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Structural Fire Design of Timber Frame Assemblies Insulated by Glass Wool and Covered by Gypsum Plasterboards

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TUT PRESS

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Declaration
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

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Klaasvillaga täidetud ning kipsplaatidega kaetud puittarindite tulepüsivus

ALAR JUST

TTÜ KIRJASTUS

Just, A. (2010) **STRUCTURAL FIRE DESIGN OF TIMBER FRAME ASSEMBLIES INSULATED BY GLASS WOOL AND COVERED BY GYPSUM PLASTERBOARDS.** Thesis, Tallinn University of Technology

ABSTRACT

Present thesis is mainly conducted an experimental study in fire resistance of timber frame assemblies. It is intended to elaborate upon the charring models in EN 1995-1-2 with new information.

A series of fire tests as medium scale floor tests and full-scale wall tests were made with timber frame assemblies at fire laboratories of SP Trätek and TÜV Estonia to study the post-protection effect of mineral wool insulations. A new method for the design of timber frame assemblies insulated by traditional glass wool, and allowing for the effects of thermal recession of the glass wool, is presented. Research work with post-protection effect of new innovative heat-resistant glass wool and verifying of post-protection properties of stone wool is presented. The effect of mineral wool insulations on the charring is studied. Effect of density of wood and variability of charring along the timber wall studs is studied.

The second important part of the study is the database of full-scale fire test results with timber frame assemblies from similar experimental tests all over the world, although mainly from Europe. Conservative equations for failure times of gypsum plasterboards have been provided based on evaluation of collected database. Those conservative equations are as alternative to use for fire design of timber frame assemblies in the case of missing values from the producers. New information concerning start times of charring of timber elements behind gypsum cladding is provided.

Keywords: fire design, fire resistance, timber frame assembly, gypsum plasterboard, failure time, glass wool, heat-resistant glass wool

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KOKKUVÕTE

Käesolev doktoritöö koosneb põhiliselt puitkarkasstarindite katselistest uuringutest tules. Töö on suunatud EN 1995-1-2 söestumismudelite võimalikuks täiustamiseks uue informatsiooni põhjal.

Tulekahju korral puitkarkassile isolatsioonimaterjali poolt pakutava kaitse omaduste määramiseks teostati antud töö raames keskmises mõõdus põrandakarkassi ning suures mõõdus seinakarkassi tulekatsete seeria SP Trätek'i ning TÜV Eesti tulelaborites. Käesolevas töös pakutakse välja uus projekteerimismeetod tavalise klaasvillaga isoleeritud puitkarkassile, arvestades isolatsiooni pinna taandumisega tules. Töös on esitatud uue isolatsioonimaterjali – kuumakindla klaasvilla – järelkaitse mõju uurimine puitkarkassile tules ning kivivilla järelkaitse mõju kontrollimine tänase toodangu põhjal. Uuritud on mineraalvillast isolatsiooni-materjalide mõju söestumisele. Töös on esitatud puidu tiheduse mõju söestumisele ning söestumissügavuse muutus piki elementi puidust seinapostide näitel.

Teine tähtis osa esitatud uuringutes on täismõõdus puitkarkass-seinte tulekatsete andmebaasi loomine ning selle analüüs. Andmebaas koosneb tulekatsete katseandmetest, mis on saadud kogu maailmast, enamik nendest Euroopast. Kipsplaatide tõrketekkeaegade leidmiseks on käesolevas töös välja pakutud konservatiivsed valemid, mis on alternatiiviks neil juhtudel, kui kipsplaatide tootjad ei anna vastavat informatsiooni oma toodangu kohta puitkarkasside tulepüsivuse projekteerimisel. Samuti on esitatud uut informatsiooni kipsplaadiga kaitstud puitelemendi söestumise algusaegade kohta.

Märksõnad: tulepüsivus, puitkarkass-sein, kipsplaat, tõrketekkeaeg, klaasvill, kuumakindel klaasvill

AIM AND CONTENT OF THE STUDY

This PhD thesis deals with fire design of timber-frame assemblies with glass wool insulation and gypsum plasterboards claddings. The aim of the work has been to provide the following missing, or additional, information for the charring model of timber frame assemblies described in EN 1995-1-2:

- failure times of gypsum plasterboards;
- starting times of charring behind gypsum plasterboards;
- protective properties of heat-resistant glass wool;
- a design model for the post-protection phase of assemblies with traditional glass wool;
- the effect of wood density on the charring rate.

This thesis consists of five papers: three peer-reviewed journal papers and two conference publications (see list of original publications).

In this thesis failure times of gypsum plasterboards and start times of charring of timber elements behind gypsum cladding have been provided based on evaluation of experimental investigations. The effect of gypsum plasterboards on charring of timber members is described in papers I and II. The new method for design of timber parts insulated by traditional glass wool and allowing for the effects of surface recession of the glass wool is presented in paper III. Research work with new heat-resistant glass wool and verifying the post-protection properties of stone wool is presented in Paper IV. The effect of insulation materials on the charring and variability of charring along the timber part is studied in Paper V.

ACKNOWLEDGEMENTS

This work is dedicated to my father: Elmar Just- proud to follow in your footsteps.
I would like to express my sincere gratitude to my official supervisor, Professor Karl Õiger.

For the scientific support and valued collaboration throughout my study I am very grateful to Jürgen König.

I am also indebted to Birgit Östman for always making time to guide the work and provide a scientifically nurturing and friendly environment to complete the work.
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Thank you to all my colleagues at SP Trätek especially Lazaros Tsantaridis, Joakim Noren.

Thanks also to my first teacher – Martin Gustafsson – who started my passion and interest for timber structures.

For the support of Ainar Albi, Henri Lend, Marek Moorits, Aadu Simisker, Stora Enso Imavere sawmill, Saint-Gobain Isover, Saint-Gobain Ehitustooted, TÜV Estonia, SP, Kodumaja, Estonian Association of Forest Industry I am very grateful.

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Alar Just
October, 2010

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PREFACE

This work is the result of my research carried out during the period from November 2007 to September 2010 at SP Trätek– Swedish Institute for Wood Technology Research. The work forms part of the “Fire In Timber” research program within WoodWisdom-Net.

The research described in this report was co-ordinated by Jürgen König and Birgit Östman from SP Trätek, and Professor Karl Õiger as my supervisor from Tallinn University of Technology.

My interest in timber structures began in 1995 in Skellefteå, where I started to design timber bridges at Trätek. Studies in Tallinn University of Technology and practising in Norwegian Institute of Wood Technology and Helsinki University of Technology were a basis for my knowledge on timber structures.

Work in private design bureau in Estonia as a chief engineer and lectures for students, joint projects with Estonian Forest Industry Association, were practical means in my activities of promoting timber structures in my homeland – Estonia. Our team – Elmar Just, Karl Õiger and me – was responsible for modifying the requirements of Eurocode 5 to make them suitable for application in Estonia.

The Fire Safe Use of Wood group (FSUW) provides expert solutions for the needs of the European timber industry. I started in this group in 2004. The Wood Wisdom project, “Fire In Timber”, (fire safety of innovative timber structures) was mostly carried out by the members of this FSUW group. The main practical output was a first technical guideline in Europe for the design of timber structures in fire. Another handbook of Fire Safe Timber Houses (Brandsäkra trähus in Swedish) on Nordic-Baltic level is in preparation. Reseach presented in this thesis has an input to both handbooks.

Co-operation with Elar Vilt and an advanced Estonian housing manufacturer – Kodumaja – identified unsolved problems when attempting to produce designs to meet the fire resistance requirements of Eurocode 5. With the support of the Estonian Forest Industry, Kodumaja and Saint-Gobain Isover, I tried to solve those problems. Consultations with one of leading research centres in this field in Europe – SP Trätek – lead to an invitation by Birgit Östman and Jürgen König to offer a good working environment and scientific help for me in Stockholm. I was very happy to accept this kind offer to be back with my old “home club” - SP Trätek - as a guest researcher. With the kind help of Jürgen König, Birgit Östman, Joachim Schmid, Lazaros Tsantaridis and Joakim Noren, I carried out research into the performance of timber frame assemblies with glass wool insulation when exposed to fire. This work comprised a lot of theoretical and experimental investigations in Stockholm and in Tallinn, resulting in this present PhD thesis and proposals for the next generation of Eurocode 5, Part 1-2.

LIST OF ORIGINAL PUBLICATIONS

This thesis is mainly on the basis of the data presented in the following **peer-reviewed papers**:

I Just, A., Schmid, J. Start of charring of timber frames behind gypsum plasterboards – Evaluation of experimental data. *Fire Safety Journal* (submitted on 13.9.2010);

II Just, A., Schmid, J., König, J. Failure times of gypsum plasterboards. *Interflam 2010*: Proceedings of the twelfth international conference 2010. 5.-7.7.2010, Nottingham, UK. 1695-1700;

III Just, A. Post-protection behaviour of wooden wall and floor structures completely filled with glass wool. *Structures in Fire*: Proceedings of the 6th international conference, 2.-4.6.2010, East Lansing, USA. 584-592;

IV Just, A., Schmid, J., König, J. Post protection effect of heat-resistant insulations on timber frame members exposed to fire. *Fire and Materials*, (accepted for publishing 28.9.2010 with minor changes);

V Just, A., Tera, T. Variability of charring along the wooden wall studs. *Engineering structures and technologies* (submitted on 22.8.2010).

AUTHOR'S CONTRIBUTION IN PEER-REVIEWED PAPERS

The author of this thesis is the main author in all the publications. The collected database in Papers I and II was analysed by the author, and the database was partly collected by the author. In Papers III and IV the experimental study was arranged and data was analysed. A new design method was worked out. The author's contribution in Paper V was the fire tests and analysis of experimental studies.

Other published work

Just, A., Schmid, J., König, J. Gypsum plasterboards used as fire protection – Analysis of database . *SP Report 2010:29. Stockholm 2010.*

Just, A. Post-protection behaviour of wooden wall and floor structures completely filled with glass wool. *SP Report 2010:28. Stockholm 2010.*

Just, A., Schmid, J., König, J. The effect of insulation on charring of timber frame members. *SP Report 2010:30. Stockholm 2010.*

Schmid, J., Just, A. Prediction of load bearing resistance of timber beams in fire. *SP Report 2010:46. Stockholm 2010.*

Just, A. Full scale fire tests with timber frame walls. *TUT Report. Tallinn 2009.*

Just, A., Schmid, J., König, J. Failure times of gypsum boards. *Structures in Fire*: Proceedings of the 6th international conference, 2.-4.6.2010, USA. 593-601;

Part of the work for following handbooks

Fire Safety in Timber Buildings. Technical guideline for Europe. SP 2010:19. Stockholm, 2010. *Input to chapter 6. Load-bearing structures*

Brandsäkra Trähus 3. Nordic-Baltic State of the art and guidance (in preparation). *Input to chapters: III Fire safety design; IV Fire containment of timber structures*

ACRONYMS AND ABBREVIATIONS

GtA	gypsum plasterboard, Type A
GtF	gypsum plasterboard, Type F
GF	gypsum fibreboard
GW	traditional glass wool
RW	rock wool, stone wool
GWF	heat-resistant glass wool

A	cross-sectional area, mm^2;
A_{fi}	cross-sectional area of the residual cross-section, mm^2;
b	cross-sectional width, mm;
b_{fi}	cross-sectional width of the charred cross-section, mm;
c	specific heat, kJ/kgK;
d_{char}	charring depth, mm;
$d_{char,n}$	notional charring depth, mm;
$d_{char,1,n}$	notional charring depth of wide side of the cross-section, mm;
$d_{char,2,n}$	notional charring depth of narrow side of the cross-section, mm;
f_k	characteristic strength, N/mm^2;
$f_{d,fi}$	design strength in fire, N/mm^2;
$f_{m,d,fi}$	characteristic bending strength in fire, N/mm^2;
$f_{c,d,fi}$	characteristic compressive strength in fire, N/mm^2;
f_{20}	20% fractile strength at normal temperature, N/mm^2;
h	cross-sectional height, mm;
h_{fi}	maximum height of residual cross-section, mm;
h_{PB}	thickness of wooden plasterboard, mm;
h_p	thickness of protective cladding, mm;
$h_{p,tot}$	total thickness of protective claddings, mm;
i	radius of inertia, mm;
I	moment of inertia, mm^4;
I_{fi}	moment of inertia of the residual cross-section, mm^2;
k_s	cross-section factor;
k_p	protection factor;
k_2	insulation factor;
k_3	post-protection factor;
k_n	factor to convert the irregular residual cross-section into a notional rectangular cross-section;
$k_{mod,fi}$	modification factor in fire;
$k_{c,y}$	instability factor;
k_y	instability factor;
k_{fi}	coefficient;
k_{dens}	density factor;
L	span;
l_y	buckling length;
t	time from test start, min;

t_{ch}	start time of charring, min;
t_f	failure time of cladding, min;
$t_{f,ins}$	failure time of insulation, min;
$v_{rec,ins}$	recession speed of insulation, mm/min;
$v_{rec,gw}$	recession speed of glass wool, mm/min;
W_{fi}	section modulus of the charred cross-section, mm^3;
W_n	section modulus of the equivalent rectangular cross-section, mm^3;
q	distributed load;
β	one-dimensional design charring rate, mm/min;
β_n	notional charring rate, mm/min;
β_{PB}	charring rate of wooden particle board, mm/min;
$\gamma_{M,fi}$	partial factor for material property in fire;
λ	thermal conductivity, W/mK;
λ_y	slenderness;
$\lambda_{rel,y}$	relative slenderness;
ρ	density, kg/m^3;
ρ_k	characteristic density, kg/m^3.

1 INTRODUCTION

1.1 Background

Timber is a popular building material because of its good strength-to-weight ratio, simplicity of working, and the fact that it is a natural material.

Wall and floor structures, made as a timber-frame assembly, consist usually of a timber frame, insulation between the members and cladding, as shown in Figure 1.1. Floors are usually load-bearing (R or REI). Insulation in the timber frame can often be mineral wool, or particularly glass wool because of its light weight, good sound performance and ease of installation. Walls or floors can be load-bearing (R, REI-criteria for fire performance) or simply separating structures (EI-criteria for fire performance).

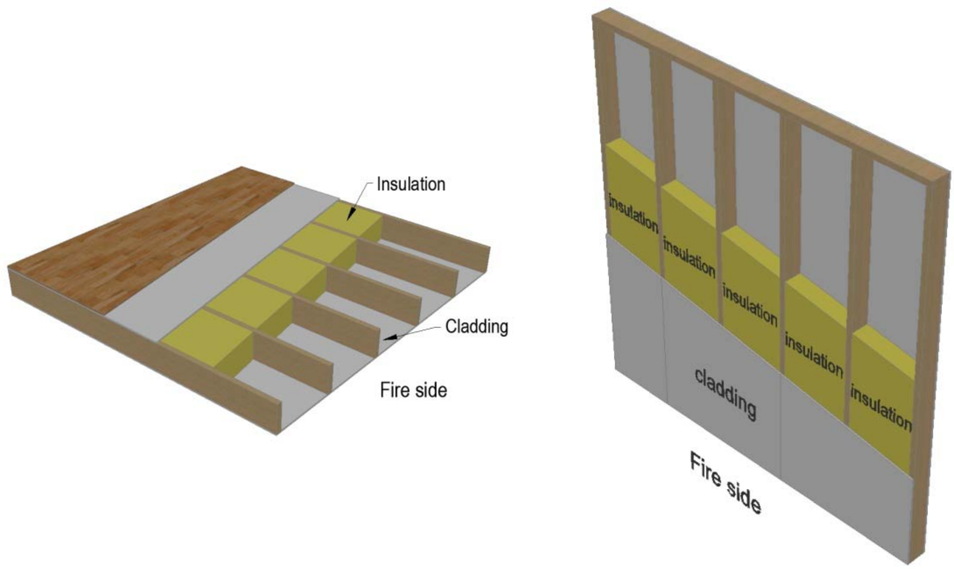
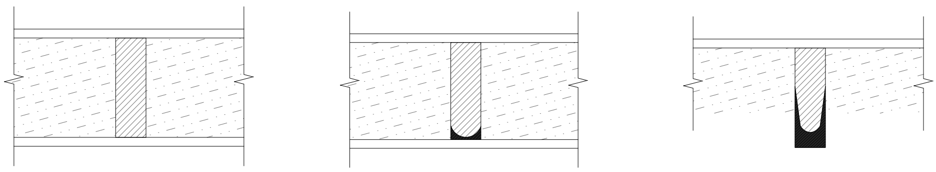


Figure 1.1. Timber frame assemblies: floor (left) and wall (right)

Fire safety is one of the six essential performance requirements set out in the Construction Products Directive [1] and is a critical aspect when designing timber structures. Cladding on the fire- exposed side is the first and the most important barrier for fire resistance. Reduction of cross-section by charring depth is the parameter that has most effect on the load-bearing capacity of wood. Reduction of strength and stiffness properties must be considered for small cross-sections because of the heat flux through the whole section. The time-dependent thermal degradation of wood is referred to as the charring rate, and is defined as the ratio between the distance of the charline from the original wood surface and the fire duration time [2]. The charring rate differs at different protection phases in a fire. Charring begins with slow charring behind the protective cladding. This is the case when the cladding remains in place before failure. After the cladding falls off, charring increases to a much higher rate than that of initially unprotected wood. The starting time of charring and the failure time of gypsum boards are therefore important properties for the fire safety design of timber frame construction.



No charring

Charring during the protected phase

Charring during the post-protection phase

Figure 1.2. Protection phases of timber frame assemblies in fire

European standard EN 1995-1-2 [3] provides rules for the design of timber structures in fire. Structural design is based on the charring model by König et al [4], who performed a lot of experimental and simulation studies of timber-frame assemblies.

Design rules in EN 1995-1-2 [3] have no method for determining the post-protection phase of timber-frame assemblies with glass wool insulation in a fire. Failure times of gypsum boards are to be given by producers or to be determined by tests. In practice, there are very few producers who provide such failure times for their products. Testing, on the other hand, is costly and time-consuming, and not common in practical design of structures.

European standard EN 520 [5] gives requirements for different types of gypsum plasterboards. The fire-rated gypsum plasterboard, Type F, is required to fulfil a core cohesion test, but this is not sufficient to provide all the data needed for design of timber-frame assemblies in a fire – the starting time of charring, failure time etc. Sultan et al [6, 7] performed an extensive experimental study of gypsum plasterboards in floor and wall assemblies. Some results of this study are used in this thesis.

The European standard for mineral wools, EN 13162 [8], specifies different requirements for factory-made products, but does not provide information related to the protection performance of different mineral wools when exposed to fire.

Mineral wools have been grouped as *stone wool* or *glass wool* in order to describe their protective properties in fire situations. This classification is not specified in the product standard [8]. Typical classification of them from a fire safety point of view is that stone wool has better fire resistance than glass wool. New glass wool products on the market call for a change in this classification: the properties and performance of the new materials need to be investigated.

Frangi et al. [9] performed new research with timber-frame floors with voids. The results showed faster charring of studs than the method in EN 1995-1-2 estimates.

Experimental studies in this research are only based on standard fire curve according to EN 1363-1 [10].

1.2 The EN 1995-1-2 design model

EN 1995-1-2 [3] is the first European code to provide a new approach for timber structures in fire. The effect of reduced cross-sections of timber members due to charring is dealt with by using different charring rates

Annex C of EN 1995-1-2 describes the design procedure for timber-frame assemblies with insulation. The model, created by König et al [4], should be used for calculation of the fire resistance of lightweight timber structures. It covers the protected phase for glass wool and stone wool, and the post-protection phase for stone wool as long as the insulation stays in place.

There is an order of importance of contribution to fire resistance. The greatest contribution to fire resistance is provided by the cladding on the fire-exposed side that is first directly exposed to the fire, both with respect to insulation and to failure (fall-off) of the cladding. In general, it is difficult to compensate for poor fire protection performance of the first layer by improved fire protection performance of the following layers [11].

In general, for determining the degree of fire resistance of a timber member, the original cross-section must be reduced by the charring depth. Different charring rates apply for timber members, depending on whether they are initially protected or initially unprotected from direct fire exposure.

Unprotected members start to char immediately when exposed to fire: see Line 1 in Figure 1.3. For protected members, charring is divided into different phases. No charring occurs during Phase 1 until a temperature of 300 ºC is reached behind a protective layer. Phase 2 is referred to as the *protection phase*, and protection is assumed to remain in place until the end of this phase – which is failure time t_f. The charring is relatively slow during this phase (Line 2, Figure 1.3). Phase 3 is the *post-protection phase*, and begins at failure time t_f. Charring is fast (Line 3a, Figure 1.3). For large cross-sections, there is a consolidation time t_a, when a protective char layer is built up and charring continues, but at a slow rate again. Small cross-sections, such as those studied in this thesis, do not have this consolidation time because of extensive heating from the wide sides, and so charring continues for them at a fast rate.

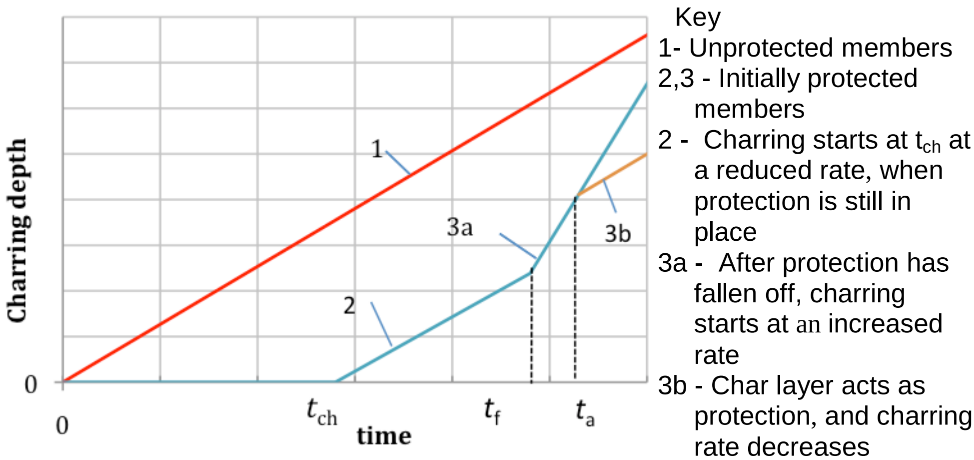
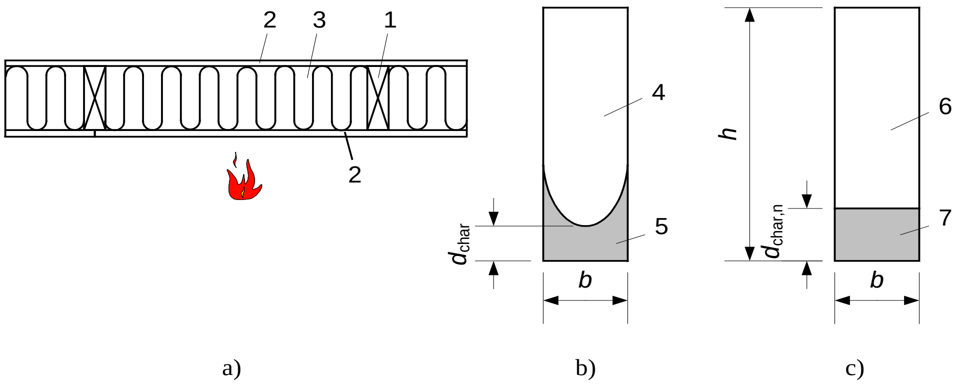


Figure 1.3. Charring of unprotected and protected timber members

When timber members are protected by thermal insulation batts on their wide sides, charring takes place mostly on their fire-exposed narrow side. However, due to the heat flux through the insulation, the timber members also char on their wide sides, giving rise (h×b) to extensive arris roundings, see Figure 1.4.b. For simplicity, the irregular residual cross-section is replaced by an equivalent rectangular cross-section, replacing the charring depth d_{char} and arris roundings with the notional (or equivalent) charring depth $d_{char,n}$.



Key:
1 Solid timber member (stud or joist)
2 Cladding
3 Insulation
4 Residual cross-section (real shape)
5 Char layer (real shape)
6 Equivalent residual cross-section
7 Char layer with notional charring depth

Figure 1.4. Charring of timber frame member (stud or joist): a. Section through assembly. b. Real residual cross-section and char layer. c. Notional charring depth and equivalent residual cross-section [18].

Notional charring depth $d_{\mathrm{char,n}}$ is counted as

$$d_{\mathrm{char}} = \beta_{\mathrm{n}} t \tag{1.1}$$

The notional charring rate, $\beta_{\mathrm{n},}$ of small sized timber frame members is given as

$$\beta_{\mathrm{n}} = k_{\mathrm{p}} k_{\mathrm{s}} k_{\mathrm{n}} \beta_0 \tag{1.2}$$

where β_0 is the one-dimensional charring rate for timber given as

$$\beta_0 = 0,65 \frac{\mathrm{mm}}{\mathrm{min}}$$

Coefficients k_{p}, k_{s} and k_{n} are explained as follows:

The protection factor k_{p} takes the effect of protective cladding on charring into account. During the protected phase, factor $k_{\mathrm{p}}= k_2$. During the post-protection phase, factor $k_{\mathrm{p}}= k_3$. Values for insulated timber members are given in Annex C of EN 1995-1-2. For members without cladding, factor $k_{\mathrm{p}} = 1$.

The cross-section factor k_{s} takes the width of the cross-section into account. Charring is faster when the cross-section is smaller, due to two-dimensional heat flux within the member. In [4], it is given as

$$k_s = \begin{cases} 0,000167b^2 - 0,029b + 2,27 & \text{for } 38 \text{ mm} \le b \le 90 \text{ mm} \\ 1 & \text{for } b > 90 \text{ mm} \end{cases} \tag{1.3}$$

while [3] gives only a table with values for specific widths *b*.

Expression (1.3) assumes a linear relationship between d_{char} and time, which is slightly conservative for $d_{\mathrm{char}} < 30$ mm and non-conservative for $d_{\mathrm{char}} > 30$ mm. For $d_{\mathrm{char}} > 30$ mm, the load resistance is normally exhausted.

Coefficient k_{n} converts the irregular charring depth into a notional charring depth, see Figure 1.4.b and 1.4.c. It depends on the time and cross-section properties (area, section modulus or second moment of area). The value k_{n}=1,5, given by EN 1995-1-2 [3], is a reasonable approximation for the notional charring depth, that would be relevant for a relative resistance between 40% and 20% of the initial section modulus W (t = 0).

Before failure of the protective cladding, there is no difference in the fire behaviour of assemblies with stone wool or with glass wool. After the cladding fails, traditional glass wool insulation will undergo decomposition, gradually losing its protecting effect for the timber member by surface recession. The model described in EN 1995-1-2 [3] cannot be used for this condition. Stone wool insulation, provided that it remains in place, will continue to protect the sides of the timber member facing the cavity.

This thesis investigates and proves the assumption that heat-resistant glass wool provides similar fire protection to stone wool, and fits the model given in Annex C of EN 1995-1-2 [3]. However, if the insulation consists of traditional glass wool, the model described in this chapter is valid only for the protected phase, until failure of the cladding occurs.

Mechanical resistance in fire

According to [3], the design values of strength properties shall be determined from

$$f_{\mathrm{d,fi}} = k_{\mathrm{mod,fi}} \frac{f_{20}}{\gamma_{\mathrm{M,fi}}} \tag{1.4}$$

where

$$f_{20} = k_{\mathrm{fi}}\, f_{\mathrm{k}} \tag{1.5}$$

and

$f_{\mathrm{d,fi}}$ strength property in the fire situation, e.g. bending strength;

f_{20} 20% fractile of the strength property;

f_{k} characteristic strength property,

$\gamma_{\mathrm{M,fi}}$ partial safety factor for timber in fire.

$k_{\mathrm{mod,fi}}$ modification factor for fire, expressing the reduction of strength in a fire situation;

k_{fi} factor converting characteristic strength (5% fractile) into the 20% fractile of strength. For solid wood elements, the coefficient k_{fi} is 1,25.

There are two options when analysing mechanical resistance according to EN 1995-1-2:

1) The effective cross-section method, using a zero strength layer (d_{o}), as given in Clause 4.2.2 of EN 1995-1-2 [3]. The cross-section is reduced by the charring depth and the zero-strength layer (usually 7 mm). Strength and stiffness properties are not reduced. $k_{\mathrm{mod,fi}}$= 1,0.
2) Reduced strength and stiffness properties according to clause 4.2.3 of EN 1995-1-2 [3].

The cross-section is reduced only by the charring depth. Strength and stiffness are reduced by factor $k_{mod,fi}$, which will remain below 1,0.

The recommendation for the future is to use only the effective cross-section method, which is more understandable. The effective cross-section method for timber-frame assemblies is given by König [12].

Design data and design methods for proper design in many design situations are missing in EN 1995-1-2 [3]. Design by tests is often the only option for design, but is expensive and time-consuming and not easy to use for practical design.

1.3 Materials used to achieve fire safety of timber frame assemblies

1.3.1 Gypsum boards

Gypsum plasterboards

Gypsum plasterboards are often used as cladding on timber frame assemblies. The gypsum core of plasterboard consists of natural gypsum, industrial gypsum and/or recycled plasterboards. The difference between the two gypsum types is that the industrial gypsum has smaller crystals than the natural gypsum, because it has taken thousands of years to crystallize the natural gypsum, but both have identical chemical composition. Gypsum plasterboards are usually in the thickness range of 9 - 30 mm. Producers of gypsum boards do not specify whether their boards are made of natural or industrial gypsum, but it may affect their properties in fire. In addition to natural raw gypsum, industrial gypsum is used for manufacturing gypsum boards. It is produced as a by-product from the flue gas cleaning of power stations. This gypsum consists of crushed limestone mixed with water, air and sulphur dioxide. Using the sulphur dioxide to make plaster prevents acidification of the environment as well as providing pure gypsum material.

There are many types of gypsum plasterboards in Europe that comply with EN 520 [5]. Most common types are:
Type A – regular common boards with porous gypsum core and no reinforcement except the paper laminated surface. This report uses the abbreviation GtA when referring to this board or similar.
Type F – fire protection board with improved core cohesion at high temperatures. The abbreviation GtF is used for this board in this thesis.

In accordance with [5] there are also other types of gypsum plasterboards: examples include Type D, with a density over 800 kg/m^3, and Type H, with water-resistant properties etc.

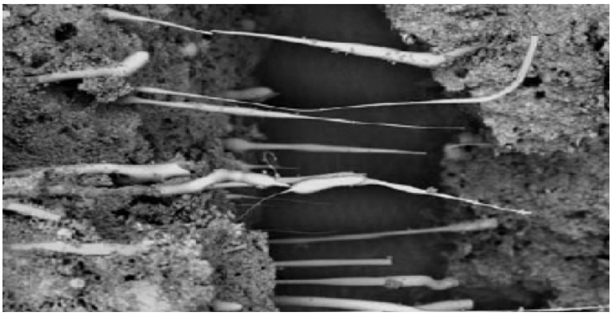


Figure 1.5. Glass fibres in fire-rated gypsum plasterboard

Fire-protection gypsum (GtF) boards contain glass fibres (see Figure 1.5) which control shrinkage, causing a maze of fine cracks rather than a single large crack which can initiate premature failure of regular board. One of the most critical aspects of fire-resistant gypsum board is the extent to which the glass fibre reinforcement can hold the board together after the gypsum has dehydrated, to prevent the board pulling away from nailed or screwed connections when the board shrinks. Shrinkage can be reduced with various additives, such as vermiculite [13].

Gypsum plasterboards are usually in the thickness range of 9 - 30 mm.

In accordance with [5] there are also other types of gypsum plasterboards: examples include Type D, with a density over 800 kg/m^3, and Type H, with water-resistant properties etc.

In Europe, fire-rated gypsum boards must be tested in accordance with EN 520 [5]. Unfortunately, this test does not consider thermo-mechanical properties, such as fall-off times for the design of timber frame assemblies

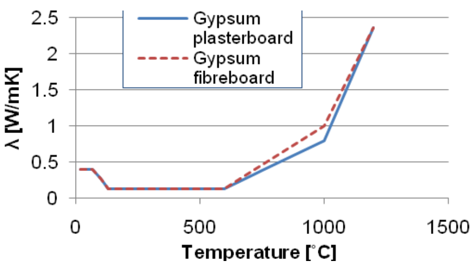
In North America, Type X gypsum boards are commonly used as fire protection, and are similar to the European GtF boards. In this study, test results from GtX boards are treated as GtF boards.
Type X is standardised by ASTM C 1396-09a [14]. Gypsum board, Type X must provide not less than 1-hour fire-resistance rating for boards 15,9 mm thick, or 45 minutes' fire-resistance rating for boards 12,7 mm thick, applied parallel with and on each side of load bearing wood studs 51 x 102 mm spaced 406 mm on centres with 6d coated nails, 47,6 mm long, 2,3 mm diameter shank, 6,35 mm diameter heads, spaced 178 mm on centres with gypsum board joints staggered 406 mm on each side of the partition and tested in accordance with Test Methods E 119 [14] (units above have been converted to SI units).

Gypsum fibreboards

Gypsum fibreboards are high-performance building boards with cellulose reinforcement, complying with EN 15283-2 [15] and can be used as an alternative to plasterboards or for flooring. Gypsum fibreboard is made from 80-85% burned gypsum (recycled gypsum recovered from industrial desulphurisation plants), and 15-20% cellulose fibres (recycled newsprint). The boards are impregnated with aqueous coating-based starch and silicone. The boards have more homogenise behaviour in fire. This report uses the abbreviation GF when referring to this type of board.

1.3.2 Fire-performance of gypsum boards

Because of the moisture-related reactions described above, all gypsum board products exhibit similar behaviour in fire. Gypsum is a non-combustible material and makes no contribution to fire: it works, in fact, as a built-in sprinkler. One square meter of a 12.5 mm gypsum board contains approximately two litres of water of crystallisation in the gypsum core. Its high water content provides up to 90% of the fire resistance protection of gypsum boards. The calcination process takes place when the gypsum is exposed to heat at a temperature of at least +80 °C, and this water prevents the fire from penetrating the board while it is evaporating. The calcination process is mostly complete when the gypsum board reaches a temperature of 125 °C and becomes an anhydrate, $CaSO_4$. This process requires much energy and time. After dehydration, the gypsum has almost no strength because it has been converted to a powdery form: any residual strength depends on glass fibre reinforcement to hold the board together.



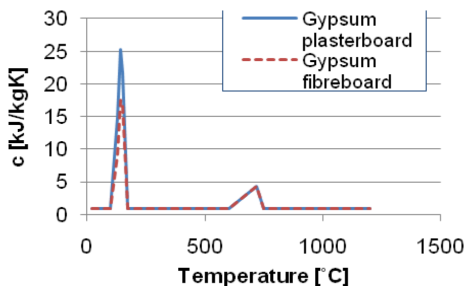


Figure 1.6. Relationship between thermal conductivity, λ, and specific heat , c, of gypsum boards, and temperature [16]

The specific heat of gypsum plaster is shown in Figure 1.6, right. The two peaks indicate chemical changes as moisture is driven off during heating. The first main reaction is at 100 ˚C, which results in a delay in the temperature rise of protected wood members. Thermal conductivity also depends on the density of the gypsum board. The value of thermal conductivity above about 400 ˚C will be affected by the presence of shrinkage cracks in the gypsum board, which will depend on the formulation of the individual board and the type of fire: see Figure 1.6, left. Cracking may be more severe in a fire with rapidly increasing initial temperatures [13].

Gypsum boards as claddings in timber frame assemblies

The fire resistance of assemblies made with gypsum-based panel products depends on several important interrelated properties:

- The thermal insulation of the board, which protects internal structural members and delays temperature rise on unexposed surfaces;
- The ability of the board to remain in place and not disintegrate or fall off after dehydration;
- Resistance to shrinkage, which usually causes cracking within the board or separation at joints between sheets;
- The ability of the core material to resist ablation from the fire side during extreme fire exposure.

