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ISBN 978-82-471-2222-8 (printed ver.)
ISBN 978-82-471-2223-5 (electronic ver.)
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Printed by Tapir Uttrykk

In loving memory of my wonderful, caring, strong and brave mum.
You remain forever in our hearts.

Summary

This thesis presents research on the charring rate of large structural members of timber and the material properties and external factors that influence on the charring of these members. The most commonly used temperature-time curves for large structures, and calculation models for the charring rate of wood, are evaluated and used to establish the documented charring rates.

The most important material properties and external factors that influence the charring rate of large timber structures are found by an extensive literature review, and total impact of the properties and factors are listed in tables. However, the change in charring rate due to the various properties and factors is not unambiguous and more systematic research should be carried out to determine rules. An evaluation of calculation models for the charring rate of solid wood, nail-, glue- and cross-laminated structural members was performed and the models giving results closest to test results from the literature were determined. The standard model, EN 1995-1-2, was only accurate in a few cases. The models that include more of the properties and factors found to influence the charring rate were most accurate. Evaluation of standard and parametric temperature-time curves for the design of timber structures reveal that the “Swedish” fire and iBMB fire give the best representation of a real fire in a timber structure. The EN 1991-1-2 Standard fire does not include the contribution to the fire load from the timber structure, and the EN 1991-1-2 Parametric fire has an unrealistic linear cooling stage. The experimental tests on the charring rate of cross-laminated timber panels show that the calculation models for the charring rate are inaccurate for this type of structural member. The charring rate is affected by the growth rate of the fire and the maximum temperature. High initial growth rates result in higher charring rates. Short fires with steep cooling rate will have a short charring period, while a long fire will reach constant charring rate after a while. Comparing the obtained test results with test results from other researchers gave good matches. The charring rates found during the experimental tests are compared with charring rates found using the calculation models from the literature evaluated earlier in the thesis. As the experiments only resulted in a few measurements for the “Swedish” fire and the EN 1991-1-2 Parametric fire there was not much to compare with. The char depths for the EN 1991-1-2 Standard and Parametric fires match well with each other, but the charring rates have a wide scatter.

This research has pointed out several issues where knowledge is lacking for fire safe design of large timber structures. The behaviour of exposed timber structures in compartment fires should be studied further, and the influence the timber structure has on the temperature development over time needs more research. This can result in the development of better temperature-time curves for fire exposed timber structures. The models for, calculation of the charring rate given in EN 1995-1-2 should be improved by introducing more factors and carrying out more research on the properties and factors that influence the charring rate.

Preface

The present work is the result of my PhD research at the Norwegian University of Science and Technology (NTNU), Department of Civil and Transport Engineering, carried out during the period September 2003 to March 2010.
The project is part of the Strategic University Programme (SUP) "Wood as a building material", funded by the Research Council of Norway, and coordinated by my supervisor Professor Per Jostein Hovde. The aim of the SUP was:
- to develop knowledge, competence and tools for innovative and increased use of wood as a renewable resource and sustainable material, and increased added value in the wood and building industry.
- to establish collaboration with the Norwegian industry, and with universities and research institutes in Norway and abroad, as a basis for further network and collaboration.
- to strengthen and improve the competence for basic and continued education on wood at NTNU (research based education) in collaboration with other teaching and research activities.

During my Master studies at NTNU my interest to work with fire safety in buildings became apparent to me. Together with a good friend I signed up for all available subjects on fire and materials or buildings, but when I started working I took another direction. After working with structural steel and glazing in Singapore for two and a half years, and roofing membranes at the Norwegian Building Research Institute (NBI) for a while, I had an itch to "return" to fire safety engineering. When the opportunity to do research on fire safety in wooden buildings at NTNU arose, I grabbed it, with the hope that it will open up the possibility to work with fire safety engineering when I complete my PhD. With the support from my employer at the time (NBI) I started my PhD in 2003, with the plan to complete it within 4 years. As we now are well into 2010, I have some explaining to do; my husband and I have been very lucky to be able to bring into this world two wonderful children. And with the benefits of being a taxpayer in Norway, I have been able to spend two years at home taking care of these two wonders. In addition, we had to fight the battle against cancer together with my mother. A battle we unfortunately lost, and my mother sadly passed away. I took some time off after this.

I have always had great support in my mother, and therefore it is important for me to finish what she encouraged me to start. This thesis is a tribute to my mother, who never gave up.

Acknowledgements

This research was funded by the Research Council of Norway, and I am very grateful to them for giving me this opportunity.

I would like to thank my main supervisor Professor Per Jostein Hovde at the Norwegian University of Science and Technology (NTNU) for guidance, manuscript readings and for taking care of administrative issues. I am also appreciative of my supervisors Harald Landrø's (Professor II at NTNU) and Vidar Stenstad's (Senior Engineer at the National Office of Building Technology and Administration, BE) valuable guidance, manuscript readings and encouragement throughout my research period.

I am much obliged to SINTEF Building and Infrastructure (B&I) for encouraging me to carry through with my PhD and for granting me leave for such a long time. There are two people that have been especially important in this matter, namely Terje Jacobsen, head of my department at NBI when I first commenced on my PhD, and Einar Aassved Hansen, who is my current Research Director at SINTEF B&I.

Terje Jacobsen and Lisbeth Alnæs at SINTEF B&I have proof read some of my articles, and given important feedback. This is much appreciated.

My dear colleagues at SINTEF B&I have been of great support, and made sure my social skills and good mood was held up. Being a PhD student is a very lonesome profession, and it has therefore been very important and helpful to have such great colleagues around. You have helped me to "look on the bright side of life".

I am very grateful to Atle Heskestad, Managing Director of SINTEF NBL AS (Norwegian Fire Research Laboratory), for taking me under his wings and encouraging me to complete my thesis. He also enabled me to carry through with my costly experiments. I also want to thank my "colleagues" at SINTEF NBL AS, especially Kjell Nygård for help with understanding thermocouples, Mads Grimsby for administering my experiments, and last, but not least, Fred Horghagen for running the fire tests for me. And I could not have managed without Staff engineer Ole Aunrønning from NTNU for the drilling of holes and instrumentation of the timber panels.

I would also like to thank Halvor Narvestad (former Master Student at NTNU) for our fruitful discussions on fire scenarios and the fire tests.

Without my friend and PhD-colleague Petra Rüther I would probably be lost in frustration. To all my other friends who have supported me and encouraged me – Æ e gla' i dåkk.

Dear Pappa and Storesystå – Thank you for encouraging me and cheering me on. I love you.

And when the research is completed and papers written, I go home to my own little family.
Franky – Y*ou fill my heart with gladness, take away all my sadness, ease my troubles, that's what you do* (van Morrison).
Bianca Rosita my rose and Frederik Ingolv my joker – our wonderful kids and my treasures. They fill our lives with love and fun.
You're simply the best!

He must look upon the fire,
smell of it,
warm his hands by it,
stare into its heart,
or remain forever ignorant,
from Lord of light by Roger Zelazny

Table of Contents

My works

All conference and journal papers written as part of this PhD project are listed below. They are numbered chronologically in the sequence they were produced. *Paper III.b* and *IV.b* are listed as *Other published work* because they were heavily reworked and the new versions were published as *Paper III* and *IV*.

Conference and journal papers included in the thesis

I Kathinka L Friquin. "Material properties and external factors influencing the charring rate of solid wood and glue-laminated timber". In a review process with the journal *Fire and Materials*.

The entire work was carried out by the author.

II Kathinka L Friquin. "Evaluation of natural and parametric temperature-time curves for the fire design of cross-laminated wood slabs". Published in the *Proceedings of International Conference Application of Structural Fire Design*, pp. 563-568. Czech Technical University, Prague, Czech Republic, 19-20 February 2009.

The entire work was carried out by the author.

III Kathinka L Friquin. "A review of models for the charring rate of solid wood, nail- and glue-laminated structural elements". Published in J*ournal of Structural Fire Engineering*, Volume 1, Issue 1, pp. 61-72, 2010.

The entire work was carried out by the author.

IV Kathinka L Friquin, Mads Grimsbu and Per Jostein Hovde. "Cross-laminated timber panels - Experimental study of the charring rates when exposed to standard and parametric fires". In a review process with *Fire Safety Journal*.

I planned the tests and interpreted the results together with Per Jostein. Mads was responsible for the furnace and running the tests.

V Kathinka L Friquin. "Experimental charring rates for cross-laminated timber panels compared to calculated charring rates". Accepted as a poster paper at and publication in the conference proceedings of the *12th International Conference on Fire Science and Engineering* (InterFlam), Nottingham, England, 5-7 July 2010.

The entire work was carried out by the author.

Other published work

In addition to the included papers, the following work has been prepared:

III.b Kathinka L Friquin. "A review of models for calculation of the charring rate of solid wood structural elements and glue-laminated beams/columns". Published in *Proceedings of the Fifth International Conference on Structures in Fire* (SiF'08), pp. 699-710. Nanyang Technological University, Singapore, 28-30 May 2008.

This is the first version of *Paper III*, and was revised, improved and extended into Paper III. The entire work was carried out by the author.

IV.b Kathinka L Friquin, Mads Grimsbu and Per Jostein Hovde. "Charring rates for cross-laminated timber panels exposed to standard and parametric fires". Accepted for oral presentation at and publication in the conference proceedings of the *11th World Conference on Timber Engineering* (wcte2010), Trentino, Italy, 20-24 June 2010.

This is a short version of *Paper IV*.

1.3 What will tomorrow bring?

Wood as a building material has many advantages:
- available in large areas,
- a renewable resource and comes from sustainable forestry,
- production is often local and the transport therefore short,
- production phase requires little energy and has low emissions compared to other traditional building materials. In addition to the short transportation of the materials this results in a low total emission of pollutants and lower energy consumption than for many other building materials,
- simple prefabrication,
- short construction time,
- closed/sealed building early in the construction process reduces built in moisture and the damage this can lead to, for example fungus or rot,
- easy to adjust at site,
- lighter than other traditional building materials,
- higher strength-to-mass ratio than other traditional building materials,
- wood can absorb large amounts of carbon dioxide (CO_2), illustrated in *Figure 1.10*. The CO_2 is stored in living trees in the forests, and also in wooden building materials,
- every 1 m^3 of wood used in a building binds approximately 0.8 ton CO_2. (In comparison, the use of 430 litres of petrol will release 1 ton CO_2 into the atmosphere.) [2]
- if 1 m^3 of wood replaces the same amount of steel or concrete in a building, the emission of CO_2 is reduced by approximately 0.8 ton CO_2, [2]
- wooden buildings can be very flexible and easy to adjust according to the current situation and use,
- reduced waste at the building site,
- good indoor environment; wood equalizes humidity and store heat,
- wooden building elements can be reused or recycled with ease,
- waste from the production and demolition can be used for bioenergy.

.. and some challenges:
- anisotropic material; different properties in different directions,
- low stiffness and strengths perpendicular to grain,
- high variability in mechanical properties from tree to tree, and even within one tree,
- moisture dependant properties,
- reduction of forests to make space for industry, buildings or livestock grazing,
- biological decay in outdoor environment,
- our knowledge on the performance of large timber structures in natural fires is still limited. The need for further research and easily available calculation methods is apparent,
- the reaction to fire needs sometimes to be improved to achieve the desired fire safety.

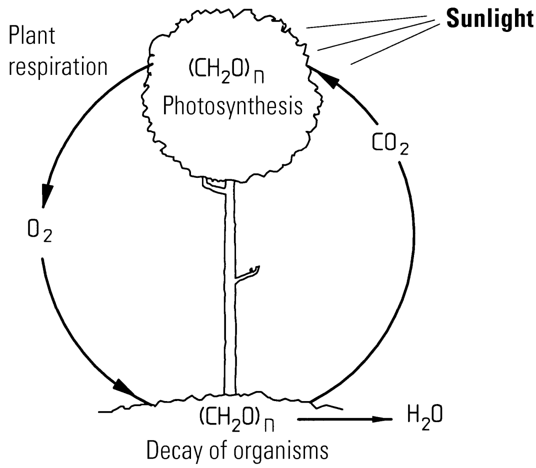

Figure 1.10. Trees and other green plants absorb carbon dioxide (CO_2) as part of the photosynthesis, and release oxygen (O_2) (Illustration: SINTEF Building and Infrastructure)

However, all the advantages of wood have lead to an increased interest from governments and developers to use more wood in their constructions. The new Norwegian government's political platform [3] for the period 2009-2013 declares that it will stimulate the use of wood materials in buildings, according to Report to the Storting No. 39 (2008-2009) [4] (from the Ministry of Agriculture and Food), Chapter 6. The report stimulates an increased use of wood, because of its ability to store CO_2 longterm both in the forests and as building material, and the possibility to exchange materials that put more strain on the environment with wood. The government and the Norwegian Research Council provide funds to promote innovation and product development within wood buildings.

In France the Decree on the use of wooden materials in certain buildings was enforced on December 26th in 2005, and is currently being amended [5] to define the scope of application in providing that the obligation applies to all new buildings, with an exclusion clause in the event of incompatibility with safety or health requirements. The intent of the decree is to increase the quantity of wood in new buildings by requiring a minimum volume of wood material per square meter floor area. For example, the quantity of wood material in a single-family dwelling may not be less than 35 dm^3 per m^2 of floor area, with exception of buildings with frames of other materials. Industrial, storage or transport buildings must have at least 5 dm^3 per m^2 of floor area, and all other buildings must have a minimum volume of wood of 10 dm^3 per m^2 of floor area.

The huge interest in wood as a building material from politicians, architects, designers, developers and entrepreneurs results in innovative and creative use of wood. Wood has a green profile and many possibilities. Some projects already planned for the future are presented below in *Figure 1.11*, *Figure 1.12* and *Figure 1.13*.

The Norwegian Pavilion at the World Exhibition in Shanghai in 2010 is made of 15 "trees" of glue-laminated wood, with a sail membrane roof. After the exhibition the "trees" can be dismantled and re-erected at other locations.

The compliance with the fire safety requirements described in [7] shall be documented in one of two ways, § 7-21 [7]:
- by executing the construction works in conformity with pre-accepted design criteria and solutions, or
- by analyses and/or calculations which proves a satisfactory safety against fire.

"The analysis and/or calculation shall simulate the fire development and present the necessary margins of safety for the most unfavourable conditions which may occur in the use of the construction works. The suitability of the applied method of analysis/calculation shall be documented, and the design fire load determined by recognized and documentable methods" [7].

Construction works are divided into four fire classes (1, 2, 3 and 4) on which requirements to the construction works' load-bearing capacity in case of fire are based. The fire classes are based on the consequence which a fire may have to life, health, community interests and environment. Buildings with 3 or more stories where large crowds gather, but not everyone are familiar with the escape routes, and all buildings with five or more stories are in fire class 3. Buildings where a fire might have a very high risk of injuries to people, environmental impact and damage to the surroundings are in fire class 4. TEK 1997 [7] requires that "The principal load-bearing system in fire classes 3 and 4 shall be made such as to let the construction works maintain its stability and load-bearing capacity through a complete fire development." However, the complete fire development is not described in TEK 1997 or in its guidance document [8]. One can assume that a complete fire development includes the initial fire, fully developed fire and cooling of the fire, as shown in *Figure 1.14*. In the guidance document to TEK 1997 [8], the requirement for the structure to maintain its load-bearing capacities is reduced to 90 minutes for non-combustible main load-bearing structures, while the requirement for timber structures and other combustible structures remain.

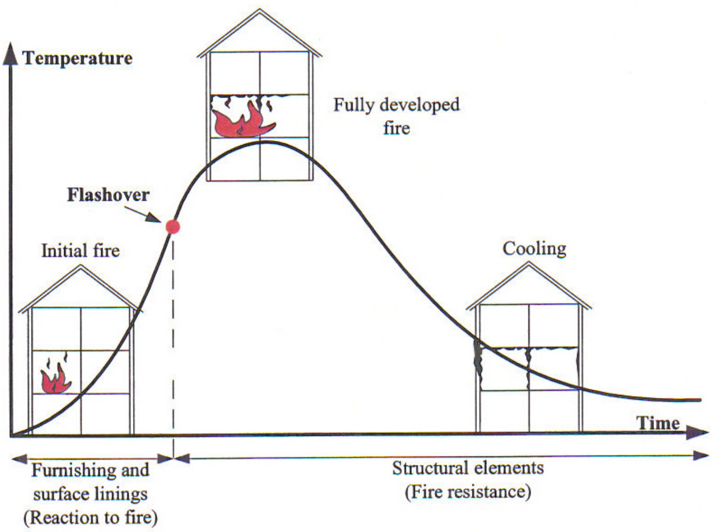

Figure 1.14. An example of a complete fire development. The figure also indicates which part of the compartment is included in the fire during the various stages and the important properties during these stages; Reaction to fire and Fire resistance (Source: SP Technical Research Institute of Sweden)

Construction Products Directive in the EU – Safety in case of fire

A new Harmonized system has been introduced in Europe to assure fire safety in buildings. The system includes product standards, performance classes in case of fire, testing and calculation standards for fire performance and national fire regulations, see *Figure 1.15*. The system is based on the Construction Products Directive (CPD) [10] and its essential requirements.

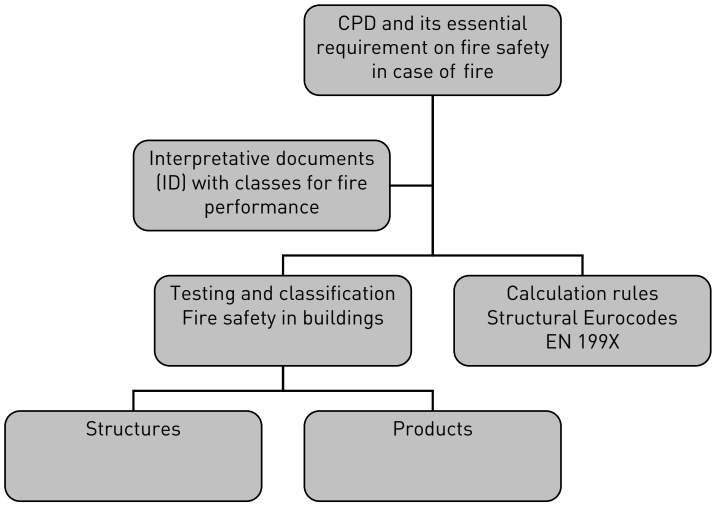

Figure 1.15. Principles for European fire standards for building products

CPDs essential requirements on fire safety are:
"The construction works must be designed and built in such a way that in the event of an outbreak of fire:
- the load-bearing capacity of the construction can be assumed for a specific period of time,
- the generation and spread of fire and smoke within the works are limited.
- the spread of the fire to neighbouring construction works is limited,
- occupants can leave the works or be rescued by other means.
- the safety of rescue teams is taken into consideration."

The fire scenarios are described in Interpretative document No. 2 [11]:
"(4) For the evaluation of fire resistance of structures the following possibilities are prevailing in Member States:

(a) consideration of natural fire scenarios (i.e. parametric fire)
(defined by parameters listed below)
A calculation of the thermal action caused by fire in a construction works (e.g. room, group of rooms, part of a construction works) should consider:
- the fire load (type, amount and burning rate),
- air supply to the fire,
- geometry and size of enclosure (defined by the fire compartment),
- thermal properties of the enclosure,
and depending on the particular fire safety strategy or engineering approach, consideration can also include:

- influence of fire suppression installation (e.g. sprinkler installation), and
- fire brigade/rescue team action (which may be initiated by a fire detection installation).

(b) consideration of conventional fire scenarios (i.e. standard fire)
The Essential Requirement requires that fire spread is limited and that the load-bearing capacity of the construction is adequate for a specific period of time. These requirements can be satisfied by proving fire resistance of load-bearing and/or separating members. Internationally it is agreed to use the 'standard temperature/time curve' (see ISO 834 Part 1 [12] (identical with EN 1991-1-2 [13])) as a model for a fully developed fire."

The required period of stability depends on the requirements of regulators. Examples of requirements can be:
- No specified fire resistance requirements for buildings with limited fire load density or where the consequences of collapse of structures are acceptable.
- Fire resistance for a specified but limited period of time, where the time requirements can be specified to allow for safe evacuation of occupants and intervention of rescue teams.
- Fire resistance of the main structure to ensure it can survive a full burn out of all combustible materials in the building, or a specified part of it, without taking into account the intervention of the fire brigade/rescue teams.

2 Context, scope and research approach

2.1 Context

A fire is every property owner's biggest nightmare, and by right. Fires cause big property losses every year, and many people are hurt or die in these fires. Fires can occur in any kind of building, most of the time unwanted and unexpected. There are ways of reducing the probability of occurrence, but it is not possible to prevent all major fires. Fire safety design is the main tool to secure the safety of people using the building, to reduce the impact of the fire, the spread of flames and the damage to property. It is also crucial to provide mechanisms for the detection and notification of fire, and to create paths to facilitate safe evacuation and rescue of people from the building, and for safe fire fighting [14]. It is therefore important to choose the best suited building material for the structure, and that the behaviour and capacity of the material and structure in a fire is well known.

Over the last decade, wood has attained increased interest as an environmentally friendly and sustainable material, and many countries have stated increased use of wood as a national goal. On the other hand wood is a combustible material, and has therefore traditionally been regarded not to be suitable for multi-storey buildings. It is a common misconception that a building with a timber frame structure or solid wood members will have poor fire resistance. Research and test results [15,16,17] show that wooden structures can have a sufficient fire resistance if designed correctly.

The building regulations in many countries have until recently been *prescriptive*, and therefore limited the use of wood in multi-storey buildings since there are few pre-accepted solutions for such structures. However, *performance-based* fire design codes are now widely being implemented. 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. The new performace-based codes open up for more extensive use of wood as a structural material, also in multi-storey buildings like apartment blocks, office buildings, etc., even in urban areas, and not only in small private houses. For example, the number of stories a timber-framed building could contain was formerly specified by the national building regulations. While performance-based codes allow the designers to use any fire safety strategy they wish, provided that adequate safety can be documented. This includes documentation proving that the structure will withstand a complete fire scenario and that there will be enough time to evacuate the building.

The increasing interest in wood as a building material and its benefits during the last two decades, and the new performance-based building regulations, have resulted in the development of new structural members and new utilization of traditional elements. For example, using timber structures in large and multi-storey buildings, the development of glue-laminated members in all shapes and sizes, cross-laminated timber panels introduced as walls, floors, roofs and wind stabilizing plates in buildings, and new architectural trends. The fire resistance of the members used in multi-storey buildings where they were not allowed to be used earlier, must be determined in such a way that the information can be used by all fire safety engineers around the world, i.e. become standardized.

Both TEK 1997 [7] and CPD [10] have requirements for the fire safety of structures, and TEK 1997 categorizes the building types and gives them different fire classes based on the risk of a potential fire. The evaluation of the fire resistance of the structures must be based on a fire scenario, which in TEK 1997 only is defined as "a complete fire development". It is natural to assume that the European standards (EN) are to be used here. CPD's Interpretative document No. 2 [11] describes which parameters a natural fire scenario shall be based on and which standard fire to use. However, while the national regulations in Norway, TEK 1997 and its guidance document VTEK [8], define the requirement for the fire duration, the local regulators define the required period of stability for the construction in the EU. Therefore, the required period of stability might vary within the EU members, and even within each country.

European standards (EN) with design procedures (also called Eurocodes) have been developed and implemented in most European countries, and are widely used. The nominal/standard fire exposure and natural/parametric fire exposure are described in EN 1991-1-2 [13], and the structural fire design of timber structures is given in EN 1995-1-2 [18]. Unfortunately, the standards and codes are not all-inclusive. The methods have limitations and many situations or details are not covered. For example, models to define the charring rate of wood are given in EN 1995-1-2 [18], but they are only applicable to the standard or parametric fires as defined in [18]. If other parametric fire curves are used, the charring rate must be found elsewhere or by testing.

With the performance-based design codes the fire safety of a structure can be calculated based on the rules in the European standards, EN, or other documented methods can be used. Models to determine the temperature-time development are given in EN 1991-1-2 [13], but other recognized and well-documented methods can also be used. The charring rates for both standard/nominal and natural/parametric fire developments can be found in EN 1995-1-2 [18], or charring rates documented in other sources can be applied.

There are four basic requirements to load-bearing and separating structural elements in EN 1995-1-2 [18]:

- they shall be designed in such a way that their load-bearing function, R, is maintained during the relevant fire exposure,
- integrity, E, failure shall not occur,
- insulation, I, failure shall not occur,
- thermal radiation from the unexposed side is limited.

Structural elements that are only load-bearing, not separating, shall maintain their load-bearing function during the relevant fire exposure. In some cases the deformation of the load-bearing structure might have to be taken into account.

In EN 1995-1-2 [18] a flow chart is given as guidance for structural fire design of initially protected (left hand side) and unprotected (right hand side) structural members exposed to Standard fire as descried in EN 1991-1-2 Section 3.2.1 [13], see *Figure 2.1*. Walls and floors are not included in this flow chart, but for unprotected load-bearing walls and floors the procedure to determine the residual load-bearing capacity, R, is similar to the right hand side of this chart. In addition, the insulation, I, and integrity, E, of the walls and floors must be calculated or tested. The charring rate for wood exposed to Standard fire [13] is given in Table 3.1 [18].

The procedure for structural fire design of timber members exposed to parametric fires is similar when the fire exposure has been determined, but the charring rate is calculated based on Annex A [18]. And the char depth has to be determined by iteration of the fire duration and temperature development as follows:

1. Determine the fire load density for the fire compartment, $q_{f,d,1}$, through calculations or tabulated values, Annex E [13].

2. Determine the parametric temperature-time curve, $\theta_{g,1}$, based on the fire load density in the compartment, excluding the exposed timber structure, Annex A [13].

3. Calculate the charring rate, $\beta_{par,1}$, for the heating phase of the fire, Annex A [18].

4. Calculate the total char depth, $d_{char,1}$, based on the duration of the fire and $q_{f,d,1}$, Annex A [18].

5. Determine the new fire load density for the compartment, $q_{f,d,2}$, including the charred part of the timber structure, Annex E [13].

6. Determine the new parametric temperature-time curve, $\theta_{g,2}$, including the timber structure's contribution, Annex A [13].

7. Calculate the new char depth, $d_{char,2}$, based on the duration of the fire and $q_{f,d,2}$, Annex A [18].

8. Continue the iteration until the added contribution from the timber structure becomes relatively small. For large surfaces of exposed timber several iterations might be needed.

When the total char depth has been determined the residual load-bearing capacity of the structure can be calculated using one of two methods; the *reduced cross-section method* or the *reduced properties method*.

Reduced cross-section method

An effective cross-section is calculated by reducing the initial cross-section by the effective charring depth, d_{ef}. It is assumed that the fresh wood material close to the char front has zero strength and stiffness, while the properties of the remaining cross-section are unchanged. The effective charring depth is therefore defined as the calculated char depth, d_{char}, plus a layer of maximum 7 mm thickness, d_0*k_0. d_0 is 7 mm and k_0 is a factor that changes linearly from 0 to 1 between 0 and 20 minutes into the fire. 10 minutes into the fire $d_{ef} = d_{char,n} + 3.5\ mm$. 20 minutes into the fire $d_{ef} = d_{char,n} + 7\ mm$. The residual load-bearing capacity of the structure is calculated based on the effective cross-section with properties as for fresh wood.

Reduced properties method

This method only applies to rectangular cross-sections of softwood exposed to fire on three or four sides, and round cross-sections exposed to fire along their whole perimeter, i.e. it does not apply to timber panels used as walls or floor exposed to fire on one side only. The residual cross-section is determined by reducing the cross-section with the calculated total charring depth. It is assumed that the residual cross-section has reduced properties. The reduced properties can be found by multiplying the bending strength, compressive strength, tensile strength and modulus of elasticity, respectively, for fresh wood with a modification factor, $k_{mod,fi}$. The modification factor takes into account the reduction in strength and stiffness properties at elevated temperatures. The residual load-bearing capacity of the residual cross-section is calculated based on the reduced properties of the wood at elevated temperatures.

A computer programme for the structural fire design of timber structures was not found during this research.

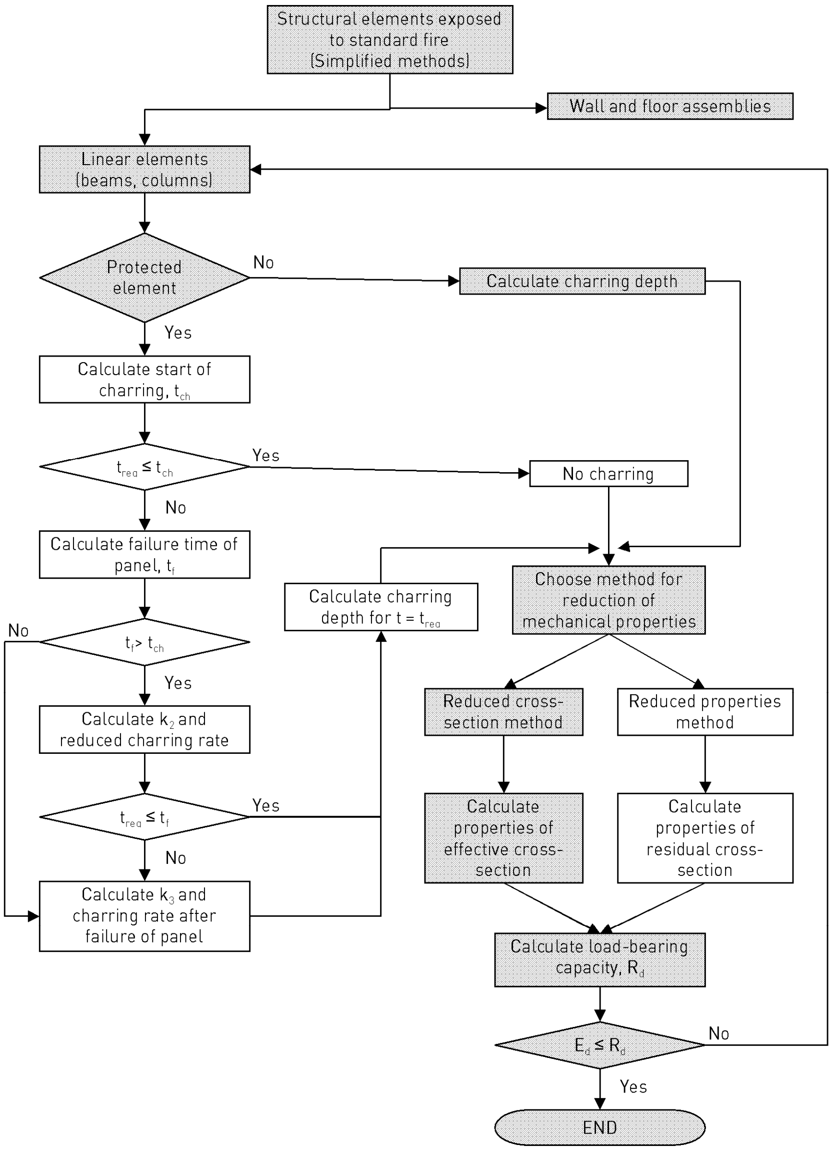

Figure 2.1. Flow chart outlining the design procedure to check the load-bearing function of structural members [18]. E_d is the design effect of actions for the fire situation

2.2 Objectives

The main objectives of this research were to:

- determine the material properties and external factors that have influence on the charring rate of wood and therefore should be included in calculation models for the charring rate,
- evaluate calculation models for the charring rate of nail-, glue-, and cross-laminated structural members,
- evaluate parametric temperature-time curves for the design of wooden structures,
- determine through laboratory experiments the charring rate of cross-laminated timber panels normal to the grain under various fire exposure,
- relate the rates to the fire exposure intensity and duration,
- relate the charring rates to the thickness of the panels,
- compare the charring rates with other experimental results,
- compare measured charring rates with the design rules given in EN 1995-1-2, and
- compare measured charring rates with calculated rates based on the models evaluated in the project.

Determination of charring rate and which parametric fire curves are applicable to solid, nail-, glue- and cross-laminated timber members, are important for:

- the calculation of the load bearing capacity of the structure,
- generation and spread of fire and smoke (integrity and insulation of the structural member),
- evacuation (contain the fire in one area),
- safety of the rescue team (avoid early collapse of the building), and
- fire fighting (for their safety and to give them time to put out the fire).

