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EHITUSTEADUSKOND
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PROTECTIVE EFFECT OF GYPSUM PLASTERBOARDS FOR THE FIRE DESIGN OF TIMBER STRUCTURES

KIPSPLAATIDE KAITSVA MÕJU ARVESTAMINE PUITTARINDITE TULEPÜSIVUSE PROJEKTEERIMISEL

EEK 60 LT

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……………………

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FIRE PROTECTION BY GYPSUM PLASTERBOARDS. RECOMMENDATIONS FOR PARAMETERS FOR FIRE DESIGN OF TIMBER STRUCTURES

Tulekaitse kipsplaatidega.

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Kipsplaatide täismõõdus tulekatsete andmebaasi alusel pakkuda välja erinevate kipsplaatkatete kaitseaegade (söestumise algusaeg ning tõrketekkeaeg) arvutuseeskirjad EN 1995-1-2 arvutusmeetodite jaoks.

Lõputöö sisu:

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Andmed esitada 5%-fraktiilväärtustena.

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Töö osa nimetus	Konsultandi nimi	Konsultandi allkiri	Kuupäev

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Contents

1 Introduction

1.1 General

Throughout the history, wood has been used in building constructions. Wood has good thermal and accoustic properties, it is aesthetically pleasing, easy to work with and durable, if properly maintained and most importantly, a renewable resource, if used wisely. Due to all its positive properties, the usage of wood in building constructions has increased over the last decades, especially when it comes to smaller residential and industrial buildings. In every case, it is important to grant the safety of the building. An important part of the safety design is the resistance to fire. Since wood is a combustible material, it is essential to protect wooden constructions from high temperatures in case of fire.

In light timber frame assemblies, which are widely used as wall or floor partitions in different constructions, the timber frame is protected by the cladding attached to each side of the frame, with void or insulated cavities. The cladding can consist of different types of wood-based panels or gypsum boards. Gypsum boards are widely used because of their fire protective properties. A cladding of gypsum boards slows down the temperature rise of wood in fire, as long as it remains in place. As the effect of gypsum cladding has an important role in the fire safety of timber frame assemblies, the start time of charring and the failure time of the board are therefore important properties for the fire safety design of timber frame constructions. It is desirable to model these effects in such way that they reflect real performance.

The failure of the cladding of gypsum plasterboards can occur due to the thermal degradation of the cladding or due to the pull-out failure of the fasteners. European standard for the fire design of wooden constructions EN 1995-1-2 gives simplified design rules for calculation of pull-out failure. However, the failure time of gypsum plasterboard type F should be determined on the basis of tests. As the thermo-mechanical properties of gypsum plasterboard type F are not part of the classification given in the European product standard for gypsum plasterboards EN 520, failure times of different makes may vary considerably. No generic failure times for gypsum plasterboard type F are known in practise. In case the producer is unable to provide the failure time of the board, including information about the spacing of joints, studs, battens, edge distances and spacing of fasteners, for fire design in accordance with EN 1995-1-2, there is a need for simple design rules for the start time of charring and the failure time of gypsum boards.

Alternative design methods for the start time of charring and the failure time of the gypsum boards are presented in „Fire safety in timber buildings. Technical guideline for Europe“ [1]. The Component Additive Method [2] enables to find the separating function of timber constructions and can be used to find the start time of charring, but does not provide rules for calculating failure time of gypsum boards. Based on the first analysis of the database of full-scale fire test results at SP Technical Fire Research Institute, conservative design equations were developed to find the start time of charring and failure time of the gypsum board [3]. These equations took into consideration all test results in the database, therefore they tend to be too conservative.

1.2 Previous studies

This chapter describes the previous studies in the field of determining the fire resistance of gypsum boards used in timber frame assemblies.

As a part of the research project "Fire safe wooden buildings" investigations were carried out at SP Technical Research Institute of Sweden. Results of the research were published in report by König and Walleij [30]. A charring model for the determination of the residual cross section of the timber member and a mechanical model giving modification factors for the reduction of mechanical properties of the residual cross section for solid timber frame assemblies with claddings of gypsum boards or gypsum boards backed with wood-based panels and cavity insulation of rock or glass fibre exposed to ISO 834 standard fire exposure was developed. Based on the research, the failure time of the gypsum cladding is dependent on two parameters: the temperature of mechanical degradation of the material and the length of the fasteners where charring occurs behind the lining. The results of this study are the basis for calculating the start time of charring behind gypsum claddings in EN 1995-1-2.

The charring of wood studs protected by gypsum plasterboards has been studied in SP Trätek – Swedish Institute of Wood Technology and Research by Östman and Tsantaridis [31]. As a result, a simple small scale technique was developed to measure the heat transfer through the gypsum boards and the charring depth of wood studs. Based on the results, the use of gypsum plasterboard, irrespective of type, increases the time to reach the start of charring temperature in wood stud.

Sultan [23] [24] [32] has investigated the effects that the set-up of the assembly has on the fire resistance, by conducting a large number of full scale tests for timber lightweight wall and floor assemblies with gypsum boards. He has found that the temperature of gypsum board when the first piece falls off is not an appropriate criterion for gypsum board failure, as it varies too extensively with no identifiable correlation to assembly parameters.

In Switzerland, a comprehensive research project on the behaviour of protective claddings made of gypsum boards and wood-based panels was carried out in ETH Zurich and as a part of it fire behaviour of gypsum boards was investigated with a large number of small-scale fire tests by Schleifer et.al. [29]. As a result, a component additive method was developed for the verification of the insulation and integrity criteria of light timber frame wall and floor assemblies with gypsum boards, which was also published in “Fire safety in timber buildings. Technical guideline for Europe”. [1]

1.3 Aim of this thesis

The aims of this thesis are:

- To add new data and organize the database of full-scale fire test results of assemblies including claddings of gypsum plasterboards
- Analyse the protective effect that the type of gypsum board, the number of layers, insulation or void cavities and loading have on timber frame assemblies in fire
- Find 5% fractile values for the start time of charring and the failure time of the gypsum boards for gypsum claddings by the number of layers and type of gypsum board
- Compare the results with other methods and provide design rules for the protection times of gypsum boards based on the test results of the database.

1.4 Acknowledgements

I would like to acknowledge all the institutions and people that helped me with composing my thesis.

First of all, my supervisor, Alar Just, who helped me with his guidance and support throughout the whole process. I would like to thank him for entrusting the subject of this thesis to me, for introducing and explaining the world of fire safety to me, for helping me with his knowledge in writing and composing of the thesis and for the opportunity to collaborate with SP Technical Research Institute of Sweden.

I would also like to thank SP Technical Research Institute of Sweden, for hosting me in Stockholm and all the people in the fire group, who contributed to my work with their knowledge and experience. Especially Birgit, Lazaros, Joachim, Daniel, Magdalena and Mattia who supported me in the process of writing my thesis.