Regular gypsum board can fall off a wall or ceiling as soon as the gypsum plaster has dehydrated, at about the same time as charring of the timber studs begins. Boards with glass fibre reinforcement and closely spaced fixings will not fall off until the glass fibres melt, when the entire board reaches a temperature of about 700 ˚C [13]. König et al [17] report that the critical falling-off temperatures are 600 ˚C for ceiling linings and 800 ˚C for wall linings.

Ablation is a term used to describe the slow process whereby dehydrated gypsum powder slowly falls off the heated surface of a fire-exposed gypsum board, resulting in a reduction in board thickness during the fire. In fire-resistant boards, ablation does not occur until after the glass fibres in the board have melted at about 700 ˚C. Ablation is a minor effect, but can be included in finite-element modelling by increasing the thermal conductivity at high temperatures [13].

Figure 1.7 compares the temperature rise behind 12,5 mm thick Type A gypsum plasterboard and 15 mm thick Type F plasterboard. The calcination phase can be clearly seen. First, the temperature rises until 80 °C to 100 °C is reached behind the board. Water starts to evaporate and a plateau can be seen in the temperature curve (Figure 1.7). Evaporation time basically depends on the board thickness. After the evaporation process, the temperature rises again.

The time when charring starts behind the gypsum board and the failure time of cladding are important times for design of fire resistance of timber frame assemblies (see Figure 1.3). When the cladding is made of fire rated gypsum plasterboard, the value of failure time is needed for design.

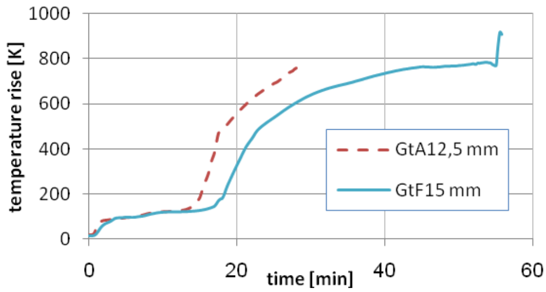


Figure 1.7. Temperature rise behind Type A and Type F gypsum claddings in standard fire tests (example)

1.3.3 Mineral wool

Mineral wools have been widely used for more than 100 years in thermal insulation, acoustic insulation and fire protection. They do not burn, rot or absorb moisture or odours. Dimensionally stable products with binders based on synthetic resins with added dust suppressant agents were developed in the 1940s. The curing process by hot air drying hardens the resins and removes volatile substances from the product.

Depending on their different protection properties for timber members in a fire situation, mineral wool products are divided into two types in EN 1995-1-2: *stone wool* and *glass wool* [18].

Stone wool (rock wool) is a mineral wool manufactured predominantly from molten naturally occurring igneous rocks [19]. Densities of stone wool insulation, used in structures, are usually 26 to 180 kg/m^3. For thermal conductivity see Figure 1.10.

Stone wool was regarded as the only one fire resistant mineral wool in EN 1995-1-2. It is assumed to protect structures even after fall off of protective cladding on fire-exposed side. Minimum density for the use of design model in EN 1995-1-2 is 26 kg/m^3. In Figure 1.8 the microstructure of stone wool is shown.

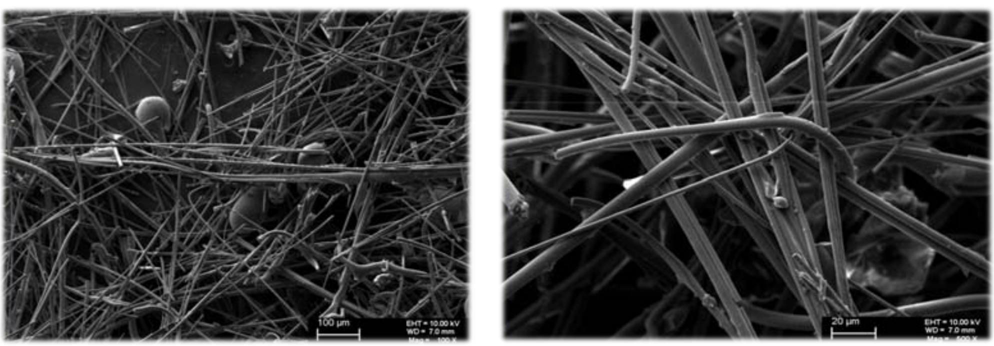


Figure 1.8. Structure of stone wool at 100µm (left) and 20 µm scale (right)

Glass wool is a lightweight thermal insulation that consists of intertwined and flexible glass fibres, which cause it to "package" air, resulting in a low density that can be varied through compression and binder content [19]. 100% of the glass content of glass wool is fiberised, making a woolly structure able to decrease air permeance. Depending on the applications and the property requirements, products with low, medium or high densities can be produced. It can be a loose-fill material, blown into attics or, together with an active binder sprayed on the underside of structures, in the form of rolls and panels that can be used to insulate flat or curved surfaces such as cavity wall insulation, ceiling tiles, curtain walls and ducting. It is also used to insulate piping and for soundproofing.

Densities of glass wool insulations, used in structures, are usually around 12 to 20 kg/m^3. The microstructure of traditional glass wool is shown in Figure 1.9. Effective thermal conductivity is shown in Figure 1.10.

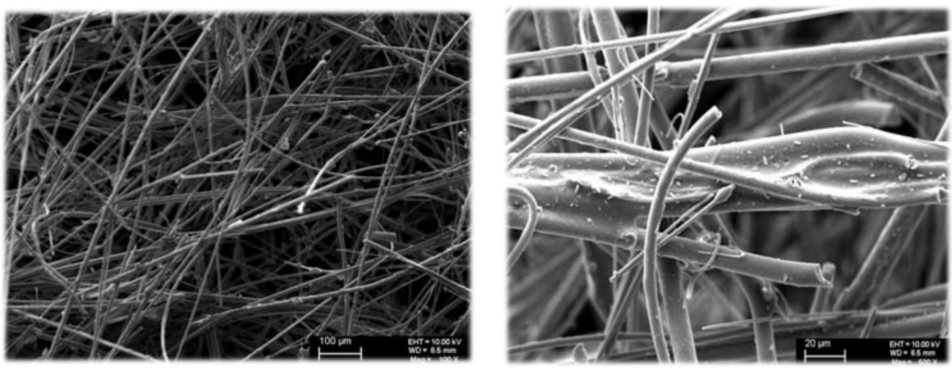


Figure 1.9. Structure of glass wool at 100µm (left) and 20 µm scale (right)

During the present research work it was found that *rock fibre* and *glass fibre* are not the correct terms to use. The recommendation for the next generation of EN 1995-1-2 is to use *stone wool* and *glass wool*. This brings the terms into line with the standard for definitions of mineral wool [19]. Furthermore, consideration needs to be given to changing the wording to *heat-resistant* and *non heat-resistant* mineral wool insulation materials in order to classify mineral wools by their different behaviour in fire.

EN 13162, Thermal insulation Products for Buildings [8], does not classify materials in terms of their structural fire design performance. Changes in mineral wool standards are foreseen.

Traditional glass wool does not provide effective protection in a fire when the cladding has fallen off and the insulation is directly exposed to fire, but stone wool does generally provide an effective protection for timber members when directly exposed to fire. The thermal conductivity values and specific heat for stone wool and glass wool are shown in Figure 1.10.

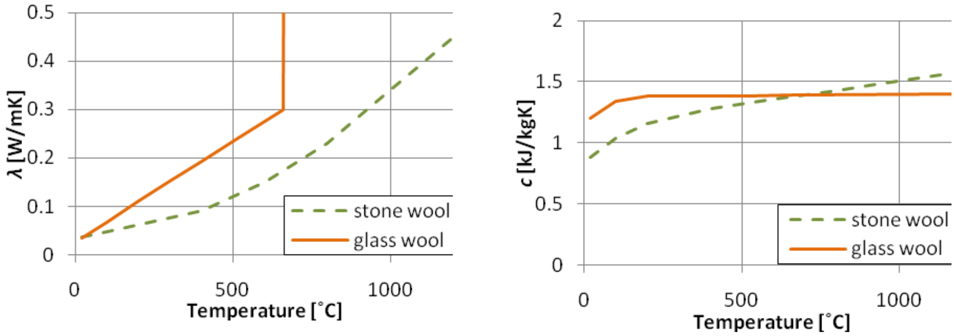


Figure 1.10. Effective thermal conductivity, λ, and specific heat, c, of stone wool and glass wool [16]

Heat-resistant glass wool is a new insulation product, which is being increasingly used in marine applications. Leading research projects concerning this material have been carried out at ETH Zürich [20]. New heat-resistant glass wool on the market differs from the basis of classification given in EN 1995-1-2. This new material is made from glass using glass wool technology, but its structure and resistance to high temperatures are similar to that of stone wool.

The difference between heat-resistant and traditional glass wool lies in a higher quality of the raw material and a higher temperature of the production process. The use of a proprietary and patented mix of materials further increased the temperature resistance of the glass. The insulation properties of the material at normal temperatures are similar to those of traditional glass wool. Densities of glass wool insulations as used in structures are usually in the range 14 to 21 kg/m^3. The microstructure of heat-resistant glass wool is shown in Figure 1.11.

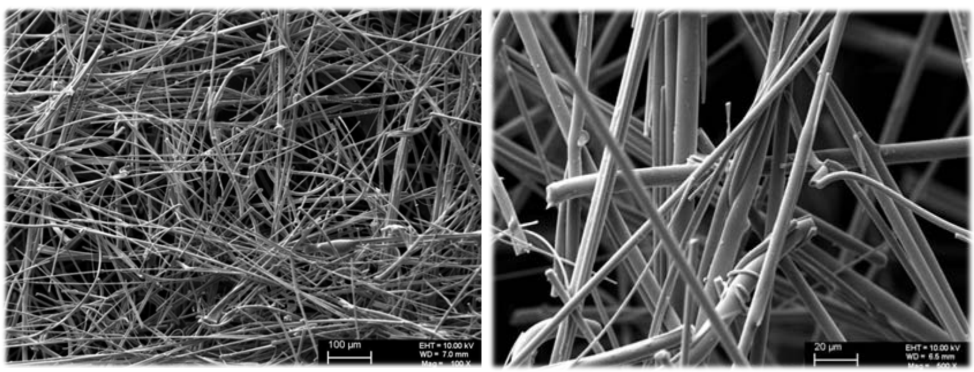


Figure 1.11. Structure of the heat-resistant glass wool at 100µm (left) and 20 µm scale (right)

1.4 Previous studies on fire safety of timber frame assemblies

1.4.1 Effect of gypsum plasterboards on charring

König, Tsantaridis, Östman [17,21] investigated the performance of typical gypsum plasterboards of Scandinavian production. Comparison was made with the boards from North America, Japan and New Zealand.

Sultan [6, 7, 22] performed an extensive study of floor and wall structures with gypsum plasterboards. He studied the falling off of the first piece and the last piece of gypsum plasterboard during the fire tests.

Much research in this field has been carried out in the USA. Park et al [23] determined the thermal properties of fire-rated gypsum plasterboards produced in the US and Japan. The thermal conductivity, specific heat, mass loss and linear contraction of gypsum board types were measured using small, 152 x 152 mm samples both at room temperature and at elevated temperatures. A large difference in linear contraction among gypsum board samples was observed at elevated temperatures, implying a significant difference in mechanical behaviour at fire temperatures.

Benichou and Sultan [24] measured thermal conductivity as a function of temperature for Type X board. They used different measurement techniques and obtained slightly lower thermal conductivity values than Park et al [23]. To be able to model the behaviour of gypsum board wall assemblies, thermal property data are needed as a function of temperature. For gypsum board, critical data are either not available as a function of temperature, or large differences exist in the data reported [23]. Properties of interest include specific heat, density and thermal conductivity as functions of temperature [23].

Shipp [25] introduces a method of three bench tests at high temperature – core cohesion, shrinkage and thermal insulation – to classify gypsum boards, instead of full-scale tests.

A recent study has been performed in Austria (Teibinger et al [26]), as a proposal for an Austrian standard concerning failure times. Proposed values of failure times are also shown in Figures 4.2 and 4.3.

Research work has been carried out at ETH Zürich [16] to investigate the fire protection properties of different materials. The method described in [16] can also be used for calculating the start of charring time as a protection time for cladding layers. Values from that method are shown in Figure 4.1.

1.4.2 The effect of mineral wool on charring

Takeda [27] researched timber-frame walls with glass wool insulation, developing the WALL2D computer model. Many small-scale experiments were also carried out. The glass wool began to melt at 430-450 °C, and was completely lost at about 650 °C. Rock wool started to shrink at 700 °C, and had decreased in volume by 60% at about 800 °C [27]. He measured the recession of glass wool in between 51 x 101 mm wall studs over a time period of 15 minutes. He found that Type X fire-rated gypsum board was still covering the structure and that the joint between gypsum boards was open. Takeda also noticed a slow melting of glass fibre in the case of a protected structure with no joints between gypsum cladding sheets.

Frangi [2] performed tests of sandwich elements with stone wool and glass wool insulation in EMPA's small furnace. Elements with glass wool lost the insulation due to melting. König [17] studied timber frame assemblies with glass wool insulation and noted the same phenomena that glass wool disappears when exposed directly to the fire. This lead to the rule in EN 1995-1-2: Where the cavity insulation is made of ***glass fibre***, failure of the member should be assumed to take place at time t_f. (Subclause C.2.1 (6)).

Richardson et al [28] observed that for assemblies with glass wool batts the ceiling fall-off was followed by melting of the glass wool into small droplets within 2 to 3 minutes. Sultan [29] has found that mineral wool batts and cellulose fibre insulation can provide a significant increase in fire resistance, but glass wool batts may lead to reduced fire resistance.

Frangi et al [9] studied timber frame assemblies with voids. The new method proposes faster charring rates compared to EN 1995-1-2. The method published by Frangi et al [9] is incorporated in the model for design of timber-frame assemblies using traditional glass wool insulation, as created in this study.

Coray, Remo, Frangi [20,30] have researched heat-resistant glass wool from the aspect of protection against charring.

2 METHODS

This study was mainly conducted as an experimental study.

2.1 Fire tests with timber frame assemblies

A series of medium-scale floor tests and full-scale wall tests were made at SP Trätek [31], [32] and at TÜV Estonia [33], to study the post-protection effect of insulation, see Figure 2.3. All the tests were made with non-load-bearing structures. Floor structures, handled in this thesis, have had fire only below the structure.

Full-scale walls, tested in Tallinn, had dimensions 3 x 3 m, see Figure 2.1. Medium-scale tests have been made with test floors with dimensions 0,6 x 1 m and 1 x 1 m, see Figure 2.2. Studs with typical cross-section of 45 x 145 mm were used for timber framing. Standard fire conditions (EN 1363-1, ISO 834) [10] were used. Test set-ups are given in Table 2.1.

During the experiments temperatures were measured inside and on the sides of cross-sections of timber. Thermocouples, type K with diameter 1 mm were used. Visual observations were made on the unexposed side, and temperatures of the exposed side were measured by thermocamera.

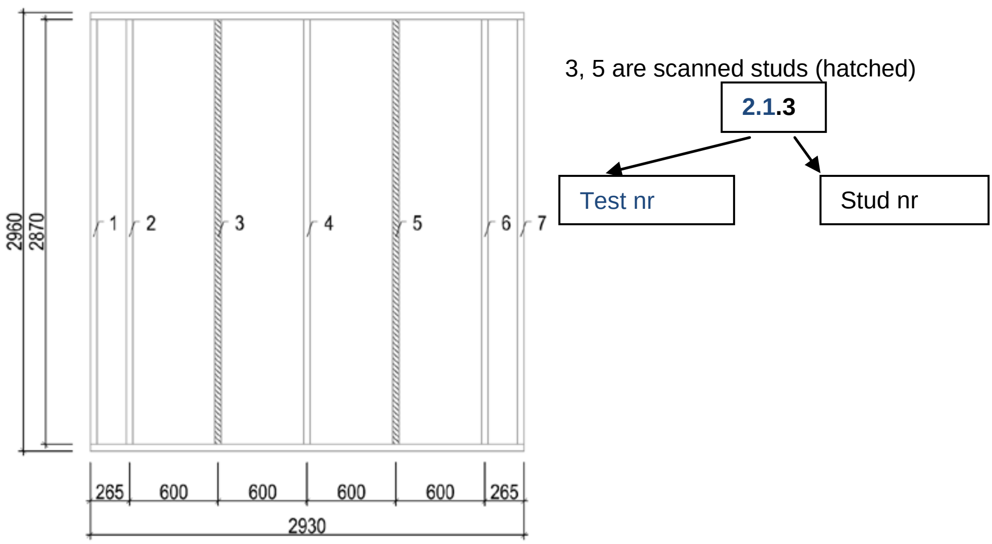


Figure 2.1. Definition of stud numbers of tested full-scale walls. View from the fire side

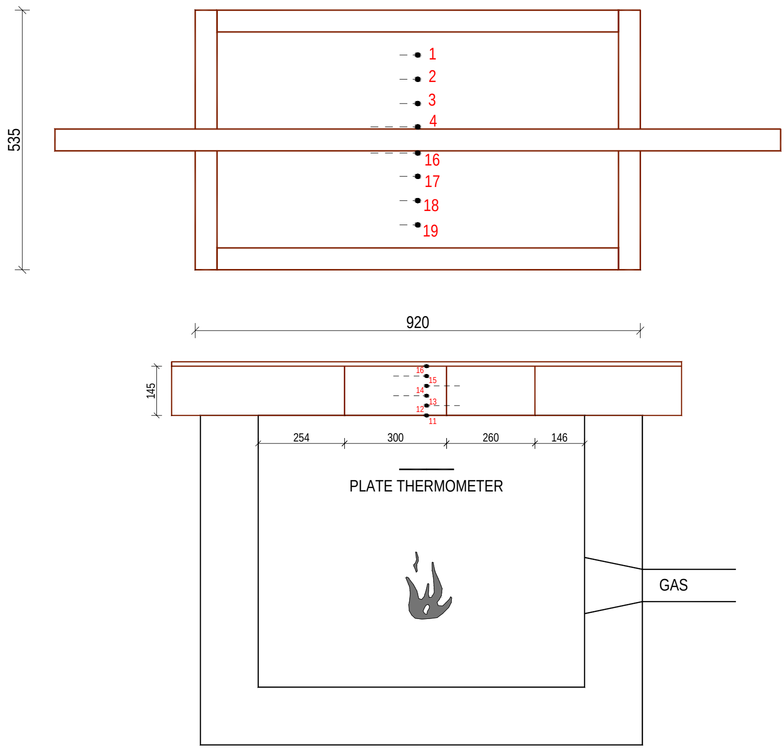


Figure 2.2. Medium scale floor test sample with location of thermocouples. Layout (upper) and view from side (lower).

Insulation materials used in the test specimens were chosen from the manufacturers' packets, but omitting the two outer layers in order to avoid pieces that might be damaged. Insulation was cut by bandsaw and placed as ideally as possible in between timber members. Stone wool insulation that was used in assemblies is called *reference stone wool* in this thesis.

Timber studs for all of the wall test series were from the same batch. The material was strength-graded to Strength Class C24 according to EN 338 [34].

Before the test, wooden specimens were conditioned at temperatures between +19 and 21 ˚C, and relative humidity between 48 and 52%.

Figure 2.3. Model furnace at SP Trätek (left) and full-scale test furnace at TÜV Estonia (right)

Thermocouples for measuring the charring inside and on the sides of cross-section (Figure 2.4, Figure 2.5) were placed at the centre height of studs or the middle span of beams respectively.

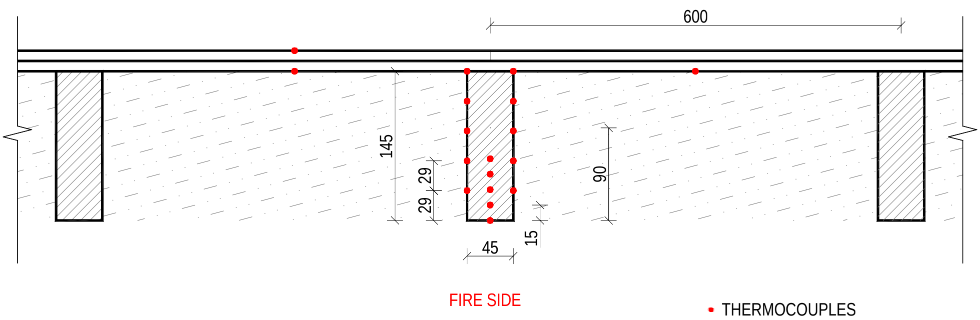


Figure 2.4. Location of thermocouples inside and on sides of cross-section without cladding on the fire exposed side

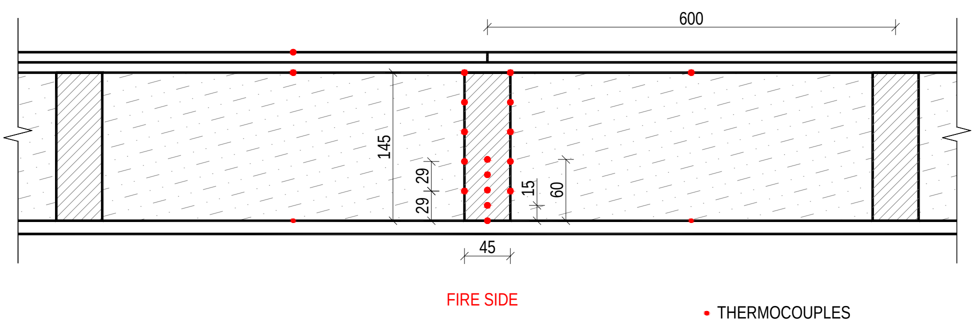


Figure 2.5. Location of thermocouples inside and on sides of cross-section with cladding on the fire exposed side

Table 2.1. Main characteristic data of test set-ups

Test no.	Test date	Ex-po-sed side	Stud	Insu-lation 1	Insu-lation 2	Un-ex-po sed side	Turn off of fire [min]	Test re-port
2.1	30.10.08	GtA	45x145	GW	Void	2GtA	33	[33]
2.2	28.1.09	-	45x145	RW1 RW3	RW2 RW4	2GtA	58	[33]
2.3	29.1.09	-	45x145	GWF2	GWF1	2GtA	58	[33]
2.4	11.2.09	-	45x145	GWF2	RW4	2GtA	55	[33]
2.5	12.2.09	GtA GtF	45x145 45x145	GWF2	 GW	GtA GtF	59	[33]
A	21.5.08	GtA	45x145	GW		PB	31	[31]
B	10.10.08	GtA	45x145	GW		PB	27.10	[32]

2.2 Experimental study of post-protection effect of traditional glass wool

The model for post-protection behaviour of timber-frame assemblies insulated by glass wool was created on the basis of results of evaluation of the medium-scale tests at SP Trätek and full-scale tests at TÜV Estonia.

Figure 2.6. Assembly of a test specimen at SP Trätek (left). Test specimen after fire test (right)

The spread of charring was measured by thermocouples, placed on the sides of the timber studs, see Figure 2.5. The start of charring was defined as occurring at a temperature of 300 °C. Recession speed was determined by thermocouples. Figure 2.6 shows the mounting of glass wool insulation and test specimen after the fire test.

2.3 Measuring density and cross-sections properties

After the full-scale fire tests, the studs were saved in their entire lengths. The char layer was mechanically removed from the studs under investigation. Studs were scanned by optical scanner at Tallinn University of Technology and three-dimensional models created. Cross-section properties and densities of the studs were measured for each 50 mm slice.

Definition of stud numbers is shown in Figure 2.1. Detailed section properties of all charred cross-sections are given in [11]. Detailed procedure is described in Paper V and in [35].

2.4 Evaluation of database of other experiments

The second important part of the study was to assemble a database of similar experimental tests from all over the world, although mainly from Europe, and use this for evaluation of the protective properties of gypsum plasterboards.

Since fall-off is a failure which cannot be calculated using finite element programs due to the complex failure mechanism, easy-to-use rules were developed as the result of extensive evaluation of available test data. Different constructions and fixings were taken into account, since failure is not only a question of the cladding itself. The rules presented in this thesis are a worst-case approach to the failure times. The equations provide design failure times that are more conservative than the failure times from all the relevant tests, except those that differ very much from the rest.

A database with data from full-scale fire tests was assembled at SP Trätek to provide material for creating design rules for fire safety design of timber structures clad with gypsum boards. The database contains results from more than 340 full-scale tests from different institutes all over the world, although mainly from Europe. Part of the work was done in [36].

Failure time is defined as a time when 1% of board area is fallen off in the fire situation. This criteria is stated by the author of this thesis to set a limit for evaluation of database.

3 RESULTS

3.1 Effect of gypsum plasterboards on charring of timber

The proposed equations created in this thesis from an evaluation of the database are shown in Table 3.1. The equations are conservatively created, following minimum test results: see Figure 4.1, for example. Papers I and II, as well as reference [37], deal with evaluation of the database.

The types of joints between plasterboard sheets, stud spacing, and insulation type are disregarded because effects due to them are not significant when creating conservative design equations based on minimum performance values. Joint types showed in Figure 4.1 are numbered as in EN 1995-1-2. See also Figure 4 in Paper I.

Based on evaluation of experimental data in the database, described above, conservative equations are proposed for starting times of charring and failure times of gypsum boards. The equations are presented in Tables 3.1 and 3.2. Graphical explanation is provided in Figures 4.1 to 4.3. See also Papers I and II for more detailed descriptions.

Table 3.1. Start of charring behind gypsum plasterboards t_{ch} in minutes

<table>
<tr><th rowspan="2">Cladding: gypsym plaster-board</th><th colspan="4">Start of charring behind gypsum plasterboards t_{ch} in minutes</th></tr>
<tr><th colspan="2">Walls</th><th colspan="2">Floors</th></tr>
<tr><td rowspan="2">Type A, F one layer</td><td>$1,8h_p - 7$ (3.1)</td><td>9 mm ≤ h_p ≤ 18 mm</td><td>$1,8h_p - 7$</td><td>9 mm ≤ h_p ≤ 18 mm</td></tr>
<tr><td>25,5</td><td>h_p > 18 mm</td><td>25,5</td><td>h_p > 18 mm</td></tr>
<tr><td>Type F two layers

Type F +Type A two layers</td><td>$\min\begin{cases}2,1h_{p,tot} - 7\\3,5h_p + 7\end{cases}$ (3.2)</td><td>25 mm ≤ $h_{p,tot}$ ≤ 31 mm
9 mm ≤ h_p ≤ 18 mm</td><td>$\min\begin{cases}2,1h_{p,tot} - 7\\4h_p - 14\end{cases}$ (3.4)</td><td>25 mm ≤ $h_{p,tot}$ ≤ 31 mm
9 mm ≤ h_p ≤ 18 mm</td></tr>
<tr><td>Type A two layers</td><td>$\min\begin{cases}2,1h_{p,tot} - 7\\1,6h_p + 13\end{cases}$ (3.3)</td><td>18 mm ≤ $h_{p,tot}$ ≤ 31 mm
9 mm ≤ h_p ≤ 18 mm</td><td>$\min\begin{cases}2,1h_{p,tot} - 7\\1,6h_p + 11\end{cases}$ (3.5)</td><td>18 mm ≤ $h_{p,tot}$ ≤ 31 mm
9 mm ≤ h_p ≤ 18 mm</td></tr>
</table>

Table 3.2. Failure times of gypsum boards t_f in minutes

Cladding	**Failure times of gypsum boards t_f in minutes.**			
	Walls		**Floors**	
Gypsum plasterboard Type F, one layer	$4,5h_p - 24$ (3.6)	9 mm ≤ h_p ≤ 18 mm	$h_p + 10$ (3.7)	12,5 mm ≤ h_p ≤ 16 mm
	57	h_p > 18 mm	26	h_p > 16 mm
Type F, two layers	$4h_{p,tot} - 40$ (3.8)	25 mm ≤ $h_{p,tot}$ ≤ 31 mm	$2h_{p,tot} - 3$ (3.9)	25 mm ≤ $h_{p,tot}$ ≤ 31 mm
	84	$h_{p,tot}$ ≥ 31 mm	59	$h_{p,tot}$ ≥ 31 mm
Type F + Type A[a]	81	h_p ≥ 15 mm[b] $h_{p,tot}$ ≥ 27 mm	50	h_p ≥ 15 mm[b]
Type A, one layer	$1,9h_p - 7$ (3.10)	9 mm ≤ h_p ≤ 15 mm	$1,8h_p - 7$ (3.11)	12,5 mm ≤ h_p ≤ 15 mm
	21,5	h_p > 15 mm	20	h_p > 15 mm
Type A, two layers	$2,1h_{p,tot} - 14$ [c] (3.12)	25 mm ≤ $h_{p,tot}$ ≤ 30 mm		
	49	$h_{p,tot}$ ≥ 30 mm		
Type A, three layers	55	$h_{p,tot}$ ≥ 37,5 mm	–[d]	
Gypsum fibreboard, one layer	$2,4h_p - 4$ (3.13)	10 mm ≤ h_p ≤ 12,5 mm	–[d]	

[a] Outer layer Type F, inner layer type A
[b] Thickness of first layer (Type F)
[c] Same as EN 1995-1-2 Clause 3.4.3.3(3)
[d] No data available.

There are few results for failure times of gypsum fibreboards in the database. As an indication, the proposal for wall structures with a single layer of gypsum plasterboards is shown in Figure 3.1. According to present test results, failure of gypsum fibreboards occurs earlier than failure of Type F gypsum plasterboards. The failure itself is more unified over the boards' area. See also comparison in Figure 3.1.

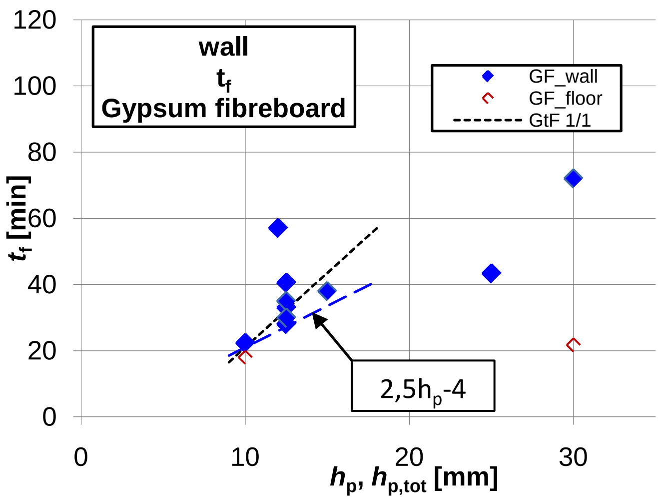


Figure 3.1. Failure times of gypsum fibreboards in wall assemblies

Figure 3.2 shows examples of the relationship between failure times and density of board with GtF boards in wall structures. Figure 3.3 shows examples of the relationship between temperature of failure, as measured behind the single-layer cladding of GtF, and the boards' thickness.

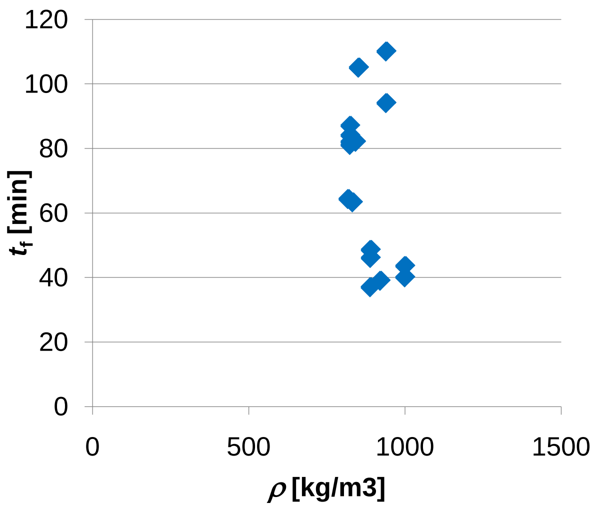


Figure 3.2. Relationship between density of board and failure time of single-layer claddings in wall structures with GtF boards

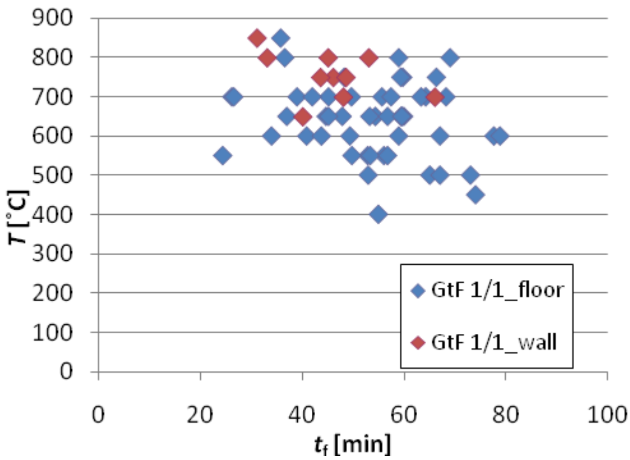


Figure 3.3. Relationship between fall-off temperatures behind the board and failure times of single layer claddings in wall structures with GtF boards

3.2 New design model for timber frame walls with traditional glass wool insulation

3.2.1 Introduction of the trapezoidal model

The model briefly described below is presented in Paper III and in [38]. The main result of this research is the new approach regarding recession speed of insulation.

For the stage before failure of the cladding (protection phase $t \leq t_f$) (see Figure 1.3), both stone wool and glass wool insulation perform approximately equally. However, once the cladding has fallen off and the insulation is directly exposed to the fire (post-protection phase $t \geq t_f$), glass wool insulation will undergo decomposition, gradually losing its protecting effect for the timber member by surface recession. Stone wool insulation, on the other hand, provided that it remains in place, will continue to protect the sides of the timber member facing the cavity [18].

EN 1995-1-2 assumes immediate failure of the assembly with glass wool after failure of the fire-protective cladding. This is a conservative assumption. From full-scale wall tests, it is known that it will take some time until the glass wool insulation has completely recessed, once it has been directly exposed to the fire.

The design model for timber-frame assemblies insulated with glass wool consists of the protection phase (Phase 2, Figure 1.3), as given in Annex C of EN 1995-1-2. A new method for the post-protection phase is given as a result of this work, combining it with the design method for assemblies with voids [9].

An assumption is made: that batt-type mineral wool insulation should always be secured mechanically, through the use of battens or steel channels or oversizing.

The volume of glass wool insulation decreases rapidly as the temperature rises. The post-protective behaviour of ordinary glass wool insulation is not comparable with that of stone wool insulation, although it does provide some small protection after cladding failure in comparison with structures with void cavities. The effect can be noticeable for higher cross-sections.

Floor and wall tests [31,32,33] showed the recession of glass wool insulation with speed of 15 to 28 mm/min, see Table I on Paper III. A recession rate of 30 mm/min of glass wool insulation is proposed for design purposes, in order to provide sufficient safety margin.

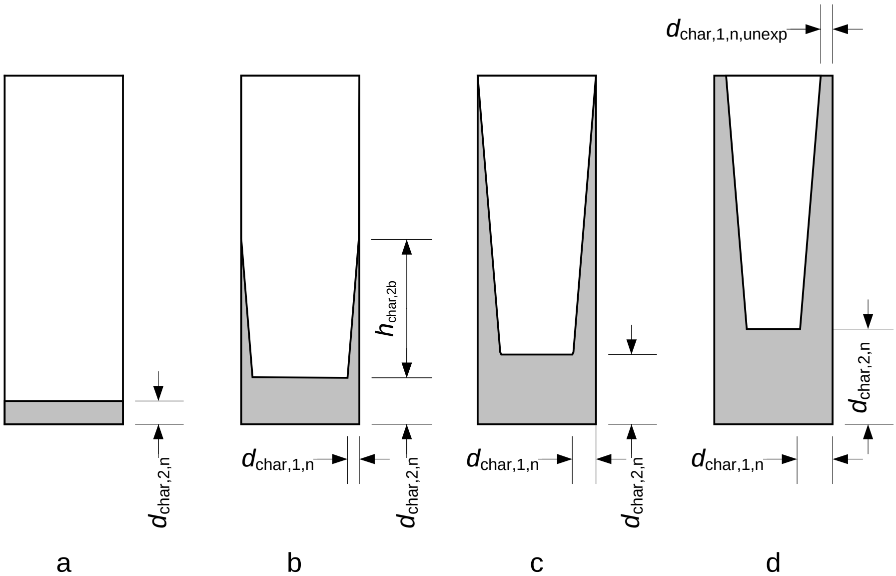
$v_{rec,gw}$ = 30 mm/min

Because of different starting times of charring in different cross-section heights, the shape of the notional cross-section is treated as trapezoidal. For practical design two simplifications as rectangular models are made for bending or compression elements.

