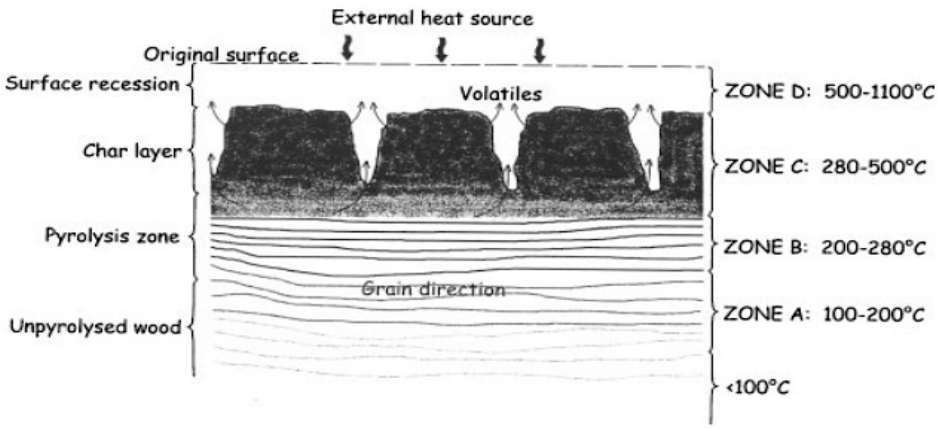



**Figure 3-9 Temperature zones in a solid wood cross-section exposed to fire (Friquin, 2011)**

The charring rate is essential to the burning and load bearing capacity of timber. It is affected by both material- and external properties. When the charring rate of the material is known, calculations can be done to find the load bearing capacity of a fire exposed timber element. To estimate the charring rate, the material properties of wood are needed.

### 3.8.2 Thermal properties at elevated temperatures

The thermal properties of wood changes significantly with temperature; one of the main factors causing this change is the moisture content of the material. The curves in Figure 3-10 show the change in specific heat and conductivity.

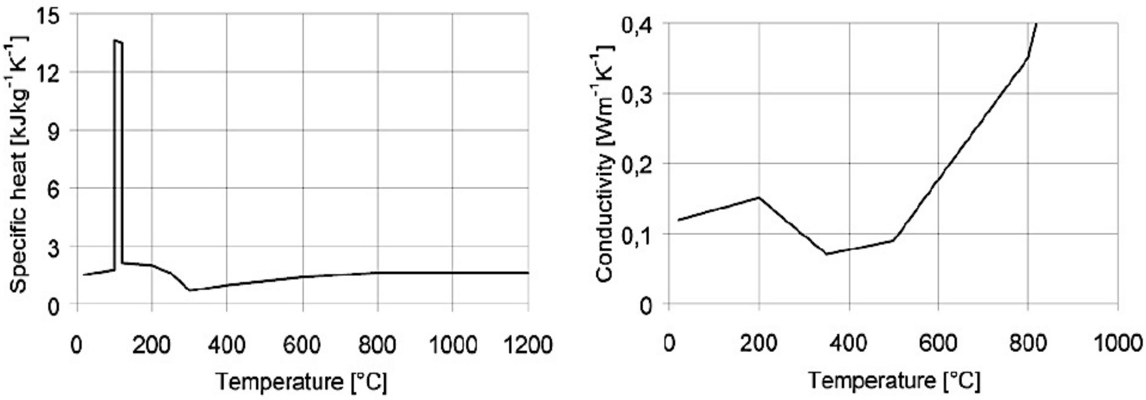



**Figure 3-10 The specific heat and conductivity of wood (Norsk Standard, 2010)**

The specific heat of timber, changes distinctively when the temperature reaches 100°C. The reason for this is the increase in energy needed to evaporate the water in the material. As the water evaporates, the specific heat drops back to its original value and continues sinking until the temperature reaches 300°C. At this temperature the water is gone, the decomposition of timber starts, and char is formed. When this happens the specific heat stabilizes, and remain close to constant for the rest of the temperature rise.

Compared to the specific heat the change in conductivity is relatively small at first, but increases rapidly when char is formed at 300°C. This explains why char works as insulation for the remaining wood, and the temperature rise in the core of the structural element is slowed down when a solid layer of char is formed.

### 3.8.3 Mechanical properties at elevated temperatures

The specific heat and thermal conductivity are not the only factors that change with increasing temperature. The modulus of elasticity and yield strength is also affected. This is shown in Figure 3-11.

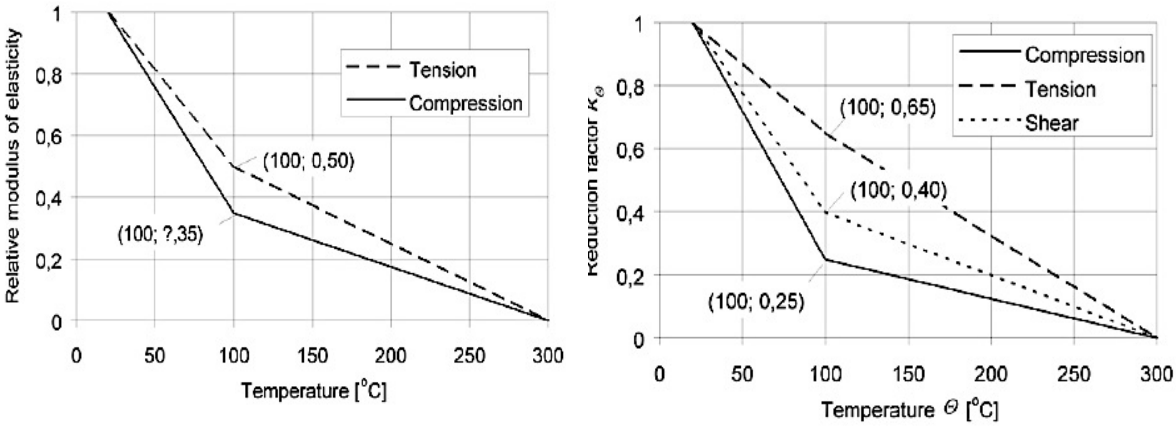



**Figure 3-11 The effect of temperature on modulus of elasticity and the reduction factor for strength parallel to the grain of softwood (Norsk Standard, 2010)**

Both curves presented in Figure 3-11 have been retrieved from NS-EN 1995-1-2. The standard positions the char-line at the position of the 300-degree isotherm, and assume that the load-bearing capacity of char is zero (Norsk Standard, 2010).

Figure 3-11 show that the wood close to the char-line will have reduced capacity. Depending on the temperature the wood is exposed to, the temperature gradient beneath the char layer varies some. This variation is mainly effected by rate of the vaporization of the moisture in wood. In the calculation methods presented in the standard a "safety zone" is added for the area with a temperature rise. The wood, beneath the char-line and this zone, is assumed to have the capacity of wood that has not been exposed to fire.

## 3.9 Methods used for estimating charring depth

NS-EN 1995-1-2 (Norsk Standard, 2010) covers the topic of structural fire design in timber constructions. The standard deals with passive methods of fire protection. Some of the calculation methods presented in this standard are given in the following subsections. These methods only apply to standard fire exposure.

### *3.9.1.1 Charring depth, unprotected timber*

The charring rate and depth influences the capacity of timber dramatically. According to the standard there are two different ways of estimating charring depth. Figure 3-12 illustrates these two.

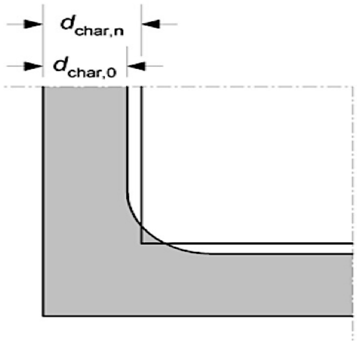



**Figure 3-12 One-dimensional charring depth and notional charring depth (Norsk Standard, 2010)**

*Design charring depth:*

For unprotected surfaces throughout the time of fire exposure, the design charring depth should be calculated using the following equation,

$$d_{char,0} = \beta_0 t \tag{3.13}$$

where $d_{char,0}[mm]$ is the design charring depth for one-dimensional charring, $\beta_0[mm/min]$ is the one-dimensional design charring rate under standard fire exposure and $t[min]$ is the time of fire exposure.

This method can be used on cross-sections with an original minimum width $b_{min}[mm]$, as long as the increased charring near the corners is taken into account. This is done by assuming that the radius of the corner roundings are equal to the charring depth $d_{char,0}$.

$$b_{min} = \begin{cases} 2\, d_{char,0} + 80 & for \quad d_{char,0} \geq 13mm \quad (3.14a) \\ 8.15\, d_{char,0} & for \quad d_{char,0} < 13\, mm \quad (3.14b) \end{cases}$$

*Notional design charring depth:*

The other method compensates for the corner roundings. This method uses the notional design charring rate to calculate the charring depth,

$$d_{char,n} = \beta_n t \tag{3.15}$$

where $d_{char,n}[mm]$ is the notional design charring depth and $\beta_n[mm/min]$ is the design notional charring rate under standard fire exposure.

The design charring rates, $\beta_0$ and $\beta_n$, can be found in NS-EN 1995-1-2, Table 3.1 (Norsk Standard, 2010).

It is important to note that for one-dimensional charring of softwood the charring rate in the standard is given as independent of species and densities. For the time being the variety in species of softwoods is not substantial in Europe, compared to for instance in North America (which in their standards presents charring rates dependent on species) (König, 2005). However, increased trade might change this, which means that the presented value in the standard needs to be considered more carefully.

#### 3.9.1.2 Charring depth, partly or fully protected timber

For timber partly or fully protected by fire protection claddings, other protection materials or by other structural members, the charring behaviour is slightly different. The effect of the protection, and a brief explanation, is given in Figure 3-13, Figure 3-14 and Figure 3-15.

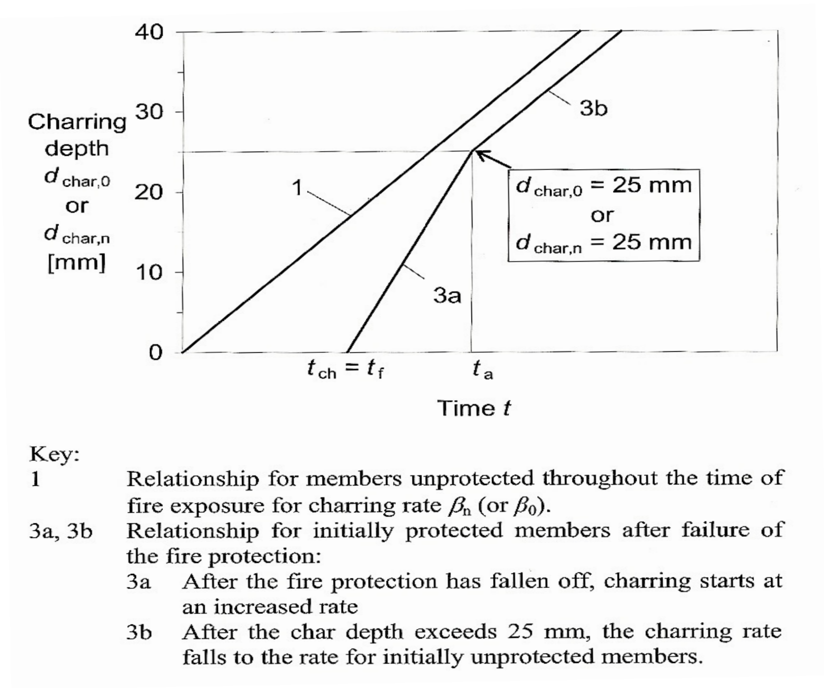



**Figure 3-13 Variation of charring depth with time when $t_{ch} = t_f$ and the charring depth at time $t_a$ is at least 25 mm (Östman et al., 2010)**

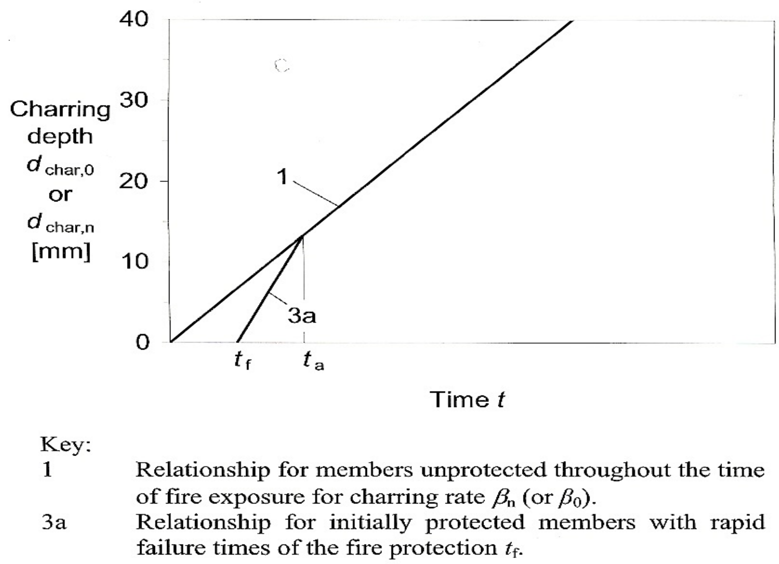
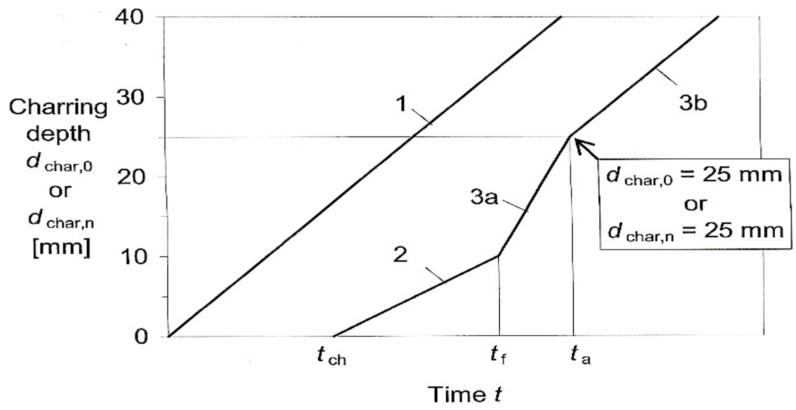



**Figure 3-14 Variation of charring depth with time when $t_{ch} = t_f$ and the charring depth at time $t_a$ is less than 25 mm (Östman et al., 2010)**




Key:

1 Relationship for members unprotected throughout the time of fire exposure for charring rate $\beta_n$ (or $\beta_0$).

2, 3a, 3b Relationship for initially protected members where charring starts before failure of the fire protection:

- 2 Charring starts at $t_{ch}$ at a reduced rate when the fire protection is still in place
- 3a After the fire protection has fallen off, charring starts at increased rate
- 3b After the char depth exceeds 25 mm, the charring rate reduces to the rate for initially unprotected members.

**Figure 3-15 Variation of charring depth with time when $t_{ch} < t_f$ (Östman et al., 2010)**

In cases where the protective layer is maintained throughout the fire but charring still occurs, the charring rates given in NS-EN 1995-1-2 should be multiplied with factors depending on the thickness of the protection layer.

## 3.10 Gypsum – Fire protection cladding

Production and marking of gypsum boards varies across the world. Even though the same products are not available in all countries, the product types seem to be the same. Gypsum boards can be divided into three groups (Buchanan, 2002):

*Regular board:*

> This is a generic gypsum board sold very competitively for residential construction. As opposed to Type GF- and Special purpose boards, the regular ones do not need to have a fire-resistance rating. These boards are normally low in density, as a result of air entrainment during the production and no added reinforcement except for the

external paper. A regular gypsum board, compared to the two other types, perform bad in fire situations. The main reason for this is that they crack and fall down when the external paper burns up and the water evaporates from the core.

*Type GF Board (/Type X board):*

The definition of a Type GF board is that it will give a 60-minute load-bearing fire resistance rating when one layer of 15.9 mm board is fixed to each side of a wood or steel stud wall assembly (or a 45-minute rating for a 12.7 mm board). To improve fire performance Type GF boards are added glass fibre reinforcing, and in some cases other additional additives.

*Special purpose board (/Type C board):*

These boards are made so that the fire or structural performances exceed the expected performance of Regular- and Type GF boards. The Special purpose boards are not standardized, which means that they can be ordered in different sizes and thicknesses to meet the criteria they are meant for. This type is often added even more glass fibre, and other core additives, compared to the Type GF board.

### 3.10.1 Material properties

Driving the moisture out of gypsum rock is the first step in creating solid gypsum plaster. This reaction is an endothermic decomposition reaction, and occurs in the temperature range $100-120°C$,

$$CaSO_4 \cdot 2H_2O \rightarrow CaSO_4 \cdot \tfrac{1}{2}H_2O + \tfrac{3}{2}H_2O \tag{3.16}$$

The reaction is then reversed to become a hydration reaction, when the powder is mixed with water and formed into gypsum plaster,

$$CaSO_4 \cdot \tfrac{1}{2}H_2O + \tfrac{3}{2}H_2O \rightarrow CaSO_4 \cdot 2H_2O \tag{3.17}$$

The water content of gypsum is what makes it such a fire-resistant material. Because the gypsum plaster normally contains about 21% water by weight and, depending on ambient temperature and relative humidity, about 3% free water, a lot of the energy from a potential fire goes to dehydration of the material. As a result of this energy consuming process, the complete dehydration of gypsum does not happen until a temperature of approximately 700 ºC is reached in the material (Buchanan, 2002).

### 3.10.2 Thermal properties

Based on tests on Canadian Type X boards by Sultan (Sultan, 1996), the trends of the thermal properties of gypsum plaster can be illustrated as in Figure 3-16 and Figure 3-17. The figures are retrieved from Structural Design for Fire Safety (Buchanan, 2002).

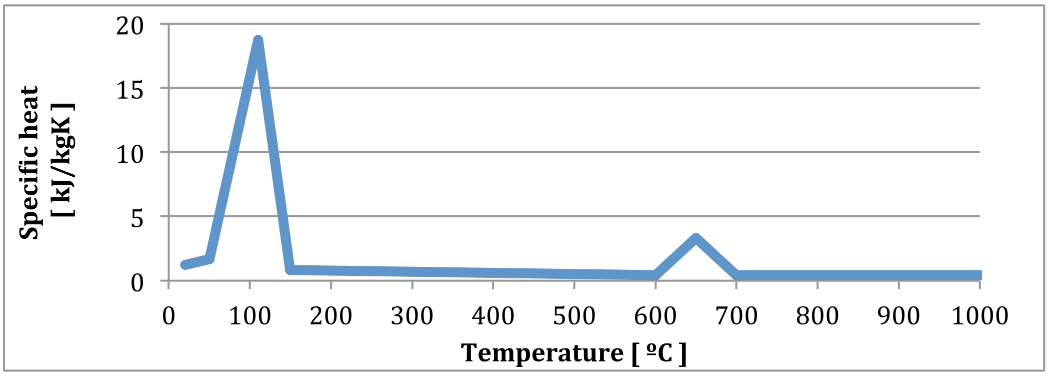



**Figure 3-16 Specific heat of gypsum plaster, for varying temperatures**

The two places where the value of the specific heat rises significantly in Figure 3-16 marks chemical changes in the material as it dehydrates. Equation (3.16) describes this reaction. The first peak happens at approximately 100 ºC, and is the reason why gypsum works so well as a fire protection cladding.

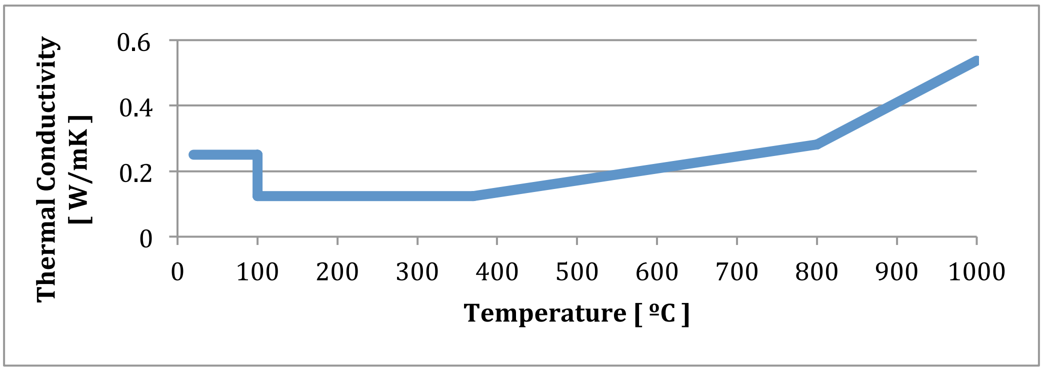



**Figure 3-17 Thermal conductivity of gypsum plaster, for varying temperatures**

Figure 3-17 shows how the thermal conductivity of gypsum boards varies with rising temperature. The value drops when the temperature reaches 100 ºC, and stays constant until the temperature exceeds 400 ºC. As the temperature keeps increasing from this point the thermal conductivity is strongly related to development of cracks. How severe cracking that occurs is dependent on the specific gypsum plaster, and how fast the fire temperature increases. Research has shown that the density of the material also will influence the thermal conductivity (Clancy, 1999).

Published values do scatter some, but most are similar to the ones in these figures. Results from experiments conducted by Park *et al.* on Type X and C gypsum boards are illustrated in Figure 3-18 and Figure 3-19 (Park et al., 2010).

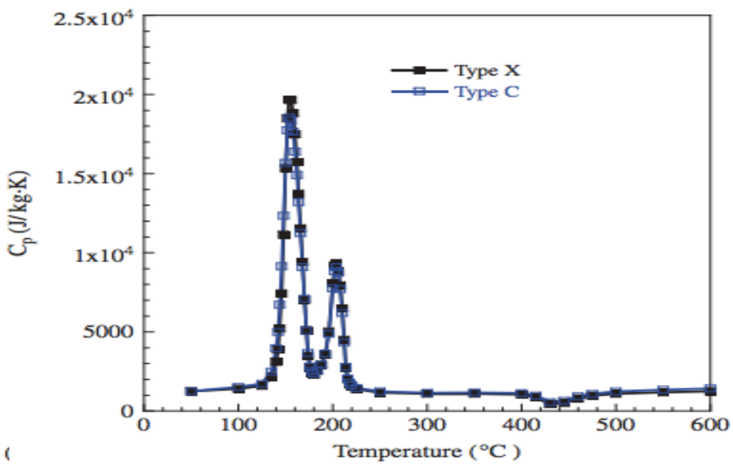



**Figure 3-18 Specific heat of Type X and C gypsum plaster (Park et al., 2010)**

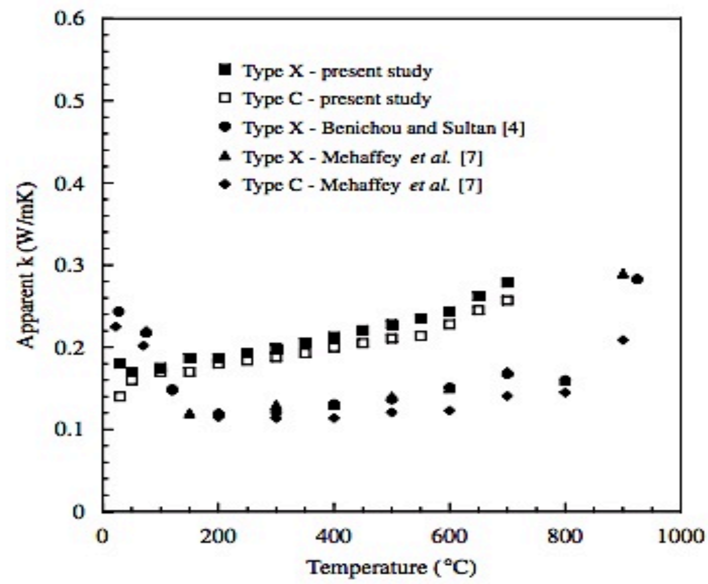



**Figure 3-19 Thermal conductivity vs. temperature Type X and C gypsum plaster (Park et al., 2010)**

# 4 Uncertain factors in fire design of timber constructions

As timber is a combustible material deviations from the pre-accepted solutions given in the Norwegian technical regulations guideline are inevitable at the moment. Knowing how different factors influence fire development is therefore of interest.

Basic information about fire design and timber as a construction material has been presented in Chapter 3. It is clear that changes needs to be done to the Norwegian technical regulations guideline if the aim is to decrease the design phase when timber is implemented in high-rise buildings. Gathering more information about the uncertainties that cause the deviations can help build a basis for developing conceptual solutions for use in documentation of fire safety in high-rise timber buildings in the future.

The next subsections dive deeper into some of the fields that need further research, and presents some of the research already conducted. There are a lot of factors that are uncertain when glue-laminated and cross-laminated timber is used. How to compare the characteristics of the materials in testing environments (standard temperature-time fire curve exposure) and natural fire conditions (parametric fire curve) is one of them. Other factors are:

- How combustible surfaces contribute to the fire load
- The opening factors effect on the fire development
- What burning- and mass loss rate can be assumed for timber in compartment fires

This is only some of the numerous amounts of topics than can be addressed. The challenging part when timber is used is that most of the factors depend on each other, which creates a circle of uncertainties.

Which material is chosen, how much exposed cross-laminated timber should be implemented in the design of a building and what opening factors to be chosen are all factors that can be determined by the fire safety engineer. Making good decisions and being able to determine whether or not the fire safety of a building is satisfying requires a lot of knowledge and good judgement.

The first uncertainty to be discussed in this report is the relationship between standard and parametric temperature-time curves. This uncertainty can affect how different elements of a building are assumed to behave in a fire situation, and what fire safety level they can be assumed to satisfy.

## 4.1 Duration of the fire and fire severity

When timber and all other materials are tested, the method usually involves exposing it to a fire equivalent to a standard temperature-time curve. Almost all the available information about timber in fire conditions is based on tests using this curve.

One of the problems associated with this, occurs when the Norwegian technical regulation states the following (Kommunal- og moderniseringsdepartementet, 2010):

*§ 11-4 (4):*

> "Main load bearing systems in structures in fire classes 3 and 4 shall be designed to maintain adequate load bearing capacity and stability for the complete duration of a fire, as this can be modelled"

"The complete duration of a fire" is here assumed to be the duration of a natural fire, but this is not specified. The technical regulations guideline then refers to NS-EN 1991-1-2 Section *3.3 Natural fire models*, for the different methods that can be used for modelling when the pre-accepted solutions cannot be applied. For a compartment fire, one is further referred to Annex A, which presents the method for calculating parametric temperature-time curves.

To illustrate the difference between the assumed natural fire development, the temperature-time curve that is used for testing of materials (standard curve) and the parametric temperature-time curve that are used for fire safety design, they have all been plotted in Figure 4-1 together.

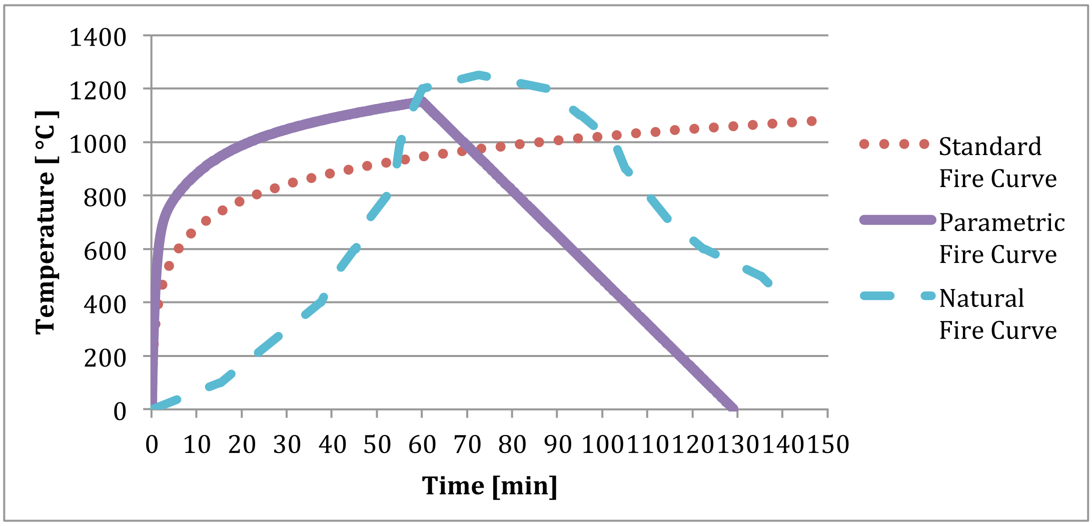



**Figure 4-1 Illustration of the two temperature-time curves presented in NS-EN 1991-1-2 and a assumed natural fire development**

The natural fire curve is fictional, illustrating how a fire is assumed to develop. The standard fire curve is given by NS-EN 1991-1-2 Section *3.2.1 Standard temperature-time curve*, and the parametric temperature-time curve illustrated in Figure 4-1 is based on NS-EN 1991-1-2 Annex A. The parametric temperature-time curve presented here is illustrative, and should not be used for estimations.

As materials are tested based on the standard temperature-time curve and the Norwegian technical regulations guideline states that calculations for fire safety design should be done for a natural fire development (using a parametric temperature-time curve), a correlation between the parametric and the standard curve is needed. Different models have been developed for this.

Many of these models are primarily meant for steel and concrete structures. This means that they cannot be applied when timber is used, as it is a combustible material. Examples of models like this are,

*Minimum load capacity concept:*

The minimum load capacity concept is difficult to implement for wood members, as the minimum load capacity is not clearly defined for this material. This is caused by the fact that charring can continue after fire temperatures start to decrease.