Last, but not least, I would like to thank my family and friends, for supporting me in writing the thesis and throughout the whole period of my studies.

2 Gypsum and gypsum plasterboards

2.1 Gypsum

2.1.1 Gypsum as a material

Gypsum is a soft white or grey mineral called *calcium sulfate dihydroxide* or *hydrated calcium sulphate*. The chemical formula of gypsum is

$$CaSO_4 * 2H_2O$$

Gypsum consists of calcium, sulphur bound to oxygen and water. For each calcium sulfate molecule, there are two water molecules.

Natural gypsum is the most common sulfate mineral. In addition to natural gypsum, industrial gypsum is used in the making of gypsum boards. Industrial gypsum, also known as synthetic gypsum, is a by-product from the flue gas cleaning of power stations. From chemical and crystallographical point of view, it is identical to natural gypsum. However the difference between the two types is that industrial gypsum has smaller crystals than natural gypsum. Natural gypsum exists as a solid rock and it has taken thousands of years to crystallize. Prior to its use in gypsum boards, it must be crushed, ground and dried, whereas synthetic gypsum is already finely divided. [4]

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. [3]

2.1.2 Natural gypsum

Natural gypsum is a common constituent of sedimentary rocks, particularly marine salt deposits and soils formed directly by evaporation or by hydration of anhydrite. It was formed by the reaction between sulfuric acid and carbonate rock in oxidizing sulfide deposits, and by the action of sulfurous volcanic gases on surrounding calcium bearing rock. Gypsum mineral exists as efflorescences in mines and as speleothems in caves. Gypsum rock contains 21% chemically combined water by weight. [5]

Natural gypsum is normally white or light grey but depending on the impurities present can also be pink, dark grey or almost black. It exists in large quantities in over 85 countries.

Especially fine or large specimens can be found in Italy, Germany, Austria, France, Spain, Poland, Australia, Mexcio and USA. [4]

In order to produce gypsum products, natural gypsum rock is mined or quarried, then crushed and ground into a powder. [5] First step in the manufacturing process is driving the moisture out of the grounded gypsum powder to create the powdery white material of calcium sulphate hemihydrate $CaSO_4 * \frac{1}{2} H_2O$, commonly known as "Plaster of Paris". The dehydration reaction, called calcination, is an endothermic decomposition reaction which occurs between 100 °C and 120 °C:

$$CaSO_4 * 2H_2O \rightarrow \; CaSO_4 * \frac{1}{2} H_2O + 1\frac{1}{2} H_2O \tag{1}$$

When the powder is mixed with water and formed into flat sheets of gypsum plaster, the reverse action takes place:

$$CaSO_4 * \frac{1}{2} H_2O + 1\frac{1}{2} H_2O \rightarrow \; CaSO_4 * 2H_2O \tag{2}$$

The resulting gypsum contains 21% of chemically bound water and about 79% of calcium sulphate, which is inert below a temperature of 1200°C. [3]

2.1.3 Industrial gypsum

Industrial gypsum, also known as FGD gypsum, has been used in gypsum boards for over 30 years. The abbreviation FGD derives from *flue gas desulfurization*. FGD gypsum is produced as a by-product of desulfurization of flue gas from the stacks of fossil-fuelled power plants, where polluting gases from smoke stacks can be purified into a hard substance and manufactured into gypsum. [5] The production process can be seen in Figure 1.

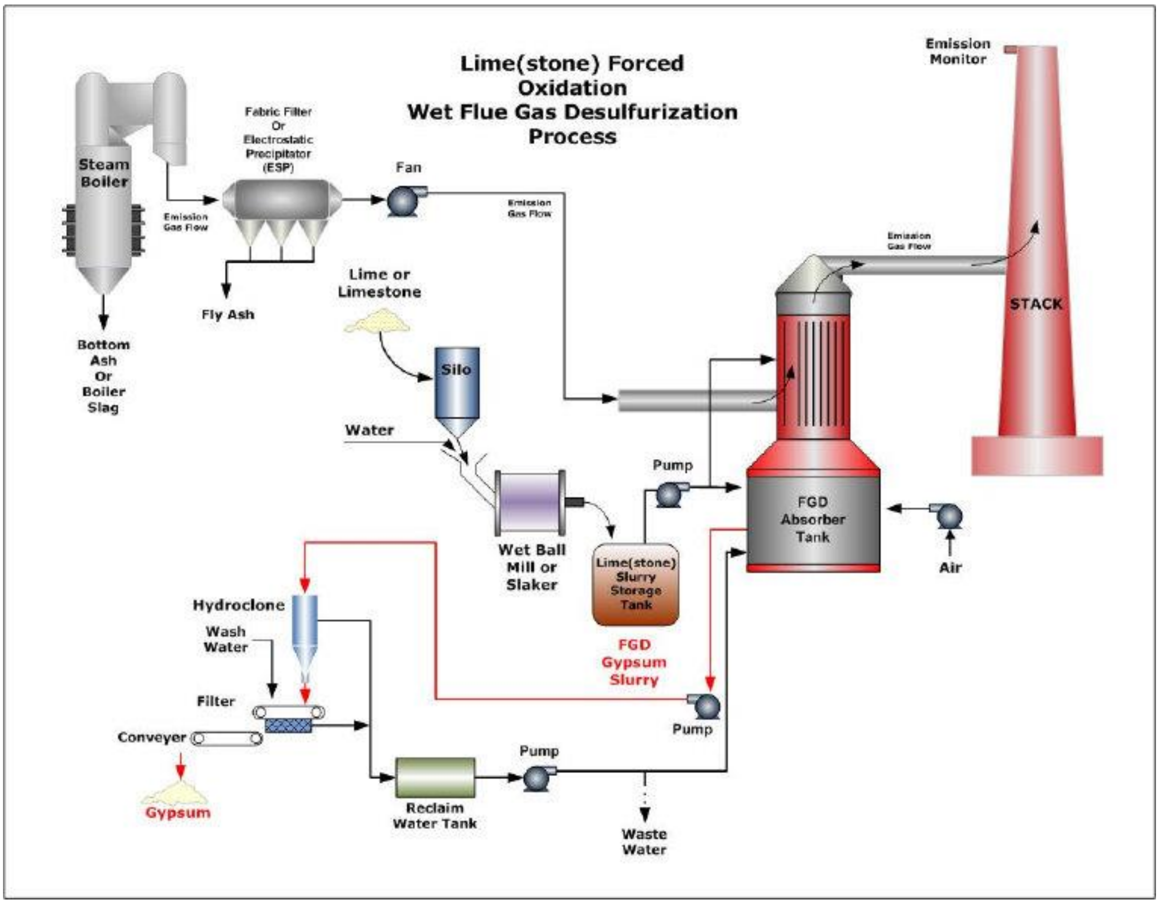


Figure 1 - Production process of industrial (FGD) gypsum [6]

Instead of merely storing the "waste" from fossil fuelled power plants, the production and sales of FGD gypsum encourages power producers to recycle it. In addition to that, using FGD gypsum in gypsum boards enables us to save natural gypsum material.