2.3 Limitations

The research is limited to the fire behaviour of wooden structural members for use in multi-storey wooden buildings in given fire scenarios. The structural members relevant to this project are structures of solid wood, nail- or glue-laminated, or cross-laminated timber panels. The solid wood members have a limitation to their size and load-bearing capacity, and can therefore only be used in smaller buildings. The nail- and glue-laminated members can be produced in large dimensions and be used in multi-storey buildings. It is natural to compare the fire behaviour of nail- and glue-laminated members with solid wood as solid wood is the basis.

Fire tests to examine the charring of cross-laminated timber panels were performed because these panels are relatively new to building structures, and little information on its fire behaviour is available. The panels are popular due to the possibility to prefabricate the panels with windows, doors, installation cut outs, and it is easy to adjust at site. The prefabrication facilitates a quick erection, low building costs and a quick "seal" of the building. A quick “seal” of the building reduces built in moisture and gives better working conditions for the builders. Laminated timber panels were developed in Canada in the early 1970s for use in bridge decks. In the 1990s the panels were introduced into buildings. Several types of timber panels have been developed and sketches of the most common types are shown in *Figure 2.2*, where sketch e) is a cross-laminated panel, like the panels tested and discussed in *Paper IV and V*.

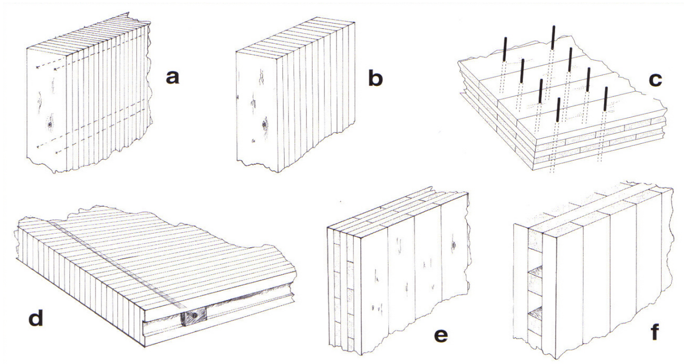

Figure 2.2. Prefabricated panels of solid wood: a) Laminated panel with mechanical fasteners, b) Glue-laminated panel with parallel boards, c) Cross-laminated member with wooden dowels, d) Pre-stressed panel with parallel boards, e) Glued cross-laminated panel, f) Cross-laminated panel with open cells in the middle layer

As mentioned in paragraph *2.1 Context* the residual load bearing capacity of a timber structure can be calculated in two ways, either by the *Reduced cross-section method* or the *Reduced properties method*. The reduction of the tensile, compression and bending strength has not been part of this study, as focus has been on the *Reduced cross-section method*. In *Figure 2.1* the structure type and method for calculation of residual load-bearing capacity focused on in this research are marked in a grey colour.

Other structural materials than wood, such as steel, concrete or masonry, are not included. Neither are initially protected, painted or fire retardant-treated wooden members. The chemical reactions in the material, and the effect of active fire protection systems, such as sprinkler systems, are not handled by this research. Neither is the evacuation and rescue of people from the buildings, but the safety of people is taken into account in the formulation of the requirements to the fire resistance of the structures.

2.4 Research approach

Several methods were used in the present research. A short presentation of the methods is given below. The methods are described in more detail in each paper.

Literature study

It was natural to start the research with a literature study to map the knowledge on charring rates and temperature-time developments for large timber structures. The literature study was guided by Internet searches in acknowledged databases and journals. From there it was relatively easy to follow references in current documents back to the origins of the line of research examined in the literature study. It also gave good information about the universities, institutes and other bodies performing research on the fire safety of heavy timber structures. Searches on the web pages of these bodies gave access to additional information and literature. To keep up to date and avoid having to perform time consuming searches in the databases and journals repetitively over the long research period, automatic Search Alerts and Table of Content (TOC) alerts were used in relevant online databases and journals where possible. This method was used in almost all of the papers as it was natural to map the existing research and knowledge before embarking on new studies.

Evaluation of charring rate models, and standard and parametric temperature-time curves

Through the literature study calculation models for the charring rate of wood and models for temperature-time developments in compartment fires were gathered. Charring rates were calculated using the charring rate models, and the results compared to experimental results found in the literature and with the charring rates founding the experiments performed as part of the present research. The accuracy of the charring rate models were determined based on this comparison. The temperature-time models' applicability to heavy timber structures were evaluated and established through discussions around their shape, included parameters and possibility to change fire load density. The method was used in *Paper II*, *III* and *V*.

Laboratory experiments: Charring rate of wood through all stages of a fire

The only way to accurately determine the charring rate for a given wooden element exposed to a described fire development is through laboratory experiments. Three laboratory experiments on large cross-laminated timber panels exposed to three different temperature-time curves were performed as part of this research. A large-scale horizontal furnace was chosen because the temperature development could follow any temperature-time curve, although the accuracy of the temperature during the cooling stage was unknown. The char depths were measured using thermocouples, and the charring rates calculated based on the char depth development over time. The experiments are described in *Paper IV*.

Comparison of experimental and calculated charring rates

In *Paper V* the charring rate results from the experiments performed as part of the current study are compared with charring rates calculated using models found in the literature. The comparison is important to establish the applicability of the models to heavy timber structures.

3 Research outcome

3.1 Relationship between the papers

As described in paragraph *2.1 Context* the structural fire design of timber structures is based on the temperature-time development in the fire compartment, the charring rate, char depth, residual cross-section and reduced properties of the wooden members.

One of the first steps was to evaluate the existing models for calculation of the charring rate and charring depth of the wooden structural members. To be able to evaluate these models, the most important internal properties and external factors had to be determined, *Paper I*. The models could then be assessed based on which of these properties and factors they included, *Paper III*. They were also compared with charring rate results from the literature. However, not many charring rate results on nail-, glue, and cross-laminated structural members are found in the literature. Experimental research on cross-laminated timber panels in particular is very limited.

A very important part of the structural fire design of timber structures is to determine the temperature development in the fire compartment. Most of the currently available temperature-time curves and models are developed for non-combustible materials like steel, aluminium, gypsum boards and concrete. It was necessary to look at these curves and evaluate whether they could be used for structures of combustible materials also, *Paper II*.

The literature reviews revealed the lack of systematic research and knowledge particularly on cross-laminated timber panels, and on timber structures exposed to parametric fires. A test experiment in a large-scale horizontal furnace was therefore planned and carried out, *Paper IV*. The aim was to determine the charring rates through all stages of the fire for cross-laminated timber panels exposed to different temperature-time curves. The effects of the furnace temperature, i.e. heating rate early in the fire and maximum temperatures, different panel thicknesses, and panel layers, were also investigated.

The charring rates found during the experiments were in *Paper V* compared with charring rates calculated using the models found in the literature and evaluated in *Paper III*.

3.2 Summary of the included papers

Paper I - Material properties and external factors influencing the charring rate of solid wood and glue-laminated timber

The species of wood are divided into two types, hardwood and softwood. The hardwood trees have broad leaves and the softwoods are cone-bearing trees. The cells of the wood are mainly aligned in the longitudinal direction, but there are also some cells that are aligned in the transversal plane, in rays. Wood is therefore an anisotropic material, which means that the structure varies with the different directions of the material. The exposed surface of a beam or column can therefore be characterized as being parallel to the grain, tangential to the grain or radial to the grain. Seasonal growth results in the formation of growth rings, also called annual rings. Each growth ring has a light coloured spring section called springwood or earlywood, and a darker summer section called summerwood or latewood. This is due to the different growth rates during the two seasons. Springwood is less dense, with larger cells and thinner cell walls because the tree grows faster in this period. The outer part of the stem is called sapwood, and the inner part is called heartwood. The heartwood consists of dead cells, and is often denser than sapwood. Heartwood contains extractives which clog tiny passages in the cell walls, and the permeability is therefore significantly lower than for sapwood. The cross-section, radial-section and tangential-section in *Figure 3.1* show the longitudinal and radial cells, growth rings, sapwood, heartwood, pith, and inner and outer bark.

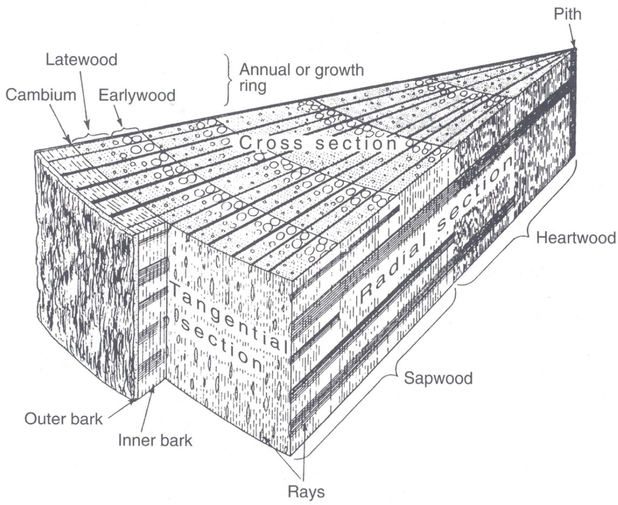

Figure 3.1. Illustration of a wedge-shaped segment cut from a five-year old hardwood tree, showing the principal structural features [32]

Wood contains water in three ways: free water in the cells, water hygroscopically bound to the cellulose molecules and water forming the bond between cellulose molecules. This water content can affect the charring behaviour of the wood. The chemical constituents of wood are cellulose, hemicellulose, lignin and extractives. The proportion of the components varies from species to species, and between softwood and hardwood.

Due to the complexity of the chemical and physical structure of wood its reaction to elevated temperatures is influenced by many material properties, like the density, moisture content, chemical composition, grain orientation, permeability, scale effect, char contraction and char oxidation. In addition, some external factors such as thermal exposure, oxygen concentration and opening factor will affect the charring behaviour of the wood.

Paper I describes how these material properties and external factors influence the charring rate. Results from researchers around the world have been collected and it has been determined whether the properties and factors increase or decrease the charring rate. However, it is not possible to determine how great the impact of each property and factor is because the test methods, samples and test conditions used by the researchers are very different from each other.

The impact of some of the properties and factors on the charring rate for different wood species, found by the researchers referred to in the paper, are:

- *Table 3.1*Density affecting the charring rate

- *Table 3.2* Moisture content affecting the charring rate
- *Table 3.3* Species group affecting the charring rate
- *Table 3.4* Chemical composition affecting the charring rate
- *Table 3.5* Permeability affecting the charring rate
- *Table 3.6* Char contraction affecting the charring rate
- *Table 3.7* External heat flux affecting the charring rate
- *Table 3.8* Oxygen concentration and opening factor affecting the charring rate.

The change in charring rate as a result of changing one property or factor varies greatly, as can be seen in the tables. But there are some trends, as described below and in the paper. The structure of wood is also briefly described below, because the structure has an impact on the charring rate in different ways. The values are from various types of specimen size, test set-ups and apparatus, and are not necessarily directly comparable.

Table 3.1. Density affecting the charring rate

References	Comments	Change in property (Density)	Change in charring rate
[33] Schaffer	Douglas fir[a], Moisture 5%w	400 kg/m^3 to 600 kg/m^3	-28%
[33] Schaffer	Douglas fir[a], Moisture 20%w	400 kg/m^3 to 600 kg/m^3	-28%
[33] Schaffer	Southern pine[a], Moisture 5%w	400 kg/m^3 to 600 kg/m^3	-8%
[33] Schaffer	Southern pine[a], Moisture 20%w	400 kg/m^3 to 600 kg/m^3	-9%
[34] White	Western red cedar – Southern pine Moisture 10%	310 kg/m^3 to 509 kg /m^3	0%
[34] White	Redwood – Engelmann spruce Moisture 10%	343 kg/m^3 to 425 kg /m^3	-22%
[34] White	*Basswood – Hard maple* Moisture 10%w	399 kg/m^3 to 691 kg /m^3	-25%
[34] White	*Red oak – Hard maple* Moisture 10%w	664 kg/m^3 to 691 kg /m^3	14%
[35] Collier	Radiata pine[a], Moisture 0%w	455 kg/m^3 to 621 kg /m^3	-15%
[35] Collier	Radiata pine[a], Moisture 0%w	409 kg/m^3 to 544 kg/m^3	16%
[35] Collier	Radiata pine[a], Moisture 20%w	407 kg/m^3 to 620 kg/m^3	-12%

[a]Oven dried *Italic font* - Hardwood

Some results are as one would expect; higher charring rates for lower densities, but this is not always the case (*Table 3.1*). Western red cedar and Southern pine have the same charring rate although the density of the pine is much higher than for the cedar. Red oak has a lower density than Hard maple but it also has a lower charring rate. The charring rate for Radiata pine with 0% moisture increases by 16% from 409 kg/m^3 to 544 kg /m^3. This seems to be coincidental.

The charring rate is lower for all specimens with higher moisture content, *Table 3.2*, but the effect varies greatly. There is no unambiguous tendency for the charring rates for hardwood versus softwood. Comparing two species shows that the hardwood might have a higher charring rate than the softwood, while for two other species the softwood has the higher charring rate, *Table 3.3*. *Table 3.4* shows that the charring rate increases with increasing Klason lignin content in the wood – at least for the two cases shown. The charring rate clearly increases with increasing penetration depth, *Table 3.5*, which is an indication of the permeability of the wood. The two results for the char contraction factor in *Table 3.6* do not give any reliable information. As expected, increasing heat flux increases the charring rate greatly, *Table 3.7*. The oxygen concentration and the opening factor are related to each other, and the results in *Table 3.8* seem reasonable. The charring rate increases with increasing ventilation and oxygen concentration.

Table 3.2. Moisture content affecting the charring rate

References	Comments	Change in property (Moisture)	Change in charring rate
[36,37,38,39]	Spruce	0%w to 10%w	-30%
[36,37,38,39]	Spruce	10%w to 20/25%w	-20%
[33] Schaffer	Douglas fir[a] 400 kg/m^3	5%w to 20%w	-16%
[33] Schaffer	Douglas fir[a] 600 kg/m^3	5%w to 20%w	-18%
[33] Schaffer	Southern pine[a] 400 kg /m^3	5%w to 20%w	-5%
[33] Schaffer	Southern pine[a] 600 kg/m^3	5%w to 20%w	-6%
[35] Collier	Radiata pine[a] 408 kg /m^3	0%w to 21%w	-25%
[34] White	Southern pine[a] 509 kg/m^3	6%w to 16%w	-7%
[34] White	Western red cedar[a] 310 kg/m^3	6%w to 16%w	-14%
[34] White	Redwood[a] 343 kg/m^3	6%w to 16%w	-14%
[34] White	Engelmann pruce[a] 425 kg/m^3	6%w to 16%w	-22%
[34] White	*Hard maple*[a] 691 kg/m^3	6%w to 16%w	-7%
[34] White	*Red oak*[a] 664 kg/m^3	6%w to 16%w	-9%
[34] White	*Yellow poplar*[a] 504 kg/m^3	6%w to 16%w	-14%
[34] White	*Basswood*[a] 399 kg/m^3	6%w to 16%w	-31%
[40] Cedering	Norway spruce[a] 321-454 kg/m^3	6%w to 18%w	-9%

[a]Oven dried *Italic font* - Hardwood

Table 3.3. Species group affecting the charring rate (Hardwood vs Softwood)

References	Comments	Change in property (Hardwood vs Softwood)	Change in charring rate
[34] White	Density[a] 400-425 kg/m^3 Moisture 6%w	Engelmann spruce to *Basswood*	54%
[34] White	Density[a] 506 kg/m^3 Moisture 6%w	Southern pine to *Yellow poplar*	0%
[34] White	Density[a] 400-425 kg/m^3 Moisture 10%w	Engelmann spruce to *Basswood*	49%
[34] White	Density[a] 506 kg/m^3 Moisture 10%w	Southern pine to *Yellow poplar*	-9%
[34] White	Density[a] 400-425 kg/m^3 Moisture 16%w	Engelmann spruce to *Basswood*	38%
[34] White	Density[a] 506 kg/m^3 Moisture 16%w	Southern pine to *Yellow poplar*	-18%

[a]Oven dried *Italic font* – Hardwood

Table 3.4. Chemical composition affecting the charring rate

References	Comments	Change in property (Chemical composition)	Change in charring rate
[34] White	*Basswood*[a] 399 kg/m³– Redwood[a] 343 kg /m³, Moisture 10%w	Klason lignin 19.8% to 37.1%	16%
[34] White	Engelmann spruce[a] 425 kg/m³ – Redwood[a] 343 kg /m³ Moisture 10%w	Klason lignin 27.3% to 37.1%	29%

[a]Oven dried *Italic font* – Hardwood

Table 3.5. Permeability affecting the charring rate

References	Comments	Change in property (Permeaility)	Change in charring rate
[34] White	Western red cedar[a] 310 kg /m³ – Redwood[a] 343 kg /m³ Moisture 10%	Penetration depth[b] 3 mm to 4 mm	1%
[34] White	Engelmann spruce[a] 425 kg /m³ – Southern pine[a] 509 kg /m³ Moisture 10%w	Penetration depth[b] 3 mm to 31 mm	29%
[34] White	*Red oak*[a] 664 kg /m³– *Hard maple*[a] 691 kg /m³ Moisture 10%w	Penetration depth[b] 3 mm to 47 mm	14%
[34] White	*Red oak*[a] 664 kg /m³ – *Basswood*[a] 399 kg /m³ Moisture 10%w	Penetration depth[b] 3 mm to 30 mm	52%
[41] Hugi	*Sycamore maple* 605 kg/m³ - *English oak* 625 kg/m³ Moisture 10%w	Oxygen Permeability Index 9.76 to 10.75	-24%

[a]Oven dried [b]Penetration depth of chemical treatments *Italic font* - Hardwood

Table 3.6. Char contraction affecting the charring rate

References	Comments	Change in property (Char contraction)	Change in charring rate
[34] White	Western red cedar[a] 310 kg /m³ - Redwood[a] 343 kg /m³ Moisture 10%w	0.784 to 0.862	1%
[34] White	*Hard maple*[a] 691 kg /m³ – *Red oak*[a] 664 kg /m³ Moisture 10%w	0.594 to 0.703	-12%

[a]Oven dried *Italic font* - Hardwood

Table 3.7. External heat flux affecting the charring rate

References	Comments	Change in property (External heat flux)	Change in charring rate
[38] Mikkola	Spruce 490 kg/m^3 Moisture 10%w	25 kW/m² to 50 kW/m²	43%
[38] Mikkola	Spruce 490 kg/m^3 Moisture 10%w	50 kW/m² to 75 kW/m²	27.5%
[38] Mikkola	Spruce 490 kg/m^3 Moisture 10%w	25 kW/m² to 75 kW/m²	82%
[42] Tran	Redwood 343 kg/m³	17.8 kW/m² to 56.3 kW/m²	75%
[42] Tran	Southern pine 509 kg/m³	17.4 kW/m² to 56 kW/m²	104%
[42] Tran	*Red oak* 664 kg /m³	17.8 kW/m² to 53.6 kW/m²	84%
[42] Tran	*Basswood* 399kg/m³	17.6 kW/m² to 53.4 kW/m²	77%

[a]Oven dried *Italic font* - Hardwood

Table 3.8. Oxygen concentration and opening factor affecting the charring rate

References	Comments	Change in property (Oxygen concentration and opening factor)	Change in charring rate
Oxygen concentration in the fire compartment			
[40] Cedering	Norway spruce[a] 321-454 kg/m³	4% to 10%	8%
Opening factor			
[43] König	Any species	0.04 to 0.12	45%
[43] König	Any species	0.06 to 0.12	21%

[a]Oven dried *Italic font* - Hardwood

Paper II - Evaluation of natural and parametric temperature-time curves for the design of cross-laminated wood slabs

The temperature-time curves are important for the fire safety design of wooden structures. The most commonly used temperature-time curves are the Standard fires from ISO 834-1 [12], EN 1991-1-2 [13], or ASTM E119 [44], which are all very similar to each other, and Parametric fires from EN 1991-1-2 [13]. There are a few other curves to choose from, but they are not all developed for use on combustible structures. There are some limitations to the three mentioned curves. The Standard temperature-time curves [13,44] mainly describe the fully developed fire, and do not include the significant amount of time that sometimes elapses from the beginning of a fire until the fully developed fire. They also do not include the decay stage of the fire. Another important factor lacking in these curves is the design fire load; the load included in the curves is not specified, and it cannot be changed. The type of structure or boundaries in the fire compartment is not taken into account in the standard fire curves given in [13] and [44]. The Parametric fire [13] only applies to fire compartments up to 500 m² floor area, without openings in the roof and with a maximum height of 4 m. The Parametric fire is also limited to fire compartments with mainly cellulosic type fire loads. However, the Parametric fire curve from [13] includes the thermal properties of the boundaries and it is also possible to increase the design fire load to include the contribution from the exposed combustible structure. Other parametric fire curves can for example include the influence of activated sprinkler systems on the fire, breaking of windows, etc., like the iBMB curve [45,46].

The temperature development over time for a fire will be affected by many factors, for example the design fire load, heat release rate of materials, ventilation, oxygen concentration, thermal properties of the boundaries, breakage of windows, activation of sprinkler system, fire fighting, etc. The factors have different effects on the fire; a larger design fire load will give a longer fire with higher temperatures, smaller ventilation openings will give a longer fire with lower temperatures, lower oxygen concentration will give a slower fire with lower temperatures, materials with low heat conductivity will retain heat in the compartment, breakage of windows will increase ventilation and the temperature will increase rapidly, active fire fighting measures will decrease temperatures and hopefully shorten the fire.

Hakkarainen [47] measured gas temperatures inside heavy timber construction rooms without protection. The temperatures were relatively low, around 700°C during the most intense burning phase of the mobile fire load. The reason for the low temperature was insufficient ventilation in relation to large amounts of pyrolysis gases being released. The pyrolysis gases were released from both the mobile fire load and the compartment boundaries. The generation and heating of the volatiles consumed a lot of energy, and only some of the gas could burn inside the compartment. The unburned gases flowed out the window opening and caused severe combustion outside the compartment where oxygen was available. When the generation of new pyrolysis gases decreased and most of the mobile fire load was consumed by the fire, the temperature increased as more oxygen could enter the compartment. When the construction was protected by a double layer of gypsum plasterboards, the temperature reached a maximum of 1000-1200°C for both a light timber-frame structure and a heavy timber structure.

In *Paper II* four models for calculating the temperature-time development in a fire compartment have been evaluated based on their ability to describe the temperature development in fire compartments with boundaries of cross-laminated slabs, and their applicability and suitability to these types of structures have been established. The models evaluated are; the "Swedish" model [49,50], the EN 1991-2 Standard and Parametric models [13], and the iBMB model [45,46]. The "Swedish" model was chosen because it is well known and recognized, the EN 1991-2- models are commonly used, and the iBMB model is a new model with possibilities to include other parameters than the "Swedish" and EN 1991-1-2 models. The "Swedish" model and the iBMB model were found to be best suited for a fire compartment with large exposed wooden surfaces.

Paper III - A review of models for the charring rate of solid wood, nail- and glue-laminated structural members

Paper III is a review of simple calculation models for the charring rate of solid wood, nail- and glue-laminated structural elements for use in fire design of wooden structures. The models are found in the literature. The applicability of the models to these structural elements, and their accuracy, have been evaluated based on parameters influencing the charring rate, as described in *Paper I*. Results from charring rate tests found in the literature are compared with results calculated using the charring rate models. The comparison shows that the models that include most of the influencing properties and factors give the most accurate results, but there is a wide spread of the tested and the calculated charring rates. More details are given in the paper.

Paper IV – Cross-laminated timber panels – Experimental study on the charring rates when exposed to standard and parametric fires

Paper IV describes three charring rate tests for cross-laminated timber (CLT) panels exposed to three different temperature-time developments. The CLT panels were tested in a large scale horizontal furnace, and the objectives were to examine the development of the charring rates through the fires, whether the charring rates varied between the different temperature-time curves, if the rates were affected by the panel layers or panel thicknesses, and how the furnace temperature influenced the charring rate. The charring rates did vary greatly between the different temperature-time curves and an initially fast temperature growth increased the initial charring rate. Some additional information to the paper, regarding the fire compartment, test set-up, materials, and measurements, is given below.

The fire compartment

Little research has been carried out on the charring rate in the last part of a fire, even though the building regulations in some countries require that structures have to withstand a complete fire development. The temperature-time curves were calculated based on a small compartment, with descriptions as given in *Table 3.9*.

Table 3.9. Properties of the fire compartment and the boundaries

Property	Value	Unit
Length x Width	4.08 x 3.08	m
Height	3.00	m
Floor area, A_{floor}	12.57	m²
Area of exposed wood, A_{wood}	12.57	m²
Total area incl. openings, A_{total}	68.09	m²
Area of vertical openings, A_w	2.23	m²
Average height vertical openings, h_w	1.5	m
Ventilation factor, $A_w\sqrt{h_w}$	2.73	$m^{3/2}$
Opening factor, O	0.04	$m^{1/2}$
Density, wood	500	kg/m³
Heat conduction, wood	0.13	W/mK
Specific heat capacity, wood	1900	J/kgK
Combustion value, wood	17.5	MJ/kg
Average thermal property wood, $b_{wood} = \sqrt{\rho c k}$	337	$J/m^2s^{0.5}K$
Density, concrete	850	kg/m³
Heat conduction, concrete	0.31	W/mK
Specific heat capacity, concrete	1047	J/kgK
Average thermal property of concrete, $b_{concrete} = \sqrt{\rho c k}$	525	$J/m^2s^{0.5}K$
Average thermal property enclosure, $b_{room} = \sqrt{\rho c k}$	507	$J/m^2s^{0.5}K$
Fire load density/floor area, office	511	MJ/m²

The CLT panels

The CLT panels are described in the paper, but panel T2D was not produced according to the specifications. It was supposed to have seven layers, like panel T1B and T3F, but instead it has nine layers, see *Figure 3.2* and *Table IV-1*.

more information. The panels could have been cut after testing to measure the depth of the char front and compare with the TC results as a control. The fires could have been longer or with a higher maximum temperature. However, the funding of the project and the capacity of the furnace made these things impossible.
- It would have been very interesting to incorporate some of the influencing material properties and external factors into the test set-up, but as the tests were large and comprehensive as they were this was not prioritized. In a continuation, however, this would be very interesting to include.

Paper V – Experimental charring rates for cross-laminated timber panels compared to calculated charring rates

In *Paper V* the results from the experiments on the charring rates of CLT panels reported in *Paper IV* are compared to the charring rates from EN 1995-1-2 Table 3.1 and Annex A, and charring rates calculated by the models evaluated in *Paper III*. The aim was to establish the applicability of the different charring rate models to fire exposed CLT panels. The calculated results did not match well with the experimental charring rates. Some of the calculation models need further explanations, and therefore some more information is given here. However, for complete explanations and background information refer to the sources. Many of the properties included in the calculation models are described in *Paper I*, where the most important material properties and external factors that influence the charring rate are discussed. Due to limited space, the comparison between the test results for CLT panels exposed to the "Swedish" fire and the calculated charring rates was not included in *Paper V.* However, the comparison is included here.

White and Nordheim

The model developed by White & Nordheim [48] (their Equation 11) includes char contraction and permeability of the wood by introducing two factors, f_c and Z_1, representing char contraction and permeability respectively. The char contraction factor is determined through an equation that includes the oven dry density, ρ, hardwood-softwood classification, c (c=1 for softwoods, -1 for hardwoods), and penetration depth of chemical treatment transverse to grain, d. The penetration depths for the eight species tested in [48] are listed in *Table 3.10*. The species-specific factors representing the permeability, Z_1, are also given in *Table 3.10*. Highly permeable species have low Z_1 factors, while more impermeable species have higher Z_1 factor. The impermeability will prevent the vaporized moisture from being driven into the wood and recondense. These species will therefore have a slower charring rate.

Table 3.10. Species-specific coefficients (Z_1) for Equation 11 in [48]

Species	Z_1	d (mm)
Southern pine	0.0050	31
Hard maple	*0.0063*	*47*
Basswood	*0.0080*	*30*
Yellow poplar	*0.0097*	*5*
Western red cedar	0.0113	3
Redwood	0.0156	4
Red oak	*0.0161*	*3*
Engelmann spruce	0.0205	3

Italic font - Hardwood

EN 1995-1-2

The charring rates are given in Table 3.1 of the standard for Standard fire exposure and in Annex A of the standard for Parametric fire exposure. The char depths are calculated by multiplying the charring rate with the fire duration. Annex A contains an equation for calculation of the initial Parametric charring rate and a model for the development of the Parametric charring rate over time. The parametric charring rate decreases to zero after a given time period. The development is shown in the bottom curve of *Figure V-2* in the paper. The charring rate is constant during the first third-part of the fire, after that it decreases linearly to reach zero at the end of the fire, see Figure A1 in [18]. The time period with a constant charring rate, which is also one third of the fire duration, is t_0:

$$t_0 = 0.009 * q_{t,d} / O$$

where $q_{t,d}$ is the design fire load density related to the total area of floor, walls and ceiling which enclose the fire compartment, in MJ/m², see EN 1991-1-2 [13], and O is the opening factor based on the ventilation openings. A large fire load density gives a longer t_0, i.e. longer time before the charring rate starts decreasing. A larger opening factor gives smaller t_0, i.e. shorter time before the charring rate starts decreasing.

The charring rate can be calculated at any time of the fire, based on t_0 and the charring rate β_{par}, using one of three equations given in Section A2(2) in [18].

"Swedish" fire exposure

As mentioned above, the comparison between the test results and the calculated results for CLT panels exposed to the "Swedish" fire, (see *Paper IV)* were not included in *Paper V* due to space limitations. The results are therefore reported here.

The char depth and charring rate results for the CLT panels exposed to the "Swedish" fire [49,50] have been compared with char depths and charring rates calculated by the model in EN 1995-1-2 Annex A Parametric [18] and Bobacz [51], because they are the only models for parametric charring rates, see *Table V-2* and *Figure 3.4*. During the last experiment only one charring rate measurement was achieved because the fire duration was very short and only resulted in charring at 10 mm depth for both panels. The char front reached 10 mm at the same time for both CLT panels in the test, thus the two results are shown in one common point in the figure.

The char depth increases very fast for the EN 1995-1-2 model, while for Bobacz's model it has a much slower growth (see *Figure 3.4*). For both curves the char depth grows slower with time.

The char depths from the experiments were distinctively lower than the EN 1995-1-2 Annex A Parametric model, and slightly lower than Bobacz's model. EN 1995-1-2 has a constant charring rate in the initial stage of the fire, while Bobacz's model does not calculate the rate during the first 10 minutes of the fire (see *Figure 3.4*). Both curves have a drop in the charring rate after the initial stage of the fire, but Bobacz's model has an earlier drop in the rate than the EN 1995-1-2 model. During the decay stage of the fire, the charring rate for Bobacz's model decreases slower than earlier in the fire.

It is impossible to draw any conclusions on how well the calculation models match the test results based on only one measuring point, but Bobacz's curve is closer to the test result than the EN 1995-1-2 Parametric model.