Because of the relatively narrow typical cross-sections, as studied in this work, the consolidation phase (Phase 3b, Figure 1.3) is not used in this study, because of the inability to create a protective char layer on the 45 mm wide cross-sections considered here. Rapid heat transfer begins from the sides of studs before a char layer forms.

The trapezoidal model is shown in Figure 3.4. The design method is explained in Paper III and in [38]. Table 3.3 gives a brief overview of the design method.

The effect of the method is greater for wider cross-sections e.g. 95 x 225 mm.



Key:
a. Charring on narrow fire-exposed side before cladding has fallen off ($t_{ch} \leq t \leq t_f$)
b. Charring on narrow side and wide sides during surface recession of glass wool insulation ($t_f \leq t \leq t_{f,ins}$)
c. Recession of glass wool completed ($t = t_{f,ins}$)
d. Charring on three sides after failure of glass wool insulation ($t \geq t_{f,ins}$)

Figure 3.4. Illustration of charring phases

Table 3.3. Equations for charring depths for different protection phases

Phase	Time period	$d_{char,2,n}$	$d_{char,1,n}$	$d_{char,1,unexp}$	$h_{char,3}$	Source
2	$t_{ch} \leq t_f$	$k_2 k_s k_n \beta_0 (t_f - t_{ch})$ (3.14)				[3]
3	$t_f \leq t_{f,ins}$	$k_2 k_s k_n \beta_0 (t_f - t_{ch}) + k_3 \beta_n (t - t_f)$ (3.15)	$k_3 \beta_0 (t - t_f)$ (3.17)			This work
3	$t > t_{f,ins}$	$k_2 k_s k_n \beta_0 (t_f - t_{ch}) + k_3 \beta_n (t - t_f)$ (3.16)	$k_3 \beta_0 (t - t_f)$ (3.18)	$k_3 \beta_0 (t - t_{f,ins})$ (3.19)	$v_{rec,ins} (t - t_f)$ (3.20)	[9]

Failure time of the insulation is counted as

$$t_{f,ins} = t_f + \frac{h}{v_{rec,ins}} \tag{3.21}$$

where

$v_{rec,ins}$ is the surface recession rate. For glass wool insulation it is:

$$v_{rec,ins} = 30 \text{ mm/min}$$

h is the cross section height

k_2 is the insulation factor of the cladding from[3] expressions (C.3) or (C.4), given as:

$k_2 = 1{,}05 - 0{,}0073 h_p$ for unjointed claddings

$k_2 = 0{,}86 - 0{,}0073 h_p$ for jointed claddings

k_3 is the post-protection factor, given as

$$k_{3a} = 1 + \frac{8}{75} t_f \qquad \text{for } 0 \le t_f \le 15 \text{ min} \tag{3.22}$$

$$k_{3a} = 1{,}9 + \frac{7}{150} t_f \qquad \text{for 15 min} \le t_f \le 60 \text{ min} \tag{3.23}$$

k_s is the cross-section factor

k_n is the factor to convert irregular cross-section into a notional cross-section

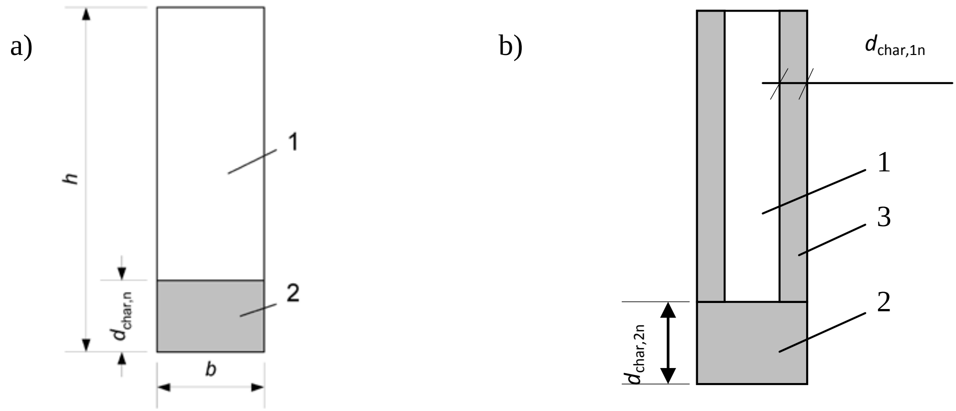
If there is a risk of insulation falling off before complete recession, the time $t_{f,ins}$ should be taken

$$t_{f,ins} = t_f$$

The reduced cross-section method with zero-strength layer, or the reduced properties method, should be used for structural design. The reduced cross-section method, given by Clause 4.2.2 in EN 1995-1-2 [3], should be used for $t > t_f$, i.e. the charring depth should be increased by d_0 = 7 mm.

3.2.2 The rectangular model

A further simplified model for calculations is that of the rectangular cross-section. Compared to the trapezoidal model, it is not universal for bending and compression members. Figure 3.6 shows the relationship between cross-sectional areas of trapezoidal and rectangular cross-sections to provide an equivalent section modulus of trapezoidal and rectangular cross-sections. Taking section modulus equal for trapezoidal and rectangular cross-section leads to two times smaller cross-section area after nine minutes of charring and respectively the same effect with equal cross-sectional areas. For this reason, two different rectangular models should be used for the two basic cases. The section modulus is important for bending elements, and it is assumed that the section modulus of a rectangular cross-section is similar to the section modulus of a trapezoidal cross-section. For compression elements, it is assumed that the cross-sectional area of the notional rectangular cross-section is similar to the section modulus of a trapezoid.



Key:
a. Charring on narrow fire-exposed side before cladding has fallen off ($t_{ch} \leq t \leq t_f$)
b. Charring on three sides after failure of glass wool insulation ($t \geq t_{f,ins}$)

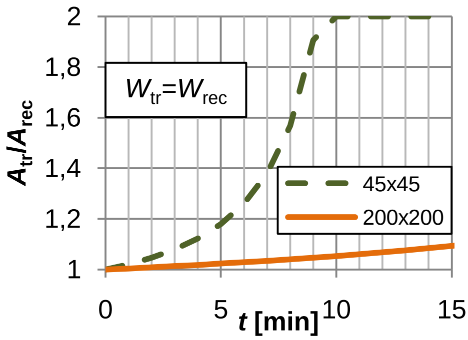
1 Notional residual cross-section
2 Notional char layer
3 One-dimensional char layer

Figure 3.5. Simplified rectangular model of charring

Table 3.4. Simplified method for charring depths for different protection phases

Phase	Time period	Bending and compression element	Bending element	Compression element
		$\boldsymbol{d_{char,2,n}}$	$\boldsymbol{d_{char,1,n}}$	$\boldsymbol{d_{char,1,n}}$
2	$t_{ch} \leq t_f$	$k_2 k_s k_n \beta_0 (t_f - t_{ch})$ (3.24)	0	0
3	$t_f \leq t_{f,ins}$	interpolation	interpolation	interpolation
3	$t > t_{f,ins}$	$k_2 k_s k_n \beta_0 (t_f - t_{ch}) + k_3 \beta_n (t - t_f)$ (3.25)	$k_3 \beta_0 (t - t_f - 0{,}3h/v_{rec})$ (3.26)	$k_3 \beta_0 (t - t_f - 0{,}5h/v_{rec})$ (3.27)

The rectangular model based on equal-section modulus of a trapezoid can give a corresponding rectangular cross-sectional area up to two times less, after only 5-10 minutes after cladding failure. See Figure 3.6.



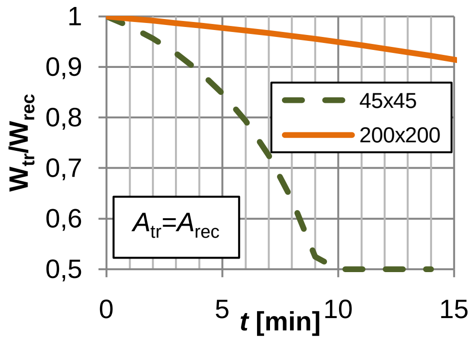
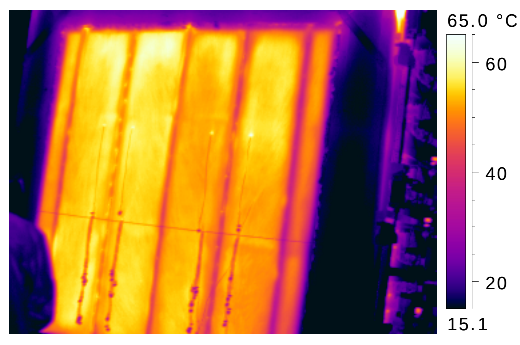


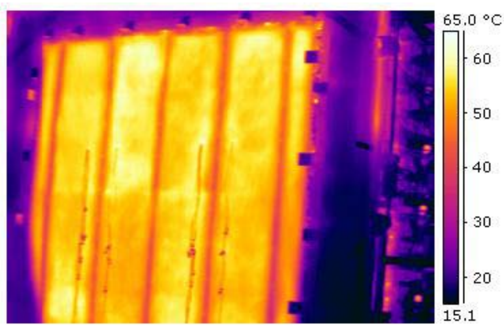
Figure 3.6. Comparison of change of section properties of trapezoidal and rectangular cross sections during fire development

3.3 Effect of heat-resistant glass wool insulation on charring of timber members

Heat-resistant glass wool expands at elevated temperatures. This was noted during the observations of fire tests with heat-resistant glass wool. Figure 3.7 shows the temperature distributions on the unexposed sides of similar test walls with heat-resistant glass wool (left) and stone wool (right). The pictures are recorded after 60 minutes of fire tests without cladding on the exposed side. In the case of stone wool, higher temperatures can be seen at joints between insulation pieces, where the joints of stone wool have shrunk slightly. Heat-resistant glass wool, on the other hand, has expanded and joints are closed. Only the fire exposed part is opened, see Figure 3.8.a. Temperature distribution is more even. Figure 3.8 shows the joints during the fire test. Figure 3.9 shows the situation after the fire test. Stone wool insulation has bowed downwards due to shrinkage, while heat-resistant glass wool has stayed in place due to expansion.

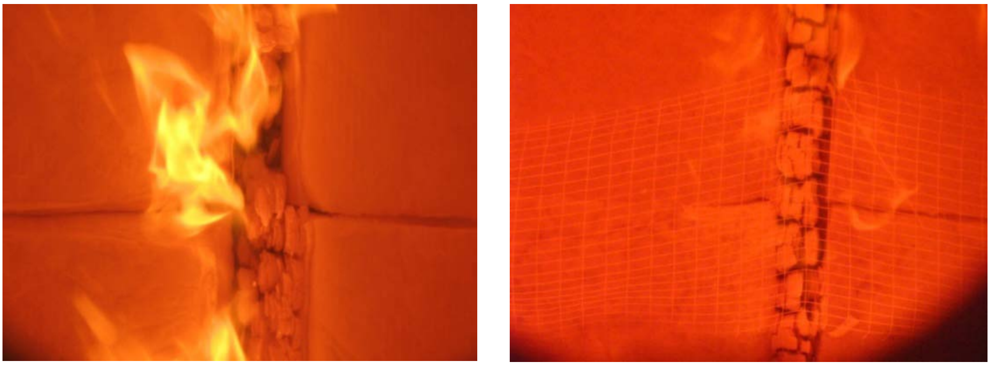


a) heat resistant glass wool



b) stone wool

Figure 3.7. Temperature distribution at unexposed side in fire test after 60 minutes



a) Heat-resistant glass wool b) Stone wool
Figure 3.8. Joints during the fire test. Picture is taken from fire exposed side

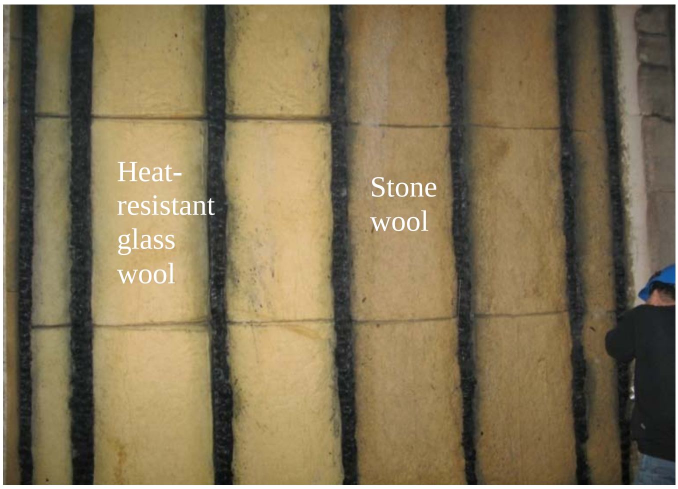


Figure 3.9. Insulation after the 60 minutes fire test. Heat-resistant glass wool (left) and stone wool (right)

3.4 Design model for timber frame assemblies with heat-resistant insulation

Paper IV describes the effect of heat-resistant insulation for timber frame assemblies.

Based on experimental results, it could be stated that the protective properties of stone wool insulation have declined. Reasons for this could be optimisation of the insulation's production costs, change of content for ecological reasons etc.

Heat-resistant glass wool provides a similar protection ability to that of stone wool. This phenomena was observed in full-scale tests during this study [33] and by

Schmid [43]. This was also indicated by direct comparison in the same full-scale fire test (Test 2.4 in [33]). Based on this study and on comparisons, the conclusion can be drawn that the model given in Annex C of EN 1995-1-2 is valid also for designs incorporating heat-resistant glass wool.

On the basis of the results of this study, the following proposal is made for a new cross-section factor, as shown in Figure 4.4. See also Equation (1.3) for comparison.

$$k_s = \begin{cases} 0,00023b^2 - 0,045b + 3,19 & \text{for } 38 \text{ mm} \le b \le 90 \text{ mm} \\ 1 & \text{for } b > 90 \text{ mm} \end{cases} \tag{3.28}$$

The factor is proposed for use with heat-resistant insulation, including stone wool. Figure 8, Paper IV, compares the proposed cross-section factor with the present factor as given in EN 1995-1-2[3].

3.5 Effect of density on charring of timber member

Measurements of the density of wood in a single wall stud have revealed differences of up to 41% between one part and another. Charring rate can also vary widely over the full length of a single timber wall stud. In this study, the effect of density of wood can influence the charring rate by up to 20%.

The definition of stud numbers is explained in Figure 2.1. Detailed section properties of all charred cross-sections are given in [11].

Coefficient k_{dens} is given in Paper V as an indication for taking into account the influence of density on the charring rate.

Some examples of charring and density distribution along the studs of this study are shown in Figures 3.10 and 3.11. A comparison of charring made with EN 1995-1-2 (k_s=1,3) and with the proposal in this work (k_s=1,6) is also given in Figures 3.10 and 3.11. Figures 3.12 and 3.13 show the charring of studs insulated by traditional glass wool. Stud No. 2.1.3 was covered by Type A gypsum plasterboard on the fire-exposed side. Stud No. 2.5.5 was covered by Type F gypsum plasterboard on the fire exposed side. The variability of charring is greater than in the case of studs with no cladding. Failure of cladding is different at different positions, and can therefore influence the variability of charring depths.

Joints between adjacent pieces of insulation can slightly increase the charring rates when thermally resistant glass wool is being used. Joints in insulation are shown as dotted lines in Figures 3.10 and 3.11. Stud numbers and test set-ups are given in Figure 2.1 and Table 2.1.

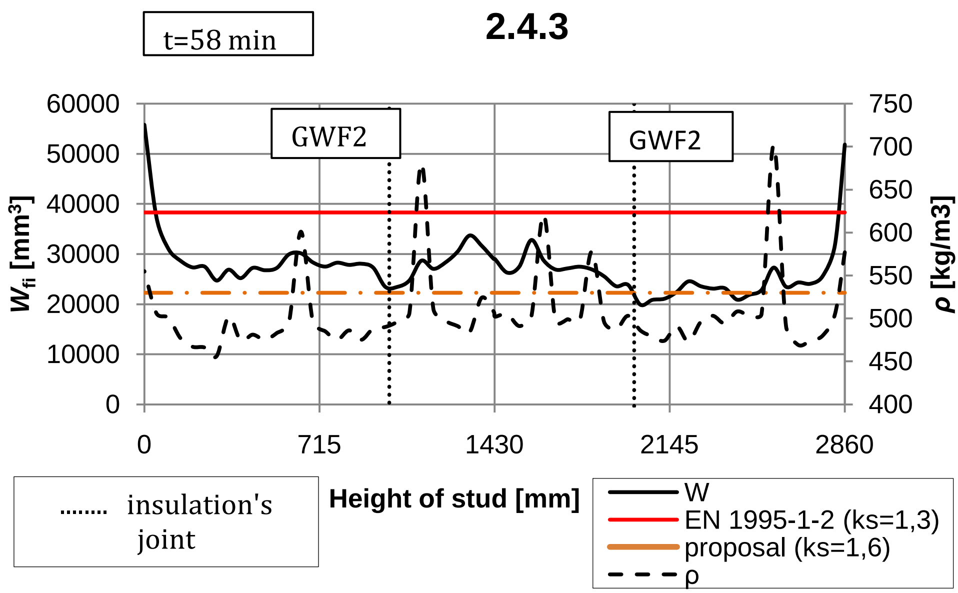


Figure 3.10. Variability of charring along a wooden stud insulated by heat-resistant glass wool

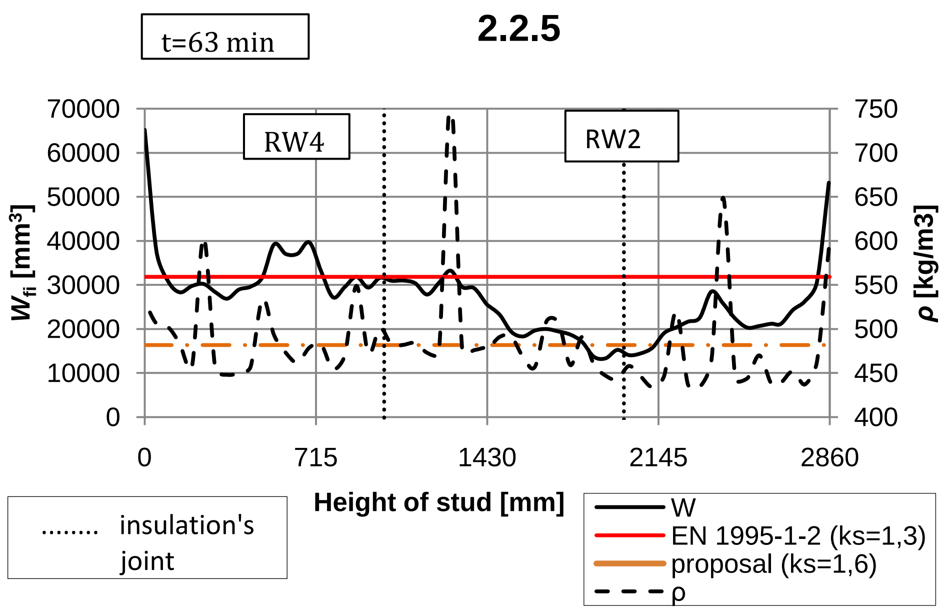


Figure 3.11. Variability of charring along a wooden stud insulated by two different stone wools

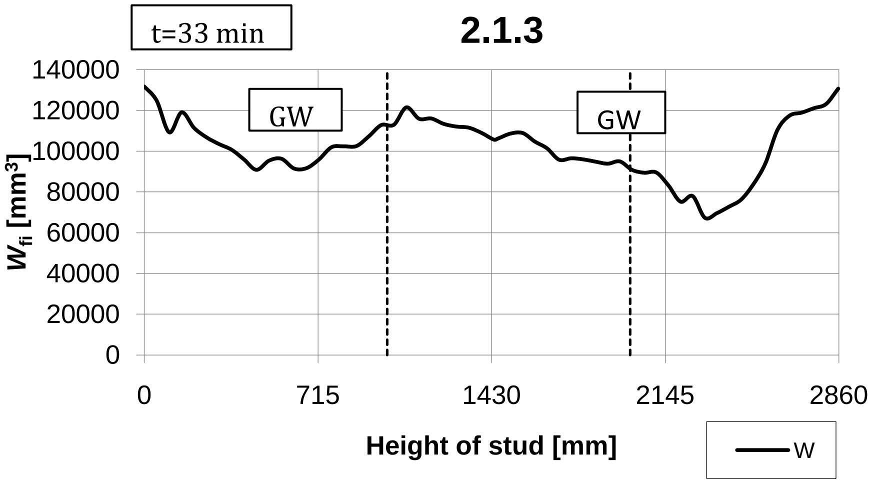


Figure 3.12. Variability of charring along a wooden stud insulated by glass wool and covered by Type A gypsum plasterboard

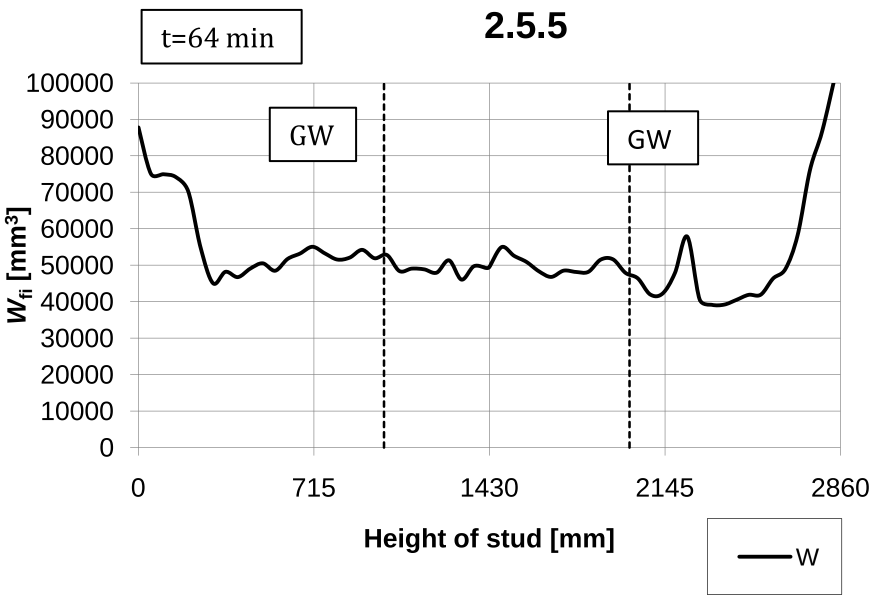


Figure 3.13. Variability of charring along a wooden stud insulated by glass wool and covered by Type F, gypsum plasterboard

4 DISCUSSION

4.1 The effect of gypsum plasterboards on charring of timber members

Sultan [6, 7, 22] studied the falling off of first piece and last piece during the fire tests. Difference between falling off of the first and the last piece was 2 to 8 minutes in most cases [20]. In my present studies the failure times are created considering falling off of first piece only. Some results of the studies of Sultan [6, 7, 22] are used in my thesis including them in collected database.

Tsantaridis, Östman, König [21] made small scale tests and comparison with results from New Zealand, Japan and North America. Test pieces consisted of timber stud 45x145x100 mm with gypsum board piece of 100 x 100 mm. The authors get good correlation on start time of charring behind different boards from different countries. Present study showed large variety of start times of charring related to thickness of board. See Figure 4.1. In most cases the charring started earlier in full-scale tests with timber frame assemblies compared to small scale tests in [21]. The effect of heating from sides of cross-section in full-scale assembly has influence on that.

According to Winter and Meyn [39] shrinkage of gypsum plasterboards is less than 1% at 300 °C. This is confirmed by tests made during this thesis.

Research work has been carried out at ETH Zürich [16] to investigate the fire protection performance of different materials. The method described in [16] can also be used for calculating the starting time of charring as a protection time for cladding layers. Line showing the values from that method is shown in Figure 4.1. For comparison, the present values from database of start time of charring for single layer gypsum plasterboards are shown in Figure 4.1.

Figure 4.2 and 4.3 contain equations for failure times, proposed in this study and also comparison with existing normative values of failure times from other sources.

EN 520 [5] requires only a core cohesion test for proofing Type F boards. The standard for gypsum plasterboards [5] does not give the necessary data for fire design of timber structures with gypsum plasterboards. Some values for failure times are given in *Brandsäkra trähus* ("Fire safe timber house") [40], but those are mainly from one Scandinavian manufacturer, which have relatively good values for failure times. The values from [40] in Figure 4.2 and Figure 4.3 situate above the proposed equations in this study. Values of failure times of typical thicknesses of gypsum plasterboards are also given in the Finnish National Annex of EN 1995-1-2 [41]. Failure times from [41] are situated in-between the failure times according to [40] and equations by this study.

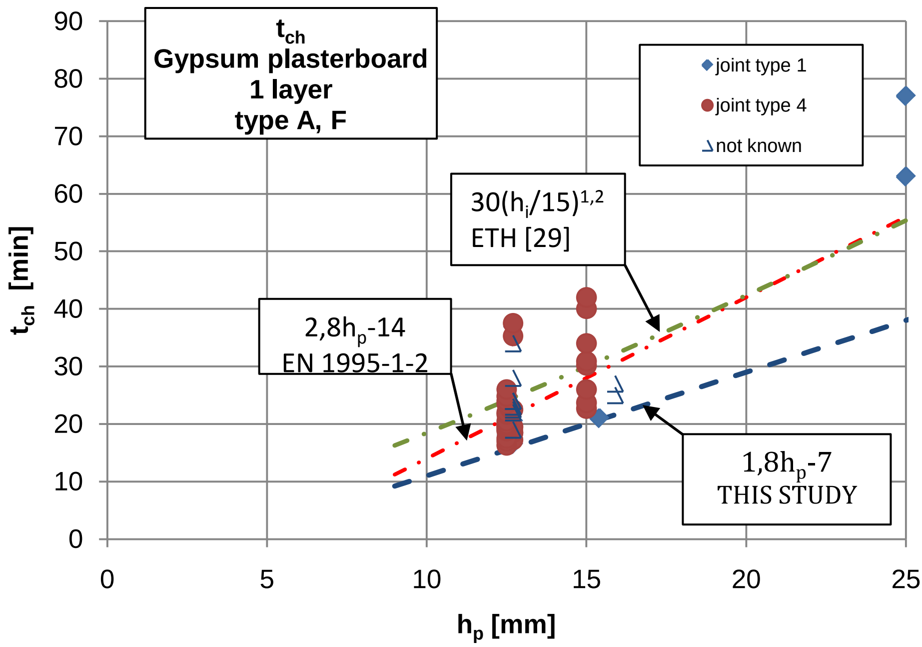


Figure 4.1. Start times of charring t_{ch} from database. Comparison of different methods

Recent work in Austria (Teibinger et al [26]) has resulted in a proposal for an Austrian standard concerning failure times. Proposed values of failure times from [26] are even more conservative compare to proposals of this study. Probably, extra safety is included in the Austrian study.

The equations provided in this study are taking large variety of products into account. The values are conservative and safe to use. Producers of gypsum boards should provide their values of failure times to utilise better performance of their products. There is a slow procedure to change European standards of gypsum boards [5, 15] according to needs for fire performance of timber frame assemblies. The recommended intermediate way to classify different gypsum plasterboards of Type F for timber frames according to protection times, is to use the European Technical Approval procedure with certain prescribed test set-ups.

Higher density generally improves the fire performance of gypsum board, as it indicates the use of a greater quantity of gypsum, resulting from fewer air voids. This gives greater heat-absorbing capacity and requires more water of crystallization to be driven off. Richardson and McPhee [42] refer to tests where a 6% increase in density produced an 8% increase in fire resistance for otherwise identical structures. There is no correlation found between density and failure time of gypsum board 3 in this study, taking into account different products, see Figure 3.2.

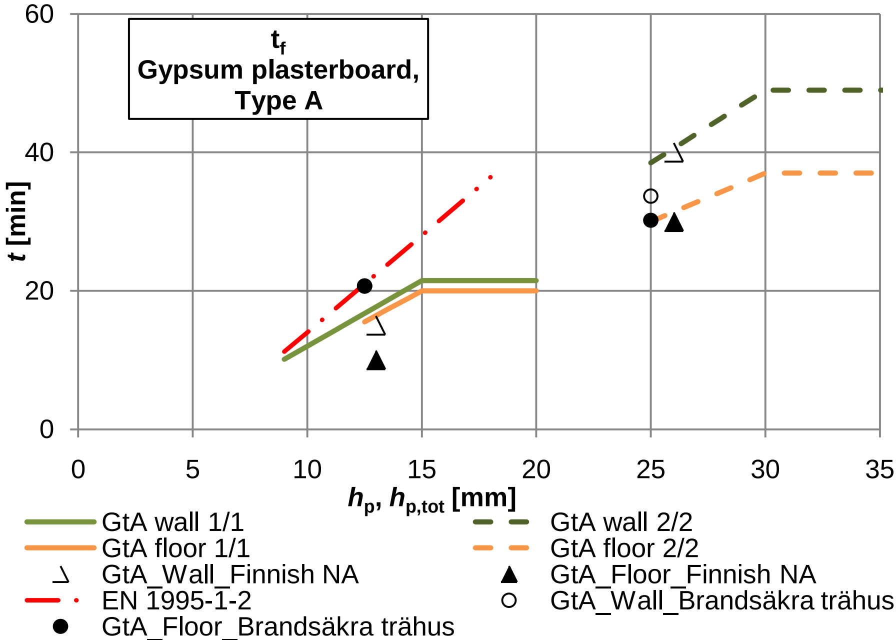


Figure 4.2. Failure times of Type A gypsum plasterboards. Comparison of present research with other resources

Buchanan [13] found that multiple layers of thin gypsum boards may be cheaper and lighter to fix than one thick board, but multiple layers do not usually provide the same fire resistance as a single layer of the same total thickness, because of the outer layers can fall off sequentially, leading to much greater thermal exposure to the inner board. This study confirmed the phenomena, that failure time of double layer of the same type of boards is less than the sum of failure times of single layers. EN 1995-1-2 uses reduced thickness of the second layer when calculating start time of charring. The proposed equations are based on total thickness in this study.

Critical fall-off temperature according to results on database can vary quite noticeably. Temperature range for fall off of gypsum plasterboards, Type F in wall structures is 650 to 850 ˚C and in floor structures it is 400 to 850 ˚C, see Figure 3.3. König et al [17] found that critical fall off temperatures are 600 ˚C for gypsum plasterboards in ceilings and 800 ˚C for walls.

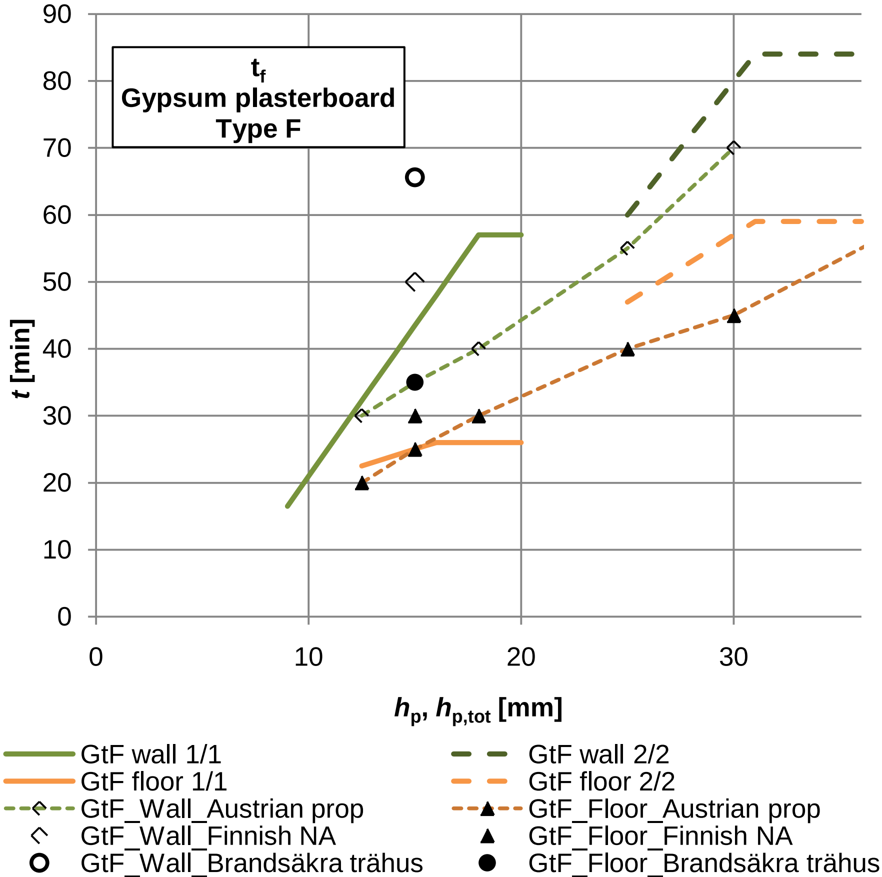


Figure 4.3. Failure times of Type F gypsum plasterboards. Comparison of present research with other resources

4.2 The effect of heat-resistant insulations on charring of timber frame members

Paper IV describes the effect of heat-resistant insulations on timber frame assemblies.

Experimental analysis showed the increased charring rate compared to the model given in EN 1995-1-2 [3]. Figure 4.4 shows a comparison of tests results with stone wool in 1995 and test results with stone wool and heat-resistant glass wool in 2009, made during this study and by Schmid [43]. The present test results have been achieved using non-load-bearing wall structures made of timber of strength class C24: Schmid performed load-bearing floor tests with using Class C30 timber.

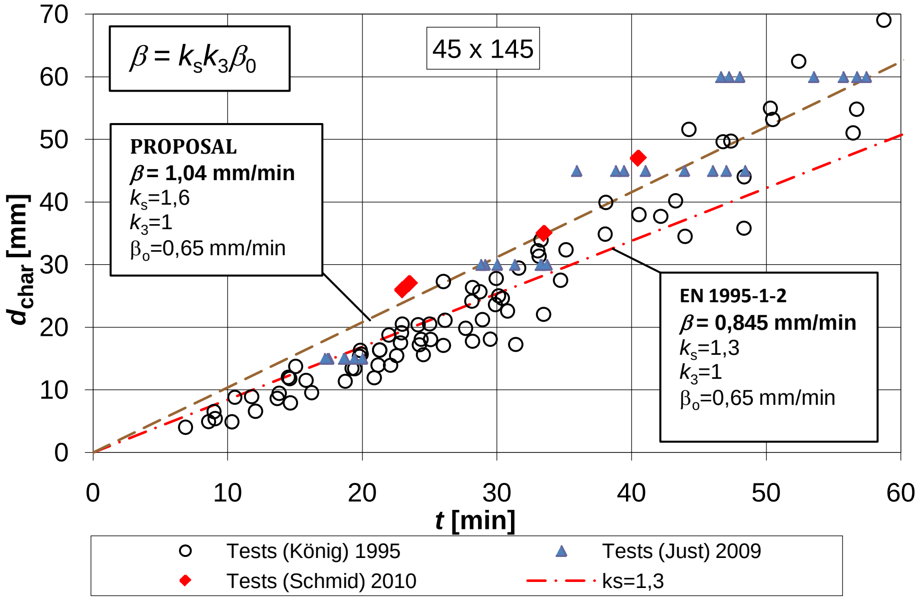


Figure 4.4. Charring rate of tested timber members insulated with heat-resistant glass wool. Comparison of results from the past with recent findings

Based on experimental results, it could be stated that the protective properties of stone wool have decreased. The reasons could be optimising of the insulation's production costs, changing of content for ecological reasons etc.