2.1.4 Behaviour of gypsum in fire

The chemically bound water in gypsum plaster contributes to its excellent fire-resistant behaviour. When gypsum plaster is exposed to heat at a temperature of at least 80°C, the calcination process takes place and the chemically bound water prevents the fire to penetrate the material during the evaporation. The calcination process is usually complete when gypsum reaches a temperature of 125 °C, which is under the melting point, and becomes an anhydrate $CaSO_4$. This anhydrate is inert below a temperature of 1200°C and has a low thermal conductivity, which helps to sustain a large temperature gradient between the exposed and unexposed surfaces. To make the chemical change which releases the water in the crystal structure, a significant amount of energy is needed. Complete dehydration does not occur until the temperature reaches about 700°C, requiring additional energy input. [7] [8]

2.2 Gypsum plasterboards

2.2.1 Definition and types

According to EN 520 gypsum plasterboard is a product composed of a plaster core encased in, and firmly bonded to strong durable paper liner to form a flat rectangular board. The paper adds tensile strength to the gypsum core to resist forces experienced in handling and use of the gypsum boards. The paper surfaces may vary according to the use of the particular type of board and the core may contain additives to impart additional properties. Raw materials for gypsum plasterboards are gypsum, paper and additives. [9] [10]

Gypsum plasterboard, also known as drywall, is a wildly used building material for wall, ceiling, and partition systems in residential, institutional, and commercial structures. The reasons for its popularity are easy installation, ease of production and low cost, versatility, good accoustic, thermal and fire-resisting properties. A monolithic surface is provided when joints and fastener heads are covered with a joint treatment system.

In this study, gypsum plasterboards are referred to as gypsum boards.

Types of gypsum plasterboards according to EN 520 are presented in Table 1:

Table 1 - Types of gypsum plasterboards

Type	**Defined performance**
A	Plasterboard with a face to which suitable gypsum plasters or decoration may be applied
F	Fire protection board with improved core cohesion at high temperatures
H	Plasterboard with reduced water absorption rate
E	Boards specifically manufactured to be used as sheathing in external walls and are not intended to receive decoration
P	Boards, which have a face intended to receive gypsum plaster or to be combined by collage with other materials in form of boards of panels
D	Gypsum plasterboard with controlled density
R	Gypsum plasterboard with enhanced strength
I	Gypsum plasterboard with surface hardness

In this study, abbreviation GtA is used, when referring to Type A board or similar. For Type F, the abbreviation is GtF.

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. [3]

The measurements of gypsum boards vary according to different manufactures. The most common width for gypsum boards is 1200 mm, though 900 mm and 600 mm wide sheets are also produced, mostly for ceiling boards. The length of the boards commonly varies from 2000 to 3600 mm. Most common thicknesses of gypsum boards in the market are 12,5 and 15 mm for type F gypsum boards, 9 and 12,5 mm for type A gypsum boards.

2.2.2 History of gypsum boards

The use of gypsum boards in construction began in the late 19th century in USA, after Augustine Sackett patented "Sackett Board" in 1894. This board consisted of four plies of paper and three layers of stucco plaster. By 1916, this product was a ready-to-finish board for use in construction. Subsequently, an Adamant board was developed, which consisted of a gypsum core faced with top and bottom paper. To meet increasing construction demands, the board was developed further by adopting a round edge and adding foam and fiber into the gypsum core. This product became known as Rocklath and it exists today in various adaptions. [4]

The economic boom of the 1950´s brought upon new innovations in gypsum technology. Gypsum boards became more fire-resistant, adaptable to curved partitions and application in sound control systems. Later air entrainment technology made boards lighter and less brittle, joint treatment materials and systems also evolved. [11]

2.2.3 Manufacturing of gypsum boards

To produce gypsum board, calcined gypsum is mixed with water and additives. Additives can be fibers (paper and/or fiberglass), plasticizers (to reduce the water and hence the drying time), foaming agents, finely ground gypsum crystals as an accelerator, EDTA (Ethylenediaminetetraacetic acid), starch or other chelate as a retarder, wax emulsion or silanes for lower water absorption, and various additives that may decrease mildew and increase fire resistance. For Type F and Type X gypsum boards glass fiber, unexfoliated vermiculite or clay is added, to increase their fire protection properties. [4]

The manufacturing process can be seen in Figure 2. First, a slurry is formed, which is fed between continuous layers of paper on a board machine. As the board moves down a conveyer line, the calcium sulfate recrystallizes or rehydrates, reverting to its original rock state. The paper becomes chemically and mechanically bonded to the core. The board is then cut to length and conveyed through dryers to remove any free moisture. [5]