*Time-equivalent formulae:*

Generally time-equivalent formulae are derived from calculations based on a particular set of design fires for small rooms and the maximum temperature concept for certain protected steel members with various thicknesses of insulation. As such they may not be applied to other shapes of temperature-time curve, to larger rooms, to other types of protection, or to other structural material (Buchanan, 2002).

There are however models that can be used for timber structures. Two of these are presented below.

### 4.1.1 Equal area concept

Ingberg first introduced this concept in 1928 (Ingberg, 1928). The model considers two fires to have the same severity when the area underneath the fire curves are the same, above a given reference temperature. When used for fire design, the standard fire curve is compared to the parametric.

Using this method gives an estimate on how long building elements tested for fires corresponding with the standard temperature-time curve can withstand a natural fire. Figure 4-2 illustrates the principles of the concept. The reference temperature is normally set to 300°C when the method is used for timber, as this is the temperature where the formation of the char layer starts.

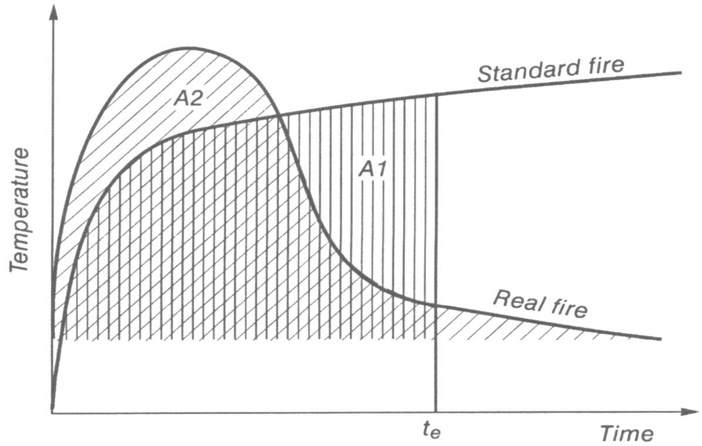



**Figure 4-2 Equivalent fire severity on equal area basis (Buchanan, 2002)**

As the units of area are not meaningful, this concept is not theoretically sound. One of the weaknesses of the model is that it does not compare the heat transfer of short fires with high temperatures and long fires with low temperatures very well. The reason why this comparison is not very accurate is because the biggest amount of heat transfer happens through radiation. As radiation is proportional to the fourth of the absolute temperature, this causes deviations.

If this method is still chosen, conservative assumptions should be made for the parameters of the parametric temperature-time curve. The fire load, opening factor and material properties of the enclosure area of the fire should all be conservative. The reason for this is to make sure that the severity of the fire does not get underestimated.

### 4.1.2 Maximum temperature concept

This concept is more realistic. It is based on the temperature rise in a protected steel member. The method works by comparing the maximum temperature that would occur in a protected steel member in a complete burnout of a fire compartment, with the time needed for the same temperature to occur in the member when exposed to a standard fire. Figure 4-3 illustrates the main principle of the concept.

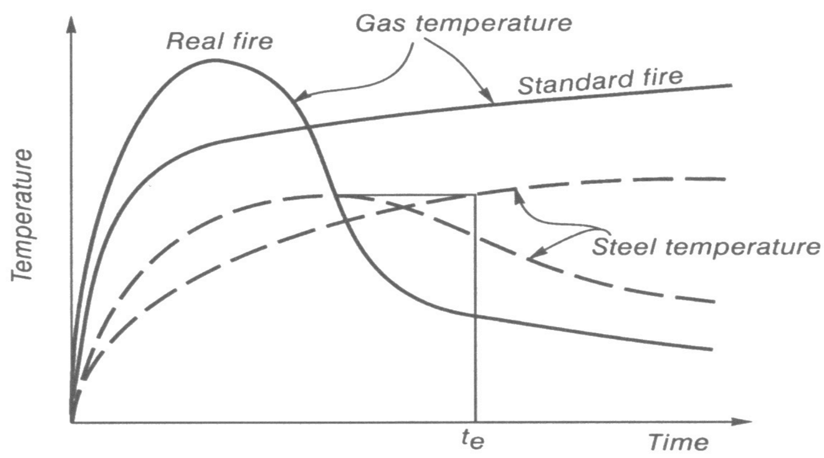



**Figure 4-3 Equivalent fire severity on temperature basis (Buchanan, 2002)**

Law, Petterson et al. and others developed this concept (Pettersson et al., 1976; Law, 1971). Figure 4-3 shows the concept used on a steel member, but the method can be applied to any insulated member if the steel temperature is changed to the temperature of the unexposed surface of the insulation. Which means that the method can be utilized for wooden members. However, if the maximum temperatures used in the derivation of a time-equivalent formula are much greater or lower than those that would cause failure in a particular building, the results obtained from this concept can be misleading (Buchanan, 2002).

## 4.2 Fire load

Following ignition, the fire initially grows primarily as a function of the fuel itself, with little or no influence from the compartment (Walton and Thomas, 1995). This means that in the pre-flashover stage, further fire development depends on the variable fire load.

If there is sufficient fuel and ventilation for a growing fire to develop to a significant size, a flashover will happen after some time. The main focus of the fire safety, usually changes from safety of human life to the high temperatures influence on the structure of the building at this point in time. The increasing temperature will affect the behaviour of the timber, as shown in Section 3.8. When entering this stage of the fire, the permanent fire load will start influencing further development.

To make sure the fire safety of a building is sufficient the requirements given in laws and regulations needs to be met. The first step towards documenting the fire safety is often done my estimating the fire load available. These estimations show how big a potential fire can get, and what the structure needs to be able to withstand. As mentioned, the fire load can be divided into two: variable and permanent. Variable fire load is mainly movable items and is affected by the occupancy of the compartment, while permanent fire load is based on choice in surface materials.

NS-EN 1991-1-2 defines fire load as (Norsk Standard, 2008):

> "The sum of thermal energies which are released by combustion of all combustible materials in a space (building contents and construction elements)"

According to NS-EN 1991-1-2 Annex E calculating the design value of the fire load $q_{f,d}[MJ/m^2]$ should be done using the following equation,

$$q_{f,d} = q_{f,k} \cdot m \cdot \delta_{q1} \cdot \delta_{q2} \cdot \delta_n \tag{4.1}$$

where $m$ is the combustion factor, $\delta_{q1}$ is a factor taking into account the fire activation risk due to the size of the compartment, $\delta_{q2}$ is a factor taking into account the fire activation risk due to the type of occupancy, $\delta_n$ is a factor taking into account the different active fire fighting measures and $q_{f,k}[MJ/m^2]$ is the characteristic fire load density per unit floor area.

The different factors are found using values presented in tables in the standard. These tables are cited in Table 4-1, Table 4-2 and Table 4-3.

**Table 4-1 Factor taking into account the fire activation risk due to the size of the compartment (Norsk Standard, 2008)**

| Compartment floor area $A_f[m^2]$ | Danger of Fire Activation $\delta_{q1}$ |
|---|---|
| 25 | 1.10 |
| 250 | 1.50 |
| 2500 | 1.90 |
| 5000 | 2.00 |
| 10000 | 2.13 |

**Table 4-2 Factor taking into account the fire activation risk due to the type of occupancy (Norsk Standard, 2008)**

| Examples of Occupancies | Danger of Fire Activation $\delta_{q2}$ |
|---|---|
| Art gallery, museum, swimming pool | 0.78 |
| Offices, residence, hotel, paper industry | 1.00 |
| Manufactory for machinery & engines | 1.22 |
| Chemical laboratory, painting workshop | 1.44 |
| Manufactory of fireworks or paints | 1.66 |

**Table 4-3 Factor taking into account the different active fire fighting measures (Norsk Standard, 2008)**

<table>
<tr><th colspan="12">$\delta_{ni}$ Function of Active Fire Fighting Measures</th></tr>
<tr><td colspan="4">Automatic Fire Suppression</td><td colspan="3">Automatic Fire Detection</td><td colspan="5">Manual Fire Suppression</td></tr>
<tr><td rowspan="2">Automatic Water Extinguish-ing System</td><td colspan="3">Independent Water Supplies</td><td colspan="2">Automatic Fire Detection & Alarm</td><td rowspan="2">Automatic Alarm Transmission to Fire Brigade</td><td rowspan="2">Work Fire Brigade</td><td rowspan="2">Off Site Fire Brigade</td><td rowspan="2">Safe Access Routes</td><td rowspan="2">Fire Fighting Devices</td><td rowspan="2">Smoke Exhaust System</td></tr>
<tr><td>0</td><td>1</td><td>2</td><td>By heat</td><td>By smoke</td></tr>
<tr><td>$\delta_{n1}$</td><td colspan="3">$\delta_{n2}$</td><td>$\delta_{n3}$</td><td>$\delta_{n4}$</td><td>$\delta_{n5}$</td><td>$\delta_{n6}$</td><td>$\delta_{n7}$</td><td>$\delta_{n8}$</td><td>$\delta_{n9}$</td><td>$\delta_{n10}$</td></tr>
<tr><td>1.0 1)</td><td>1.0</td><td>1.0</td><td>1.0</td><td colspan="2">1.0</td><td>1.0</td><td colspan="2">1.0</td><td>1.0</td><td>1.0</td><td>1.0</td></tr>
<tr><td colspan="12">1) Normally for automatic water extinguishing systems $\delta_{n1} = 1.0$ . When fire design analysis is conducted, values as far down as 0.6 can be used provided the stipulation of the value is part of the fire safety strategy of the building.</td></tr>
</table>

### 4.2.1 Design value of the variable fire load

Calculating the design value of the variable fire load can be done relatively easy. The value is dependent on the occupancy of the fire compartment. Different types of occupancy and the fire load associated with it are given in the standard. Table 4-4 cites this information.

**Table 4-4 Fire load densities $q_{f,k}$ for different occupancies**

| Occupancy | Average | 80% Fractile |
|---|---|---|
| Dwelling | 780 | 948 |
| Hospital (room) | 230 | 280 |
| Hotel (room) | 310 | 377 |
| Library | 1500 | 1824 |
| Office | 420 | 511 |
| Classroom of a school | 285 | 347 |
| Shopping centre | 600 | 730 |
| Theatre (cinema) | 300 | 365 |
| Transport (public space) | 100 | 122 |
| NOTE Gumbel distribution is assumed for the 80% fractile | | |

The 80% fractile is used for $q_{f,k}$ in the equation for design fire load. This is a safety measure based on probability, using Gumbel distribution. This means that the fire load density will not exceed the value presented in the right column of Table 4-4 in 80% of fires in compartments of the given occupancy. Inserting all the factors and the 80% fractile into Equation (4.1) gives an estimate of the design value of the variable fire load density of a fire compartment.

### 4.2.2 Design value of the permanent fire load

According to NS-EN 1991-1-2 the permanent characteristic fire load density $q_{t,k}[MJ/m^2]$ can be estimated using,

$$q_{t,k} = \frac{Q_{fi,k}}{A_t} \tag{4.2}$$

where $Q_{fi,k}[MJ]$ is the permanent characteristic fire load defined in Equation (4.3), and $A_t[m^2]$ is the total surface area of the fire compartment of interest.

$$Q_{fi,k} = \sum M_{k,i} \cdot H_{ui} \cdot \Psi_i \tag{4.3}$$

The net calorific value $H_{ui}\ [MJ/kg]$ can be found using values presented in the standard combined with material properties of the exposed surface materials. $\Psi_i$ is an optional factor assessing protected fire loads. This factor is set to 1.0 for exposed cross-laminated timber, and should be reduced if fire retardant materials are used. The challenges start when $M_{k,i}\ [kg]$ is to be calculated. This is the amount of permanent combustible material.

When cross-laminated timber is used, an estimation of charring depth is normally conducted to determine the amount of combustible material available. This value depends on a lot of different factors, and making an accurate estimation is not easy.

NS-EN 1991-1-2 Annex A presents the calculation method for parametric temperature-time curves. By using this method in combination with the method presented in NS-EN 1995-1-2 Annex A and iterations, an estimate of the contributing fire load from cross-laminated timber can be made. In the next subsection a brief illustration of this method is shown.

### 4.2.3 Example – Estimating contributing fire load from exposed cross-laminated timber, using the method presented in the Eurocode

For the carried out calculations the case presented in Section 6.1 have been used. It has however in this example been assumed that all surfaces except the floor are of cross-laminated timber.

#### *4.2.3.1 General estimations for the compartment*

Firstly the factors that do not vary with time are calculated. The equations used to determine the weighted average of opening heights on all walls and the opening factor is presented and further discussed in Section 4.5.3.

*Total floor area:*

$$A_f = (L_{wall1} \cdot L_{wall2}) - 2 = (5.65 \cdot 2.2) - 2 = 10.43m^2$$

*Total area of enclosure:*

$$A_t = 2\left(h \cdot L_{wall1} + h \cdot L_{wall2} + A_f\right) = 2(2.75 \cdot 5.65 + 2.75 \cdot 2.2 + 10.43) = 64.035m^2$$

*Total area of vertical openings on all walls (door and window):*

$$A_V = (1.2 \cdot 1.6 + 0.9 \cdot 2.0) = 3.72m^2$$

*Weighted average of opening heights on all walls:*

$$h_{eq} = \sum \frac{A_i h_i}{A} = \frac{1.2 \cdot 1.6 \cdot 1.6}{3.72} + \frac{0.9 \cdot 2.0 \cdot 2.0}{3.72} = 1.79m$$

*Opening factor:*

$$O = \frac{A_V}{A_t}\sqrt{h_{eq}} = \frac{3.72}{64.035}\sqrt{1.79} = 0.078m^{1/2}$$

*Absorptivity for the total enclosure:*

To calculate this the properties of three different materials are needed; cross-laminated timber, linoleum and screed (A-plan). The values that have been used are presented in Table 4-5.

**Table 4-5 Material properties (Norsk Standard, 2010; International Organization for Standardization, 2007; SINTEF Byggforsk, 2013; Aker Byggteknikk AS, 1997)**

| Material | Thermal conductivity, $\lambda$ $[W/mK]$ | Density, $\rho$ $[kg/m^3]$ | Specific heat, $c$ $[J/kgK]$ | Absorptivity, $b=\sqrt{\rho c \lambda}$ $[J/m^2 s^{1/2} K]$ |
|---|---|---|---|---|
| **Wood** | 0.12 | 500 | 1530 | 302.985 |
| **Linoleum** | 0.17 | 1200 | 1400 | 534.416 |
| **Screed (A-plan)** | 1.87 | 2200 | 900 | 1924.214 |

$$b_{linoleum} < b_{screed} \Rightarrow b_{floor} = b_{linoleum}$$

The total absorptivity of the fire compartment can then be found using,

$$b_{total} = \frac{\sum b_j A_j}{A_t - A_V} \tag{4.4}$$

where $b_j \left[J/m^2 s^{1/2} K\right]$ is the absorptivity of the different materials, and $A_j[m^2]$, $A_t[m^2]$ and $A_V[m^2]$ are surface area of a specific material, the total surface area of the fire compartment and total surface area of openings, respectively. For the case presented this gives,

$$b_{total} = \frac{b_{wood}\left(A_t - A_f - A_V\right) + b_{linoleum} A_f}{A_t - A_V}$$

$$b_{total} = \frac{302.985(64.035 - 10.43 - 3.72) + 534.416 \cdot 10.43}{64.035 - 3.72} = 343.005\, J/m^2 s^{1/2} K$$

*The factor accounting for the thermal properties of the boundaries of the compartment:*

The factor is given by the following equation,

$$\Gamma = \frac{\left(\frac{O}{b}\right)^2}{\left(\frac{0.04}{1160}\right)^2} \tag{4.5}$$

where $O\left[m^{1/2}\right]$ is the opening factor of the fire compartment, and $b\left[J/m^2s^{1/2}K\right]$ is the total absorptivity. For this case,

$$\Gamma = \frac{\left(\frac{0.078}{343.005}\right)^2}{\left(\frac{0.04}{1160}\right)^2} = 43.182$$

#### *4.2.3.2 Variable design fire load*

The variable design fire load can then be calculated,

$$q_{f,d} = q_{f,k} \cdot m \cdot \delta_{q1} \cdot \delta_{q2} \cdot \delta_n = 948 \cdot 0.8 \cdot 1.1 \cdot 1.0 \cdot 1.0 = 834.24\, MJ/m^2$$

To be able to use this number in combination with the permanent fire load it needs to be convert it into the fire load per total surface area instead of per floor area,

$$q_{t,d} = q_{f,d} \frac{A_f}{A_t} = 834.24 \frac{10.43}{64.035} = 135.881\, MJ/m^2$$

#### *4.2.3.3 Permanent design fire load*

Starting by finding the net calorific value $H_u[MJ/kg]$ of cross-laminated timber. This should be done using the following equation,

$$H_u = H_{u0}(1 - 0.01u) - 0.025u \tag{4.6}$$

where $u$ is the moisture content expressed as percentage of dry weight, and $H_{u0}[MJ/kg]$ is the calorific value of dry materials. Lumber used for producing cross-laminated timber is normally dried to a moisture content of 12 ± 3% (Mohammad et al., 2012). Based on this, moisture content of 12% has been used in these calculations. $H_{u0}$ is taken from NS-EN 1991-1-2 Table E.3, which gives a value of 17.5 $MJ/kg$ for wood. The net calorific value of cross-laminated timber is then,

$$H_u = 17.5(1 - 0.01 \cdot 12) - 0.025 \cdot 12 = 15.1\, MJ/kg$$

For unprotected softwood the relation between the charring rate $\beta$ and time $t$ is illustrated in Figure 4-4. This figure can be found NS-EN 1995-1-2 Annex A.

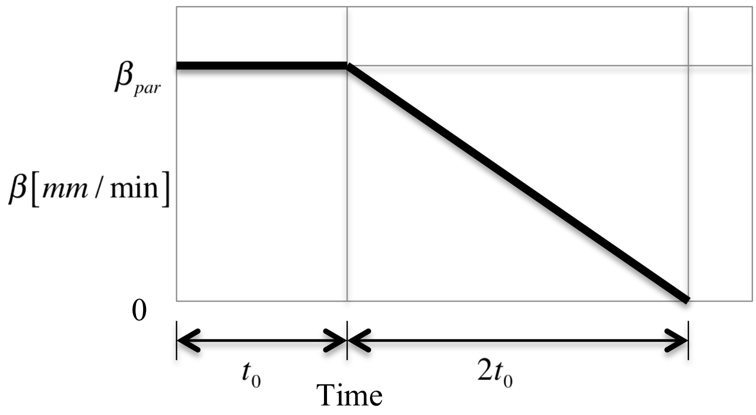



**Figure 4-4 Relationship between charring rate and time (Norsk Standard, 2010)**

The charring rate $\beta_{par}$ during the heating phase of a parametric fire curve is given by:

$$\beta_{par} = 1.5 \cdot \beta_n \frac{0.2\sqrt{\Gamma} - 0.04}{0.16\sqrt{\Gamma} + 0.08} \tag{4.7}$$

where $\beta_n = 0.7\, mm/min$ is found in Table 3.1 NS-EN 1995-1-2. This gives,

$$\beta_{par} = 1.5 \cdot 0.7 \frac{0.2\sqrt{43.182} - 0.04}{0.16\sqrt{43.182} + 0.08} = 1.18\, mm/min$$

The time period with a constant charring rate $t_0[min\,]$ is then estimated using,

$$t_0 = 0.009 \frac{q_{t,d}}{O} \tag{4.8}$$

By combining Equation (4.7) and Equation (4.8), the charring depth can be estimated based on the following criteria:

$$d_{char} = \begin{cases} \beta_{par} t & for \quad t \le t_0 \quad (4.9a) \\ \beta_{par}\left(1.5t - \dfrac{t^2}{4t_0} - \dfrac{t_0}{4}\right) & for \quad t_0 < t \le 3t_0 \quad (4.9b) \\ 2\beta_{par} t_0 & for \quad 3t_0 < t \le 5t_0 \quad (4.9c) \end{cases}$$

The presented equations for charring rate and depth during the heating phase are, however, only valid for:

$$t_0 \le 40min \qquad (4.10a)$$

$$d_{char} \le \frac{b}{4} \qquad (4.10b)$$

$$d_{char} \le \frac{h}{4} \qquad (4.10c)$$

where $b[mm]$ is the width of the cross section and $h[mm]$ is the depth.

From this the amount of combustible material, characteristic fire load and the design value of the contributing permanent fire load from exposed cross-laminated timber can be calculated using the following equations:

$$M_{k,i,t} = d_{char} \cdot \rho[kg/m^2] \qquad (4.11)$$

$$q_{t,k} = M_{k,i,t} \cdot H_{ui}[MJ/m^2] \qquad (4.12)$$

$$q_{t,d} = q_{t,k} \cdot m \cdot \delta_{q1} \cdot \delta_{q2} \cdot \delta_n [MJ/m^2] \qquad (4.13)$$

Table 4-6 shows the resulting total fire load density when permanent fire load is not taken into account, and the first iteration estimating the cross-laminated timbers contribution to the permanent fire load. It also shows the obtained charring depth of the original parametric curve where only variable fire load is taken into account and the first iteration, which includes the burning of the cross-laminated timber.

**Table 4-6 Iterations calculated to estimate the contribution to the fire load from exposed cross-laminated timber**

| | Only variable fire load | $1^{st}$ iteration |
|---|---|---|
| $q_{t,d}\left[MJ/m^2\right]$ | 135.881 | 529.066 |
| $t_{\max}\left[h\right]$ | 0.350 | 1.361 |
| $t^*_{\max}\left[h\right]$ | 15.099 | 58.788 |
| $\Theta_{\max}\left[°C\right]$ | 1324.04 | 1345.00 |
| $t_0\left[\min\right]$ | 15.679 | 61.046 |
| $t\left[\min\right]$ | 28 | 89 |
| $d_{char}\left[mm\right]$ | 30.184 | 101.244 |
| $M_{k,i,t}\left[kg/m^2\right]$ | 15.092 | 50.622 |
| $q_{t,k}\left[MJ/m^2\right]$ | 227.887 | 764.391 |
| $q_{t,d,permanent}\left[MJ/m^2\right]$ | 200.541 | 672.664 |

After only one iteration $t_0 \geq 40min$, this means that this method should not be used as the rules implemented in it cannot be validated. In addition to this the charring depth exceeds the limit given by the standard when only the variable fire load is included, as the cross-laminated timber is only 100mm thick in the case used for the calculations. After the first iteration the walls are burned through. To illustrate the effect the burning cross-laminated timber would have on the fire development the two parametric curves have been plotted in Figure 4-5.

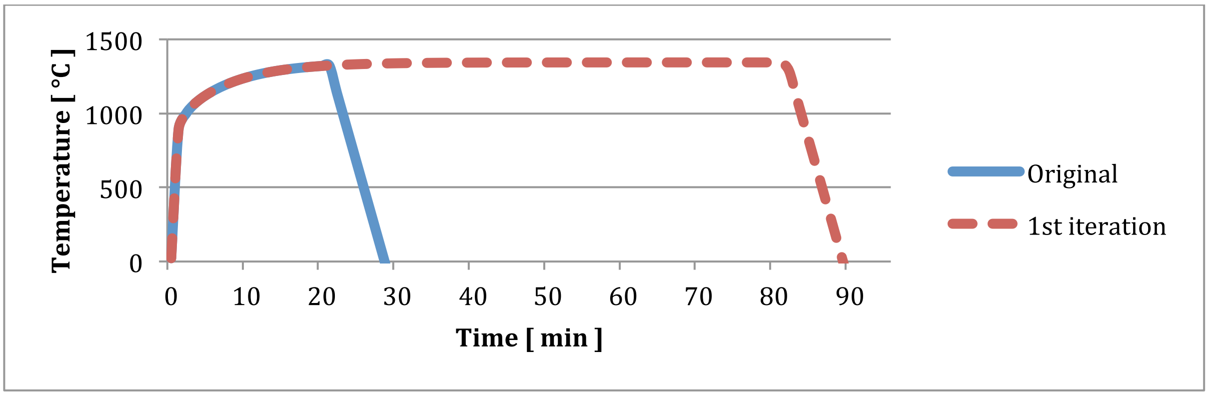



**Figure 4-5 Iteration of parametric temperature-time curve**

### 4.2.4 Brief discussion of the results

The method used for the calculations in the previous section is based on work originally carried out by Hadvig (Hadvig, 1981). More experiments has later been conducted by Hansen and Olesen supporting the results found by Hadvig (Hansen and Olesen, 1992).

Research carried out by Hopkin *et al.* in 2011 suggests that the limitation of the application area of the method presented in the NS-EN 1995-1-2 Annex A could be expanded beyond $t_0 \leq 40\ min$ by conducting more experiments for an extended range of heating rates and fire loads (Hopkin et al., 2011). However, this is not done, and according to the standard the calculations conducted in Section 4.2.3 is not valid.

Even though the validity of the rules this method is based on is exceeded, it is clear that the fire load from the structure will be way beyond what is accepted for a fire class 3 building in the pre-accepted solutions presented by the Norwegian technical regulations guideline. The result of this is that the fire safety of the building needs to be documented in an alternative way, or fire retardant materials need to be implemented.

By adding a fire protection cladding, like gypsum boards, the contributing fire load from the cross-laminated timber can be reduced significantly. This was done for ¾ of the walls in the compartments in Moholt 50|50.

The results of the experiment conducted in December 2014 (Hox, 2015) did however not show any signs of the fire self-extinguishing. The experiment had a smaller amount of exposed cross-laminated timber as surface area compared to the calculations conducted above, but still experienced that it contributed significantly to the fire load.

Gypsum boards is one of several ways to ensure that the fire safety of a building is sufficient. The problem with using gypsum on all walls in a high-rise timber building is that the aesthetic benefits of the wooden surface materials are lost. In addition to this when people use timber for high-rise buildings they usually want the world to know. Boxing all the cross-laminated and glue-laminated timber in will make a timber-building look like every other building.

An alternative to fire retardant materials is to enhance the active fire protection of the building. This aspect will not be further discussed in this report, but are in many cases the best solution to reach the fire safety measures presented in laws and regulations.

## 4.3 Charring rate/depth, how wood burns

Research has shown that the charring rate of timber is affected by numerous factors. Friquin lists these factors, divided into two groups (Friquin, 2011):

*Material properties:*

- Density
- Moisture content
- Chemical composition
- Grain orientation and permeability
- Char contraction factor
- Char oxidation
- Scale effect

*External factors:*

- Thermal exposure/Heat flux
- Oxygen concentration
- Opening factor

In this report the focus is mainly on the external factors, as these vary when changes are made to the fire compartment. The oxygen concentration is assumed to be something the fire engineer cannot control to a wider degree than the effect of the openings. Before looking further into the effect thermal exposure/heat flux and opening factor has on charring, some basic information about the chemical composition, heat of combustion and heat of gasification of wood is presented.

### 4.3.1 Chemical composition of wood

Compared to other materials, wood is a complex mixture of natural polymers of high molecular weight, the most important of which are cellulose (~50%), hemicellulose (~25%) and lignin (~25%) (Madorsky, 1964). The amount of different polymers varies between species. The difference between dry softwood and hardwood, in percent mass, is presented in Table 4-7. The numbers are retrieved from research conducted by Ji *et al*. (Ji et al., 2003).

**Table 4-7 Chemical composition of dry wood in percent mass**

| Type | Cellulose [%] | Hemicellulose [%] | Lignin [%] |
|---|---|---|---|
| **Hardwood** | 40-44 | 23-40 | 18-25 |
| **Softwood** | 40-44 | 20-32 | 25-35 |

The three main components of wood have quite different thermal degradation characteristics. This is illustrated by thermogravimetric analysis, showing that the constituents decompose to release volatiles over different temperature ranges, typically (Drysdale, 2011):

| | |
|---|---|
| Hemicellulose | 200-260ºC |
| Cellulose | 240-350ºC |
| Lignin | 280-500ºC |

When wood is heated to/burns at a temperature exceeding $450\ ^\circ\text{C}$ in normal air, normally $15-25\ \%$ remains as char, with the biggest amount of this being caused by the lignin content (up to $10-12\%$ of original wooden mass) (Drysdale, 2011).

Depending on the wooden specie and where the wooden product is stored, the moisture content of it varies. This will have an effect on both thermal conductivity and specific heat, thus affecting ignition and burning rate of wood. As a result of this dry wood is easier to ignite, and when burning the heat release rate of it is higher than for a wood sample containing water.

### 4.3.2 Heat of combustion

Multiple people have conducted research on the composition of the volatiles when wood burns. Some have found no evidence of the composition changing as a layer of char is formed, while others have found that the volatiles gets more combustible as the degradation proceed. Browne and Brendan carried out experiments in 1964 with the following results (Drysdale, 2011),

$$\text{At 10\% weight loss} \quad \Delta H_c(volatiles) = 11.0\, kJ/g$$
$$\text{At 60\% weight loss} \quad \Delta H_c(volatiles) = 14.2\, kJ/g$$
$$\text{Parent wood} \quad \Delta H_c(wood) = 19.4\, kJ/g$$

By using a cone calorimeter the instantaneous value of the effective heat of combustion of wood can now be measured as the burning progresses. The result from an experiment performed on western red cedar is illustrated in Figure 4-6. The values will vary some between species.