Heat-resistant glass wool provides similar protection to that provided by stone wool. This was also shown by direct comparisons in a full-scale fire test.

Based on this study and on comparisons, the conclusion can be drawn that the model given in Annex C of EN 1995-1-2 is valid also for structures incorporating heat-resistant glass wool.

As a result of this study, the following proposal is made for a new cross-section factor, see Figure 4.4. See also Equation (1.3) for comparison.

$$k_s = \begin{cases} 0,00023b^2 - 0,045b + 3,19 & \text{for } 38 \text{ mm} \le b \le 90 \text{ mm} \\ 1 & \text{for } b > 90 \text{ mm} \end{cases} \tag{4.1}$$

This factor is proposed for use with heat-resistant insulation, including stone wool. Figure 8, Paper IV, compares the proposed cross-section factor with the present one as given in EN 1995-1-2[3].

4.3 The effect of heat-resistant glass wool on charring of timber members

Coray, Remo and Frangi [33, 34] have investigated heat-resistant glass wool from the point of view of protection against charring.

The proposed equation for the start of charring behind insulation was given as:

$$t_{\mathrm{ch}} = 36\left(\frac{h}{80}\right)^{0,8}\left(\frac{\rho}{20}\right)^{0,9} \tag{4.2}$$

Results from full-scale tests showed better performance than as given by the proposed relation [5].

1) The start time of charring behind 145 mm thick heat-resistant glass wool with a density of 14 kg/m^3, is in accordance with Equation (4.2):

t_{ch}= 42 min

2) Respective times from a test, measured at different locations, were 48 to 55 minutes.
3) Timber protected by heat-resistant glass wool with a density of 21 kg/m3 did not reach charring temperature before the end of the test, see Figure 4.5, left.
4) One of the tested stone wools showed quite early charring behind the insulation. Charring started 3 - 4 minutes earlier than should be expected to the design rule in EN 1995-1-2. Temperatures behind other tested insulations did not reach 300 °C during the test. See Figure 4.5, right.

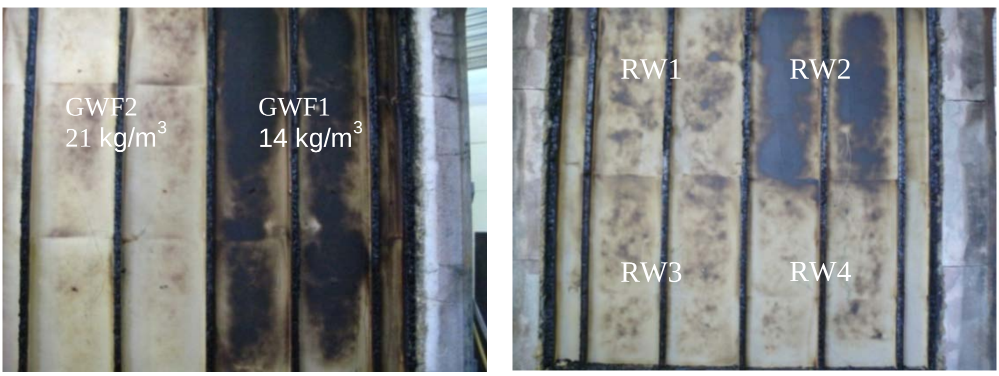


Figure 4.5. Surface behind heat-resistant glass wool (left) and different stone wools (right)

Determining of cross-sections was made with NX6 software [44] and AutoCAD. Determination is described briefly in paper V.

Quality of mounting

The quality of fitting is an important issue. The design model in EN 1995-1-2 and in this present thesis assume that all the insulation is fitted correctly, e.g. ideally. In reality, there could be unfilled parts and gaps between the insulation and timber elements. Charring could develop from three sides, even with heat-resistant insulation. A safety factor for quality could be introduced.

4.4 The effect of traditional glass wool insulation on charring of timber members

Many authors e.g. König [4], Frangi [2], Richardson [28] have concluded that timber frame assemblies with glass wool insulation will lose their bearing capacity when exposed directly to fire. That is also stated in annex C of EN 1995-1-2. Still there exist design rules for timber frame assemblies with voids.

The effect of glass wool is not noticeable for small sections as investigated in this thesis. For bigger sections, as used in central Europe, the effect could be remarkable. Compare Figure 4.6 and 4.7. Even for small cross-sections, the possibility to continue fire design on post-protection phase should be given in design rules. Examples of charred cross-section (without counting d_0) are shown on the next diagrams for different studs and protection.

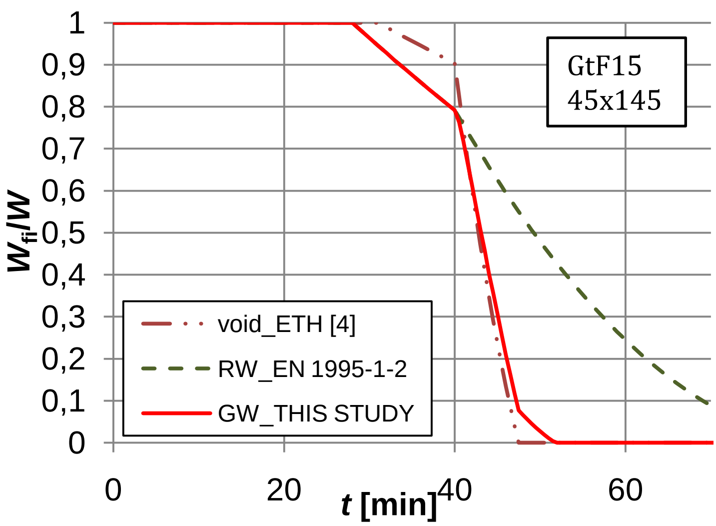


Figure 4.6. Decreasing of section modulus. Example of existing and new design models for timber frame assembly with Type F gypsum plasterboard and 45x145 mm timber studs. Comparison with test results

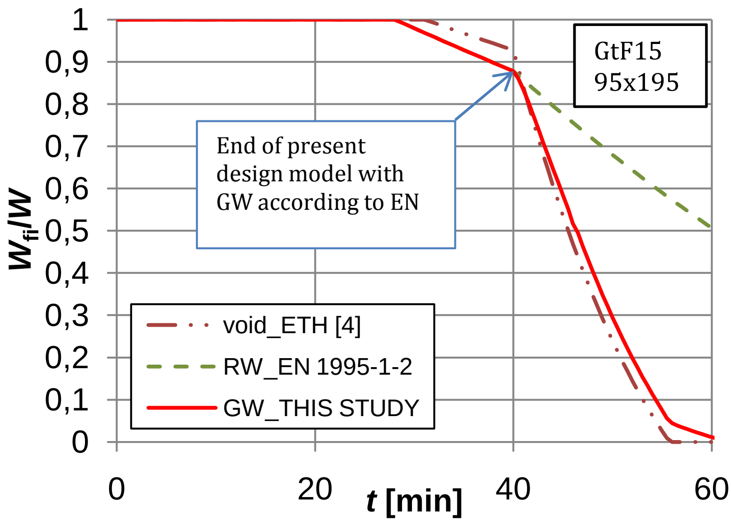


Figure 4.7. Example of the new design model for a structure with Type F gypsum plasterboard and 95x195 mm timber studs

Charring at corners is taken into account by using β_n on the narrow side of the cross section. Charring on the wide side could be calculated by using one-dimensional charring rate β_0. Test results show that β_0 gives the appropriate result.

Mechanical strength must be analysed using the effective cross-section method according to [3]. See also Section 2. The zero strength layer is d_0=7 mm.

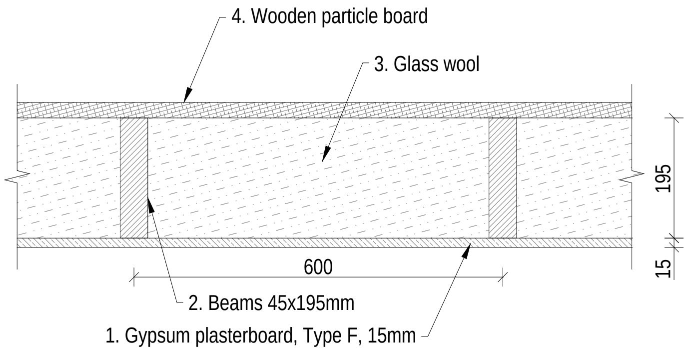
The following two examples illustrate the method.

4.4.1 Design examples of timber frame assemblies with traditional glass wool

Design example 1: Bending capacity of timber floor beam with glass wool insulation

Consider a floor assembly with a length of 3000 mm. The dimensions of the beams are 45 × 195 mm, spaced at 600 mm centres. The strength class of the timber is C24. The cavities are completely filled with batt-type glass wool. The cladding on the fire-exposed side consists of one layer of 15 mm Type F gypsum plasterboard. The cladding on the unexposed side is made of one layer of wooden particle board.

The length of the screws on the fire-exposed side is ℓ_f = 35 mm. Determine the design value of the bending resistance of a beam for a fire resistance of R30. The fire load is situated below the structure.



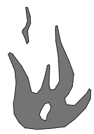


Figure 4.8. Cross-section of the floor structure

The time of start of charring, as given by Expression (3.1), is:
$t_{ch} = 1{,}8h_p - 7 = 1{,}8x15–7=20$ min

The failure time of the cladding with respect to thermal degradation is (see Table 3.1, Expression (3.7)):

$t_f = h_p + 10 = 15+10=25$ min

The failure time of the cladding with respect to pull-out failure of the screws is (see EN 1995-1-2, Expression (C.9)):

$$t_{\mathrm{f}} = t_{\mathrm{ch}} + \frac{l_{\mathrm{f}} - l_{\mathrm{a,min}} - h_{\mathrm{p}}}{k_{\mathrm{s}} k_2 k_{\mathrm{n}} k_{\mathrm{j}} \beta_0} = 20 + \frac{35-10-15}{1,3\times 0,94\times 1,5\times 1\times 0,65} = 28,4 \ \text{min} > 25 \ \text{min}$$

Charring of timber stud

Failure time of the insulation is:

$$t_{\mathrm{f,ins}} = t_{\mathrm{f}} + \frac{h}{v_{\mathrm{rec,ins}}} = 25 + \frac{195}{30} = 31\,\text{min}$$

Protected phase.
Insulation factor according to Expression (C.3) of EN 1995-1-2 is:
$k_2 = 1,05 - 0,0073h_p = 1,05 - 0,0073 \times 15 = 0,94$

Post-protection factor according to Equation (3.23) is:
$$k_3 = 1,9 + \frac{7}{150}t_{\mathrm{f}} = 1,9 + \frac{7 \times 25}{150} = 3,1$$

Size factor according to C.2.1(3) in EN 1995-1-2 is:
k_{s}=1,3

Factor to convert irregular charring depth into notional charring depth:
k_{n}=1,5

Charring rates
$$\beta_0 = 0,65\frac{\mathrm{mm}}{\mathrm{min}}$$
$$\beta_{\mathrm{n}} = 0,8\frac{\mathrm{mm}}{\mathrm{min}}$$

The notional charring depth at 30 minutes is (Table 3.4, Expression (3.25)):
$$d_{\mathrm{char,2,n}} = k_2 k_s k_n \beta_0 (t_{\mathrm{f}} - t_{\mathrm{ch}}) + k_3 \beta_{\mathrm{n}} (t - t_{\mathrm{f}}) =$$
$$= 0,94 \times 1,3 \times 1,5 \times 0,65(25-20) + 3,1 \times 0,8(30-25) = 18,4 \text{ mm}$$

Charring on wide sides at time $t = t_{\mathrm{ins}}$ (Table 3.4, Expression (3.26)):
$$d_{\mathrm{char,1,n}} = k_3 \beta_0 (t - t_{\mathrm{f}} - 0,3\frac{h}{v_{\mathrm{rec,ins}}}) = 3,1 \times 0,65(31-25-0,3\frac{190}{30}) = 8,26 \text{ mm}$$

Interpolation for charring at time t = 30 min
$$\frac{t - t_{\mathrm{f}}}{t_{\mathrm{f,ins}} - t_{\mathrm{f}}} d_{\mathrm{char,1,n,tfins}} = \frac{30-25}{31-25} \times 8,26 = 6,9 \text{ mm}$$

The effective cross-section method is used for strength analysis. The zero strength layer, as given by Equation (4.1) in EN 1995-1-2 is:
d_0=7 mm

The dimensions of the residual cross-section of the studs are:
$$b_{\mathrm{fi}} = 45 - 2 \times (6,9 + 7) = 17,2 \text{ mm}$$
$$h_{\mathrm{fi}} = 195 - (18,4 + 7) = 169,6 \text{ mm}$$

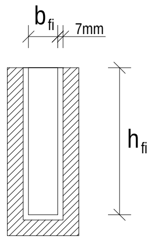


Figure 4.9. Notional effective cross-section

The design values of bending strength and modulus of elasticity are (see Expressions (1.4) and (1.5)):

Design value of bending strength:

$$f_{\mathrm{m,d,fi}} = k_{\mathrm{mod,fm,fi}} \frac{f_{20}}{\gamma_{\mathrm{M,fi}}}$$

where

$$f_{20} = k_{\mathrm{fi}} f_{\mathrm{m,k}} = 1,25 \times 24 = 30 \frac{\mathrm{N}}{\mathrm{mm}^2}$$

k_{fi} = 1,25
$k_{\mathrm{mod,fi}}$ = 1,0
$\gamma_{\mathrm{M,fi}}$ = 1,0

Design bending strength is
$f_{\mathrm{m,d,fi}}$ = 30 N/mm^2

Section modulus of residual cross-section

$$W_{\mathrm{fi}} = \frac{17,2 \times 169,6^2}{6} = 82457 \ \mathrm{mm}^3$$

Maximum bending moment:

$$M_{\max} = W_{\mathrm{fi}} f_{\mathrm{m,d,fi}} = 82457 \times 30 = 2,47 \times 10^6 \,\mathrm{Nmm}=2,47 \mathrm{\ kNm}$$

Maximum load per unit length (including self-weight):

$$q = \frac{8M}{L^2} = \frac{8 \times 2,47}{3,0^2} = 2,20 \ \frac{\mathrm{kN}}{\mathrm{m}}$$

Bearing capacity of the floor beam for R30 criteria is 2,2 kN/m including selfweight.

According to EN 1995-1-2:2004 the maximum fulfilled R-criteria is 25 minutes, which is the failure time of cladding.

Design example 2: Bearing capacity of timber wall stud with glass wool insulation

Consider a wall assembly with a height of 2800 mm. The dimensions of the beams are 95 × 225 mm. Distance 600 mm. The strength class of timber is C24. The cavities are completely filled with batt-type glass wool. The cladding on the fire-exposed side consists of one layer of 12,5 mm thick Type A gypsum plasterboard and 12 mm thick wooden particleboard (density 550 kg/m^3). The cladding on the unexposed side is made of one layer of wooden particleboard. The length of the screws on the fire-exposed side is ℓ_f = 51 mm. Determine the design value of the bending resistance of a beam for a fire resistance of R60. Fire load is situated below the structure.

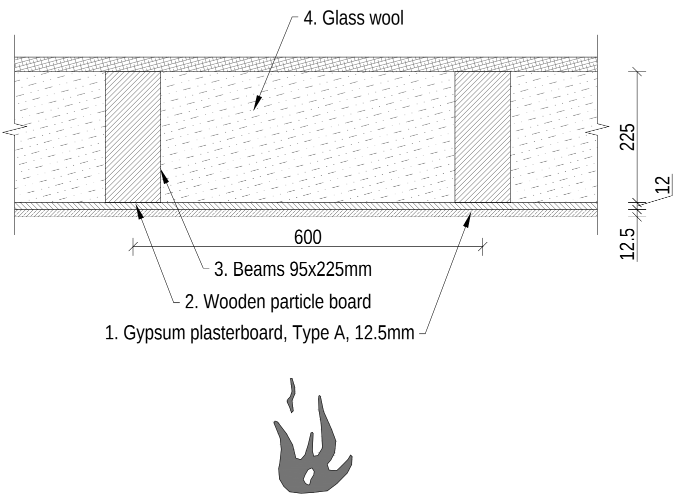


Figure 4.10. Cross-section of wall assembly

The time of start of charring according to Table 3.1, Expression (3.1)
$t_{ch} = 1{,}8h_p - 7$ = 1,8x12,5–7=15,5 min

The failure time of the cladding with respect to thermal degradation is (see Table 3.2, Expression (3.10)):
$t_f = 1{,}9h_p - 7$ = 1,9x12,5–7=16,7 min

Charring of wooden particle board
Charring rate of wooden particle board with β_0 = 0,9 mm/min from Table 3.1 in [3]:

$$\beta_{0,\rho,t} = \beta_0\, k_\rho\, k_h = \beta_0 \sqrt{\frac{450}{\rho_k}} \sqrt{\frac{20}{h_p}} = 0{,}9 \times \sqrt{\frac{450}{550}} \sqrt{\frac{20}{12}} = 1{,}05 \text{ mm/min}$$

The charring rate of particle board for 15,5 min $\leq t \leq$ 16,7 min is

$$\beta_{\mathrm{pb}} = k_2 \beta_{0,\rho,t} = 0,78 \times 1,05 = 0,82 \ \text{mm/min}$$

with

$$k_2 = 1 - 0,018 h_{\mathrm{p}} = 1 - 0,018 \times 12,5 = 0,78$$

The charring rate of particle board for t > 16,7 min is

$$\beta_{\mathrm{pb}} = k_3 \beta_{0,\rho,t} = 2 \times 1,05 = 2,1 \ \text{mm/min}$$

with

k_3 = 2

Failure of claddings and start of charring of timber stud according to (C.7) in EN 1995-1-2.

$$t_{\mathrm{ch}} = 15,5 + 1,2 + \frac{12,5 - 1}{2,1} - 4 = 18,2 \ \text{min}$$

Charring depth at protected phase

1,2*0,82=1 mm

Failure time of the insulation is

$$t_{\mathrm{f,ins}} = t_{\mathrm{f}} + \frac{h}{v_{\mathrm{rec}}} = 18,2 + \frac{225}{30} = 25,7 \ \text{min}$$

Post-protection factor according to Expression (3.23):

$$k_3 = 1,9 + \frac{7}{150} t_{\mathrm{f}} = 1,9 + \frac{7 \times 18,2}{150} = 2,7$$

Size factor according to C.2.1(3) in EN 1995-1-2:

k_{s}=1,3

Charring rates

$$\beta_0 = 0,65 \frac{\text{mm}}{\text{min}}$$

$$\beta_{\mathrm{n}} = 0,8 \frac{\text{mm}}{\text{min}}$$

The notional charring depth at 30 minutes is (Expression (3.25)):

$$d_{\mathrm{char,2,n}} = k_3 \beta_{\mathrm{n}} (t - t_{\mathrm{f}}) = 2,7 \times 0,8(30 - 18,2) = 25,5 \ \text{mm}$$

Charring on wide sides (Table 3.4, Expression (3.27)):

$$d_{\mathrm{char,1,n}} = k_3 \beta_0 (t - t_{\mathrm{f}} - 0,5 \frac{h}{v_{\mathrm{rec,ins}}}) = 2,7 \times 0,65(30 - 25,7 - 0,5 \frac{225}{30}) = 14,1 \ \text{mm}$$

The effective cross-section method is used for strength analysis. Zero strength layer is, according to Equation (4.1) in EN 1995-1-2:
d_0=7 mm

Dimensions of the residual cross-section of the studs are

$$b_{\mathrm{fi}} = 95 - 2\times(14,1+7) = 52,8 \text{ mm}$$

$$h_{\mathrm{fi}} = 225 - (25,5+7) = 192,5 \text{ mm}$$

See also Figure 4.9.

A_{fi} = 10164 mm^2
I_{fi} = 31,39x10^6 mm^4

The design values of compression strength and modulus of elasticity are, see Expressions (1.4) and (1.5):

Design value of compression strength:

$$f_{\mathrm{c,d,fi}} = k_{\mathrm{mod,fc,fi}} \frac{f_{20}}{\gamma_{\mathrm{M,fi}}}$$

where

$$f_{20} = k_{\mathrm{fi}}\, f_{\mathrm{c,k}} = 1,25\times 21 = 26,3 \ \frac{\mathrm{N}}{\mathrm{mm}^2}$$

k_{fi} = 1,25
$k_{\mathrm{mod,fi}}$ = 1,0
$\gamma_{\mathrm{M,fi}}$ = 1,0

Design compression strength is
$f_{\mathrm{c,d,fi}}$ = 26,3 N/mm^2

Only outward buckling out of the wall plane is considered. Inward buckling in the wall plane is avoided through the use of wooden particle board on the unexposed side.

Buckling length is regarded according to [40]:
l_y= 0,7l = 0,7 x 2,8 = 1,96 m

With EN 1995-1-1 [45], Expressions (6.21) to (6.29), we get

$$\lambda_{\mathrm{y}} = \frac{l_{\mathrm{y}}}{i} = \frac{1960}{55,6} = 35,3$$

$$i = \sqrt{\frac{I_{\text{fi}}}{A_{\text{fi}}}} = \sqrt{\frac{31,39\times10^6}{10164}} = 55,6\ \text{mm}$$

$$\lambda_{\text{rel,y}} = \frac{\lambda_{\text{y}}}{\pi}\sqrt{\frac{f_{\text{c,0,k}}}{E_{0,05}}} = \frac{35,3}{\pi}\sqrt{\frac{26,3}{7400}} = 0,67$$

β_{c} = 0,2 for solid wood

$$k_{\text{y}} = 0,5(1+\beta_{\text{c}}(\lambda_{\text{rel,y}} - 0,3) + \lambda_{\text{rel,y}}^2) = 0,5(1+0,2(0,67-0,3)+0,67^2) = 0,76$$

Buckling factor is

$$k_{\text{c,y}} = \frac{1}{k_{\text{y}} + \sqrt{k_{\text{y}}^2 - \lambda_{\text{rel,y}}^2}} = \frac{1}{0,76+\sqrt{0,76^2 - 0,67^2}} = 0,89$$

The design value of the axial load resistance of one stud is

$$N_{\text{d,fi}} = A_{\text{fi}} k_{c,y} f_{\text{c,d,fi}} = 10164\times0,89\times26,3 = 237908\ \text{N=238 kN}$$

Bearing capacity of the wall stud for R30 criteria is 238 kN.

According to EN 1995-1-2:2004, the maximum fulfilled R-criteria is 27,6 minutes, which is the failure time of claddings.

4.5 The effect of density on charring of timber

Paper V describes the results of investigations of relations between density and charring along the wall studs. The charring model by König [4] is described in Chapter 1.2. This is the base of the method in EN 1995-1-2 [3].

The results of this study showed that charring of timber members insulated by heat-resistant insulation could be faster in reality than the design model in EN 1995-1-2. The reason is also discussed in previous sections.

The difference in density of wood within a single wall stud has been measured as up to 41% in many cases. The charring rate can also have a wide variation within the full length of a single timber wall stud. In this study, the effect of the density of the wood is assumed to influence the charring rate by up to 20%.

Friquin [46] compares different factors affecting charring rate on her PhD thesis. The change of charring rate as a result of changing one property or factor varies greatly [46]. The difference in charring rate between different softwood species is about 12 to 28%. Schaffer [47] found an obvious relationship between the dry specific density and the charring rate of wood, where the charring rate decreases with increasing density. A study by White [48], with Engelmann spruce with 10% moisture content, shows a 22% difference in charring rate for a change in density from 343 kg/m^3 to 425 kg/m^3. My studies with Nordic spruce show the same rate. A change in density from 450 kg/m^3 to 650 kg/m^3 gives a decrease in charring rate of 20%.

The charring rate values in the usual charring model of EN 1995-1-2 are independent of density for softwood with densities above 290 kg/m^3. For hardwoods the charring rate varies linearly for densities between 290 and 450 kg/m^3.

5 CONCLUSIONS

The main results of this thesis have practical value as proposals for the modification of EN 1995-1-2.

Design equations for failure times of gypsum plasterboards are provided. Equations, based on large number of evaluated experimental results relate failure time to thickness of the board. These equations are conservative, giving sufficient safety level for wide range of existing products.

Correction of starting times of charring behind the gypsum plasterboards is proposed. Experimental data showed that charring could often start earlier behind gypsum plasterboards compared to present design method in EN 1995-1-2. The method in EN 1995-1-2 could lead to overestimated cross-sections in fire design.

A model for analysis of timber-frame walls with traditional glass wool insulation is given. This method enables to design bearing capacity of timber members insulated with traditional glass wool after falling off of protection in fire, extending the limits of design model in EN 1995-1-2. The method can also be adapted for other insulation having similar behaviour in fire characterised by surface recession.

Application of the proposed methods for typical timber frame assemblies with traditional glass wool is presented.

The design value of charring rate of timber-frame assemblies with stone wool insulation in the design model of EN 1995-1-2 should be slightly increased to have better agreement with experimental results. A new factor taking into account the influence of width of the cross-section on charring rate is proposed on the basis of recent experimental results.

The design model described in Annex C of EN 1995-1-2 can be applied for timber frame assemblies insulated with heat-resistant glass wool.

Experiments in this study showed the variability of charring rate along the tested wall studs. An indicative factor, taking into account the influence of density on charring rate, is introduced in this study.

Product standards EN 520 and EN 13162 do not provide information required for design by EN 1995-1-2. Material properties in those standards are not described and classified in the way that they can be used for practical fire safety design. Recommended way to classify different gypsum plasterboards of Type F for timber frames according to protection times, is to use the European Technical Approval procedure with certain prescribed test set-ups.

REFERENCES

[1] CPD 1988. Council Directive 89/106/CE on the Construction Products.

[2] Fontana, M., Frangi, A. Fire performance based design of multi-storey timber buildings. Proceedings of the IABSE Symposium on “Structures and Extreme Events”, Lisbon, Portugal, September 14-17, 2005, Conference Report edited by IABSE, ETH Zurich, pp 294pp.

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

[4] König, J, Walleij, L. Timber frame assemblies exposed to standard and parametric fires. Part 2: A design model for standard fire exposure. Trätek, Swedish Institute for Wood Technology Research, Report No. 0001001, Stockholm, 2000.

[5] EN 520:2004, Gypsum plasterboards – Definitions, requirements and test methods. European Committee for Standardization, Brussels, 2004.

[6] Sultan, Mohamed A and Roy-Poirier, Audrey. *NRCC-49240 Gypsum board fall-off temperature in floor assemblies exposed to standard fires.* s.l. : NRCC, 2007.

[7] Sultan, M, Lougheed, G. Results of fire resistance tests on full-scale gypsum board wall assemblies. IR-833. NRC, Canada, 2002.

[8] EN 13162:2008, Thermal insulation products for buildings - Factory made mineral wool (MW) products – Specification. European Committee for Standardization, Brussels, 2008.

[9] Frangi, A, Erchinger, C, Fontana, M, 2008, Charring model for timber frame floor assemblies with void cavities. Fire Safety Journal 43 (2008) 551–564.

[10] EN 1363-1, ISO 834. Fire resistance tests - Part 1: General requirements. European Standard. European Committee for Standardization, Brussels, 1999.

[11] Just, A., Schmid, J., König, J. The effect of insulation on charring of timber frame members. SP Report 2010:30, Stockholm, 2010.

[12] König, J, The reduced cross-section method for light timber frame construction with solid timber members. SP-Report 2009:46, Stockholm, 2009.

[13] Buchanan, Andrew H. *Structural Design for Fire Safety.* Canterbury : John Wiley & Sons Ltd., 2001.

[14] ASTM C 1396-09a. Standard specification of gypsum board. 2009.

[15] EN 15283-2:2008, Gypsum boards with fibrous reinforcement – Definitions, requirements and test methods - Part 2: Gypsum fibre boards, European Standard, CEN, Brussels, 2008.

[16] Schleifer, V, Zum Verhalten von raumabschliessenden mehrschichtigen Holzbauteilen im Brandfall. PhD Thesis No. 18156, ETH Zürich, 2009.

[17] König, J., Noren, J., Olesen, F., Hansen, T. Timber frame assemblies exposed to standard and parametric fires. Part 1: Fire tests. Trätek, Report I 9702015. Stockholm 1997.

[18] Fire Safety in Timber Buildings. Technical guideline for Europe. SP 2010:19. Stockholm.

[19] CEN/TC88. prEN ISO 9229 Thermal insulation - Definitions of terms. CEN, 2006.

[20] Coray, S., Hug, R. Brandverhalten von Dämmplatten aus Glaswolle. ETH Zürich, 2008.

[21] Tsantaridis, L., Östman, B., König, J. Short communication: Fire protection of wood by different gypsum plasterboards. Fire and Materials, 23, pp 45-48. 1999.

[22] Sultan, Mohamed A. *Gypsum board performance in fire rated floor assemblies. NRCC-50275.* s.l. : National Research Council Canada , 2008.

[23] Park S., Manzello S, Bentz D, Mizukami T, Determining thermal properties of gypsum board at elevated temperatures. Fire and materials 2010; 34:p 237-250.

[24] Benichou N, Sultan M. Thermal properties of lightweight-framed construction components at elevated temperatures. *Fire and Materials 2005*; 29, p165-179.

[25] Shipp P. Thermophysical properties of fire protection membranes – a study of Type X gypsum board. ASTM Commitee E05. Research review.

[26] Teibinger, M. et al, Feuerviderstand von Holzkonstruktionen. OIB aktuell.

March 2010.

[27] Takeda H, Kahsay F. The effects of insulation on the Fire Resistance of Wood-stud Walls. World Conference on Timber Engineering. Whistler, 2006.

[28] Richardson, L.R., McPhee R.A., Batista, M. Sound-transmission-class and fire-resistance ratings for wood-frame floors. Fire and Materials, 24, pp 17-27. 2000.

[29] Sultan M.A., Lougheed, G.D. Results of fire resistance tests on full-scale gypsum board wall assemblies. IRC internal report No.833. Ontario 2002.

[30] Schleifer, V., Frangi, A. Untersuchungen zum Raumabschluss von Bauteilen mit Isoresist 1000. ETH Zürich, 2009.

[31] Trätek, SP. *Test report P705487A.* Stockholm : SP Trätek, 2009.

[32] Trätek, SP. *Test report P705487B.* Stockholm : SP Trätek, 2009.

[33] Just, Alar. *Full scale wall tests of timber frame assemblies. Test report.* Tallinn : Tallinn University of Technology, 2009.

[34] EN 338:2008, Structural timber – Strength classes, European Standard, CEN, European Committee for Standardization, Brussels, 2008.

[35] Tera, T. Charring of timber studs insulated by heat-resistant glass wool and rock wool batts. Master thesis. Tallinn : Tallinn University of Technology, 2010.

[36] Karlsson, K., Munez, N. Failure times of gypsum claddings in standard fire. KTH. Stockholm, 2009.

[37] Just, A, Schmid, J, König, J, Gypsum plasterboards used as fire protection – Analysis of a database. SP Report 2010:28, Stockholm, 2010.

[38] Just, A, Post protection behaviour of wooden wall and floor construction completely filled with glass wool. I, SP-report 2010:28, Stockholm, 2010.

[39] Winter, S., Meyn, W. Advanced calculation method for the fire resistance of timber framed walls. Meeting of CIB-W18. Dubbendorf, Switzerland, August, 2009.

[40] Östman, B., König, J., Mikkola, E., Stenstad, V., Carlsson, J., and Karlsson, B., Brandsäkra trähus. Version 2. Trätek, Swedish Institute for Wood Technology Research, Publ. No. 0210034, Stockholm, 2002.

[41] National Annex to standard SFS-EN 1995-1-2:2004. Design of timber structures. Part 1-2: General. Structural fire design.

[42] Richardson, L., McPhee, R. Fire-resistance and Sound-transmission-class Ratings for Wood-frame Walls Fire and Materials, 20, 123-131. 1996.

[43] Schmid J, König J. Model scale fire tests of Isover Ultimate – step 1.2 – Load Bearing Capacity. SP report 2010:26. SP Trätek, Stockholm, 2010.

[44] Christman A., Siemens PLM Software NX 6 CAM A Product Review, CIMdata, 2008.

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

[46] Friquin, K.L. Charring Rates of Heavy Timber Structures for Fire Safety Design. Thesis for the degree of Philosphiae Doctor. NTNU. Trondheim, 2010.

[47] Schaffer EL. Charring rate of selected woods - transverse to grain. FPL Research Paper 69. Forest Products Laboratory: Madison, Wisconsin, USA: 1967.

[48] White, R.H. Charring rates of different wood species. PhD, University of Wisconsin-Madison. Madison, USA 1988.

Original publications

I Start of charring of timber frames behind gypsum plasterboards – Evaluation of experimental data

II Failure times of gypsum plasterboards

III Post-protection behaviour of wooden wall and floor structures completely filled with glass wool

IV Post protection effect of heat-resistant insulations on timber frame members exposed to fire

V Variability of charring along the wooden wall studs

PAPER I

Just, A., Schmid, J. (2010) Start of charring of timber frame behind gypsum plasterboards – evaluation of experimental data. *Fire Safety Journal*. (Under revision process).

Start of charring of timber frame behind gypsum plasterboards – evaluation of experimental data

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ABSTRACT

Timber frame assemblies consist of timber wall studs or floor joists and a cladding. The cavities may be void or filled with insulation. Cladding on the fire exposed side is the first and most important barrier for fire resistance. The database was collected at SP Trätek with results from more than 340 full-scale fire tests with assemblies covered by gypsum boards from different institutes all over the world, mainly from Europe. Easy-to-use rules were developed for start times of charring as a result of an extensive evaluation of available test data. The aim of the rules is to provide data for calculating start times of charring behind gypsum boards in wooden wall and floor assemblies according to EN 1995-1-2. As the test results show there is a need to decrease the times given in EN 1995-1-2 for single layer gypsum claddings.

KEYWORDS

Start time of charring, gypsum plasterboards, timber frame assemblies

SYMBOLS

GtA	gypsum board, type A
GtF	gypsum board, type F
t_f	failure time of gypsum board
$t_{f,1}$	failure time of first layer of gypsum board
t_{ch}	start of charring time
$t_{prot,i}$	protection time of cladding, layer i
h_p	thickness of cladding, 1 layer
$h_{p,tot}$	total thickness of cladding
$h_{p,red}$	reduced thickness of cladding
$h_{p,1}$	thickness of outer layer of cladding

1 INTRODUCTION

Typical timber frame assemblies consist of timber wall studs or floor joists and claddings. The cavities may be void or filled with insulation. See Figure 1. One of the main requirements in design of timber frame assemblies is safety in the case of fire.

Cladding on the fire exposed side is the first and most important barrier for fire resistance. At certain stage of fire cladding falls off. Concerning timber members, the reduction of cross-section by charring depth is the most important parameter. Development of char layer is characterized by charring rate. Charring rate changes in the course of fire. In some cases charring begins at low rate behind the protective cladding. After the cladding's fall off the charring increases to much higher rate, which is even higher than the charring rate of initially unprotected wood. The start time of charring and the failure time of boards are therefore important properties for the fire safety design of timber frame construction. See Figure 2.

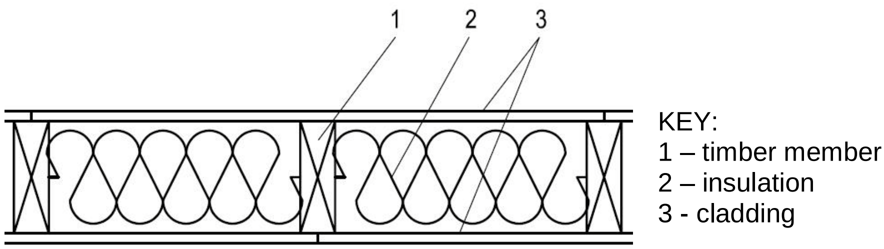


Figure 1 – Typical timber frame assembly

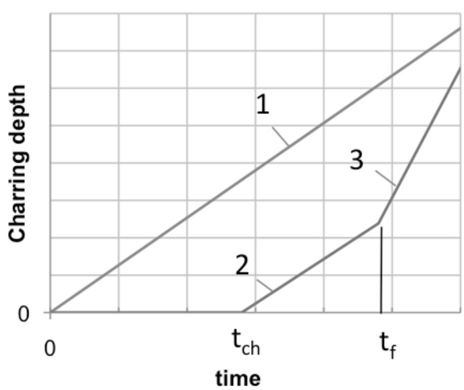
Start time of charring depends on thickness of gypsum plasterboard and a type of joints. In this study the charring is regarded to start when 300°C is reached on the surface of timber.