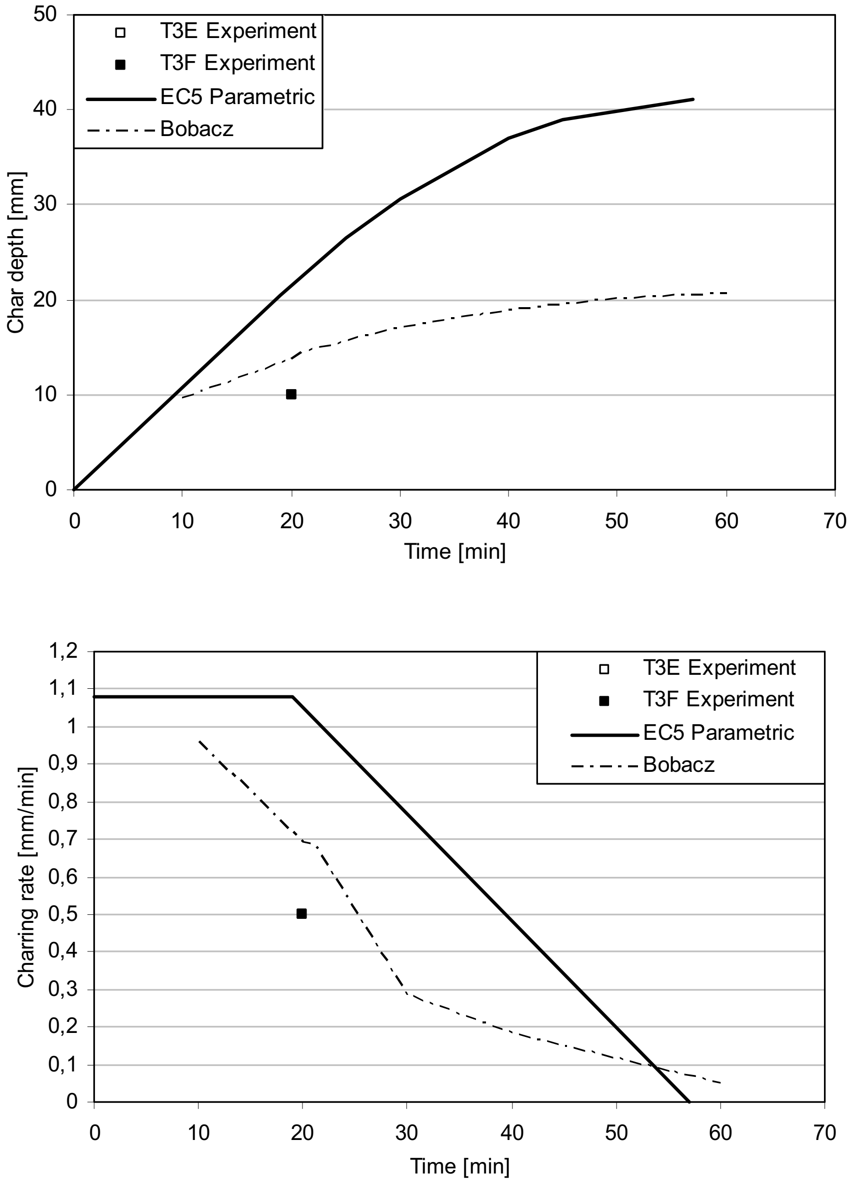

Figure 3.4. Char depths and charring rates from experiments and calculations. The results for T3E and T3F coincide with each other. "Swedish" fire exposure [49,50]

3.3 Paper I – Material properties and external factors influencing the charring rate of solid wood and glue-laminated timber

by
Kathinka Leikanger Friquin

In a review process with the journal:
Fire and Materials

Is not included due to copyright

3.4 Paper II - Evaluation of natural and parametric temperature-time curves for the design of cross-laminated wood slabs

by
Kathinka Leikanger Friquin

Published in:
Wald, F., Kallerova, P., Chlouba, J. (Eds.), *Proceedings of International Conference Application of Structural Fire Design*, Czech Technical University in Prague, pp. 563-568, 2009.

Presented at:
International Conference Application of Structural Fire Design, Prague, Czech Republic, 19-20 February 2009.

Introduction

Many temperature-time curves for performance-based fire design have been developed, but most of them are only applicable to concrete, brick, lightweight concrete and steel structures. As most of the methods for determining the temperature-time development in a fire compartment only include the fire load of the furniture and other contents in the fire compartment, few of the temperature-time curves developed give a correct picture of the temperature development in a compartment surrounded by combustible wooden structures. The contributions made to the fire load by the wooden boundaries and structures are very often ignored, resulting in an optimistic temperature development. In the present article, temperature-time curves found in the literature for complete fires, including growth stage, flashover, fully developed fire and decay stage, have been evaluated based on their ability to describe the temperature development in compartments with boundaries of cross-laminated slabs, their applicability and suitability to these types of structures. Four models for determining temperature-time curves that might be applicable to wooden structures were found. The project is funded by the Norwegian Research Council.

Description of temperature-time curves for wooden structures

As many of the temperature-time curves for fires in compartments are developed mainly for testing and design of non-combustible structures, such as concrete and steel, the applicability of these curves to wooden structures must be evaluated. There are a few different types of wooden structures, like light frame walls, glue-laminated structures with insulation and plasterboards between the columns, fully exposed glue-laminated structures, and partly or fully exposed cross-laminated slabs. The different structures will give different temperature-time curves, and the charring rate may vary. In this paper only cross-laminated slabs have been considered. The curves consider various parameters, and for wooden structures the important parameters might be different from steel and concrete structures. The applicability to wooden structures therefore has to be considered for each and every temperature-time curve.

The "Swedish curves"

Magnusson and Thelandersson (1970) developed temperature-time curves describing all stages of the fire (growth, flashover, fully developed and decay/cooling) for seven different compartments, designated A-G, based on their bounding surfaces, see *Figure II-1*. Curves for compartments with wooden boundaries are not developed. The curves are developed based on the fire load density (MJ/m² of bounding surface area), the area and height of the ventilation openings, the thermal properties of the bounding surfaces, and the heat balance in the compartment, i.e. heat transfer through the structures bounding the enclosed space, radiation through the openings, and the replacement of combustion gases by cold air. *Figure II-1* below shows temperature-time curves for compartment A with opening factors 0.04 and 0.08 $m^{1/2}$, and various fire loads.

The curves developed by Magnusson and Thelandersson (1970) are based upon a few assumptions:

a) The temperature in the interior of the whole enclosed space is uniform at any given instant.
b) The coefficient of heat transfer to the interior bounding surfaces of the enclosed space is uniform at every point.

c) The heat flow through the bounding structures of the enclosed space is one-dimensional and, except for the window and door openings, if any, uniformly distributed.

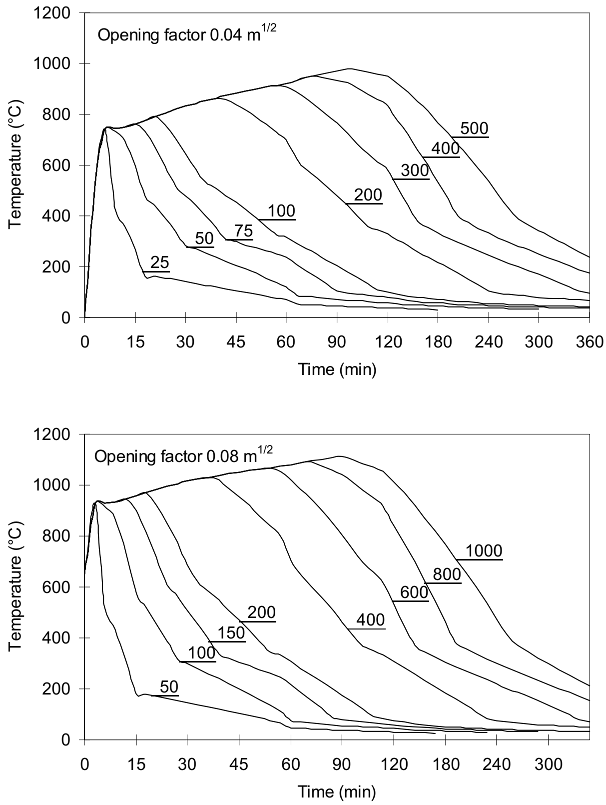

Figure II-1. Temperature-time curves for a complete fire developed, for compartment A with opening factors 0.04 and 0.08 m$^{1/2}$. The numbers on each curve are the fire load densities distributed on the total surface area

Pettersson and Ödeen (1978) developed correction factors, k_{fict}, to convert the curves for the standard compartment A into curves for the other defined compartments. The correction factors range from 1.0, for bounding surfaces with thermal properties averaging between concrete, brick and lightweight concrete, to 3.0, for steel sheets and mineral wool. The correction factors are based upon thermal differences in the bounding surfaces of the compartments. Magnusson and Thelandersson (Magnusson & Thelandersson, 1970) did not calculate curves for compartments with wooden boundaries, and Pettersson and Ödeen (1978) did not calculate correction factors for such compartments. However, according to König et al. (König et al., 1997) the correction factors can be calculated based on the thermal properties of the boundaries of the compartments, as given in *Eq. (1)*:

$$k_{fict} = \frac{1160}{\sqrt{\lambda \rho c}} \tag{1}$$

where λ is the thermal conductivity of the enclosure [W/mK], ρ is the density of the enclosure [kg/m³] and c is the specific heat of the enclosure [J/kgK]. For a fire compartment with uniform boundaries of cross-laminated wooden elements of pine or spruce typically used in Scandinavia, with density 500 kg/m³, specific heat 1900 J/kgK, and thermal conductivity 0.12 W/mK, the correction factor k_{fict} will therefore be 3.44. Procedure:

1. Calculate the opening factor, O:

$$O = A_v \sqrt{h} / A_t \tag{2}$$

where A_v is the total area of vertical openings on all walls [m²], A_t the total area of the enclosure (walls, ceiling and floor, including openings) [m²], and h the weighted average of window heights on all walls [m].

2. Determine the fire load density, $q_{t,d}$ (fire load density per unit total surface area):

$$q_{t,d} = \Sigma(M_{k,i} \cdot H_{ui} \cdot m) / A_t \quad \text{[MJ/m}^2\text{]} \tag{3}$$

where $M_{k,i}$ is the amount of the combustible material *i* in the compartment [kg], H_{ui} the net calorific value of material *i* [MJ/kg], *m* the combustion factor, and A_t the total area of the enclosure (walls, ceiling and floor, including openings) [m²].

3. Calculate the correction factor, k_{fict}, as given in *Eq. 1*.

4. Find corrected opening factor, O_{fict}, and fire load density, $q_{t,d,fict}$, by multiplying O and $q_{t,d}$ with k_{fict}.

5. Find the curve for compartment A with O_{fict} and $q_{t,d,fict}$, and use it as the temperature-time curve for the fire. For fire compartments with O_{fict} and $q_{t,d,fict}$ other than those found in the curves, interpolation can be used to determine the temperature-time development.

The curves can be found in Magnusson and Thelandersson (1970) and Pettersson and Ödeen (1978).

EN 1991-1-2 Standard temperature-time curve

The standard temperature-time curve in (EN 1991-1-2, 2003) is given by:

$$\theta_g = 20 + 345 \log_{10}(8t + 1) \tag{4}$$

where θ_g is the gas temperature in the fire compartment [°C] and *t* the time [min].
In Sweden a cooling rate of 10°C/min has been used.

EN 1991-1-2 Parametric temperature-time curve

The procedure to calculate a temperature-time curve based on (EN 1991-1-2, 2003) is as follows:

1. Calculate temperature-time curve for the heating stage, found in EN 1991-1-2 Annex A (3):

$$\theta_g = 20 + 1325\ (1 - 0.324e^{-0.2t^*} - 0.0204e^{-1.7t^*} - 0.472e^{-19t^*}) \tag{5}$$

where θ_g is the gas temperature in the compartment [°C]. The gas temperature is a function of time, opening factor, and thermal properties (density, specific heat and thermal conductivity) of the boundary of the compartment.

2. Calculate the maximum temperature, $\theta_{\max}$, in the heating stage using EN 1991-1-2 Annex A (7). If t_{max}= t_{lim} the fire is fuel controlled, and if t_{max}> t_{lim} the fire is ventilation controlled.

3. The cooling stage of the fire is calculated based on the maximum temperature, $\theta_{\max}$, the opening factor, *O*, the product of the density and thermal properties, *b*, $t*_{\max}$, and a factor x, which express whether the fire is fuel controlled or ventilation controlled. Three different equations describe the cooling stage, based on the duration of the fire. The cooling stage is a function of time, opening factor, and thermal properties of the boundary of the compartment.

iBMB parametric fire curve

The iBMB parametric fire model is described by (Zehfuss & Hosser, 2007) and (Zehfuss, 2004) as a model that considers the actual boundary conditions of the fire compartment concerning fire load, ventilation conditions, geometry and thermal properties of the enclosure. The parametric equations for the temperature-time curve were developed for a reference fire load density of $q'' = 1300$ MJ/m² (upper value for residential and office buildings). The procedure when determining iBMB parametric fire curves:

1. Calculate opening factor *O*, fire load density *q*, total fire load Q, averaged thermal property of the boundaries, total area of boundaries incl. openings A_t, total area of boundaries excl. openings A_T.

2. Calculate the maximum rate of heat release $\dot{Q}_{\max} = \min\left[\dot{Q}_{\max,v};\dot{Q}_{\max,f}\right]$ and determine whether the fire is ventilation or fuel controlled during the fully developed fire stage.

3. The curves have three distinct points at the times t_1, t_2 and t_3, where the slope of the curves changes, see *Figure II-2*. Growth stage: From the initiation of the fire until t_1, the RHR rises quadratically, $\dot{Q}(t) = \dot{Q}_0\left(t/t_g\right)^2$[MW], where $\dot{Q}_0 = 1$ MW and $t_g = 300$ s (for residential and office buildings). The upper layer temperature increases rapidly at this stage. Fully developed fire: At t_1 the RHR has reached its maximum, $\dot{Q}_{\max}$, and remains constant until t_2. Between t_1 and t_2 the upper layer temperatures increases moderately, reaching its maximum at t_2. Cooling stage: 70% of the fuel is consumed at t_2 and the RHR drops off linearly, at the same time the upper layer temperature starts to decline. At t_3 the total fire load is consumed and the RHR decreases to 0, and the upper layer temperature-time curve bends and declines slower than before. The times t_1, t_2 and t_3 must be calculated for both the maximum fire load density, q'', for the actual building category, and the actual fire load density for the specific compartment, q''_x. The first point, t_1, is common for both fire load densities. For fire load densities less than the maximum q'', the maximum temperature is achieved accordingly earlier, see *Figure II-2*.

4. The temperatures T_1, T_2 and T_3 for the maximum fire load density of $q'' = 1300$ MJ/m² can be calculated based on the RHR curve, and the temperature-time curve can be calculated based on the parametric equations for ventilation or fuel controlled fires, according to the

results from bullet No. 2 above. The equations are given in (Zehfuss, 2004 and Zehfuss & Hosser, 2007).

5. When the temperature-time curve for the maximum fire load density q'' is drawn, the temperatures $T_{2,x}$ and $T_{3,x}$ can be found. $T_{2,x}$ is found on the curve at time $t_{2,x}$. $T_{3,x}$ is found on the $T_{3,x}$ Log_{10}-curve described by $T_{3,x} = (T_3 / \log_{10}(t_3 + 1)) \cdot \log_{10}(t_{3,x} + 1)$ at time $t_{3,x}$. The temperature-time curve for a fire compartment with a fire load density $q'' \leq 1300$ MJ/m² can now be drawn based on the parametric equations given in (Zehfuss, 2004 and Zehfuss & Hosser, 2007).

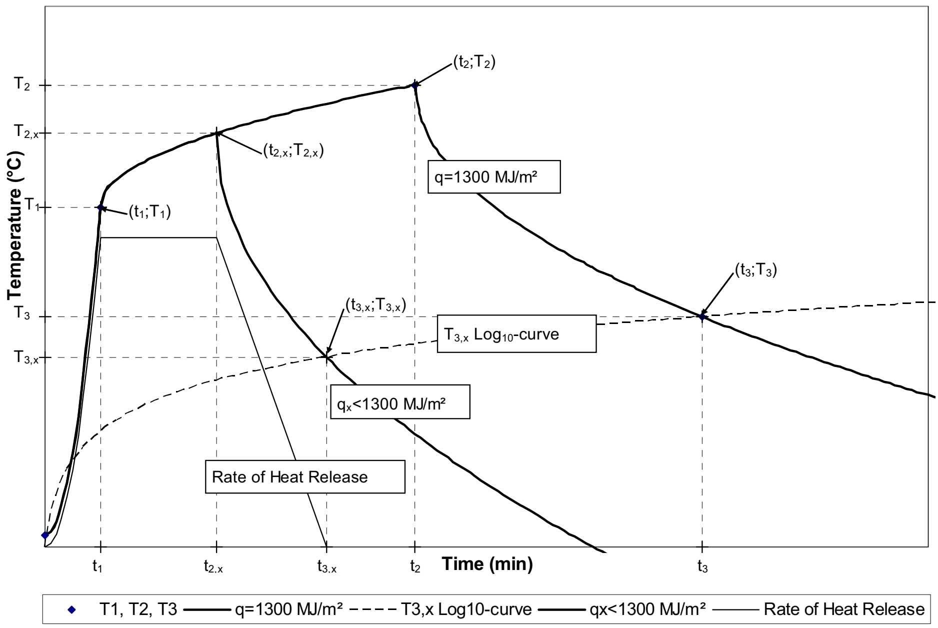

Figure II-2. Determination of the temperatures $T_{2,x}$ and $T_{3,x}$. Rate of Heat Release and temperature-time curve for q<1300 MJ/m², and the temperature-time curve for q=1300 MJ/m². $T_{3,x}$ Log_{10}-curve for determination of $T_{3,x}$

The trend of some of the curves described in this paper is shown in *Figure II-3*.

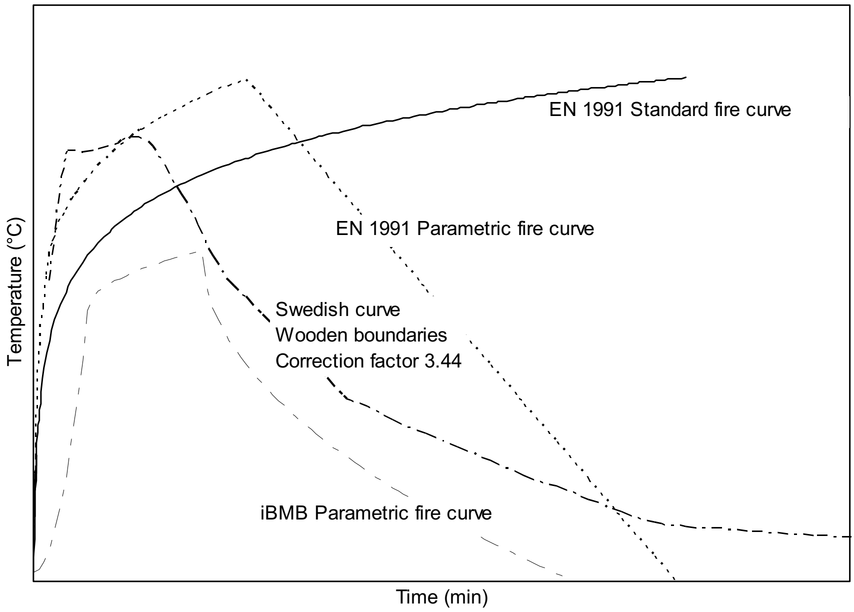

Figure II-3. The typical trend of some of the temperature-time curves described; EN 1991-1-2 Standard fire curve and Parametric fire curve, "Swedish fire curve", and iBMB Parametric fire curve. The curves are not to scale with each other.

Summary and discussions

The models and curves described above have been evaluated based on their ability to describe the temperature development in compartments with boundaries of cross-laminated slabs, their applicability and suitability to these types of structures. Five models for determining temperature-time curves that might be applicable to wooden structures were found. Most of the curves are initially developed for testing and design of non-combustible structures, but have later also been assigned for combustible structures. Experimental research, performed through the years by various laboratories, has shown that the accuracy of the temperature-time development compared to real fires is not always good. And from time to time new models for determination of temperature-time curves are developed. It is therefore necessary to study the various models and determine which ones are more applicable to wooden structures.

The "Swedish curves"

Magnusson and Thelandersson (1970) and Pettersson and Ödeen (978) have not given correction factors for fire compartments with wooden boundaries, but König et al. (König et al., 1997) describes how to calculate the correction factor for compartments with boundaries of various thermal properties. For a compartment with exposed cross-laminated slabs on all surfaces, the correction factor was here calculated to be 3.44. This correction factor considers the thermal properties of the boundaries, i.e. the density, the thermal conductivity and the specific heat capacity of the material. The charring rate and fire load of the boundary material is not considered. It might be reasonable to first determine the temperature-time curve only based on the fire load of the inventory to find the fire duration, and then add the fire load from the boundaries calculated based on the nominal charring rate from EN 1991-1-2 and the fire duration first found. A new curve can then be found based on the new fire load density and the old opening factor. The assumptions made when developing the method simplify the curves considerably.

EN 1991-1-2 Standard temperature-time curve

The development of the fire is very dependant on the type of building you are designing. The standard temperature-time curve given by EN 1991-1-2 (2003) is very conservative for slow growing fires, less so for medium growth fires and only a little for fast growing fires. The curve only describes the heating stage, and does not consider the boundary conditions or the fire load density. A cooling stage of 10°C/min has been used in Sweden, but the real cooling stage for combustible structure is not linear.

EN 1991-1-2 Parametric fire

There are many limitations to the use of the parametric fire curve given by EN 1991-1-2 (2003). For example, the maximum floor area is 500 m², maximum compartment height 4 m, thermal properties $b = \sqrt{\rho c \lambda}$ between 100 and 2200 J/m^{2}s$^{1/2}$K, and opening factor between 0.02 and 0.20. To incorporate the charring of the structure, the maximum fire duration is 120 min, with a maximum char depth of ¼ of the height or width of the structural member. The thermal properties can be taken at ambient temperature, but for most materials these properties are strongly temperature dependant.
The fire load density is calculated based on the combustible inventory in the compartment and "the relevant combustible parts of the construction, including linings and finishing. Combustible parts of the construction which do not char during the fire need not to be taken into account" (EN 1991-1-2, 2003). The "relevant combustible parts of the construction" can only be found when we know the development of the fire, which in turn can only be found when we know the total fire load density. Through iterations the temperature-time development and the contribution from the construction to the fire load density can be found.

iBMB model

The iBMB parametric fire curves can be used to determine the occurrence of flashover, breakage of windows with additional ventilation, a failure of the enclosure with loss of compartmentation, or the effect of fire fighting and sprinkler systems. The connection between the design fire and the parametric fire curve makes it possible to consider all events influencing on the natural fire and resulting in a variation of the RHR.

Experiments performed by (Hakkarainen, 2002) show that the temperature-time curve for a small compartment with exposed heavy timber structures a relatively small opening factor can have a plateau at a relatively low temperature due to insufficient ventilation. As much as 50% of the pyrolysis gases burnt outside the compartment. When most of the movable fire load has burnt, the temperature might increase as the generation of pyrolysis gases decrease, allowing more oxygen into the compartment. None of the curves above show this phenomenon.

Conclusions

Four temperature-time curves have been evaluated based on their applicability to exposed wooden structures. Based on the evaluation of the temperature-time curves, the following conclusions can be drawn:

1. The geometry of the compartment, and the position and size of the ventilation openings will have a great effect on the temperature, flashover and decay stage of the fire.
2. Many of the curves have growth rates much higher than real fires.
3. Linear cooling stages are not realistic. Fire curves with linear cooling stage give too fast cooling for compartments with large surfaces of exposed wooden structure.
4. None of the curves include the fire load from the structure directly. Iterations have to be made to incorporate this contribution to the fire.
5. Assumptions can be made to determine a relevant part of the structure to be part of the fire load.
6. The "Swedish curves" and the iBMB curves resemble a real fire in a compartment with exposed wooden structures most.

Using a realistic fire development and determining the overall structural behaviour can lead to an efficient and aesthetical construction.

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3.5 Paper III - A review of models for the charring rate of solid wood, nail- and glue-laminated structural members

by
Kathinka Leikanger Friquin

Published in:
Journal of Structural Fire Engineering (2010), Volume 1, Issue 1, pp. 61-72.

Abstract

Simple calculation models for charring rate of solid wood, nail- and glue-laminated structural elements for use in fire design of wooden structures have been compared with test results from the literature. The applicability to these structural elements, and the accuracy of the models, have been evaluated based on parameters influencing the charring rate, which include species, density, moisture content, char contraction factor, external heat flux, oxygen concentration and duration of the fire. The models evaluated in this article are applicable to one- or two-dimensional charring under standard fire exposure.

Introduction

The use of solid wood elements and glue-laminated beams and columns in buildings and structures is gaining popularity in the Nordic countries, and these types of structural members have already been widely used around the world. In countries where timber is a readily available resource, it is a natural choice as construction material. The fire resistance of solid wood, cross-laminated slabs, and nail- or glue-laminated structural members is important when used in buildings, and in many cases, the fire safety of a building with these wooden elements can match or even succeed that of other structural materials. To design a fire safe wooden building the thermal properties of the material, the thermal conditions in the fire compartment and the charring rate of the material must be known. When wood is exposed to elevated temperatures, several factors regarding the material, the conditions in the room and the heat source affect the charring rate. Many attempts have been made to develop models to describe the charring rate of wood and how different factors influence on the charring, but most models only include a few of these factors.

The charring rate of wood can be influenced in many ways. For instance, large wooden elements are not oven-dry like many test specimens, they have a smaller exposed surface to volume-ratio, and the mass and heat transfer in large cross sections is different from the small test pieces that are commonly used in experiments. Multi-storey wooden structures, with the requirement of maintaining their load bearing abilities through a natural fire, will be exposed to a varying heat flux. This will also change the charring rate. There are several other parameters that will affect the charring rate. Many thorough reviews of pyrolysis models for wood can be found, but few of them emphasize on the charring rate of solid wood or glue-laminated structural elements, nor the importance of including the density, moisture content, chemical composition and other factors in the models.

In the present paper, several models for calculating the charring rate of solid wood, nail- or glue-laminated structural members from the literature are evaluated in regards to which parameters influencing the charring rate they include, i.e. species, density, moisture content, char contraction factor, external heat flux, oxygen concentration and duration of the fire. The reliability and fitness for use of the models are examined based on the parameters included in the model, and the possibility to adjust the material properties and thermal conditions with variations in the species, room or exposure conditions. The models most suited for calculation of charring depths of solid or cross-laminated wood elements and glue-laminated timber beams and columns are determined. The charring rate for a few solid, nail- and glue-laminated cross sections have been calculated and compared with experimental results found in the literature. The current study is limited to unprotected solid wood elements and nail- or glue-laminated beams and columns exposed to standard fire. Models for parametric fire exposure are not included in this article, because these models require that the opening factors and heat exposure for the experiments are known in order to compare them with each other. Only wood species commonly used in Europe and North-America are included.

Calculation models for charring

Several charring rate models for structural wooden slabs and members have been found in the literature and evaluated here. The models are; EN 1995-1-2[1] (EC 5) (one- and two-dimensional, designated a and b respectively), Schaffer[2], White and Nordheim[3] Babrauskas[4] Yang et al.[5]and American Wood Council (AWC)[6]. The models are in *Table III-1* separated into two groups; one-dimensional charring models and two-dimensional charring models. The one-dimensional charring models do not include corner rounding, while the two-dimensional models do (See *Figure III-1*). Charring models are developed for various types of fire exposure, and in the current research focus is set on EN 1991-1-2[7] and ASTM E119[8] standard fire exposure, in the following referred to as EC1s and ASTM fires, respectively. The models include various factors that might have an influence on the charring rate, as can be seen in the last column in *Table III-1*.

Table III-1. Separation of models for charring of wood into a group for one-dimensional charring and a group for two-dimensional charring

Reference	Year	Fire exposure EC1s	ASTM	Other*	Factors included in model
One-dimensional					
EC 5a[1]	2004	X			Softwood/hardwood, density, solid or laminat
Schaffer[2]	1967		X		Dry density, moisture content, species
White & Nordheim[3]	1992		X		Dry density, moisture content, species, char contraction factor, permeability of wood
Babrauskas[4]	2005	X	X		Density, oxygen concentration, heat flux, duration of fire
Yang et al.[5]	2008			X	Density, time-increasing heat flux rate.
Two-dimensional					
EC 5b[1]	2004	X			Softwood/hardwood, density, solid or laminated, cross-section
AWC[6]	2003		X		Duration of fire

* Time-increasing heat flux (Yang et el. used 0.070, 0.113, 0.208, 0.306 and 0.425 kW/m²s).

Table III-2. EN 1995-1-2[1]: Design charring rate β_0 and notional charring rate β_n of timber

	β_0 mm/min	β_n mm/min
a) Softwood and beech		
Glue-laminated timber with characteristic density of ≥ 290 kg/m³	0.65	0.7
Solid timber with a characteristic density of ≥ 290 kg/m³ (incl. beech)	0.65	0.8
b) Hardwood		
Solid/glue-laminated hardwood, characteristic density of 290 kg/m³	0.65	0.7
Solid/glue-laminated hardwood, characteristic density of ≥ 450 kg/m³	0.50	0.55

Note: Charring rates for solid hardwoods, except beech, with characteristic densities between 290 and 450 kg/m³, may be obtained by interpolation between the values.

Table III-3. Models for charring rate of wood

References, comments and limitations	Equation
One-dimensional – EC1s fire	
EN 1995-1-2 Model a (EC 5a)[1]	β_0 (mm/min) (1) where β_0 is taken from *Table III-2*.
One-dimensional – ASTM E119	
Schaffer[2] Charring rate converted to (mm/min) by: $\beta = 25.4/\tilde{\beta}$.	Douglas fir $\tilde{\beta} = 2\left[(28.726 + 0.578\omega)\rho_{dry} + 4.187\right]$ (min/inch) (2) Southern pine $\tilde{\beta} = 2\left[(5.832 + 0.120\omega)\rho_{dry} + 12.862\right]$ (min/inch) (3) White oak $\tilde{\beta} = 2\left[(20.036 + 0.403\omega)\rho_{dry} + 7.519\right]$ (min/inch) (4)
White and Nordheim (W & N)[3] Their equation No. 11.	$\beta = 0.1526 + 0.5080\rho_{dry} + 0.1475 f_c + Z_f\omega$ (mm/min) (5)
Babrauskas[4] The equation is applicable to both EC1s fire and ASTM E119 fire.	$\beta = 113 k_{O2} \frac{(\bar{\dot{q}}'')^{0.5}}{\rho t^{0.3}}$ (mm/min) (6) where $k_{O2} = 1.0$ for charring in high oxygen concentration, 0.8 for charring in 8-10%, and 0.55 for charring in 4% oxygen concentration.
One-dimensional – Others	
Yang et al.[5] For time-increasing heat flux. The increasing rate of heat flux for ASTM fire, approximately 0.07 kW/m²s, is used in *Table III-5*.	$\beta_\gamma = 136\gamma^{0.51} \cdot \rho^{-0.76}$ (mm/min) (7)
Two-dimensional – EC1s fire	
EN 1995-1-2 Model b (EC 5b)[1] Notional charring rate.	β_n (mm/min) (8) where β_n is taken from *Table III-2*.
Two-dimensional – ASTM E119	
American Wood Council (AWC)[6]	$\beta_{eff} = \frac{2.58\beta_n}{t^{0.187}}$ (mm/min) (9) where β_n is assumed to be 0.635 mm/min and t in min.

Figure III-1. EN 1995-1-2[1]: a) One-dimensional charring of wide cross-section with fire exposure on one side. b) Charring depth, $d_{char,0}$*, for one-dimensional charring and notional charring depth,* $d_{char,n}$*, for two-dimensional charring*

Calculated charring rates compared with test results

General

The calculation models listed in *Table III-3* have been compared with charring rate results from experiments performed by various laboratories. A short description of the experiments referred to in this article is given in *Table III-4*.

Test results for dry density wood have only been compared with models using dry density in the equation, and models using wet density have only been compared with test results for wet density wood. The only exception is calculation results for EN 1995-1-2[1] which normally are valid for wet density wood, but is also applicable to dry density wood where the wet density can be assumed based on the dry density. This is because the charring rate is constant for densities above 290 kg/m³ for softwoods, and for hardwoods the charring rate is constant for wood densities at 290 kg/m³ and for densities above 450 kg/m³. The comparisons are given in *Table III-5* and *Table III-6* below. The left half of the tables gives details and results from the experiments, while the right part gives results from the calculation models. For the experiments the species, reference number, density and charring rate results for two different moisture contents of the wood are given. In the other half of the tables, where the calculation model results are given, the models' short name, equation number and results for 60, 90 and 120 minutes exposure are given.