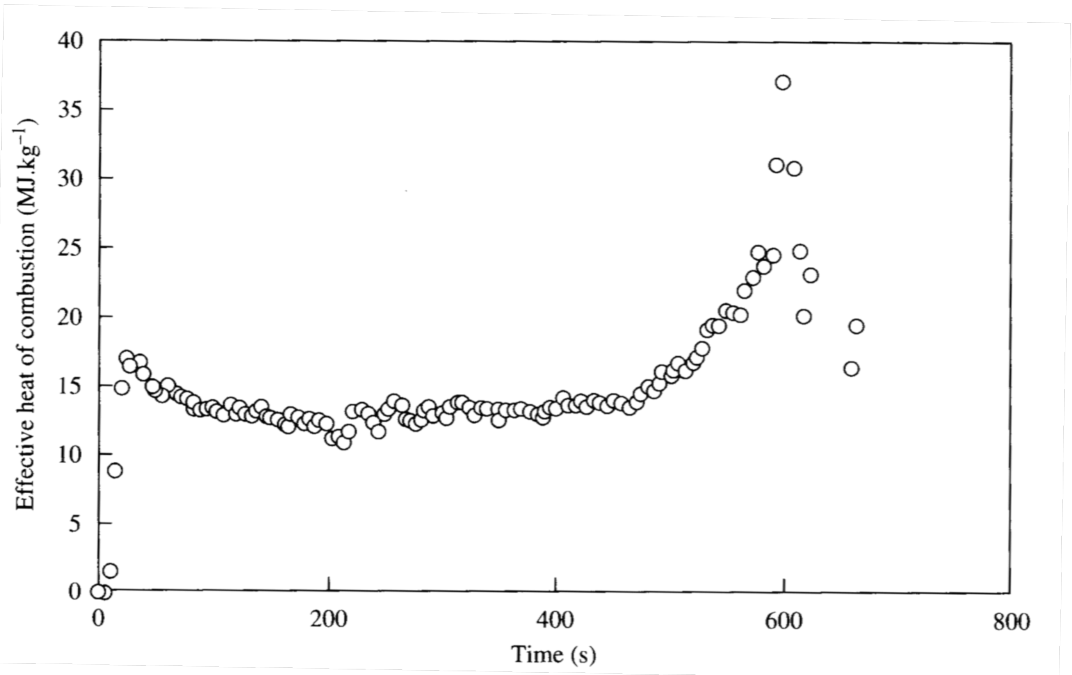



**Figure 4-6 Instantaneous values of the effective heat of combustion of Western red cedar (17mm thick samples) at an imposed radiant heat flux of 65 kW/m2 in the cone calorimeter, retrieved from: (Drysdale, 2011)**

### 4.3.3 Heat of gasification

When it comes to heat of gasification this has previously been linked to both lignin content and permeability of the wooden material. In 1993 Janssens carried out a thorough study on this topic by using a cone calorimeter to obtain experimental data for six different species of wood (Janssens, 1993). The data was analysed using an integral heat transfer model. He found that the heat of gasification varies as the depth of char increases. The result from his research is presented in Table 4-8. It shows that the average heat of gasification for softwood is $3.2\,kJ/g$, while it for hardwood is $2.6\,kJ/g$. There is one exception to this, the Douglas fir. The resin content of this softwood causes a heat of gasification of $2.64\,kJ/g$.

**Table 4-8 Average values for the heat of gasification of woods. S = Softwood, H = Hardwood (Janssens, 1993)**

| Material | $L_V[kJ/g]$ |
|---|---|
| Western red cedar (S) | 3.27 |
| Redwood (S) | 3.14 |
| Radiata pine (S) | 3.22 |
| Douglas fir (S) | 2.64 |
| Victorian ash (H) | 2.57 |
| Blackbutt (H) | 2.54 |

The tests performed by Janssens were carried out with the samples oriented vertically. This might affect the result, but the relevance of this factor is not clear.

## 4.4 Thermal exposures/heat fluxes effect on burning of wood

Before discussing the thermal exposures/heat fluxes effect on charring some basic information about heat transfer is presented. Heat transfer can be divided into three different types. Figure 4-7 shows where the types occur in the burning process of a wooden member.

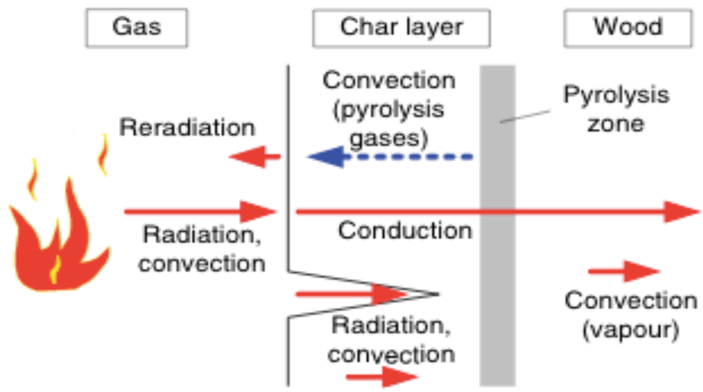



**Figure 4-7 Heat flux components in fire-exposed semi-infinite wood slab due to external heat source (König, 2006)**

The different types of heat transfer play a varying role throughout the fire development. Table 4-9 summarizes the main characteristics of the three different types. It also gives information about what part of the fire development they influence. The mathematical equations for the three is given below (Drysdale, 2011).

**Table 4-9 Heat transfer: Conduction, convection and radiation**

| | **Conduction** | **Convection** | **Radiation** |
|---|---|---|---|
| **How it works** | Result of a mixing process driven by buoyancy. Heat will flow from an area of high temperature to one of lower temperature. | Exchange of heat between a gas or liquid and a solid, involves movement of the fluid medium. | Mechanism by which objects at a distance from a fire are heated to the fire point condition. It is the transfer of energy by electromagnetic waves. |
| **Influence on fire development** | Important in problems related to ignition and spread of flame over combustible solids, and to fire resistance. | Particularly important in the early stage of a fire, when thermal radiation is low | Normally determines the growth and spread of fires in compartments. |

*Conduction:*

The heat flux of the conduction can be calculated using,

$$\dot{q}_x'' = -\kappa \frac{\Delta T}{\Delta x} \tag{4.14}$$

where $\Delta T$ is the temperature difference over a distance $\Delta$x. It can also be expressed in a differential form. This is known as Fourier's law of heat conduction and is given by,

$$\dot{q}_x'' = -k \frac{dT}{dx} [W/m^2] \tag{4.15}$$

where $k\left[W/mK\right]$ is the thermal conductivity of the material.

*Convection:*

The empirical relationship for convection, first discussed by Newton, is,

$$\dot{q}'' = h\Delta T [W/m^2] \tag{4.16}$$

where $h$ is the convective heat transfer coefficient, and ranges from $5-25W/m^2K$ for free convection and $10-500W/m^2K$ for forced convection in air.

*Radiation:*

According to the Stefan-Boltzmann equation, the total energy emitted by a body is proportional to $T^4$, where $T$ is the temperature in Kelvin.

The intensity of radiant energy $\dot{q}''$ falling on a surface remote from the emitter can be found by using the appropriate 'configuration factor' $\phi$, which takes into account the geometrical relationship between the emitter and the receiver. The configuration factor can be found using NS-EN 1991-1-2 Annex G. It is given by,

$$\phi = dF_{d1-d2} = \frac{cos\theta_1 cos\theta_2}{\pi S_{1-2}^2} dA_2 \tag{4.17}$$

The factor measures the fraction of the total radiative heat leaving a given radiating surface that arrives at a given receiving surface. The parameters in Equation (4.17) are shown in Figure 4-8 below, retrieved from NS-EN 1991-1-2.

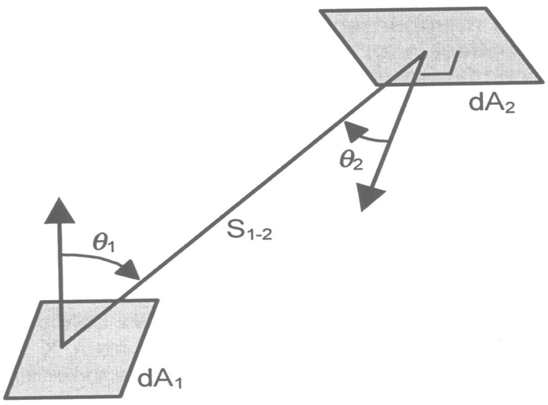



**Figure 4-8 Radiative heat transfer between two infinitesimal surface areas (Norsk Standard, 2008)**

Based on this the following equation can be used to estimate the heat transfer through radiation:

$$\dot{q}'' = \phi\varepsilon\sigma T^4 \tag{4.18}$$

where $\sigma$ is the Stefan-Boltzmann constant and $\varepsilon$ is the emissivity.

### 4.4.1 Ignition of wood

For ignition of wood to occur the mass rate of volatiles must exceed what is needed to create a flammable mixture near the surface. Mathematically this can be presented as,

$$\dot{m}'' = \frac{\dot{Q}_F'' - \dot{Q}_L''}{L_V} > \dot{m}_{crit}'' \tag{4.19}$$

where $\dot{m}''[kg/m^2s]$ is the rate of burning, $\dot{Q}_F''[kW/m^2]$ is the heat flux supplied by the flame, $\dot{Q}_L''[kW/m^2]$ is the losses expressed as a heat flux through the fuel surface and $L_V[MJ/kg]$ is the heat required to produce volatiles (Drysdale, 2011). This criterion can be fulfilled in four different ways:

*Pilot ignition:*

A material is exposed to a radiative heat flux which raises the surface temperature to a level where a mass rate of volatiles create a flammable mixture which is ignitable by a small flame or spark

*Auto ignition:*

A radiative heat flux alone raises the surface temperature to a level where a mass rate of volatiles creates a sufficiently warm and flammable mixture for it to spontaneously ignite.

*Impinging ignition:*

A flame impinging on the material causes ignition.

*Glowing ignition:*

An external heat source causes glowing in the material, but if removed no continued combustion will take place.

### 4.4.2 Ignition temperature and time to ignition

As a result of wood being such a complex material it is difficult to interpret the burning behaviour in terms of Equation (4.19). Research has shown that the thickness of the test material effects the time to ignition. For a thicker specimen the time to ignition will be longer than for a thinner one (Mačiulaitis and Praniauskas, 2010). The time to ignition is also longer for species with high density compared to lower densities (Gardner and Thomson, 1991).

These factors are only some of many contributing to variation in the ignition temperature of wood. The following factors all influences the temperature needed for ignition to occur:

- Density
- Thermal conductivity
- Moisture content
- Geometric factors
- Previous heating history
- Intensity of heat flux

As a result of all the affecting factors, a lot of people have carried out experiments throughout the years trying to establish ignition temperature, time to ignition and needed radiant heat flux for ignition to occur. Babrauskas gathered the results from numerous experiments on ignition temperature in 2002. A summary of these are presented in Table 4-10 (Babrauskas, 2002).

**Table 4-10 Summary of ignition temperature data (Babrauskas, 2002)**

| Type of test | Ignition temperature [ºC] | |
|---|---|---|
| | Piloted | Autoignition |
| A few grams plunged into a furnace | 220-260 | 220-300 |
| Radiant heating of a largish specimen | 296-497 | 254-530 |
| Others; unidentified | 210-450 | 200-525 |

Table 4-10 clearly shows that the span in the results obtained from experiments conducted over the last 100 years is very big. Babrauskas presents the following reasons to be considered accountable for the spread:

- The definition of ignition that is used
- Piloted vs. autoignition conditions
- The design of the test apparatus and its operating conditions
- Specimen conditions (e.g., size, moisture, orientation)
- Species of wood

The final result from his research is presented in Table 4-11. The numbers are based on analysis of data available, but as pointed out in the article; there is a need for more experimental data on this topic.

**Table 4-11 Summary of ignition temperatures results (Babrauskas, 2002)**

| **Flux** | **Minimum** | **Low** | **Medium** |
|---|---|---|---|
| **Ignition type** | **Glowing or glowing/flaming** | | **Flaming** |
| $T_{ig}\,(°C)$, **Piloted** | 250 | 350-400 peak, lower for fluxes close to minimum | 300-310 hardwoods<br>350-365 softwoods |
| $T_{ig}\,(°C)$, **Autoignition** | 250 | No data | 380-500?? |

As can be seen from the result shown in Table 4-11, the ignition temperatures vary with the heat flux the material is exposed to. This is also the case for the time it takes before ignition takes place.

Experiments and studies on pyrolysis and heat release rate of wood exposed to weak external heat fluxes for long times were in 2004 carried out by Chen et al. (Chen et al., 2004). The different wooden species included was oak ($650\,kg/m^3$), rosewood/kempas ($850\,kg/m^3$), cherry wood ($625\,kg/m^3$) and beech ($700\,kg/m^3$), all conditioned in a room at 20 °C and 65% relative humidity, leaving them with a moisture content of approximately $0.12\,kg/kg$.

The results obtained showed that a heat flux of 20 $kW/m^2$ gave the highest heat release rate (presented in Section 4.4.3.). However, to ignite at this heat flux all the tested species needed to be exposed for 20 minutes or longer (4-30 times longer than when exposed to other, higher heat fluxes). Figure 4-9 present the times to ignition obtained from the experiment; dependent on the heat flux the samples were exposed to.

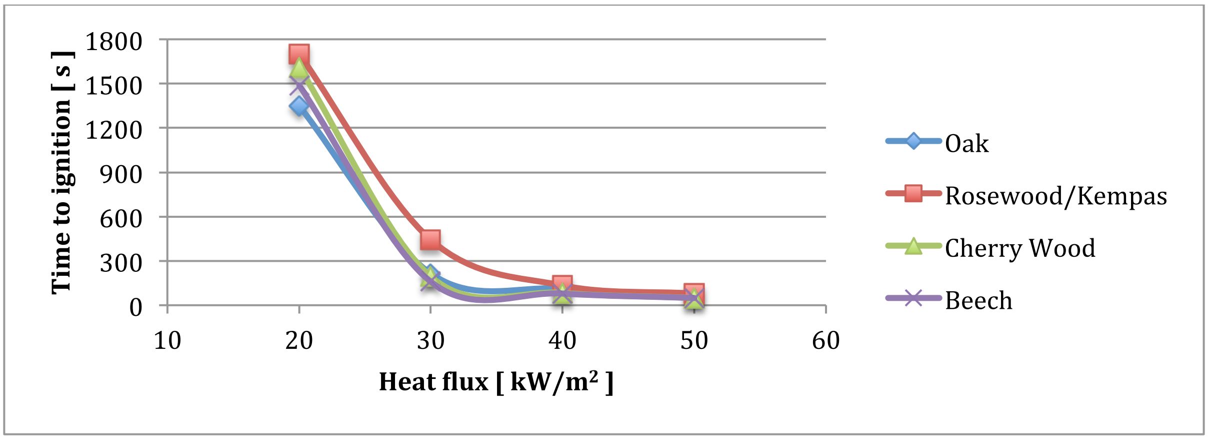



**Figure 4-9 Ignition time for varying heat flux (Chen et al., 2004)**

Figure 4-9 shows an evident trend. The time to ignition of wood varies some for the different species, but depends more so on the heat flux it is exposed to.

### 4.4.3 Burning- /Mass loss- /Heat release rate of wood

Burning rate is a general term used to describe the rate at which a given material is consumed by fire. Specifically, burning rate can be described in terms of heat release rate, mass loss rate or, in the case of charring materials, charring rate (Tran and White, 1992).

After ignition of wood, what happens is normally a flaming combustion where heat is released. Measuring average and peak heat release rates in experiments have been the background to developing a lot of different models for estimating mass loss- and charring rate of wood.

Many people have done research on the effect of different heat fluxes on the pyrolysis of wood. Tran and White showed, by exposing 4 different species of wood to heat fluxes ranging from $15 - 55\ kW/m^2$, that heat release-, mass loss- and charring rate of wood all increase with increasing heat flux, while time to ignition decreases (Tran and White, 1992). The conducted data on heat release rate and mass loss rate for varying heat fluxes in this experiment are presented in Figure 4-10 and Figure 4-11. The material properties of the different species tested are presented in Table 4-12.

**Table 4-12 Material properties of wood species tested by Tran and White (Tran and White, 1992)**

| Type | Density, $\rho[kg/m^3]$ | Moisture [%] |
|---|---|---|
| Redwood (softwood) | 312 | 8.33 |
| Southern Pine (softwood) | 508 | 9.71 |
| Red Oak (hardwood) | 660 | 8.53 |
| Basswood (hardwood) | 420 | 8.06 |

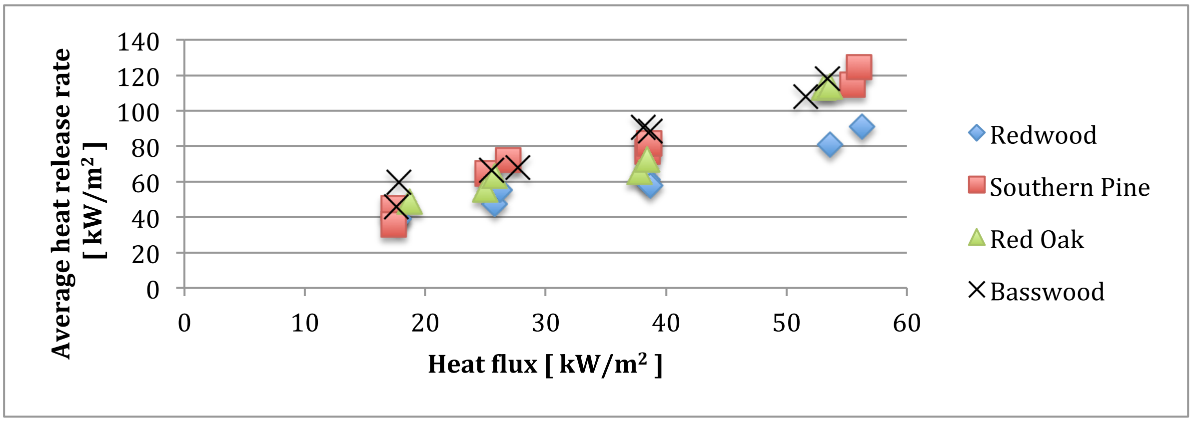



**Figure 4-10 Average heat release rate for various heat fluxes (Tran and White, 1992)**

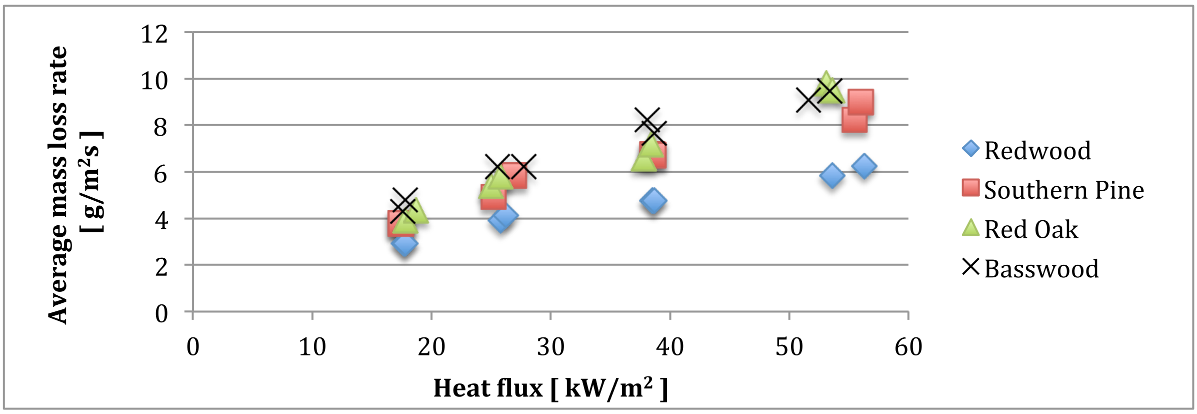



**Figure 4-11 Average mass loss rate for various heat fluxes (Tran and White, 1992)**

The previously mentioned research (in Section 4.4.2.) conducted by Chen *et al*. shows that the relationship between the average rate of heat release (from ignition to extinguish) and external heat flux is more of a parabolic than a simple linear relationship. It also showed that Tran's linear formula is approximately true for higher heat fluxes (Chen et al., 2004; Tran and White, 1992). The result obtained concerning average heat release rate from the experiment conducted by Chen *et al*. is presented in Figure 4-12.

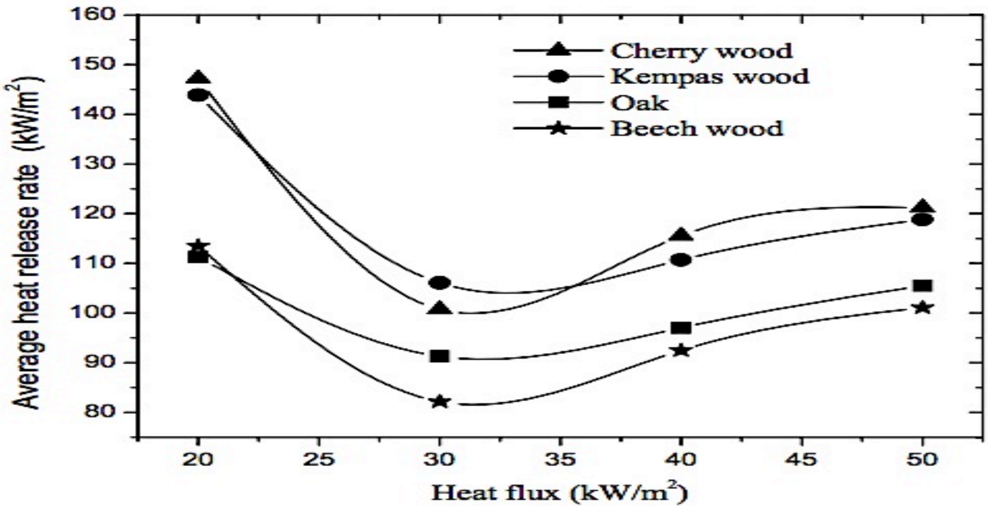



**Figure 4-12 Average heat release rate of wood for varying heat flux. Retrieved from "The Pyrolysis and Haet Release Rate of Wood Exposed to Weak External Heat Flux for Long Times" (Chen et al., 2004)**

Experiments to establish the effect different heat flux levels have on the heat release rate of four different species of wood, were also conducted by Ji *et.al* in 2003 (Ji et al., 2003). The same species and conditions was used as in the experiments conducted by Chen *et al*. (Chen et al., 2004). The data obtained for mass loss rate in this experiment is presented in Figure 4-13.

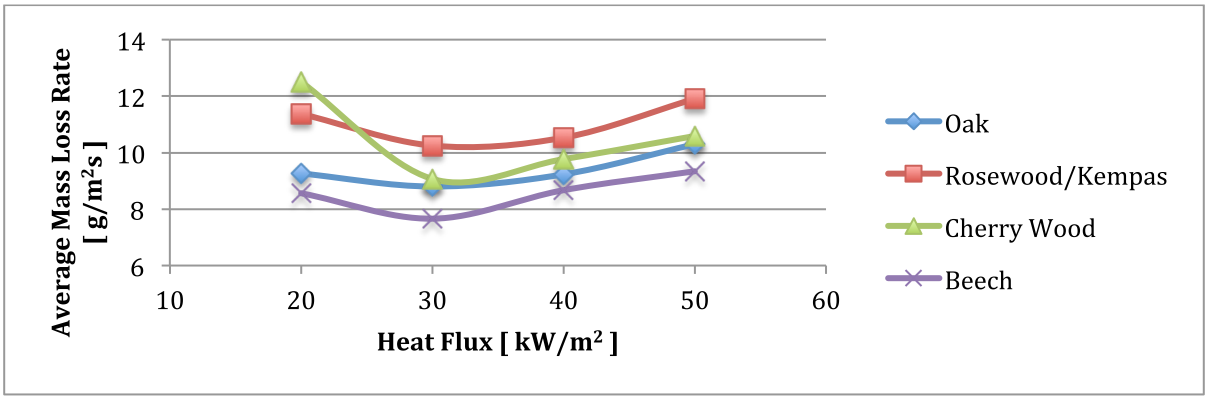



**Figure 4-13 Average mass loss rate after ignition for various heat fluxes (Ji et al., 2003)**

### 4.4.4 Heat fluxes in fire compartments

In the previous subsection the relationship between average mass loss- and heat release rate of different timber species is presented. Both heat release rate and mass loss rate are clearly dependent on the heat flux the wooden sample is exposed to.

Based on this, it is clear that the heat flux occurring in a compartment fire plays a big role in the burning of wooden surfaces. To be able to make realistic assumptions for fire development, and document the fire safety level of buildings, an understanding of heat fluxes occurring in compartment fires is necessary.

In a compartment fire both the actual fire and the compartment environment influence the heat flux to the surfaces. As a result of the Room Corner Test being the preferred method for evaluating the combustibility of lining materials, a number of experiments have been carried out to characterize the heat flux from a fire inside a compartment (Quintiere and Cleary, 1994; Williamson et al., 1991; Dillon, 1998; Tran and Janssens, 1993).

Dillon performed an analysis of the ISO 9705 Room Corner test in 1998 (Dillon, 1998). From his research it is clearly demonstrated that the compartment environment have an effect on the obtained heat fluxes. He established a method to define material properties including the heat of combustion, heat of gasification, thermal inertia, ignition temperature and the total energy released per area.

Parts of the results from Dillon's research is presented in The SPFE Handbook in *Heat Fluxes From Fires to Surfaces* (Lattimer, 2008). The heat fluxes from only the fire, measured by using a heat flux gauge, are rendered in Figure 4-14 and Figure 4-16. Figure 4-15 and Figure 4-17 shows the heat fluxes obtained due to the fire and the compartment environment (i.e. hot gas layer and reradiation from boundary surfaces). All four figures are retrieved from The SPFE Handbook (Lattimer, 2008).

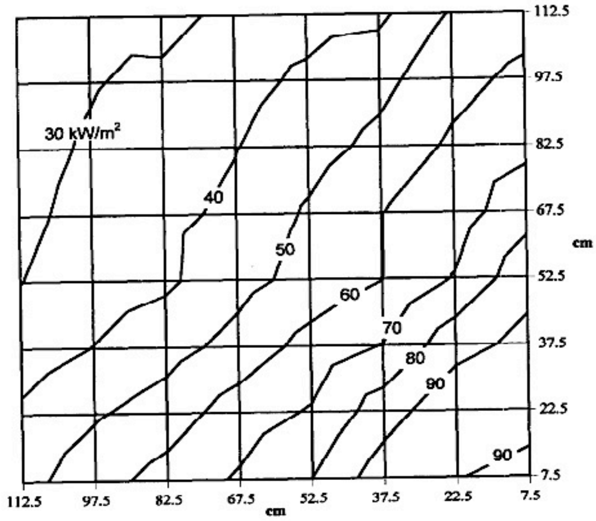



**Figure 4-14 Incident fire plume distribution to a cold ceiling. 0.17x0.17m square burner at 300kW, top surface 30cm from floor.**

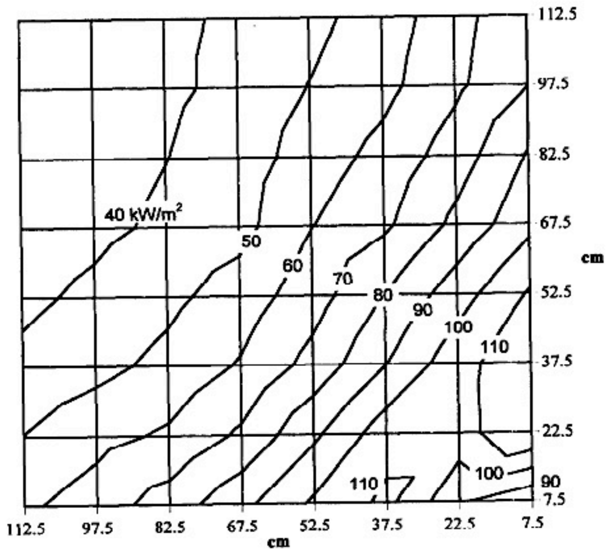



**Figure 4-15 Incident fire plume and room feedback heat flux distribution to a cold ceiling. 0.17x0.17m square burner at 300kW, to surface 30cm from floor.**

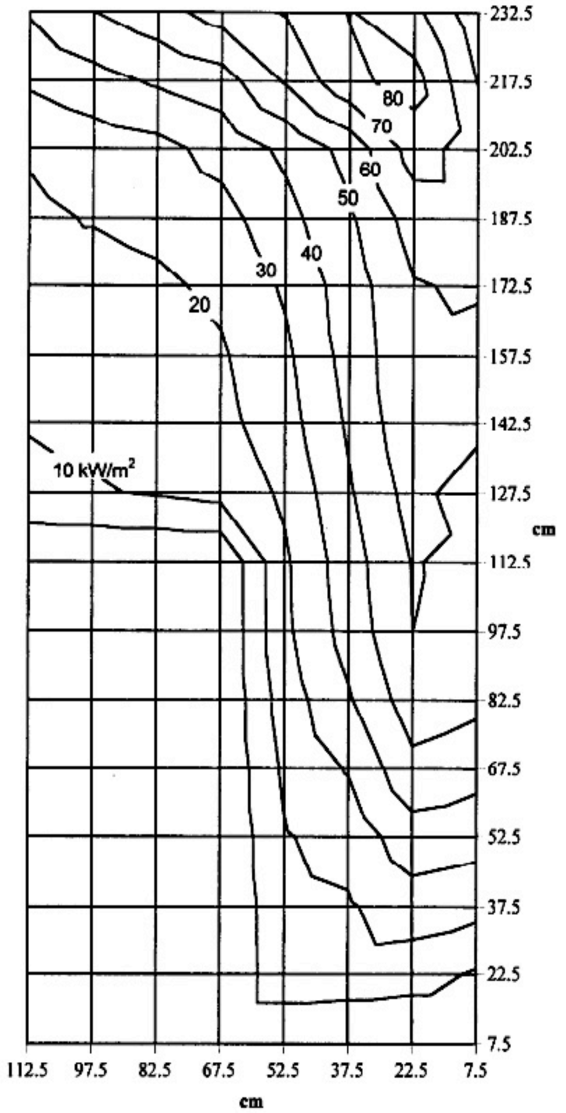



**Figure 4-16 Incident fire plume distribution to a cold wall. 0.17x0.17m square burner at 300kW, to surface 30cm from floor.**

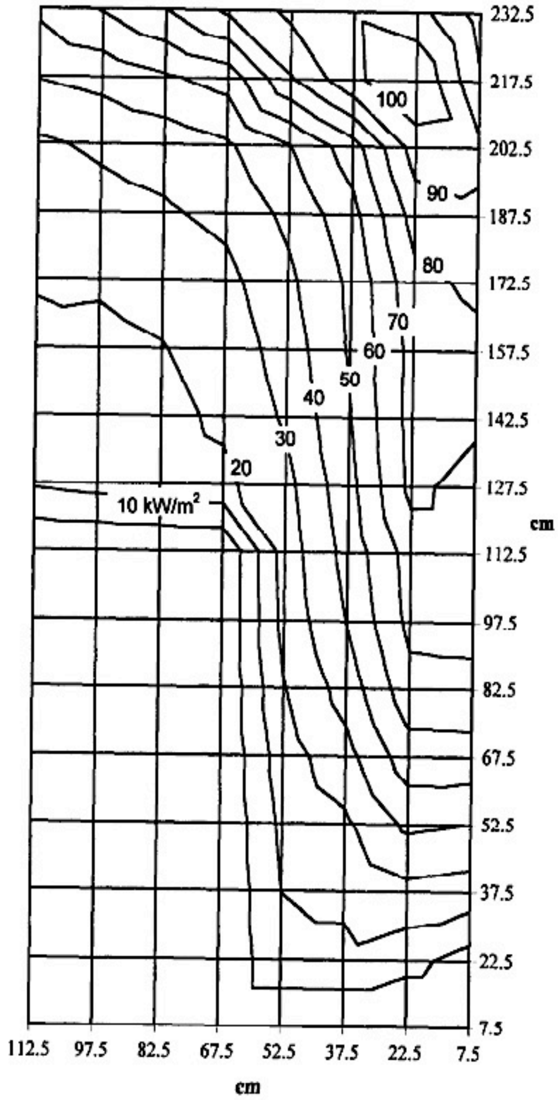



**Figure 4-17 Incident fire plume and room feedback heat flux distribution to a cold wall. 0.17x0.17m square burner at 300kW, to surface 30cm from floor**

The figures illustrate that the heat fluxes measured from the fire alone is significantly smaller than the ones where the room environment is taken into account. The biggest difference occurs close to the ceiling, where the heat fluxes increases $20\,kW/m^2$ . The hot layer of gases that are formed underneath the ceiling are the main cause of this.