Design rules for analysis of fire resistance of timber frame assemblies are based on charring phenomena and are given in annexes C, D and E of EN 1995-1-2 [1]. Many experimental results from past 5 to 10 years show the tendency of earlier start time of charring compared to the rules mentioned. This can be caused by optimization of production of gypsum plasterboards, influencing the homogenity and composition of the boards. Consequently, following the present EN 1995-1-2 [1] rules may lead to unsafe design results.

A new method developed in ETH [2] provides rules for calculation of protection times which can be interpreted as start times of charring. The method leads to similar results with EN 1995-1-2.

European standard of gypsum plasterboards – EN 520 [3] – gives fire performance criteria for gypsum plasterboards. Requirements can be fulfilled by different products of different quality. But unfortunately, the regulated fire protection properties are not applicable to design of timber frame assemblies.

The aim of the present paper is to propose conservative design rules based on experimental results which consider wide range of products of gypsum plasterboards.



KEY:
1 - unprotected members
2,3 – initially protected members
2 – protected phase; charring starts at t_{ch} at a reduced rate when protection is still on place
3 – post-protection phase
charring continues at increased rate when protection is fallen off

Figure 2 – Charring of timber studs with and without protection

2 GYPSUM PLASTERBOARDS

Raw materials for gypsum plasterboards are gypsum, paper and additives. The gypsum core consists of natural gypsum, industrial gypsum and/or recycled plasterboards. The difference between the two gypsum types is that the industrial gypsum has smaller crystals than the natural gypsum. Both have the identical chemical composition. Producers of gypsum boards do not specify whether their boards are made of natural or industrial gypsum, but it may have influence to the properties in fire.

According to EN 520 [3] there are many types of gypsum plasterboards.

Gypsum plasterboard, type A (GtA) is a common board with porous gypsum core and no reinforcement except the paper laminated surface.

Gypsum plasterboard, type F (GtF) is a fire protection board with improved core cohesion at high temperatures. This type of boards contain glass fibres which control shrinkage, causing a maze of fine cracks rather than a single large crack which can initiate premature failure of regular board. One of the most critical aspects of fire-resisting gypsum board is the extent to which the glass fibre reinforcing can hold the board together after gypsum has dehydrated, to prevent the board pulling away from nailed or screwed connections when the board shrinks.

According to [3] there are also other types of gypsum plasterboards classified. For example type D with density over 800 kg/m^3, type H with water resistance properties etc.

Gypsum plasterboards have usually thickness from 9 to 30 mm.

Gypsum is a non-combustible material and gives no contribution to fire. Gypsum works as a built in sprinkler. One square meter of a 12,5 mm gypsum board contains approximately 2 liters of crystallized water in the gypsum core. Its high water content provides up to 90% of the fire-resistance capacity of gypsum boards. The calcination process takes place when the gypsum is exposed to heat at a temperature of at least 80°C and this water prevents the fire to penetrate the board during the evaporation. The calcination process is for the most part complete when the gypsum board reaches a temperature of 125 °C and becomes an anhydrate. This process requires much energy and time. Complete dehydration does not occur until the temperature reaches about 700 °C, requiring additional energy input [4].

In Figure 3 the comparison of temperature rise behind 12,5 mm thick gypsum plasterboard, type A and 15 mm thick gypsum plasterboard, type F is shown. Start time of charring depends mainly on thickness not on type (see 300 °C, Figure 3).

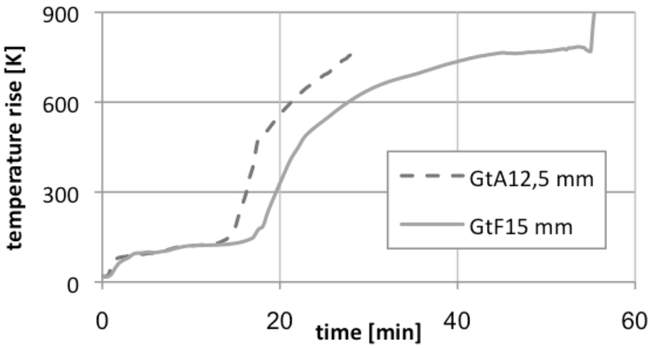


Figure 3 – Temperature rise behind gypsum claddings type A and F in standard fire test (example)

3 DESIGN MODEL OF CHARRING OF PROTECTED MEMBERS

Rules for fire design of wall and floor assemblies insulated by stone wool and glass wool are given in annex C of EN 1995-1-2 [1].

Unprotected members start to char immediately when exposed to fire. For protected members there is no charring until 300ºC is reached behind a protection. Then slow charring starts and continues until failure of the protection when fast charring begins, see Figure 2. In general for the design of fire resistance of timber member the original cross-section is to be reduced by the charring depth.

Start time of charring is the time when charring of wood starts behind the cladding. In this study start time of charring is taken as time of reaching 300ºC on wooden surface behind cladding. The principle is according to [1].

3.1 DESIGN PROCEDURE BY EN 1995-1-2

For narrow sides of timber floor and wall elements with void cavities and with insulation, the start time of charring is counted as follows [1]:

For claddings consisting of one layer of gypsum plasterboard of type A or F according to [3], at internal locations or at the perimeter adjacent to filled joints, or unfilled gaps with a width of 2 mm or less, the time of start of charring t_{ch} should be taken as:

$$t_{ch} = 2{,}8\ h_p - 14 \quad (1)$$

At locations adjacent to joints with unfilled gaps with a width of more than 2 mm, the time of start of charring t_{ch} should be calculated as

$$t_{ch} = 2{,}8\ h_p - 23 \quad (2)$$

Since other types of gypsum plasterboard have equal or better thermal and mechanical properties than gypsum plasterboard of type A, the expressions for the calculation of start of charring of gypsum plasterboard type A may be conservatively used for those types. Although not explicitly stated, the same applies to gypsum plasterboard of type F.

EN 1995-1-2 also provides information on the start of charring where two layers of gypsum plasterboard are attached to the timber member. In the case of cladding where both layers are of Type A, the contribution of the inner layer is reduced by taking into account only 50% of its thickness since, after failure of the outer layer, the inner layer is already preheated and has partially calcined and is exposed to a higher temperature.

In the case of cladding where two layers of different quality, e.g. Type F and Type A are attached to the timber member, it is important that the better quality (Type F, in this example) is used as the outer layer, while the contribution of the inner layer (Type A) is reduced by taking into account only 80 % of its thickness. If the outer layer is of Type A, and the inner layer of Type F, it should conservatively be assumed that both layers are of Type A.

3.2 ADAPTED DESIGN METHOD FOR SEPARATING FUNCTION

New method for design of separating function of the wall and floor assemblies in fire is worked out. Research work has been carried out at ETH [2] to study the fire protection abilities of different materials, which is based on extensive experimental results and finite - element thermal analysis

The developed design method is based on the additive component method given in EN 1995-1-2. The total fire resistance is therefore taken as the sum of the contributions from the different layers (claddings, void or insulated cavities), considering different heat transfer paths and according to their function and interaction.

The method can be used also for calculating start of charring time.

$$t_{\mathrm{ch}} = \sum t_{\mathrm{prot,i}} \tag{3}$$

where $\Sigma t_{\mathrm{prot,i}}$ is the sum of protection times of *i* layers protecting timber members.

Protection time of the cladding is assumed to be satisfied in this method where the average temperature rise over the whole exposed surface of the particleboard is limited to 250K, and the maximum temperature rise at any point on that surface does not exceed 270K.

The method gives similar values as the EN 1995-1-2, see Figure 5.

4 DATABASE OF TEST RESULTS

A database with data from full-scale fire tests was collected at SP Trätek [5] to create necessary design rules for fire safety design of timber structures with gypsum boards. The database consists of results from more than 340 full scale tests from different institutes all over the world, mainly from Europe. All full-scale tests in the database were tested under standard fire conditions according to EN 1363-1 [6].

Parameters recorded in the database are the following:

1. General test data – date, report number, fire exposion sides, loading.
2. Frame structure – height, span, stud material and cross-section, distance, nogging structure.
3. Insulation – type, density, thickness.
4. Cladding – producer, type, orientation, thickness, density, edge shape, fastener parameters, resilient channels.
5. Observations – failure time, thermocouple readings.

Database is still an increasing. Not all data from every test have been available. There are 342 full-scale test results in the database provided by 13 countries.

According to type of structure and the data of gypsum boards, the database consists of following structures and claddings:

Walls	189
Floors	153
GtA	72
GtF	233
others	37

5 EVALUATION OF THE DATABASE

Collected data show that gypsum plasterboards of similar types have large scatter of performance properties in fire. The charring behind gypsum boards often starts earlier than stated in present EN 1995-1-2 [1] which leads to unsafe results. This can be caused by less homogeneity of gypsum plasterboards compared to the past due to optimizing cost and content of the boards. Therefore there is a clear need to decrease the design value of the time of start of charring.

Start times of charring behind gypsum boards from the full-scale fire tests are shown in Figures 5 to 10 and tables 1 and 2. The equations derived in this work provide design values for start times of charring remaining below the values from all the relevant tests to ensure safe results. In Figure 5 the equation for start time of charring derived in this work is compared to equations of EN 1995-1-2 and improved method [2]. Compared to the safe design method based on the database to the methods of EN 1995-1-2 [1] and ETH [2] are too optimistic for one layer claddings to take large variety of products into account, see Figure 5.

For structures with 2 layers the important issue is the fall-off of the first layer. If charring behind the second layer starts before the first layer has fallen off, the similar design rules can be given for gypsum plasterboards type F and type A. If charring starts after the first layer has fallen off, the design rule for start time of charring should include failure time of the first layer. Differences between failure times of the first layer and start time of charring are shown in Figures 7 and 8. For GtA the difference can be conservatively taken as 11 minutes. For GtF the fall off of the first layer and start time of charring can be conservatively regarded to occur at the same time.

Safe design equations for failure of the first layer of gypsum plasterboards, type A and type F in wall and floor structures are presented in Figures 9 and 10.

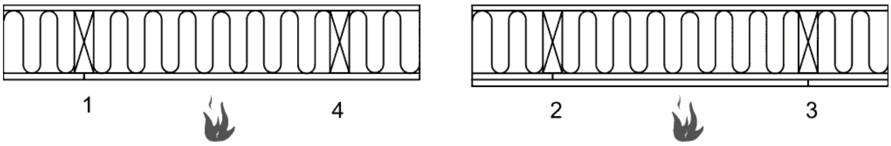


Figure 4 – Joint types by EN 1995-1-2 [1]

In the diagrams of start of charring (Figure 5 to Figure 10) the influence of joints is shown. See Figure 4 for explanation of joint types. Unfortunately, there is no information about joints for every case. Therefore this paper does not deal with different joint types and provides united equations for all joint types.

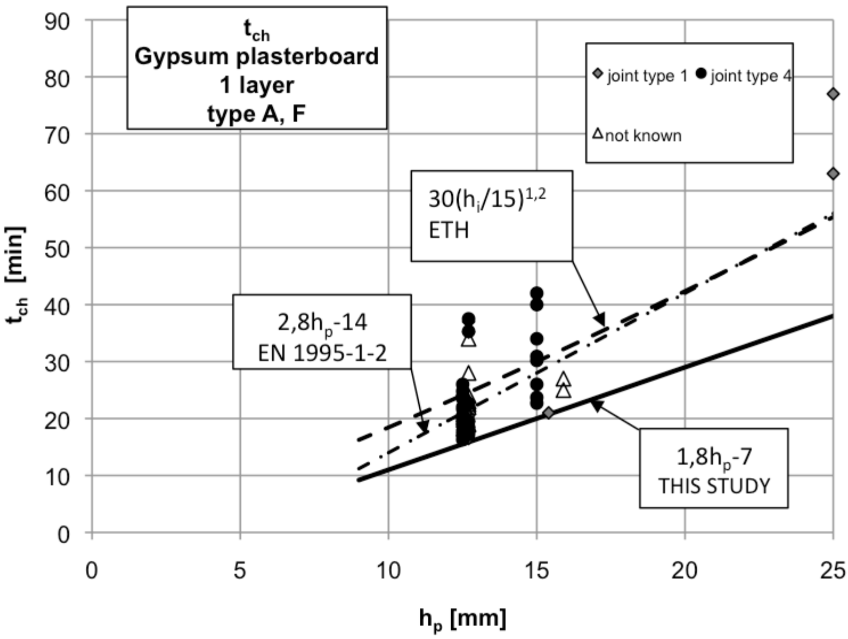


Figure 5 – Start time of charring for cladding of one layer of gypsum plasterboard. Equation provided by this work is compared to other methods.

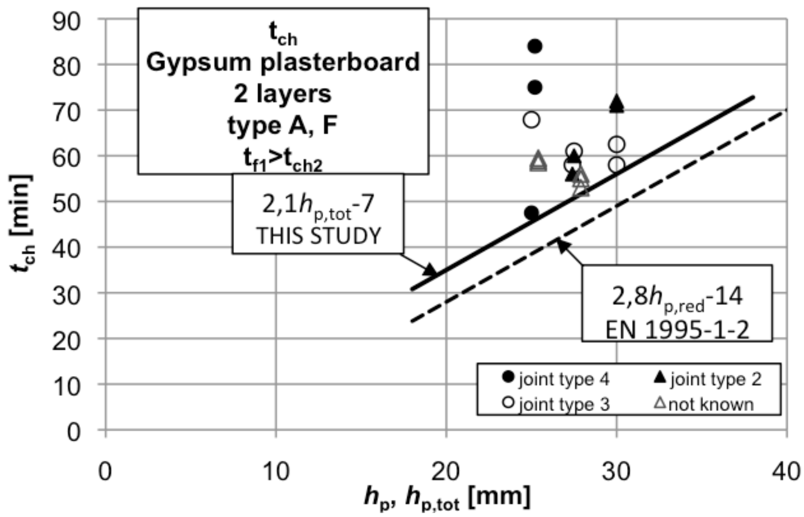


Figure 6 – Start time of charring for cladding of two layers of gypsum plasterboards when first layer does not fall off before the charring starts. Equation provided by this work is compared to EN 1995-1-2.

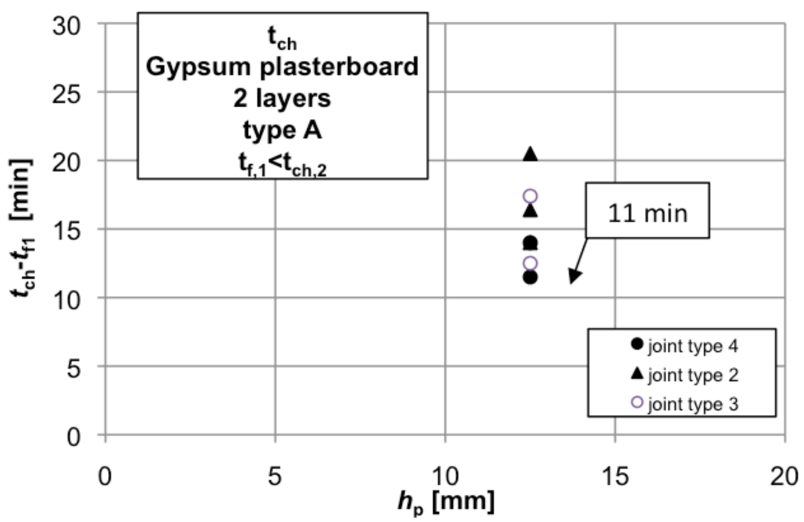


Figure 7 – Start time of charring after fall off of first layer for gypsum plasterboard type A

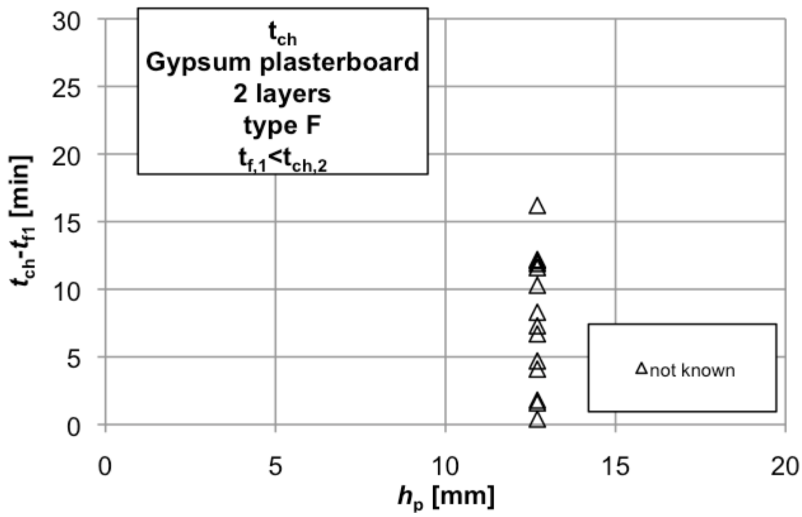


Figure 8 – Start time of charring after fall off of first layer for gypsum plasterboard type F

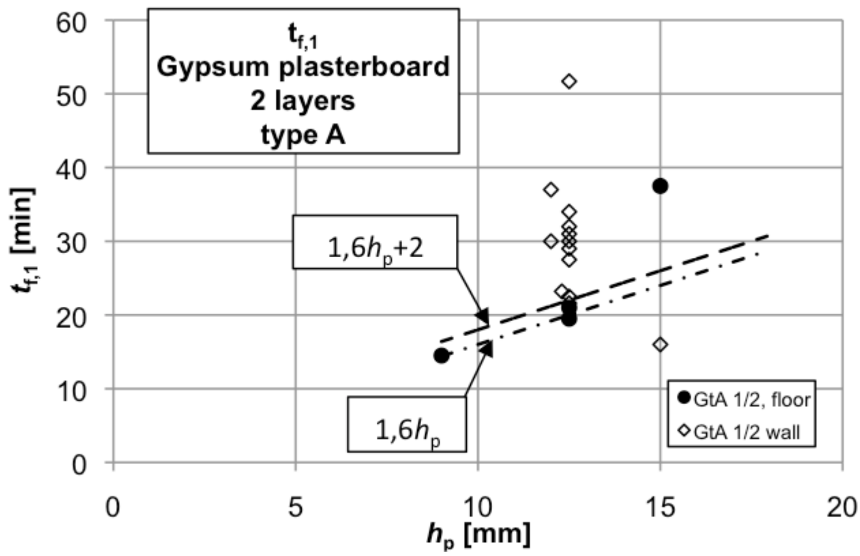


Figure 9 – Fall off of first layer of two for gypsum plasterboards type A. Equations provided for wall and floor structures by this study.

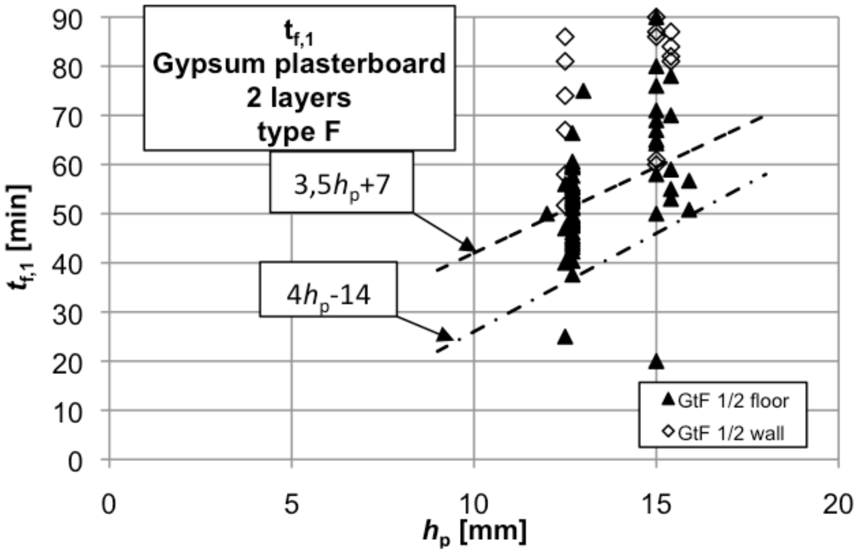


Figure 10 – Fall off of first layer of two for gypsum plasterboards type F. Equations provided by this study.

Based on the database the safe design equations with the limitations of use are shown in

Table 2 and Table 3. The limitations of thickness come from the available test data.

Table 2 – Design equations for start of charring time t_{ch}

Cladding	**Walls, Floors**	
Type A, F one layer	$1{,}8 h_p - 7$ (4)	$9\text{ mm} \leq h_p \leq 18\text{ mm}$
Type A, F two layers $t_{f,1} > t_{ch,2}$	$2{,}1 h_{p,tot} - 7$ (5)	$25\text{ mm} \leq h_{p,tot} \leq 31\text{ mm}$
Type F two layers $t_{f,1} < t_{ch,2}$	$t_{f,1}$ (6)	$25\text{ mm} \leq h_{p,tot} \leq 31\text{ mm}$
Type A two layers $t_{f,1} < t_{ch,2}$	$t_{f,1} + 11$ (7)	$25\text{ mm} \leq h_{p,tot} \leq 31\text{ mm}$

Table 3 – Design equations for failure time of first layer $t_{f,1}$

Cladding	Walls		Floors	
Type F $t_{f,1}$	$3,5h_{p,1}+7$ (8)	9 mm $\leq h_p \leq$ 18 mm	$4h_{p,1}-14$ (9)	9 mm $\leq h_p \leq$ 18 mm
Type A $t_{f,1}$	$1,6h_{p,1}+2$ (10)	9 mm $\leq h_p \leq$ 18 mm	$1,6h_{p,1}$ (11)	9 mm $\leq h_p \leq$ 18 mm

For structures with 2 layers the important issue is the fall-off of first layer. If charring behind the second layer starts before the first layer has fallen off, the similar design rules can be given for GtF and GtA.

If the charring starts after the first layer has fallen off, then the design rule for start time of charring depends on the failure time of first layer.

6 CONCLUSIONS

Scatter of start times of charring is quite large due to different properties influencing the fire protection ability of gypsum plasterboards. No significant influence of joint type has been considered relevant to the start times of charring.

On the basis of test results it can be concluded that start times of charring for gypsum plasterboards given in EN 1995-1-2 are too optimistic for single layer claddings.

Design equations derived in this paper are suited for design method of timber frame assemblies presented in EN 1995-1-2 and are conservatively valid for all products under consideration.

For specific products with better performance, producers may give higher values of start times of charring, if relevant proofs are supplied. For application of this principle, common standard procedures should be developed.

7 REFERENCES

[1] EN 1995-1-2:2004, Eurocode 5: Design of timber structures - Part 1-2: General rules-structural fire design. European Standard. European Committee for Standardization, Brussels, 2004.
[2] Schleifer, V. Zum Verhalten von raumabschliessenden mehrschichtigen Holzbauteilen im Brandfall. PhD Thesis No.18516. Zürich : ETH, 2009.
[3] EN 520:2004, Gypsum plasterboards. Definitions, requirements and test methods, European Committee for Standardization, Brussels, 2004.
[4] Sultan, M. Gypsum board performance in fare rated floor assemblies, NRCC-50275, National Research Council Canada, Ottawa, 2008.
[5] Just, A.,Schmid, J., König, J. Gypsum plasterboards used as fire protection – analysis of a database. SP report, Sockholm, Sweden, 2010.
[6] EN 1363-1, ISO 834. Fire resistance tests – Part 1: General requirements. European Standard. European Committee for Standardization, Brussels, 1999.

II

PAPER II

Just, A., Schmid, J., König, J. (2010) Failure times of gypsum plasterboards.

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FAILURE TIMES OF GYPSUM PLASTERBOARDS

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ABSTRACT

Gypsum plasterboards are widely used for wall and floor assemblies but very little information is given for the failure times of gypsum plasterboards in fire in EN 1995-1-2 and standards for gyspum plasterboards.

The failure time of board is an important property for the fire safety design of timber frame constructions. Charring rates of wooden studs are significantly different before and after the failure of protective cladding. The residual cross section of timber member is a decisive factor for the design of load bearing capacity (R).

Since fall-off is a failure which can't be calculated using finite element programs due to the complex failure mechanism, easy-to-use rules were developed as a result of an extensive evaluation of available test data. Furthermore different build-ups and fixings were taken into account since failure is not only a question of the cladding itself. The presented rules are a worst case approach to the failure times. The given equations provide design failure times remaining below the failure times from all the relevant tests except those that differ very much from the rest.

A database with data from full-scale fire tests was collected at SP Trätek[1] to create necessary design rules for fire safety design of timber structures with gypsum boards. The database consists results from more than 340 full scale tests from different institutes all over the world, mainly from Europe.

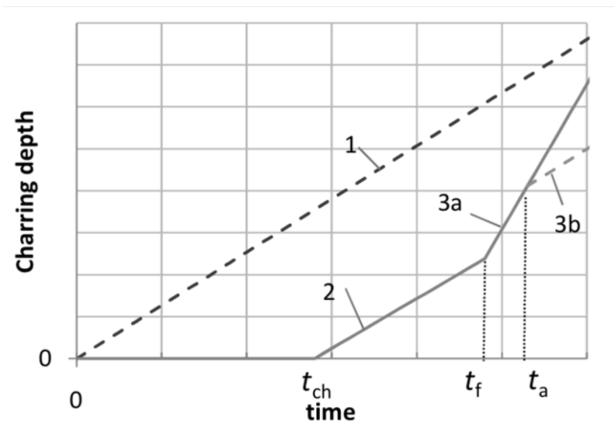
The aim of the rules in this paper is to provide conservative way for calculating failure times of gypsum boards in wooden wall and floor assemblies according to EN 1995-1-2[2]. This conservative way is needed when manufacturers of gypsum boards do not provide necessary data for design.

CHARRING OF PROTECTED MEMBERS OF TIMBER FRAME ASSEMBLIES

Timber frame assemblies are usually built up of the timber frame, with the cladding attached to each side of the timber frames. The cavities in-between the frame members may be void or partially or completely filled with insulation. Since the timber frame is sensitive to fire exposure, it must be effectively protected against fire.

In the design and optimization of a timber frame assembly with respect to maximizing fire resistance, there exists a hierarchy of contribution to fire resistance of various layers of the assembly. The greatest contribution to fire resistance is obtained from the cladding on the fire-exposed side that is first directly exposed to the fire, both with respect to insulation and failure (fall-off) of the cladding. In general, it is difficult to compensate for poor fire protection performance of the first cladding layer by improved fire protection performance of the following layers.

Figure 1. Charring of timber studs with and without protection.



1- Unprotected members
2,3 - Initially protected members
2 - Charring starts at t_{ch} at a reduced rate when protection is still in place
3a - After protection has fallen off, charring continues at increased rate
3b - Char layer acts as a protection and charring rate decreases

EN 1995-1-2[2] gives rules how to calculate fire resistance (R, E, I) for timber framed walls and floors. For the design of load bearing capacity (R) the residual cross section is one of the decisive factors. Charring rates of wooden studs are significantly different before and after the failure of protective cladding. Charring of protected wooden member can start before the failure of cladding. Charring rate of wood is much slower in this protected stage compared to charring of initially unprotected wood. After the claddings fall off the charring increases to much higher rate than the charring rate of initially unprotected wood. The start of charring time and the failure time of boards are therefore important properties for the fire safety design of timber frame construction.

Rules for fire design of wall and floor assemblies insulated by stone wool and glass wool are given in annex C of EN 1995-1-2:2004[2]. See Figure 1.

The start of charring time t_{ch} is predictable using design method in EN 1995-1-2:2004[2]. Failure time t_f of gypsum cladding is often determined by fire tests.

GYPSUM PLASTERBOARDS

Raw materials for gypsum plasterboards are gypsum, paper and additives. The gypsum core consists of natural gypsum, industrial gypsum and/or recycled plasterboards.

There are many types of gypsum plasterboards classified according to EN 520[3]. In the EN 1995-1-2:2004[2] the three main types are mentioned.

Type A – regular common boards with porous gypsum core and no reinforcement except the paper laminated surface. When referring to this board or similar the abbreviation GtA is used.

Type H – regular board with high water resistance properties. The boards are behaving similarly with GtA in fire and are therefore held similarly. When referring to this board the abbreviation GtA is used as well.

Type F – fire protection board with improved core cohesion at high temperatures. When referring to this board or similar the abbreviation GtF is used.

Fire protection gypsum boards contain glass fibres which control shrinkage, causing a maze of fine cracks rather than a single large crack which can initiate premature failure of regular board. One of the most critical aspects of fire-resisting gypsum board is the extent to which the glass fibre reinforcing can hold the board together after the gypsum has dehydrated, to prevent the board pulling away from nailed or screwed connections when the board shrinks. Shrinkage can be reduced with various additives such as vermiculite.

In North America gypsum boards, Type X are commonly used as fire protection and are similar to the European GtF boards. In this study the test results with type X boards are handled as GtF boards.

According to EN 520[3] there are also other types of gypsum plasterboards classified. For example Type D with density over 800 kg/m^3. Gypsum plasterboards have usually thickness from 9 to 30 mm. Fire rated gypsum boards (GtF) are to be tested according to EN 520. However this test is not relevant to qualify thermo-mechanical properties such as fall-off times for design of timber frame assemblies.

Behaviour of gypsum plasterboards in fire

Gypsum is a non-combustible material and gives no contribution to fire. Gypsum works as a built in sprinkler. One square meter of a 12,5 mm gypsum board contains approximately 2 liters of crystallized water in the gypsum core. Its high water content provides up to 90% of the fire-resistance protection of gypsum boards. According to Sultan et al[5] the calcination process takes place when the gypsum is exposed to heat at a temperature of at least 80 °C and this water prevents the fire to penetrate the board during the evaporation. The calcination process is for the most part complete when the gypsum board reaches a temperature of 125 °C and becomes an anhydrate, $CaSO_4$. This process requires much energy and time.

FAILURE TIME

Regular gypsum board can fall off a wall or ceiling as soon as the gypsum plaster has dehydrated, at about the same time as charring of the timber studs begins. Boards with glass fibre reinforcing and closely spaced fixings will not fall off until the glass fibres melt, when the entire board reaches a temperature of about 700 ºC[4].

Sultan et al[6] have found that the temperature of gypsum board at the first piece fall-off is not an appropriate criterion for gypsum board failure, as it varies too extensively from assembly to assembly with no identifiable correlation to assembly parameters. In the present study we have nearly no information about failure of the last piece.

Failure time or *fall-off time* of cladding in the present study is the time from test start when at least 1% of the board area has fallen down (author’s definition). Generally the whole board is falling off in a short period after that first piece.

The failure time of cladding made of gypsum plasterboard is a combination of two types of failures:

- thermal degradation of the cladding;
- pull-out failure of fasteners due to insufficient penetration length into unburnt wood.

Existing design rules give simplified solution for calculation of pull-out failure. Failure times caused by thermal degradation are generally not available. Since the thermo-mechanical properties of gypsum plasterboard Type F are not part of the classification given in EN 520 – the European product standard for gypsum plasterboards[3] – even failure times of different batches may vary considerably. According to EN 1995-1-2[2] it is expected that the producer should declare failure times determined on test basis, including information on spacing of joists, studs, battens etc as well as edge distances and spacing of fasteners. For the time being, the European system of CE-marking does not include such information. It is important that the failure times of gypsum plasterboards should be related to thermo-mechanical degradation of the boards, i.e. issues such as position (horizontal or vertical), span and edge distances of fixings (screws, nails, staples). Related literature as well as national annexes of EN 1995-1-2[2] gives some values for failure times of gypsum cladding but knowledge is restricted and some given rules are dubious.

Pull-out failure of fasteners due to charring behind the cladding should be verified by the designer; expressions for this failure type are only given for screws: it is required that the minimum penetration length into uncharred wood is 10 mm.

DATABASE OF GYPSUM BOARDS

A database with data from full-scale fire tests was collected at SP Trätek[1] to create necessary design rules for fire safety design of timber structures with gypsum boards. The database contains results from more than 340 full scale tests from different institutes all over the world, mainly from Europe. This article is based on data which was collected to the database until April 2010. The amount of data is still increasing continuously.

Parameters recorded in the database are the following:

6. General test data – date, report number, fire curve, fire exposion sides, loading.
7. Frame structure – height, span, stud material and cross-section, distance, nogging structure.
8. Insulation – type, density, thickness.
9. Cladding – producer, type, orientation, thickness, density, edge shape, fastener parameters, resilient channels.
10. Observations – failure time, thermocouple readings.

Test results are provided by the following countries (number of tests in the brackets): Austria (22), Canada (62), Denmark (13), Germany (22), Estonia (6), Finland (3), France (42), Netherlands (2), New Zealand (6), Norway (5), Sweden (136), Slovenia (2), UK (32).

The database consists of 189 walls and 153 floors. The division according to types of plasterboards is: GtF (233), GtA (72).

Analysis of the database

Since fall-off is a failure which can't be calculated using finite element programs due to the complex failure mechanism, easy-to-use rules were developed as a result of an extensive evaluation of available test data. Furthermore different build-ups and fixings were taken into account since failure is not only a question of the cladding itself. The presented rules are a worst case approach to the failure times. The given equations provide design failure times remaining below the failure times from all the relevant tests except those that differ very much from the rest, so called outliners.

Data in the database show that gypsum plasterboards of same types have a very large scatter of performance properties in fire. The charring behind gypsum boards often starts earlier than stated in present EN 1995-1-2[2]. This is probably caused by less homogeneity of gypsum plasterboards compared to the past due to optimizing cost and content of the boards.

The aim of the rules provided in this article is to give conservative approach to consider high range of gypsum plasterboards in wooden wall and floor assemblies according to EN 1995-1-2. As an alternative to the conservative equations, producers should declare protection times of their specific products to extend the protection phase given in EN 1995-1-2.

Failure times of gypsum boards from the full-scale fire tests are shown in figure 2 and figure 3. Resulting equations are given in table 1. In general, failure times of gypsum boards of floors (ceilings) are shorter compared to walls due to the self-weight.

The reason of failure is not always possible to read out from test reports. Some of the test results of failure times presented here may be not caused by thermal degradation of plasterboard (e.g. by pull-out of fasteners). To find the design failure time, the values according to the proposed rules according to this study and values due to pull-out of fasteners according to EN 1995-1-2:2004[2] should be calculated and minimum selected.

Figure 2. Equations for failure times of wall claddings of gypsum plasterboards type A (left) and type F (right).