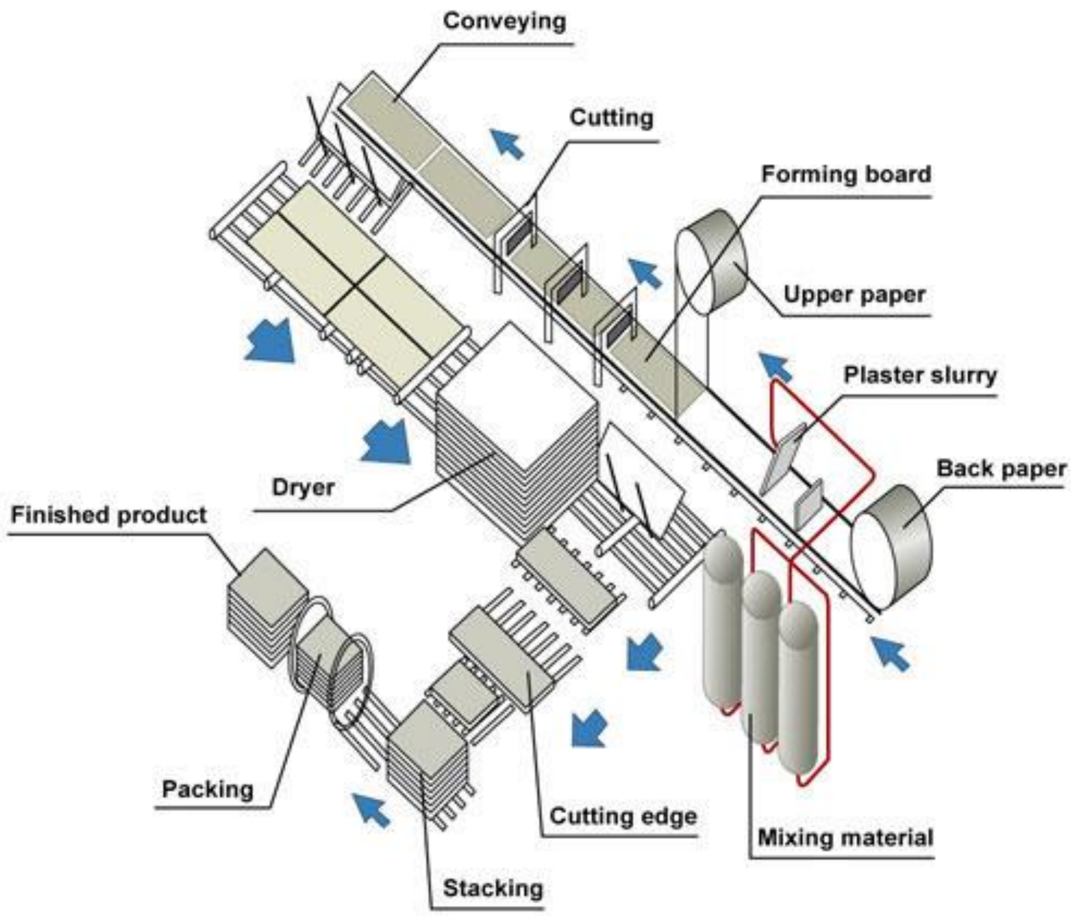
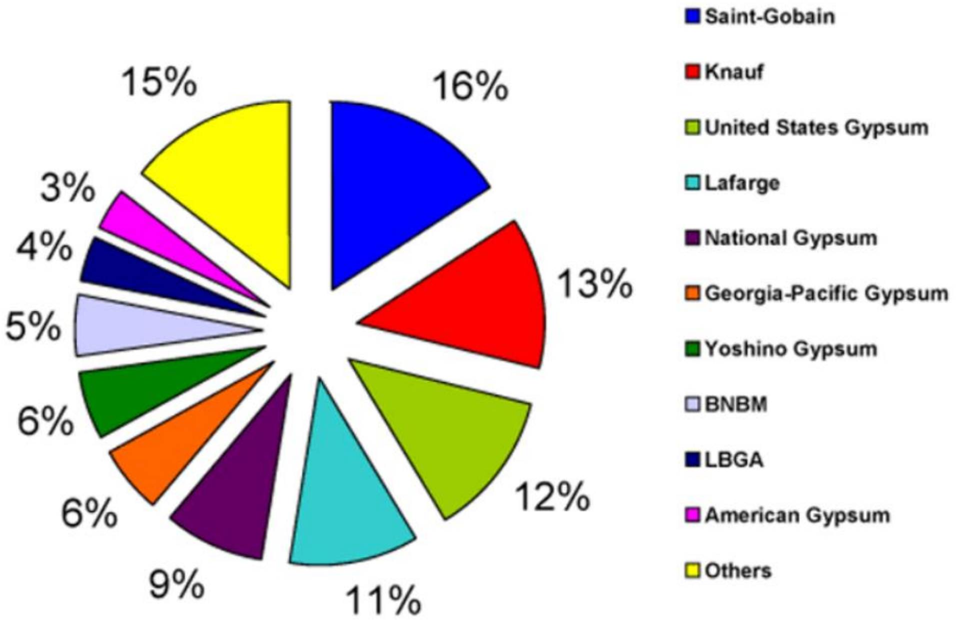


Figure 2 - Manufacturing process of gypsum boards [12]

2.2.4 Overview of producers of gypsum boards

Gypsum boards to some extent are local products, since the long distance transport of the boards is uneconomical due to their heavy weight and fragility. However, the main producers of gypsum boards have joined into big international companies. The biggest gypsum board producers at the year 2009 are presented in Graph 1.



Graph 1 - Top 10 World gypsum board manufacturers in 2009 [13]

Following is a short history of the main gypsum board producers in Europe.

Saint-Gobain Group, the largest gypsum board producer, has a history that dates back to 17th century, when a royal factory for producing glass mirrors was founded in Paris, France. Over the next centuries, the company started manufacturing glass products and today, their products include glass, high-performance materials and different kinds of construction products. Their factories are located throughout North & South America, Europe, Africa, and Asia. Gypsum boards are manufactured under the brand Gyproc, the word coined from Gypsum and Rock. Gypsum board brands Rigips and Placo are also members of Saint-Gobain Group. [13] [14]

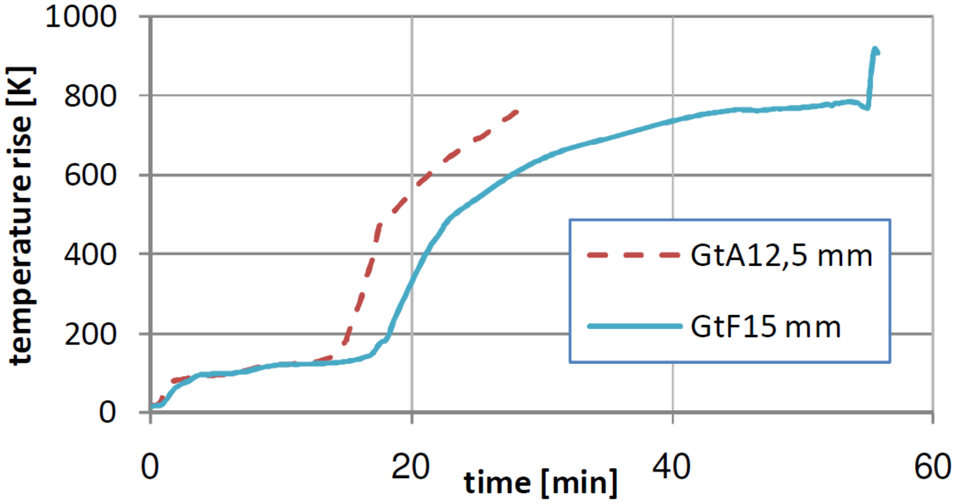
Knauf was founded in 1932 by the brothers Karl and Alfons Knauf, by securing the mining rights to gypsum deposits in Obermosel, Germany. Their first gypsum board factory was established in 1933 and over the years they continued to develop their products and production methods. Today, Knauf is one of the largest producers of gypsum-based building materials in the UK and has over 150 production facilities worldwide. In 1992 Danish company Danogips and in 2004 Norwegian-Polish company Norgips became a part of the Knauf group. [15] [16] [17]

Lafarge, a French based company, was founded in 1833 by regular extraction operations in the limestone quarries at a place called „Lafarge“, which means „the forge“ in French. The company developed limestone and cement products in the 19th century and in 1931 acquired another company producing gypsum in southern France. During the 20th century the company expanded its business to Africa, North America and Asia. However, nearly all of the Group Gypsum activities were disposed of in Asia, Europe, South America, Australia and United States in 2011 and 2013. By the end of 2014, Lafarge had retained Gypsum operations only in a few countries in the Middle East and Africa region. [18] [19]