This layer of gases is dependent on fire size, room geometry, ventilation and thermal properties of the enclosure. Change in any of these factors will affect the temperature of the gas layer and through this, the heat flux contribution from the compartment environment.

Tanaka *et al*. carried out research concerning the influence of the hot layer of gases on the heat fluxes in fires in 1986 (Tanaka et al., 1986). Tests were conducted in a room measuring $3.3m \times 3.3m \times 2.35m$, with a propane fire in the centre of the room. Figure 4-18 shows the average heat flux measured in the upper layer of the room vs. the layer temperature for different compartment door widths. The line plotted in the figure is the blackbody heat flux, given by,

$$\dot{q}'' = \sigma T^4 \tag{4.20}$$

where $T[K]$ is the temperature of the gas layer and $\sigma[W/m^2K^4]$ is the Stefan-Boltzmann constant. As Figure 4-18 illustrates, by using the temperature of the gas layer and inserting it in the equation for the blackbody heat flux, a reasonable estimate of the incident heat flux to the upper part of the walls inside the compartment can be found (Lattimer, 2008).

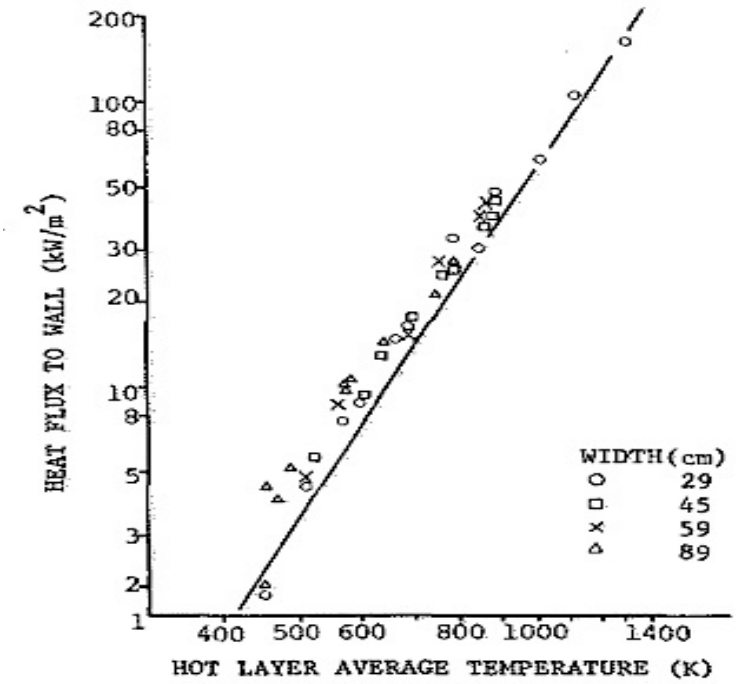



**Figure 4-18 Correlation between the average temperature of the hot layer of gases in a compartment and the heat flux on the walls of the compartment (Tanaka et al., 1986)**

## 4.5 Ventilation controlled vs. fuel controlled compartment fires

During a flashover the behaviour of the fire changes dramatically. All exposed combustible surfaces starts pyrolysis; this produces large amounts of combustible gases, which burn where there is sufficient oxygen (Buchanan, 2002). The rate of which a fire burns is affected by whether it is ventilation controlled or fuel controlled.

### 4.5.1 Fuel controlled fire

Fires will in some cases be fuel controlled. When this is the case the burning rate is dependent on the surface of the burning fuel and what type of material it is. If both total fuel load and the duration of the burning are known, the average heat release rate of a fuel controlled fire can be calculated using,

$$Q_{fuel} = E/1200 \tag{4.21}$$

where $E\ [MJ]$ is the total fuel load and 1200 is a number obtained by Law based on observations of experimental fires (Law, 1983). The number represents an approximation to the duration (20 minutes) of a typical furniture fire.

If the duration of the fire is not known, the heat release rate has to be estimated based on information about the fuel and the temperature development in the given compartment. When this is the case the available surface area of the fuel controls the rate of burning. The heat release can then be estimated using (Drysdale, 2011),

$$Q_{fuel} = \dot{q}_i'' A_{fuel} \Delta H_c / L_V \tag{4.22}$$

where $\dot{q}_i''[MW/m^2]$ is the incident radiation reaching the fuel surface, $A_{fuel}[m^2]$ is the exposed surface area of the fuel, $\Delta H_c[MJ/kg]$ is the heat of combustion of the volatiles and $L_V[MJ/kg]$ is the heat of gasification.

Some compartment fires start out as fuel controlled, but most are ventilation controlled. The majority of ventilation controlled fires do however become fuel controlled in the decay phase.

### 4.5.2 Ventilation controlled fire

As opposed to fuel controlled fires, when a fire is ventilation controlled the rate of combustion is dependent on the design of ventilation openings. As presented in Section 3.6.3 based on experiments by Kawagoe, the burning rate of wood $\dot{m}[kg/s]$ in compartments with only one opening can be described by Equation (3.8) (Buchanan, 2002),

$$\dot{m} = 0.092 A_V \sqrt{H_V}$$

where $A_V[m^2]$ is the area of the window opening and $H_V[m]$ is the height of the window opening. This equation shows that the main factor influencing the burning rate is the height of the window, but that the area also is of importance.

If the total mass of fuel in the room is known, the duration of the burning period $t_b[s]$ can be calculated using,

$$t_b = \frac{m_f}{\dot{m}} \tag{4.23}$$

where $m_f[kg]$ is the total mass of fuel available for combustion. If however the total amount of fuel is known in energy units $[MJ]$, the duration of the burning period $t_b[s]$ is given by,

$$t_b = \frac{E}{Q_{vent}} \tag{4.24}$$

where $E[MJ]$ is the fuel load available for combustion and $Q_{vent}[MW]$ for steady state burning is given by,

$$Q_{vent} = \dot{m} \Delta H_c \tag{4.25}$$

where $\Delta H_c[MJ/kg]$ is the heat of combustion of the fuel.

There are many reasons why the accuracy of these equations are not a hundred percent, one consideration, is that an unknown proportion of the pyrolysis product may burn as flames outside the window. Other factors are; that parts of the fuel are not available for combustion, or the fire becomes fuel controlled after a period of time. The size of the window opening compared to the wall where the window is located may also effect the ventilation because of occurring turbulence. Despite the uncertainties these equations are still the most used, and will probably form the basis for most post-flashover fire calculations until further research is conducted.

### 4.5.3 Opening factor

The opening factor, $O[m^{1/2}]$, is the most common way to describe the ventilation of a fire compartment. This factor can be found using the following equation,

$$O = \frac{A_V}{A_t}\sqrt{H_V} \tag{4.26}$$

where $A_V[m^2]$ is the area of the window opening, $H_V[m]$ is the height of the window opening, and $A_t[m^2]$ is the total internal area of the bounding surface (including openings).

#### *4.5.3.1 Multiple openings*

Equation (4.26), and the other equations presented in this subsection, take into account that there is only one ventilation opening. When a compartment has more than one opening (e.g. door and window), all of them need to be taken into account. Inserting the weighted average height of the openings $h_{eq}[m]$ instead of $H_V[m]$, and the total area of the ventilation openings for $A_V[m^2]$ in Equation (4.26) does this. NS-EN1991-1-2 (Norsk Standard, 2008) uses the following equation,

$$O = \frac{A_V}{A_t}\sqrt{h_{eq}} \tag{4.27}$$

where $A_V[m^2]$ is the total area of openings in vertical boundaries of the compartment, $A_t[m^2]$ is the total area of floors, walls and ceilings that enclose the fire compartment and $h_{eq}[m]$ is the weighted average of heights of all vertical openings.

When using this equation, an assumption is made that the airflow is similar in all openings and that there are no strong wind blowing which would create a cross flow through the room.

When horizontal openings are involved it gets somewhat more comprehensive to calculate the opening factor. An equivalent opening factor can be calculated by using the coefficient $f_k$ (Magnusson and Thelandersson, 1970). This factor can be found using the graph presented in Figure 4-19.

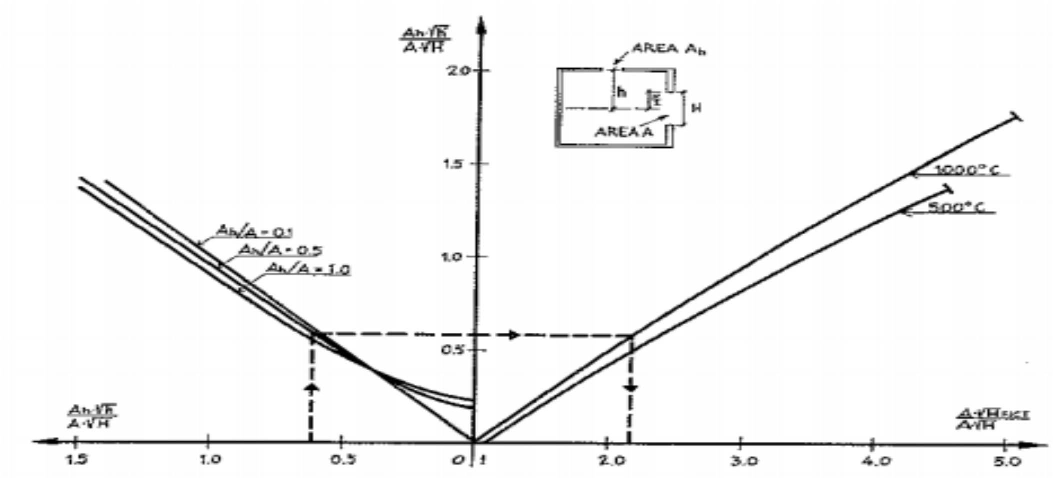


**Figure 4-19 Graph for finding fk, coefficient for calculatin opening factor when a compartment have both horizontal and vertical openings (Magnusson and Thelandersson, 1970)**

The first step is to calculate the total area of vertical openings and the weighted average of their heights, and the area of the horizontal openings. The distance between the geometrical points of gravity (given by h in Figure 4-19) for the openings need to be determined, before finding the value on the left side of the axis using the following two equations,

$$\frac{A_h\sqrt{h}}{A_V\sqrt{h_{eq}}} \quad (4.28)$$

$$\frac{A_h}{A_V} \quad (4.29)$$

where $A_h[m^2]$ is the area of horizontal openings, $A_V[m^2]$ is the area of vertical openings and $h_{eq}[m]$ is the weighted average of heights of all vertical openings. ($h_{eq} = H$ and $A_V = A$ in Figure 4-19).

Where the two values from Equation (4.28) and (4.29) interact on the left side of the figure will then determine where on the y-axis the line should be drawn and how big the coefficient $f_k$ should be. An example is illustrated with the small square in the middle of the figure giving the coefficient a value of 2.2.

This coefficient is then implemented in Equation (4.27),

$$O_{ekv} = f_k \frac{A_V}{A_t} \sqrt{h_{eq}} \tag{4.30}$$

### 4.5.4 The effect of varying opening factor on charring rate/depth

Research conducted by Hadvig shows that an increase in opening factor escalates the charring rate (Hadvig, 1981). His results are presented in Figure 4-20.

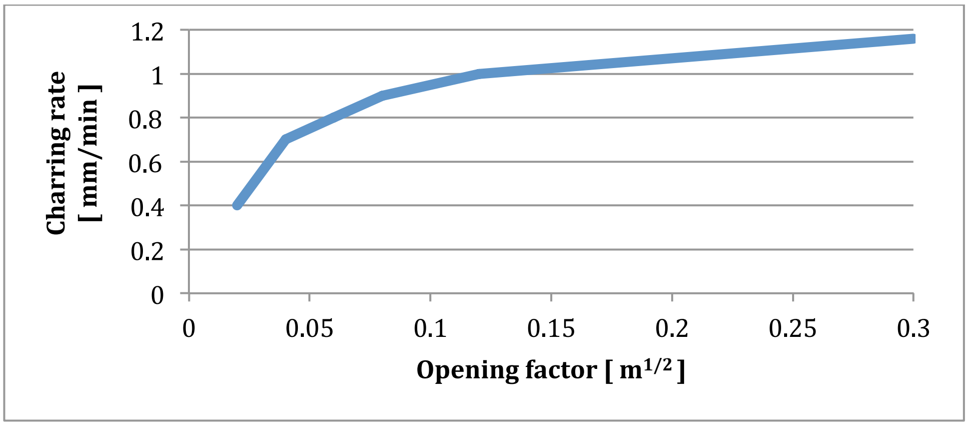



**Figure 4-20 Effect of opening factor on the charring rate**

The method presented in NS-EN 1995-1-2 Annex A *Parametric fire exposure* is based on this research carried out by Hadvig (Hadvig, 1981), and later on supported by Hansen and Olesen (Hansen and Olesen, 1992), as mentioned earlier. By using the method presented in the standard and inserting varying opening factors, the influence of the opening factor on charring depth becomes very clear. Figure 4-21 illustrates this for the heating phase of a fire.

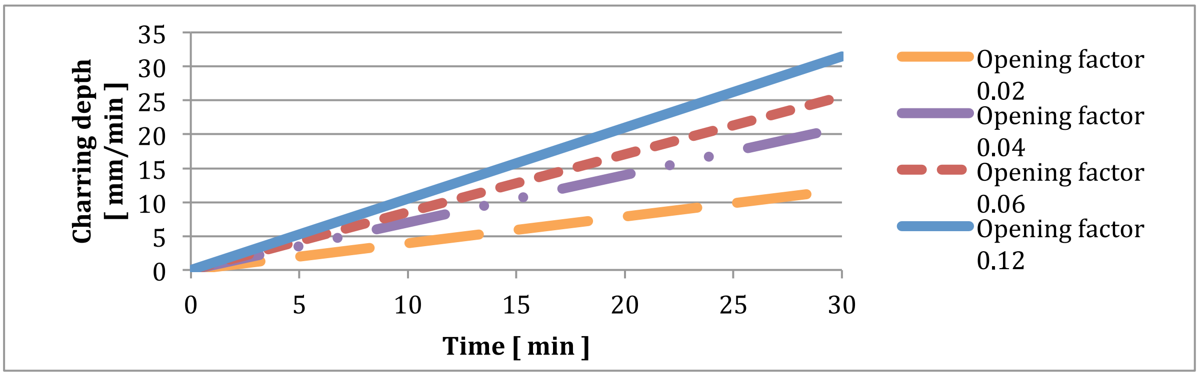



**Figure 4-21 Char depth vs. time for varying opening factors, using the method presented in NS-EN1995-1-2 Annex A**

Figure 4-21 clearly shows that the opening factor influences the charring depth in estimation of parametric fire curves.

### 4.5.5 Windows exposed to fire

It is well known that the window of a compartment exposed to fire can be of great impact on the fire development. The main reason for this is the changes the breaking of a window makes when it comes to ventilation conditions. Before the window breaks it works as a boundary/wall, after it contributes to ventilation of the compartment. The thermal breakage of glass depends on various parameters such as glass type, edge shading, edges conditions and constraints on the glass (Dembele et al., 2012). As a result of this many people have carried out experiments for the behaviour of windows exposed to elevated temperatures.

Skelly *et al*. conducted an experiment comparing the behaviour of glass with and without edge-protection. The compartment used for the experiments was designed to achieve a two-layer fire environment characteristic of normal building fires (Skelly et al., 1991). The results obtained from the experiments showed that the breakage of glass was caused by critical temperature differences between the centre of the window, and the protected parts on the edges. For the window with protected edges cracks spread throughout the glass, joined together and caused catastrophic collapse of the pane when a temperature difference of 70 °C was reached. The glass that was evenly heated (no edge-protection) developed relatively few cracks, and no window collapse occurred. Breakage of this glass started for a consistent glass temperature of 197 °C. To increase the time it takes before a window breaks, multiple layers can be used, or different types of glazing implemented.

# 5 Simulating fires using computer programs

One way of documenting the fire safety of a building through performance based alternative design is by using computer programs to simulate a potential fire. Several programs have been developed with this purpose in mind. In the analysis conducted in this thesis PyroSim and Fire Dynamics Simulator (FDS) have been utilized.

Generally a modelling program is used to render the design of a compartment or building, implementing material properties and adjusting external factors so that the result of a carried out simulation becomes as close to reality as possible. The factors that need to be implemented in a program like this are numerous, and most of them include assumptions made by the person creating the model. As a result of this, making accurate models are very challenging.

### 5.1.1 A priori vs. a posteriori

*A priori* and *a posteriori* is two terms used to distinguish two different types of knowledge, justification or argument. While *a priori* is independent of experience, *a posteriori* is dependent on experience or empirical evidence.

When utilizing computer programs for simulating fires in buildings for documentation of fire safety, the analysis conducted is *a priori*. This is a result of the fact that the numbers obtained from the simulations cannot be verified, until the day a fire occurs in the building the simulations have been carried out for. Whether or not the results of the analysis can be trusted is highly dependent on the fire safety engineer conducting the analysis.

To determine/make people aware of the uncertainties attended with simulating fires, several people have carried out research in this field. The results from research show the *a posteriori* point of view.

Two of the people that have conducted studies on this topic are Pope and Baily (Pope and Bailey, 2006). They compared the results of eight large-scale fire tests with the numbers obtained from two parametric fire modelling techniques (Eurocode 1, and BFD curve method) and one field model (Fire Dynamics Simulator). Their result shows that the output temperature profile predicted by FDS always is lower than the measured test values. This, and the differences in the specific predictions of the field model and the output during the cooling phase, led them to the conclusion that the parametric methods of modelling is more reliable, compared to FDS. This is however only based on one single testing procedure.

An important factor that needs to be considered is the resolution of the mesh used for the FDS model in this experiment: $0.2m \times 0.2m$ and $0.4m \times 0.4m$. This could be the source for some of the experienced deviations from reality. The authors justified their choice of mesh based on the time required for simulations. Choosing a higher grid resolution increases the time needed, and needing several weeks to carry out the simulations reduces the benefits of using these types of models.

Rein *et al*. also carried out research on the accuracy of fire models (Rein et al., 2009). Prior to the Dalmarnok Fire Test One, a series of experiments conducted in a high-rise building in 2006, seven round-robin teams independently simulated the test scenario. They were given a description of the geometry of the compartment, fuel packages, ignition source and ventilation conditions.

To carry out the simulations, different fire models were taken into use. Table 5-1 is retrieved from the report of the experiment. It gives information about the models used and a general description of the input to the simulations.

**Table 5-1 Input data used in the different fire simulations conducted for the Dalmarnok Fire Test One (Rein et al., 2009).**

| Sim # | Fire model | ERT[1] [$h$] | Grid [$mm$] | General description of input to the simulation |
|---|---|---|---|---|
| A1 | CFAST | 0.01 | - | Domain includes the whole flat. HRR is partially prescribed and partially predicted. Initial fire source prescribed using the HRR from a NIST sofa experiment. Ignition of secondary items predicted by ignition temperature and material properties. |
| A2 | FDS 4 | 153 | 50 | Domain includes only main compartment. HRR is partially prescribed and partially predicted. Initial fire source prescribed using the HRR from a NIST sofa experiment. Ignition of secondary items predicted by ignition temperature, material properties and prescribed surface burning rate. |
| B | FDS 4 | 23 | From 5 to 500 | Domain includes whole flat. HRR is partially prescribed and partially predicted. Initial fire source prescribed using measured HRR from sofa replica experiment plus the remaining 2/3 sofa mass that way allowed to burn further. Ignition of secondary items predicted by ignition temperature, material properties and prescribed heat of vaporization. |
| C | CFAST | 0.01 | - | Domain includes the whole flat and the main floor access corridor. HRR is partially prescribed and partially predicted. Initial fire source prescribed using the measured HRR from sofa replica experiment as given. Ignition of secondary items predicted by ignition temperature and material properties. |
| D1 | FDS 4 | 19 | 100 | Domain includes the whole flat. HRR is fully prescribed using initially a uniform t-square fire over the sofa area and then values based on ventilation conditions. |
| D2 | FDS 4 | 128 | From 50 to 100 | Domain includes whole flat. HRR is fully predicted. Ignition of secondary items predicted by material properties and pyrolysis model for flame spread. |
| E1 | FDS 4 | 55 | 100 | Domain includes the whole flat. HRR is fully predicted except ignition that is a small wastepaper basket fire. Ignition of secondary items predicted by ignition temperature and material properties. |
| E2 | FDS 4 | 33 | 100 | Domain includes the whole flat. HRR is full prescribed using initially a uniform t-square fire over the sofa area and then values based on ventilation conditions. |
| F1 and F2 | FDS 4 | 170 | 90 | Domain includes the main compartment, kitchen, bedroom -1 and hallway. HRR is partially prescribed and partially predicted. Initial fire source prescribed using the measured HRR from sofa replica experiment but extrapolated with a t-square fire for the remaining 2/3 of sofa mass. The peak HRR is raised by 20% in F1 and by 40% in F2. Ignition of secondary items predicted by ignition temperature, material properties and prescribed surface burning rate |

[1] Estimated running time on the respective computers used.

Some of the results from the simulations and the Dalmarnok Fire Test One are presented in Figure 5-1 and Figure 5-2.

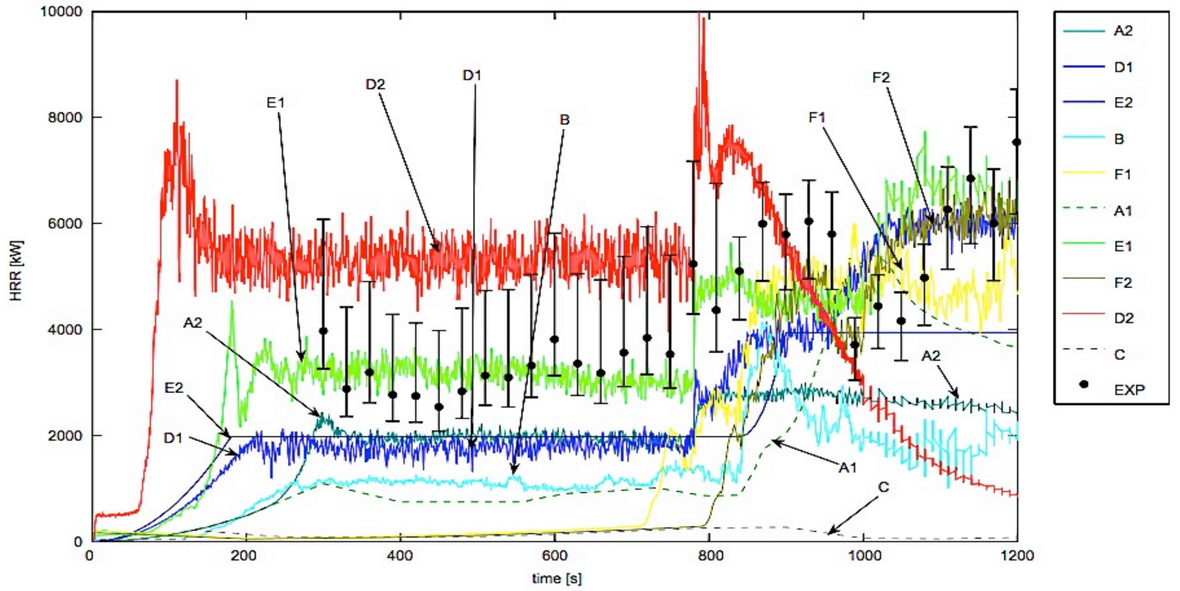



**Figure 5-1 Results gathered through simulations and observations conducted on the Dalmarnok Fire Test One. Evolution of the global heat release rate in the compartment. The black dotted line is the data conducted in the experiment, with error bars (Rein et al., 2009).**

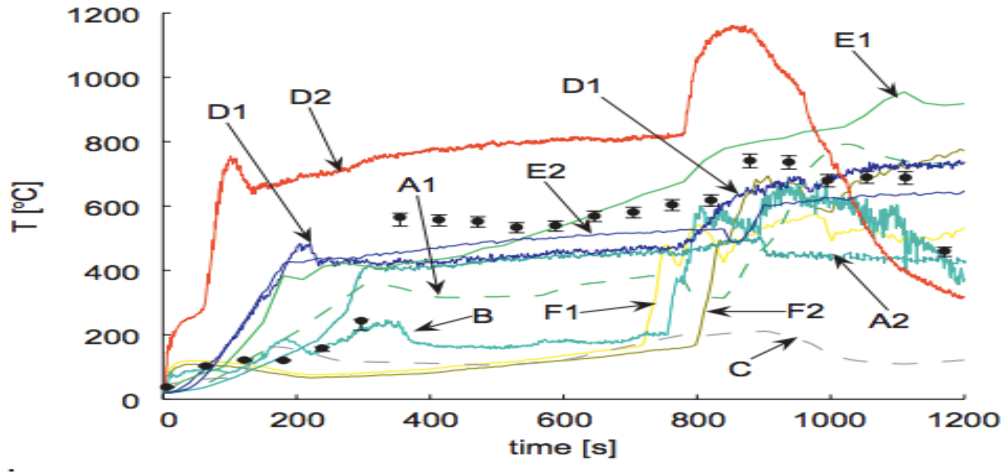



**Figure 5-2 Results gathered through simulations and observations conducted on the Dalmarnok Fire Test One. Evolution of the average temperature of the hot gas layer in the compartment. The black dotted line is the data conducted in the experiment, with error bars (Rein et al., 2009).**

The goal of the conducted experiment was to simulate a fire with high accuracy, not to present an engineering analysis based on safety factors and conservative assumptions. It is clear from Figure 5-1 and Figure 5-2 that even though the accuracy was meant to be high, the deviations from the real fire are extreme.

This illustrates the challenges and uncertainties with simulating fires. Given the same input data, and only having to make some assumptions, the results from the simulations conducted still vary significantly.

# 6 Analysis – The effect of variation in opening factor

## 6.1 Presentation of the case used for calculations and simulations

The case used when calculations and analysis have been conducted in this report is Moholt 50|50. The project consists of five high-rise timber buildings, and is currently under construction in Trondheim, Norway. The student association in Trondheim (SiT) is the project owner, and the project includes 632 new dorm rooms for student accommodation.

All five high-rise buildings are being built with timber as their main load-bearing material, which makes the case relevant for this thesis. Looking at an entire building is very comprehensive; because of this the analysis conducted focuses on one single compartment.

Figure 6-1 shows the floor plan of the compartment that has been used in the calculations and analysis. The walls are numbered to allow the reader to easily identify the specific elements. This is especially important when it comes to the composition of them, as most of the walls are different from each other.