Babrauskas[4] found the average heat flux in the ceiling during ASTM E119 fire to be approximately 92 kW/m² at 60 minutes. This heat flux is therefore used in the calculations, together with 8-10% oxygen, where applicable.

Table III-4. Details about the experiments used for comparisons

Author	Species	Test apparatus / Fire exposure / Orientation / Exposed sides, duration	Specimen size (mm x mm)
White[9]	*Softwood*: Engelmann spruce, Western cedar, Southern pine, Redwood *Hardwood*: Hard maple, Yellow poplar, Red oak, Basswood	Small gas-fired furnace ASTM E119 Vertical One side, 60 minutes	Glue-laminated slabs 63 x 230, 510 mm long, 38 or 46 mm thick laminates
Cedering[10,11]	*Softwood:* Norway spruce	Gas-fired furnace EC1s fire Vertical One side, 60 minutes	Nail-laminated 40 x 140, 1000 mm long Samples nailed together to form a wall of 55-60 planks
König[12]	*Softwood:* Spruce	Small gas-fired furnace EC1s fire Horizontal One side, 30-60minutes	Nail-laminated slabs 315 x 1500, 95 mm thick, 7 laminates of 45 mm thickness nailed together
Landrø[13]	*Softwood:* Spruce	Gas-fired furnace EC1s fire Horizontal One side, 90 minutes	Cross-laminated timber panel 4800 x 3600, 160 mm thick. Loaded with 3 kN/m².
Frangi and Fontana[14]	*Softwood:* Spruce	EC1s fire Beams; three sides Slabs; one side 30-110 minutes	Glue-laminated timber beams, and slabs made of nailed planks, 120 mm thick
Landrø[15]	*Softwood:* Spruce	Gas-fired furnace EC1s fire Beams; three sides Columns; four sides 30 minutes	Glue-laminated timber beams and columns 90 x 300, 1400 mm long 1300 mm long

One-dimensional charring

One-dimensional charring rate results from the experiments listed in *Table III-4* have been compared with calculated results using the one-dimensional models from *Table III-3*. The results are given in *Table III-5* below. The equation for the char contraction factor, f_c, and the values for the species-specific coefficient, Z_1, in eqn (5) can be found in White and Nordheim[3]. The char contraction factor is calculated based on the permeability of the wood, hardwood/softwood, and dry density. The species-specific coefficient is a value for the permeability of the wood, based on the hypothesis that the charring rate is slower when the impermeability of the wood prevents the vaporized moisture from being driven into the wood and recondensing. König[16] suggested that the notional charring rate for solid timber, eqn (8) in *Table III-3*, should be used for nail-laminated timber slabs with normal gap widths to achieve conservative results. This is included in the table. Schaffer's models take into account the moisture level in the wood, and charring rates for the two moisture levels have therefore been calculated. The appropriate moisture level is marked with a cross in the correct column. Species written with *italic font* are hardwood species, while calculation results written in <u>underlined font</u> have the best match with the test results. The charring rate test results are compared with the calculated results with the same or similar exposure time.

Table III-5. Calculated charring rates (mm/min) compared with test results from the literature, for one-dimensional charring of nail- and glue-laminated wood

Experiments – Results (mm/min)					Calculation models – Results (mm/min)				
	Density		Moisture (%w)				Exposure time (min)		
Species	(kg/m³)	Ref	10-12	16-18	Model	Eqn	60	90	120
Nail-laminated									
Spruce	370	10,11	0.71	0.64	EC 5a	(1)	0.65	0.65	0.65
	370				Babrauskas	(6)	0.69	-	-
	370				Yang et al.	(7)	0.39	0.39	0.39
	370				König[16]	(8)	0.80	0.80	0.80
Spruce	425	12,14	0.70		EC 5a	(1)	0.65	0.65	0.65
	425		0.70		Babrauskas	(6)	0.60	-	-
	425				Yang et al	(7)	0.35	0.35	0.35
	425				König[16]	(8)	0.80	0.80	0.80
Glue-laminated									
Spruce	400*	9	0.59	0.52	EC 5a	(1)	0.65	0.65	0.65
(Douglas fir)	400*		x		Schaffer	(2)	0.69	0.69	0.69
				x	Schaffer	(2)	0.64	0.64	0.64
	400*		x		W & N	(5)	0.61	0.56	0.53
	400*			x	W & N	(5)	0.53	0.49	0.47
	475	13	0.64		EC 5a	(1)	0.65	0.65	0.65
	475				Babrauskas	(6)	0.54	-	-
	475				Yang et al	(7)	0.32	0.32	0.32
Cedar	285*	9	0.75	0.73	EC 5a	(1)	0.65	0.65	0.65
	285*		x		W & N	(5)	0.75	0.69	0.66
	285*			x	W & N	(5)	0.68	0.63	0.60
Pine	485*	9	0.76	0.83	EC 5a	(1)	0.65	0.65	0.65
	485*		x		W & N	(5)	0.76	0.70	0.66
	485*			x	W & N	(5)	0.72	0.67	0.64
Redwood	324*	9	0.76	0.62	EC 5a	(1)	0.65	0.65	0.65
	324*		x		W & N	(5)	0.68	0.63	0.60
	324*			x	W & N	(5)	0.61	0.56	0.53
Maple	650*	9	0.66	0.64	EC 5a	(1)	0.50	0.50	0.50
	650*		x		W & N	(5)	0.66	0.62	0.58
	650*			x	W & N	(5)	0.63	0.59	0.56
Yellow poplar	482*	9	0.68	0.68	EC 5a	(1)	0.50	0.50	0.50
	482*		x		W & N	(5)	0.70	0.65	0.61
	482*			x	W & N	(5)	0.65	0.60	0.57
Oak	635*	9	0.57	0.56	EC 5a	(1)	0.50	0.50	0.50
	635*		x		Schaffer	(4)	0.55	0.55	0.55
				x	Schaffer	(4)	0.51	0.51	0.51
	635*		x		W & N	(5)	0.57	0.53	0.50
	635*			x	W & N	(5)	0.52	0.48	0.46
Basswood	385*	9	0.87	0.70	EC 5a**	(1)	0.62	0.62	0.62
	385*		x		W & N	(5)	0.78	0.73	0.69
	385*			x	W & N	(5)	0.73	0.68	0.64

* Dry density **Interpolated

Conclusions

Test results from experiments found in the literature have in this article been compared with calculation models for the charring rate of wood. The experiments differ widely in the type of species tested, moisture content, cross-section sizes, heat flux, oxygen content etc. and are therefore difficult to compare. Detailed guidelines and methods for testing of charring rates of wood must be developed, where the moisture content, oxygen concentration, sample size and orientation, heat exposure, etc are described for various types of end uses of the test results. This will enable researchers all over the world to compare their test results with each other, and the reproducibility of the tests would be better.

There is a need for more comprehensive charring rate experiments on the most commonly used wood species for building construction. The test results can be used to develop more accurate charring rate models, incorporating several of the influencing factors like; density, moisture content, species, heat flux, fire duration, opening factor, permeability, etc.

For one-dimensional fire exposure of nail-laminated members EC 5a, eqn (1), and Babrauskas' model, eqn (6), gave the most accurate charring rates compared with the test results. Babrauskas gave the best fit for the lowest density, while EC 5a gave the best fit for the higher density. The suggestion from König[16]for nail-laminated slabs was very conservative.

For glue-laminated spruce White and Nordheim's model, eqn (5), gave the best fit with the test results for dry density 400 kg /m³, while EC 5a, eqn (1), gave the best fit for wet density 425 kg/m³. For the other softwood species the calculated results from White and Nordheim's model matched the test results with various accuracy, always better than EC 5a. The calculated charring rates for oak with 10-12% moisture content based on White and Nordheim's model, and Schaffer's model, eqn (4), compared very well with the test results, while for 16-18% moisture content the match was not as satisfactory. The comparison between test results and calculated results using White and Nordheim's model was very good for maple and yellow poplar, good for basswood with moisture content 16-18%, and not good for basswood with moisture content 10-12%.

The comparison of the test results and calculation models for two-dimensional charring shows that for solid *spruce* the AWC model, eqn (9), is closer to the test results, but still 15% higher at 60 minutes. The calculation results from EC 5b, eqn (8), are 19% higher than the test results. For glue-laminated *spruce* the model in EC 5b matches very well with the test results, while the AWC model is very conservative at 60 minutes.

The comparisons of the models with test results show that the models that include more factors also give more accurate results, and the variations between species are large.

- White and Nordheim's model, eqn (5), contains the most factors and was in most cases where it could be used the best match with the test results. However, it would be an advantage if the wet density could be used in the calculations.
- The models from EC 5a and EC 5b, eqns (1 and 8), include variations between softwood and hardwood, density regions, and whether the member is solid or glue-laminated, but did not match the test results in many cases.
- Schaffer's models, eqns (2-4), include both dry density and moisture content, and differ between species. Unfortunately, Schaffer only developed variations of the model for three species. Model variations for more species should be developed.

- Babrauskas' model, eqn (6), includes density, oxygen concentration, heat flux and fire duration, and gave a good match in some cases.
- Other models also include density, heat flux or fire duration, but none of them differ between species, or include heat flux, density and fire duration at the same time.

The wide spread of test results and calculated results for the charring rate shows the obvious need for more research on charring rates for various wood species and fire exposures, and for redevelopment of charring rate models for use in fire safety design of wooden buildings.

Acknowledgements

The project is part of the Strategic University Programme "Wood as a building material" at the Norwegian University of Science and Technology, funded by the Research Council of Norway.

Nomenclature

Latin letters

Z_1	Species-specific coefficient
$d_{char,0}$	Charring depth for one-dimensional charring (mm)
$d_{char,n}$	Notional charring depth (mm)
f_c	Char contraction factor
k_{O2}	Coefficient for oxygen concentration
$\bar{\dot{q}}''$	Test-average total heat flux (kW/m²)
t	Time of fire exposure (min or hrs)

Greek letters

β	Charring rate (mm/min)
β_0	Design charring rate for one-dimensional charring under standard fire exposure; Initial rate of charring (mm/min)
β_{eff}	Effective charring rate (in/hr)
β_n	Design notional charring rate under standard fire exposure (mm/min)
$\tilde{\beta}$	Charring rate (min/inch)
β_γ	Charring rate for time-increasing heat flux (mm/min)
γ	Time-increasing rate of heat flux (kW/m²s)
ρ	Wood density; Density of the boundary of the compartment (kg/m³)
ρ_{dry}	Dry specific gravity (g/cm³)
ω	Moisture content (%)

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3.6 Paper IV – Cross-laminated timber panels – Experimental study on the charring rates when exposed to standard and parametric fires

by
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Table IV-1. Thicknesses and designations of the timber panels

Test No.	Fire exposure	Thickness (mm)	Design-ation	Layer thickness (mm)
1	Parametric fire curve, EN 1991-1-2 [11]	120	T1A	19.5-30-21-30-19.5
1	Parametric fire curve, EN 1991-1-2 [11]	240	T1B	29.5-39-32-39-32-39-29.5
2	Standard fire curve, EN 1991-1-2 [11]	180	T2C	32-41-34-41-32
2	Standard fire curve, EN 1991-1-2 [11]	240	T2D [a]	31.5-21-32-21-32-21-32-21-28.5
3	"Swedish" curve [5,6]	120	T3E	19.5-30-21-30-19.5
3	Swedish" curve [5,6]	240	T3F	29.5-39-32-39-32-39-29.5

[a] This panel was not produced according to the specifications given by the manufacturer. It was supposed to have seven lamellas with the same thicknesses as T1B and T3F, but has 9 layers.

Temperature-time curves

The CLT panels were exposed to three different temperature-time curves in three separate tests (see *Table IV-1* and *Figure IV-2*). EN 1991-1-2 Standard curve was included because it is very commonly used for all structures, and the Parametric curve was chosen because it will normally be used for large wooden structures. The "Swedish" curves are well known and recognized, and therefore included here. The curves have been evaluated for the use on CLT panels in an earlier work by Friquin [10].

The curves are calculated based on a fictitious small office compartment with length 4 080 mm, width 3 080 m, and 3 000 m height. The office has concrete walls and floor, and ceiling made of CLT panels. All surfaces are fully exposed to the fire. The energy from the CLT panels was not included in the fire load density due to restrictions on the furnace, where the maximum temperature could not exceed 1 100°C. This results in shorter fires and lower temperatures than if the timber panels were included in the fire load density. The main objective of the experiments was to measure the change in charring rate through the three stages of the fire, and therefore the reduced fire load density was not considered important. The shapes of the curves are similar to what they would be with the fire load from the timber panels included, but with different maximum temperatures and fire duration.

The characteristic fire load density per unit floor area is set to be 511 MJ/m² for an office (found in [11] Annex E, Table E.4). This value is multiplied by four factors given in [11] Annex E, Section E.1 to find the design value of the fire load per unit floor area. For our fire compartment (office) the following factors are used; combustion factor m = 0.8, compartment size factor δ_{q1} = 1.10, occupancy type factor δ_{q2} = 1.00, and factor for active fire fighting measures δ_n = 1.00. The design value per floor area is then multiplied with the floor area and divided on the total surface area, including openings, to find the design fire load per unit surface area.

The "Swedish" curves [5,6] are based on a "standard fire compartment A" with thermal properties of the boundaries corresponding to structures consisting of concrete, brick and lightweight concrete. This compartment is characterised by a k-factor equal to 1. Pettersson and Ödeen [6] developed *k*-factors for a few different compartment types, but none of them containing any wood. König [12] has therefore developed a formula to calculate the k-factor for compartments with wooden boundaries. In our fictitious fire compartment the k-factor is calculated to be 2.37. The fire load density and the opening factor is multiplied with the k-factor to find a fictitious fire load density and opening factor, which are used to find the temperature-time development for the specific compartment.

For the fictitious fire compartment studied here the design fire load per unit surface area was calculated to 83 MJ/m² for the Standard fire and the Parametric fire, and 197 MJ/m² for the "Swedish" curve.

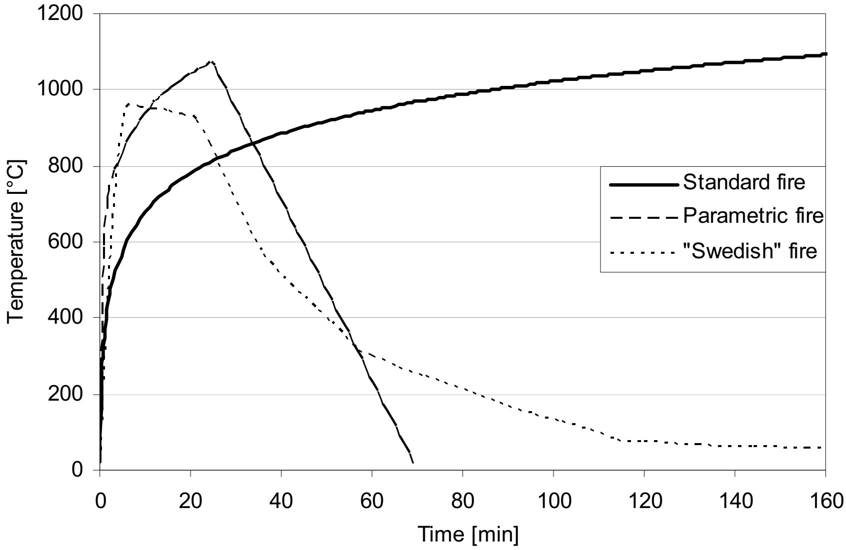
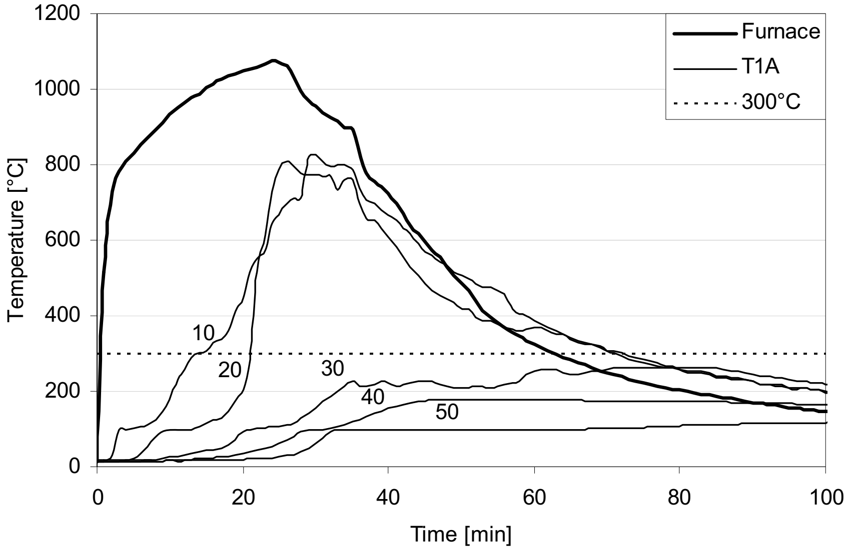


Figure IV-2. The three temperature-time curves used in the experiments; EN 1991-1-2 Standard fire and Parametric fire, and the "Swedish" fire

Large-scale horizontal test furnace

The tests were run in a large-scale horizontal gas-fired test furnace, with a top opening 3 080 mm wide by 4 060 mm long, and 1 500 mm deep. The furnace has 16 gas-burners, eight burners on each of the long walls, 480 mm below the surface of the test samples. They produce a total of 11 000 MJ/h. Propane gas mixed with 4% oxygen is used. The furnace has two vertical, circular flue ducts with a diameter 500 mm at floor level of the furnace on one of the long walls, and is also fitted with two pressure gauges which are located on the same wall as the flue ducts. Six plate thermocouples (TC) are placed 1 400 mm above the floor to measure the temperature in the furnace. The position of the plate TCs, propane burners and flue ducts are shown in *Figure IV-3*, *Figure IV-4* and *Figure IV-5*.

The temperature in the furnace is controlled by an automatic control system during heating stage, fully developed fire and the early parts of the cooling stage. During the cooling stage the burners had to be turned off at a point and further temperature adjustments were manual, using the fan and/or making openings between the Ziporex elements to achieve cooling of the furnace temperature.



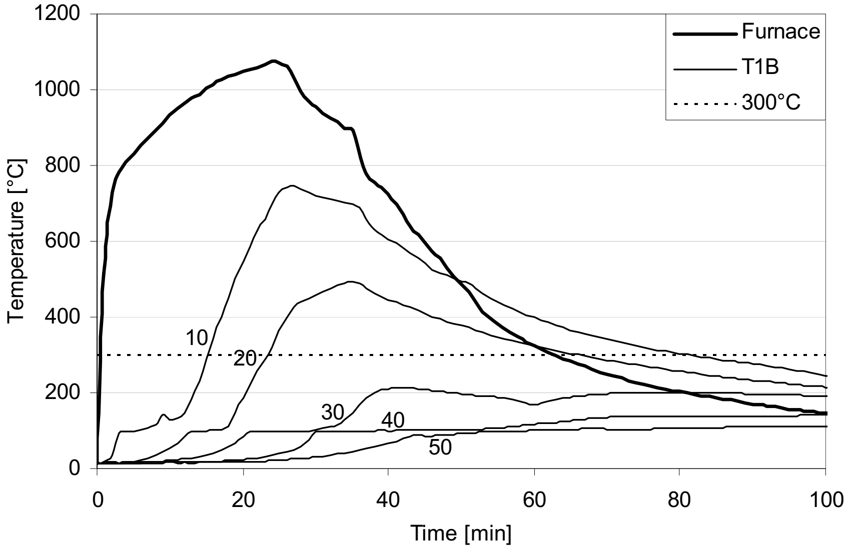


Figure IV-11. Temperature development in the cross-sections of test specimens T1A and T1B at given depths

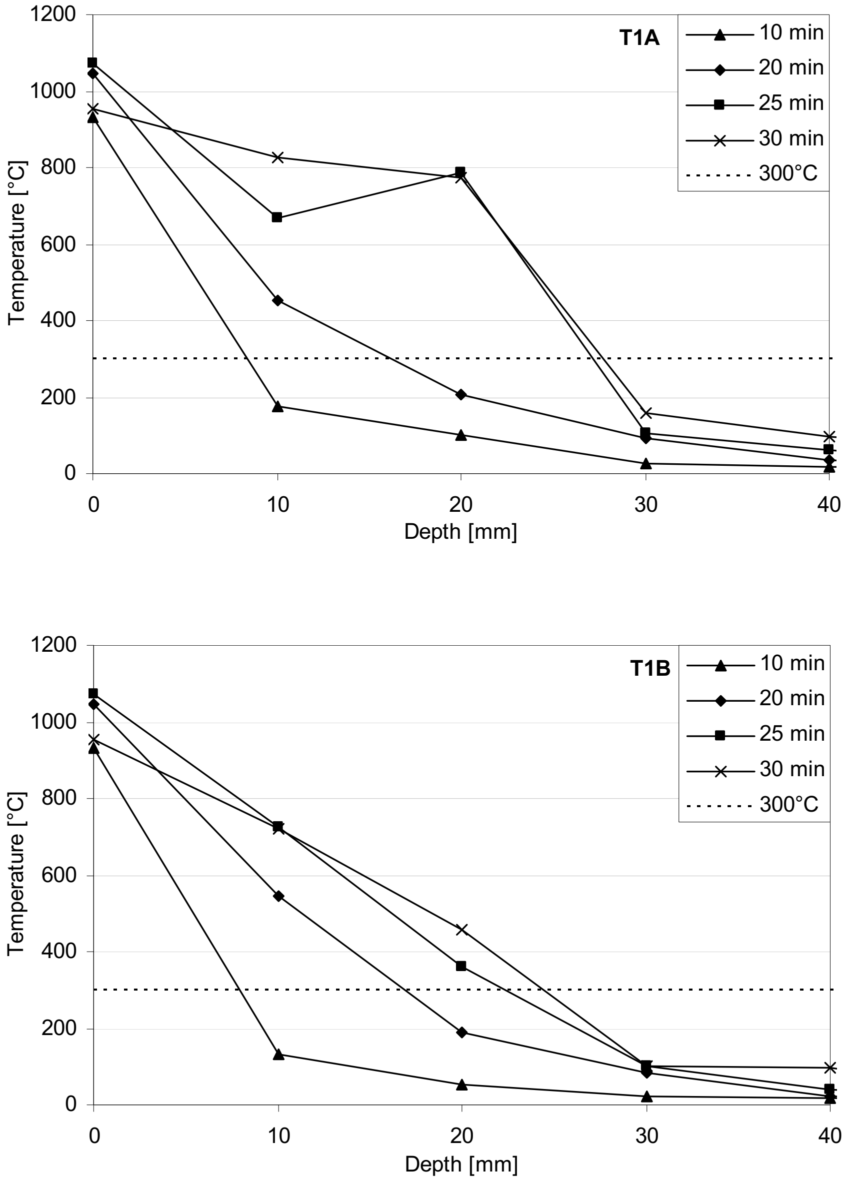


Figure IV-12. Temperature profiles in the T1A and T1B cross-sections at different times

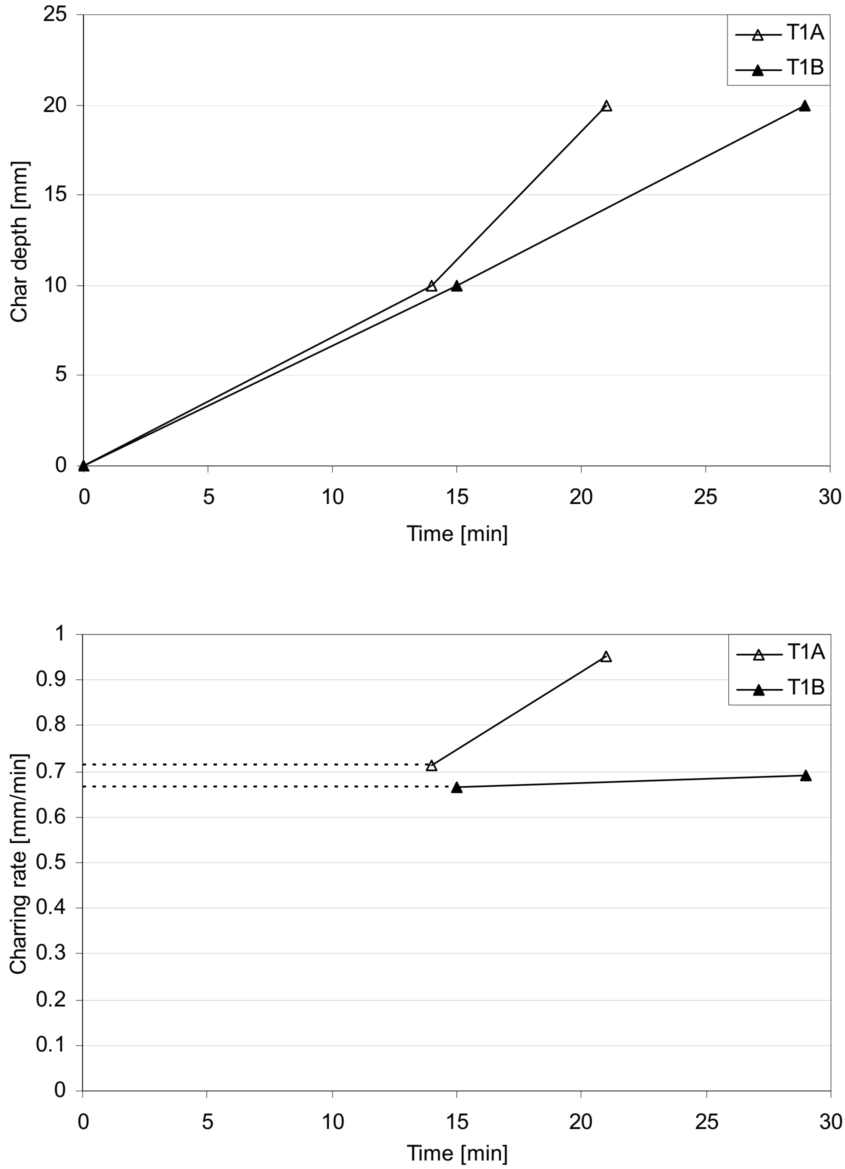


Figure IV-13. Char depth and charring rate as a function of time for specimens T1A and T1B. Maximum temperature was reached after 24 minutes

Test 2 – EN 1991-1-2- Standard fire

The average measured temperature in the furnace follows the calculated development very well also here, *Figure IV-14*. Due to limitations to the furnace (maximum 1 100°C) the gas burners were turned off after 120 minutes when the furnace temperature was 1 056°C. The panels were left on the furnace and the flue duct fan was left on to see the temperature development for a while after the gas burners had been turned off. At 180 minutes the Ziporex panels were removed to allow cooling of the furnace, and logging of the temperatures inside the cross-sections was stopped.

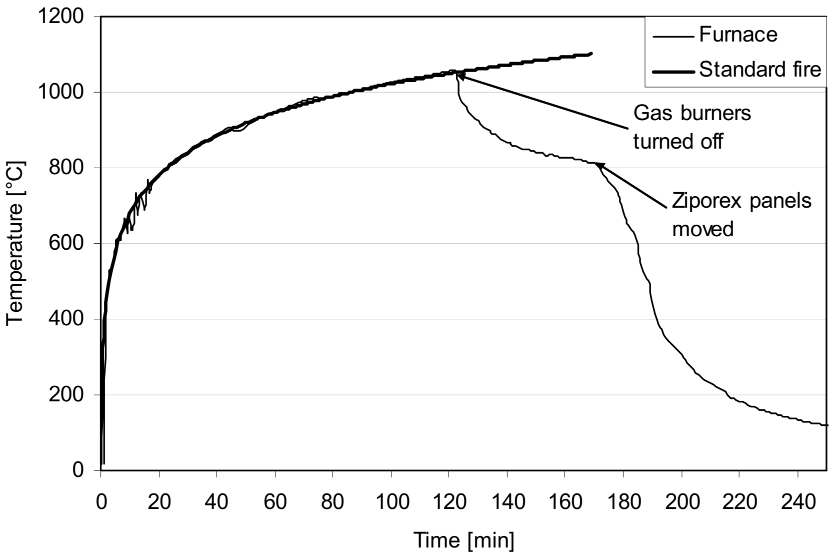


Figure IV-14. Calculated EN 1991-1-2 Standard temperature-time curve and average measured furnace temperature through Test 2

The temperature development and temperature profiles at different depths of the cross-sections are shown in *Figure IV-15* and *Figure IV-16*. The char front in each panel is found where the curve for a given depth passes the 300°C mark. In *Figure IV-15* and *Figure IV-16* it can be seen that the curves follow each other well. However, after 50 minutes the temperature at 30 mm depth for panel T2D reaches the same level as at 20 mm depth, see the T2D curves in *Figure IV-15* and *Figure IV-16*. This overlap of the temperature curves is probably due to cracks in the wood, or gaps between lamellas. When the gas burners were turned off the cross-section temperatures decreased at almost the same rate as the furnace temperature.

The time at which the temperature at different depths reached 300°C, and the charring rates at given times are shown in *Figure IV-17* (first point at 10 mm, second at 20 mm, and so on). The dotted lines show that the charring rate is assumed to be constant between time zero and the first measurement. When reaching 10 mm depth the char front had a charring rate between 0.31 mm/min and 0.5 mm/min, at 20 mm both timber panels had a charring rate of 0.45 mm/min, and at 60 mm the charring rate was between 0.45 mm/min and 0.68 mm/min. The rate for the 180 mm thick panel started decreasing at 70 min, while the rate for the 240 mm panel was still increasing at that time. The gas burners were turned off at 121 minutes, but the charring rate continued at approximately the same level until the logging of the TCs was turned off. There was actually a small increase in the charring rate at 100 mm to 110 mm depth. This might be due to cracks in the wood or gaps between lamellas, or the inhomogeneous character of wood. The thicker cross-section (240 mm) had the highest charring rate. The charring rate for the 240 mm thick panels continued almost unchanged even after the gas burners were turned off, while the charring rate for the thinner panel decreased shortly after the burners were turned off. The temperature on the unexposed side of the panels never exceeded 23°C as long as the furnace was completely covered by timber and Ziporex panels.

The temperature on the surface of the timber panels was assumed to be equal to the furnace temperature. This results in a very steep temperature drop from the surface to the thermocouple at 10 mm depth during the early parts of the fire.