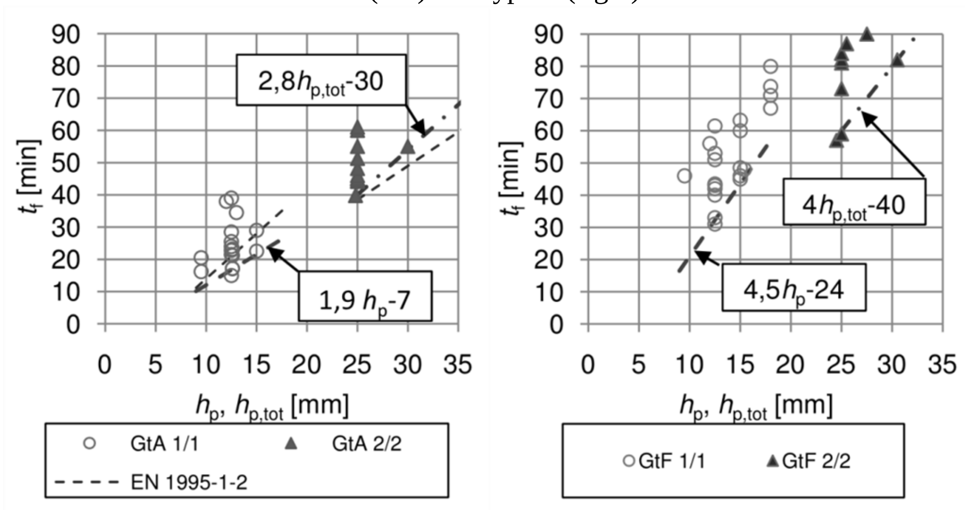
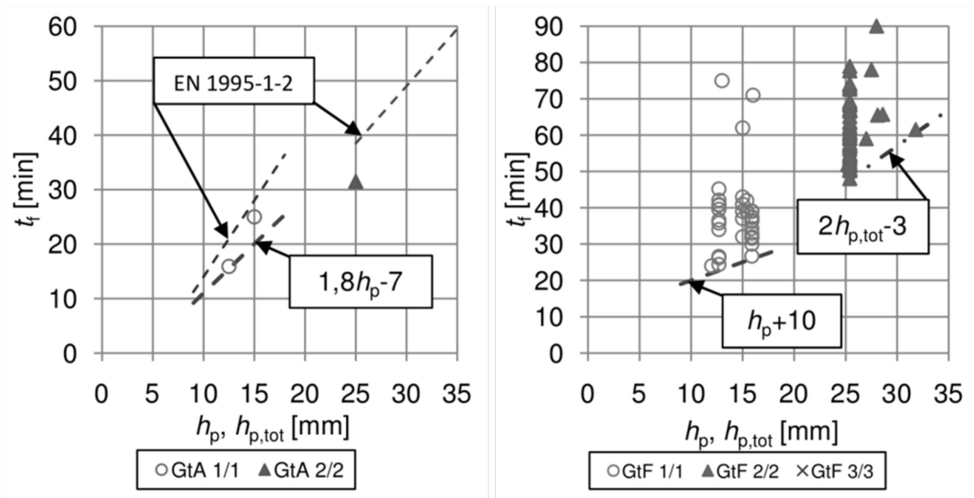


Figure 3. Equations for failure times of floor claddings of gypsum plasterboards type A (left) and type F (right).



The database consists of test walls with timber studs and steel studs. Difference of failure times can not be seen. According to test results in database it can be stated that the failure times of gypsum boards on steel studs and on wooden studs are similar. A distance between floor beams or resilient channels can be neglected when creating conservative equations. However the use of the results presented here are restricted to a spacing of 600 mm.

There is a difference in failure times of gypsum plasterboards backed by insulation and void cavity. In the worst case approach in present study the difference can be neglected.

Full scale tests in database show that failure of gypsum board type A occurs often earlier compared to existing design values according to EN 1995-1-2:2004. There is not sufficient data for failure times of claddings for floors, consisting two or three layers of gypsum plasterboards, type A. All data with two-layer claddings with gypsum plasterboard type F on fire exposed side backed by gypsum plasterboard type A have all showed the failure of two layers at the same time.

Table 1. Design equations for failure times t_f.

Cladding	**Walls**		**Floors**	
Type F, one layer	$4,5h_p - 24$	9 mm ≤ h_p ≤ 18 mm	$h_p + 10$	12,5 mm ≤ h_p ≤ 16 mm
	57	h_p> 18 mm	26	h_p> 16 mm
Type F, two layers	$4h_{p,tot} - 40$	25 mm ≤ $h_{p,tot}$ ≤ 31 mm	$2h_{p,tot} - 3$	25 mm ≤ $h_{p,tot}$ ≤ 31 mm
	84	$h_{p,tot}$ ≥ 31 mm	59	$h_{p,tot}$ ≥ 31 mm
Type F + Type A[a]	81	h_p ≥ 15 mm[b]	50	h_p ≥ 15 mm[b]
Type A, one layer	$1,9h_p - 7$	9 mm ≤ h_p ≤ 15 mm	$1,8h_p - 7$	12,5 mm ≤ h_p ≤ 15 mm
	21,5	h_p> 15 mm	20	h_p> 15 mm
Type A, two layers	$2,1h_{p,tot} - 14$	25 mm ≤ $h_{p,tot}$ ≤ 30 mm	-[c]	
	49	$h_{p,tot}$ ≥ 30 mm		

[a] Outer layer Type F, inner layer type A
[b] Thickness of first layer (Type F)
[c] No data available.

CONCLUSIONS

The variety of properties influencing the fire protection ability of different products of gypsum plasterboards is very large. No significant influence of stud material and insulation has been found relevant to the minimum failure times.

Design equations presented in this paper give information on failure times for design of timber frame assemblies according to EN 1995-1-2:2004[2].
Producers should give failure times of their specific products if their products have better values. There is a need for common procedure for that.

The work with the database[1] is an ongoing process and producers are still asked to give access to further reports.

REFERENCES

[1] Just, A., Schmid, J., König, J., Gypsum plasterboards used as fire protection – analysis of a database, SP report, Stockholm, Sweden, 2010

[2] EN 1995-1-2:2004, Eurocode 5: Design of timber structures - Part 1-2: General rules-structural fire design, European Committee for Standardization, Brussels, 2004.

[3] EN 520:2004, Gypsum plasterboards. Definitions, requirements and test methods, European Committee for Standardization, Brussels, 2004.

[4] Buchanan, A., Structural Design for Fire Safety, John Wiley & Sons Ltd., Canterbury, New Zealand, 2001.

[5] Sultan, M., Gypsum board performance in fire rated floor assemblies, NRCC-50275, National Research Council Canada, Ottawa, Canada, 2008

[6] Sultan, M., Roy-Poirier, A. Gypsum board fall-off temperature in floor assemblies exposed to standard fires, NRCC-49240, National Research Council Canada, Ottawa, Canada, 2007.

III

PAPER III

Just, A. (2010) Post protection behaviour of wooden wall and floor structures completeley filled with glass wool.

Structures in Fire: *Proceedings of the 6th international conference*. *East Lansing, USA. June 2nd to 4th, 2010*. pp 584–592

Structures in Fire 2010
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Post protection behaviour of wooden wall and floor structures completeley filled with glass wool

Alar Just

1. ABSTRACT

The use of glass wool insulation in timber frame houses is popular because of it's elasticity, sound and thermal insulation properties. Since fire design is an important part of the design procedure EN 1995-1-2 [1] gives rules for timber design in fire. Based on experiences of fire tests design rules are different for stone wool and glass wool even if differences are not specified in standards for mineral wool. Annex C of EN 1995-1-2:2004 gives design rules for walls and floors insulated by mineral wool. While for stone wool insulated construction a post protection phase is considered, constructions filled with glass wool are counted to fail directly after the failure of the cladding. There exists a design method for wall and floor assemblies with void cavities for this post protection phase.

This paper presents a design method for post protection behavior of timber frame assemblies insulated by glass wool insulation. It is based on non-load bearing small-scale tests at SP Trätek and full scale tests at TÜV Estonia at standard fire exposure according to EN 1363-1 [2]. Considering start of charring at 300 °C recession of glass wool insulation was measured during tests as a basic parameter for the presented method. Frangi et al [3] introduced a post protection study of floors with void cavities to complete the calculation model in EN 1995-1-2:2004 [1].

According to the method of this paper fire resistance of glass wool insulated walls and floors should be calculated similarly to stone wool insulated constructions according to existing rules during the protected phase. The proposed design model takes into account 3 phases: protected phase, recession phase and finally post protection phase similarly to design of timber frame assemblies with void cavities.
In the future this method is imaginable for other recessible insulations for example cellulose fibers, wood wool and -fiber and other natural insulation products where the recession rate can be defined by fire tests.

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2. INTRODUCTION

Timber frame assemblies are normally built up of the timber frame (floor joists or wall studs) and a cladding attached to each side of the timber. The cavities may be void or partially or completely filled with insulation. Since the timber frame is sensitive to fire exposure, it must be effectively protected against fire. The greatest contribution to fire resistance is obtained from the membrane (layer) on the fire-exposed side first directly exposed to the fire, both with respect to insulation and failure (fall-off) of the membrane. In general, it is difficult to compensate for poor fire protection performance of the first membrane by improved fire protection performance of the following layers.

In small-sized timber frame members, e.g. floor joists or wall studs in assemblies with void cavities, increased charring takes place after failure of the cladding. However, the timber member will normally collapse before reaching the consolidation phase with a char depth of 25 mm. Such conditions are described in Annex D of EN 1995-1-2 [1].

For small-sized timber frame members in assemblies with cavity insulation, charring mainly takes place on the narrow, fire-exposed side. Since there is a considerable heat flux through the insulation to the sides of the member during the stage after failure of the lining (provided that the cavity insulation remains in place), the effect of increasing arris rounding becomes dominant and no consolidation of the charring rate is possible.

For the stage before failure of the cladding (protection phase $t \leq t_f$), both stone wool and glass wool insulation perform approximately equally. However, once the cladding has fallen off and the insulation is directly exposed to the fire (post-protection phase $t \geq t_f$), glass wool insulation will undergo decomposition, gradually losing its protecting effect for the timber member by surface recession. Stone wool insulation will continue to protect the sides of the timber member facing the cavity. It is assumed that insulation remains in place.

Immediate failure of the assembly with glass wool by EN 1995-1-2:2004 [1] is a conservative assumption. From full-scale wall tests it is known that it will take some time until the glass wool insulation has completely recessed once it has been directly exposed to the fire.

The aim of the article is to give design rules for post protection phase of wooden floor and wall assemblies insulated with traditional glass wool.

3. GLASS WOOL

Glass wool is a mineral wool manufactured predominantly from natural sand or molten glass [4].

After the fusion of different raw mineral materials at 1450 °C, the liquid glass produced is converted into wool (mixture of fibers). Stable dimensions, cohesion and mechanical strength of the product is obtained by the addition of a binder. Most of the fiber intersections are “blocked” by a drop of binder. This wool is then heated above 200 °C to polymerize the binder. During that stage, the wool is calendared to give it strength and stability. The final stage involves cutting the wool and packing it in rolls or panels (with or without compression) before palletizing the finished product in order to facilitate transport and storage. Densities of glass wool insulations, used in timber structures, are usually 14 to 20 kg/m^3.

Traditional glass wool is sensitive for high temperatures standard fire. When temperature rises over more than 500 °C, there will be a fast recession of traditional glass wool insulation. This will occur usually after the cladding failure.

4. CHARRING OF WALL AND FLOOR STUDS

Rules for fire design of wall and floor assemblies insulated by mineral wool are given in annex C of EN 1995-1-2:2004 [1], see Figure 1.

For larger cross-sections the time limit t_a exists. After that the charring rate is similar to charring of unprotected timber because of protective properties of char layer. For smaller floor and wall studs the protective char layer cannot be developed because of too small dimensions and two dimensional heat flux subsequently. Thus the time limit t_a cannot be used and high charring rate is valid until the end.

For timber members protected by claddings on the fire-exposed side, the notional charring rate is calculated as (equations (C.1) and (C.2) at [1]:

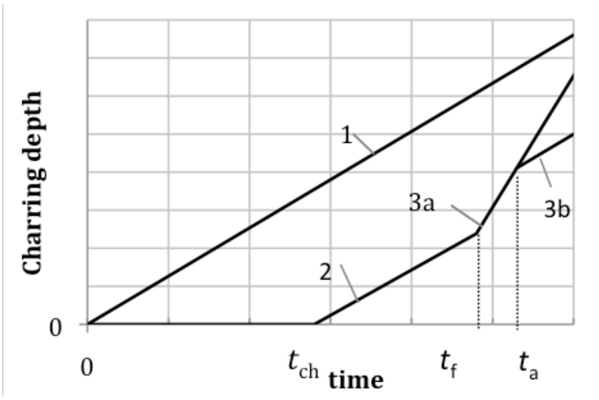
$$\beta_n = k_2\, k_s\, k_n\, \beta_0 \qquad \text{for } t_{ch} \le t \le t_f \tag{1}$$

$$\beta_n = k_3\, k_s\, k_n\, \beta_0 \qquad \text{for } t \ge t_f \tag{2}$$

where conversion factor $k_n = 1{,}5$

The cross-section factor is $k_s = 1{,}1..1{,}4$, depending on width of cross-section of stud. Factors k_2 and k_3 represent the reduced and decreased charring rates at protection phases 2 and 3.

At the protected phase 2 on Figure 1 the behavior of wall studs in stone wool and glass wool insulated walls and floors is similar. The behavior of structures with void cavities is different. Where the cavity insulation is made of glass wool, failure of the member should be assumed to take place at the time t_f. (Subclause C.2.1 (6) in [1]).



1-	Unprotected members
2,3 -	Initially protected members
2 -	Charring starts at t_{ch} at a reduced rate when protection is still in place
3a -	After protection has fallen off, charring starts at increased rate
3b -	Char layer acts as a protection and charring rate decreases

Figure 1. Charring of timber studs with and without protection

Method by EN 1995-1-2:2004 for Void Cavities

Charring of timber members at the protected stage is slower in the case of void cavities compare to the insulated cavities sine no local heat increase occurs. At the protection stage 2 the notional charring of narrow side of timber member is taken into account by notional charring rate β_n and factor k_2.

When the cladding has fallen off there will be charring from 3 sides of timber studs. For the stage after failure of the protection the post protection factor $k_3 = 2$.

Method by ETH for Wall and Floor Assemblies with Void Cavities

Frangi et al [3] made a post protection study of floors with void cavities to complete the calculation model in EN 1995-1-2:2004. Increased charring rates compared to

[1] were proposed. The reason for very fast charring is the missing protective char layer after cladding failure to protect from high temperatures.

The model in [3] is created for cross-section's width of 60 mm and larger. The method introduces also a phase 2c (resp 3b on Figure 1) to take into account the protective char layer created within 5 minutes. Using the notional charring rate β_n instead of β_0 is recommended for cross sections less than 60 mm wide.

5. INVESTIGATION OF POST PROTECTION EFFECT BY TESTS

Serie of small-scale tests at SP Trätek [5,6] and large scale tests at TÜV Estonia [7] were made to study the post protection effect of glass wool insulation. All of them were tested as non-load bearing structures in standard fire conditions (EN 1363-1, ISO 834) [2]. Studs with typical Scandinavian cross-section of 45x145 mm^2 were used.

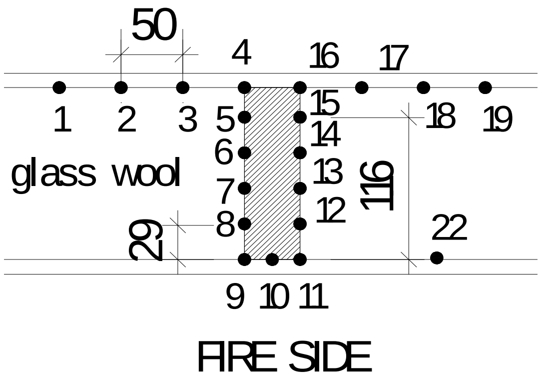


Figure 2. Test set-up for floor structures

TABLE I. RECESSION OF GLASS WOOL INSULATION IN TESTS

Test	Cladding	t_f [min.sec]	Delay of start of charring (from 29 to 116 mm height) [min.sec]	Recession speed [mm/min]
Floor test A [5]	GtA 12,5	19.50	5.50 4.00	15 22
Floor test B [6]	GtA 12,5	16.15	3.50 3.10	27 28
Wall test 2.1 [7]	GtA 12,5	26.30	5.15	16
Wall test 2.5 [7]	GtF 15,4	48.30	1.15	28

Test floors were covered by one layer of gypsum plasterboard, type A on the fire exposed side. Test walls had gypsum board, type A and type F on fire exposed side.

Charring spread was measured by thermocouples, placed on sides of timber studs with 29 mm distance.

Start of charring was counted to occur at temperature of 300 °C. Table I describes the start of charring times (in minutes) of glass wool insulated studs. t_f shows the fall-off time of cladding.

Conclusions from Test Results

Tests show that decreasing of volume of glass wool insulation is fast after the claddings fall off. The post protective behavior of ordinary glass wool insulation is not comparable with stone wool insulation. Although the glass wool insulation provides some small protection after cladding failure compared to structures with void cavities. This effect can be noticeable for bigger cross-section height.

As it is shown in examples on Table I, start of charring spread within 4...5 minutes from down to top of cross-section of timber stud. Floor and wall tests showed similar effect of charring due to recession of glass wool insulation and are comparable.

Based on the test results [5, 6, 7] recession of glass wool insulation is proposed to design with 30 mm/min with sufficient safety margin. The shapes of charred cross-sections are close to trapezoid because the charring starts later on unexposed side of cross-section height when insulation recesses. The phase 3b (see Figure 1) is not used in this paper because of no ability to create the protective char layer on 45 mm wide cross-sections. Rapid heat transfer begins from the sides of studs before char layer will be built.

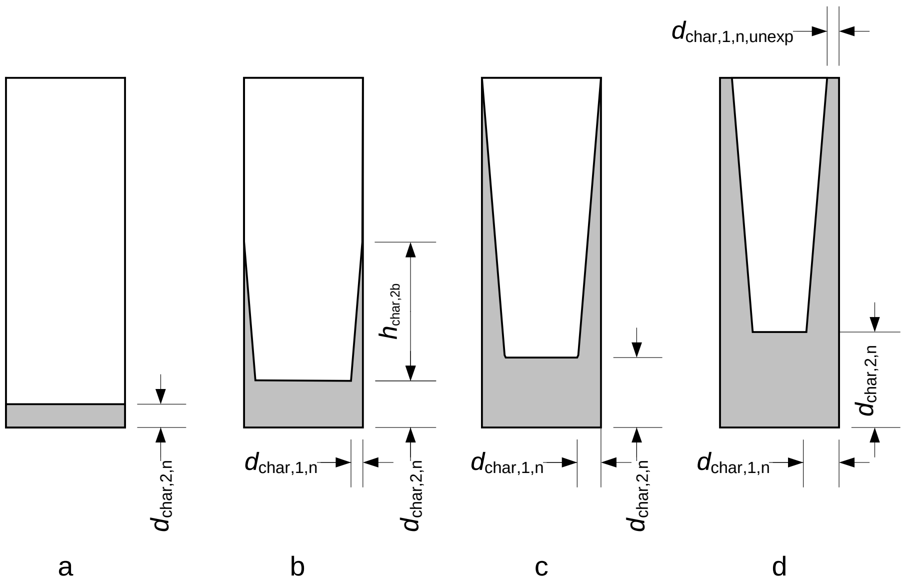
When the glass wool insulation is completely recessed, timber frame burns similarly to the structure with void cavities; the method of [3] should be used.

6. DESIGN METHOD FOR TIMBER WALL AND FLOOR STUDS PROTECTED BY GLASS WOOL

Based on test results and the method by ETH [3] for floors with void cavities the following design procedure is proposed.

For the time before failure of the cladding, charring takes place. The design model in annex C in [1] for phase 2 is valid for this case. See Figure 3 a. Once the cladding has fallen off at time $t = t_f$, surface recession of the glass wool insulation takes place due to thermal decomposition, so that the wide sides of the timber member are increasingly exposed to the fire and start to char, see Figure 3 b.

When surface recession of the glass wool insulation has reached the unexposed side of the insulation at $t = t_{f,ins}$, (Figure 3 c), charring on the wide sides of the timber member will take place over the whole depth of the cross-section (Figure 3 d).
In the following, it is either assumed that the cladding remains in place after the start of charring of the timber member, i.e. , $t_{ch} \leq t_f$, or that the cladding falls off at the time of start of charring, i.e. $t_{ch} = t_f$.



a. Charring on narrow fire-exposed side before cladding has fallen off ($t_{ch} \leq t \leq t_f$)
b. Charring on narrow side and wide sides during surface recession of glass wool insulation ($t_f \leq t \leq t_{f,ins}$)
c. Recession of glass wool completed ($t = t_{f,ins}$)
d. Charring on three sides after failure of glass wool insulation ($t \geq t_{f,ins}$)

Figure 3. Illustration of charring phases

Failure time of the insulation is counted as

$$t_{f,ins} = t_f + \frac{h}{v_{rec,ins}} \tag{3}$$

where h is the cross-section height and the surface recession rate for glass wool is

$v_{rec,ins} = 30$ mm/min

Charring depth on different stages is calculated as
1) Phase 2 $t_{ch} \leq t \leq t_f$ (Figure 3 a)

$$d_{char,2,n} = k_2\, k_s\, k_n\, \beta_0 (t_f - t_{ch}) \tag{4}$$

2) Phase 3. $t_f \leq t \leq t_{f,ins}$ (Figure 3 b):

$$d_{char,1,n} = k_3\, \beta_0 \left(t - t_f \right) \tag{5}$$

$$h_{char,3} = v_{rec,ins} (t - t_f) \tag{6}$$

$$d_{char,2,n} = k_2\, k_s\, k_n\, \beta_0 (t_f - t_{ch}) + k_3\, \beta_n\, (t - t_f) \tag{7}$$

This stage is relatively short and could be replaced by linear interpolation of section modulus between times t_f and $t_{f,ins}$.

3) Phase 3. $t \geq t_{f,ins}$ (Figure 3 d):

$$d_{char,1,unexp,n} = k_3\, \beta_0 (t - t_{f,ins}) \tag{8}$$

where
k_2 is the insulation factor of the cladding from [1] expressions (C.3) or (C.4).
k_3 is the post-protection factor, given as

$$k_{3a} = 1 + \frac{8}{75} t_f \qquad \text{for } 0 \leq t_f \leq 15 \text{ min} \tag{9}$$

$$k_{3a} = 1{,}9 + \frac{7}{150} t_f \qquad \text{for } 15 \text{ min} \leq t_f \leq 60 \text{ min} \tag{10}$$

If there is a risk of insulation to fall down before completely recessed, the time

$$t_{f,ins} = t_f \tag{11}$$

A further simplified model for calculations is a model using rectangular cross-sections. Compared to the trapezoidal model it is not universal for bending members and compression members. For that reason two different rectangular models should be used for two basic cases based on either the reduction of section modulus or cross-section area respectively. For more information see [8].

Strength and Stiffness Properties

The reduced cross-section method is recommended to use for calculating strength and stiffness. For $t_{ch} \leq t \leq t_f$ the method of [9] for counting zero-strength layer should be used for structural design. For the time period $t > t_f$ the zero strength layer should be taken as $d_o = 7$ mm from three side of cross-section.

Examples

Examples of charred cross-section are shown on the next diagrams for different studs and protection. The charring in corners is taken into account with using β_n on the narrow side of cross-section. Charring on the wide side could be calculated using one-dimensional charring rate β_o. Alternatively the curve with charring rate β_n on wide side is shown in Figure 5. Test results show that β_0 gives the realistic approach.

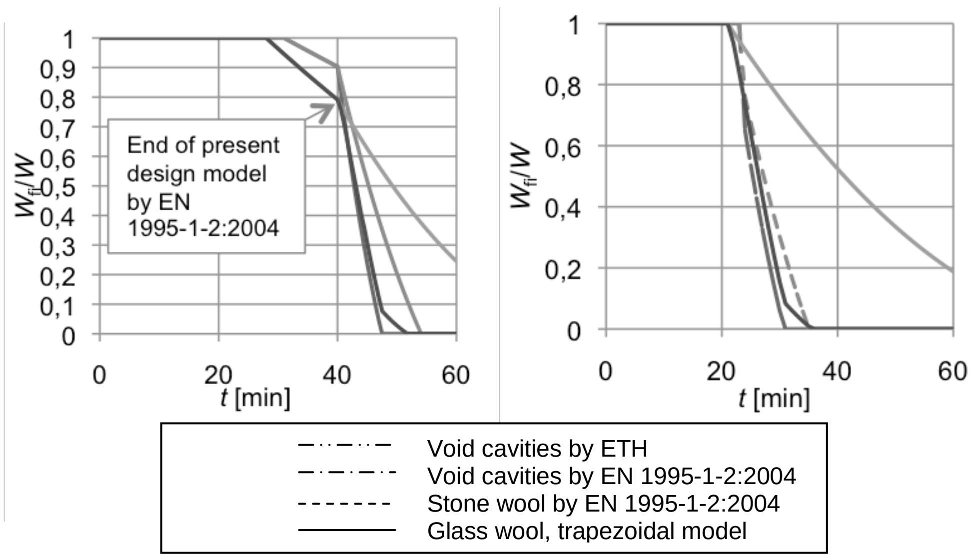


Figure 4. Example of existing and new design models for timber frame assembly with gypsum plasterboard type A (left) and type F (right) with timber studs 45x145 mm^2.

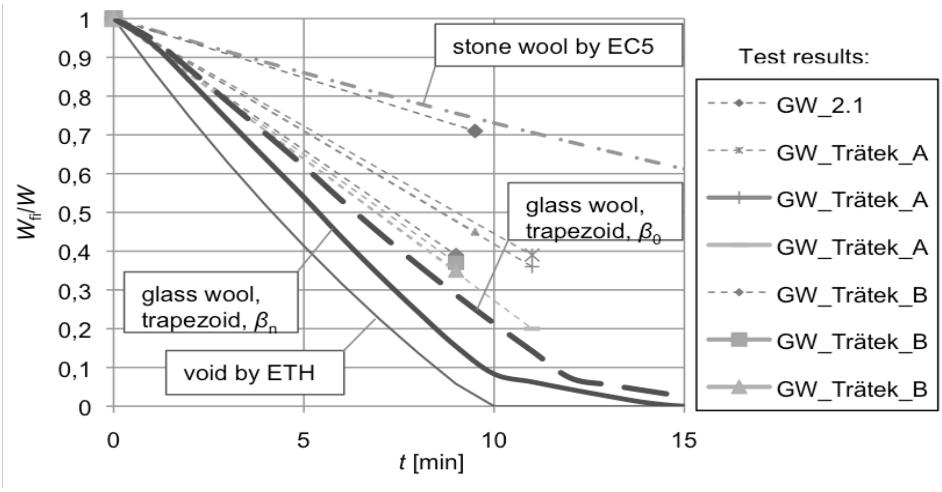


Figure 5. Comparison of calculation method with the test results.

7. CONCLUSIONS

Fire resistance of glass wool insulated walls and floors should be calculated similarly to stone wool insulated walls and floors when protected from direct fire by claddings (protection phase 2 according to EN 1995-1-2:2004). Post protection phase 3a begins with delay of start of charring on wide side of studs cross-section caused by recession of glass wool. After the delay the method by A. Frangi et al [3], created for timber frame floors with void cavities, should be used for phase 3a. Residual cross-section may be counted as trapezoid.

Recession of glass wool insulation with densities from 14 kg/m^3 could be counted as 30 mm/min respectively to the insulation thickness. Post protection phase 3b should only be used for cross-sections wider than 60 mm. Reduced properties method [1] or reduced cross-section method [9] should be used for structural design.

8. REFERENCES

1. EN 1995-1-2:2004. "Eurocode 5: Design of timber structures - Part 1-2: General rules-structural fire design", European Committee of Standardization, Brussels, 2004.
2. EN 1363-1. "Fire resistance tests. General requirements", European Committee of Standardization, Brussels, 1999.
3. Frangi A., Erchinger C., Fontana M., "Charring model for timber frame floor assemblies with void cavities", *Fire Safety Journal*, 43, Elsevier Ltd, 2008.
4. prEN ISO 9229 "Thermal insulation - Definitions of terms", CEN/TC88, 2006.
5. Test report P705487A, SP Trätek, Stockholm, 2009.
6. Test report P705487B, SP Trätek, Stockholm, 2009.

7. Just A., "Full scale wall tests of timber frame assemblies", Test report, Tallinn University of Technology, 2009.
8. Just A., "Post protection behaviour of wooden wall and floor structures completely filled with glass wool". SP Trätek, Stockholm, 2010.
9. König J., "The effective cross-section method for light timber frame construction with solid timber members", SP Trätek, Stockholm, 2010.

IV

PAPER IV

Just, A. (2010) Post protection effect of heat-resistant insulations on timber frame members exposed to fire.

Fire and Materials. (accepted for publishing)

Post protection effect of heat-resistant insulations on timber frame members exposed to fire

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SUMMARY

In lightweight walls and floors the load bearing timber members are protected by a cladding on the sides to divide two fire compartments or to provide appropriate fire protection to the load-bearing member. The spaces between the timber members can be void or filled with insulation materials. Even thought if a huge number of different insulation materials exist the mainly used material is mineral wool insulation.

The existing design model for glass wool insulated timber frame constructions given in EN 1995-1-2 assumes collapse after cladding's failure. However, a new form of glass wool insulation, suitable for the use at high maximum service temperatures, is now available in the market place. The phase of charring after the cladding's failure is known as post-protection phase. The behaviour of the new heat-resistant glass wool in post protection phase in fire is similar to that of stone wool and considerably better than traditional glass wool. Protective properties of stone wool have been changed during the last decades.

Charring is one of the main parameters needed to calculate the resistance in fire. Based on experimental investigations, this paper describes the analysis of the effect of the insulation with regard to its capability of protecting timber members against charring in post-protection phase.

KEYWORDS

Timber frame assemblies, heat-resistant glass wool, stone wool, charring

SYMBOLS

A_{fi}	cross-section area of the charred cross-section, in mm^2;
A_{rec}	cross-section area of the corresponding rectangular cross-section, in mm^2;
b	cross-section width, in millimetres;
d_{char}	charring depth, in millimetres;
$d_{char,n}$	notional charring depth, in millimetres;
h	cross-section height, in millimetres;
h_{fi}	maximum height of residual cross-section, in millimetres;
h_n	height of equivalent rectangular cross-section, in millimetres;
k_s	cross-section factor;
k_p	protection factor;
k_2	insulation factor;
k_3	post-protection factor;
k_n	factor to convert the irregular residual cross-section into a notional rectangular cross-section;
t	time from test start, in minutes;
W_{fi}	section modulus of the charred cross-section, in mm^3;
W_n	section modulus of the equivalent rectangular cross-section, in mm^3;
β	one-dimensional design charring rate, in mm/min;
β_n	notional charring rate, in mm/min.

1 INTRODUCTION

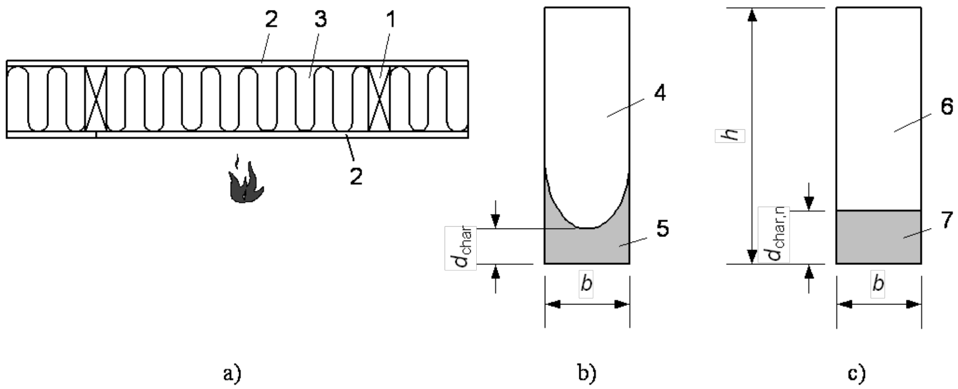
Timber frame wall and floor assemblies consist normally of the timber wall studs or floor joists, void or insulated cavities between the members, and a cladding attached to each side of the timber frame. See Figure 1. The cavities of the walls or floors are often partially or completely filled with insulation in order to satisfy requirements with regard to

- protection against noise,
- energy economy and heat retention,
- safety in the case of fire.

This paper deals with fire protection. In the European system fire protection is subdivided in different requirements. For floors and walls those are: insulation criteria I, integrity criteria E and resistance criteria R. In this paper the focus concentrates on fire resistance of load bearing timber members.

The charring depths and residual cross-sections is investigated. The strength properties of residual timber members are not considered.

The greatest contribution to fire resistance of timber frame assemblies is provided by the first layer of the cladding on the fire-exposed side directly exposed to the fire. Failure of first barrier highly affects R, E and I criteria. In general, it is difficult to compensate for poor fire protection performance of the first layer by improved fire protection performance of the following layers.



Key:
1 Solid timber member (stud or joist)
2 Cladding
3 Insulation
4 Residual cross-section (real shape)
5 Char layer (real shape)
6 Equivalent residual cross-section
7 Char layer with notional charring depth

Figure 1 – Charring of timber frame member (stud or joist): a. Section through assembly. b. Real residual cross-section and char layer. c. Notional charring depth and equivalent residual cross-section

Presented research describes the protective effect of the optional next barrier – mineral wool insulation, which becomes important after failure of the cladding since it provides a certain protection of wide sides of the timber members, exposed directly to the fire.

Cavity insulations of mineral wool, mainly stone wool or glass wool, may be more or less heat-resistant in a fire situation. During the protected stage, before failure of the cladding, both heat-resistant and non heat-resistant mineral wool insulation perform approximately equally since temperature rise is limited. Charring mainly takes place on the narrow, fire-exposed side of the timber members.

In the post-protection phase the behaviour of heat-resistant and non heat-resistant mineral wool is different. If the cavity insulation is made of heat-resistant insulation, charring mainly takes place on the narrow side of timber member. Since there is a heat transfer through the insulation to the sides of the timber member (provided that the cavity insulation remains in place), the effect of increasing arris rounding becomes important. For timber members in assemblies with non heat-resistant cavity insulation, charring takes place on both the narrow and whole wide sides since no insulation can reduce the heat transfer to the sides.

This paper deals with the behaviour of the heat-resistant mineral wool at post-protection phase and influence on charring of timber frame members.

2 MINERAL WOOL INSULATION

The European standard for mineral wool EN 13162 [2] gives numerous properties of mineral wool, but not any specific properties or requirements with respect to their performance in fire regarding their capability of protecting timber structures when exposed to fire.

Contrary EN 1995-1-2 [1] divides mineral wool insulation into two groups, depending on their different behaviour in a fire situation based on experimental observations. These two groups are *stone wool* and *glass wool.*

Stone wool (rock wool) is a mineral wool manufactured predominantly from molten naturally occurring igneous rocks [3]. When the rock is heated to a temperature of about 1600°C, air is blown through the molten rock. After formation, the fibres are sprayed with binding agents, water repellents and mineral oil, and are passed through an oven and are formed into the appropriate products. The final product is a mass of fine, intertwined fibres with a typical diameter of 6 to 10 micrometers. Stone wool is usually not sensitive to high temperatures which appear in a standard fire. The density of stone wool insulation used in building construction is usually in the range from 26 to 100 kg/m^3.

Glass wool (named *traditional glass wool* in this paper) is a mineral wool manufactured predominantly from sand and molten recycled glass [3]. It consists of intertwined and flexible glass fibres, which cause it to trap air, resulting in a low density that can be varied through compression and binder content. The density of glass wool insulation, used in building construction is usually in the range from 14 to 20 kg/m^3. Traditional glass wool is sensitive to high temperatures in fire. When the temperature exceeds 500°C, there can be a fast recession observed of the insulation. This will usually occur after failure of the cladding when the insulation is directly exposed to fire.

Heat-resistant glass wool is manufactured predominantly from sand and molten patented glass compound. This material is produced using conventional glass wool technology. The speciality is a higher quality of the raw material and a higher temperature in the production process. The glass compound has a very high temperature resistance. The insulation properties and the density of the material at normal temperatures are similar to those of traditional glass wool.

According to [1] when the cladding has fallen off in fire situation, traditional glass wool insulation provides no further significant protection against fire in the post-protection phase and no rules are given for design of floor and wall assemblies. Stone wool is well known to provide excellent protection of the timber member against charring and was, for a long time, the only mineral wool performing well in fire resistance tests when directly exposed to the fire (after the cladding was fallen off). Therefore, stone wool was taken as a reference heat-resistant mineral wool for the rules of EN 1995-1-2 [1] for insulated constructions during the post-protection phase after failure of the cladding. The rules were based on the assumption that all common stone wool products would perform reasonable equal. Since products in the past may be optimised for other aspects (production costs etc.), and no standard exists for verification of the fire resistance of mineral wool in fire resistance tests, the protective properties of those stone wool products need to be verified again.