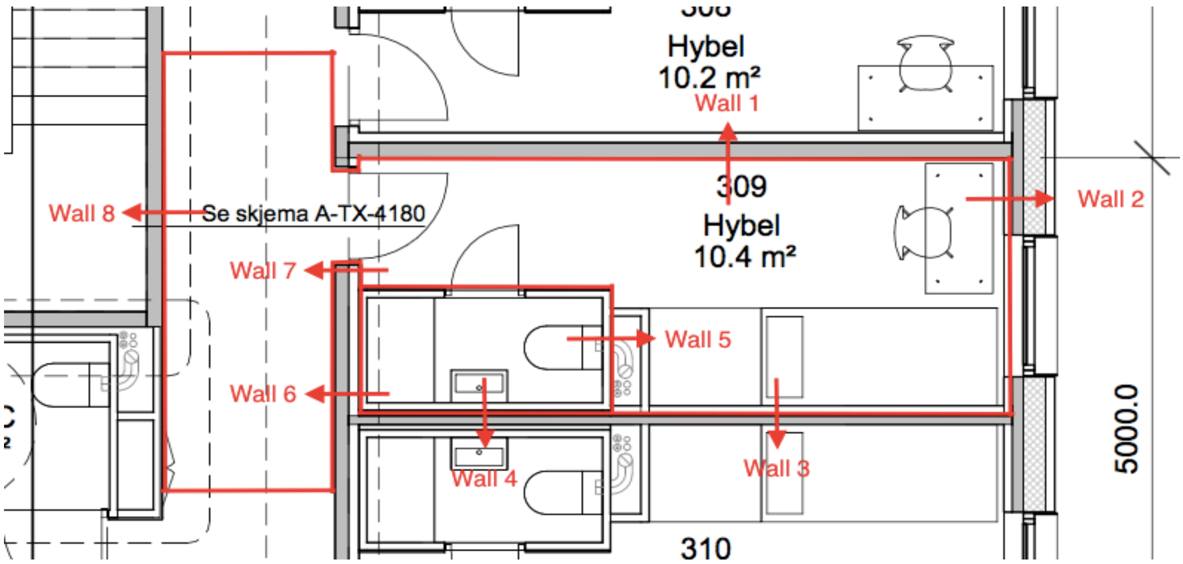



**Figure 6-1 Floor plan, showing wall identity**

The modelled room is the same as the one that was built and experimented on by SP Fire Research in December 2014 (Hox, 2015). Measurements of the compartment are presented in

Figure 6-2 and Figure 6-3, while Figure 6-4 gives the measurements of the part of the hallway that has been included. Table 6-1 presents information about the compositions of the door, window, walls, ceiling and floor. The measurements have been done manually off the floor plan for the building, which may cause small deviations from reality.

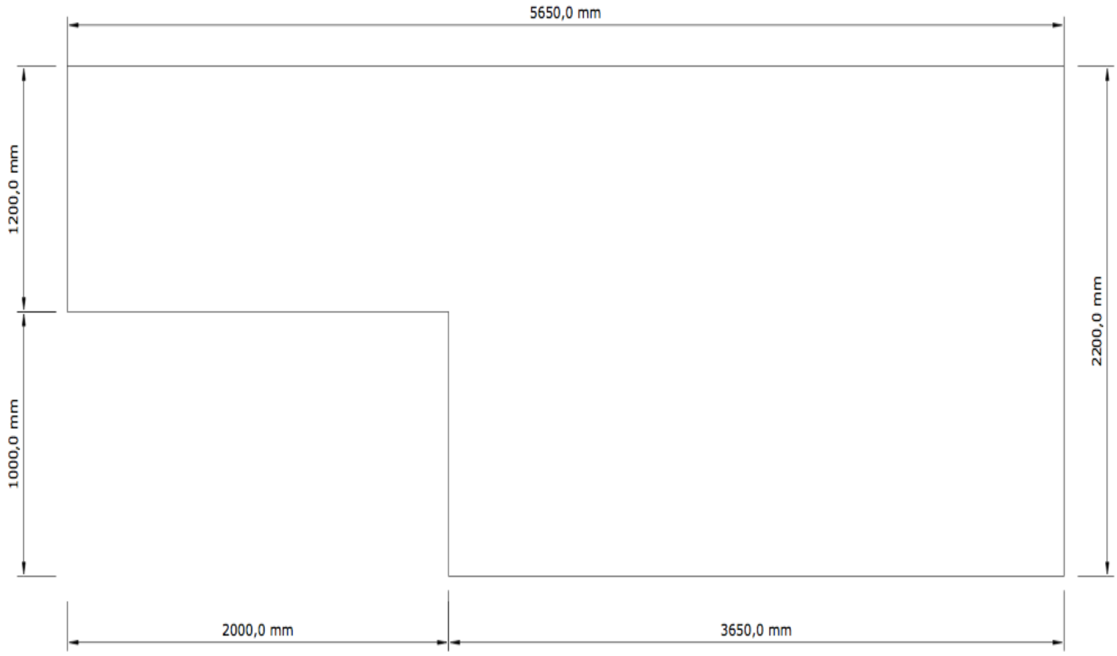



**Figure 6-2 Sketch presenting the measurements of the floor area used in calculations. The measures have been carried out manually and may deviate some from the floor plan**

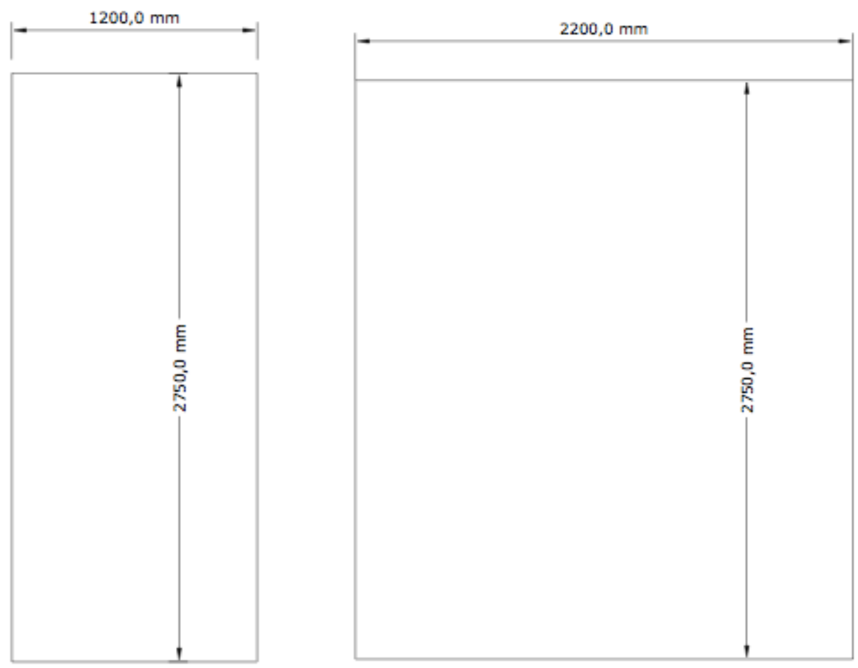



**Figure 6-3 Sketches presenting the measurements of height and width of the compartment used in calculations. Left sketch is the width in the entrance of the compartment, while right sketch is further in. The measures have been carried out manually and may deviate some from the original floor plan.**

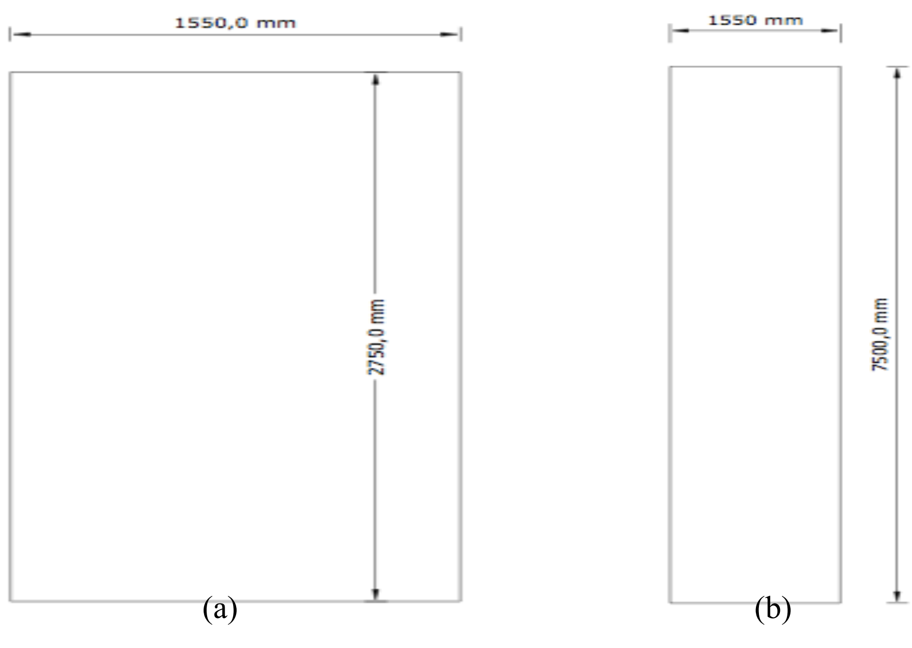



**Figure 6-4 Sketches presenting the measurements of (a) height and width of the hallway and (b) length and width. The measures have been carried out manually and may deviate some from the original floor plan.**

**Table 6-1 Composition of door, window, walls, ceiling and floor in the compartment used as case in calculations**

| Element | Composition of element, inside→outside |
| --- | --- |
| **Wall 1** | 100 mm cross-laminated timber (5x20 mm laminas)<br>10 mm empty cavity<br>50 mm rock wool between 75 mm steel studs<br>13 mm standard gypsum<br>15 mm fire retardant gypsum |
| **Wall 2** | 13 mm standard gypsum<br>100 mm cross-laminated timber (5x20 mm laminas)<br>200 mm rock wool<br>Façade (not included in models) |
| **Wall 3** | 15 mm fire retardant gypsum<br>13 mm standard gypsum<br>50 mm rock wool between 75 mm steel studs<br>10 mm empty cavity<br>100 mm cross-laminated timber (5x20 mm laminas) |
| **Wall 4** | 100 mm cross-laminated timber (5x20 mm laminas) |
| **Wall 5** | 13 mm standard gypsum on one side of 75 mm steel studs |
| **Wall 6** | 100 mm cross-laminated timber (5x20 mm laminas) |
| **Wall 7** | 13 mm standard gypsum<br>100 mm cross-laminated timber (5x20 mm laminas) |
| **Wall 8** | 100 mm cross-laminated timber (5x20 mm laminas) |
| **Ceiling** | 100 mm cross-laminated timber (5x20 mm laminas)<br>30 mm acoustic underlay<br>40 mm screed (A-Plan) |
| **Floor** | Linoleum<br>40 mm screed (A-Plan)<br>30 mm acoustic underlay<br>100 mm cross-laminated timber (5x20 mm laminas) |
| **Suspended ceiling in hallway** | Mounted using support rails along the walls and perpendicular to the walls |
| **Door** | 0.9x2.0 m<br>40 dB<br>$EI30S_a$ |
| **Window** | 1.2x1.6 m<br>Placed 1.13 m above the floor<br>3 layers of glass |

### 6.1.1 Fire safety strategy of the case building

In the fire safety strategy of the case building each floor is designed as one fire cell. All five high-rise buildings have been equipped with two sets of stairs. In addition to this some of the windows in the kitchen/living room have been designed according to the criteria of an escape route.

For the windows to have a positive effect on the fire safety strategy, the fire brigade in Trondheim was contacted. This was necessary as the building exceeds 8 floors and 23 meters in height. Originally, according to the Norwegian technical regulations guideline, the buildings are too tall for the fire brigade to extract people from the top floor using normal machinery. Because of the location of the building being in one of Norway's biggest cities, the fire brigade has the equipment needed and have approved the windows in the common areas as escape routes.

This results in the designed escape routes being either through one of the two sets of stairs, or through windows in the kitchen/living room accompanied by the fire brigade. The windows in the compartments are not part of the escape rout in the fire safety strategy of Moholt 50|50.

## 6.2 The Analysis

To find the opening factors effect on the heating/growing phase of a fire, a model of the compartment and parts of the hallway presented in Section 6.1 have been drawn in PyroSim. A print screen of the model is shown in Figure 6-5. FDS was then used to conduct a 10-minute simulation of a fire in the compartment. The model is an approximation to reality, assumptions and limits have been drawn to make the simulating process more efficient. These limitations and assumptions will be presented in the following subsections, together with reasoning for choice of values for different factors.

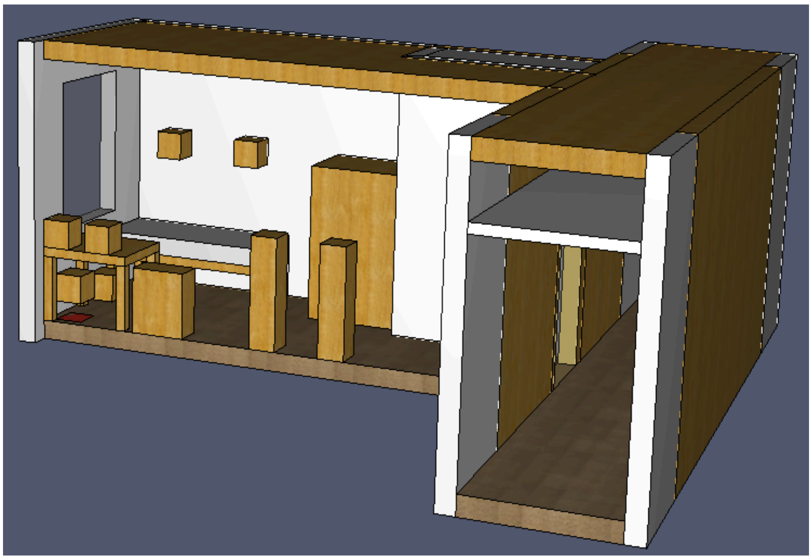


**Figure 6-5 Model built in PyroSim**

### 6.2.1 Opening factor

Based on the fact that the window in the compartment does not need to work as an escape route, the only thing influencing the size of it is the need of daylight and view. As the room is meant to work as bedroom/living area the Norwegian technical regulation states that there has to be a source of daylight. How big this source (window) needs to be can be calculated in two different ways (Direktoratet for byggkvalitet, 2010):

- The daylight factor needs to be 2% or higher.
- The area that provides daylight needs to be 10%, or more, of utility floor space.

Using the second one gives the lower limit of window size,

$$A_{window,min} = 0.1(5.7 \cdot 2.2 - 2) = 1.054m^2$$

At the start of the fire in the carried out experiment and simulations, only the door opening contributes to the ventilation. As soon as the temperature gets high enough, the window breaks and increases the original ventilation of the compartment. When calculating the variation in opening factor, both door and window have been taken into account.

With the original window $(1.2m\times1.6m)$ the opening factor of the compartment can be calculated using Equation (4.27) presented in Section 4.5.3.1,

$$O = \frac{A_V}{A_t}\sqrt{h_{eq}}$$

$$A_V = (0.9 \cdot 2.0) + (1.2 \cdot 1.6) = 3.72$$

$$A_t = 2(5.7 \cdot 2.8) + 2(2.2 \cdot 2.8) + 2(5.7 \cdot 2.2 - 2.0 \cdot 1.0) = 65.32$$

$$h_{eq} = \sum \frac{A_i h_i}{A_V} = \frac{0.9 \cdot 2.0 \cdot 2.0}{3.72} + \frac{1.2 \cdot 1.6 \cdot 1.6}{3.72} = 1.79m$$

$$O = \frac{3.72}{65.32}\sqrt{1.79} = 0.076m^{1/2}$$

### 6.2.2 Windows chosen to vary the opening factor

As the window implemented in the experiment conducted in December 2014 had 3 layers of glass, this has been assumed for the alternative windows too. Simulations have been carried out for windows of five different sizes.

Windows come in all sizes; they often vary with 10cm intervals. To get a spread in opening factors, the windows chosen for the simulations range from the smallest size allowed in the given example case, to windows exceeding the size of the original one.

As the height of the window impacts the opening factor the most, it has been chosen to only vary the width, to reduce the uncertainties. Addition to/subtraction from the width of the window has been done on the side of the window furthest away from the wall with cross-laminated timber.

The four windows presented in Table 6-2 have been chosen for the simulation, in addition to the original.

**Table 6-2 Opening factor for varying window size**

| Window size | $A_V\left[m^2\right]$ | $h_{eq}\left[m\right]$ | $O\left[m^{1/2}\right]$ |
|---|---|---|---|
| **Window 1** $(\mathbf{0.7m \times 1.6m})$ | 2.92 | 1.85 | 0.061 |
| **Window 2** $(\mathbf{1.0m \times 1.6m})$ | 3.4 | 1.81 | 0.070 |
| **Window 3** $(\mathbf{1.4m \times 1.6m})$ | 4.04 | 1.78 | 0.083 |
| **Window 4** $(\mathbf{1.7m \times 1.6m})$ | 4.52 | 1.76 | 0.092 |

## 6.3 Limitations

To be able to make a model efficiently and to reduce the time needed for the simulating process, limitations are necessary.

### 6.3.1 Mesh

To make the model as accurate as possible when it comes to the dimensions of walls, ceilings etc. the mesh would have to be divided into squares of $0.05m \times 0.05m$. Compared to dividing the mesh into squares of $0.1m \times 0.1m$, this would prolong the simulation process considerably. As a result of this it has been chosen to use a $0.1m \times 0.1m$ mesh, which means that the measurements have been adjusted slightly to fit the mesh. Where adjustments were needed the lengths have been adjusted to the closest $0.1m$.

The result of this is a slightly bigger boundary area of the compartment, and a slightly narrower hallway than the values measured from the floor plan. The difference between the measured values and the ones used in the model, for floor area and total surface area in the compartment, are,

$$A_{f,floorplan} = (5.65 \cdot 2.2) - (2.0 \cdot 1.0) = 10.43m^2$$

$$A_{f,PyroSim} = (5.7 \cdot 2.2) - (2.0 \cdot 1.0) = 10.54m^2$$

$$Deviation_f = 100 - \frac{10.43}{10.54} \cdot 100 = 1.04\%$$

$$A_{t,floorplan} = 2A_{f,floorplan} + 2(5.65 \cdot 2.75 + 2.2 \cdot 2.75) = 64.035m^2$$

$$A_{t,PyroSim} = 2A_{f,PyroSim} + 2(5.7 \cdot 2.8 + 2.2 \cdot 2.8) = 65.32m^2$$

$$Deviation_t = 100 - \frac{64.035}{65.32} \cdot 100 = 1.97\%$$

As the differences are fairly small it is assumed that the effect from this will be negligible.

The model is based on four meshes. This number is chosen to make the simulation process as efficient as possible, as the computer it is carried out on has two processing cores.

## 6.4 Thermal properties

The model includes five different surface materials. The thermal properties used for the different materials in the model are presented below.

### 6.4.1 Wood

The thermal properties of wood change with increasing temperature, the two main reasons for this are the evaporation of water and formation of char. In the calculations conducted for fire load in Section 4.2.3 the moisture content was assumed to be 12%. In that case constant numbers for thermal conductivity and specific heat could be implemented without it having a negative effect on the result.

In this model the moisture content has been taken as the one NS-EN 1995-1-2 presents for wood (Norsk Standard, 2010). By doing this the standard can be used to find the varying thermal conductivity and specific heat based on increasing temperature, and a more accurate simulation can be achieved. Table 6-3 and Table 6-4 have been retrieved from NS-EN 1995-1-2 Annex B. They present the varying specific heat and thermal conductivity of wood.

**Table 6-3 Specific heat of wood (Norsk Standard, 2010)**

| **Temperature** $[°C]$ | **Specific heat capacity** $[kJ/kgK]$ |
|---|---|
| 20 | 1.53 |
| 99 | 1.77 |
| 99 | 13.60 |
| 120 | 13.50 |
| 120 | 2.12 |
| 200 | 2.00 |
| 250 | 1.62 |
| 300 | 0.71 |
| 350 | 0.85 |
| 400 | 1.00 |
| 600 | 1.40 |
| 800 | 1.65 |
| 1200 | 1.65 |

**Table 6-4 Thermal conductivity of wood (Norsk Standard, 2010)**

| **Temperature** $[°C]$ | **Thermal conductivity** $[W/mK]$ |
|---|---|
| 20 | 0.12 |
| 200 | 0.15 |
| 350 | 0.07 |
| 500 | 0.09 |
| 800 | 0.35 |
| 1200 | 1.50 |

#### *6.4.1.1 Density*

SINTEF Byggforsk presents the following density for cross-laminated timber (SINTEF Byggforsk, 2013),

$$\rho_{cross-laminated\ timber} = 500\ kg/m^3$$

#### *6.4.1.2 Heat of gasification*

The average heat of gasification of softwood is presented in Section 4.3.3. The value implemented in the model is,

$$L_{V,softwood} = 3200\,kJ/kg$$

#### *6.4.1.3 Mass loss rate*

Assumptions for the mass loss rate of wood have been done based on the research presented in Section 4.4.3 and Section 4.4.4. The average temperature in the top layer of the compartment is assumed to be the same in the simulation as in the experiment conducted in December 2014 (Hox, 2015). Figure 6-6 presents the temperatures in the compartment during the first 10 minutes of the carried out experiment.

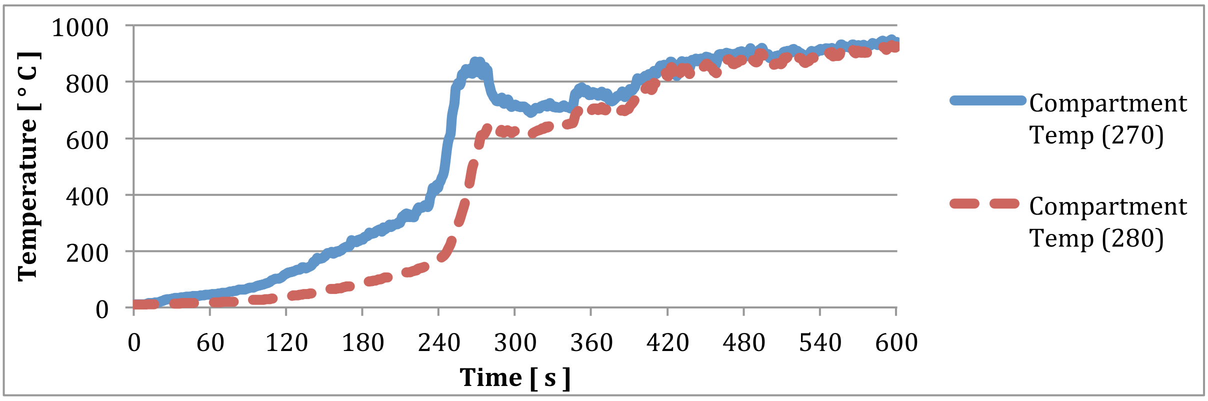



**Figure 6-6 Temperature measured in the compartment in the conducted experiment 270 cm and 280 cm above the floor**

As timber is assumed not to ignite before a temperature of approximately 350°C (see Section 4.4.2.) is reached, the average temperature after this have been used for the calculation of mass loss rate. From Figure 6-6, it can be assumed that this average temperature will be close to 750°C.

Using this temperature and Equation (4.20) for the blackbody heat flux, the following heat flux can be assumed in the upper layer of the fire compartment:

$$\dot{q}'' = \sigma T^4 = 5.67 \cdot 10^{-8} \cdot 1023^4 = 62.1\, kW/m^2$$

Out of the wooden species presented experimental data for in Section 4.4.3, the Southern Pine ($508\, kg/m^3$) is the one most similar to the wooden materials used for cross-laminated timber in Norway ($500\, kg/m^3$). Exposed to a heat flux of $50 - 60\, kW/m^2$, the mass loss rate of the Southern Pine is approximately $8.6\, g/m^2 s$.

The heat flux is difficult to assume/estimate, as it is dependent on a lot of factors and will vary for the different parts/heights of the compartment. The highest value is achieved in the upper layer where hot gases are gathered. As the value presented in the theory for the Southern Pine is based on a heat flux that is somewhat lower than the maximum heat flux calculated for this case, this is used as an approximation to the average heat flux the wooden surfaces in the room are exposed to.

For the wooden cribs and Euro pallets, this mass loss rate has been additionally adjusted. The reason for this is because the surface area of the elements drawn in the model is much smaller than the ones in the experiment. More information about this and the calculations carried out is presented in Section 6.5.9.1 and 6.5.9.2.

### 6.4.2 Gypsum

In the carried out experiment two different types of gypsum was used. For most walls regular gypsum was applied. For walls separating two compartments, one layer of fire resistant gypsum was added on top of the normal one. The thermal properties (at 20 °C) of the two different types of gypsum used, provided by the manufacturer through product data sheets, are, Type GF board (Gyproc AS, 2008a):

- Density, $\rho_{GF} = 825\,kg/m^3$
- Thermal conductivity, $\lambda_{GF} = 0.25\,W/mK$

Regular board (Gyproc AS, 2008b):

- Density, $\rho_{Regular} = 720\,kg/m^3$
- Thermal conductivity, $\lambda_{Regular} = 0.25\,W/mK$

As presented in Section 3.10, the varying specific heat of gypsum boards can be illustrated as in Figure 3-16. A more accurate presentation of the specific heat is given in Figure 3-18. In the model created in PyroSim numbers for the specific heat have been retrieved from the graph presented in the report of the experiment conducted by Park *et al*. (Park et al., 2010). Table 6-5 presents the numbers implemented in the model. The accuracy of the numbers are not extremely high, as they are read from a graph, but the essence of the variation in specific heat is maintained.

**Table 6-5 Specific heat of gypsum**

| **Temperature** $[°C]$ | **Specific heat** $[kJ/kgK]$ |
|---|---|
| 20 | 1.25 |
| 140 | 2.00 |
| 160 | 20.00 |
| 180 | 2.00 |
| 200 | 9.00 |
| 220 | 1.25 |
| 400 | 1.00 |
| 440 | 0.50 |
| 500 | 1.25 |
| 600 | 1.25 |

The thermal conductivity of gypsum also changes with varying temperature. Figure 3-17 presented in Section 3.10 illustrates the trend of this variation for a GF board. The numbers presented in Table 6-6, and also implemented in the PyroSim model, have been read from this graph.

**Table 6-6 Thermal conductivity of Type GF gypsum board**

| **Temperature** $[°C]$ | **Thermal conductivity** $[W/mK]$ |
|---|---|
| 20 | 0.25 |
| 100 | 0.25 |
| 100 | 0.124 |
| 370 | 0.124 |
| 800 | 0.281 |
| 1000 | 0.537 |

As the thermal conductivity varies with density and the rate of the temperature rise in the compartment, there will be differences between the conductivity of the two different types of gypsum boards used in the experiment. A lot of research has been done on the thermal conductivity, and the results vary considerably. The biggest differences between boards occur after a temperature of 400 ℃ is reached, as this is when cracking of the material usually starts.

In the conducted analysis it has been assumed that the conductivity of the two different boards are the same. This means that the only factor that has been implemented that differs between the two is the density. As the carried out simulations only takes the first 10 minutes of the fire into account, it is assumed that this will not affect the results significantly.

### 6.4.3 Linoleum

Using the data collected from the experiment conducted in December 2014 (Hox, 2015) it is clear that the temperature rise at the level of the floor is approximately zero. The temperature does increase slightly after a long period of time, which can be assumed is due to char residue from walls and pallets/cribs. This is however not relevant for the simulations, as they only take the first 10 minutes into account. Based on this the different thermal properties of the materials used in the floor has been assumed constant.

With this assumption the thermal properties of linoleum presented in Section 4.2.3 can be applied,

- Density, $\rho_{Linoleum} = 1200\, kg/m^3$
- Thermal conductivity, $\lambda_{Linoleum} = 0.17\, W/mK$
- Specific heat, $c_{Linoleum} = 1400\, J/kgK$

Thicknesses of linoleum products range from 2.0 - 4.5 mm. In the model it has been assumed that the thickness of the material is 2.5 mm. SINTEF byggforsk recommends this value for rooms with high usage, and 2.0 mm for normal housing (SINTEF Byggforsk, 2012). As the building is meant for student accommodation and the same linoleum is used in both hallway and compartment, the thicker one seems most suitable.

Even though the temperature along the floor is low, linoleum is a combustible material and this needs to be implemented in the model. The following parameters are used (Tewarson, 2008):

- Heat of combustion, $\Delta H_c = 16.4\, MJ/kg$
- Heat of gasification, $L_{V,Linoleum} = 2.4\, MJ/kg$
- Ignition temperature, $T_{ig,Linoleum} = 346\,°C$ (The value varies between $318 - 374\,°C$, average is used)

With the given density, the total mass of linoleum in the compartment that the experiment was performed on can be calculated using,

$$m = \rho \cdot V \qquad (6.1)$$

where $\rho[kg/m^3]$ is the density of the material and $V[m^3]$ is the volume. This gives,

$$m_{linoleum,experiment} = 1200\, kg/m^3 \cdot 0.0025m \cdot 10.43m^2 = 31.29kg$$

For the model in PyroSim the mass is calculated to be,

$$m_{linoleum,PyroSim} = 1200\,kg/m^3 \cdot 0.0025m \cdot 10.54m^2 = 31.62kg$$

Because the deviation is only 1%, no further calculations have been carried out based on this difference. To get the result from the simulations to be as close to the result of the experiment as possible, the mass of linoleum in the experiment has been used for further calculations. By doing this the burning time of linoleum can be estimated for the experiment and implemented in the simulation.