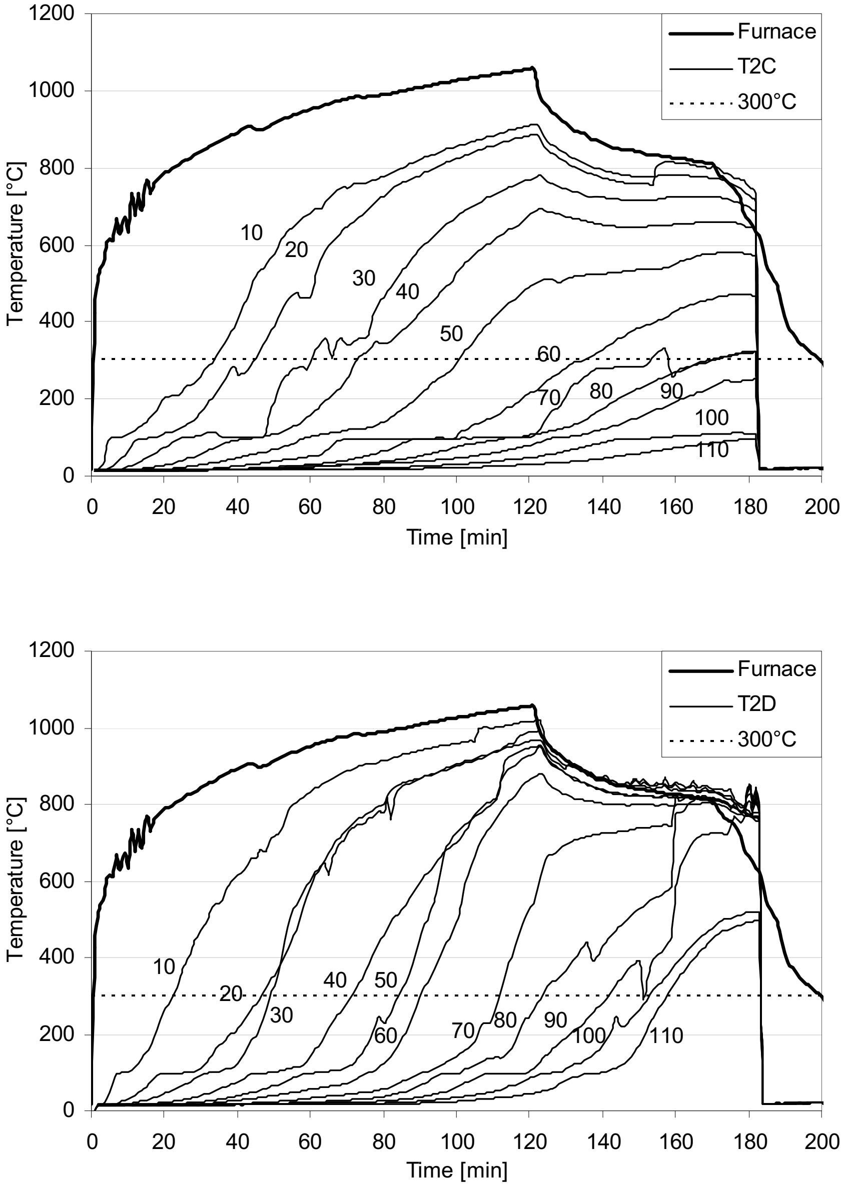
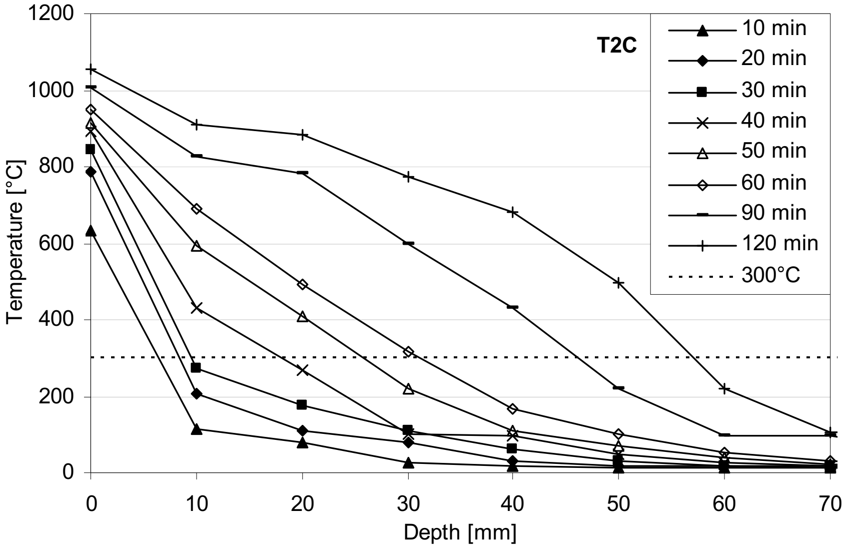


Figure IV-15. Temperature development in the cross-sections of test specimen T2C and T2D, at given depths



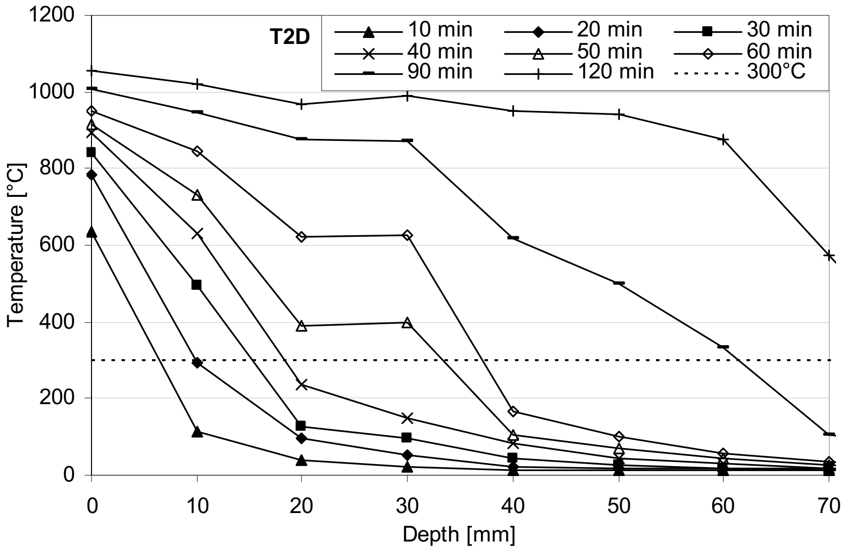


Figure IV-16. Temperature profiles in the T2C and T2D cross-sections at different times

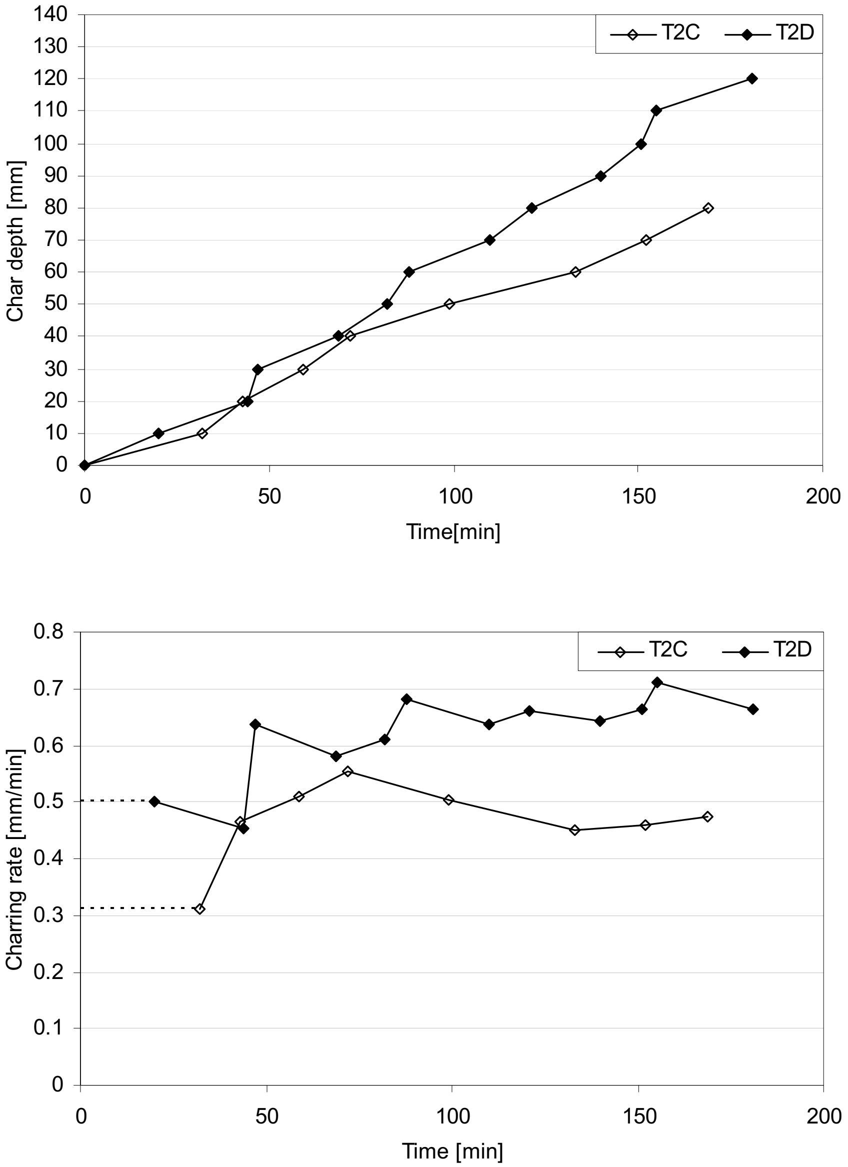


Figure IV-17. Char depth and charring rate as a function of time for specimens T2C and T2D. Maximum temperature was reached after 121 minutes

Test 3 – "Swedish" fire

The average measured furnace temperature follows the calculated curve well, with some deviations before it reaches the maximum temperature, see *Figure IV-18*. During the decay stage the burners were turned off early and the temperature adjusted by turning on/off the fan in the flue ducts. After a while the Ziporex panels had to be removed to facilitate further cooling.

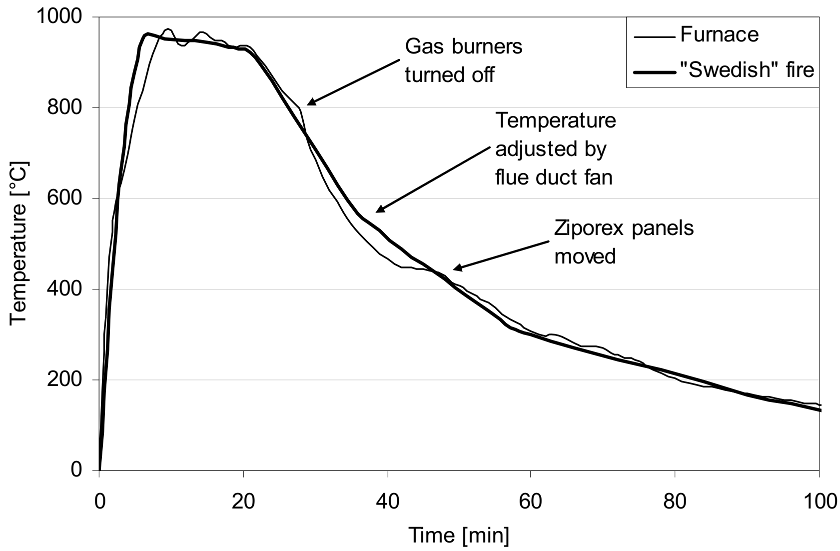


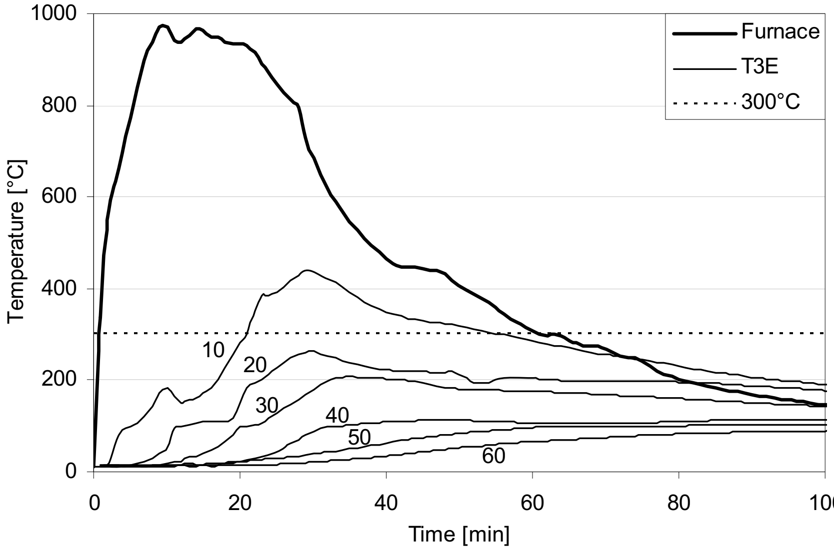
Figure IV-18. Calculated "Swedish" temperature-time curve and average measured furnace temperature, Test 3

The temperature development and temperature profiles at different depths of the cross-sections are shown in *Figure IV-19* and *Figure IV-20*. The char front is found where the curve for a given depth crosses the 300°C mark.

As can bee seen from *Figure IV-19* and *Figure IV-20* the charring only reached 10 mm into the cross-sections. This is due to the slow heating and low temperatures in the fire. The decrease in the temperatures inside the cross-sections was slightly slower than the furnace temperature during the cooling stage.

The time at which the temperature at different depths reached 300°C, and the charring rates at given times are shown in *Figure IV-21*. The charring was assumed to start at time zero and be constant between zero and the first measuring point. This is illustrated by the dotted lines. The fire was very short, with low temperatures, and the timber panels only reached charring temperature at 10 mm depth. The charring rate for both samples was 0.5 mm/min at 10 mm depth at time 20 minutes. This is 6 minutes after the peak temperature. The temperatures inside the cross-section start decreasing approximately 10 minutes after the furnace temperature. The temperature on the unexposed side of the panels never exceeded 14°C as long as the furnace was completely covered by timber and Ziporex panels.

The temperature on the surface of the timber panels was assumed to be equal to the furnace temperature. This results in a very steep temperature drop from the surface to the thermocouple at 10 mm depth.



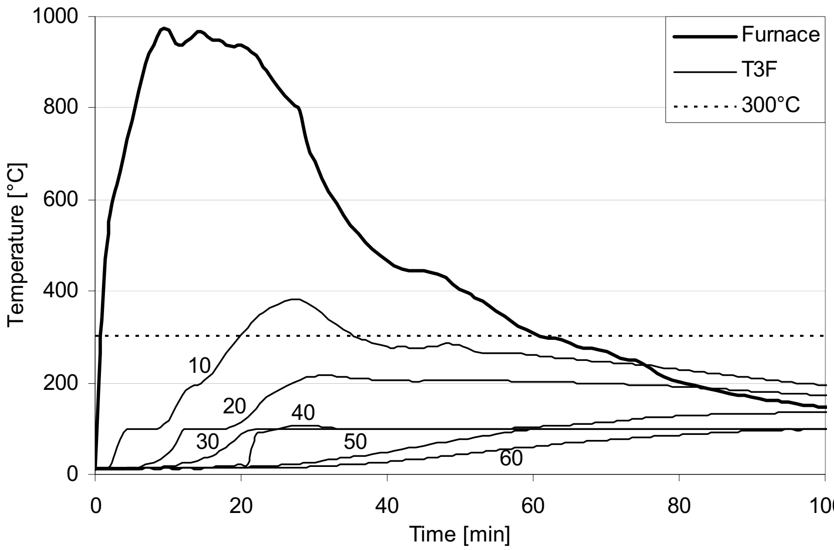


Figure IV-19. Temperature development in the cross-section of test specimens T3E and T3F, at given depths

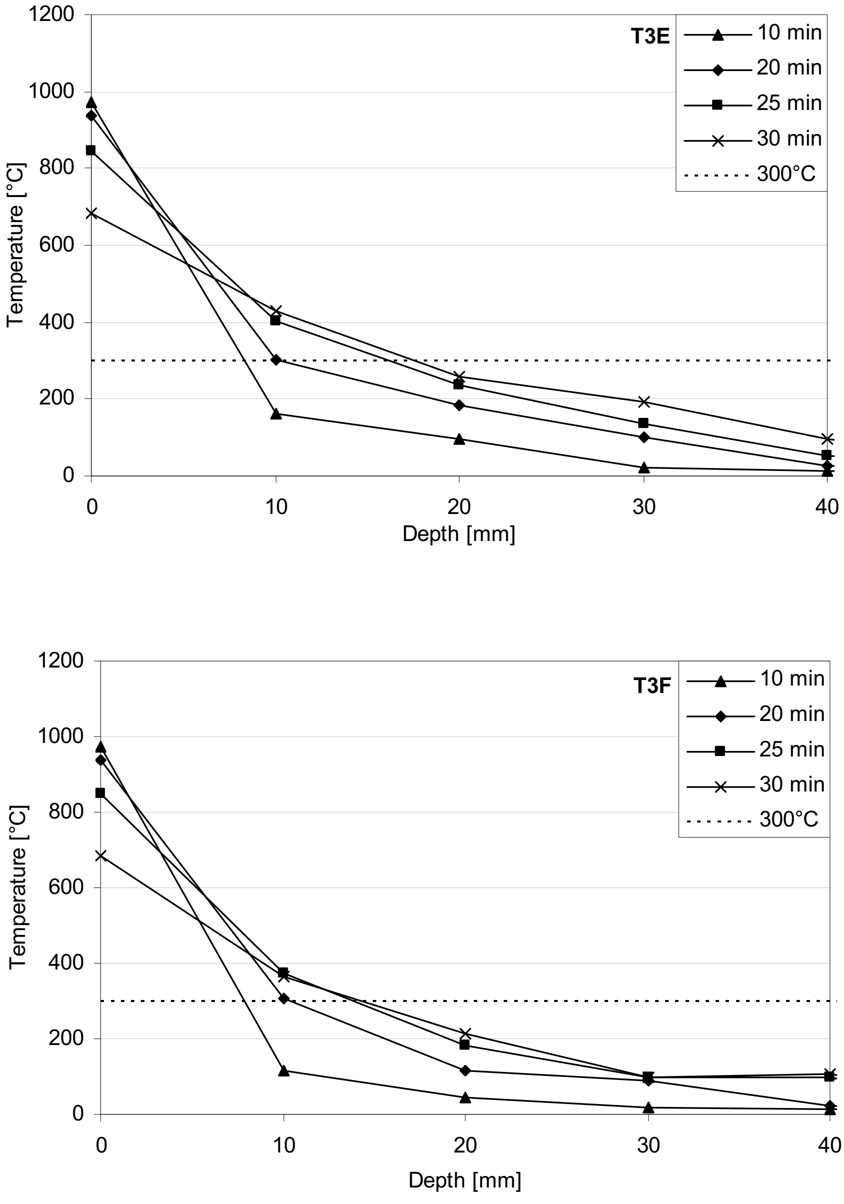
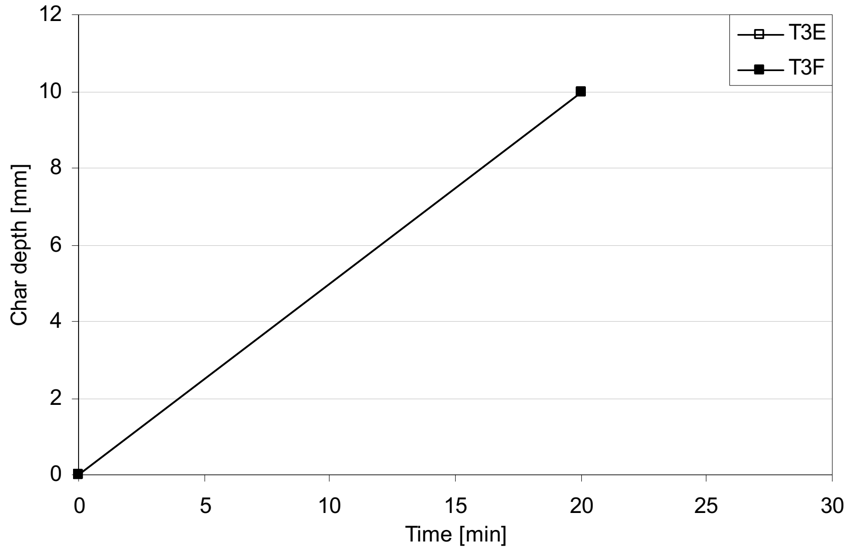


Figure IV-20. Temperature profiles in the T3E and T3F cross-sections at different times



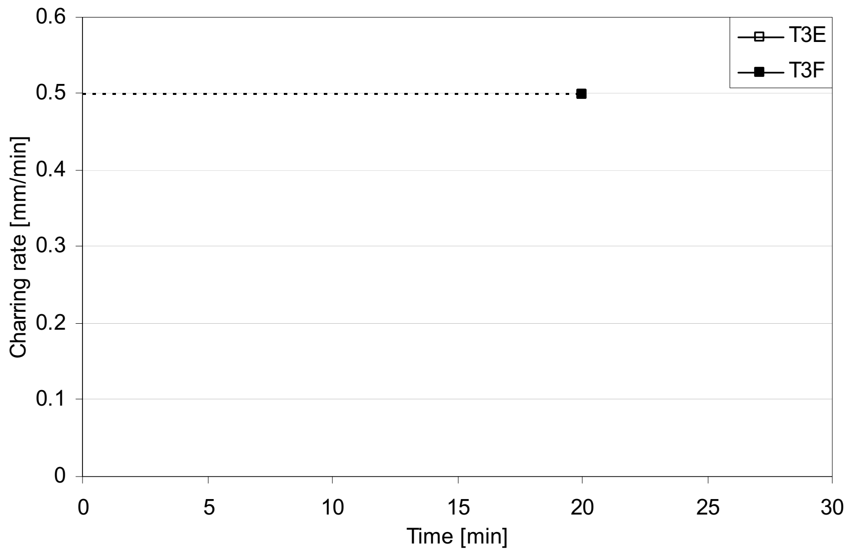


Figure IV-21. Char depth and charring rate as a function of time for specimens T3E and T3F. The markers coincide with each other, i.e. one point. Maximum temperature was reached after 14 minutes

Discussion

Thermocouples were placed at every 10 mm into the cross-section, but not on the exposed surface. It was assumed that the surface temperature would be equal to the furnace temperature, but the results would have been more accurate if the surface temperatures were measured, as well. Thermocouples could also have been placed in other parts of the timber panels to collect more information on the charring of the panels. As the charring was only measured in the middle section of the panels very few results were collected, and the accuracy was not determined.

The char depths and charring rates for the three different fires vary greatly, from 0.31 mm/min to 0.95 mm/min, see *Table IV-2* and *Figure IV-22*. However, the results for the two panels exposed to the "Swedish" fire (T3E and T3F) coincide with the first measure of the thickest panel exposed to the Standard fire (T2D). Highest is the charring rate for the fastest increasing fire with the highest maximum temperature, i.e. the Parametric fire. For the Standard fire, that has the lowest heating rate and middle maximum temperature, the charring rate is slower than for the Parametric fire, and equal to or lower than for the "Swedish" fire. This indicates that the heating rate and maximum temperature has an impact on the charring rate, in agreement with Frangi et al. [3]. Unfortunately, the char front for the "Swedish" fire only reached as far as 10 mm, and therefore only gave one single measurement. This is due to the very low charring rate achieved in the early stages of this fire. The Parametric fire and the "Swedish" fire are quite similar in the early stages of the fire, but the charring rates are significantly different. This is probably a result of the difference in temperature growth rate and temperature level. The cross-section temperatures for the short fires, i.e. Parametric and "Swedish" fires began to decrease shortly after the cooling stage of the fire started. This resulted in a short charring period.

Table IV-2. Charring rates β at various depths for all test specimens

Specimen	d_{char} (mm)	10	20	30	40	50	60	70	80	90
T1A	$t_{300°C}$ (min)	14	21	-	-	-	-	-	-	-
T1A	β (mm/min)	0.71	0.95	-	-	-	-	-	-	-
T1B	$t_{300°C}$ (min)	15	29	-	-	-	-	-	-	-
T1B	β (mm/min)	0.67	0.69	-	-	-	-	-	-	-
T2C	$t_{300°C}$ (min)	32	43	59	72	99	133	152	169	-
T2C	β (mm/min)	0.31	0.47	0.51	0.56	0.51	0.45	0.46	0.47	-
T2D	$t_{300°C}$ (min)	20	44	47	69	82	88	110	121	140
T2D	β (mm/min)	0.5	0.45	0.64	0.58	0.61	0.68	0.64	0.66	0.64
T3E	$t_{300°C}$ (min)	20	-	-	-	-	-	-	-	-
T3E	β (mm/min)	0.5	-	-	-	-	-	-	-	-
T3F	$t_{300°C}$ (min)	20	-	-	-	-	-	-	-	-
T3F	β (mm/min)	0.5	-	-	-	-	-	-	-	-

Charring rates for the 120 mm thick timber panels (T1A and T3E) compared to the 240 mm thick panels (T1B, T2D and T3F) were not consistently faster or slower. However, there are great differences between the charring rates for the two panels tested together in the same fire for both Parametric and Standard fire. During the Parametric fire the thinnest panel (120 mm) had the fastest charring rate, while during the Standard fire the thickest panel (240 mm) had the fastest charring rate. The charring rate for the 180 mm thick panel was consistently the lowest at all depths and times. There is no obvious explanation to these results, and it might be a coincidence as the number of measurements is very small.

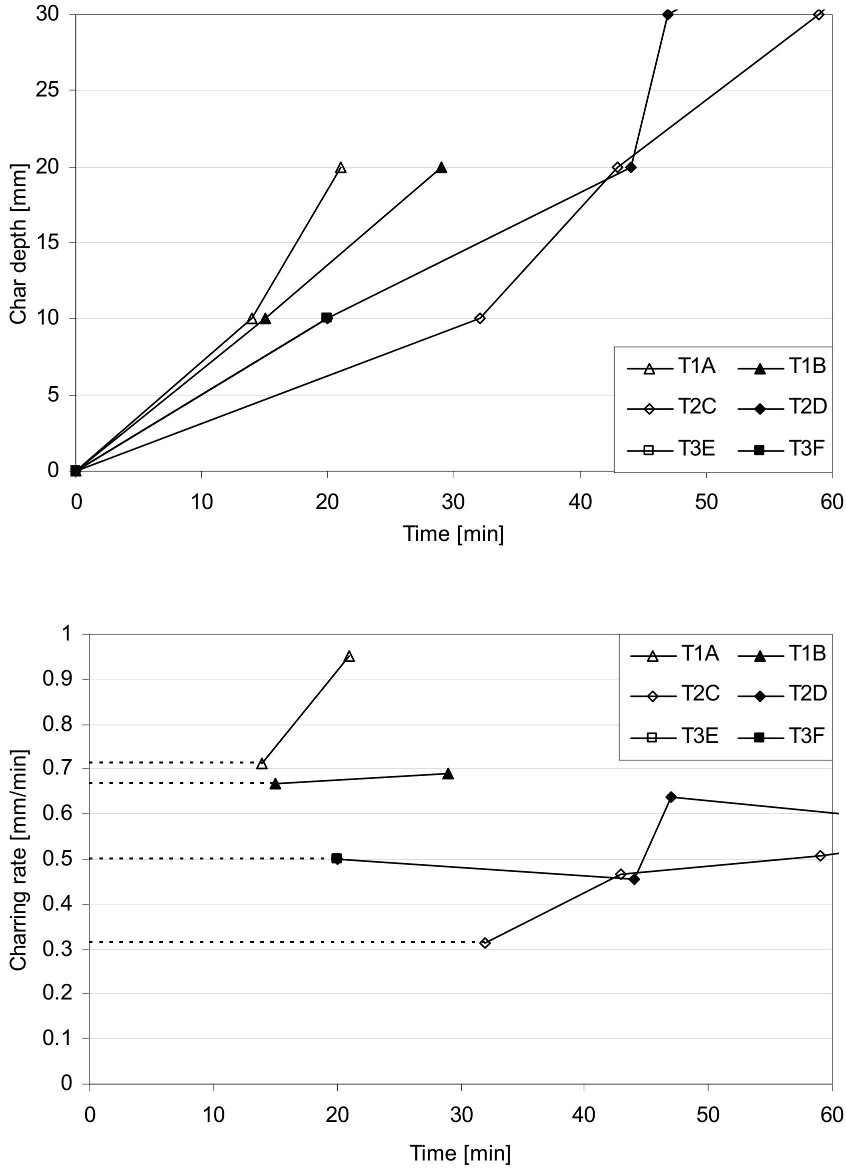


Figure IV-22. Char depth and charring rate as a function of time for all specimens. Markers for T2D, T3E and T3F coincide with each other

From the temperature developments inside the cross-sections (*Figure IV-11*, *Figure IV-15* and *Figure IV-19*) it can be seen that at some depths adjacent curves overlap each other. This is probably due to cracks in the wood or gaps between lamellas, and will inflict on the charring rate. Based on *Figure IV-11*, *Figure IV-15* and *Figure IV-19* it can be assumed that at 20 mm depth for the T1A specimen, and at 20 mm and 40 mm for the T2D specimen the temperatures, and therefore also the charring rates, are affected by such cracks or gaps. It can also be assumed that the charring rate at 20 mm depth for T1A should, in theory, be lower, and the charring rate at 20 mm and 40 mm for T2D should be higher. This would give a closer match between the charring rates for the two panels tested in Test 1 Parametric fire, and a smoother charring rate curve for T2D, but it would still be higher than T2C.

The charring rate as a function of the furnace temperature was also considered, and the results are shown in *Figure IV-23*. For both Test 1 and Test 3 there are too few results to see any trend, but the trend line for T2D is almost completely horizontal while T2C increases slightly. However, the slope of T2C's trend line is mainly caused by an outlier, and would therefore be almost horizontal if the outlier was ignored. Taking this into account the charring rate was almost constant for both panels exposed to Standard fire. Usually, a higher temperature would cause a higher charring rate, but as the temperature here slowly increases to 1 000°C the char layer will grow thicker and protect the fresh wood. The char layer will continue to grow until it reaches its maximum thickness at about 1 000°C. After this the char layer will have a constant thickness as it advances further into the wood because carbon is consumed at the surface at the same speed as the char front penetrates into the wood [14].

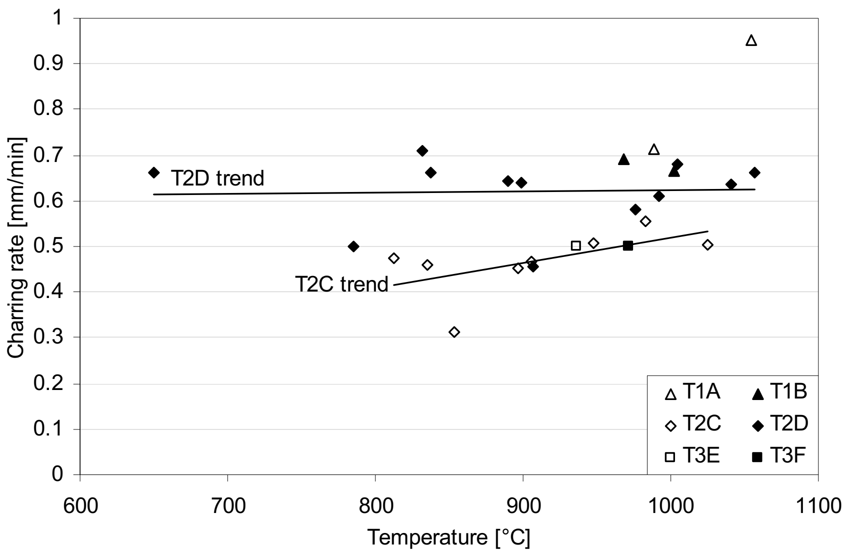


Figure IV-23. Charring rate as a function of furnace temperature for all specimens. Trend lines for specimens T2C and T2D are included

There were no indications that the lamella thickness had an influence on the temperature development in the cross-section or on the charring rate.

During the fire exposure the heated zone below the char layer increased to a maximum thickness of 25-35 mm and did not grow significantly further.

For the Parametric and "Swedish" fires the furnace temperature drops very fast to below 300°C (in about 40 minutes), while the furnace temperature during the Standard fire only drops below the charring temperature after 80 minutes. This is because the furnace was only actively cooled down after 175 minutes during the Standard fire, and only then the temperature dropped below 800°C. Therefore the internal temperatures in the panels were high enough for the charring to continue a long while after the gas burners were turned off, giving a constant charring rate until 175 minutes when the logging was turned off.

In *Figure IV-24* the results from the present study are compared to the studies referred to in *Chapter 1 Introduction*. The results from Landrø [1] and Frangi et al. [3], who both exposed CLT panels to ISO 834 fire, are between the charring rates found in the current study for 180 mm and 240 mm thick CLT panels. The charring rates for CLT panels exposed to "Swedish" fires cannot be compared because the fire curves are not similar, König & Walleij [4]. The charring rates for glue-laminated panels with parallel boards exposed to fire in an edgeways position, König & Walleij [4] and Fornather [7], compare well with the present test results, as can be seen from the long-dash lines. However, the scatter is wide ranging from 0.5 mm/min to 0.7 mm/min.