Novel heat-resistant glass wool insulation has been in the market place for some time. This type of glass wool provides protection comparable with stone wool insulation but does not fit the design rules in EN 1995-1-2 [1].

3 DESIGN MODEL OF CHARRING

Charring is the most important parameter for design of timber frame members for fire resistance. Unprotected members start to char immediately when exposed to fire. For protected members there is no charring until 300ºC is reached behind a protection. Then slow charring starts and continues until failure of the protection when fast charring begins. In general for the design of fire resistance of timber member the original cross-section is to be reduced by the charring depth.

Annex C of EN 1995-1-2 [1] gives a charring model for small size timber members of wall and floor assemblies insulated by mineral wool. The model, created by König et al [4], should be used for calculation of fire resistance of lightweight timber structures. It covers the protected phase for glass wool and stone wool and post-protection phase for stone wool as long as the insulation stays in place.

Although the timber members are protected by insulation batts on their wide sides, it is not only on their fire-exposed narrow side that charring takes place. Due to the heat transfer through the insulation, the timber members also char on their wide sides, giving rise to extensive arris roundings, see Figure 1. For simplicity, the irregular residual cross-section is replaced by an equivalent rectangular cross-section, replacing the charring depth d_{char} and arris roundings with the notional (or equivalent) charring depth $d_{\mathrm{char,n}}$.

Notional charring depth is counted as

$$d_{\mathrm{char,n}} = \beta_{\mathrm{n}} t \tag{1}$$

The notional charring rate of small sized timber frame members is given as

$$\beta_{\mathrm{n}} = k_{\mathrm{p}} k_{\mathrm{s}} k_{\mathrm{n}} \beta_0 \tag{2}$$

where β_0 is the one-dimensional charring rate for timber given as

$$\beta_0 = 0,65 \frac{\mathrm{mm}}{\mathrm{min}} \tag{3}$$

The coefficients k_{p}, k_{s} and k_{n} are explained as follows:

The protection factor k_p takes the influence of protective cladding on charring into account. For unprotected members k_p = 1. In this research no cladding was used to exclude the influence of protection.

The cross-section factor k_s takes the width of the cross-section into account. Charring is faster when the cross-section is smaller, due to two-dimensional heat transfer within the member. In [4] it is given as

$$k_s = \begin{cases} 0,000167\, b^2 - 0,029\, b + 2,27 & \text{for } 38 \text{ mm} \leq b \leq 90 \text{ mm} \\ 1 & \text{for } b > 90 \text{ mm} \end{cases} \quad (4)$$

while [1] gives only a table with values for specific widths *b*.

Expression (4) assumes a linear relationship between d_{char} and time, which is slightly conservative for d_{char} < 30 mm and non-conservative for d_{char} > 30 mm, see Figure 3. For $d_{char} > 30$ mm the load resistance is normally exhausted. According to [1] expression (4) can be used for stone wool insulation of minimum density of 26 kg/m^2.

The coefficient k_n converts the irregular charring depth into a notional charring depth, see Figure 1.b and c. Strictly speaking, it depends on time, cross-section dimensions and the cross-section properties (area, section modulus or second moment of area). The value $k_n = 1,5$ given by EN 1995-1-2 [1] is a reasonable approximation for the notional charring depth. That would be relevant for a relative resistance between 40 to 20% of the initial section modulus W (t = 0).

According to König et al [4], the linear model given in EN 1995-1-2 is a reasonable approximation of charring depths up to 25 mm.

Before failure of the protective cladding, there is no difference in the fire behaviour of assemblies with stone wool or with glass wool. After the claddings failure the traditional glass wool insulation will undergo decomposition, gradually losing its protecting effect for the timber member by surface recession. Then the model can’t be used. Stone wool insulation, provided that it remains in place, will continue to protect the sides of the timber member facing cavity. Heat-resistant glass wool insulation is supposed to have the same protective behaviour as stone wool.

In the following the assumption that heat-resistant glass wool provides similar protection with stone wool and fits into the model of annex C in EN 1995-1-2 [1] is analysed.

4 EXPERIMENTAL INVESTIGATION

A series of fire tests in mid- and full-scale was performed in Tallinn [5] and in Stockholm [6] to investigate the post-protection behaviour of the heat-resistant insulations. The standard fire temperature-time curve given by EN 1363-1 [7] was used in all cases.

Several tests included different insulation products in order to compare their fire performance under the same test conditions. Timber frame assemblies were tested without a cladding on the fire exposed side to eliminate the uncertainty of the scattered effect of cladding's failure because of different failure times in different places. The work included investigations of timber frame assemblies with 2 different heat-resistant glass wool products (densities 14 kg/m^3 and 21 kg/m^3) and with stone wool products of 4 different producers (densities of 27 to 38 kg/m^3). The stone wool product used by König to develop the model in [1] and [4] was included. All of the tested materials were produced in 2009.

The full-scale fire tests were conducted as unloaded wall tests. All studs were cut from the same batch of timber. The studs were strength graded and were within strength class C24 in accordance with EN 338 [8], produced by Stora Enso Imavere sawmill in Estonia. The characteristic density of the studs was in the range from 404 to 538 kg/m^3, and their moisture content was in the range from 10 to 12% before the fire tests. The cross-section of the studs was 45 mm × 145 mm.

The mid-scale fire tests were conducted as loaded and unloaded floor tests. The studs were strength graded and were within strength class C30 in accordance with EN 338 [8], produced by in Sweden. The cross-section of the studs was 45 mm ×145 mm.

Temperature measurements were made using thermocouples located on the sides and inside of the timber studs, on the unexposed side of the insulation, see Figure 2. Thermocouples located on the mid height of the studs. The densities of the insulations used in the tests were measured by weighing the packets in the fire laboratory before fitting the insulation into the test structures. See Table 1.

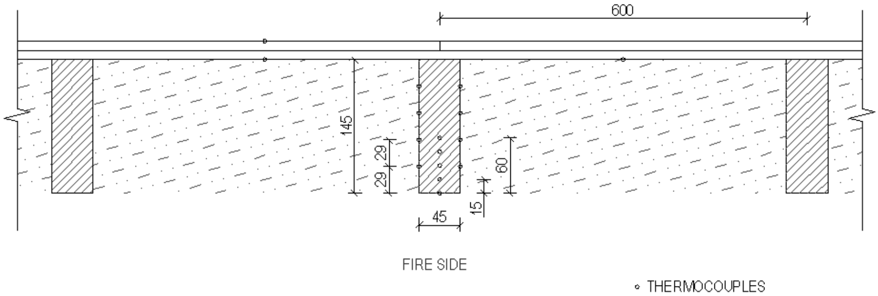


Figure 2 – Location of thermocouples on timber member

Table 1 – Densities of tested insulation materials

Material	**Densities, kg/m^3**	**Average density, kg/m^3**
Heat-resistant glass wool GWF2	20,5 to 21,1	21,0
Heat-resistant glass wool GWF1	13,8 to 14,7	14,3
Stone wool, RW4	29,0 to 30,0	29,4
Stone wool, RW3	36,2 to 37,1	36,6
Stone wool, RW2	28,9	28,9
Stone wool, RW1	27,9 to 30,5	29,4

5 ANALYSIS OF CHARRED CROSS-SECTIONS

The rules of EN 1995-1-2 for insulated structures were created in the end of 1990-s based on fire tests using stone wool, delivered by one producer, with a nominal density of 28 kg/m^2. However, the standard EN 13162 [2] does not give a minimum density for the insulation. The general assumption that all stone wool products are equal can’t be done because the quality between different producers vary and products may have been optimized since the tests of König et al [4] (e.g. weight and cost optimizing, ecological aspects) without verifying the influence on fire resistance tests of timber constructions.

The following includes the analysis of charred cross-sections from tests in [5] and [6] with stone wool and heat-resistant glass wool insulation. All of the tests analysed in this paper were conducted without a cladding attached to the fire-exposed side. All of the timber members were with cross-section of 45 × 145 mm as in the research of König et al [4] for comparison reasons. Residual cross-sections of the studs after the fire tests were measured by an ATOS II optical scanner. The cross-section properties (area, section modulus, charring depth etc.) were determined using AutoCAD. In the analysis the factors k_s and k_n were determined and compared with the results of König [4] and the model in EN 1995-1-2 [1].

5.1 CROSS-SECTION FACTOR

Size factor k_s is determined by charring depth of 30 mm from the narrow side, as it is done in [4].

$$k_s = \frac{\beta_{30}}{\beta_0} \tag{5}$$

Thus, charring rate for 30 mm charring is:

$$\beta_{30} = \frac{30}{t_{ch,30}} \tag{6}$$

where

$t_{ch,30}$ – time from start of charring until 30 mm of charring depth, in minutes.

Figure 3 compares the present results with research of König [4] and Schmid [6]. Polynomial trend lines of test results in Figure 3 with reference material – stone wool – show the difference between previous and present results: the charring rate is slightly higher today. The reason for that could probably be a change in the composition of the stone wool by the producers during the past due to cost optimizing and ecological requirements.

Results from tests of König et al [4] made with stone wool lead to the following relation:

$$d_{\text{char}} = 0,0091t^2 + 0,55t \qquad (7)$$

The present research found the charring depth for 45 mm wide cross-section, protected with stone wool as follows:

$$d_{\text{char}} = 0,0042t^2 + 0,86t \qquad (8)$$

Charring of studs protected by heat-resistant glass wool is described as (see Figure 4)

$$d_{\text{char}} = 0,0049t^2 + 0,77t \qquad (9)$$

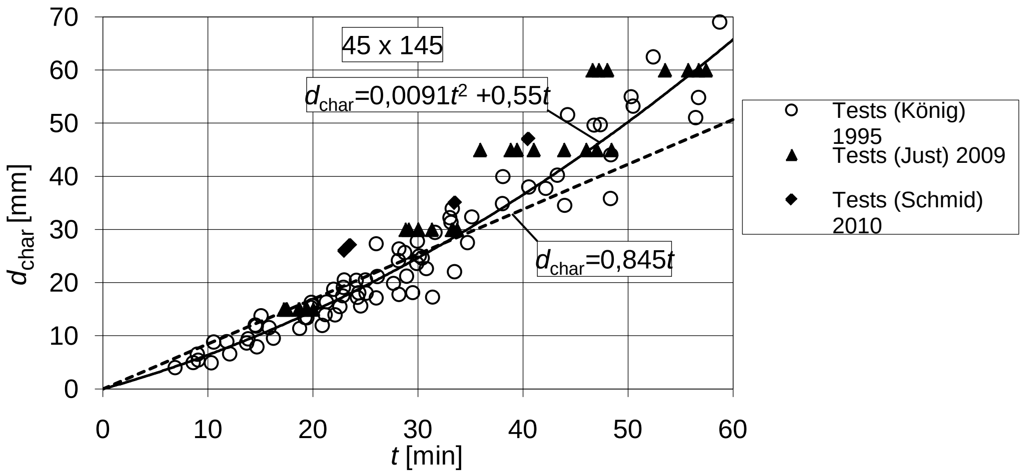


Figure 3 – Comparison of charring depths from [7] insulated by stone wool with new results of charring depth of wall studs insulated with heat-resistant mineral wool.

Expressions (8) and (9) show that charring of studs protected with stone wool or with heat-resistant glass wool is similar. See Figure 4. For simplification, a linear approach for charring depth has been used. Linear trend lines of stone wool and heat-resistant glass wool products are shown in Figure 5. The charring rate of structures without cladding is calculated as

$$\beta = k_{\text{s}}\beta_0 \qquad (10)$$

Charring depth is calculated as

$$d_{\mathrm{char}} = \beta t \tag{11}$$

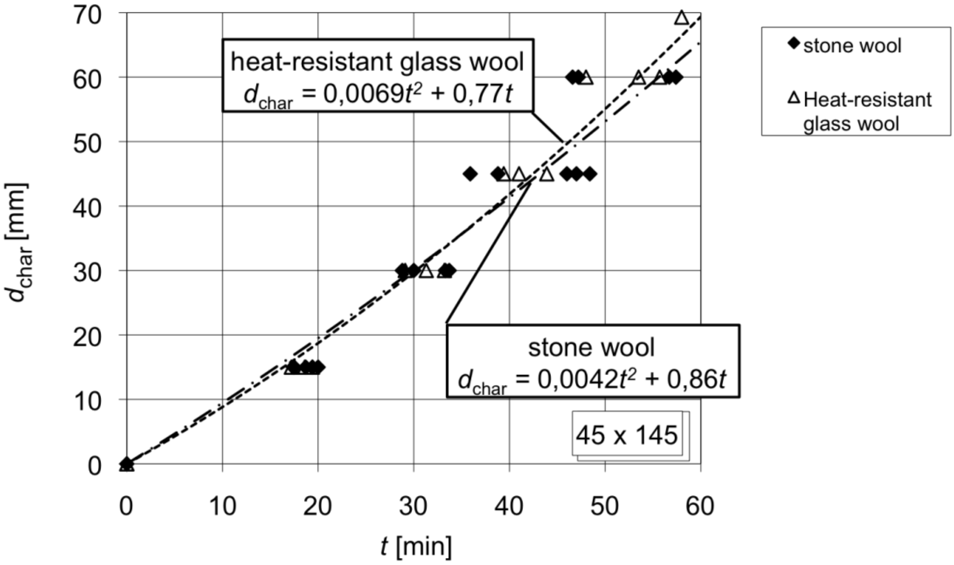


Figure 4 – Charring depth for studs protected by stone wool and heat-resistance glass wool respectively. Polynomial trendlines.

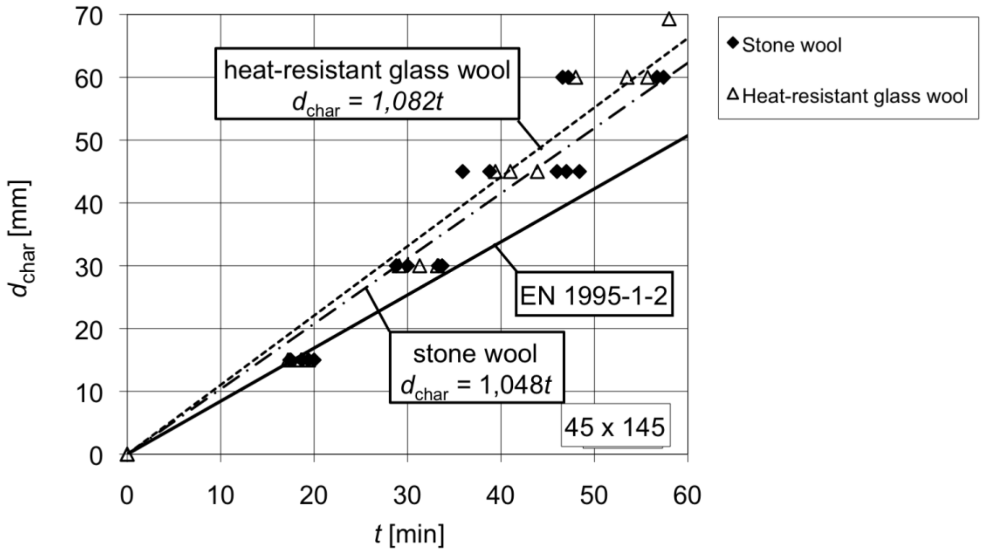


Figure 5 – Linear explanation of the charring rates for studs insulated by heat-resistant glass wool and stone wool.

In the present standard, EN 1995-1-2 [1], the value for k_s is 1,3. The charring depth for 45 mm wide wall studs protected with stone wool is expressed as:

$$d_{char} = 0,845t \tag{12}$$

A charring depth of 30 mm is taken as a basis for design requirements. A greater charring depth for relatively small width of the narrow side of wall or floor studs would be irrelevant, because of loss of bearing capacity. According to the test results, the proposal for charring depth of a 45 mm wide stud when protected by heat-resistant glass wool should be (see Figure 6):

$$d_{char} = 1,04t \tag{13}$$

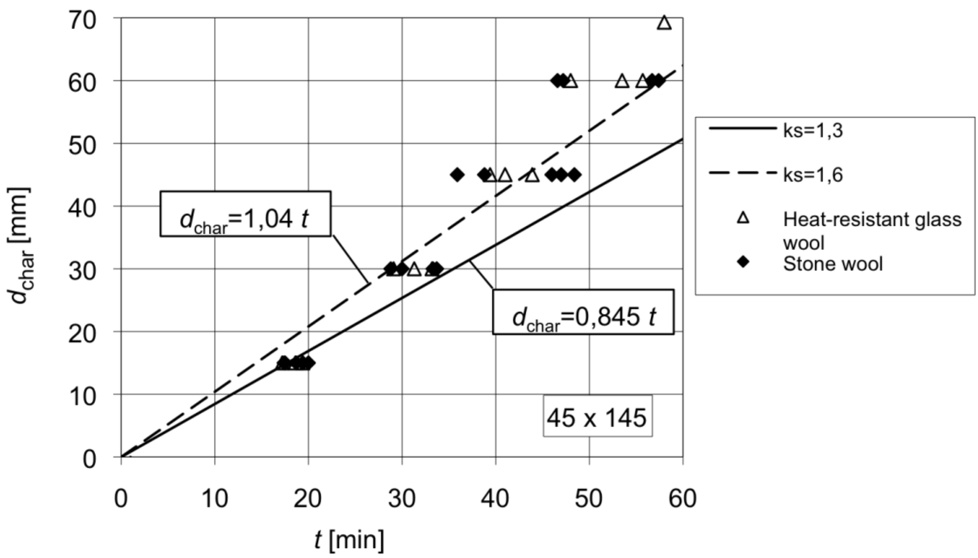


Figure 6 – Proposal for cross-section factor for heat-resistant insulations.

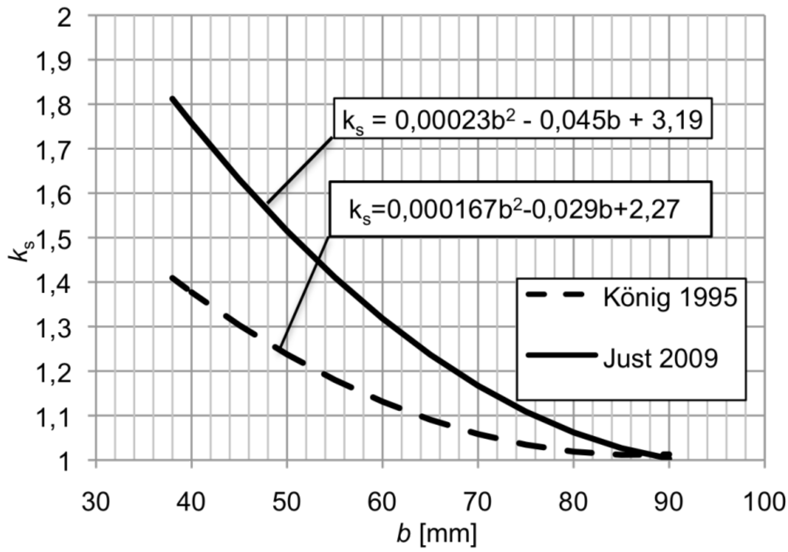


Figure 7 – Coefficient k_s depending on cross-section width.

The same charring depth is proposed for use for the same studs insulated by stone wool. The recommended new value for cross-section factor for 45 mm wide cross-sections is $k_s = 1,6$.

Results of present study show that stone wool from various producers provides somewhat less fire protection of the wide sides of the timber member than reported in [4]. Expression (4) should therefore be replaced with

$$k_s = \begin{cases} 0,00023b^2 - 0,045b + 3,19 & \text{for } 38 \text{ mm} \le b \le 90 \text{ mm} \\ 1 & \text{for } b > 90 \text{ mm} \end{cases} \tag{14}$$

This expression is illustrated in Figure 7. Based on the test results, the expression can be used for heat resistant glass wool with a minimum density of 14 kg/m^3 and for stone wool with a minimum density of 26 kg/m^3.

5.2 CONVERSION FACTOR

The section modulus W_n of residual cross-section was determined after the tests using AutoCAD for digitalizing residual cross-sections. The same value has been set to the section modulus of the equivalent rectangular cross-section

$$W_{\mathrm{n}} = W_{\mathrm{fi}} \tag{15}$$

The depth of the equivalent rectangular cross-section is

$$h_{\mathrm{n}} = \sqrt{\frac{6W_{fi}}{b}} \tag{16}$$

where b = 45 mm

Notional charring

$$d_{\mathrm{char,n}} = h - h_{\mathrm{n}} \tag{17}$$

Conversion factor is the following relation:

$$k_{\mathrm{n}} = \frac{d_{\mathrm{char,n}}}{d_{\mathrm{char}}} \tag{18}$$

Since the real value of k_{n} changes during char development, EN 1995-1-2 gives a simplification, k_{n}=1,5, which gives overestimated results in the early phase of a fire and more conservative results with thicker charring depth. For load ratios relevant in practice, the chosen value k_{n}=1,5 is a reasonable approximation.

The development of residual cross-section was measured in the presented test series by thermocouples on the sides of, and inside, the cross section. See Figure 2. Residual cross sections are calculated by drawing polynomials through the three points (thermocouple locations) and adding the rectangular unburnt part of the cross section. Values between thermocouples are interpolated when necessary. Developing residual cross-sections with different insulations are shown in Figure 8.

The measurements confirm that the simplification k_{n} = 1,5 is non-conservative for small charring depths, and conservative for larger charring depths when the mechanical resistance is very low. The important range of

W_{2c}/W is between 0,2 and 0,4 where the bearing capacity is achieved in the fire design.

The relationships from the present test results match well with research by König [4]. See Figure 9, where the present results are added to the results from König [4]. The cross section insulated with heat-resistant glass wool show similar relations with the stone wool insulated cross section when converting an irregular residual cross section into a notional rectangular cross-section.

Relations for section modulus and cross-section area are shown in Figure 9 and Figure 10. Each point represents a different section.

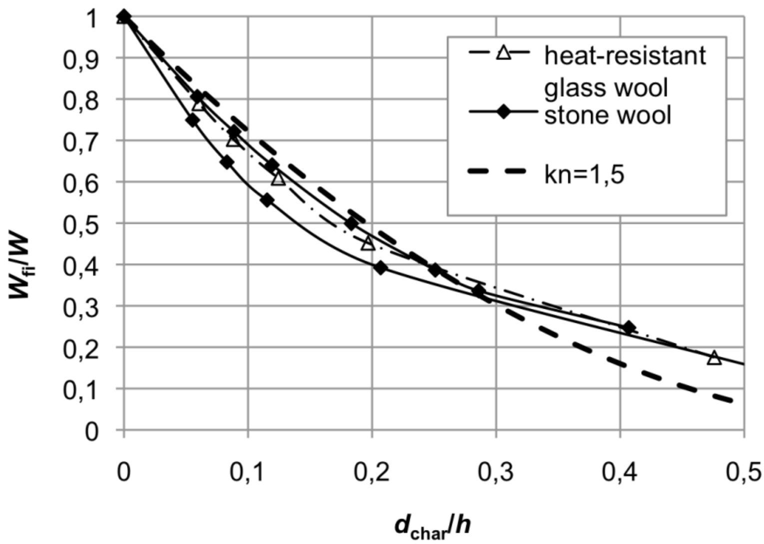


Figure 8 – Change of section modulus versus charring depth ratio during the test.

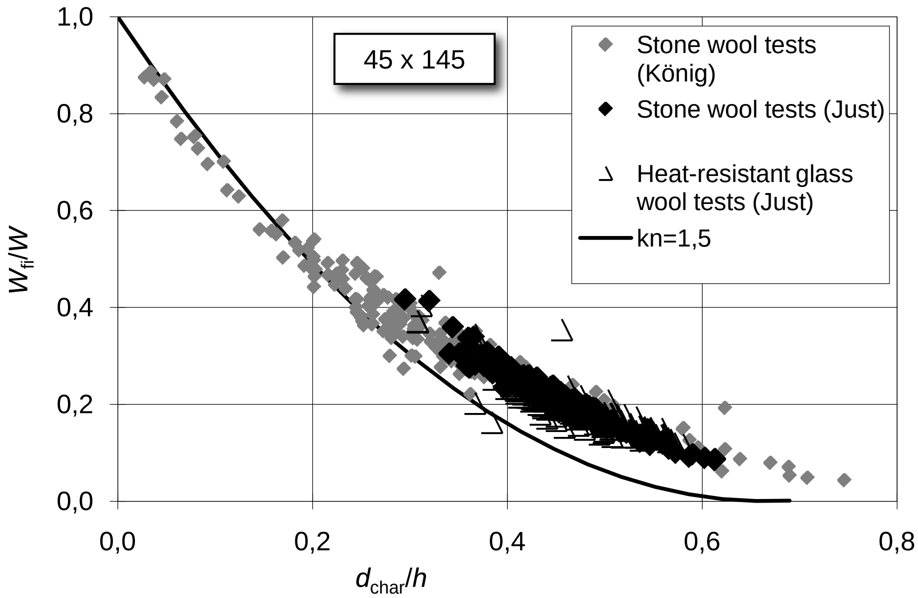


Figure 9 – Reduction of section modulus versus charring depth ratio. Comparison of test results.

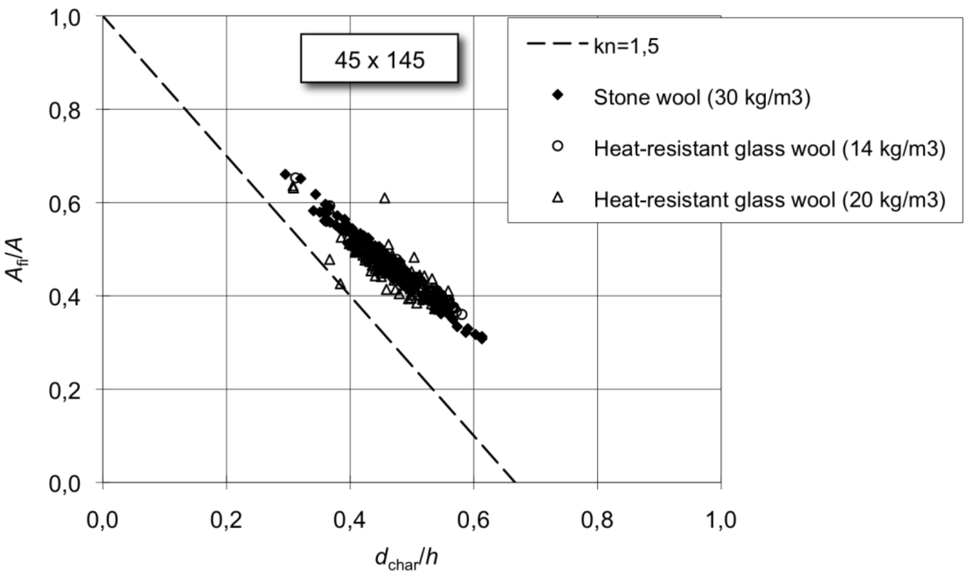


Figure 10 – Reduction of cross-section area versus charring depth ratio. Test results.

6 CONCLUSIONS

Division into *stone wool* and *glass wool* could be misleading.Due to the new type of mineral wool in the market the wording in EN 1995-1-2 [1] concerning mineral wools is considered for review. The authors of this paper recommend the terminology *heat-resistant mineral wool* and *non-heat-resistant mineral wool*.

The fire-protective properties of stone wool from different producers vary more than expected. Charring of timber wall studs with stone wool insulation is faster than given by design model according to EN 1995-1-2. This paper proposes new values for the cross-section factor k_s, taking into account the effect of cross-section width on charring rate.

Based on the analysis of the test results the design model described in Annex C of EN 1995-1-2 for timber frame assemblies insulated with stone wool can also be applied for timber frame assemblies insulated with heat-resistant glass wool using new value for cross-section factor k_s.

No changes are proposed for the other factors k_p and k_n, influencing the charring rate of timber member. Test results confirmed the reliability of factor k_n. Protection factor k_p was not targeted in this study.

For a general application of the results a classification system and testing method of mineral wool insulation with regard to the fire performance is required to develop in future research.

7 REFERENCES

1. EN 1995-1-2:2004, Eurocode 5: Design of timber structures - Part 1-2: General rules-structural fire design. European Standard. European Committee for Standardization, Brussels, 2004.
2. EN 13162:2008. Thermal insulation products for buildings - Factory made mineral wool products - Specification. European Standard. European Committee for Standardization, Brussels, 2008.
3. CEN/TC88. prEN ISO 9229 Thermal insulation - Definitions of terms. European Standard. European Committee for Standardization, Brussels, 2006.
4. König J, Walleij L. Timber frame assemblies exposed to standard and parametric fires. Part 2: A Design model for standard fire exposure. Trätek, Stockholm, 2000.
5. Just A. Full scale wall tests of timber frame assemblies. Test report. Tallinn : Tallinn University of Technology, 2009.
6. Schmid J, König J. Model scale fire tests of Isover Ultimate – step 1.2 – Load Bearing Capacity. SP report 2010:26. SP Trätek, Stockholm, 2010.
7. EN 1363-1, ISO 834. Fire resistance tests - Part 1: General requirements. European Standard. European Committee for Standardization, Brussels, 1999.
8. EN 338:2008, Structural timber – Strength classes, European Standard, CEN, European Committee for Standardization, Brussels, 2008.

V

PAPER V

Just, A., Tera, T. (2010) Variability of charring along the wooden wall studs.

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Variability of charring along the wooden wall studs

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Abstract
The effect of densities on the charring of timber members insulated by heat-resistant mineral wool is studied in this paper. Special attention is given to variability of charring along the stud. After the fire tests, the studs were saved in whole length. Char layer was mechanically removed from the studs, which were under investigation. Charred studs of timber frame walls were scanned three-dimensionally over the full length after full-scale fire tests. Densities were measured by X-ray and optical vibration scanner. Cross-section properties and densities of the studs were measured along the sud.

Charring rate is not uniform within the full length of a single timber wall stud. This corresponds probably to the variation of density of wood. Adjusting of design model of charring of timber frame assemblies of EN 1995-1-2 according to influence of density may give an advantage for members with higher density.

Keywords

Charring rate, timber frame assemblies, variability of charring, effect of density

SYMBOLS

b	cross-section width;
d_{char}	charring depth;
$d_{\mathrm{char,n}}$	notional charring depth;
k_{p}	protection factor;
k_{s}	cross-section factor;
k_{n}	factor to convert irregular charring depth into a notional charring depth;
k_{dens}	factor to take effect of density into account;
t	time from the start of fire;

t_{ch}	start time of charring;
t_f	failure time of cladding;
W	section modulus;
W_{fi}	section modulus of the residual cross-section;
β	charring rate;
β_0	one-dimensional basic design charring rate;
β_n	notional charring rate;
ρ	density.

Abbreviations

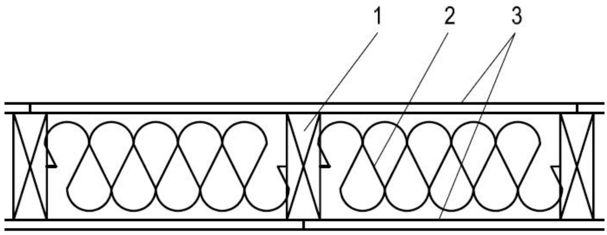
GtA	gypsum plasterboard, type A
RW	stone wool, rock wool
GW	glass wool
GWF	glass wool with high maximum service temperature, heat resistant glass wool

1 INTRODUCTION

Typical timber frame assemblies consist of timber wall studs or floor joists and claddings, see Figure 1. The cavities between timber elements may be void or filled with insulation. Cladding on the fire-exposed side is the first and the most important barrier. If to take timber stud into consideration, the reduction of cross-section by charring depth is the most important design procedure.

EN 1995-1-2 [1] gives rules how to calculate fire resistance (R, E, I) for timber framed walls and floors. For the design of load bearing capacity (R) the residual cross section is one of the decisive factors. Cross-section decreases due to charring. The start time of charring behind the fire protective cladding and the failure time of cladding are important properties for the fire safety design of timber frame construction. When cladding of the structures has fallen off the insulation plays important role of protection of timber members on sides. If the insulation is heat-resistant and remains in place, the stud is more or less protected on wide sides of cross-section. If the insulation is non heat-resistant or if the cavities are void, then there is a fast surface recession when exposed to fire. Charring takes place both - on narrow and wide sides.

Failure of claddings does not occur simultaneously in different places. In this research we did not have cladding due to wish to eliminate the uncertain effect of cladding’s fall off.



KEY:
1 – timber member
2 – insulation
3 - cladding

Figure 1 – Typical timber frame assembly

The charring rate values in EN 1995-1-2 are independent of density for softwood with densities above 290 kg/m^3. For hardwoods the charring rate varies linearly for densities between 290 and 450 kg/m^3.

Babrauskas [2] has compared works of different authors and concludes that if the density of solid wood is in the range of 400-550 kg/m^3, then the charring rate under fire-resistance test furnace conditions will be in the range of 0,5-0,8 mm/min. Cachim and Franssen [3] show the numerical analysis based on conductive model of EN 1995-1-2. They found a good agreement of charring rate values of EN 1995-1-2 with the conductive model for densities around 450 kg/m^3.

Friquin [4] compares different factors affecting charring rate. The change of charring rate as a result of changing one property or factor varies greatly [4]. The difference in charring rate between different softwood species is about 12 to 28 %. Schaffer [5] found an obvious relationship between the dry specific density and the charring rate of wood, where the charring rate decreases with increasing density. A study by White [6], with Engelmann spruce with 10% moisture content, shows a 22% difference in charring rate for a change in density from 343 kg/m^3 to 425 kg/m^3.

Syme [7] found an effect of wood density to the charring depth in Australian tests with fire similar to ISO 834 fire. This effect covered only specimens with density 500 to 900 kg/m^3.
Australian fire design rules for timber structures [8] consist of rules for calculating notional charring rate dependent on density:

$$C = 0{,}4 + (280/D)^2 \qquad (1)$$

where
C – notional charring rate (mm/min)
D – wood density at moisture content 12% (kg/m^3)

The aim of this article is to study the effect of variability of charring along the members of wooden floor and wall assemblies insulated with heat-resistant mineral wools as stone wool and heat-resistant glass wool and to detect the possible influence of density of wood to the charring rate. Heat-resistant glass wool is a new innovative glass wool with high maximum service temperature.

2 CHARRING RATE ACCORDING TO EN 1995-1-2

Rules for fire design of wall and floor assemblies insulated by stone wool and glass wool are given in annex C of EN 1995-1-2 [1].

Charring is the most important parameter in design of timber frame members for fire resistance. Unprotected members start to char immediately when exposed to fire. For protected members there is no charring until 300ºC has been reached behind the protection. Then slow charring starts and continues until failure of the protection. After that starts fast charring, see Figure 2. In general for the design of fire resistance of a timber member the original cross-section is to be reduced by the charring depth. Annex C of EN 1995-1-2 [1] gives a charring model for small size timber members of wall and floor assemblies insulated by mineral wool. The model, created by König et al [9], should be used for calculation of fire resistance of lightweight timber structures. It covers the protected phase for glass wool and stone wool and post-protection phase for stone wool as long as the insulation stays in place.