The contributing fire load from the linoleum can then be estimated by multiplying the heat of combustion $\Delta H_c[MJ/kg]$ with the mass $m[kg]$ of the material,

$$q_f = \Delta H_c \cdot m \tag{6.2}$$

This gives,

$$q_{linoleum} = 16.4\,MJ/kg \cdot 31.29kg = 513.156MJ$$

Assuming the heat flux reaching the floor is less than the one used for walls and ceiling, it has been chosen to carry out the calculations for a heat flux of $30\,kW/m^2$. The mass loss rate can then be found using,

$$\dot{m}'' = \frac{\dot{Q}_F'' + \dot{Q}_E'' - \dot{Q}_L''}{L_V} \tag{6.3}$$

which gives,

$$\dot{m}'' = \frac{30\,kW/m^2}{2400\,kJ/kg} = 0.0125\,kg/m^2s$$

Based on this the time $t[s]$ it takes from the linoleum ignites until it has burned out, is estimated using the volume $V[m^3]$ of the material and the surface area $A_f[m^2]$,

$$t = \frac{m}{\dot{m}'' \cdot A_f} \tag{6.4}$$

For the given case this gives,

$$t = \frac{31.29kg}{0.0125\, kg/m^2 s \cdot 10.43m^2} = 240\ s = 4\ min$$

This is the time it would take from the ignition of the linoleum until the linoleum in the experiment has burnt out. To adjust the heat release rate in the model and make the results from the simulations as accurate as possible, the floor area of the PyroSim model, have been used for the calculation of heat release rate per unit floor area. This value was then implemented in the model,

$$HRRPUA = \frac{q_f}{t \cdot A_f} \tag{6.5}$$

$$HRRPUA = \frac{513.156MJ}{240s \cdot 10.54m^2} = 0.203\, MW/m^2 = 203\, kW/m^2$$

### 6.4.4 Screed (A-Plan)

This is a calcium sulphate based material that can be pumped into its location. It is self-equalizing, with a relatively high thermal conductivity, which makes it a suitable material for floors (especially those containing heating mechanisms).

As a result of the assumption made in Section 6.4.3, the thermal properties of this material has also been set as constant. This assumption is made for the screed in both floor and ceiling, as 100 mm cross-laminated timber and a 30 mm thick acoustic underlay protect the layer of screed in the ceiling, and the simulations are only planned to last for 10 minutes.

The following properties of the material have been gathered from the product data sheet (Aker Byggteknikk AS, 1997) and by contacting Aker Byggteknikk AS,

- Density, $\rho_{Screed\ (A-plan)} = 2200\ kg/m^3$
- Thermal conductivity, $\lambda_{Screed\ (A-plan)} = 1.87\ W/mK$
- Specific heat, $c_{concrete} = 900\ J/kgK$

As the manufacturer did not present any number for the specific heat, in person or in the product data sheet, an assumption has been made for this factor. As the screed in many ways shows similarities to concrete, the specific heat of concrete has been used.

### 6.4.5 Acoustic underlay

The assumption made in Section 6.4.3 affects this material as well. As the conducted simulations only take the first 10 minutes of the fire into account, the temperature rise in the floor will not be substantial. This leads to it not being necessary to adjust the thermal properties of the materials according to temperature.

In the ceiling this material is protected by 100 mm of cross-laminated timber, as a result of this it has been assumed that a rapid temperature rise in this material will not happen here either.

The thermal properties at 20°C for the acoustic underlay was found using the product data sheet (Paroc Group, 2015b) and contact with the manufacturer. They are,

- Density, $\rho_{Acoustic\ underlay} = 115\ kg/m^3$
- Thermal conductivity, $\lambda_{Acoustic\ underlay} = 0.035\ W/mK$
- Specific heat, $c_{Acoustic\ underlay} = 900\ J/kgK$

### 6.4.6 Rockwool between steel studs

For product information about Rockwool, the manufacturer was contacted. The following information was retrieved about the product, and has been implemented in the model,

- Density, $\rho_{Rockwool} = 30\,kg/m^3$
- Specific heat, $c_{Rockwool} = 1200\,J/kgK$

The thermal conductivity of the product is highly variable with temperature. The values presented in Table 6-7 were suggested from the manufacturer. The middle temperature is given by,

$$T_{middle} = \frac{T_{Unexposed\ side} + T_{Exposed\ side}}{2} \tag{6.6}$$

**Table 6-7 Thermal conductivity of Rockwool varying with temperature**

| $T_{middle}\ [°C]$ | **Thermal conductivity,** $\lambda[W/mK]$ |
|---|---|
| 50 | 0.046 |
| 100 | 0.059 |
| 150 | 0.077 |
| 200 | 0.101 |
| 250 | 0.129 |
| 300 | 0.161 |
| 350 | 0.199 |
| 400 | 0.242 |
| 450 | 0.289 |
| 500 | 0.342 |
| 550 | 0.399 |
| 600 | 0.461 |

As the steel studs do not take up a considerable amount of space compared to the Rockwool insulation, it has been assumed that the layer only consists of Rockwool in the computer model.

### 6.4.7 Suspended ceiling

In the report from the conducted experiment the only information given about the suspended ceiling is that it is of the type "A-Edge" and that the steel carrying it goes both parallel and perpendicular to the length of the hallway.

After contacting both the project leader of the conducted experiment and Rambøll Norge AS without finding specific information about the type of suspended ceiling implemented in the experiment, an assumption was made. *Glava Venus A* seems like it would fit the given situation. The manufacturer was contacted to find the following information, (the two properties presented is for the suspended ceiling boards, and not the entire system including steel)

- Density, $\rho_{Suspended\ Ceiling} = 72\ kg/m^3$
- Thermal conductivity, $\lambda_{Suspended\ Ceiling} = 0.033\ W/mK$

The manufacturer did not have information about the specific heat of *Glava Venus A*. As the core of it consists of an insulating material, it has been assumed that the specific heat will be close to the one of Rockwool,

- Specific heat, $c_{Rockwool} = 1200 J/kgK$

This might cause a small deviation from the one used in the experiment, but as the simulations main purpose is to study what is happening inside the compartment, it is assumed that this deviation will not affect the outcome greatly.

### 6.4.8 Window/glass

In the report of the conducted experiment, there is no information about the window other than the fact that it consists of three layers of glass. As the frame of the window is not mentioned, it has been assumed that the entire size of the window has thermal properties of argon and glass. It has also been assumed that the entire window area will contribute to the ventilation after breaking.

The following thermal properties have been implemented in the PyroSim model for the window. The numbers have been retrieved from NS-AN ISO 10456 (Norsk Standard, 2007). It is assumed that the window consists of three layers of 6 mm glass, with 13 mm gaps filled with argon in between. As the temperature rise in the glass/argon is relatively small prior to breaking, the thermal properties have been given as independent of the temperature for these materials.

*Glass:*

- Density, $\rho_{Glass} = 2500\, kg/m^3$
- Thermal conductivity, $\lambda_{Glass} = 1\, W/mK$
- Specific heat, $c_{Glass} = 750\, J/kgK$

*Argon:*

- Density, $\rho_{Argon} = 1.7\, kg/m^3$
- Thermal conductivity, $\lambda_{Argon} = 0.017\, W/mK$
- Specific heat, $c_{Argon} = 519\, J/kgK$

The transmission through the window is neglected.

## 6.5 Assumptions

In addition to limiting the model and inserting thermal properties, a number of assumptions have been made concerning other factors. This is due to it being impossible to graphically render every part of the case this analysis is based on. In the following subsections assumptions made for different factors not evolving thermal properties, are presented and explained.

### 6.5.1 Reaction

The following factors have been changed from what is originally used in PyroSim,

- CO Yield, $Y_{CO} = 0.005$
- Soot Yield, $Y_S = 0.015$

These changes have been done based on table 3-4.16 in the fourth edition of the SFPE Handbook (DiNenno and Drysdale, 2008)

In addition to this the composition of the fuel is changed to fit the burning of timber,

- Carbon atoms, 1.0
- Hydrogen atoms, 1.7
- Oxygen atoms, 0.74
- Nitrogen atoms, 0.002

### 6.5.2 Cavity between model and mesh

When drawing the model it does not fill the entire mesh. FDS takes all open space into account when simulating, so to eliminate unnecessary time spent on the simulation process most of these cavities have been filled with solid material. This can be done because these areas will not have any effect on what is happening inside the compartment.

A similar assumption has also been made when it comes to the bathroom. The results from the experiment conducted in December 2014 shows that the gypsum surrounding the bathroom will maintain its original position for the first 25 minutes (Hox, 2015). Since the carried out simulation in this case only lasts for 10 minutes, it has been assumed that the area behind these gypsum walls will not influence the fire. Based on this, the bathroom has been filled with the same type of solid material as the cavities outside.

When choosing the properties of the surface area of the solid material in the cavities it has been set to "Adiabatic". PyroSim describes this type of surface as,

> "A surface where there is no net heat transfer. FDS internally calculates the wall temperature to assure the sum of the radiative and convective heat flux is zero"

This means that it will not contribute to change in temperature, or other fire conditions.

### 6.5.3 Open mesh

Some areas outside the drawn model are of importance for the fire occurring inside. Where there are openings in the model, in this case window and both ends of hallway, the mesh needs to be "Open". The distance from the opening in the model out to the mesh also needs to be of a certain length. This length, from the opening in the model to the mesh, can be calculated using the hydraulic diameter $D_H\,[m]$,

$$D_H = \frac{4A_V}{P} \tag{6.7}$$

where $A_V\,[m^2]$ is the area of the opening, and $P[m]$ is the perimeter.

For the hallway openings this means that the distance from the opening to the mesh will have to be a minimum of,

$$D_{H,Hallway} = \frac{4(1.5 \cdot 2.8)}{2(1.5 + 2.8)} = 1.95m \approx 2m$$

The distance from the original window opening $(1.2m{\times}1.6m)$ to the mesh has to be at least,

$$D_{H,window(1.2m\times1.6m)} = \frac{4(1.2 \cdot 1.6)}{2(1.2 + 1.6)} = 1.37m \approx 1.4m$$

For the four windows that have been chosen to demonstrate a change in opening factor, the needed diameter from the window to the mesh is presented in Table 6-8,

**Table 6-8 Hydraulic diameter for varying window size**

| | Window 1 $(0.7m \times 1.6m)$ | Window 2 $(1.0m \times 1.6m)$ | Window 3 $(1.4m \times 1.6m)$ | Window 4 $(1.7m \times 1.6m)$ |
|---|---|---|---|---|
| $D_H$ $[m]$ | 1 | 1.2 | 1.5 | 1.7 |

### 6.5.4 Door sill

To make sure the water from the sprinkling system does not enter the compartment, the floor in the hallway has been lowered 10 cm compared to the floor in the compartment. The reason why this is done is because of the high heat capacity of water. By letting water infiltrate the compartment, a lot of heat from the fire would be lost to heating this water.

### 6.5.5 Breakage of the window/glass

In the conducted experiment the third glass of the three-layered window breaks after 5 minutes and 45 seconds, when a temperature of 770 °C is reached inside the compartment.
It is impossible to achieve an identical temperature-time curve for the simulations as the one retrieved from the experiment. The one from the simulation will be an approximation to real life. As a result of this it has been chosen to use the time until the window breaks, when programming the "disappearance" of the window in the PyroSim model. By doing this the opening factor will change at the exact same time for all five simulations, even though the temperature in the room might deviate some.

As mentioned in Section 4.5.5, windows usually break as a result of temperature difference between the edge of the glass and the centre. The temperature difference creates stress in the glass, which result in collapse. How long it takes for the window to break depends on a lot of things, the size of it being one of them. This factor has been chosen to disregard in the conducted simulations.

When varying the size of the window the same time settings have been used for when it will break. This will cause some deviations from what would happen in real life. As a positive, the same amount of time is simulated with the "new" opening factor for all models.

### 6.5.6 Suspended ceiling falls down

The suspended ceiling fell down after 8 minutes and 30 seconds in the conducted experiment, when a temperature of 891 °C was reached inside the compartment.

To make the ventilation conditions as accurate as possible, it has been chosen to use the time aspect, and not the temperature, here as well. The suspended ceiling is programmed to "disappear" when 510 seconds of the simulations have gone by.

### 6.5.7 Thermocouples

Three thermocouples have been implemented in the model. The positioning of them can be seen in Figure 6-7. As the report from the experiment conducted in December 2014 (Hox, 2015) do not give exact measures of where the thermocouples where positioned, the ones in the model might not be at the exact same place. The positioning in the model has been done based on the illustrations in the report from the experiment, to try and achieve a positioning as close to reality as possible.

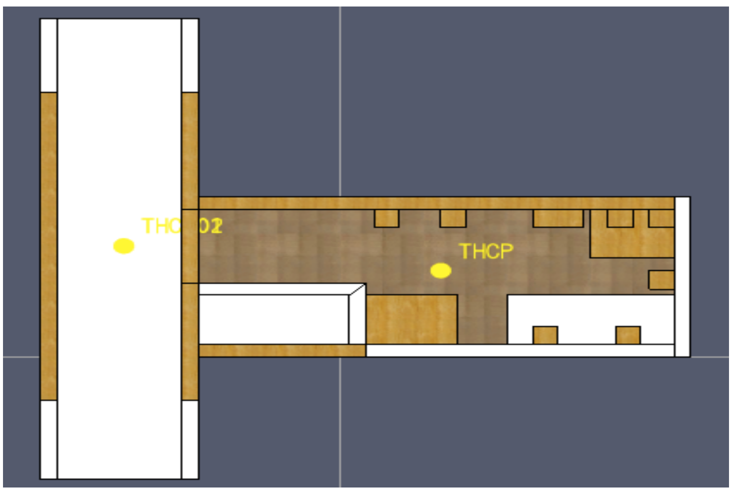



**Figure 6-7 Positioning of thermocouples**

One thermocouple is placed in the middle of the compartment, 2.7 meters above the floor. The two others are localized outside the door opening, measuring the temperature rise over and under the suspended ceiling in the hallway.

### 6.5.8 Sprinklers

Four nozzles have been added to the model. The positioning of these are approximately the same as in the experiment carried out in December 2014, this is to make the results as equal as possible. Figure 6-8 shows the positioning of the four nozzles; they are positioned over/under the suspended ceiling, which is why the model only shows two.

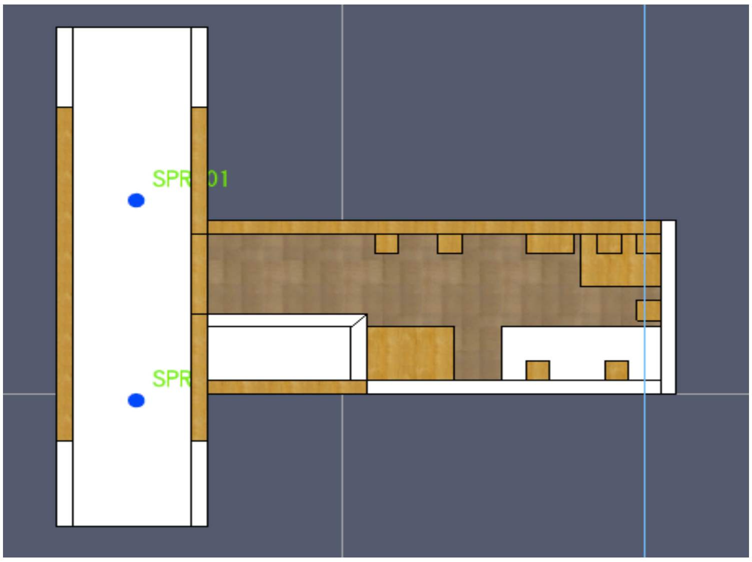



**Figure 6-8 Positioning of sprinkling system/nozzles**

As the PyroSim model is based on the second test that was carried out in the experiment, and the sprinkling system inside the compartment was not used in this test, these two nozzles have not been included in the model.

The sprinkling system is built according to NS-EN 12845[5] OH1 sprinkler (Norsk Standard, 2009a). The specifications of the system/nozzles are as follows:

- $k = 5.5$
- $k - factor : 79\, l/\text{min} \cdot bar^{1/2}$
- Distance between nozzles in the hallway is 3m
- Operating pressure: 0.35bar (Minimum criteria according to NS-EN 12845)
- This gives flow rate, $79 \cdot \sqrt{0.35} = 46.737\, l/\text{min}$

### 6.5.9 Variable fire load

In the experiment conducted a fixed amount of wooden elements in combination with some other objects were placed in the compartment. The amount was calculated by SP Fire Research to be the equivalent to the variable fire load of 8735MJ estimated by Rambøll Norge AS. The following elements was added the compartment:

- Heptane burner
- 20 Wooden cribs
- 12 Euro pallets
- Wooden desk
- Wooden bed
- Mattress

The positioning of the variable fire load in the PyroSim model is done using photos from the experiment. As the distances between stacks of wooden cribs, Euro pallets, bed etc. is not given in the report from the experiment, the result is not a hundred percent accurate. In addition to this uncertainty, FDS do not calculate turbulent burning in narrow clearances very well. Based on this, and a wish to reduce the time needed for simulations, it was chosen to position the wooden cribs and stack of Euro pallets in contact with the walls instead of 10 cm from them. The deviation in surface area that is caused by positioning everything in contact with the walls has been taken into account when the mass loss rate of wood has been adjusted for the different elements.

Another factor the mass loss rate has been adjusted for is the cavities in the cribs and pallets. In the model all cribs and pallets have been drawn as massive blocks. The adjustment is done using the ratio between surface area in real life and the PyroSim model.

The mass loss rate is calculated using,

$$\dot{m} = \dot{m}'' \cdot A \tag{6.8}$$

where $\dot{m}''[kg/m^2s]$ is the rate of mass loss per square meter, and $A[m^2]$ is the surface area of the material.

As the burning surface area is much smaller for a massive block in contact with a wall compared to a stack of cribs/pallets standing in the open, $\dot{m}''$ must be increased so that the resulting $\dot{m}$ is the same for the massive block and the cribs/pallets. This has been done in the following subsections.

Even though an adjustment of the mass loss rate has been carried out based on the ratio between real and fictional surface area, there will still be some degree of deviation between the two.  Both Euro pallets and wooden cribs consist of small planks, which present a different thermal thickness than the solid blocks. In addition to this the cavity in the pallets and cribs will cause back-radiation, this is not the case for the blocks and the mass loss rate has not been adjusted for this.

#### *6.5.9.1 Euro pallets*

The measurements of a standard Euro pallet are presented in Figure 6-9.

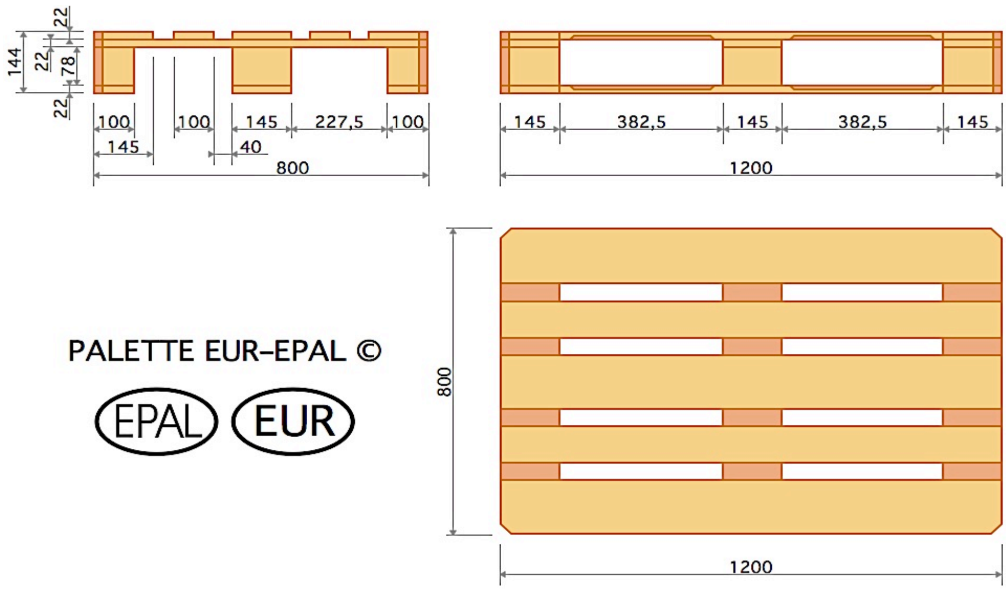



**Figure 6-9 Measurements of a standard Euro pallet**

The experiment included 12 Euro pallets in one stack as part of the variable fire load. A stack of 12 pallets has a total height of 1.728 m and a surface area of 47.56 m$^2$. To fit the mesh in PyroSim the stack was modelled as a massive block with the following measurements,

| | |
|---|---|
| Height | 1.7 m |
| Width | 0.8 m |
| Length | 1.2 m |

The surface area of this block that will contribute to the fire is,

$$A = (1.7 \cdot 0.8) + (1.7 \cdot 1.2) + (1.2 \cdot 0.8) = 4.36m^2$$

The reason why only half of the massive block's total surface area is taken into account is because the rest is in contact with either walls or floor of the compartment.

The mass loss rate of the original stack of pallets is,

$$\dot{m} = 8.6\, g/m^2 s \cdot 47.56 m^2 = 409\, g/s$$

An estimation of the mass loss rate of the exposed parts of the solid block drawn in the model can then be made using Equation (6.8),

$$\dot{m}'' = \frac{\dot{m}}{A} = \frac{409\, g/s}{4.36 m^2} = 93.8\, g/m^2 s$$

#### *6.5.9.2 Wooden crib*

The wooden cribs used in the experiment were made according to FM 5560 G. They were dimensioned to be approximately $305mm \times 305mm \times 305mm$, and met the criteria of both weight and moisture content presented in the Approval Standard (FM Approvals, 2012).

The Standard says that the wooden cribs should consist of four alternate layers of trade side $1.5in \times 1.5in$ lumber. As this was not possible to get a hold of, three alternate layers of trade side $2.0in \times 2.0in$ lumber were used for the experiment instead. Figure 6-10 shows the wooden cribs used in the experiment.

**Figure 6-10 Wooden crib, Photo: Hege Stusvik**

In the drawn model in PyroSim the same assumption has been made for the cribs as for the Euro pallets. To get the mass loss rate as realistic as possible, the ratios between the surface area of the block drawn in the model, and the actual wooden crib/stacks of cribs have been calculated. The blocks drawn in the model are $0.3m \times 0.3m \times 0.3m$, this gives a surface area of,

$$A = 6(0.3 \cdot 0.3) = 0.54m^2$$

This is the total surface area (all six sides of the drawn massive block). As the blocks in the experiment in some cases was hung on the wall, or placed on top of each other, a small variation in surface area occurs depending on where the blocks are positioned.

The total surface area of the actual wooden crib is $1.20m^2$. Depending on where in the model it is localized and what is next to it, this value will vary in the same way the area of the massive block varies.

#### *6.5.9.3 Heptane burner*

Figure 6-11 shows how the heptane burner was positioned in the experiment conducted, and the naturally assumed way of drawing this in PyroSim. However, as the clearance underneath the desk is relatively small the burner has been drawn as a "Vent" with the function of a burner in the model instead. By doing this the burner can be positioned in the same level as the floor and the clearance is increased. An illustration of this is shown in Figure 6-12.

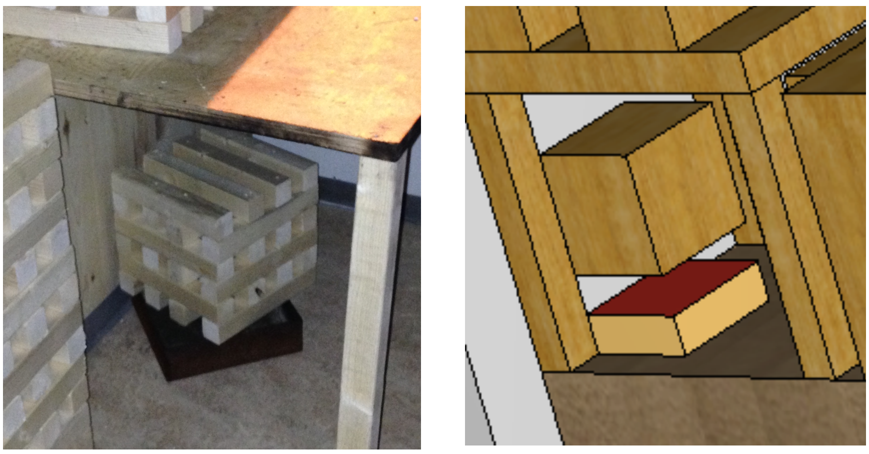


**Figure 6-11 Positioning of heptane burner in experiment and heptane burner drawn as "Block Obstruction" in PyroSim**

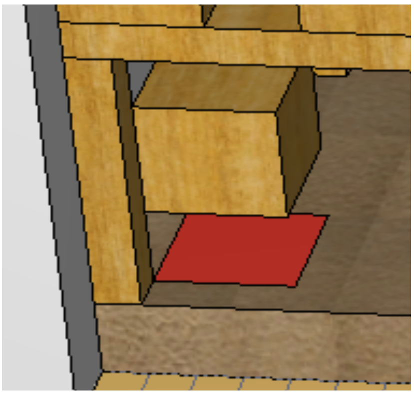


**Figure 6-12 Heptane burner drawn with "Vent" function in PyroSim**

This adjustment helps to create a more accurate burning behaviour in the simulations, as the original method makes the clearance too small for FDS to make a good estimation. Even though this improves the situation the clearance is still small, which may cause some errors to the result.

Material and burning properties of heptane can be found in the 3rd edition of "An Introduction to Fire Dynamics" (Drysdale, 2011),

- Mass loss rate (large pool fires), $\dot{m}'' = 0.101\, kg/m^2 s$
- Density, $\rho = 675\, kg/m^3 = 0.675\, kg/L$
- Heat of combustion, $\Delta H_c = 44.66\, MJ/kg$
- Heat of gasification, $L_V = 0.318\, MJ/kg$

Based on this the amount of heptane burning in the experiment can be converted from five litres to kilograms,

$$m_{Heptane} = 0.675\, kg/L \cdot 5L = 3.375 kg$$

Conducted experiments on pool fires by Zabetakis and Burgees led to them recommending that the following equation is used to estimate the burning rate of the fuel (Zabetakis and Burgess, 1961),

$$\dot{m}'' = \dot{m}''_{\infty}\left(1 - e^{-k\beta D}\right) \quad (6.9)$$

For this case the mass loss rate can then be found by estimating the diameter of a pool fire with the same surface area as the heptane burner in the PyroSim model, and inserting this and values proposed by Babrauskas for $\dot{m}''_{\infty}$ and $k\beta$ (Babrauskas, 1983) in Equation (6.9),

$$D = 2\sqrt{\frac{A}{\pi}} = 2\sqrt{\frac{0.09}{\pi}} = 0.34m$$

$$\dot{m}'' = 0.101(1 - e^{-1.1 \cdot 0.34}) = 0.032\, kg/m^2s$$

The time it takes for the fuel to burn out is then,

$$t = \frac{3.375kg}{0.09m^2 \cdot 0.032\, kg/m^2s} = 1172s = 19.5min$$

To make sure that the burning behaviour of the burner in the model does not deviate too much from the one that occurs in the experiment, with a heptane burner a bit bigger ($A = 0.1m^2$), the mass loss rate and time it takes before the fuel is burnt out for the burner in the experiment has been estimated too,

$$D = 2\sqrt{\frac{A}{\pi}} = 2\sqrt{\frac{0.1}{\pi}} = 0.36m$$

$$\dot{m}'' = 0.101(1 - e^{-1.1 \cdot 0.36}) = 0.033\, kg/m^2s$$

$$t = \frac{3.375kg}{0.1m^2 \cdot 0.033\, kg/m^2s} = 1023s = 17.1\, min$$

The deviation between the two rates of mass loss is only 3%. As both burners will burn for a much longer period of time than what is simulated, the time does not affect the choice in what number to implement in the simulation. The remaining calculations are based on the mass loss rate of the burner in the simulation.

Total fire load from the heptane burner is then found using Equation (6.2),

$$q_{heptane} = 44.66\,MJ/kg \cdot 3.375kg = 150.7MJ$$

This gives a heat release rate of,

$$HRRPUA = \frac{150.7MJ}{1172s \cdot 0.09m^2} = 1.429\,MJ/m^2s = 1429\,kW/m^2$$

#### *6.5.9.4 Bed*

The bed is assumed to be $0.8m\times 2.0m$. Both legs and the main part of the bed have been given the same thermal properties as the wall with exposed wooden surface, $\dot{m}'' = 0.0086\,kg/m^2s$.

The mattress used in the experiment is in accordance with IMO Res 265(84) (International Maritime Organization, 2008). It should satisfy the following when tested according to ISO STANDARD 5660: Cone calorimeter test with an irradiance of $35\,kW/m^2$,

Sample size, $0.8m\times 2.0m\times 0.05m$:

| Test results | Mattress |
|---|---|
| Time to ignition $[s]$ | 2-6 |
| 3 min average HRR, $q_{180}$ $[kW/m^2]$ | 270 ± 50 |
| Minimum heat of combustion $[MJ/kg]$ | 25 |
| Total heat release $[MJ/m^2]$ | 50 ± 12 |

Based on this it has been chosen to use a heat release rate of $270\,kW/m^2$ in the model.

Polyether, which is the main material of the mattress, has an ignition temperature of $310\ ℃$ (Lokensgard and Richardson, 2010). It has been assumed that the thin layer of cotton does not influence this ignition temperature significantly.

#### *6.5.9.5 Desk*

The desk is modelled to be $1.0m\times 0.8m$. The same has been assumed here as for the bed, that the thermal properties of both legs and the desk plate are the same as for the wooden wall, $\dot{m}'' = 0.0086\, kg/m^2s$.