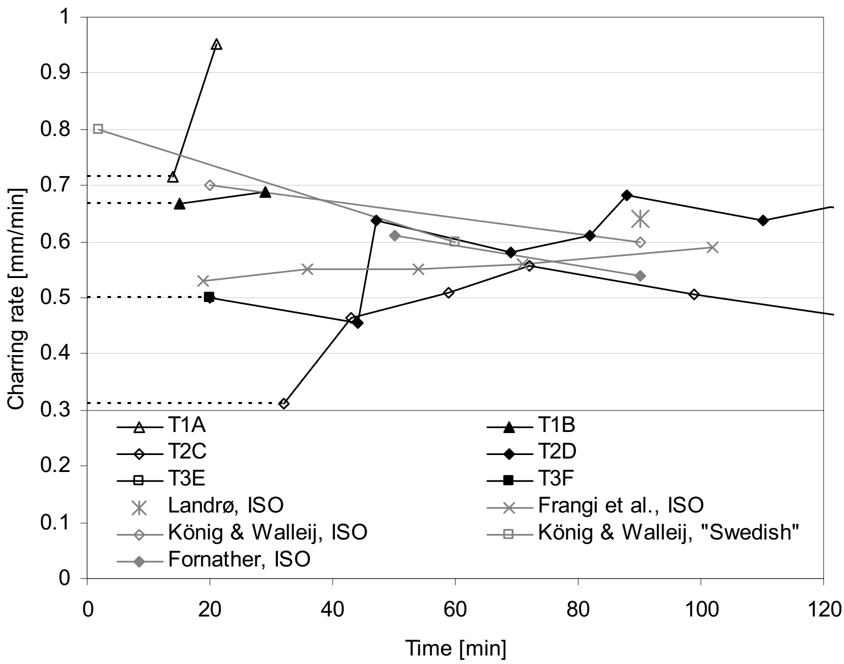


Figure IV-24. Present charring rate results compared with results from earlier studies

Conclusions

The results from the fire tests on cross-laminated timber panels show that the charring rates vary greatly for the different temperature-time curves. Even for Parametric and "Swedish" curves, where the start of the fire was very similar, the charring rate is significantly different. The results indicate that the charring rate will be faster when the fire has a fast temperature growth and high temperatures. Temperature-time developments with slower temperature growth and lower maximum temperatures will result in slower charring. The charring rates given in EN 1991-1-2 might therefore not be applicable to other fire developments than Standard and Parametric fires described in EN 1991-1-2. If other temperature-time curves are used for fire safety design of a timber structure, the charring rate for that particular curve must be determined by other calculations or by testing. Due to the limited number of measurements in these tests it is not possible to say whether the thickness has an impact on the charring rate. The lamella thickness had no effect on the charring rate. The heated zone below the char layer grew to a constant thickness of 25-35 mm. For a short fire with a steep cooling rate the charring will stop early in the cooling stage. A long fire will reach a constant charring rate after a while. The charring rate results from the present study compare well with results from previous experiments on cross-laminated timber panels and glue-laminated parallel board panels exposed to ISO 834 fires. The conclusions are based on a limited statistical background and should be examined further. More research on the charring rate for cross-laminated timber panels is needed. The temperature on the exposed surface should have been measured and the charring rates should have been measured in several parts of the timber panels, to achieve more accurate results.

Acknowledgements

The project is financed by the Research Council of Norway. The cross-laminated timber panels were supplied by Moelven MassivTre AS, and the tests were performed at SINTEF NBL AS (Norwegian Fire Research Laboratory). The authors would like to thank the contributors for all help and support.

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3.7 Paper V – Experimental charring rates for cross-laminated timber panels compared to calculated charring rates

by
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To be published in:
Proceedings of the 12th International Conference on Fire Science and Engineering (InterFlam 2010), Interscience Communications Ltd, London, UK

To be presented at:
The *12th International Conference on Fire Science and Engineering* (InterFlam 2010), 5-7 July 2010, University of Nottingham, UK

Abstract

In the current study, experimental charring rates for cross-laminated timber panels (CLT) exposed to standard and parametric fires have been compared to the charring rates given in EN 1995-1-2 Table 3.1 and Annex A, and charring rates calculated by other models found in the literature. The aim was to determine whether the values and equations for standard and parametric charring rate found in EN 1995-1-2 give an accurate picture of the charring of CLT panels. Results from other calculation models were also compared to the experimental results to examine their applicability to this type of structural elements. The charring rate results from the tests did not match well with the calculations.

Introduction

Two important steps of fire safety design of large timber structures are to determine the temperature-time development and to find the charring rate and char depth of the wood. Many models for calculation of the charring rate and char depth of wood have been developed through the years, but some of them are only applicable to species of specific origins or one temperature-time curve. Limitations are often based on small test ranges. Further testing could expand their area of applicability. Comparisons of char depth and charring rate results with calculated char depths and charring rates have earlier been carried out by Friquin[1] and Frangi et al.[2]. Friquin compared simple calculation models for charring rate of solid wood, nail- and glue-laminated structural elements for use in fire design of wooden structures, with test results found in the literature. Frangi et al. tested cross-laminated timber panels (CLT) made with Polyurethane (PU) glue and Melamine Urea Formaldehyde (MUF) glue exposed to standard ISO 834 fire[3] in a small horizontal furnace, and compared the results with EN 1995-1-2[4]. The present study compared experimental charring rates for CLT panels exposed to standard and parametric fires with the charring rates given in EN 1995-1-2 Table 3.1 and Annex A[4], and charring rates calculated using other models developed by Cachim & Franssen[5], Schaffer[6], White & Nordheim[7], Babrauskas[8], Yang et al.[9], and Bobacz[10]. The models have been compared to other test results found in the literature in previous work by the author[1]. The calculation models include various factors and wood properties.

Materials, experiments and models

The charring rate experiments were performed on cross-laminated timber panels of Norway spruce (*Picea abies*) with approximate properties; dry density 400 kg/m³, wet density 440 kg/m³, and moisture 9%. The tests were run in a large-scale horizontal test furnace and are described in detail in Friquin et al.[11]. The CLT panels were 1 200 mm wide and 3 600 mm long. Thicknesses and designations of the CLT panels are given in *Table V-1*. The CLT panels were exposed to the Standard fire curve and the Parametric fire curve from EN 1991-1-2[12], see *Table V-1*, in two separate tests. The curves have been evaluated for the use on CLT panels in an earlier work by Friquin[13].

Table V-1. Thicknesses and designations of the CLT panels

Test No.	Temperature-Time curves	Thickness / Designation	Thickness / Designation
1	Parametric fire[12]	120 mm / T1A	240 mm / T1B
2	Standard fire[12]	180 mm / T2C	240 mm / T2D

The progress of the char front (defined as the 300°C isotherm) was obtained by thermocouples that measured the wood temperature at various depths in the specimen. Thermocouples of the type K (Chromel/Alumel) were placed in 3 mm wide holes drilled from the unexposed surface of the timber panels. They were placed in the panels at 10 mm intervals from 10 mm to 180 mm depth from the exposed surface, details given in Friquin[11].

The measured char depths and charring rates were compared with calculated results based on models developed by other researchers. The models' applicability, the material properties and external factors taken into account, and the equations are listed in *Table V-2*. The name of the method, publication year, what fire exposure it is valid for and the properties taken into account are listed. *EN 1995-1-2 Table 3.1*[4] gives the design charring rate as 0.65 mm/min for one-dimensional charring of glue-laminated wood with density higher than or equal to 290 kg/m³. *Cachim & Franssen*[5] proposed an expression to modify the one-dimensional charring rate given in EN 1995-1-2 Table 3.1[4], to give more accurate charring rates according to the density and moisture content of the wood. The expression calculates the charring rate as a function of the wood moisture content and wood density at 12% moisture content. The one-dimensional charring rates given in EN 1995-1-2 Table 3.1[4] were found to be accurate for softwood with density of 450 kg/m³ at a moisture level of 12%. Correction factors were developed for wood with other densities and moisture levels. *Schaffer*[6] developed equations for three different wood species exposed to constant temperatures or the ASTM E119 fire[14]. Amongst them was Douglas fir, which has been used here as it is assumed to be more similar to Norway spruce than the two other species Schaffer tested. *White & Nordheim*[7] established empirical models to define the charring rate in terms of fundamental properties. They tested eight species for charring rates and material properties, and used regression analysis to develop the models. Their results show the importance of surface recession and moisture content to wood charring. *Babrauskas*[8] performed studies on charring of wood with the objective of providing guidance for interpretation of char patterns in fire investigation. Based on analysis of data from experiments carried out by other investigators he developed several equations of various accuracies. The equation containing the most variables is used in this study. *Bobacz*[10] developed equations for the char depth development during initial charring and for the charring rates after the initial charring. The model is developed based on experiments performed on glue-laminated spruce with gross density 426-571 kg/m³ and a mean moisture content of 12%. Because charring only starts a few minutes after the ignition of the fire Bobacz has incorporated a delay of 5 minutes in the initial char depth equations. He also considers the difference in charring rate by introducing separate equations for the initial char depth at 10 and 20 minutes, an equation for the charring rate at constant temperature after the initial charring, and an equation for the charring rate during cooling of the fire. Correction factors are developed to adjust the char depth results for other dry densities and moisture contents than the equations are based on. However, there are some inconsistencies and explanations in the model that need clarification. For parametric fire exposure, *EN 1995-1-2*[4] gives another method for calculating the charring rate and charring depth, based on Hadvig[15] and Toft Hansen & Bolonius Olesen[16]. For unprotected softwood, the charring rate is constant during the heating phase, and dependent on the fire load density and the opening factor. During the decay phase, the charring rate decreases linearly to zero. *Yang et al.*[9] investigated the charring of wood exposed to a time-increasing and a constant heat flux by using a modified partial differential equation model. They found that the charring rate of wood under time-increasing heat fluxes is smaller than for wood exposed to a constant heat flux, and developed a linear regression to predict the charring rate for wood exposed to time-increasing heat flux and a power regression for wood exposed to constant heat flux.

Table V-2. Models for the calculation of charring rate of wood

References, properties	Equations and comments
EN 1995-1-2[4] (EC5) Table 3.1 EC1s[a] Softwood/hardwood, density, solid or laminated	β_0 (mm/min) (1) where β_0 is the design charring rate taken from Table 3.1[4].
Cachim & Franssen[5] (C & F) EC1s[a] Density, moisture	$\beta_{\rho,\omega} = k_\rho k_\omega \beta_{450,12}$ (mm/min) (2) where $k_\rho = \sqrt{(450 / \rho_{12})}$ and $k_\omega = [1.12 / (1+\omega)]^{1.5}$ and ρ_{12} is the density at 12% moisture content (kg/m³), and ω is the moisture content (% decimal).
Schaffer[6] ASTM[c] Dry density, moisture content, species	Douglas fir $\tilde{\beta} = 2[(28.726 + 0.578\omega)\,\rho_{dry} + 4.187]$ (min/inch) (3) where ω is the moisture content (%) and ρ_{dry} is the dry density (g/cm³) of wood. Charring rate converted to (mm/min) by: $\beta = 25.4 / \tilde{\beta}$.
White & Nordheim[7] (W & N) ASTM[c] Dry density, moisture content, species, char contraction factor, permeability of wood	$\beta = 0.1526 + 0.5080\rho_{dry} + 0.1475 f_c + Z_1\omega$ (mm/min) (4) where ρ_{dry} is the dry density (g/cm³), f_c is the char contraction factor, Z_1 is a species-specific coefficient and ω is the moisture content (%) of wood.
Babrauskas[8] EC1s[a] and ASTM[c] Density, oxygen concentration, heat flux, duration of fire	$\beta = 113 k_{O2} \{[(\tilde{\dot{q}}'')^{0.5}] / [(\rho t)^{0.3}]\}$ (mm/min) (5) where k_{O2} = 1.0 for charring in high oxygen concentration, 0.8 for charring in 8-10%, and 0.55 for charring in 4% oxygen concentration (4% O_2 is used in the calculations), $\tilde{\dot{q}}''$ is the test-average total heat flux (kW/m²), ρ is the density (kg/m³) of wood, and t is the time of fire exposure (min).
Bobacz[10] EC1s[a], EC1p[b] and ASTM[c] Temperature, duration of fire, heating/cooling stage	Char depth after 10 minutes (corresponding to temperature T at 5 minutes): $d_{char,10} = -8.212 + 0.033T - 2.102\cdot10^{-5}T^2 + 7.031\cdot10^{-9}T^3$ (mm) (6) Char depth after 20 minutes (corresponding to temperature T at 15 minutes): $d_{char,20} = -11.218 + 0.046T - 3.143\cdot10^{-5}T^2 + 1.136\cdot10^{-8}T^3$ (mm) (7) Charring rate at constant temperature (corresponding to temperature T): $\beta_T = -0.427 + 0.002T - 1.492\cdot10^{-6}T^2 + 6.857\cdot10^{-10}T^3$ (mm/min) (8) Charring rate for decreasing temperature (corresponding to temperature T): $\beta_{T,dc} = -0.211 + 0.001T - 4.966\cdot10^{-7}T^2 + 1.129\cdot10^{-10}T^3$ (mm/min) (9)
EN 1995-1-2[4] (EC5) Annex A EC1p[b] Density, opening factor, boundaries, design fire load, fire duration	$\beta_{par} = 1.5\beta_n\,[(0.2\sqrt{\Gamma} - 0.04) / (0.16\sqrt{\Gamma} + 0.08)]$ (mm/min) (10) where Γ is a factor accounting for the thermal properties of the boundaries of the compartment, including opening factor, thermal conductivity, density and specific heat, and β_n is the nominal charring rate given in Table 3.1[4].
Yang et al.[9] Other[d] Density, time-increasing heat flux rate.	$\beta_\gamma = 136\gamma^{0.51}\,\rho^{-0.76}$ (mm/min) (11) where γ is the time-increasing rate of heat flux (kW/m²s) and ρ is the density (kg/m³) of wood. The increasing rate of heat flux for ASTM fire, approximately 0.07 kW/m²s, is used in the calculations.

Explanations to the notes in *Table V-2*:
The calculation models are developed for use with different temperature-time curves, and are marked in the left hand column accordingly:
[a]EC1s - Standard fire curve[12]   [c]ASTM - ASTM E119 fire curve[14]
[b]EC1p - Parametric fire curve[12]   [d]Time-increasing heat flux

In the figures the EN 1995-1-2 Table 3.1 model is referred to as EC5 Table 3.1, and the model in EN 1995-1-2 Annex A is referred to as EC5 Parametric.

Experiments compared to calculations

EN 1991-1-2 Standard fire exposure

The char depth and charring rate results for the CLT panels exposed to the EN 1991-1-2 Standard fire[12] have been compared with char depths and charring rates calculated by the models in EN 1995-1-2[4] Table 3.1, Cachim & Franssen[5], Schaffer[6], White & Nordheim[7], Babrauskas[8], Yang et al.[9] and Bobacz[10], see *Figure V-1*.

All the calculated char depths for Norway spruce exposed to Standard/ASTM fire are linear, except Bobacz's model which is a degree three polynomial function (see *Figure V-1*). The EN 1995-1-2 Table 3.1, Cachim & Franssen, Schaffer and Bobacz curves are similar to each other, while White & Nordheim's model has a slightly slower growth rate. The models of Yang et al. and Babrauskas result in distinctively lower char depths. The char depth results for T2C did not match well with any of the curves from the calculation models, but lay between the highest and lowest curves. The char depth for T2C increased faster during the early stages of the fire than later in the temperature-time development. The char depth for T2D increased almost linearly. Due to cracks in the panel the char front reached the second and fourth thermocouples (20 mm and 40 mm) for the T2D panel later than expected[11]. If the results were adjusted the char depth development for T2D would be smoother. The results for T2D matched well the curve from Bobacz. The char depths calculated using EN 1995-1-2 Table 3.1, Cachim & Franssen and Schaffer are slightly higher than the test results, while White & Nordheim's model gives slightly lower char depths. The models by Babrauskas and Yang et al. return much lower char depths.

Four of the models have constant charring rates (see *Figure V-1*); EN 1995-1-2 Table 3.1, Cachim & Franssen, Schaffer and Yang et al., where the three first models return very similar results. Bobacz's model has an almost constant charring rate during the initial charring, before it increases gradually. White & Nordheim's model also has a constant charring rate during the initial stage of the fire, before it decreases slowly. Babrauskas' and Yang et al's models give a much lower charring rate than the other models. The experimental charring rate results for panels T2C and T2D were spread between the curves of the calculation models. The tested panels had an increasing charring rate up to about one hour into the fire, thereafter, the rate became almost constant. Due to cracks in the wood the second and fourth point for the T2D panel were slightly lower than expected[11]. The charring rate development would be smoother if these points were slightly higher. Even after adjustments of the unexpected low charring rates due to cracks in the wood, none of the model curves show a similar development. Bobacz's curve has a slightly similar development, but the charring rate continues to increase where the experimental charring rates became constant.

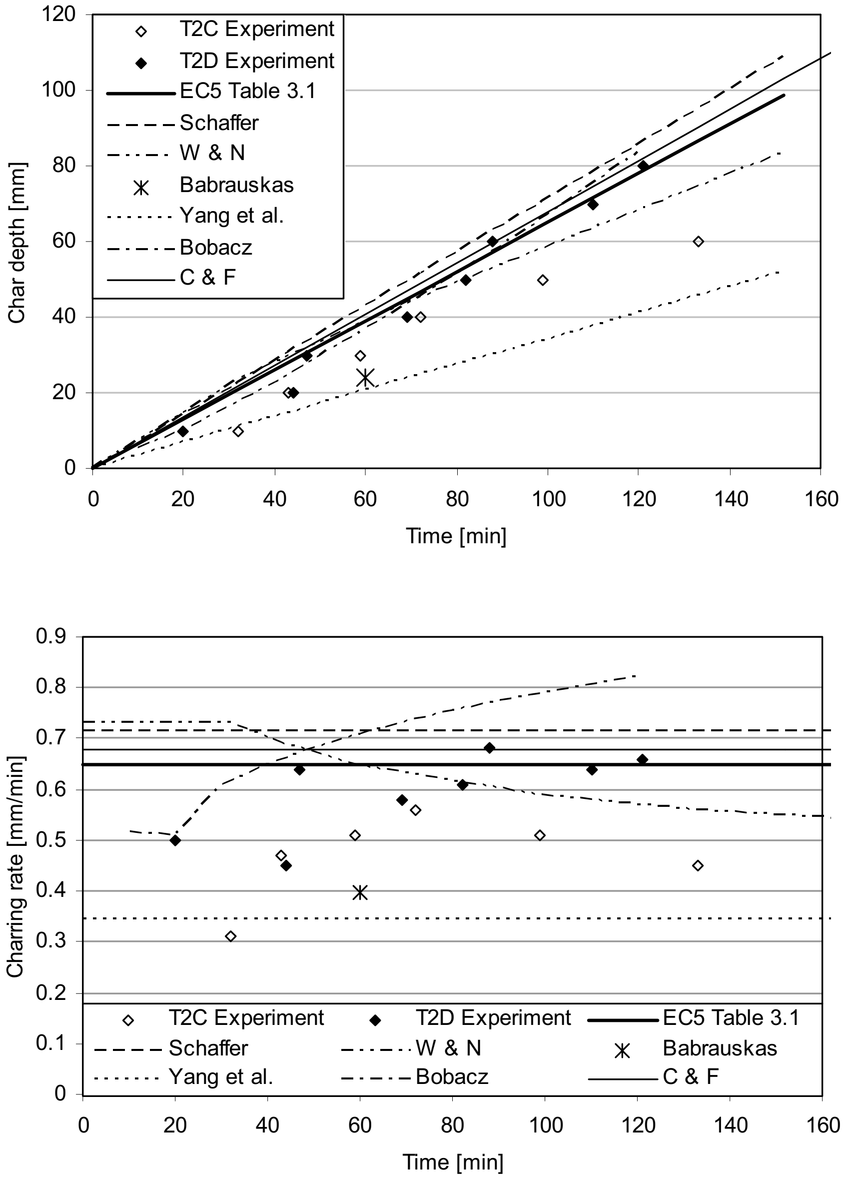

Figure V-1. Char depth and charring rate from experiments and calculations, Standard fire[12]

EN 1991-1-2 Parametric fire exposure

The char depth and charring rate results for the CLT panels exposed to the EN 1991-1-2 Parametric fire[12] have been compared with char depths and charring rates calculated by the models in EN 1995-1-2 Annex A[4] and Bobacz[10], see *Figure V-2*. The char depths calculated by the parametric model in EN 1995-1-2 Annex A and the model described by

Bobacz are very different (see *Figure V-2*), but the char depth for both models seem to reach a maximum after 50-60 minutes.

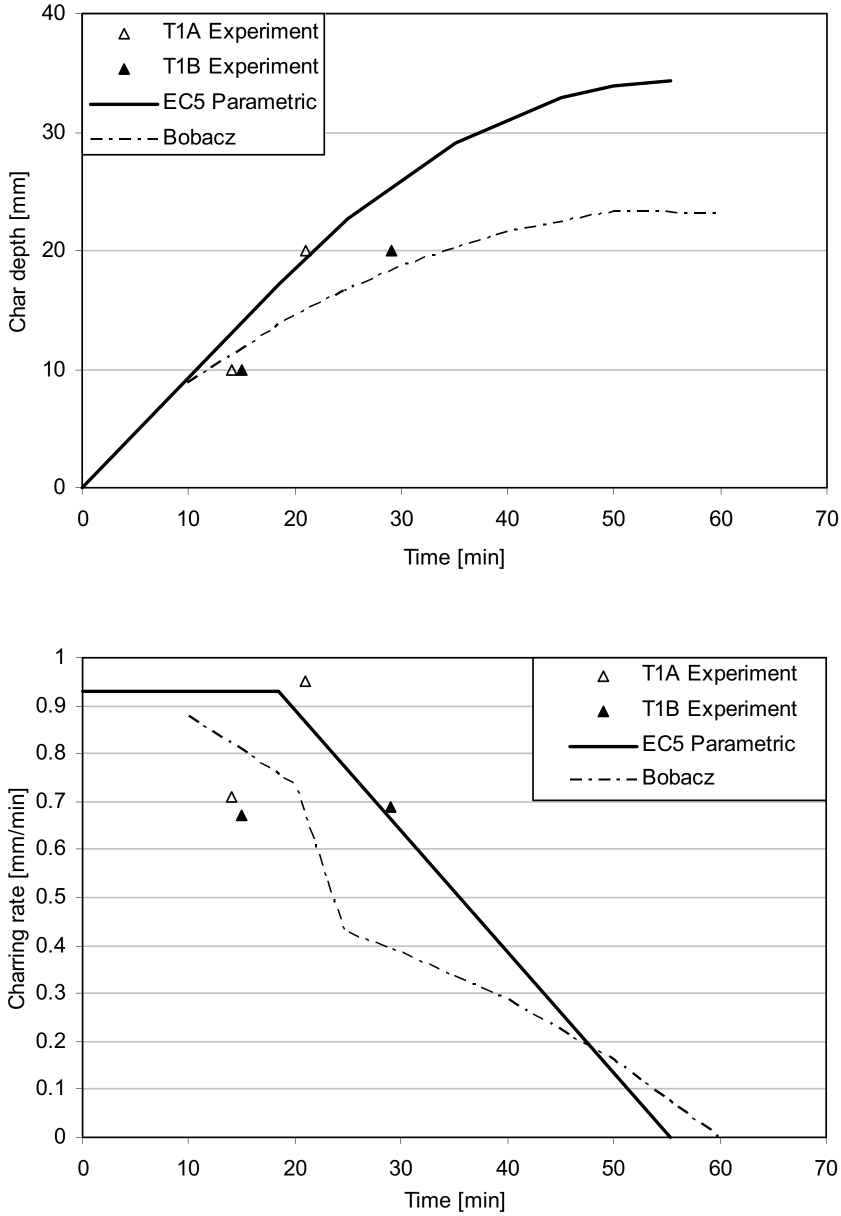

Figure V-2. Char depth and charring rate from experiments and calculations, Parametric fire[12]

The char depth for the EN 1995-1-2 Annex A model increases faster than the Bobacz model, but both curves show a slower growth over time, probably due to the increasing char layer. The second measurement for T1A (20 mm at 20 minutes) was probably higher than it should be due to cracks in the panel[11]. If there were no cracks in the wood, the char depth 20 mm would probably be reached at 25-30 minutes, which is closer to the second measurement of T1B. The results from the experiments would thereby match Bobacz's model better than the EN 1995-1-2 Annex A model, but the slope of the curve would still be steeper than Bobacz's model and more similar to the EN 1995-1-2 model. The EN 1995-1-2 model has a constant charring rate during the initial stage of the fire, before it gradually drops to zero (see *Figure V-2*). Bobacz's model does not describe the charring rate during the first 10 minutes of the fire, and from 10 minutes onwards the charring rate drops, first fast and then slower during the decay stage of the fire.
As commented earlier in this section and in Friquin[11], the charring rate for the second measurement of panel T1A was believed to be affected by cracks in the wood and should have been lower. This could result in almost constant charring rates for both the two tested panels, and thereby a trend similar to the EN 1995-1-2 model. However, the calculated charring rates were much higher than the measured. Bobacz's model did not match the measured charring rate development.

Discussion

The results for experimental and calculated char depth and charring rate for wood are widely spread. For the Standard fire exposure[12], the char depth results for T2C are lower than the T2D results. The model from White & Nordheim[7] fits the char depth results of T2C best, but is slightly higher. The EN 1995-1-2 Table 3.1[4], Cachim & Franssen[5], Schaffer[6] and Bobacz's[10] models all fit the T2D char depth results well. Charring rates calculated by the models did not match the test results well, though. The shape of Bobacz's curve[10] was similar to the T2D test results, but it was significantly higher. However, the slope of the char depth curve for the EN 1995-1-2 Annex A model[4] is similar to the test results for CLT exposed to EN 1991-1-2 Parametric fire[12] (Test 1), and the charring rate is constant even though the test results are significantly lower than calculated. However, the charring rate only fits if the assumption, that the second point of T1A is much higher than it should be due to cracks in the wood, is correct. Only one test result was achieved for both CLT panels in Test 3, and they were both exactly the same. The test results for char depth and charring rate were significantly lower than the EN 1995-1-2 Annex A model[4], and slightly lower than Bobacz's model[10]. The models are developed based on test results for different wood species exposed to various temperature-time developments. Schaffer[6], White & Nordheim[7], and Babrauskas[8] all based their models on North-American species and ASTM E119[14] fire exposure. Yang et al. based their model on Chinese species, and the EN 1995-1-2 models[4] and Bobacz's model[10] are based on European species. Similar species grown in different places might not have the same charring behaviour. Friquin[1] found EN 1995-1-2 Table 3.1[4], White & Nordheim[7], and Babrauskas[8] to have the best fit with test results for the charring rate of spruce found in the literature.

Conclusions

Char depths and charring rates for cross-laminated timber panels (CLT) exposed to two different temperature-time curves in a large-scale horizontal furnace have been compared to calculated char depths and charring rates derived using models that incorporate various factors. The charring rate results from the tests did not match well with the calculations:

- Several of the calculated char depth developments for Standard fire exposure (EN 1991-1-2[12] and ASTM E119[14]) were very similar to the test results, but when comparing the charring rates the scatter was wide.
- For EN 1991-1-2 Parametric fire[12] exposure the parametric charring model in EN 1995-1-2 Annex A[4] showed a similar development to the test results, but the char depth and charring rates from the tests were much lower than calculated.

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4 Discussion

The research on fire safety design of heavy timber structures and the development of design methods for these structures are relatively new sciences. Due to many large, devastating fires in towns and cities with many small wooden buildings, local and national building regulations limiting the use of wooden structures in built-up areas were introduced in the 19th and 20th century. During the last two decades the ban on large wooden structures in cities and other built-up areas has been lifted, and replaced by performance-based building regulations. However, the knowledge on the fire behaviour of large wooden structures must be extended.

An important part of this knowledge is the charring rate of large wooden structural elements and finding the most appropriate fire scenario. In *Paper I* it was stated that the charring rate of wood is dependant on many material properties and external factors, and the impact of the properties and factors vary greatly. An attempt to tabulate the results from a large numer of research experiments found in the literature was made, but few tests were performed on each species, density, etc. and the sample sizes varied, the test set-ups and conditions were different. Due to this the results varied greatly, as mentioned above, and it was difficult to find any clear tendency for the effect of the various properties and factors. Experiments on the charring rate should be carried out on several species and various densities and permeability, etc. to obtain more data on the influence of each property and factor. The tests should be performed under the same test conditions and test set-ups, to achieve comparable results.

It is probably not possible to develop charring rate models that incorporate all of the influencing parameters found in *Paper I*, and that is probably not necessary, either. Nevertheless, the comparisons between calculated charring rates, results reported in the literature (*Paper III*) and results from the experiments performed during the current research (Paper V) show that improvements are needed to make the models applicable to heavy wooden structural elements. Through additional research on the influencing properties and factors a few of them will probably be conspicuous having higher impact than others. The tendencies of the parameters will become clearer, and new charring rate models can be developed for heavy wooden structural elements. The improved models can then be used to calculate the charring rates of various species, densities, moisture contents etc. with better accuracy, the reduction of the cross-section will be more precise, and thereby a more economical fire safety design can be achieved.

When performing fire tests on construction elements and building components the temperature development in the furnace must be chosen and described. The appropriate curves must also be chosen to achieve a satisfactory fire safety design of the building. The temperature-time development in a fire compartment with exposed timber structures will be different than in a fire compartment with non-combustible structures. The existing temperature-time curves are mainly developed for non-combustible structures, and it was therefore necessary to evaluate and establish their applicability to wooden structures (*Paper II*). Four curves were evaluated; a "Swedish" curve, EN 1991-1-2 Standard and Parametric curves, and a relatively new iBMB curve. The three first curves were also used in the charring rate experiments (*Paper IV*) to investigate the variation in charring rate for the different curves; a "Swedish" curve, and the Standard and Parametric curves from EN 1991-1-2. It is reasonable to assume that the Standard fire curve from EN 1991-1-2 in many cases has too low temperatures, because it is not possible to include the exposed wooden structure in the fire load density. It is therefore only valuable when *comparing* structural members, and does not give a realistic picture of the charring. A few parameters for the room, fire load and thermal properties of the boundaries are included in the two other models. But none of the curves seem to consider that it might take a few minutes before the fire reaches a rapid temperature growth. The fourth curve, iBMB, is the only model based on the rate of heat release (RHR) of the materials in the compartment, and it has a delayed initial heating which results in a delayed start for the charring. It can also include changes during the fire, like breakage of windows, fire fighting actions, etc. Unfortunately, the budget for the fire tests only covered three tests, and the iBMB model was therefore not included in the experiments reported in *Paper IV*. The fire curves were not compared to a "real" fire, which would have been interesting. The temperatures might not match a "real" fire exactly, but determining the shape of the curve and comparing it with the theoretical fire curves would have given important information.

Only two charring rate tests of CLT were reported in the available literature. Both of them only exposed the CLT to ISO 834-fire. It was therefore of great interest to perform charring rate experiments on CLT exposed to other fire curves and compare the results with results from standard fire (ISO 834 [12] or EN 1991-1-2 [13]). The charring rates for cross-laminated timber panels were examined through experiments in a large-scale horizontal furnace (*Paper IV*). The CLT panels were exposed to three of the earlier described temperature-time curves; EN 1991-1-2 Standard fire and Parametric fire [13] and "Swedish" fire [49,50]. The large scatter of the charring rates for the three different fire curves is a clear message that charring rates must be determined separately for the different fire curves. The charring rates for the "Swedish" fire and Parametric fire were lower than expected, and therefore resulted in few measurements for the panels exposed to these fires. In addition, only one thermocouple was positioned at each depth for each CLT panel, and therefore only a few results were available for comparison. The exposed surface of the CLT panels should have been fitted with thermocouples, because the surface temperature does not equal the furnace temperature. Illustrations of the temperature developments in the sections are therefore not true for the first 10 mm below the surface. However, this does not affect the charring rate calculations as they are based on the time the char front reaches the thermocouples. The test results were compared with charring rate results from other experiments, however, there are only two experiments to compare with and one of them only has one measurement. More information on the charring rate of CLT panels exposed to standard and parametric fires is needed.

In *Paper V* the charring rates found in the fire tests were compared to charring rates calculated by the charring rate models described in *Paper III*. Even though the char depths as a function of time matched fairly well for some of the models, the charring rate results were far from the calculated rates. This is because the charring rate changes through the development of the fire. Early in the fire it will usually be faster than during the later stages of the fire, where it becomes almost constant. However, almost all of the models have a linear charring rate development. For a long lasting fire, the calculated char depths will therefore eventually match the test results. On the other hand, a short fire will result in much smaller char depths than those calculated by the charring rate models used here.