2.2.5 Assemblies with gypsum boards in fire

2.2.5.1 Behaviour of gypsum boards in fire

As described in paragraph 2.1.4, gypsum is non-combustible and gives no contribution to fire. In fact, the chemically bound water in the boards used in constructions, acts as a built in sprinkler system. One square meter of a 12,5 mm gypsum board contains approximately two litres of chemically bound water in the gypsum core. Its high water content provides up to 90 % of the fire resistance protection of gypsum boards. Gypsum plaster also contains about 3 % of free water, depending on the ambient temperature and relative humidity. Significant energy is required to evaporate the free water and make the chemical change which releases the water in the crystal structure. Therefore, the thickness of the gypsum board affects the fire protective properties of the board. Thicker boards have higher water content per square meter of gypsum board and more enegry is needed in order to evaporate the water. [3]



Graph 2 - Temperature rise behind gypsum boards in fire [3]

In Graph 2, the temperature rise behind a 12,5 mm thick Type A gypsum plasterboard and a 15 mm thick Type F plasterboard can be seen. First, the temperature rises until 80 °C to

100 °C is reached behind the board. The low temperature rise during the first 15min indicates the calcination phase, where water starts to evaporate and the temperature curve is quite horizontal. Evaporation time basically depends on the board thickness. After the evaporation process, the temperature starts to rise again.

Within the first 60 seconds of a fire test, the paper on the surface of the gypsum board ignites and in about 2 minutes it is completely burned away. Therefore the fire protection ability of the gypsum board is related to the ability of gypsum board to remain in place. [20]

In type F and X gypsum boards, glass fibre, unexfoliated vermiculite and, in some plants, clay and fly ash is added to the gypsum, which all contribute to increase the boards resistance to fire.

Glass fibre changes the crack formation of the board, causing a maze of fine cracks rather than a single large crack which can initiate premature failure of a regular gypsum board. When gypsum is heated, a process called ablation takes place. It means that gypsum is transformed into calcium sulfate anhydrite, which has the appearance of a dry cohesionless powder. The glass fibre reinforcement acts as a reinforcement of the board and helps to slow the falling off of the dry cohesionless powder. 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 it shrinks. Stress is transferred from the gypsum to the fibres primarily by the interfacial bond between the two materials. The strength properties of fibre-glass are dependent on the length of the fibres and the orientation of the fibres in the board. Therefore, during the manufacturing process it has to be controlled that the fibres are in the direction of applied forces, so that they can utilize their ultimate tensile strength.

Shrinkage can be reduced with various additives, such as vermiculite. Vermiculite ore exfoliates, which means that it expands resembling an open accordion when subjected to heat and this expansion compensates for the shrinkage of the core due to the calcination of gypsum. As a result, the cracks formed in the core are fewer and smaller. Additionally, the exfoliation process absorbs energy, which slows down the heat transfer through the board.

The exact mechanism for the function of clay is not known, but it increases the fire resistance of the board. However, use of clay in gypsum boards has some negative effects as well, since it affects the setting characteristics and the water demand of the slurry.

Fly ash, chemically known as synthetic pozzolan, is a by-product of natural or man made combustion processes. Fly ash increases the workability of the gypsum core and due to the low thermal conductivity prolongs the heat transfer through the gypsum core. [4] [8] [21]

2.2.5.2 Influence of the assembly

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 frame. The cladding may be a lining or, in the case of floors, a decking or a sub-floor and additional layers. The cavities may be void, partially or completely filled with insulation.

Besides the chemical composition of gypsum boards, the behaviour of gypsum boards in fire is affected by the properties of the assembly. Protection effect of gypsum plasterboards in fire is different when protecting timber slabs, timber frame assemblies with and without insulation or larger beams and columns. Not all the aspects are taken into account with the design methods.

As stated in the previous paragraph, the thickness of the gypsum board has the most significant effect on the fire protective properties of the gypsum cladding. A thicker gypsum cladding slows down the temperature rise and therefore protects the assembly from fire for a longer period of time. However in case of floor assemblies, the thicker and therefore heavier gypsum boards might not significantly increase the failure time of the gypsum cladding, as the weight of the board causes them to fall off sooner than in wall assemblies. The setup of the different types of gypsum boards is also important. In an assembly with two or more layers of gypsum boards, the most important layer shall be on the fire side, as the first layer on the fire side provides the most efficient protection. Therefore, the first layer exposed to fire should be of gypsum board type F. Loosing the first barrier makes it very complicated to gain the same protection with next layers. Previous studies have shown, that 1 layer of gypsum board of thickness 25 mm gives better protection than 2 layers of gypsum board of thickness 12,5 mm. [3] [20]

Materials backing the gypsum boards make the fire behaviour of the boards different. The presence and the type of insulation in an assembly affects its performance in fire. Previous studies have found, that having a layer of insulation behind the gypsum board reduces its fire resistance. This can be explained by the fact, that heat accumulates in the insulation, which is in direct contact with the gypsum board. The local temperature rise can cause decomposition as additional heat accelerates calcination of the gypsum and therefore reduces the failure time of the board. A void cavity or resilient channels behind the gypsum board allow the air to ventilate and no heat is accumulating directly behind the gypsum board. Having a wood-based panel directly behind the gypsum board does not allow the air ventilation and therefore has a negative effect on the fire resistance of gypsum boards. However, the negative effect of wood-based panel is smaller than the negative effect of insulation, as wood does not heat up as fast as the insulation. This effect can be seen in Figure 3. The temperature of insulation is higher than the temperature of wood in a fire test. The gypsum board can be fastened more securely to wooden boards, which also increases the fire resistance of the gypsum board.