As mentioned when discussing the heptane burner, the clearance under the desk is small. This might affect the burning of the desk as FDS do not estimate turbulent burning in narrow clearances very well. As there is not much that can be done about this, it might be a possible cause of a small error in the model.

# 7 Results

The data collected in the experiment conducted on the Moholt 50|50 compartment in December 2014 (Hox, 2015) creates the curve for temperature development presented in Figure 6-6. The aim of the analysis conducted in this thesis was to create a model using PyroSim that would present similar fire behaviour. The results from the simulations carried out in Chapter 6 are presented in the following subsections. The deviations from the experimental data are evident.

With this model as a starting point, the size of the window was varied to determine the effect of change in opening factor. Both temperature and heat release rate was measured

As the results did not turn out as the ones from the experiment, an additional simulation was run on the original window size, to gather information about the oxygen concentration in the room and oxygen flow through openings.

There were no other differences to the models other than the change of size in window.

## 7.1 Original window (1.2m x 1.6m)

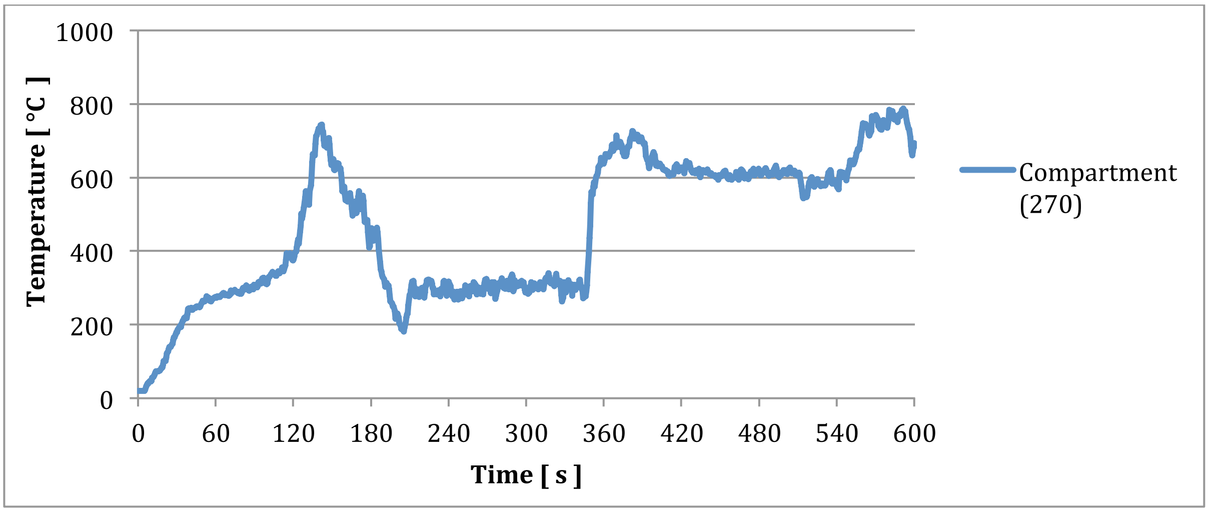



**Figure 7-1 Temperature – time curve. 270 cm above the floor in the compartment. Window: 1.2m x 1.6m**

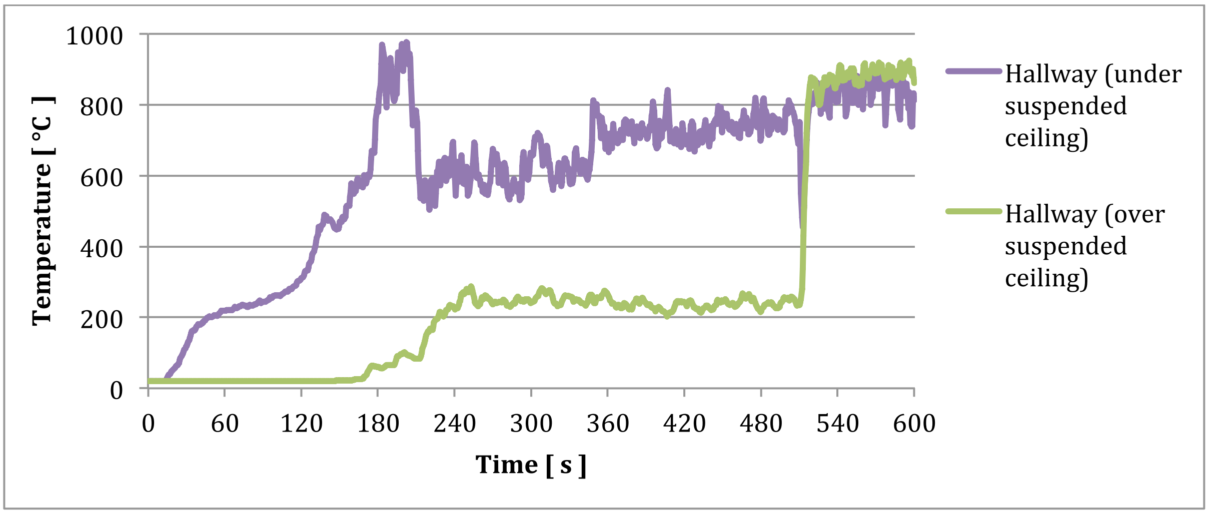



**Figure 7-2 Temperature – time curve. Over and under suspended ceiling in hallway. Window: 1.2m x 1.6m**

### 7.1.1 Oxygen concentration and fire behaviour when the window breaks

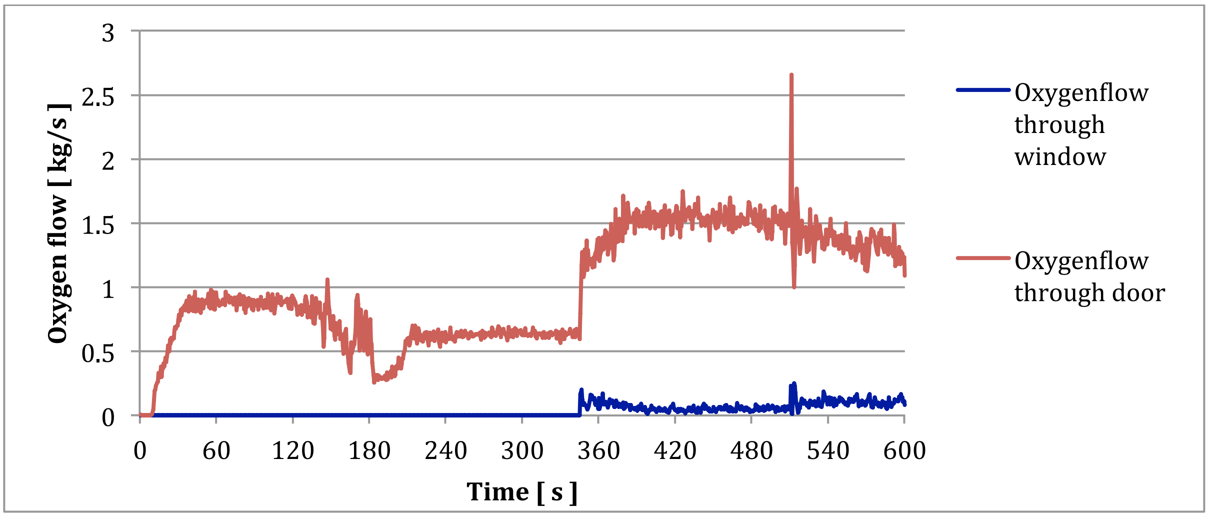



**Figure 7-3 Oxygen flow through window/door during the first ten minutes of the simulated fire. Window: 1.2m x 1.6m**

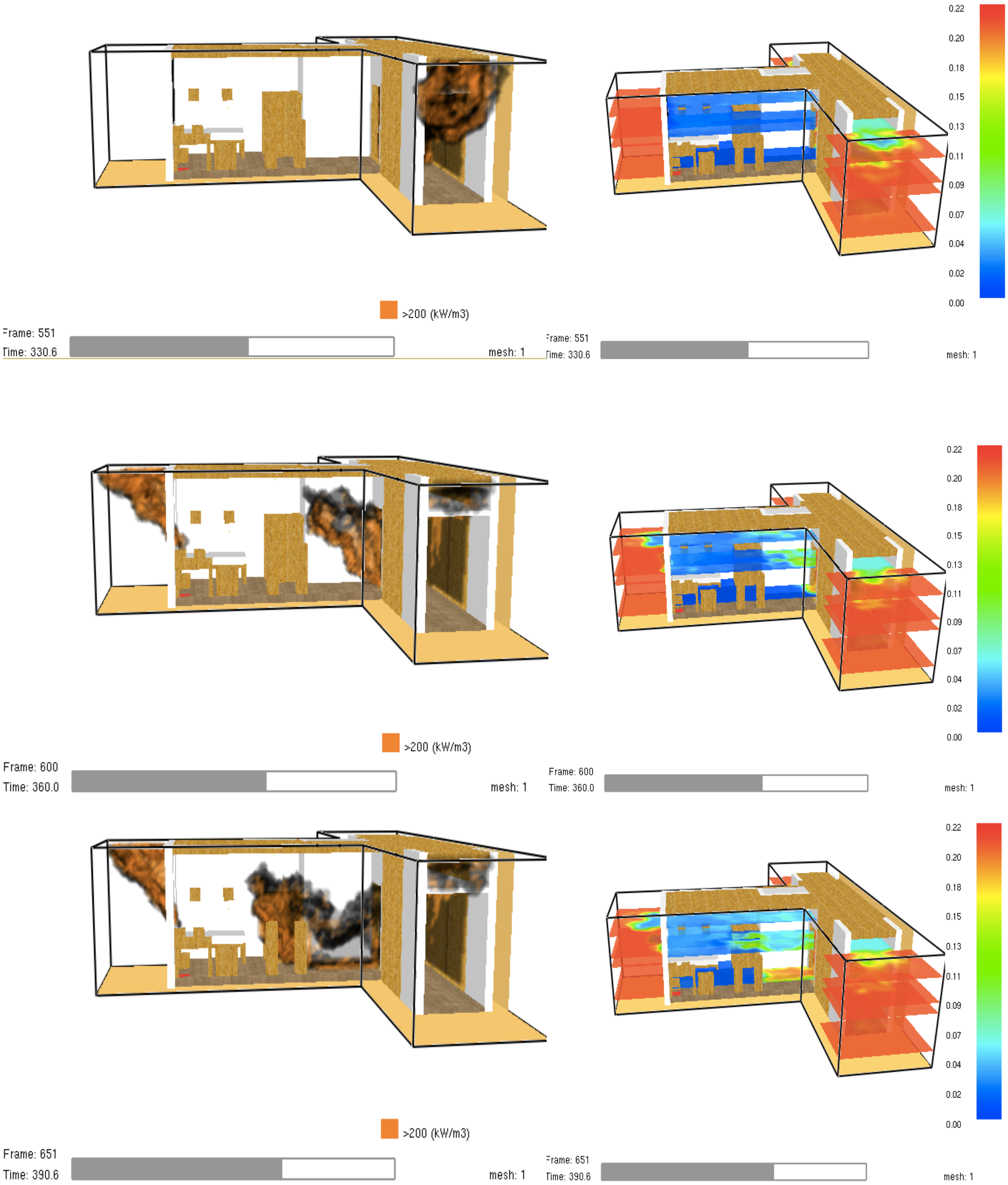



**Figure 7-4 The simulated fire behaviour 15 seconds prior to, 15 seconds after and 45 seconds after the window breaks, and the oxygen concentration in the compartment at the same time intervals. Window size: 1.2m x 1.6m.**

## 7.2 Comparison of results from varying size of window

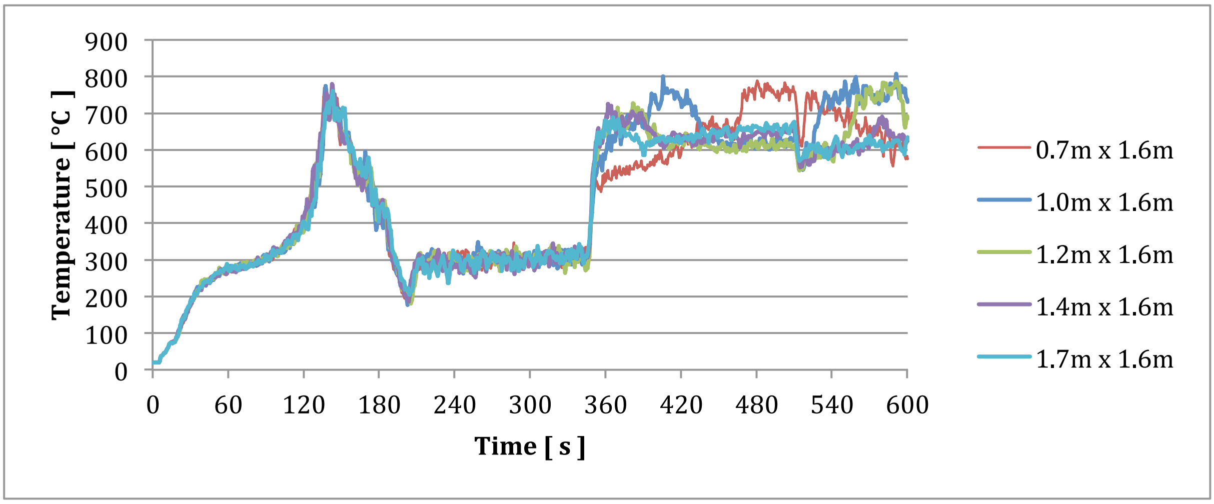



**Figure 7-5 Temperature – time curves for the first ten minutes of the fire simulated in the compartment modelled.**

As can be seen from Figure 7-5, there is no significant variation in the result before the window breaks, 345 seconds into the fire. Based on this the following presented comparisons only include the five last minutes of the simulated fire.

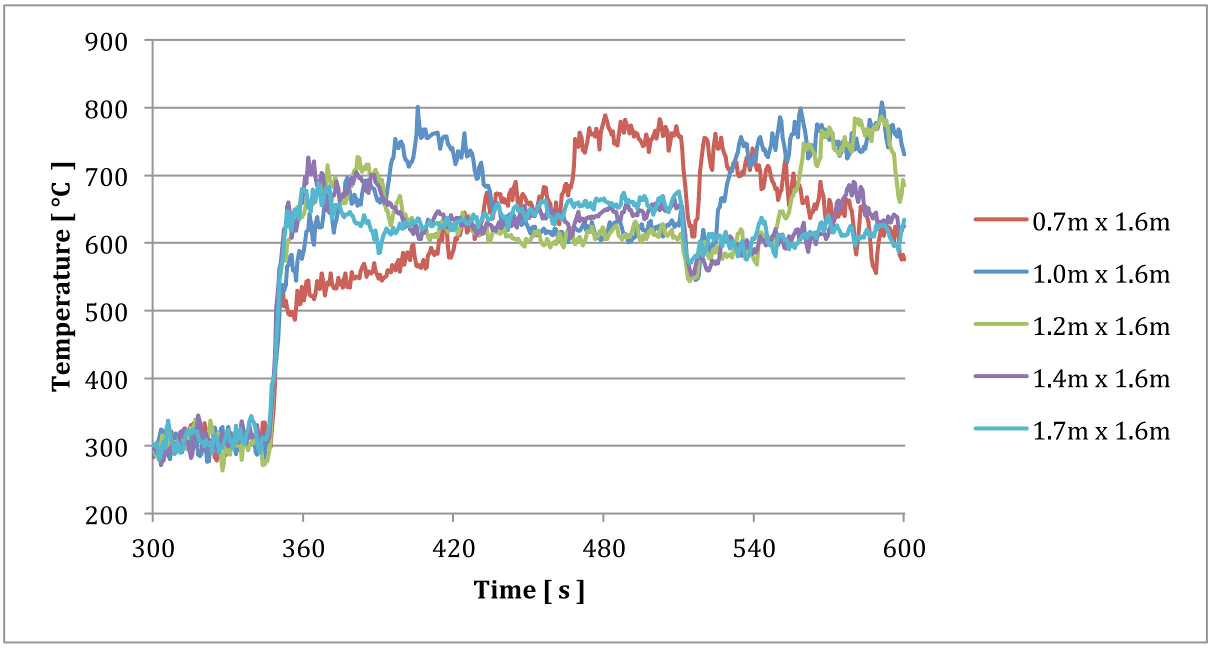



**Figure 7-6 Temperature – time curves after the window breaks for the fire simulated in the compartment modelled.**

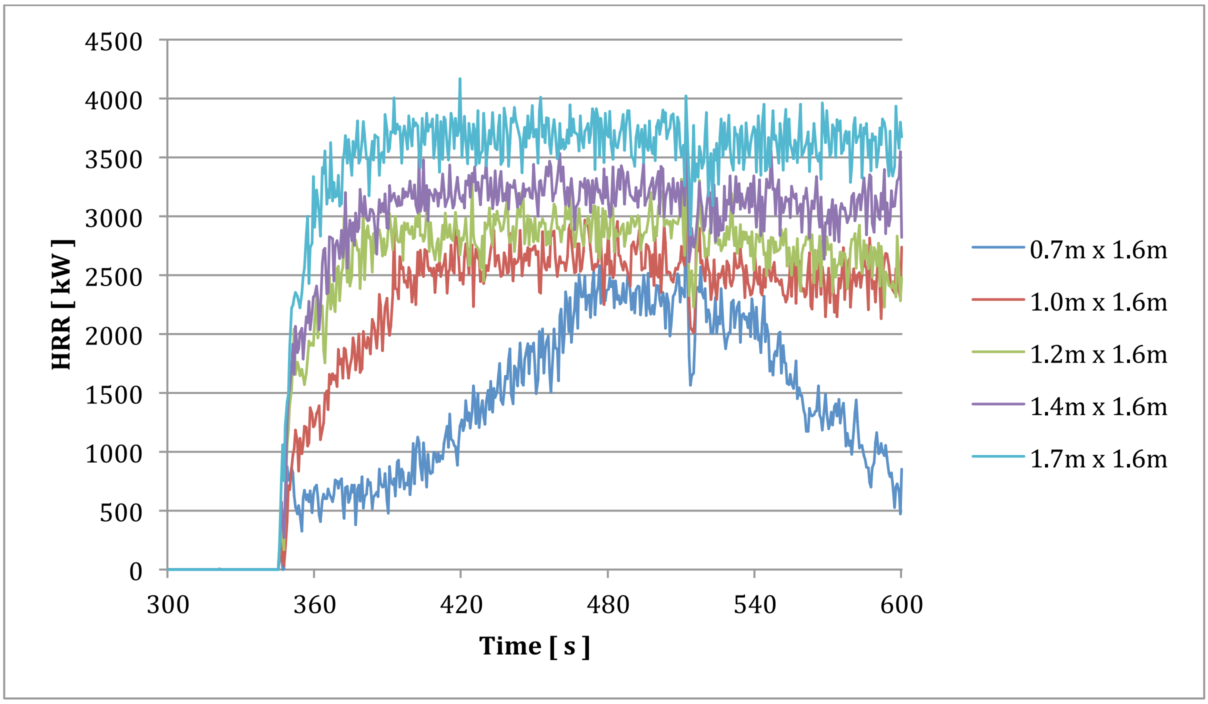



**Figure 7-7 Heat release rate – time curves after the window breaks for the fire simulated in the compartment modelled.**

# 8 Discussion

There is a lot to consider when it comes to fire safety in high-rise timber buildings. In some cases the pre-accepted solutions given in the Norwegian technical regulations guideline can be used, in many cases they cannot. Many factors influence the fire safety of timber buildings and need to be considered when fire safety design is conducted. The following subsections will discuss the questions presented in the introduction, based on the information gathered in this report.

## 8.1 In what areas do high-rise timber buildings deviate from the pre-accepted solutions given for a fire class 3, or higher classified construction in the Norwegian technical regulations guideline? What are the causes of these deviations?

When implementing timber in the load-bearing structure of high-rise buildings, the following deviations occur from the Norwegian technical regulations guideline:

### 8.1.1 §11-3 Fire classes:

It is likely that implementing large amounts of cross-laminated and glue-laminated timber in a building will contribute to the fire load increasing with more than $400\,MJ/m^2$. It is however difficult to determine the exact amount that the structure of a building will contribute. This will be further discussed in Section 8.2. If the building is classified as a fire class 4 building, approved calculation methods or performance based alternative design is needed to assure the fire safety of the building. To avoid this and use the pre-accepted solutions, measures can be applied so that the building is classified according to fire class 3. This can be done using fire protective claddings or extensive active fire protection systems. By implementing these measures some of the pre-accepted solutions can still be used, which saves a lot of time in the design phase of a building.

### 8.1.2 §11-4 Loadbearing capacity and stability:

If the building meets the criteria of fire class 3 constructions, there is no reason why the pre-accepted solutions should not be implemented. §11-4 does however present criteria that are not possible to meet when utilizing timber. The reason for this is timbers reaction to fire. As it is a combustible material, and the pre-accepted solution demands incombustible ones, other methods need to be utilized to assure the fire safety of the building according to this paragraph.

### 8.1.3 §11-7 Fire sectioning and §11-8 Fire cells:

The same problem is met here as for §11-4. As the pre-accepted solutions demand incombustible materials, timber cannot be utilized

### 8.1.4 §11-9 Material properties in a fire situation:

If looking at this paragraph by it self, the pre-accepted solutions do accept timber as surface material of walls and ceiling in fire cells not exceeding $200m^2$. For larger fire cells or fire cells being part of escape routes, timber does not satisfy the pre-accepted solutions.

Even though this paragraph allows timber as surface material for some walls/ceiling the contributing fire load from this needs to be considered according to §11-3 before blindly implementing cross-laminated timber surfaces.

### 8.1.5 Summary

All of these deviations are caused by timber being a combustible material. To be able to utilize pre-accepted solutions when building high-rise timber buildings, the Norwegian technical regulation needs to be changed accordingly. Until this happens, approved calculation methods and performance based alternative design can be used to document the fire safety of this type of building. The application area and limitations of some of the most common methods for documenting fire safety is further discussed in Section 8.2 and 8.4.

## 8.2 How does the use of cross-laminated timber in the construction of high-rise buildings affect fire development and the documentation of fire safety?

The contribution to the fire load from exposed timber surfaces is considered to be very important when documenting fire safety for high-rise timber buildings. As presented in Section 8.1, if the contribution is higher than $400\,MJ/m^2$ the fire safety of the entire building needs to be documented using approved calculation methods or performance based alternative design. This is a very time-consuming process compared to using pre-accepted solutions.

The contribution to the fire load from cross-laminated timber is also a highly challenging element to determine. As is presented in Section 8.3, there are a lot of factors affecting the burning rate of wood.

### 8.2.1 Documenting fire safety in a high-rise building with exposed timber

When the pre-accepted solutions cannot be used, the Norwegian technical regulation says to carry out analysis and calculations according to "the complete duration of a fire". It is not specified what this means exactly, but the Norwegian technical regulations guideline further refers you to calculations using parametric fire curves.

NS-EN 1995-1-2 Annex A presents one method for estimating parametric temperature-time curves when the effect of charring of wood needs to be included in the fire load. The carried out calculations in Section 4.2.3 are based on this. The calculations were conducted for a compartment with all walls, and ceiling, consisting of cross-laminated timber.

In these calculations the limits of the methods application area was exceeded after the first iteration. As pointed out in the discussion of these results, in Section 4.2.4, the validity of the method could be increased by conducting more experiments (Hopkin et al., 2011). These have however not yet been carried out, and limits the range of application for the method. Regardless of this the results showed a contribution to the fire load much higher than accepted for a fire class 3 construction in the Norwegian technical regulations guideline.

All the other calculation methods presented by NS-EN 1995-1-2 are based on standard fire exposure; this is also the case for most of the tests carried out on the behaviour of timber in fire conditions. To be able to determine the severity of a fire, a correlation between standard and parametric fire curves are needed. There are several methods for doing this, however most of these have been developed for incombustible materials like steel and concrete. Two methods that can be used for wooden elements are; *Equal area concept* and *Maximum temperature concept*, these are further explained in Section 4.1 in this report.

An alternative to the approved calculation methods is performance based alternative design. In many cases this involves utilizing computer programs developed for simulating fires. There are many uncertainties that need to be taken into account when using these types of programs; these will be further discussed in Section 8.4.

### 8.2.2 Fire safety measures

An alternative to carrying out complicated and time-consuming calculations is to increase the fire safety measures so that the building meets the criteria of a fire class 3 construction in §11-3 in the Norwegian technical regulations guideline. Implementing fire protection claddings is the easiest way of doing this. Alternatively an increase in active fire safety systems can be used to reach a satisfying level of fire safety.

With the methods currently available for determining fire safety in high-rise timber buildings, additional fire protection claddings and active fire safety systems seem inevitable.

## 8.3 What factors affect the development and spread of fire, and what can be done to enhance the fire safety when timber is implemented in the load-bearing construction of high-rise buildings?

The rate of which a fire will develop and spread in a timber building is strongly affected by the charring rate. This is further dependent on material factors and external factors; these have been presented in Section 4.3.

In this report the main focus have been on external factors, as the fire safety engineer can influence these during the design phase of a building. As a result of this, information has been gathered about thermal exposure/heat flux and opening factor. The third external factor, oxygen concentration, depends on the ventilation of the room.

### 8.3.1 Thermal exposure/heat flux

Thermal exposure/heat flux influences the fire development in many ways. The most significant ones being the ignition temperature, time to ignition and burning rate of different materials.

#### *8.3.1.1 Ignition temperature and time to ignition*

Ignition temperature and time to ignition is dependent on a lot of factors, heat flux being one of them. Research on this topic presented in Section 4.4.2 shows that with increasing heat flux the ignition temperature increases and the time to ignition decreases.

Results gathered from experiments show that the ignition temperature of wood ranges from $250 - 365°C$ for piloted ignition and from $250 - 500°C$ for autoignition (Babrauskas, 2002). Based on these results it is assumed that the average ignition temperature of softwood is approximately $350°C$.

The research gathered for time to ignition in this report shows that the variation is not substantial for heat fluxes ranging from $30 - 50\, kW/m^2$. However, for a heat flux of $20\, kW/m^2$ the time to ignition is 4-30 times longer than for one of $30\, kW/m^2$, which is a significant difference.

#### *8.3.1.2 Burning-/Mass loss-/Heat release rate*

Based on the information presented on heat release-/mass loss rate in Section 4.4.3, it is clear that these factors are highly dependant on the heat flux. For wood, both heat release- and mass loss rate increase with increasing heat flux ($\geq 30\, kW/m^2$).

For heat fluxes ranging from $20-50\,kW/m^2$ results from conducted experiments show that the trend of the correlation between heat release-/mass loss rate and the heat flux wood is exposed to can be described as a parabolic relationship. Figure 4-12 and Figure 4-13 illustrates this.

#### *8.3.1.3 How can a fire safety engineer affect the heat flux?*

The highest heat flux in a compartment is found in the upper part of the room, the layer of gas that gathers here causes this. Figure 4-14, Figure 4-15, Figure 4-16 and Figure 4-17 clearly illustrates the effect the compartment contributes, when it comes to increasing the heat flux, compared to a fire burning by itself.

As the compartment plays such a big role in the resulting heat flux, there is more than one possible way for the fire engineer to affect the occurring thermal exposure/heat flux. Any change in room geometry, ventilation or thermal properties of the enclosure will affect the layer of gas in the upper part of the compartment, and by doing this the heat flux is also affected.

### 8.3.2 Opening factor

Most compartment fires are ventilation controlled. As opposed to fuel controlled fires where the burning rate is controlled by the surface and type of material (fuel), a ventilation controlled fire is dependent on the design of ventilation openings. The openings determine how much warm gas can escape the compartment and how much air gets in.

Section 4.5.4 presents some of the research carried out in this field. It has been found that an increase in opening factor will cause an increase of the charring rate. This has been demonstrated by showing the effect the opening factor has on the charring depth when estimating parametric temperature-time curves. Figure 4-21 illustrates this. The figure shows a clear trend of the charring depth increasing over a period of time for different opening factors.

#### *8.3.2.1 How can a fire safety engineer affect the opening factor?*

Reducing window and door openings will reduce the opening factor. By doing this the oxygen concentration in the fire compartment at hand will be less than for the same compartment with bigger openings. The effect of this is a fire burning slower, self extinguishing or moving to a different location where it can get the oxygen needed to continue burning.
To better understand the effect variation in opening factors has on fire development, an analysis was carried out using PyroSim and FDS. The results are presented in Chapter 7; a discussion of them is given in the next subsection.

### 8.3.3 Discussion of results from the carried out analysis

As briefly mentioned in Chapter 7, the results obtained from the simulations do not correspond with the data measured when the experiment was conducted on the same compartment. The reasons for this can be numerous, as the model is strongly based on assumptions. Making simulations that correspond with data retrieved from experiments has been proven to be highly challenging, both in this analysis and by research (see Section 8.4).

#### *8.3.3.1 Why does the result obtained from simulations deviate from the data measured in the experiment?*

It is clear from the figures presented in Section 7.1 that the fire simulated grows too rapidly in the early stage compared to the data obtained from the experiment conducted on the same compartment. As a result of this the temperature in the compartment reaches a peak after 140 seconds and then stabilizes at a relatively low temperature until the window breaks. This is illustrated in Figure 7-1.

As can be seen from Figure 7-4, the oxygen concentration in the room is close to zero before the window breaks. As there is no oxygen in the compartment, the fire moves into the hallway where there is sufficient ventilation to keep burning. This is also supported by the data from the thermocouple underneath the suspended ceiling in the hallway. The temperature here is very high compared to inside the compartment, which shows that the volatiles find the needed oxygen here and combustion occurs.