In short; An economic and adequate fire safety design of a building can only be achieved when the chosen fire development is as realistic as possible with all relevant fire loads included, the charring rate is calculated based on the most important material properties and external factors, and the charring rate model is applicable to the fire development model in use. The current results show that the existing methods are not very accurate for heavy timber structures, and new, more accurate tools, must be developed.

5 Conclusions

5.1 Main findings

The charring behaviour of solid wood, nail- and glue-laminated structural timber members, and cross-laminated timber (CLT) panels, has been studied through literature review, laboratory experiments and calculations.

In a study of the literature on material properties and external factors that influence the charring behaviour of the timber members, *Paper I*, the following properties and factors were found to have the largest influence:
- density
- moisture content
- lignin content
- permeability
- grain direction
- char contraction factor
- char oxidation
- thickness
- surface area
- orientation of the sample
- thermal exposure
- oxygen concentration
- ventilation

All these properties have relatively large effects on the charring rate, separately or in conjunction with each other. Due to the dissimilarities of the test methods and conditions, wood species and measuring methods, it was impossible to decide which of the properties and factors are most important.

Eight tables are included in this thesis in addition to the *Paper I* to show some results on the effect of the various material properties and external factors found in the literature. From the results in *Table 3.1* to *Table 3.7* it is obvious that the effect of the various properties and factors vary greatly between species, densities, moisture content, etc.:
- the charring rate increases with lower density, or higher permeability,
- higher moisture content decreases the charring rate, but size of the change varies greatly,
- the difference between hardwood and softwood is not unambiguous,
- for Klason lignin the two cases found show increasing charring rate with increasing Klason lignin content,
- the permeability is clearly an important property, as the charring rate is higher for species with larger penetration depth,
- the charring rate increases with higher heat flux, better ventilation and more oxygen in the air.

Paper I gives important background information for *Paper III*, where calculation models are evaluated partly on which properties and factors they take into account.

A very important part of the structural fire design of timber structures is to determine the temperature development in the fire compartment, and an evaluation of four fire curves for standard and parametric fires was therefore performed, *Paper II*.

The evaluation revealed:

- that most of the curves have initial growth rates that are much higher than for real fires,
- linear cooling stages, as some of the fire curves have, are not realistic for exposed timber structures,
- the Standard fire curve from EN 1991-1-2 [13] cannot be adjusted according to the fire load representing the use of the fire compartment, and it is not possible to include the fire load contribution from the timber structure,
- the Parametric fire curve from EN 1991-1-2 [13] gives the possibility to include the fire load contribution from the structure through iterations, but if large parts of the structure is exposed several rounds of iteration must be made, which is time consuming,
- the accuracy of the result is questionable as the fire will behave differently when the mobile fire load has burnt up and only the heavy timber structure burns.

Of the four fire curves evaluated, the "Swedish" fire [49,50] and iBMB fire [45,46] were evaluated to best represent a real fire in a compartment with exposed timber structures. These two curves have slightly slower growth rates and non-linear cooling stages. This is a paradox, as the "Swedish" and the iBMB models are not developed for timber structures.

In *Paper III* models for calculation of the charring rate of different timber members were evaluated. Experimental results from the literature were collected and charring rates for the same wood species, density and moisture contents were calculated using the models. The accuracy of the calculated charring rates varied greatly. The models including more of the material properties and external factors evaluated in *Paper I* were the most accurate in many cases. The models from EN 1995-1-2 [18] gave a good match in a few cases, but could definitely gain from differentiating more between species and densities.

Because the literature reviews revealed a lack of knowledge and research on CLT panels and other wooden structural elements exposed to parametric fires, laboratory experiments were performed. The experiments are reported in *Paper IV*. The progress of the char front was followed as it advanced into the fresh wood of six CLT panels of three different thicknesses exposed to three different fire curves. The main findings from these experiments are:

- the charring rates differ greatly between the fire curves,
- the fire curves with higher growth rates initially had higher initial charring rates,
- a short lasting fire with a steep cooling rate will have a short charring period and therefore a smaller char depth,
- a long lasting fire will reach a constant charring rate after a while,
- the lamella thicknesses did not affect the charring rate,
- the heated zone below the char layer grew to a constant thickness of 25-35 mm.

The charring rate results were also compared to experimental results found by other researchers, and the results for CLT panels exposed to EN 1991-1-2 Standard fire [13] match well with each other. The results for other fire exposures cannot be compared directly as the temperature-time developments are different. Due to the wide scatter in the results it is obvious that charring rate models developed for one temperature-time model cannot be used together with another temperature-time model. Charring rate models must be developed separately for each fire development method, and used only together with this method.

In *Paper V* the charring rate results from the laboratory experiments (reported in *Paper IV*) were compared to results found using the calculation models evaluated in *Paper III*. The comparison between charring rates for CLT panels exposed to the "Swedish" fire and calculated charring rates were not included in the paper itself, but added to the chapter. Due to the small number of test results for the EN 1991-1-2 Parametric fire [13] and the "Swedish" fire [49,50] the comparison did not give much information. The calculated char depths from many of the models for the panels exposed to EN 1991-1-2 Standard fire and Parametric fire matched very well with the measured char depths, while the charring rates did not match well. This is because the charring rate changes through the stages of the fire. For a long fire this might give a close match between the tested and calculated char depth results, while for a short fire the char depths might vary greatly. The charring rate models that matched well with the test results in *Paper III*, White & Nordheim and Schaffer, did not match well with the test results for CLT panels.

The situation today is that designers who choose to use timber practically have only one method of design for large structures with the requirement to withstand a full fire development, EN 1991-1-2 Parametric fire together with EN 1995-1-2 Parametric charring rate. However, this method does not cover all situations and has many limitations, and many times the designers have to give up timber as the structural material for a building due to the shortcomings of this method. In addition, the method often returns conservative results and therefore less economical solutions than for other traditional building materials. To become more competitive with other construction materials more precise data should be obtained upon which to design and predict fire endurance of large timber structures. At the moment many designers or contractors tend to prefer other traditional materials because the design tools are more developed and the material properties better documented.

5.2 Contributions to the Fire Safety field

Through the current research substantial information regarding the material properties and external factors influencing the charring rate of wooden structures has been gathered. Many models for calculation of the charring rates of wood have also been gathered and reviewed, and their accuracy established based on the influencing factors and charring rate results from the literature. They have also been compared with the charring rates found through the experiments performed as part of this research. The impact of the properties and factors on the charring rate varied greatly, and it is documented that the models must contain more parameters to obtain better precision. The charring rates described by EN 1995-1-2 Table 3.1 and Annex A are conservative and should be improved by including more factors and differ between species and/or densities.

The current research is the first documentation of the charring rate for CLT panels exposed to parametric fires. It is also the first time the charring rate for CLT panels exposed to different temperature-time curves has been compared. Similar large-scale fire tests of wooden structural elements exposed to parametric fire exposure have not been found in the literature, probably due to the complexity in following the temperature-time curves accurately. However, the furnace temperature during the tests (*Paper IV*) followed the calculated temperature-time development very well, even during the cooling stages, thanks to the very experienced lab engineers at SINTEF Fire Research Laboratory. Comparing the charring rates from the three fire tests it was obvious that the charring rate of wood exposed to one fire curve cannot be used for wooden structures exposed to another fire curve. Therefore, it must be stated clearly in the design code, EN 1995-1-2, that the equations for the parametric charring rates and depths given in Annex A are only applicable to wooden structures exposed to the Parametric fire curve as described in

EN 1991-1-2 Annex A. Charring rates for other parametric fire curves must be determined through fire tests where the wooden elements are exposed to the fire curve in question.

5.3 Future research

This research has pointed out several issues where knowledge is lacking for fire safe design of large timber structures. The most important issues are listed below:

- More tests should be carried out on the behaviour of exposed timber structures in compartment fires.
- Research on how the exposed timber structure influences the temperature-time development in a compartment fire.
- Develop temperature-time curves that are more realistic for exposed timber structures.
- Determine the charring rate for different wood species and building elements exposed to various fire curves.
- Systematic research on how various material properties and external factors influence the charring rate.
- Develop better models for the charring rate of various species, densities, moisture contents, permeabilities, etc.
- Develop simpler methods for calculating "the relevant combustible parts of the construction" which should be included in the design fire load.

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Fire and Ice
Some say the world will end in fire,
Some say in ice.
From what I've tasted of desire
I hold with those who favor fire.
But if it had to perish twice,
I think I know enough of hate
To say that for destruction ice
Is also great
And would suffice,
by Robert Frost

Attachments

Paper III.b - A review of models for calculation of the charring rate of solid wood structural elements and glue-laminated beams/columns

by
Kathinka Leikanger Friquin

Published in:
Tan, K.H., Kodur, V.K.R., Tan, T.H. (2008). *Proceedings of the Fifth International Conference Structures in Fire* (SiF'08), Nanyang Technological University, Singapore

Presented at:
The Fifth international Conference Structures in Fire, 28-30 May 2008, Singapore

Paper IV.b - Charring rates for cross-laminated timber panels exposed to standard and parametric fires

by
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Per Jostein Hovde, the Norwegian University of Science and Technology (NTNU)

To be published in:
Proceedings of the World Conference on Timber Engineering (2010), Riva del Garda, Trentino, Italy

To be presented at:
The World Conference of Timber Engineering, 20-24 June 2010, Riva del Garda, Trentino, Italy

A REVIEW OF MODELS FOR CALCULATION OF THE CHARRING RATE OF SOLID WOOD STRUCTURAL ELEMENTS AND GLUE-LAMINATED BEAMS/COLUMNS

KATHINKA LEIKANGER FRIQUIN[1]

ABSTRACT

Calculation models for charring rate of solid, nail- and glue-laminated wood members for use in fire design of wooden structures have been compared with test results from the literature. The applicability to solid, nail- and glue-laminated wood members, and the accuracy of the models, have been evaluated based on which parameters influencing the charring rate they include, i.e. species, density, moisture content, grain orientation, char contraction factor, external heat flux, thermal conductivity, oxygen concentration and opening factor. The models evaluated in this article are applicable to one- or two-dimensional charring under standard fire exposure.

1. INTRODUCTION

The use of solid wood elements and glue-laminated beams and columns in buildings and structures is gaining popularity in the Nordic countries, and these types of structural members have already been widely used around the world. In countries where timber is a readily available resource, it is a natural choice for construction material. The fire resistance of solid wood slabs and glue-laminated structural members is important when used in buildings, and in many cases, the fire safety of a building with these wooden elements can match or even succeed that of other structural materials. To design a fire safe wooden building the thermal properties of the material, the thermal conditions in the fire compartment and the charring rate of the material must be known. When wood is exposed to elevated temperatures, several factors regarding the material, the conditions in the room and the heat source affect the charring rate. Several attempts have been made to develop models to describe the charring rate of wood and how different factors influence on the charring, but few of them include more than two of these factors.

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Large wooden elements are not oven-dry like many test specimens, they have a smaller exposed surface to volume-ratio, and the mass and heat transfer in large cross sections is different from the small test pieces that are commonly used in experiments. Multi-storey wooden structures, with the requirement of maintaining their load bearing abilities through a natural fire, will be exposed to a varying heat flux, and there are several other parameters that will affect the charring rate. There are many thorough reviews of pyrolysis models for wood, but few of them, if any, emphasize on the charring rate of solid wood or glue-laminated structural elements, nor the importance of including the density, moisture content, chemical composition and other factors in the models.

In this paper, several models for calculating the charring rate of solid wood or glue-laminated structural members from the literature are evaluated in regards to which parameters influencing the charring rate they include, i.e. species, density, moisture content, grain orientation, char contraction factor, external heat flux, thermal conductivity, oxygen concentration and opening factor. The reliability and fitness for use of the models are examined based on the parameters included in the model, and the possibility to adjust the material properties and thermal conditions with variations in the species, room or exposure conditions. The models most suited for calculation of charring depths of solid wood elements and glue-laminated timber beams and columns are determined. The charring rate for a few solid, nail- and glue-laminated cross sections have been calculated and compared with experimental results found in the literature. The current study is limited to unprotected solid wood elements and nail- or glue-laminated beams and columns exposed to standard fire. Only wood species commonly used in Europe and North-America are included. The project is part of the Strategic University Programme "Wood as a building material" funded by the Research Council of Norway, and the European WoodWisdom-Net project "FireInTimber – Fire resistance of innovative timber structures".

2. CALCULATION MODELS FOR CHARRING

Several charring rate models for structural wooden slabs and members have been found in the literature and evaluated here. The models are separated into two groups in Table 1; one-dimensional charring models and two-dimensional charring models. The one-dimensional charring models do not include corner rounding, while the two-dimensional models do (See Fig. 1). Charring models are developed for various types of fire exposure, and in the current research focus is set on ISO 834[1] (ISO) and ASTM E119[2] (ASTM) standard fire exposure. Models for parametric fire exposure are not included in this article. This is because these models require that the opening factors and heat exposure for the experiments are known in order to compare them with each other.

EN 1995-1-2:2004[3] gives two ways of calculating the cross-sectional properties, either by using the actual charring depth including corner rounding, or by calculating a notional cross-section without corner rounding based on the notional charring rate. The position of the char front should be taken as the position of the 300-degree isotherm. Design charring rates for solid hardwoods, except beech, with characteristic densities between 290 and 450 kg/m³, may be obtained by interpolation between the values in Table 2.

Table 1. Separation of models for charring of wood into a group for one-dimensional charring and a group for two-dimensional charring

		Fire exposure			Factors included
Reference	Year	ISO	ASTM	Other	
One-dimensional					
Eurocode 5a[3]	2004	X			Softwood/hardwood, density, solid or laminated
Schaffer[4]	1967		X		Dry density, moisture content, species
Babrauskas[5]	2005	X	X		Density, oxygen concentration, heat flux, duration of fire
Yang et al.[6]	2008			X	Density, time-increasing heat flux rate.
Two-dimensional					
Eurocode 5b[3]	2004	X			Softwood/hardwood, density, solid or laminated, cross-section
AWC[7]	2003		X		Duration of fire

Table 2. Design charring rates β_0 and β_n of timber[3]

	β_0 mm/min	β_n mm/min
a) Softwood and beech		
Glue-laminated timber with characteristic density of ≥ 290 kg/m³	0.65	0.7
Solid timber with a characteristic density of ≥ 290 kg/m³ (incl. beech)	0.65	0.8
b) Hardwood		
Solid/glue-laminated hardwood, characteristic density of 290 kg/m³	0.65	0.7
Solid/glue-laminated hardwood, characteristic density of ≥ 450 kg/m³	0.50	0.55

Table 3. Determination of k_0 for unprotected surfaces with *t* in minutes[3]

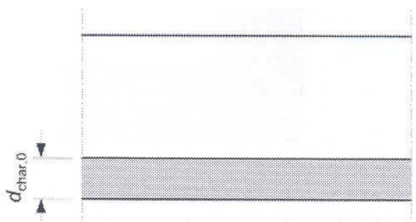
	k_0
t < 20 minutes	$t/20$
$t \geq$ 20 minutes	1.0

Table 4. Models for charring rate of wood

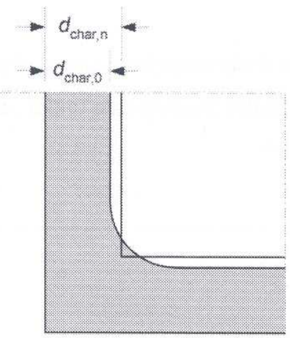
References, comments and limitations	Equation
One-dimensional – ISO 834	
Eurocode 5a[3] König[8] argues that because EN 1995-1-2 gives the corner radius as $r = d_{char,0}$ the minimum width $b_{\min}$ should for $d_{char,0} > 40mm$ be changed to: $b_{\min} = 4d_{char,0}$ König[8] also suggests that the notional charring rate for solid timber (see Table 2) is used for nail-laminated timber slabs with normal gap widths to achieve conservative results.	Design charring depth: $d_{char,0} = \beta_0 t$ (1) where the charring rate β_0 is taken from Table 2. Effective charring depth: $d_{ef} = d_{char,0} + 7k_0$ (2) where k_0 is found in Table 3.
One-dimensional – ASTM E119	
Schaffer[4] Charring rate converted to (mm/min) by: $\beta = 25.4/\tilde{\beta}$.	Charring rate: Douglas fir $\tilde{\beta} = 2\left[(28.726 + 0.578\omega)\rho_{dry} + 4.187\right]$ (3) Southern pine $\tilde{\beta} = 2\left[(5.832 + 0.120\omega)\rho_{dry} + 12.862\right]$ (4) White oak $\tilde{\beta} = 2\left[(20.036 + 0.403\omega)\rho_{dry} + 7.519\right]$ (5)
Babrauskas[5] He argued that this equation is applicable to both ISO 834 fire and ASTM E119 fire.	Charring rate: $\beta = 113k_{O2}\frac{(\bar{q}'')^{0.5}}{\rho t^{0.3}}$ (6) where $k_{O2} = 1.0$ for charring in high oxygen concentration, $k_{O2} = 0.8$ for charring in 8-10%, and $k_{O2} = 0.55$ for charring in 4% oxygen concentration.
One-dimensional – Others	
Yang et al.[6] For time-increasing heat flux. The increasing rate of heat flux for ASTM E119 is approximately 0.07 kW/m²s, and is used in Table 7.	Charring rate: $\beta_\gamma = 136\gamma^{0.51} \cdot \rho^{-0.76}$ (7)

Table 5. Models for charring rate of wood (contd.)

References, comments and limitations	Equation
Two-dimensional – ISO 834	
Eurocode 5b[3]	Notional charring depth: $$d_{char,n} = \beta_n t \quad (8)$$ where the notional charring rate β_n (mm/min) is taken from Table 2. Effective charring depth: $$d_{ef} = d_{char,n} + 7k_0 \quad (9)$$ where k_0 is found in Table 3.
Two-dimensional –ASTM E119	
AWC[7]	Effective charring rate: $$\beta_{eff} = \frac{2.58\beta_n}{t^{0.187}} \quad (10)$$ where β_n is assumed to be 0.64 mm/min.



a)



b)

Fig. 1. a) One-dimensional charring of wide cross-section with fire exposure on one side. b) Charring depth $d_{char,0}$ for one-dimensional charring and notional charring depth, $d_{char,n}$ [3]

3. CALCULATED CHARRING RATES COMPARED WITH TEST RESULTS

The calculation models listed in Table 4 have been compared with charring rate results from test experiments from various laboratories. A short description of the experiments referred to in this article is given in Table 6.

Table 6. Experiments referred to in Table 7 and Table 8

Author	Species	Test apparatus / Fire exposure / Orientation / Exposed sides and time	Specimen size (mm x mm)
White[9]	*Softwood*: Engelmann spruce, Western cedar, Southern pine, Redwood *Hardwood*: Hard maple, Yellow poplar, Red oak, Basswood	Small gas-fired furnace ASTM E119 Vertical One side, 60 minutes	Glue-laminated slabs 63 x 230, 510 mm long, 38 or 46 mm thick laminates
Cedering[10,11]	*Softwood:* Norway spruce	Gas-fired furnace ISO 834 Vertical One side, 60 minutes	Nail-laminated 40 x 140, 1000 mm long Samples nailed together to form a wall of 55-60 planks
König[12]	*Softwood:* Spruce	Small gas-fired furnace ISO 834 Horizontal One side, 30-60minutes	Nail-laminated slabs 315 x 1500, 95 mm thick, 7 laminates of 45 mm thickness nailed together
Landrø[13]	*Softwood:* Spruce	Gas-fired furnace ISO 834 Horizontal One side, 30 minutes	Cross-layered glue-laminated slab 4800 x 3600, 160 mm thick. Loaded with 3 kN/m².
Frangi and Fontana[14]	*Softwood:* Spruce	ISO 834 Beams; three sides Slabs; one side 30-110 minutes	Glue-laminated timber beams, and slabs made of nailed planks, 120 mm thick
Landrø[15]	*Softwood:* Spruce	Gas-fired furnace ISO 834 Beams; three sides Columns; four sides 30 minutes	Glue-laminated timber beams and columns 90 x 300, 1400 mm long 1300 mm long

In Eurocode 5[3], 7 mm is added to the charring depth. The charring rates given in Table 2 have therefore, in the tables below, been increased with 0.12, 0.08 and 0.06 mm/min for 60, 90 and 120 minutes respectively, to include these 7 mm. Test results for dry density wood have only been compared with models using dry density in the equation, and models using wet density have only been compared with test results for wet density wood. The only exception is calculation results for EN 1995-1-2[3] which normally are valid for wet density wood, but is also applicable to dry density wood where the wet density can be assumed based on the dry density. This is because the charring rate is the same for densities above 290 kg/m³ for softwoods, and for hardwoods the charring rate is the same for wood densities at 290 kg/m³ and for densities above 450 kg/m³. Babrauskas[5] found the average heat flux in the ceiling during ASTM E119 fire to be approximately 92 kW/m². This heat flux is therefore used in the calculations, together with 8-10% oxygen.

3.1. One-dimensional charring

In Table 7 below, one-dimensional charring rate results from the experiments listed in Table 6 have been compared with calculated results using the one-dimensional models from Table 4.

Table 7. Calculated charring rates (mm/min) compared with test results from the literature, for one-dimensional charring of nail- and glue-laminated wood

Species	Ref	Density (kg/m³)	Test results Moisture (%)		Calculation results				
							Exposure time (min)		
			10-12	16-18	Model	Eq. No	60	90	120
Nail-laminated									
Spruce	10,11	370	0.71	0.64	EC 5a	β_0(+7)	0.77	0.73	0.71
		370			König [8]	β_n	0.80	0.80	0.80
	14	425	0.70		EC 5a	β_0(+7)	0.77	0.73	0.71
	12	425	0.70		König [8]	β_n	0.80	0.80	0.80
		370			Babrauskas	(6)	0.69	0.61	0.56
		425					0.60	0.53	0.49
		370			Yang et al	(7)	0.39	0.39	0.39
		425					0.35	0.35	0.35
Glue-laminated									
Spruce	9	400*	0.59	0.52	EC 5a	β_0(+7)	0.77	0.73	0.71
(Douglas fir)		400*	x		Schaffer	(3)	0.69	0.69	0.69
				x			0.64	0.64	0.64
	13	475	0.64		EC 5a	β_0(+7)	0.77	0.73	0.71
		475			Babrauskas	(6)	0.54	0.47	0.44
		475			Yang et al	(7)	0.32	0.32	0.32
Cedar	9	285*	0.75	0.73	EC 5a	β_0(+7)	0.77	0.73	0.71
Pine	9	485*	0.76	0.83	EC 5a	β_0(+7)	0.77	0.73	0.71
Redwood	9	324*	0.76	0.62	EC 5a	β_0(+7)	0.77	0.73	0.71

Maple	9	650*	0.66	0.64	EC 5a	β_0(+7)	0.62	0.58	0.56
Yellow poplar	9	482*	0.68	0.68	EC 5a	β_0(+7)	0.62	0.58	0.56
Oak	9	635*	0.57	0.56	EC 5a	β_0(+7)	0.62	0.58	0.56
		635*	x	x	Schaffer	(5)	0.55 0.51	0.55 0.51	0.55 0.51
Basswood	9	385*	0.87	0.70	EC 5a**	β_0(+7)	0.74	0.70	0.68

EC 5 = Eurocode 5 * Dry density **Interpolated 0.62 mm/min

3.2. Two-dimensional charring

In Table 8 below, two-dimensional charring rate results from the experiments listed in Table 6 have been compared with calculated results using the two-dimensional models from Table 4. The charring rates have been calculated using the same density and moisture content as the tested samples.

Table 8. Calculated charring rates (mm/min) compared with test results from the literature, for two-dimensional charring of solid and glue-laminated wood

Species	Ref	Density (kg/m³)	Test results Moisture (%)		Calculation results				
							Exposure time (min)		
			10-12	16-18	Model	Eq. No.	60	90	120
Solid									
Spruce	14	378	0.67		EC 5b	β_n(+7)	0.92	0.88	0.86
		378			AWC	(10)	0.77	0.71	0.68
Glue-laminated									
Spruce	14	453	0.70		EC 5b	β_n(+7)	0.82	0.78	0.76
		453			AWC	(10)	0.77	0.71	0.68
Spruce	15	450		0.67	EC 5b	β_n(+7)	0.82	0.78	0.76
		450			AWC	(10)	0.77	0.71	0.68

EC 5 = Eurocode 5 * Dry density **Interpolated

4. DISCUSSION: APPLICATION OF MODELS ON GLUE-LAMINATED WOODEN ELEMENTS

Many factors influence the charring rate of wood, and researchers have different opinions and experimental results on how they affect the charring. Factors like density, moisture content, species, heat exposure, opening factor etc influence the charring rate in different ways and some are more significant than others. The factors are included in various forms and combinations in the char calculation models described in this report, and are important for the results the models give. The user of the models must know which factors are included and which are neglected, so that the results can be evaluated correctly.

All except one of the models evaluated in this article include the density of the wood, one model varies between different species, two models differs between hardwoods and softwoods, and solid or glue-laminated cross-section, the moisture content is included in one model, another includes the oxygen concentration in the fire compartment, two models include the duration of the fire, and two models include the imposed heat flux.

Comparing the charring rates for nail-laminated cross-sections of *spruce* exposed to one-dimensional fire, the test results for densities between 370-425 kg/m² are equal at about 0.70 mm/min. The calculated charring rates, however, differ widely from 0.35-0.80 mm/min (60 min). The largest values (EC 5a and König[8]) are conservative, while the lowest values (Eq. 7) seem unlikely to achieve. For a 60 minutes exposure, Babrauskas' model (Eq. 6) compares well with the test results.

For glue-laminated cross-sections exposed to one-dimensional fire (Schaffer's model (Eq. 3) for Douglas fir has here been used for spruce), the charring rate test results for *spruce* with densities between 400 kg/m³ (dry density) and 475 kg/m³ varies between 0.59-0.64 mm/min (60 min). The calculated results vary between 0.32-0.77 mm/min, and Schaffer's and Babrauskas' results are closest to the test results. The results from the model in EN 1995-1-2[3] are as much as 30% higher than the test results. The lowest charring rates (Eq. 7) are also here very unlikely.

For *oak* with a dry density of 635 kg/m³ the experiment shows a charring rate of 0.56-0.57 mm/min, while the calculations results in rates between 0.51-0.62 mm/min. Schaffer's model (Eq. 5) for White oak with moisture content 12% compares best with the experiment.

Test results for the other species have only been compared with EN 1995-1-2[3] because the test reports only give the dry density. For the softwoods *cedar*, *pine* and *redwood*, the calculation results at 60 minutes match well the test results for wood with 10-12% moisture content. The calculated charring rates for the hardwoods *maple*, *yellow poplar* and *basswood*, however, do not compare well. The results for maple are closest, while for basswood the results are very different.

The calculated charring rates for solid and glue-laminated *spruce* with a density of 378-453 kg/m³ exposed to two-dimensional fire are much larger than the test results. The results from the model in EN 1995-1-2[3] are as much as 37% higher than the test results.

5. CONCLUSIONS

A few test results have in this article been compared with calculation models for the charring rate of wood found in the literature. The experiments differ widely in species tested, moisture content, cross-section sizes, heat flux, oxygen content etc. and are therefore difficult to compare. Detailed guidelines and methods for testing of charring rates of wood must be developed, where the moisture content, oxygen concentration, sample size and orientation, heat exposure, etc are described for various types of end uses of the test results. This will enable researchers all over the world to compare their test results with each other, and the reproducibility of the tests would be better.

There is a need for more comprehensive charring rate experiments on the most commonly used wood species for building construction. The test results can be used to develop more accurate charring rate models, incorporating several of the influencing factors., like; density, moisture content, species, heat flux, time, opening factor, etc.

Amongst the calculation models evaluated in this article, Schaffer's (Eq. 3, 4 and 5) and Babrauskas' (Eq. 6) models for one-dimensional fire exposure for both nail- and glue-laminated members gave the most accurate charring rates compared with the test results. The model in EN 1995-1-2[3], and the suggestion from König[8] for nail-laminated slabs, were very conservative. For two-dimensional fire exposure, both the model in EN 1995-1-2[3] and the AWC model (Eq. 10) are very conservative.

The comparisons of the models with test results show that the models including more factors give more accurate results, and the variations between species are large. Schaffer's model includes both dry density and moisture content, and differs between species. Unfortunately, Schaffer only developed variations of the model for three species (Eq. 3, 4 and 5), but variations for more species can be developed. Babrauskas' model (Eq. 6) includes density, oxygen concentration, heat flux and fire duration. Other models also include density, heat flux or fire duration, but none of them differ between species, or include both heat flux and fire duration at the same time.

The wide spread of test results and calculated results for the charring rate shows the obvious need for more research on charring rates for various wood species and fire exposures, and for redevelopment of charring rate models for use in fire safety design of wooden buildings.

NOMENCLATURE

Latin upper case letters

A_i	Area of vertical opening "i" (m²)
A_t	Total area of floors, walls and ceilings enclosing the fire compartment (m²)
A_v	Total area of openings in vertical boundaries of compartment (windows etc.) (m²)
F	Design opening factor ($m^{0.5}$)
O	Opening factor ($m^{0.5}$)
Q	Sum of the products of density and lower calorific value of materials found in the fire compartment (MJ)

Latin lower case letters

b	Absorptivity for the total enclosure
c	Specific heat of the boundary of the compartment (J/kgK)
$d_{char,0}$	Charring depth for one-dimensional charring (mm)
$d_{char,a}$	Charring depth for wide surface (mm)
$d_{char,b}$	Charring depth for narrow surface (mm)
$d_{char,n}$	Notional charring depth (mm)
d_{ef}	Effective charring depth (mm)
f	Coefficient to account for horizontal openings
f_c	Char contraction factor
h_{eq}	Weighted average of heights of all openings (windows etc) (m)
h_i	Height of vertical opening "i" (m)
k	Transfer coefficient of bounding structure
k_0	Coefficient
k_{O2}	Coefficient for oxygen concentration
m	Reciprocal charring rate (min/mm)
q_F	Design fire load related to design opening factor F (MJ/m²)
$\bar{q}''$	Test-average total heat flux (kW/m²)
r	Corner radius (mm)

t Time of fire exposure (min or hrs)

t_0 Time period with a constant charring rate (min)

Greek upper case letters

Γ Factor accounting for the thermal properties of the boundaries of the compartment,

Greek lower case letters

β Charring rate (mm/min)

β_0 Design charring rate for one-dimensional charring under standard fire exposure; Initial rate of charring (mm/min)

β_{eff} Effective charring rate (in/hr)

β_H Charring rate (m/s)

β_n Design notional charring rate under standard fire exposure (mm/min); Nominal charring rate based on one hour exposure (in/hr)

β_{par} Design notional charring rate under standard fire exposure (mm/min)

$\tilde{\beta}$ Charring rate (min/inch)

β_γ Charring rate for time-increasing heat flux (mm/min)

γ Time-increasing rate of heat flux (kW/m^2s)

λ Thermal conductivity; Thermal conductivity of the boundary of the compartment (W/mK)

θ Time at which maximum charring is reached for the values used for F and q_F (min)

ρ Density; Density of the boundary of the compartment (kg/m^3)

ρ_{dry} Dry specific gravity (kg/m^3)

ω Moisture content (%)

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2010

CHARRING RATES FOR CROSS-LAMINATED TIMBER PANELS EXPOSED TO STANDARD AND PARAMETRIC FIRES

Kathinka Leikanger Friquin[1], Mads Grimsbu[2], Per Jostein Hovde[3]

ABSTRACT: The present study tested the charring rates for cross-laminated timber panels (CLT) exposed to standard and parametric fires. A series of fire tests were performed on horizontal cross-laminated timber panels exposed to EN 1991-1-2 Standard and Parametric temperature-time curves, and a "Swedish" curve. A large gas-fired horizontal furnace was used in the experiments. The char depth was measured through all stages of the fires. The objectives were; to examine the charring rate of CLT panels and whether the charring changed through the fire stages, to investigate if the charring rates for the various temperature-time curves were different, and if the rates were affected by the panel thicknesses. Timber panels of three different thicknesses were tested to investigate a thickness effect. The results illustrate that the charring rate for CLT panels exposed to various fires can vary greatly. Fast temperature growth gave faster charring rates. The thickness of the panels did not have an unambiguous effect on the charring rate. The charring rate of wood exposed to fires of long durations became constant after a while.