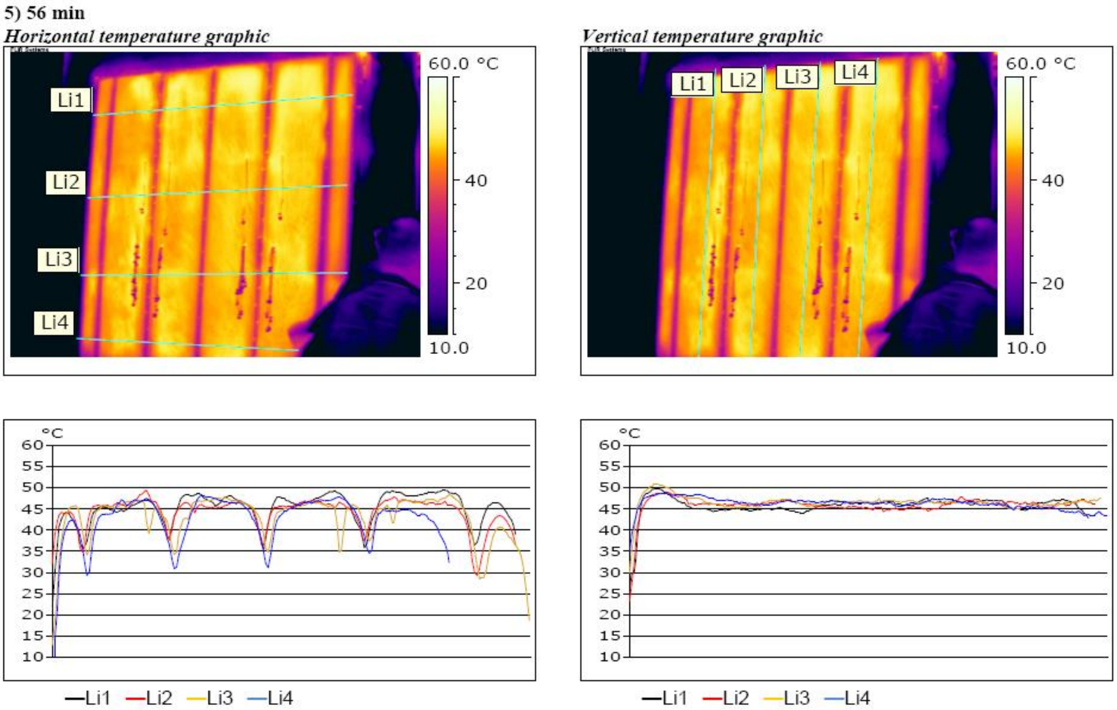


Figure 3 – Photos of thermographic camera during a fire test of a timber frame assembly (Photo by A.Just)

The effect of the material of the studs on the fire resistance of the assembly has also been analysed in the previous studies. However, the type of framing has had no significant effect on the failure time of the the gypsum board.

The set-up and the length of the fasteners of the gypsum boards affect the fire resistance of a timber frame assembly. The requirements for the length of the fasteners is given in EN 1995-1-2 in paragraph 3.4.3.4 (4). In case the length of the fasteners is not sufficient, the cladding failure may occur due to the pull-out of the fasteners rather than the thermal degradation of the gypsum board. Previous studies have shown, that longer distance of the fasteners from the gypsum boards edges increases the fire resistance of the assembly. The placement of fasteners, for example edge distances, is not taken into consideration with design methods in EN 1995-1-2 although there is a clear effect of this.

The fire resistance of a timber frame assembly also depends on whether it is used as a wall or floor assembly. The failure time of gypsum boards in floor assemblies is shorter, since the effect of gravity on this type of assembly is higher. Floor claddings hang from the studs, while wall claddings „lean“ on the studs . In wall assemblies, the orientation of the gypsum boards affects the failure time. Most wall assemblies have a vertical set-up of the gypsum boards, as it is a more economical method of installation and easier to finish. However, in this orientation, the edges along the long direction of the boards are unbacked. When the joints between sheets of gypsum boards open, the fire directly attacks the studs. Therefore, the fire resistance of a vertically oriented gypsum boards is lower.

Based on the previous studies, the application of load is also an important factor considering the fire resistance of a gypsum cladding. Loaded timber frame assemblies have a shorter resistance to fire than not loaded timber frame assemblies, as the frame deflects due to bending. Loading of the assembly has more influence on the floor assemblies, as deflections due to bending are generally bigger than deflections due to normal forces. [3] [20] [22] [23] [24]

3 Fire safety of wooden buildings

3.1 Fire resistance. General requirements

Fire protection of structures in general is necessary in order to limit risks to the individual, society and neighbouring property in the case of fire. European Construction Products Regulation No 305/2011 gives the following essential requirement for the limitation of fire risks: "The construction works must be designed and built in such a way, that in the event of an outbreak of fire

- the load-bearing resistance of the construction can be assumed for a specified period of time;
- the generation and spread of fire and smoke within the works is limited;
- the spread of fire to neighbouring construction works is limited;
- the occupants can leave the works or can be rescued by other means;
- the safety of rescue teams is taken into consideration".

The fire parts of Structural Eurocodes deal with specific aspects of passive fire protection in terms of designing structures for adequate load-bearing resistance and for limiting fire spread as appropriate. In case of fire, load-bearing structures must not collapse prematurely and separating structures have to limit fire spread beyond designated areas. For standard fire in ISO 834 this is described by using criterias R (mechanical resistance), E (intergrity) and I (insulation).

Criterion R is assumed to be satisfied when the load-bearing function is maintained during the required time of fire exposure. Criterion E is assumed when the construction does not develop any cracks of fissures, which would allow smoke or hot gases pass through during the required time of fire exposure. Criterion I may be assumed to be satisfied where the average temperature rise over the whole of the non-exposed surface is limited to 140 K, and the maximum temperature rise at any point of that surface does not exceed 180 K. [22]

3.2 Burning of wood

Wood is a burning material. Burning is a complicated procedure called pyrolysis, which means a thermochemical decomposition of cellulose at elevated temperatures in the absence of oxygen. Wood can be ignited by open flame or by high temperature. In order the ignition to happen, the surface temperature has to be over 300°C. As combustion takes place, a layer of char is created around the surface of wood (Figure 4), which acts as an insulation for the unburned wood. The reaction between the char layer and the burning gases creates a pyrolysis zone between the charred and uncharred wood. The pyrolysis zone is about 5mm thick. In this zone, wood is chemically affected by the fire, but has not decomposed yet. When the wood under the pyrolysis zone has reached the temperature of 100°C, the water in wood starts to evaporate and the vapour starts to exit through pores and knots. The rise of temperature stops, until the water evaporation process ends. [25]

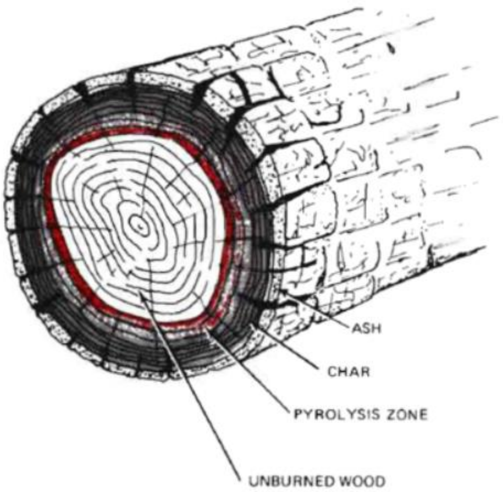


Figure 4 - The layers of wood in fire [26]

EN 1995-1-2 "Eurocode 5: Design of timber structures - Part 1-2: General - Structural fire design" is an European design standard for fire design of timber structures. According to EN 1995-1-2, the charring rate for one-dimensional charring is taken as constant with time. The design charring depth, see Figure 5 (1), should be calculated as:

$$d_{char,0} = \beta_0 * t \qquad (3)$$

Where β_0 is the one-dimensional design charring rate under standard fire exposure and t is the time of fire exposure. [22]

In order to include the effect of corner rounding and fissures, notional charring rate is used. The notional design charring depth, see Figure 5 (2), should be calculated as:

$$d_{char,n} = \beta_n * t \qquad (4)$$

Where β_n is the notional design charring rate and t is the time of fire exposure.