The cause of the deviation from the experimental data can be many; some of them might be,

- The heat flux that the assumptions are based on is too high
- The mass loss rate of wood might have been overestimated in the model, this would cause the fuel to burn faster and consume more oxygen faster.
- The mesh resolution can cause errors
- The adjustments made for mass loss rate of Euro pallets and wooden cribs might not be good enough, the positioning of these might effect the results too
- The sprinkling system might deviate some from the one in the experiment
- Thermal properties of materials might deviate some from the ones in the experiment as manufacturers has been assumed, and not given

Even though the results obtained from the simulations do not correspond with the experimental data, there are still some interesting factors to be discussed.

All five simulations show a relatively similar behaviour in the first 345 seconds. This is illustrated in Figure 7-5. The small deviations that occur are caused by the change in surface area of the window. The thermal properties of the glass, argon and gypsum will effect the temperature development slightly as the size of the window/gypsum surface is varied.

After the window breaks/is programmed to disappear the ventilation increases, this can be seen from both Figure 7-3 and Figure 7-4. Figure 7-4 clearly illustrated that there is no oxygen left in the compartment prior to the window breaking, all slices are dark blue indicating very little/no oxygen. When the window breaks the colours change slightly, as the window contributes with a new opening and more ventilation.

As the first 345 seconds are close to identical for all of the curves, the following discussion will be based on the events that happen after the window breaks.

#### *8.3.3.2 When and after the window breaks*

The "video" that is made when simulations are carried out shows the course of events occurring as the window breaks. Figure 7-4 shows the fire development and oxygen concentration 15 seconds prior to the window breaks, 15 seconds after and 45 seconds after.

The fire development changes dramatically when the window breaks. The compartment gets additional ventilation and the volatiles starts burning inside the compartment again instead of only in the hallway.

#### *8.3.3.3 Temperature development*

Figure 7-6 illustrates the temperature development in the compartment after the window breaks. The different curves each present a specific window size. The figure shows that after the window breaks the temperature rise in the compartment will be faster for a bigger window compared to a smaller one.

The two smaller windows stand out from the rest. While the three bigger ones cause a relatively similar temperature development in the compartment, the curves of the two smaller ones indicates a slower temperature rise. The reason for this is most likely the fact that the smaller windows do not contribute with a big enough oxygen supply for a fast relocation of the fire.

#### *8.3.3.4 Heat Release Rate (HRR)*

Figure 7-7 illustrates the difference in HRR in the compartment for varying size of windows. The correlation between opening factor and increasing HRR is evident.

Table 8-1 present the HRR measured (after it stabilizes) in the simulation for varying opening factor after the window breaks, and the rate of heat release estimated using Equation (3.12) for comparison. Originally Equation (3.12) does only consider one opening with the height $H_V$, as there is two openings in the compartment conducted analysis on, the weighted average height $\left(h_{eq}\right)$ have been utilized for the ventilation factor. This might cause a small error.

**Table 8-1 Comparison of HRR obtained through simulations for varying window sizes, and HRR estimated by using the equation presented in the model by Pettersson *et al. (Pettersson et al., 1976)***

| Window Size | $O[m^{1/2}]$ | HRR Simulated [kW] | Ventilation factor $A_v\sqrt{H_{eq}}$ | HRR Estimated [kW] |
|---|---|---|---|---|
| **Window 1 ($0.7m\times1.6m$)** | 0.061 | 1717 | 3.972 | 6196 |
| **Window 2 ($1.0m\times1.6m$)** | 0.070 | 2556 | 4.574 | 7135 |
| **Original Window ($1.2m\times1.6m$)** | 0.073 | 2814 | 4.977 | 7764 |
| **Window 3 ($1.4m\times1.6m$)** | 0.083 | 3161 | 5.390 | 8408 |
| **Window 4 ($1.7m\times1.6m$)** | 0.092 | 3653 | 5.996 | 9354 |

It is clear from Table 8-1 that the values obtained from the simulations are considerably lower than what could be expected from a compartment fire with the given openings. Several things can be the cause of this. From the simulation tracking the oxygen concentration and the oxygen flow through door/window (see Figure 7-3), it looks like the oxygen supply to the compartment is limited compared to what would be the case for the estimated HRR values.

One thing causing the difference in HRR could be that turbulence and airflow in the compartment creates conditions that are not ideal. Another one could be that the flames outside the openings of the compartment are so big that the amount of oxygen needed for an efficient combustion cannot enter the room. These are however just ideas and more testing is needed to determine what the real causes are.

## 8.4 Are computer programs developed for fire simulating a trustworthy method for estimating fire development, and should it be used to document fire safety in high-rise timber buildings

The computer programs developed for simulating fires are a very effective way of getting an overall picture of a potential fire. Simulating fires introduces a whole new perspective to fire safety design, and the potential of computer programs like these are very big. There are however still a lot of uncertainties when it comes to the results of simulations.

### 8.4.1 A priori vs. a posteriori

*A priori* and *a posteriori* is two terms used to distinguish two different types of knowledge, justification or argument. While *a priori* is independent of experience, *a posteriori* is dependent on experience or empirical evidence.

The results obtained from simulating fires are considered to be *a priori*, which means that it cannot be validated until a fire actually occurs in the building or compartment the simulations are carried out for. As illustrated in the analysis conducted in this report, a lot of assumptions are needed to create models for fire simulation. This leads to the results of simulations depending highly on the person creating the model. Achieving a result that corresponds with data retrieved from experiments is close to impossible.

To test the credibility of these computer programs, and gather test results that are *a posteriori*, many people have carried out experiments. The results from these show that even though people have been given the same description of the geometry of the compartment, the fuel inside, ignition source and ventilation conditions, the results obtained from simulations conducted by different people does not correspond with each other, or experimental data. To make better simulations more knowledge is needed about the input data, so that the amount of assumptions can be reduced. This can be achieved with research.

Another factor that needs to be considered is the time it takes to carry out these simulations. To make the result as reliable as possible, the resolution of the mesh used for the models should be as high as possible. However, with higher resolution more time is needed for each simulation. The development of better and faster computers will increase the possibilities when it come to using these types of programs, as the simulations will take less time. This would result in it being easier to correct errors, adjust assumptions based on the results obtained, and run new and improved simulations.

Based on the uncertainties associated with these models, simulations needs to be carried out with great care when used for documenting fire safety. However, implementing fire protection claddings or active fire protection systems are preferable.

# 9 Conclusions and recommendations

1 ***In what areas do high-rise timber buildings deviate from the pre-accepted solutions given for a fire class 3, or higher classified construction in the Norwegian technical regulations guideline? What are the causes of these deviations?***

Deviations occur for a relatively big number of pre-accepted solutions presented in the Norwegian technical regulation guideline. All the deviations are caused by timbers reaction to fire, as it is a combustible material (D-s2, d0) and the pre-accepted solutions originally were made for incombustible materials like steel and concrete.

This problem can be avoided by establishing conceptual solutions that can be used for documentation of fire safety in high-rise timber buildings, or implementing fire protection claddings or active fire protection systems.

2 ***How does the use of cross-laminated timber in the construction of high-rise buildings affect fire development and the documentation of fire safety?***

It is clear from calculations using the method presented in NS-EN 1995-1-2 Annex A that the contribution to the fire load from cross-laminated timber, when used for a large amount of the surface area in a compartment, is very high.

The limitation of the application area of the method is exceeded very fast. Researchers have previously proposed expanding the limits of this method, and suggest doing it through conducting more experiments for an extended range of heating rates and fire loads. This would improve the calculation method, and this research should definitely be conducted. However, to achieve a satisfying level of fire safety in timber buildings at the moment, fire protective claddings or extensive active fire protection systems are inevitable.

3 ***What factors affect the development and spread of fire, and what can be done to enhance the fire safety when timber is implemented in the load- bearing construction of high-rise buildings?***

A lot of factors influence the fire development and spread. They can be divided into material and external factors. This report focuses on the external ones, which are; thermal exposure/heat flux, oxygen concentration and opening factor. A lot of research has been carried out on these, but to be able to establish conceptual solutions for documenting fire safety in high-rise timber buildings, more is needed. The reason is mainly the effect of the factors influencing each other. By varying one, the others will be affected, which makes predicting fire development extremely challenging.

4 ***Are computer programs developed for fire simulating a trustworthy method for estimating fire development, and should it be used to document fire safety in high-rise timber buildings?***

The computer programs developed for simulating fires are a very effective way of getting an overall picture of a potential fire. However, because of the uncertainties associated with factors implemented in the model, extra care needs to be taken when utilized. A fire simulation provides *a priori* data, which means that the results cannot be validated until an actual fire occurs. Experiments to establish an *a posteriori* point of view have been conducted, showing that the results of a simulated fire rarely correlate with the real fire.

At the moment using these simulation tools is a very time-consuming process, and the result is not as reliable as desired. To make better programs more knowledge is needed for the input data, to reduce the need of assumptions.

The development of better and faster computers will also increase the possibilities when it comes to using these types of programs, as the simulations will take less time. This would result in an easier method of correcting errors. This offers a faster technique to adjust assumptions based on results obtained and run new simulations.

# 10 Future work

As stated in the introduction to this report: there is a lot of factors influencing the fire development and spread in timber buildings. This report has focused on deviations from the Norwegian technical regulations guideline, challenges that occur when documenting fire safety in timber buildings and external factors influencing fire development. More research needs to be conducted to create a better basis for establishing conceptual solutions for use in documentation of fire safety in high-rise timber buildings. Some of the questions that still require further research are:

- How does surface areas with exposed cross-laminated timber contribute to fire?
- How much exposed cross-laminated timber can be implemented without the fire safety being substantially influenced?
- How does the lamina thickness in cross-laminated and glue-laminated timber influence the charring rate?
- How does the room geometry influence the fire development?
- How does the orientation of glue-laminated timber beams affect the charring rate?
- How does the positioning of openings in a compartment affect airflow and turbulence in the room, and how does these factors influence the fire development?
- How does different types of adhesives in glue-laminated and cross-laminated timber influence the charring rate?

# 11 References

Aker Byggteknikk AS. (1997) PRODUKTDATABLAD A-PLAN NATUR 420, 430, 430 R, 433. Oslo, Norway.

Babrauskas V. (1983) Estimating large pool fire burning rates. *Fire Technology* 19: 251-261.

Babrauskas V. (2002) Ignition of Wood: A Review of the State of the Art. *Journal of FIre Protection Engineering* 12: 163-189.

Buchanan AH. (2002) *Structural Desig for Fire Safety*: John Wiley & Sons, LTD.

Butscher EG, Chitty TB and Ashton LA. (1966) *The temperature attained by steel in building fires,* London: H.M.S.O.

Chen X, Yang L, Ji J, et al. (2004) The Pyrolysis and Heat Release Rate of Wood Exposed to Weak External Heat Flux for Long Times. *International Association for Fire Safety Science*.

Clancy P. (1999) Time and probability of failure of timber framed walls in fire. *Centre of Environmental Safety and Risk Engineering.* Victoria, Australia: Victoria Univercity of Technology.

Custer RLP and Meacham BJ. (1997) *Introduction to Performance-based Fire Safety*: Society of Fire Protection Engineers and National Fire Protection Association.

Dembele S, Rosarino RAF and Wen JX. (2012) Thermal breakage of window glass in room fires conditions - Analysis of some important parameters. *Building and Environment* 54: 61-70.

Dillon SE. (1998) An Analysis of the ISO 9705 Room-Corner Test: Simulations, Correlations and Heat Flux Measurements. U.S. Department of Commerce, National Institute of Standards and Technology: University of Maryland.

DiNenno PJ and Drysdale D. (2008) *The SFPE Handbook of Fire Protection Engineering,* Quincy, Massachusetts, USA: National Fire Protection Association.

Direktoratet for byggkvalitet. (2010) *Veildening for Forskrift om tekniske krav til byggverk (VTEK).* Norway.

Drysdale D. (2011) *An introduction to fire dynamics*: John Wiley & Sons, LTD.

FM Approvals. (2012) Approval Standard for Water Mist Systems - Class Number 5560. *E.4.8 Wood Crib and Heptane Pool Fire.* FM Approvals.

Friquin KL. (2011) Material properties and external factors influencing the charring rate of solid wood and glue-laminated timber. *Fire and Materials* 35: 303-327.

Gardner WD and Thomson CR. (1991) Ignitability and Heat-release Properties of Forest Products. *Fire and Materials* 15: 3-9.

Gustavsson L and Sathre R. (2006) Variability in energy and carbon dioxide balances of wood and concrete building materials. *Building and Environment* 41: 940-951.

Gyproc AS. (2008a) Gyproc GFE 15 PROTECT F Ergo, Gyproc GF 15 PROTECT F. Fredrikstad, Norway.

Gyproc AS. (2008b) Gyproc GNE 13 Normal Ergo, Gyproc GN 13 Normal. Fredrikstad, Norway.

Hadvig S. (1981) *Charring of wood in building fires: practice, theory, instrumentation, measurements,* Lyngby: Technical University of Denmark, Laboratory of Heating and Air-conditioning.

Halvorsen HS. (2014) Verifikasjon og dokumentasjon av branntekniske krav i teknisk forskrift ved bruk av trekonstruksjoner i fleretasjers bygninger. Norges teknisk-naturvitenskaplige universitet.

Hansen PF and Olesen FB. (1992) Full-Scale Tests on Loaded Glulam Beams Exposed to Natural Fires. Aalborg: Dept. of Building Technology and Structural Engineering, Aalborg Universitycenter.

Hopkin DJ, El-Rimawi J, Silberschmidt V, et al. (2011) An effective thermal property framework for softwood in parametric design fires: Comparison of the Eurocode 5 parametric charring approach and advanced calculation models. *Construction and Building Materials* 25: 2584-2595.

Hox K. (2015) Branntest av massivtre. 1st ed.: SP Fire Research AS.

Ingberg SH. (1928) Tests of the severity of building fires. *National Fire Protection Quarterly* 22: 43-61.

International Maritime Organization. (2008) Resolution MSC.265(84) Annex 14 - Amendments to the revised guidelines for approval of sprinkler systems equivalent to that reffered to in SOLAS regulation II-2/12 (Resolution A.800(19)). International Maritime Organization.

International Organization for Standardization. (2007) ISO/FDIS 10456. *Building materials and products - Hygrothermal properties - Tabulated design values and procedures for determining declared and design thermal values.*

Janssens M. (1993) Cone calorimeter measurements of the heat of gasification of wood. *Proceedings of Interflam.* 549-558.

Ji J, Yang L-H, Chen X, et al. (2003) Study on the Effects of Heat Flux Levels on Heat Release Rate of Wood. *Journal of Fire Sciences* 21: 55-65.

Kommunal- og arbeidsdepartementet og Miljøverndepartementet. (1987) *Byggeforskrift 1987 - Del 3. Brannvern.* Norway.

Kommunal- og arbeidsdepartementet og Miljøverndepartementet. (1997) *Forskrift om krav til byggverk (TEK97).* Norway.

Kommunal- og moderniseringsdepartementet. (2010) *Forskrift om tekniske krav til byggverk (TEK).* Norway.

König J. (2005) Structural Fire Design of Timber Structures According to Eurocode 5. *Fire Safety Science - Proceedings of The Eight International Symposium.* Beijing, China: International Association for Fire Safety Science, 303-313.

König J. (2006) Effective thermal actions and thermal properties of timber members in natural fires. *Fire and Materials* 30: 51-63.

Lattimer BY. (2008) Heat Fluxes From Fires to Surfaces. *The SFPE Handbook of Fire Protection Engineering.* Quincy, Massachusetts, USA: National Fire Protection Association.

Law M. (1971) A relationship between fire grading and building design and contents. *Fire Research Note No. 877.* Fire Research Station, UK.

Law M. (1983) A basis for the design of fire protection of building structures. *The Structural Engineer* 61.

Lokensgard E and Richardson TL. (2010) *Industrial plastics: theory and applications,* Clifton Park, N.Y.: Delmar.

Mačiulaitis R and Praniauskas V. (2010) Fire tests on wood products subjected to different heat fluxes. *Journal of Civil Engineering and Management* 16: 484-490.

Madorsky SL. (1964) *Thermal Degradation of Organic Polymers,* New York: John Wiley & Sons Inc.

Magnusson SE and Thelandersson S. (1970) Temperature-Time Curves of Complete Process of Fire Development; Theoretical Study of Wood Fuel Fires in Enclosed Spaces. *Acta Polytechnica Scandinavica.* Civil Engineering and Building Construction Series 65.

Mohammad M, Gagnon S, Douglas BK, et al. (2012) Introduction to Cross-Laminated timber. *A Journal of Contemporary Wood Engineering* 22: 3-12.

Norsk Standard. (2007) NS-EN ISO 10456. *Building materials and products: Hygrothermal properties - Tabulated design values and procedures for determining declared and design thermal values.* Standard Norge.

Norsk Standard. (2008) NS-EN 1991-1-2. *Eurokode 1: Laster på konstruksjoner - Del 1-2: Allmenne laster - Laster på konstruksjoner ved brann.* Standard Norge.

Norsk Standard. (2009a) NS-EN 12845. *Fixed firefighting systems, Automatic sprinkler systems - Design, installation and maintenance.* Standard Norge.

Norsk Standard. (2009b) NS-EN 13501-2. *Fire classification of construction products and building elements - Part 2: Classification using data from fire resistance tests, excluding ventilation services.* Standard Norge.

Norsk Standard. (2010) NS-EN 1995-1-2. *Eurokode 5: Prosjektering av trekonstruksjoner - Del 1-2: Brannteknisk dimensjonering.* Standard Norge.

Norsk Standard. (2013) NS 3901. *Requirements for risk assessment of fire in construction works.* Standard Norge.

Östman B, König J, Mikkola E, et al. (2010) *Fire safety in timber buildings - Technical guideline for Europe*: SP Technical Research Institute of Sweden.

Park S-H, Manzello SL, Bentz DP, et al. (2010) Determining thermal properties of gypsum board at elevated temperatures. *Fire and Materials* 34: 237-250.

Paroc Group. (2015a) *Fire classification*. Available at: http://www.paroc.com/knowhow/fire/fire-classification.

Paroc Group. (2015b) Ytelseserklæring No. 10197 - PAROC SSB 1. Helsinki, Finland.

Pettersson O, Magnusson S-E and Thor J. (1976) Fire Engineering Design of Steel Structures. Sweden: Swedish Institute of Steel Construction.

Pope ND and Bailey CG. (2006) Quantitative comparison of FDS and parametric fire curves with post-flashover compartment fire test data. *Fire Safety Journal* 41: 99-110.

Quintiere JG and Cleary TG. (1994) Heat Flux from Flames to Vertical Surfaces. *Fire Technology* 30: 209-231.

Rasbash DJ. (1991) Major fire disasters involving flashover. *Fire Safety Journal* 17: 85-93.

Rein G, Torero JL, Jahn W, et al. (2009) Round-robin study of a priori modelling predictions of the Dalmarnock Fire Test One. *Fire Safety Journal* 44: 590-602.

reThink Wood. (2014a) *Cross Laminated Timber (CLT)*. Available at: http://www.rethinkwood.com/masstimber/cross-laminated-timber-clt.

reThink Wood. (2014b) *Structural Glue Laminated Timber (Glulam)*. Available at: http://www.rethinkwood.com/masstimber/structural-glue-laminated-timber-glulam.

ROCKWOOL Firesafe Insulation. Fire Protection - A guide to risk and changes in legislation.

SINTEF Byggforsk. (2012) 573.210 Halvharde golvbelegg. Typer og egenskaper. *3 Linoleum.* SINTEF Byggforsk.

SINTEF Byggforsk. (2013) 471.031 Egenlast for bygningsmaterialer, byggevarer og bygningsdeler. *67 Vegger av massivtreelementer.* 2nd ed.: SINTEF Byggforsk.

Skelly MJ, Roby RJ and Beyler CL. (1991) An Experimental Investigation of Glass Breakage in Compartment Fires. *Journal of FIre Protection Engineering* 3: 25-34.

Sultan MA. (1996) A model for predicting heat transfer through noninsulated unloaded steel-stud gypsum board wall assemblies exposed to fire. *Fire Technology* 32: 239-259.

Tanaka T, Nakaya I and Yoshida M. (1986) Full Scale Experiments For Determining The Burning Conditions To Be Applied To Toxicity Tests. *Fire Safety Science* 1: 129-138.

Tewarson A. (2008) Generation of Heat and Gaseous, Liquid, and Solid Products in Fires. *The SFPE Handbook of Fire Protection Engineering.* National Fire Protection Association, 3-166.

Tran HC and Janssens ML. (1993) Modeling the Burner Source Used in the ASTM Room Fire Test. *Journal of FIre Protection Engineering* 5: 53-66.

Tran HC and White RH. (1992) Burning Rate of Solid Wood Measured in a Heat Release Rate Calorimeter. *Fire and Materials* 16: 197-206.

Walton WD and Thomas PH. (1995) Estimating Temperatures in Compartment Fires. In: DiNenno PJ, Beyler CL, Custer RLP, et al. (eds) *The SFPE Handbook of Fire Protection Engineering.* 2nd ed. Quincy, MA: National Fire Protection Association, 134-147.

Williamson RB, Revenaugh A and Mowrer FW. (1991) Ignition Sources in Room Fire Tests and Some Implications for Flame Spread Evaluation. *Fire Safety Science* 3: 657-666.

Zabetakis MG and Burgess DS. (1961) *Research on the hazards associated with the production and handling of liquid hydrogen,* [Washington, D.C.]: U.S. Dept. of the Interior, Bureau of Mines.

# 12 Appendices

**Appendix 1:** *Task description*

**Appendix 2:** *Parametric temperature-time curve with iteration*

File name: Parametric_temperature-time_curve.xlsx

Description: Parametric temperature-time curve, with iteration to include fire load from wooden surfaces.

**Appendix 3:** *Calculation of mass loss rate for wooden cribs*

File name: Mass__loss_rate_wooden_cribs.xlsx

Description: The calculations of the ratio between surface area of modelled wooden cribs and the ones used for the conducted experiment. Carried out to find equivalent mass loss rate.

**Appendix 4:** *PyroSim model 1*

File name: Compartment_0.7x1.6.psm

Description: PyroSim model of compartment from case building
Window size: 0.7m x 1.6m

**Appendix 5:** *PyroSim model 2*

File name: Compartment_1.0x1.6.psm

Description: PyroSim model of compartment from case building
Window size: 1.0m x 1.6m

**Appendix 6:** *PyroSim model 3*

File name: Compartment_1.2x1.6.psm

Description: PyroSim model of compartment from case building
Window size: 1.2m x 1.6m

**Appendix 7:** *PyroSim model 4*

File name: Compartment_1.4x1.6.psm

Description: PyroSim model of compartment from case building
Window size: 1.4m x 1.6m

**Appendix 8:** *PyroSim model 5*

File name: Compartment_1.7x1.6.psm

Description: PyroSim model of compartment from case building
Window size: 1.7m x 1.6m

**Appendix 9:** *PyroSim model 6*

File name: Compartment_1.2x1.6.psm

Description: PyroSim model of compartment from case building, made for measuring the oxygen concentration in the compartment and the oxygen flow through window/door
Window size: 1.2m x 1.6m

**Appendix 10:** *Results from simulations*

File name: Results_Simulations.xlsx

Description:
Sheet 1: Data Original Window
Presents data from tests with the original window size, the size used for the conducted experiment (Window: 1.2m x 1.6m)
Sheet 2: Temperature:
The data for Figure 7-5 and Figure 7-6
Temperature-time curves for varying window size
Sheet 3: HRR:
The data for Figure 7-7
Heat release rate for varying window size

Comment: More data was retrieved from the simulations, but have not been included in the appendices, as they were not commented in the results

# Appendix 1 – Task description

## MASTER DEGREE THESIS

Spring 2015
for

Student: Hege Njerve Stusvik

## Establish a Basis for conceptual Solutions for use in Documentation of Fire Safety in high-rise Timber Buildings

### BACKGROUND

Research conducted by *The Intergovernmental Panel on Climate Change* (IPCC) on the human impact on climate change is acknowledged worldwide. As a result of this the focus on using environmentally friendly materials as wood, has increased. With new technologies and different ways of treating and handling wood, the application area of the material is still growing. One of the many effects of this is the increasing interest of implementing it in high-rise buildings.

Although use of timber in the load-bearing structure of high-rise buildings is now legalized in Norway, there are still some challenges when it comes to fire safety design of these buildings. The pre-accepted solutions given in the Norwegian technical regulations guideline are not adjusted for this material, which cause deviations when wood is utilized. The result of this is a more time-consuming design phase of the building, including approved calculation methods or performance based alternative design.

To further enhance the use of timber in high-rise buildings the Norwegian technical regulations guideline needs to be adjusted to the material. The occurring deviations need to be evaluated, and the importance of the different parts of the guideline determined.

### TASK

To locate the deviations that occur in the Norwegian technical regulations guideline, and evaluate the methods currently available for documenting fire safety in high-rise timber buildings.

To present a basis for conceptual solutions, using selected factors that influence fire development and spread in compartment fires of high-rise timber buildings, and providing an evaluation of these factors.

### Objective and purpose

*Result oriented goal:*

The goal of this thesis is to identify deviations in the Norwegian technical regulations guideline, when timber is implemented in the load-bearing structure of high-rise buildings. To gather information about the different factors affecting fire development and spread in these buildings, and to determine the credibility of methods and software programs developed for estimating fire safety.

*Effect oriented goal:*

To present information that can be of use to improve the current technical regulations guideline regarding implementation of timber in high-rise buildings.

**Subtasks and research questions**

1. In what areas do high-rise timber buildings deviate from the pre-accepted solutions given for a fire class 3, or higher classified constructions in the Norwegian technical regulations guideline?
   What are the causes of these deviations?
2. How does the use of cross-laminated timber in the construction of high-rise buildings affect fire development and documentation of fire safety?
3. What factors affect the development and spread of fire, and what can be done to enhance the fire safety when timber is implemented in the load- bearing construction of high-rise buildings?
4. Are computer programs developed for fire simulating a trustworthy method for estimating fire development, and should it be used to document fire safety in high-rise timber buildings?

**General about content, work and presentation**

The text for the master thesis is meant as a framework for the work of the candidate. Adjustments might be done as the work progresses. Tentative changes must be done in cooperation and agreement with the professor in charge at the Department.

In the evaluation thoroughness in the work will be emphasized, as will be documentation of independence in assessments and conclusions. Furthermore the presentation (report) should be well organized and edited; providing clear, precise and orderly descriptions without being unnecessary voluminous.

The report shall include:

- Standard report front page (from DAIM, http://daim.idi.ntnu.no/)
- Title page with abstract and keywords.(template on: http://www.ntnu.no/bat/skjemabank)
- Preface
- Summary and acknowledgement. The summary shall include the objectives of the work, explain how the work has been conducted, present the main results achieved and give the main conclusions of the work.
- The main text.
- Text of the Thesis (these pages) signed by professor in charge as Attachment 1.

The thesis can as an alternative be made as a scientific article for international publication, when this is agreed upon by the Professor in charge. Such a report will include the same points as given above, but where the main text includes both the scientific article and a process report.

Advice and guidelines for writing of the report is given in "Writing Reports" by Øivind Arntsen, and in the departments "Råd og retningslinjer for rapportskriving ved prosjekt og masteroppgave" (In Norwegian) located at http://www.ntnu.no/bat/studier/oppgaver.

**Submission procedure**

Procedures relating to the submission of the thesis are described in DAIM (http://daim.idi.ntnu.no/). Printing of the thesis is ordered through DAIM directly to Skipnes Printing delivering the printed paper to the department office 2-4 days later. The department will pay for 3 copies, of which the institute retains two copies. Additional copies must be paid for by the candidate / external partner.

On submission of the thesis the candidate shall submit a CD with the paper in digital form in pdf and Word version, the underlying material (such as data collection) in digital form (e.g. Excel). Students must submit the submission form (from DAIM) where both the Ark-Bibl in SBI and Public Services (Building Safety) of SB II has signed the form. The submission form including the appropriate signatures must be signed by the department office before the form is delivered Faculty Office.

Documentation collected during the work, with support from the Department, shall be handed in to the Department together with the report.

According to the current laws and regulations at NTNU, the report is the property of NTNU. The report and associated results can only be used following approval from NTNU (and external cooperation partner if applicable). The Department has the right to make use of the results from the work as if conducted by a Department employee, as long as other arrangements are not agreed upon beforehand.

**Tentative agreement on external supervision, work outside NTNU, economic support etc.**
Separate description is to be developed, if and when applicable. See http://www.ntnu.no/bat/skjemabank for agreement forms.

**Health, environment and safety (HSE)** http://www.ntnu.edu/hse
NTNU emphasizes the safety for the individual employee and student. The individual safety shall be in the forefront and no one shall take unnecessary chances in carrying out the work. In particular, if the student is to participate in field work, visits, field courses, excursions etc. during the Master Thesis work, he/she shall make himself/herself familiar with "Fieldwork HSE Guidelines". The document is found on the NTNU HMS-pages at http://www.ntnu.no/hms/retningslinjer/HMSR07E.pdf

The students do not have a full insurance coverage as a student at NTNU. If you as a student want the same insurance coverage as the employees at the university, you must take out individual travel and personal injury insurance.

**Startup and submission deadlines:**
Startup and submission deadlines are according to information found in DAIM.

**Professor in charge: Harald Landrø**

**Other supervisors: Dag Denstad**

Department of Civil and Transport Engineering, NTNU
Date: 14.01.2015, (revised: 23.01.2015)

Harald Landrø

______________________________________
Professor in charge
(Sign.)