KEYWORDS: wood, charring rate, parametric fire, standard fire, cross-laminated timber panel

1 INTRODUCTION

The requirement in many countries' building regulations for large wooden structures to withstand a complete natural fire creates a demand to determine the charring rate's development through all stages of the fire, i.e. growth stage, fully developed stage and decay stage. Initially the rate will be increasing because the wood is unprotected and the temperature rising, but as the char layer forms on the surface the charring rate will become constant. When the char layer reaches its maximum thickness at a furnace temperature around 1 000°C the char layer will have a constant thickness as the char front advances into the wood due to consumption of carbon at the surface. The charring rate is constant. When the fire enters the cooling stage the charring rate will be decreasing as the temperature drops and at a point it will stop all together. The development of the charring rate at this stage is of great interest as it will give a more accurate picture of the char depth at the end of the fire.

Extensive research has been carried out on the charring rate for the two first stages, but there is not much to be found in the literature on the charring rate of wood during the decay stage of a fire, or the charring rate of cross-laminated timber panels (CLT). Landrø [1] tested the fire resistance of loaded CLT panels in a large-scale horizontal furnace exposed to ISO 834 fire. Frangi et al. [2] tested CLT panels made with Polyurethane (PU) glue and Melamine Urea Formaldehyde (MUF) glue exposed to standard ISO 834 fire [3] in a small horizontal furnace. Particular attention was given to the influence the adhesive had on the fire behaviour of the CLT panels compared to homogeneous panels. They found that for the panels with PU glue the panel layer falls off when it is charred through, whereas the MUF glue does not cause such de-lamination. The fire behaviour for panels where the charred layer did not fall off is similar to that of homogeneous timber panels, and almost constant through the panels.

In addition to the experiments on CLT panels, a few tests have been performed on nail- or glue-laminated panels made of parallel lamellas, exposed to fire in an edgeways position. König & Walleij [4] investigated the one-dimensional charring of glue-laminated timber panels exposed to standard ISO 834 fire [3] and "Swedish" fires [5,6] in a small-scale furnace. The timber panels were made of parallel spruce lamellas and tested in edgeways position. Fornather et al. [7] investigated the combustion behaviour of glue-laminated wood and solid wood exposed to three different fire scenarios; ISO 834 fire [3], a slow heating fire, and a parametric fire [8].

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The present study investigated the charring rates for CLT panels exposed to the EN 1991-1-2 Standard and Parametric fires and a “Swedish” fire. The objectives were:

- to examine whether the charring rate changed through the stages of a fire,
- to compare charring rates for different temperature-time curves, and
- to compare charring rates for different panel thicknesses.

2 MATERIALS AND METHODS

2.1 CROSS-LAMINATED TIMBER PANELS

Cross-laminated timber panels of Norway spruce (*Picea abies*) fabricated by Moelven MassivTre AS were tested. The panels are made of layers of lamellas with various thicknesses stacked on one another at right angles, and glued together in a press over their entire surface. The build-up is symmetrical around the middle layer, see Figure 1. The adhesive melamine urea formaldehyde (MUF) was used in the process. The thickness of the panels and lamella layers are given in Table 1.
The first, third, fifth and seventh layers span in the lengthwise direction, while the other layers span across the slab, in a 90 degree angle to the other layers. The timber panels were 1 200 mm wide by 3 600 mm long, where 3 080 mm of the length and the entire width was exposed to the fire. The moisture content was in the range 8-9.3%, and the density approximately 440 kg/m³. Detailed information about the CLT panels can be found in SINTEF Technical Approval No. 2421 [9].

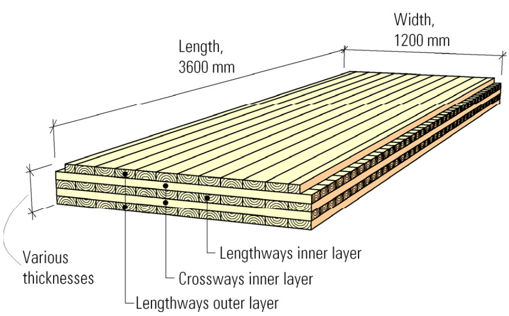

Figure 1: *Cross-laminated timber panel [9].*

Table 1: *Thicknesses and designations of the panels.*

Test No.	Thick-ness (mm)	Design.	Layer thickness (mm)
1	120	T1A	19.5-30-21-30-19.5
1	240	T1B	29.5-39-32-39-32-39-29.5
2	180	T2C	32-41-34-41-32
2	240	T2D*	31.5-21-32-21-32-21-32-21-28.5
3	120	T3E	19.5-30-21-30-19.5
3	240	T3F	29.5-39-32-39-32-39-29.5

* This panel was not produced according to the specifications given by the manufacturer. It was supposed to have seven lamellas with the same thicknesses as T1B and T3F, but has instead 9 layers.

2.2 TEMPERATURE-TIME CURVES

The CLT panels were exposed to three different temperature-time curves in three separate tests (see Figure 2):

- Test 1 – Parametric fire curve from EN 1991-1-2 [10],
- Test 2 – Standard fire curve from EN 1991-1-2 [10],
- Test 3 – “Swedish” curve developed and described by Magnusson & Thelandersson [5] and Pettersson & Ödeen [11].

EN 1991-1-2 Standard curve was included because it is very commonly used for all structures, and the Parametric curve was chosen because it will normally be used for large wooden structures. The “Swedish” curves are well known and recognized, and therefore included here. The curves have been evaluated for the use on CLT panels in an earlier work by Friquin [12].

The curves are calculated based on a fictitious small office compartment with length 4 080 mm, width 3 080 mm, and 3 000 mm height. The office has concrete walls and floor, and ceiling made of CLT panels. All surfaces are fully exposed to the fire. The energy from the CLT panels was not included in the fire load density due to restrictions on the furnace, where the maximum temperature could not exceed 1 100°C. This results in shorter fires and lower temperatures than if the timber panels were included in the fire load density. The main objective of the experiments was to measure the change in charring rate through the three stages of the fire, and therefore the reduced fire load density was not considered important. The shapes of the curves are similar to what they would be with the fire load from the timber panels included, but with different maximum temperatures and fire duration.

The characteristic fire load density per unit floor area is set to be 511 MJ/m² for an office (found in [10] Annex E, Table E.4). This value is multiplied by four factors given in [10] Annex E, Chapter E.1 to find the design value of the fire load per unit floor area. The following factors were used for the current fire compartment (office) are used; combustion factor m = 0.8, compartment size factor $\delta_{q1} = 1.10$, occupancy type factor $\delta_{q2} = 1.00$, and factor for active fire fighting measures $\delta_n = 1.00$. The design value per floor area is then multiplied with the floor area and divided on the total surface area, including openings, to find the design fire load per unit surface area.

The “Swedish” curves are based on a “standard fire compartment A” with thermal properties of the boundaries corresponding to structures consisting of concrete, brick and lightweight concrete. This compartment is characterised by a *k*-factor equal to 1. Pettersson and Ödeen [11] developed k-factors for a few different compartment types, but none of them containing any wood. König [13] has therefore developed a formula to calculate the *k*-factor for compartments with wooden boundaries. In our fictitious fire compartment the k-factor is calculated to be 2.37.

The fire load density and the opening factor is multiplied with the *k*-factor to find a fictitious fire load density and opening factor, which are used to find the temperature-time development for the specific compartment.

For the fictitious fire compartment studied here the design fire load per unit surface area was calculated to 83 MJ/m² for the Standard fire and the Parametric fire, and 197 MJ/m² for the “Swedish” curve.

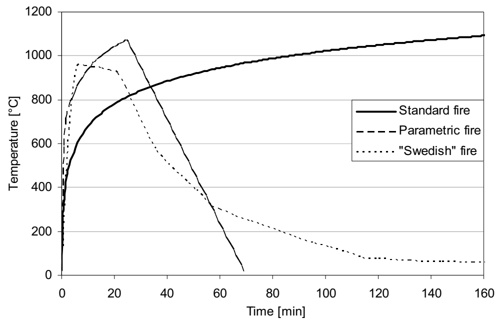

Figure 2: *The three temperature-time curves used in the experiments; EN 1991-1-2 Standard fire and Parametric fire, and the “Swedish” fire.*

2.3 LARGE-SCALE HORIZONTAL TEST FURNACE

The tests were run in a large-scale horizontal gas-fired test furnace, with a top opening 3 080 mm wide by 4 060 mm long, and 1 500 mm deep. The furnace has 16 gas-burners, eight burners on each of the long walls 480 mm below the surface of the test samples. They produce a total of 11 000 MJ/h. Propane gas mixed with 4% oxygen is used. The furnace has two vertical, circular flue ducts with a diameter 500 mm at floor level of the furnace on one of the long walls, and is also fitted with two pressure gauges which are located on the same wall as the flue ducts. Six plate thermocouples (TC) are placed 1 400 mm above the floor to measure the temperature in the furnace. The position of the plate TCs, propane burners and flue ducts are shown in Figure 3 and Figure 4.

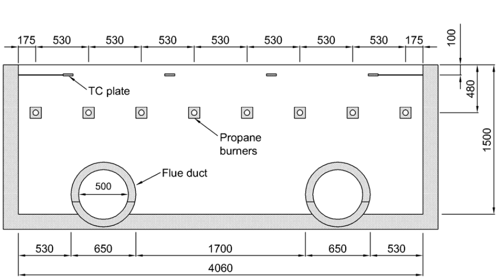

Figure 3: *Vertical cross-section of the furnace. All measures in mm.*

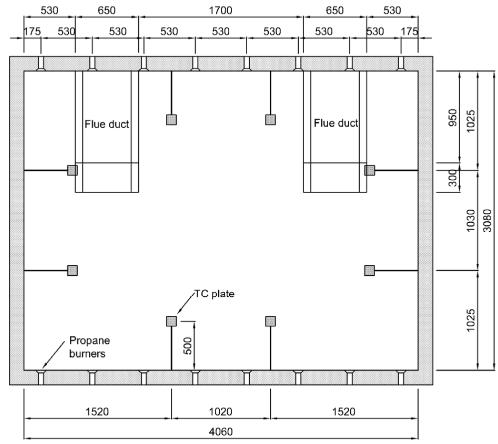

Figure 4: *Horizontal cross-section of the furnace. All measures in mm.*

The temperature in the furnace is controlled by an automatic control system during heating stage, fully developed fire and the early parts of the cooling stage. During the cooling stage the burners had to be turned off at a point and further temperature adjustments were manual, using the fan and/or making openings between the Ziporex elements to achieve cooling of the furnace temperature.

2.4 CHAR DEPTH MEASUREMENTS

The char front in wood is commonly defined to be at 288°C in North-America, while Mikkola [14] found the char front at 360°C. However, the precise temperature is not important due to the steep temperature gradient in the wood section, as described by Mikkola [14]. In the current research the char front is defined as the 300°C isotherm, as specified in EN 1991-1-2 [10].

The progress of the char front (300°C isotherm) was obtained by TCs that measured the wood temperature at various depths in the specimen. Thermocouples of the type K (Chromel/Alumel) were placed in 3 mm wide holes drilled from the unexposed surface of the timber panels. They were placed in the panels at 10 mm intervals from 10mm to 180 mm depth from the exposed surface, depending on the thickness of the panel, see Figure 5.

One thermocouple was placed in the middle of the cold face of the panels. The TCs were placed in one or two rows, depending on the thickness of the timber panel. The distance between the TCs in one row were 50 mm, and between two rows 200 mm. Due to the width of the panels (1 200 mm) it was assumed that the temperature development in the two rows were equal. The temperature on the exposed surface was presumed to be equal to the furnace temperature, which was measured with 6 plate TCs, as shown in Figure 3 and Figure 4.

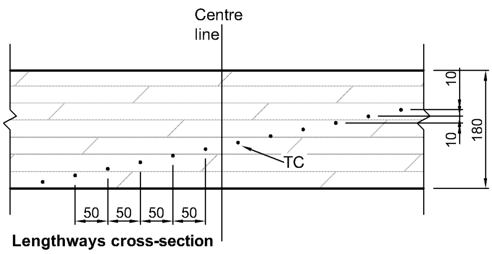

Figure 5: *Lengthways cross-section of the 180 mm thick timber panel showing the position of the TCs.*

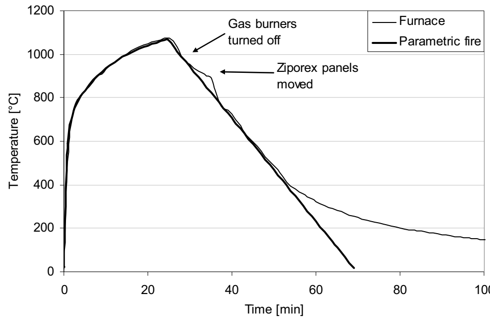

Figure 6. *Calculated EN 1991-1-2 Parametric temperature-time curve and average measured furnace temperature through Test 1.*

2.5 TEST METHOD AND SETUP

EN 1363-1, which is a European test standard for fire resistance tests of construction elements exposed to Standard temperature-time developments only, was followed.

The temperature-time development was mainly automatically adjusted to follow the three curves described in Figure 2, but during the cooling stages some adjustments had to be made manually. These adjustments were; turning off the gas burners, making gaps between Ziporex panels and timber panels, and turning off/on the flue duct fan. The pressure in the furnace was controlled at 20 Pa.

Three fire tests were run. In each test a 240 mm thick CLT panel was tested together with a 120 mm or 180 mm thick CLT panel to enable comparison of the charring rate for different panel thicknesses. The two CLT panels were placed side by side in each test according to Table 1, spanning across the top of the furnace. Two Ziporex panels were placed on each side of the timber panels to cover the whole top. The panels were not loaded. TC Firemaster blankets were placed between all the panels to tighten the joints. CLT panels will normally be exposed to the fire on one surface only, and have therefore only been tested for one-dimensional charring in these experiments. The TCs were connected to a box that transferred the data to a computer which logged the temperature measurements.

3 TEMPERATURE DEVELOPMENTS AND CHARRING RATES

3.1 TEST 1 – EN 1991-1-2 PARAMETRIC FIRE

The average furnace temperature followed the calculated temperature development very well, Figure 6. The gas burners had to be turned off early in the cooling stage (28 min), and at about 38 minutes the Ziporex panels were moved slightly to allow cool air into the furnace.

The temperature developments at different depths of the panel cross-sections are shown in Figure 7. The char front was found where the curve for a given depth exceeded 300°C. For both timber panels the charring only reached 20 mm depth, as the 300°C isotherm never reached any further into the panel.

After the maximum temperature was reached in the furnace, the temperature inside the panels also started decreasing, with a 10 minutes delay at 20 mm and longer delays at the deeper levels. At about 20 minutes the temperature in panel T1A at 20 mm exceeded the temperature at 10 mm. This is probably due to cracks in the wood or gaps between the lamellas.

The charring rates at given times and the time at which the temperature at different depths reached 300°C are shown in Figure 8 (first point at 10 mm, second at 20 mm). The charring is assumed to start at time zero and be constant between zero and the first measuring point, as illustrated by the dotted lines. The charring rates at 10 mm depth and approximately 15 minutes are 0.67-0.71 mm/min, and very similar for both panel thicknesses. Charring at 20 mm starts with an 8 minutes difference between the two panels. The char front in the thin panel reaches 20 mm first, with a charring rate of 0.95 mm/min, while the 240 mm panel has a charring rate of 0.69 mm/min at this point 8 minutes later. The charring rate decreases after 15 minutes. The thinner cross-section (120 mm) has the highest charring rate. The temperature on the unexposed side of the panels never exceeded 18°C as long as the furnace was completely covered by timber and Ziporex panels.

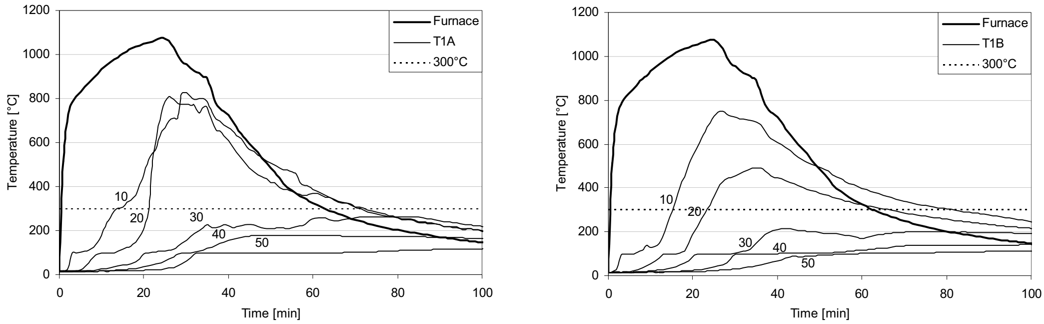

Figure 7. *Temperature development in the cross-sections of test specimens T1A and T1B at given depths.*

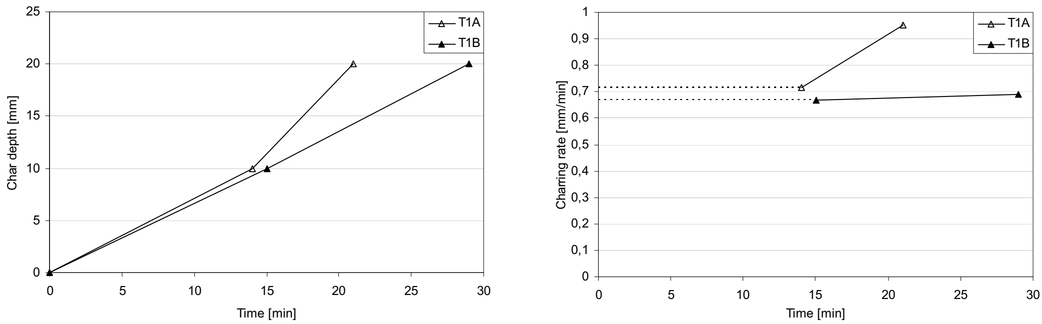

Figure 8. *Char depth and charring rate as a function of time for specimens T1A and T1B. Maximum temperature was reached at 24 minutes.*

3.2 TEST 2 – EN 1991-1-2- STANDARD FIRE

The average measured temperature in the furnace follows the calculated development very well also here, Figure 9. Due to limitations to the furnace (maximum 1 100°C) the gas burners were turned off after 120 minutes when the temperature was 1 056°C. The panels were left on the furnace and the flue duct fan was left on to see the temperature development for a while after the gas burners had been turned off. At 180 minutes the Ziporex panels were removed to allow cooling of the furnace, and logging of the temperatures inside the cross-sections was stopped.

The temperature developments at different depths of the cross-sections are shown in Figure 10. The char front in each panel is found where the curve for a given depth crosses the 300°C mark. In Figure 10 it can be seen that although the temperature curves at some depths cross with the temperature curve at other depths, the curves follow each other well. The crossing of the temperature curves is probably due to cracks in the wood, or gaps between lamellas. When the gas burners were turned off the cross-section temperatures decreased at almost the same rate as the furnace temperature.

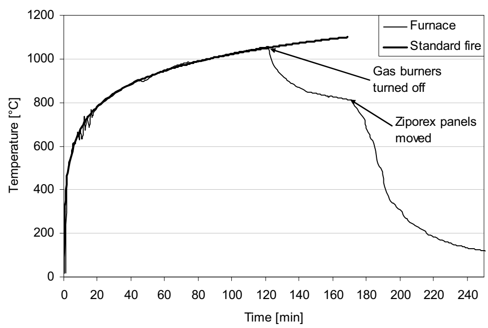

Figure 9. *Calculated EN 1991-1-2 Standard temperature-time curve and average measured furnace temperature through Test 2.*

The time at which the temperature at different depths reached 300°C, and the charring rates at given times are shown in Figure 11 (first point at 10 mm, second at 20 mm, and so on). The dotted lines show that the charring rate is assumed to be constant between time zero and the first measurement. When reaching 10 mm depth the char front had a charring rate between 0.31 mm/min and 0.5 mm/min, at 20 mm both timber panels had a charring rate of 0.45 mm/min, and at

60 mm the charring rate was between 0.45 mm/min and 0.68 mm/min. The rate for the 180 mm thick panel started decreasing at 70 min, while the rate for the 240 mm panel was still increasing at that time. The gas burners were turned off at 121 minutes, but the charring rate continued at approximately the same level until the logging of the TCs was turned off. There was actually a small increase in the charring rate at 100 mm to 110 mm depth. This might be due to cracks in the wood or gaps between lamellas, or the inhomogeneous character of wood. The thicker cross-section (240 mm) had the highest charring rate. The charring rate for the 240 mm thick panels continued almost unchanged even after the gas burners were turned off, while the charring rate for the thinner panel decreased shortly after the burners were turned off. The temperature on the unexposed side of the panels never exceeded 23°C as long as the furnace was completely covered by timber and Ziporex panels.

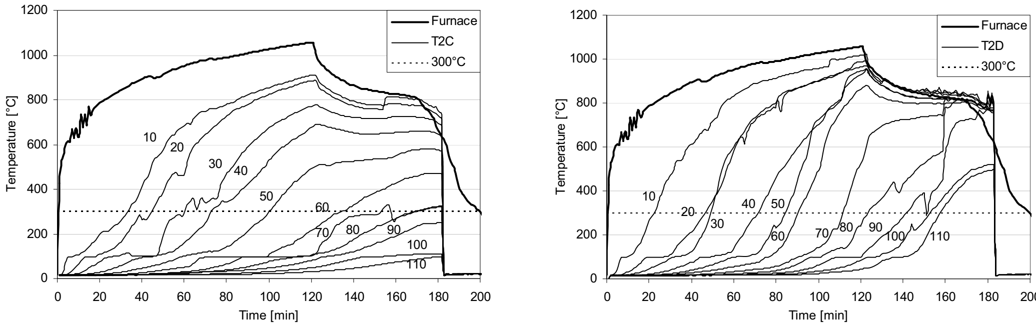

Figure 10. *Temperature development in the cross-sections of test specimen T2C and T2D, at given depths.*

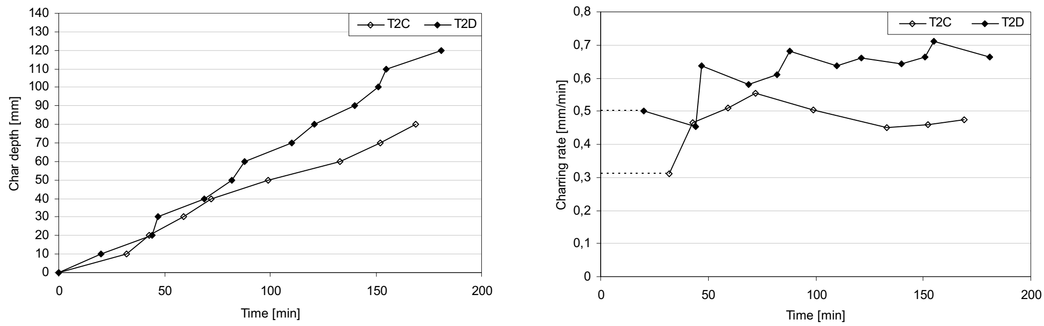

Figure 11. *Char depth and charring rate as a function of time for specimens T2C and T2D. Maximum temperature was reached at 121 minutes.*

3.3 TEST 3 – THE "SWEDISH" FIRE

The average measured furnace temperature follows the calculated curve well, with some deviations before it reaches the maximum temperature, see Figure 12. During the decay stage the burners were turned off early and the temperature adjusted by turning on/off the fan in the flue ducts. After a while the Ziporex panels had to be removed to facilitate further cooling.

The temperature developments at different depths of the cross-sections are shown in Figure 13. The char front is found where the curve for a given depth crosses the 300°C mark.

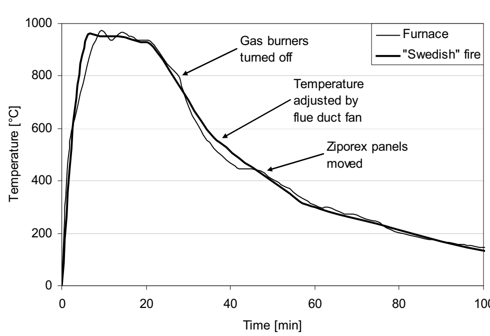

Figure 12. *Calculated "Swedish" temperature-time curve and average measured furnace temperature, Test 3.*

As can bee seen from Figure 13 the charring only reached 10 mm into the cross-sections. This is due to the slow heating and low temperatures in the fire. The decrease in the temperatures inside the cross-sections was slightly slower than the furnace temperature during the cooling stage.

The time at which the temperature at different depths reached 300°C, and the charring rates at given times are shown in Figure 14. The charring was assumed to start at time zero and be constant between zero and the first measuring point. This is illustrated by the dotted lines. The fire was very short, with low temperatures, and the timber panels only reached charring temperature at 10 mm depth. The charring rate for both samples was 0.5 mm/min at 10 mm depth at time 20 minutes. This is 6 minutes after the peak temperature. The temperatures inside the cross-section start decreasing approximately 10 minutes after the furnace temperature. The temperature on the unexposed side of the panels never exceeded 14°C as long as the furnace was completely covered by timber and Ziporex panels.

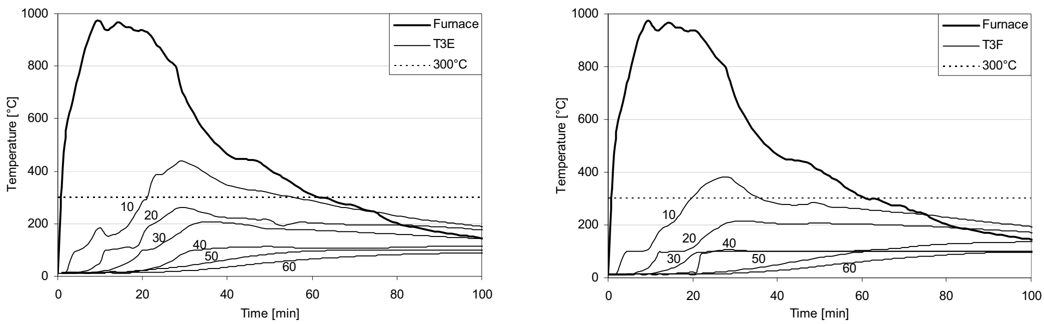

Figure 13. *Temperature development in the cross-section of test specimens T3E and T3F, at given depths.*

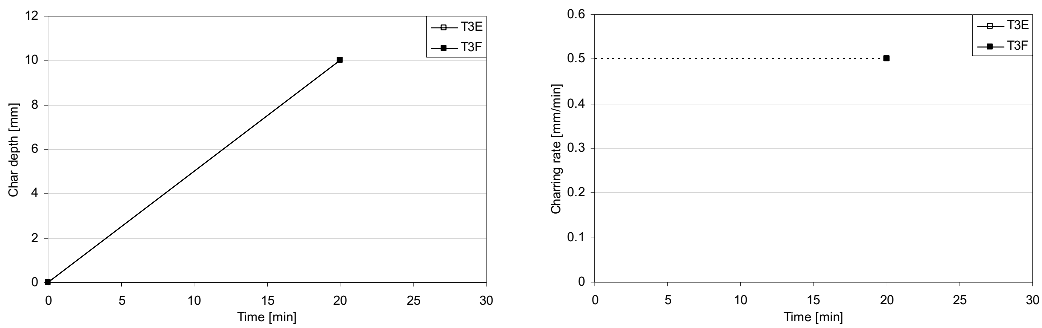

Figure 14. *Char depth and charring rate as a function of time for specimens T3E and T3F. The markers coincide with each other, i.e. one point. Maximum temperature was reached at 14 minutes.*

4 DISCUSSION

The charring rates for the three different fires vary greatly, from 0.31 mm/min to 0.95 mm/min, see Figure 15. Highest is the charring rate for the fastest increasing fire with the highest maximum temperature, i.e. the Parametric fire. For the Standard fire, that has the lowest heating rate and middle maximum temperature, the charring rate is slower than for the Parametric fire, and equal to or lower than for the "Swedish" fire. This indicates that the heating rate and maximum temperature has an impact on the charring rate. Frangi et al. [2] also found that the charring rate for fresh wood increases with increasing temperatures. Unfortunately, the char front for the "Swedish" fire only reached as far as 10 mm, and therefore only gave one single measurement. This is due to the very low charring rate achieved in the early stages of this fire. The Parametric fire and the "Swedish" fire are quite similar in the early stages of the fire, but the charring rates are significantly different. This is probably a result of the difference in temperature growth rate and temperature level. The cross-section temperatures for the short fires, i.e. Parametric and "Swedish" fires began to decrease shortly after the cooling stage of the fire started. This resulted in a short charring period.

Charring rates for the 120 mm thick timber panels (T1A and T3E) compared to the 240 mm thick panels (T1B, T2D and T3F) were not consistently faster or slower. However, there are great differences between the charring rates for the two panels tested together in the same fire for both Parametric and Standard fire. During the Parametric fire the thinnest panel (120 mm) had the fastest charring rate, while during the Standard fire the thickest panel (240 mm) had the fastest charring rate. The charring rate for the 180 mm thick panel was consistently the lowest at all depths and times. There is no obvious explanation to these results, and it might be a coincidence as the number of measurements is very small.

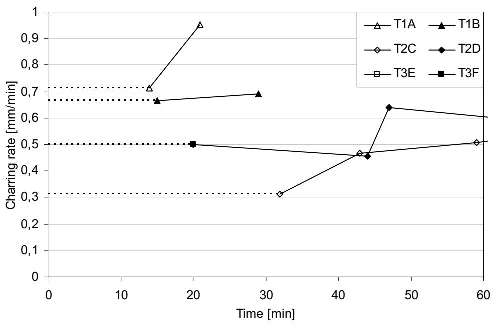

Figure 15. *Charring rate as a function of time for all specimens. Markers for T2D, T3E and T3F coincide with each other.*

From the temperature developments inside the cross-sections (Figure 7, Figure 10 and Figure 13) it can be seen that at some depths adjacent curves cross each other. This is probably due to cracks in the wood or gaps between lamellas, and will inflict on the charring rate. Based on these figures it can be assumed that at 20 mm depth for the T1A specimen, and at 20 mm and 40 mm for the T2D specimen the temperature, and therefore also the charring rate, are affected by such cracks or gaps. It can also be assumed that the charring rate at 20 mm depth for T1A should, in theory, be lower, and the charring rate at 20 mm and 40 mm for T2D should be higher. This would give a closer match between the charring rates for T1A and T1B, and a smoother charring rate curve for T2D.

5 CONCLUSIONS

The results from the fire tests on cross-laminated timber panels show that the charring rates vary greatly for the different temperature-time curves. Even for Parametric and “Swedish” curves, where the start of the fire was very similar, the charring rate is significantly different. The results indicate that the charring rate will be faster when the fire has a fast temperature growth and high temperatures. Temperature-time developments with slower temperature growth and lower maximum temperatures will result in slower charring. The charring rates given in EN 1991-1-2 might therefore not be applicable to other fire developments than Standard and Parametric fires described in EN 1991-1-2. If other temperature-time curves are used for fire safety design of a timber structure, the charring rate for that particular curve must be determined by other calculations or by testing. Due to the limited number of measurements in these tests it is not possible to say whether the thickness has an impact on the charring rate. For a short fire with a steep cooling rate the charring will stop early in the cooling stage. A long fire will reach a constant charring rate after a while. The conclusions are based on a limited statistical background and should be examined further. More research on the charring rate for cross-laminated timber panels is needed.

ACKNOWLEDGEMENTS

The project is financed by the Research Council of Norway. The cross-laminated timber panels were supplied by Moelven MassivTre AS, and the tests were performed at SINTEF Fire Research Laboratory (NBL) AS. The authors would like to thank the contributors for all help and support.

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