Timber members are protected by insulation on their wide sides. Charring takes place mainly on the fire-exposed narrow side. Due to the heat flux through the insulation, the timber members also char on their wide sides, giving rise to extensive arris roundings, see Figure 3. For simplicity, the irregular residual cross-section is replaced by an equivalent rectangular cross-section, replacing the charring depth d_{char} and arris roundings with the notional (or equivalent) charring depth $d_{\mathrm{char,n}}$.
Notional charring depth is regarded as

$$d_{\mathrm{char,n}} = \beta_{\mathrm{n}} t \tag{2}$$

The notional charring rate of small sized timber frame members is given as

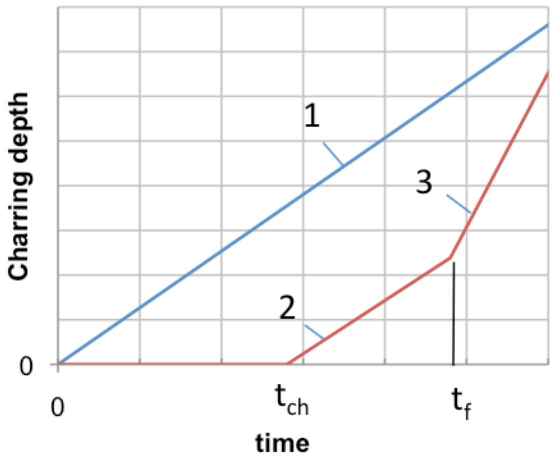
$$\beta_{\mathrm{n}} = k_{\mathrm{p}} k_{\mathrm{s}} k_{\mathrm{n}} \beta_0 \tag{3}$$

where β_0 is the one-dimensional charring rate for timber given as

$$\beta_0 = 0,65 \frac{\mathrm{mm}}{\mathrm{min}} \tag{4}$$

The coefficients k_p, k_s and k_n are explained as follows:

The protection factor k_p takes the influence of protective cladding on charring into account. In this research no cladding was used to exclude its influence on protection. For unprotected members $k_p = 1$.



KEY:
1 - unprotected members
2,3 – initially protected members
2 – protected phase; charring starts at t_{ch} at the reduced rate when protection is still in place
3 – post-protection phase; charring continues at increased rate when the protection is fallen off

Figure 2 – Charring of timber studs with and without protection

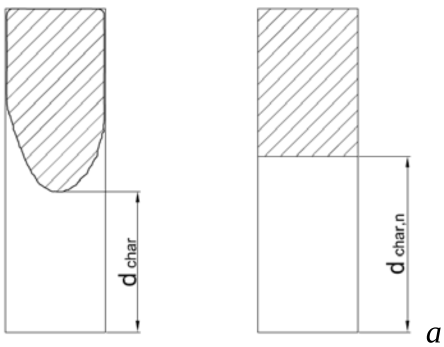


Figure 3 – Description of charring depths of cross-sections.

The cross-section factor k_s takes the width of the cross-section into account. Charring is faster when the cross-section is smaller, due to two-dimensional heat flux within the member. In [9] it is given as equation (5), while [1] gives only a table with values for specific widths b.

New results from [10] and [11] lead to increased cross-section factor as given by equation (6).

$$k_s = \begin{cases} 0,000167\,b^2 - 0,029\,b + 2,27 & \text{for } 38 \text{ mm} \le b \le 90 \text{ mm} \\ 1 & \text{for } b > 90 \text{ mm} \end{cases} \tag{5}$$

$$k_s = \begin{cases} 0,00023\,b^2 - 0,045\,b + 3,19 & \text{for } 38 \text{ mm} \le b \le 90 \text{ mm} \\ 1 & \text{for } b > 90 \text{ mm} \end{cases} \tag{6}$$

In this study the equation (6) is used for determining factor k_s. For studs with cross-section width of 45 mm the factor k_s=1,6.

The coefficient k_n converts the irregular charring depth into a notional charring depth, see Figure 3. It depends on time, cross-section dimensions and cross-section properties (area, section modulus or second moment of area). The value k_n=1,5 given by EN 1995-1-2 [1] is a reasonable approximation for the notional charring depth. That would be relevant for a relative resistance between 40 to 20 % of the initial section modulus W (t = 0). The value k_n=1,5 is on the safe side in the cases of charring depths of this study.

3 FULL-SCALE FIRE TESTS

Series of full-scale tests were performed to study the post protection behaviour of the insulations, see [3] and [4]. Test wall assemblies were equipped with additional thermocouples at sides and inside of timber studs and behind the boards and insulation. Observations were noted and photos taken both at the fire exposed side and at the unexposed side. The tests were also investigated by thermocamera. Tests were performed 30 - 60 minutes until 60 mm charring of timber is reached at the narrow side.

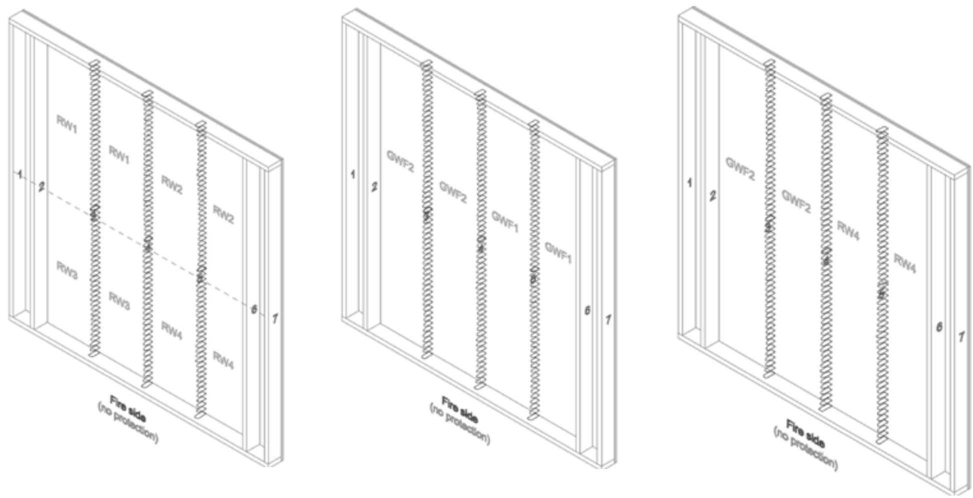
Full-scale tests presented here were performed without cladding on the exposed side to reduce the influence of hard predictable failure of the cladding. Test walls had 2 to 4 different insulations in each test, see Figure 4. In the Table 1 the main components of test assemblies are shown. There are two different times given in Table 2 for test durations. Turn off of the fire represents the time when heating in test furnace was stopped. Wooden elements continued to burn until the test wall was removed from the furnace and extinguished. Time from turn off of fire to the complete extinguishing was 3 to 5 minutes.

Table 1 – Test register

Test No.	Test date	Exposed side	Stud	Insulation 1	Insulation 2	Unexposed side
2.2	28.1.09	-	45x145	RW1 RW3	RW2 RW4	2GtA
2.3	29.1.09	-	45x145	GWF2	GWF1	2GtA
2.4	11.2.09	-	45x145	GWF2	RW4	2GtA

Table 2 – Test durations

Test No.	Turn off of fire	Extinguishing
2.2	58 min	63 min
2.3	58 min	62 min
2.4	55 min	58 min



Test 2.2 Test 2.3 Test 2.4

RW1to RW4 different stone wool products
GWF1 and GWF2 different heat-resistant glass wool products

Figure 4 – Test assemblies [5]

Only test walls without cladding are investigated in this study to eliminate the uncertainty of failure time of cladding, see Figure 4. Test results are published in [3].

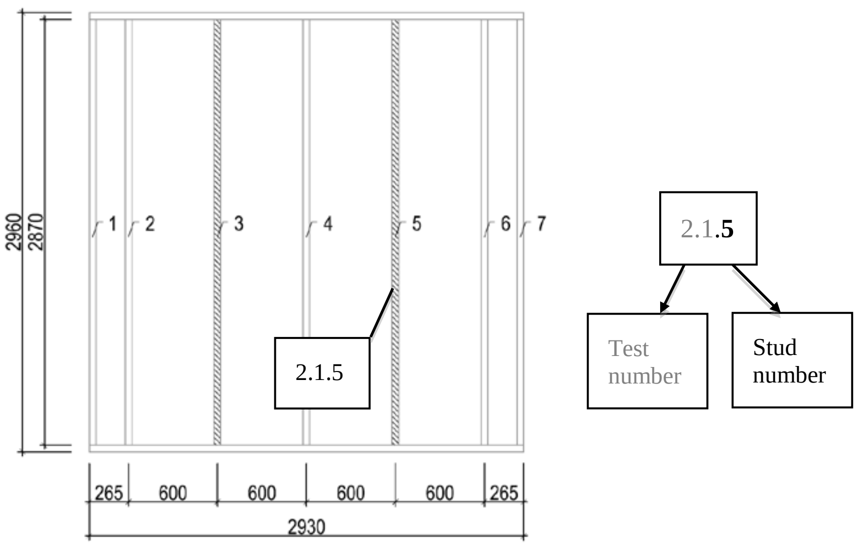
Strength graded wood, class C24, was used for wall studs. Produced by Stora Enso Imavere sawmill in Estonia. All studs were cut from the same batch of raw material. Characteristic density of the studs was measured from 404 to 538 kg/m^3.

Stone wool (rock wool) is a mineral wool manufactured predominantly from molten naturally occurred igneous rocks [13]. The maximum service temperature of stone wool is usually around 1000 °C. Stone wool used in tests was produced in 4 different factories. Densities of stone wool insulations, used in test structures, were 28 to 37 kg/m^3.

Heat-resistant glass wool (glass wool with high maximum service temperature) is a new innovative glass wool with high maximum service temperature. It is resistant to high temperatures. This is achieved with using proprietary and patented glass compound. The material is manufactured using technology, similar to traditional glass wool. Difference lies in higher quality of the raw material and higher temperature in production process. Proprietary and patented glass compound adds very high temperature resistance. Insulation properties of the material at normal temperatures are similar to the traditional glass wool. Densities of heat-resistant glass wool insulations, used in test assemblies of this study, were 14 and 21 kg/m^3.

Table 3 – Densities of tested insulation materials

Material	Densities, kg/m^3	Average density, kg/m^3
Heat-resistant glass wool GWF2	20,5 to 21,1	21,0
Heat-resistant glass wool GWF1	13,8 to 14,7	14,3
Stone wool, RW4	29,0 to 30,0	29,4
Stone wool, RW3	36,2 to 37,1	36,6
Stone wool, RW2	28,9	28,9
Stone wool, RW1	27,9 to 30,5	29,4



3, 5 – scanned studs (hatched)

Figure 5 – Definition of stud numbers of tested walls. View from the fire side

4 ANALYSIS OF CHARRED CROSS-SECTIONS

After the fire tests, the studs were saved in whole length. Char layer was mechanically removed from the studs, which were under investigation. Studs were scanned and three dimensional models created. Cross-section properties and densities of the studs were measured for each 50 mm slice.

For creating three dimensional models, the burnt studs were scanned by optical three dimensional scanner ATOS (Advanced Topometric Sensor) II in Tallinn University of Technology, Faculty of Mechanical Engineering, Department of Mechatronics, see Figure 6. For the measurement of objects, reference targets were attached to the object, see Figure 7. These targets define the object coordinate system in the particular object ranges. The single views were recorded with the sensor. The different views were transformed automatically into the object coordinate system of the ATOS II software using the reference targets. When recording the views, it is important that at least three reference targets are visible for both ATOS II cameras simultaneously. Their 3D coordinates were determined in the ATOS II sensor coordinate system and then transformed into the global coordinate system. The system checks for disturbances like ambient vibrations and automatically repeats the measurement if necessary [7]. The measured data were exported in computer-aided design programs for further three-dimensional analysis. Digitized three-dimensional model of one wall stud is shown in Figure 8.

Detailed section properties of all charred cross-sections are given in [15].

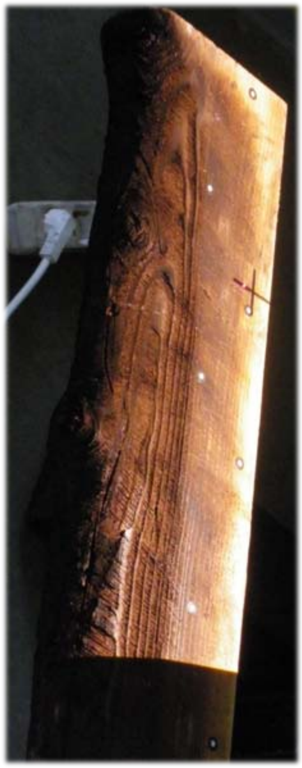



Figure 6 – 3 dimensional scanner ATOS II.

Figure 7 – Detail with reference targets.

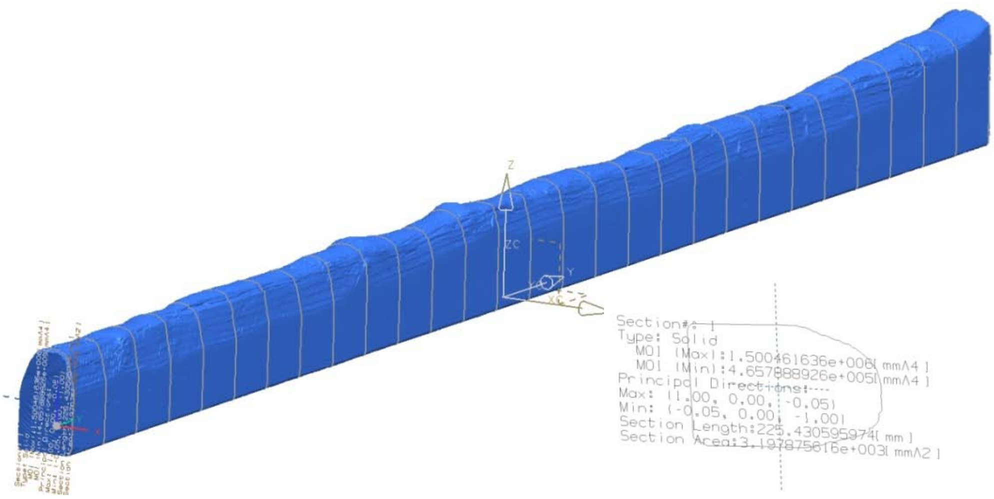


Figure 8 – Digitized 3 dimensional model with example of cross-section data.

5 MEASURING DENSITIES

Densities were measured by X-ray scanner which was combined with optical vibration scanner *Goldeneye 706*, in Stora Enso Imavere sawmill in Estonia.

The Goldeneye is designed for linear board flow and it provides ‘multi-sensorial’ scanning that includes:

- Laser scanning for geometric measurement;
- 4-face colour camera scanning for external characteristics;
- X-ray scanning for density measurement, knot identification and strength prediction.

The X-ray scanning resolution is around 0,8 mm across the board and 5 mm along the board at 450 m/min feedrate [16]. Density was determined by weighing the mass of timber or X-ray scanning with moisture determination. Goldeneye uses X-ray to determine knots and density of a board. The radiation is partially absorbed, depending on the thickness, moisture content and density of the board, this results in a grey scale image which can be processed by means of image processing. Since the density of knots is approximately twice as high as the density of the surrounding clear wood, knots can be detected accurately regarding size and position. The non-contact method allows also high speed operation – at 1600 scans/sec combined with an infeed of 400 m/min, a resolution of 4 mm in the lenght direction is achieved. X-ray scanner gives stable knottiness and density signals giving high repeatable results [16].

Optical vibration measurement (OVM) in order to determine the characteristic frequency is performed by hitting the boards during cross feeding by special ball-shaped hitting device on the front side of the board. The mechanical excitation causes the board to vibrate. For optimum performance the front side of the board has to be plane, so a chipping tool is typically used to prepare the surface of the board. A laser vibrometer is used to detect the characteristic vibrations of the board. The laser vibrometer gives a highly stable signal yielding highly repeatable results else if the board is turned or flipped. The instrument is housed in a protective casting with small footprint [16].

As mentioned, the best performance in predicting strength and stiffness is achieved by combining different and independent indicating properties. The best result is achieved by combining knottiness, density and characteristic frequency. This is achieved by connecting the X-ray scanner and vibration measurement in the same grading process. In a typical installation the vibration measurement is performed in cross feeding before of the planer intake. X-ray scanner is placed direct after the planer. The information of the vibrometer is traced until X-ray scanner analyses the board. At this point, data fusion is performed and the vibration information is used with the other indicating properties to predict strength and stiffness [16].

6 VARIABILITY OF CHARRING DEPTH AND DENSITY

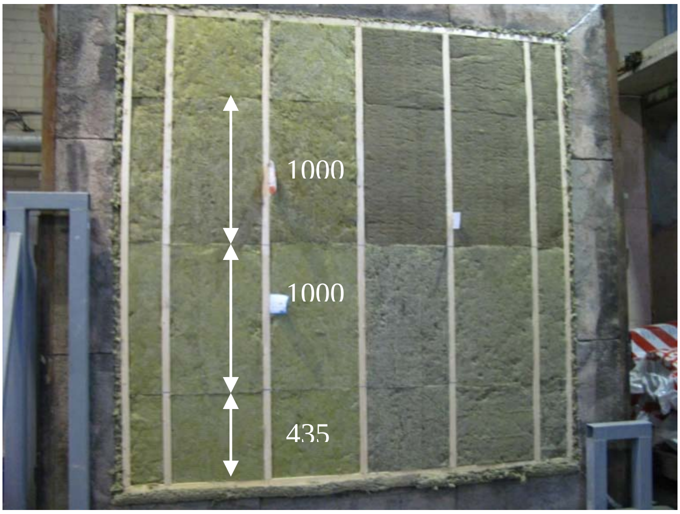
Six studs and six different heat-resistant insulation materials were under investigation. Only those without cladding on the fire exposed side were studied. Minimum and maximum values of densities were found and according to value of density, notional charring was taken into account. Two different examples of section modulus of residual cross-sections and respective densities in the full stud length are shown in Figures 10 and 11. Figure 10 represents a stud with stone wool insulation (stud number 2.2.5) and Figure 11 represents a stud insulated with heat-resistant glass wool (stud number 2.4.3). Variability of section modulus of charred cross-sections and density is remarkable. The differences in densities of wood within one stud have measured up to 41%. Peaks in Figures 10 and 11 show probably the places of knots. The knots have higher density from the surrounding wood. Charring depth calculated according to EN 1995-1-2 is shown with smooth line in Figures 10 and 11. Charring depth using new value for cross-section factor (k_s=1,6) is shown with dashed line in Figures 10 and 11.

The difference in charring rate as a result of changing one property or factor varies also, as it can be seen in Table 4. Difference in charring rate was 2,5% to 11,2% in the case of stone wool and 3,2% to 5,0% in the case of heat-resistant glass wool within one stud. Higher charring rates noticed for lower densities of timber and for lower densities of insulation.

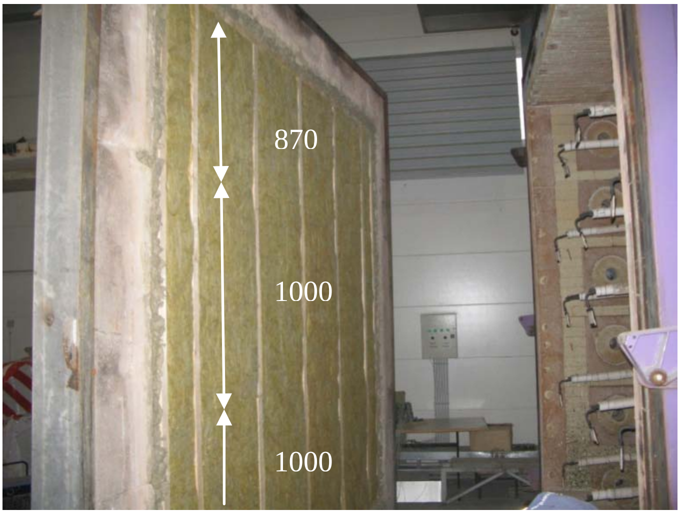
Horizontal joints of insulation are shown in Figures 9. Places of joints are marked on Figures 10 and 11 with dotted line. Although the heat-resistant glass wool have a thermal expansion on joints, the bigger charring depth is measured at the places of joints of insulation. This has been studied in [15] that only outer part of joints of heat-resistant glass wool open up on fire exposed side and stay closed at unexposed side. Timber studs insulated by stone wool did not show bigger charring depth at joints of insulation, because the shrinkage of stone wool occur normally at whole thickness.

Table 4. – Density of timber and insulation affecting charring rate of tests 2.2 to 2.4, see Figure 5 for locations.

Stud No.	Type of insulation	Density of insulation [kg/m^3]	Density of timber [kg/m^3]	Difference in density [%]	$d_{char,n}$ [mm]	Difference in charring rate [%]
2.2.3	RW1	29	467 to 599	22,0	78,6 to 80,6	2,5
2.2.3	RW3	37	501 to 704	28,8	74,0 to 83,3	11,2
2.2.5	RW2	29	434 to 649	33,1	86,4 to 90,2	4,2
2.2.5	RW4	29	448 to 762	41,2	78,4 to 85,1	7,9
2.3.3	GWF2	21	512 to 723	29,2	77,8 to 81,9	5,0
2.3.5	GWF1	14	492 to 658	25,2	87,4 to 90,3	3,2
2.4.3	GWF2	21	456 to 702	35,0	84,7 to 87,6	3,3
2.4.5	RW4	29	524 to 768	31,8	70,5 to 74,8	5,8



Test 2.2.



Tests 2.3 and 2.4.

Figure 9 – Test walls before the fire test. Location of joints of insulation.

The studs investigated in the study, where all produced in the same batch. Moisture content was 11 to 12% for all of the studs. Tests were run without claddings at fire exposed side to eliminate the uncertainty of claddings failure. That makes the results comparable and the difference in measured charring rates is mostly caused by density and size effect of cross-section. The size effect of the same studs was researched in [15] by the author of this paper. The recommended increased value for size factor is used in this study. The influence not considered in real charring rate is most probably the density of wood.

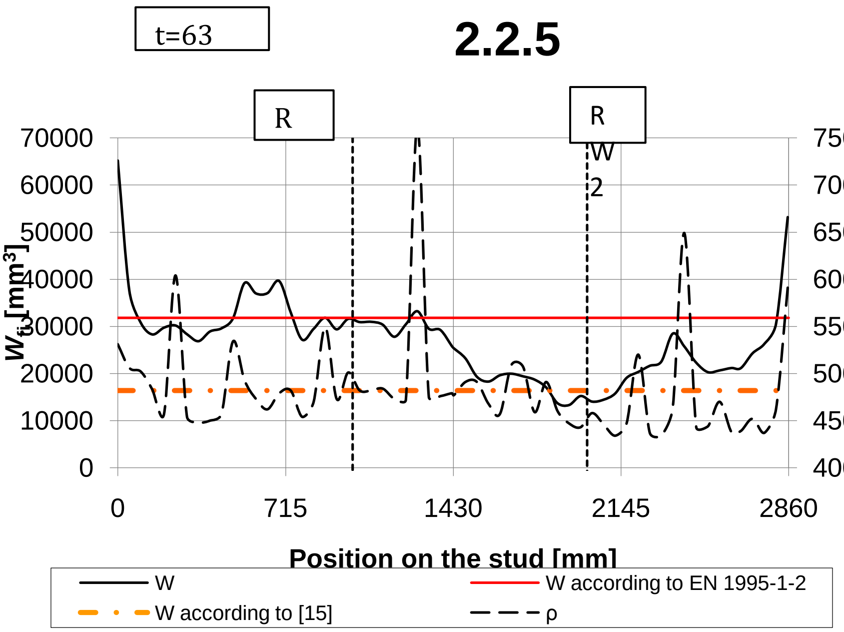


Figure 10 – Variability of section modulus of charred cross-sections and density for stud 2.2.5.

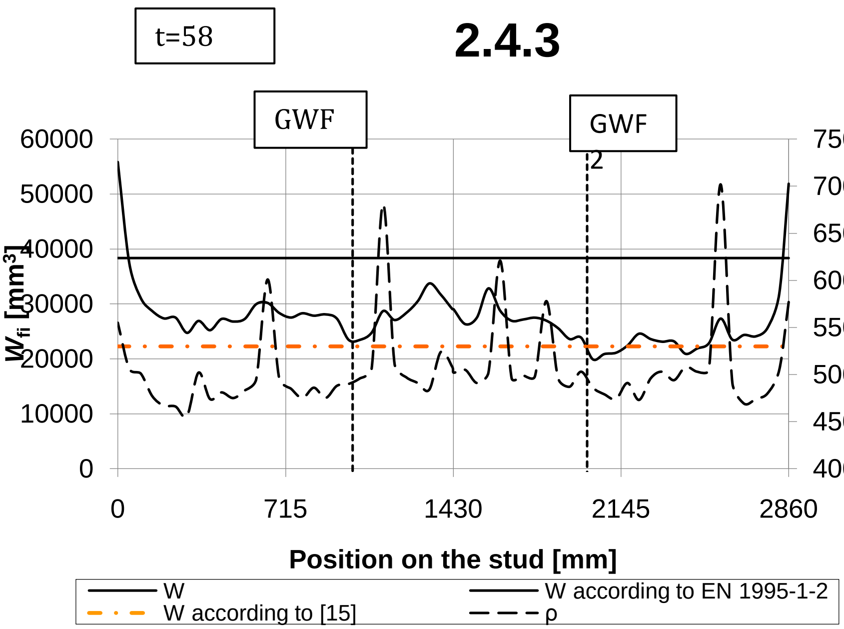


Figure 11 – Variability of section modulus of charred cross-sections and density for stud 2.4.3.

7 CHARRING RELATED TO DENSITY

Relation between charring rate of insulated member and density of wood is shown in Figure 12 and Figure 13. Each point represents different 50 mm slice of scanned stud. Figure 12 shows the sections with stone wool insulation and Figure 13 shows the sections with heat-resistant glass wool insulation.

Linear trend line is used because of better correlation with test data. The effect of density on charring rate is described as following:

Charring rate for timber frame members insulated by stone wool

$$\beta = 1{,}44 - \rho/1428 \tag{7}$$

Charring rate for timber frame members insulated by heat-resistant glass wool

$$\beta = 1{,}32 - \rho/833 \tag{8}$$

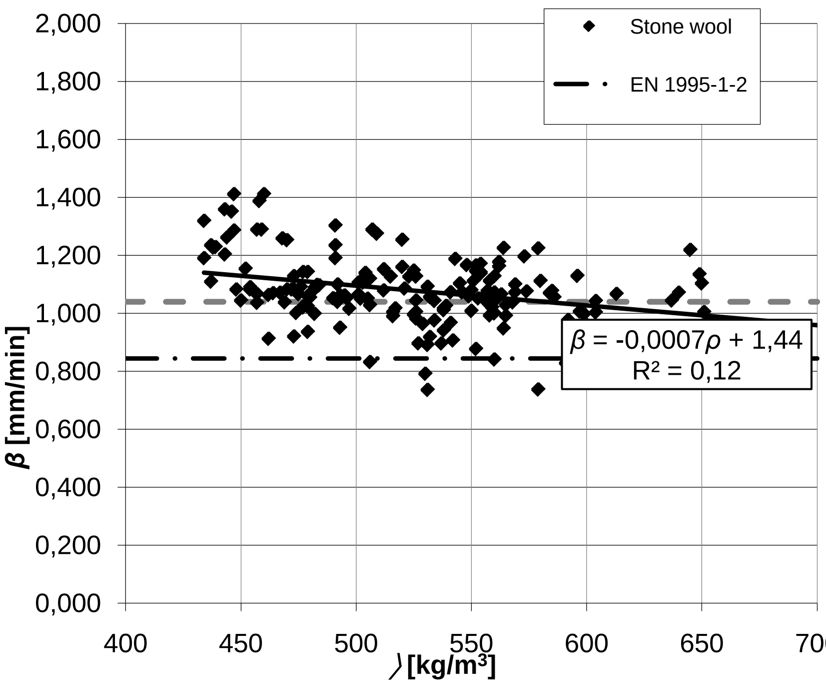


Figure 12 – Relation between density and charring rate of timber members insulated by stone wool

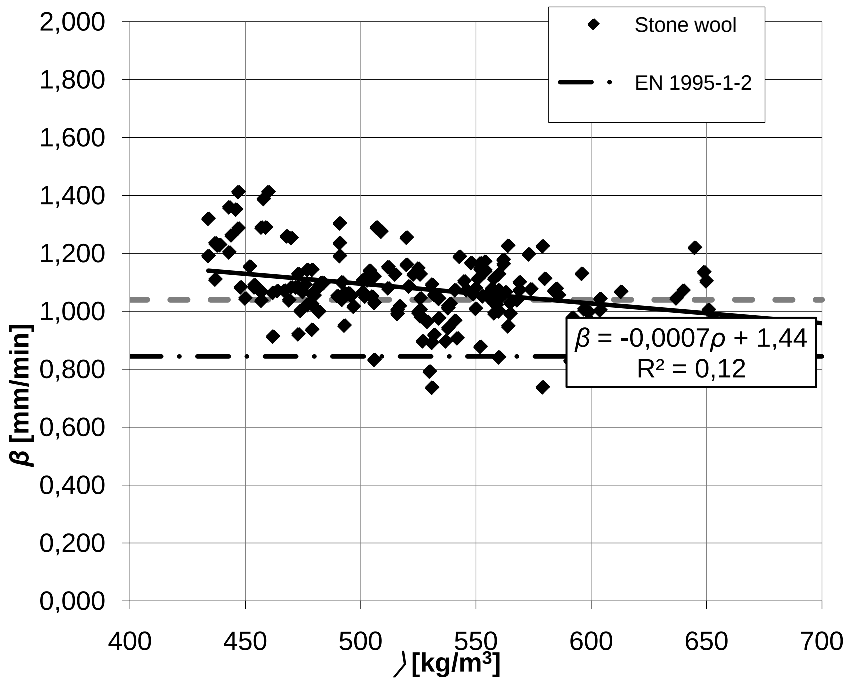


Figure 13 – Relation between density and charring rate of timber members insulated by heat-resistant glass wool

Charring rate expressed in Equations (7) and (8) consist mainly the size effect and effect of density, see Equation (9). To express the influence of density to the charring rate, the density coefficient k_{dens} is introduced just for this study. Cross-section factor k_s in Equation (9) is taken according to new results in [15]. In the present stage of studies the values of densities obtained from tests do not match to characteristic densities of strength classes according to EN 338 [17].

$$\beta = k_{dens}\, k_s\, \beta_0 \tag{9}$$

where

k_s=1,6
β_0=0,65 mm/min

According to EN 1995-1-2 there is no difference of charring rate for densities more than 290 kg/m^3. The following coefficient for charring rate related to density of wood is derived from Equations (7), (8) and (9), based on trend line of the results of this study and it is based on density of 290 kg/m^3:

For stone wool

$$k_{\mathrm{dens}} = 1{,}14 - \frac{\rho}{2230} \tag{10}$$

for heat-resistant glass wool

$$k_{\mathrm{dens}} = 1{,}20 - \frac{\rho}{1300} \tag{11}$$

where ρ is the density of wood in kg/m^3.

Results of this study showed that charring of timber members insulated by heat-resistant insulation could be faster in reality than the design model in EN 1995-1-2. This is reported in [15]. In this paper the increased charring rate with the new proposed value for cross-section factor k_s is used.

The difference in density of wood within a single wall stud has been measured as up to 41% in many cases. The charring rate can also have a wide variation within the full length of a single timber wall stud. In this study, the effect of the density of the wood is assumed to influence the charring rate by up to 20%.

8 CONCLUSIONS

Quite remarkable variation of wood density, up to 41% within a single wall stud was registered in this study.

Charring rate is not uniform within the full length of a single timber wall stud. It can vary up to 20%. This corresponds to the variation of density of wood.

Charring rate of wood is dependent on the insulation materials surrounding timber member on the wide sides. Tests showed different charring rates for studs insulated with heat-resistant glass wool or with stone wool when using the same test conditions.

Joints between insulation batts often increase charring rates in the case of using heat-resistant glass wool.

Factor relating charring rate to density of wood in timber frame wall assemblies is provided as a result of this study but it is based on small number of tests and shall be developed further.

REFERENCES

1. EN 1995-1-2:2004, Eurocode 5: Design of timber structures - Part 1-2: General rules-structural fire design. European Standard. European Committee for Standardization, Brussels, 2004.
2. Babrauskas V. Charring rate of wood as a tool for fire investigations. Fire Safety Journal 40 (2005). Elsevier. Pp 528-554.
3. Cachim P., Franssen J-M. Assessment of Eurocode 5 charring rate calculation methods. Fire Technology. 46 (2010). Springer Science & Business Media. Pp 169-181
4. Friquin, K.L. Charring Rates of Heavy Timber Structures for Fire Safety Design. Thesis for the degree of Philosphiae Doctor. NTNU. Trondheim, 2010
5. Schaffer EL. Charring rate of selected woods - transverse to grain. FPL Research Paper 69. Forest Products Laboratory: Madison, Wisconsin, USA: 1967
6. White, R.H. Charring rates of different wood species. PhD, University of Wisconsin-Madison. Madison, USA 1988.
7. Syme D. Verification of charring equations for Australian timbers based on full-scale fire resistance tests. Proceedings of Pacific Timber Engineering Conference, vol 1. Australia, Queensland University of Technology. 1994, pp 619-623
8. Australian standard AS 1720.4 Timber structures: Fire resistance of structural timber members.
9. König J, Walleij L. Timber frame assemblies exposed to standard and parametric fires. Part 2: A Design model for standard fire exposure. Trätek, Stockholm, 2000.
10. Just A. Full scale wall tests of timber frame assemblies. Test report. Tallinn : Tallinn University of Technology, 2009.
11. Schmid J, König J. Model scale fire tests of Isover Ultimate – step 1.2 – Load Bearing Capacity. SP report 2010:26. SP Trätek, Stockholm, 2010.
12. Tera T. Charring of timber studs insulated by heat-resistant glass wool and rock wool. Master thesis at Tallinn University of Technology. Tallinn, 2010.
13. EN 13162:2008. Thermal insulation products for buildings - Factory made mineral wool products - Specification. European Standard. European Committee for Standardization, Brussels, 2008.
14. Thali, M.J., Braun, M., Dirnhofer, R. *Optical 3D surface digitizing in forensic medicine: 3D dokumentation of skin and bone injuries*. Forensic Science International, Elsevier Ltd, 2003.
15. Just A, Schmid J, König J. The effect of insulation on charring of timber frame members. SP report 2010:30. SP Trätek, Stockholm, 2010.
16. Gjudiceandrea F. Stress Grading Lumber by a Combination of Vibration Stress Waves and X-ray Scanning. Italy, 2005.
17. EN 338:2008, Structural timber – Strength classes, European Standard, CEN, European Committee for Standardization, Brussels, 2008.

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Denis Juganson. Puitpaneelide teoreetiline ja katseline tulepüsivuse uurimine. (Theoretical and experimental investigation of fire performance of wood framed walls). Tallinn University of Technology, 2007

Oliver Orula. Puidust seinapaneelide tulepüsivuse teoreetiline ja katseline uurimine. (Experimental and theoretical investigation of fire resistance of timber frame walls). Tallinn University of Technology, 2007

Aili Veider. Klaasvillisolatsiooniga puitkarkass-seinte kandevõime tulekahju-olukorras (Fire resistance of timber frame assemblies with glass fibre insulation). Estonian University of Life Science. Tartu, 2008.

Karoline Karlsson, Narzisa Munez. Failure times of gypsum claddings in standard fire. Royal Swedish University of Technology. Stockholm, 2009.

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Juhendatud magistritöid:

Denis Juganson. Puitpaneelide teoreetiline ja katseline tulepüsivuse uurimine. Tallinna Tehnikaülikool, 2007

Oliver Orula. Puidust seinapaneelide tulepüsivuse teoreetiline ja katseline uurimine. Tallinna Tehnikaülikool, 2007

Aili Veider. Klaasvillisolatsiooniga puitkarkass-seinte kandevõime tulekahjuolukorras. Eesti Maaülikool. Tartu, 2008.

Karoline Karlsson, Narzisa Munez. Failure times of gypsum claddings in standard fire. (Kipsist katteplaatide tõrketekkeajad standardtulekahjus). Rootsi Kuninglik Tehnikaülikool. Stockholm, 2009.

Tarmo Tera. Kuumakindla klaasvilla ja kivivillaga isoleeritud puidust seinapostide söestumine. Tallinna Tehnikaülikool, 2010

DISSERTATIONS DEFENDED AT TALLINN UNIVERSITY OF TECHNOLOGY ON *CIVIL ENGINEERING*

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