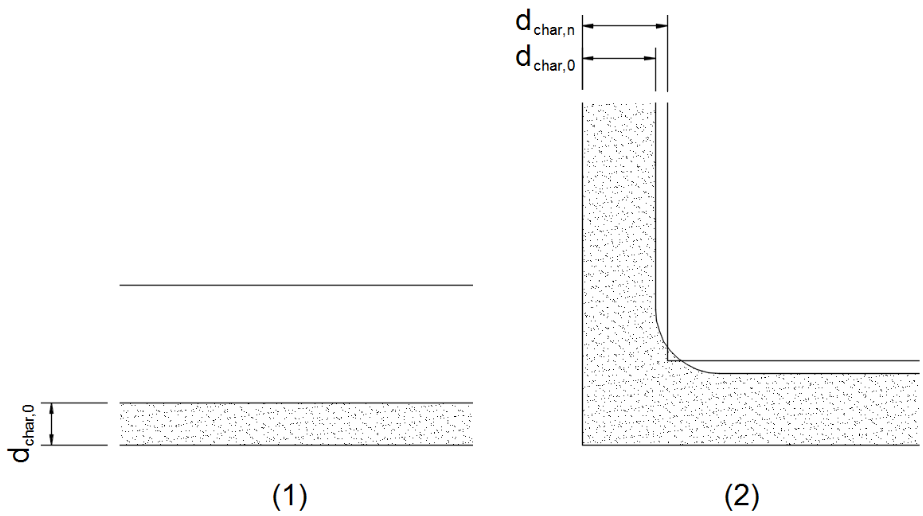


Figure 5 - One dimensional (1) and notional (2) design charring depth

For timber and wood-based materials, design charring rates β_0 and β_n are given in EN 1995-1-2 table 3.1.

3.3 Fire resistance of initially protected timber members

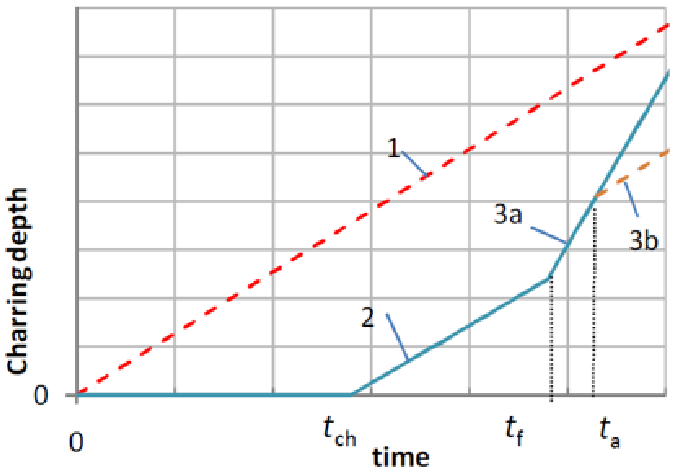
In heavy timber structures, the char-layer of fire exposed members performs as an effective protection of the remaining unburned residual cross section. However, the fire performance of light timber framed members is crucial to the protection provided by the linings and the cavity insulation. Since the timber frame is sensitive to fire exposure, it must be effectively protected against fire.

In case of fire, initially protected timber members may have a time period, during which the protection is attached to the timber member such that the member is not directly exposed to the fire, although some charring might occur during that phase. This is called *protection phase.* [27]

Start time of charring (t_{ch}) is the time when charring of wood starts behind the cladding. According to EN-1995-1-2 [22], start time of charring is taken as time of reaching 300 ºC on wooden surfaces behind cladding.

Failure time or *fall-off time* (t_f) of cladding is the time between the start of the test and the moment cladding falls off the timber member. In full scale fire tests, the failure time of the cladding is defined as the visually observed time when at least 1 % of the board area has fallen off.

Charring of unprotected and initially protected timber studs can be seen in Graph 3.



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Graph 3 - Charring of timber studs with and without protection [3]

Line 1 shows the charring rate of an unprotected timber stud. Charring starts when the fire has reached the surface of the timber stud. The time when initially protected member starts charring (t_{ch}) is delayed by the cladding that offers protection for the timber stud and slows down the rising of the temperature behind the cladding. Charring starts at a reduced rate when protection is still in place (Line 2). Line 3a indicates charring at increased rate after the protection has fallen off (t_f). At the time (t_a) when the charring depth equals either the charring depth of the same member without fire protection or 25 mm whichever is the lesser, the charring rate decreases (Line 3b).

For small-size 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 corner rounding becomes dominant and no consolidation of the charring rate is possible. Charring continues according to Line 3a.

Keeping that in mind, the protective layer has to delay the start of charring as long as possible, reduce the charring rate and remain in place as long as possible, in order to maximize the fire protection effect in fire. [3] [27]

3.4 Design methods

3.4.1 Introduction

EN 1995-1-2 provides limited information on determination of the start of charring behind applied protection, and on failure times of protective layers. In general, unless expressions are given to calculate the start of charring, failure times of protective layers and charring rates of wood behind the protection where relevant, must be determined by testing. Those expressions are described in 3.4.2. Expression for calculating the failure time of gypsum board type F is not given in EN 1995-1-2.

The design methods given in EN 1995-1-2 are based on input data that were deduced from a limited number of fire tests of wall assemblies, and cover therefore only a limited area of timber structures. For this reason, a research project was carried out in Switzerland and as a result, an improved design method for determining the separating function of timber structures has been developed. The design method is based on extensive experimental results and finite-element thermal analysis. This method is described in 3.4.3. [1]

Expressions for calculating start of charring and failure times of gypsum boards were developed during the first analysis of the database of full-scale fire tests, which is also the basis of this study. This method gives conservative expressions for the start time of charring and failure time of the panels, depending on the type of construction. The method is described in 5.2. [1] [3]

In addition to those methods, "Brandsäkra trähus 2" [28] gives values for start time of charring and the failure time of the cladding for different types of assemblies that have gypsum cladding, based on the test results of „Gyproc" gypsum boards. However, „Gyproc" is known for its good behaviour in fire, therefore adapting those values to different gypsum boards by other manufacturers is not advisable.

Finnish national annex of EN 1995-1-2 enables to find failure time for certain types of gypsum boards. The failure time is given for type F gypsum board of 15mm, with the cladding consisting of one or two layers, used in wall or floor construction.

3.4.2 Design method for load-bearing function of timber frame assemblies in EN 1995-1-2

For claddings consisting of one layer of gypsum plasterboard of type A, F or H according to EN 520 [9], the start time of charring is calculated by the formula given in EN-1995-1-2 Annex C:

$$t_{ch} = 2{,}8 * h_p - 14 \tag{5}$$

Where h_p is the total thickness of the boards.

For gypsum plasterboards type A and H, that fulfil the requirements given in EN-1995-1-2 C1 the failure time t_f should be taken as:

$$t_f = t_{ch} \tag{6}$$

In case the cladding consists of two layers of gypsum board type A, thickness h_p is taken as the thickness of the outer layer and 50% of the thickness of the inner layer. When the cladding consists of two gypsum boards type F, thickness h_p is taken as the thickness of the outer layer and 80% of the thickness of the inner layer.

For gypsum plasterboards type A and H, that are used for wall and floor assemblies with void cavities, the failure time of the board should be determined by testing. However, the failure time t_f can be calculated according to formula in EN-1995-1-2:

- for floors with the cladding fixed to timber members or resilient steel channels with a spacing of not more than 400 mm, and walls:

$$t_f = 2{,}8 * h_p - 11 \tag{7}$$

- for floors with the cladding fixed to timber members spaced more than 400 mm but not more than 600 mm:

$$t_f = 2{,}8 * h_p - 12 \tag{8}$$

Since gypsum plasterboards of types E, D, R and I have equal or better thermal and mechanical properties than types A or H gypsum plasterboard, the expressions for the start time of charring behind gypsum plasterboards type A or H may be conservatively used for those types. The same applies to type F gypsum plasterboard. [1]

For claddings made of gypsum plasterboard type F, failure times should be determined with respect to thermal degradation of the cladding and pull-out failure of fasteners due to the insufficient penetration length into unburnt wood. The failure time due to the thermal degradation of the cladding should be assessed on the basis of tests.

The failure time t_f of panels with respect to pull-out failure of fasteners may be calculated as:

$$t_f = t_{ch} + \frac{l_f - l_{a,min} - h_p}{k_s * k_2 * k_n * k_j * \beta_0} \tag{9}$$

With

$k_j = 1{,}0$ for panels not jointed over the timber member

$k_j = 1{,}15$ for joint configurations 1 and 3

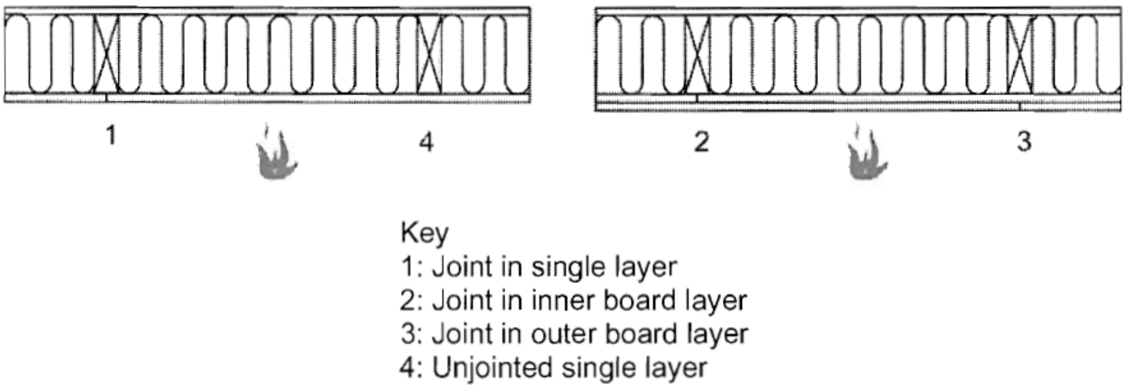


Figure 6 - Joint configurations in gypsum plasterboard panels with one and two layers [22]

t_{ch} is the time of start of charring

l_f is the length of the fastener

$l_{a,min}$ is the minimum penetration length of the fastener into unburnt wood (should be taken as 10mm)

h_p is the total thickness of the panels

k_s is the cross-section factor (EN 1995-1-2 Annex C Table C1)

k_2 is the insulation factor

For claddings made of gypsum plasterboard of type F, or a combination of type F and type A with type F as the outer layer, the insulation factor may be determined as:

- at locations where the cladding is unjointed, or for joint configuration 2, see Figure 6:

$$k_2 = 1{,}05 - 0{,}0073 * h_p \tag{10}$$

- for joint configurations 1 and 3, see Figure 6:

$$k_2 = 0{,}86 - 0{,}0037 * h_p \tag{11}$$

$k_n = 1{,}15$ is a factor to convert the irregular residual cross-section into a notional rectangular cross-section

β_0 is the design charring rate for one-dimensional charring under standard fire exposure

3.4.3 Component additive method for separating function of timber assemblies

3.4.3.1 General

The component additive method for design of separating function was developed in ETH by Frangi [29] based on extensive experimental results and finite-element thermal analysis. This design method enables the verification of the separating function of wall and floor assemblies and can be used to determine the start time of charring. The method is capable of considering timber frame assemblies with an unlimited number of layers made of gypsum board, wood panels or combinations thereof. The cavity may be void or filled with mineral wool insulation. Therefore it is applicable and offers more solutions for a greater variety of materials than the component additive method in EN 1995-1-2. [1]

The total fire resistance is taken as sum of the contributions from the different layers, considering heat transfer paths and according to their function and interaction:

$$t_{ins} = \sum t_{prot,i} + t_{ins} \tag{12}$$

Where the first component $\sum t_{prot,i}$ is the sum of protection times of the layers preceding the last layer of the assembly on the side not exposed to fire and the second component t_{ins} is the insulation time of the last layer of the assembly on the side not exposed to fire.

The start time of charring can be calculated as:

$$t_{ch} = \sum t_{prot,i} \tag{13}$$

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

The protection time of each layer is expressed as:

$$t_{prot,i} = \left(t_{prot,0,i} * k_{pos,exp,i} * k_{pos,unexp,i} + \Delta t_i\right) * k_{ji} \qquad (14)$$

For gypsum plasterboards, the basic protection value, defined as the time until loss of the fire protective function, is expressed as:

$$t_{prot,0} = 30 * \left(\frac{h_i}{15}\right)^{1,2} \qquad (15)$$

Where h_i is the thickness of the board in mm.

Position coefficients for gypsum and timber claddings are

$$k_{pos,exp,i} = 1 - 0,6 * \frac{\sum t_{prot,i-1}}{t_{prot,0,i}} \qquad \text{if} \qquad \sum t_{prot,i-1} \leq \frac{t_{prot,0,i}}{2} \qquad (16)$$

$$k_{pos,exp,i} = 0,5 * \sqrt{\frac{t_{prot,0,i}}{\sum t_{prot,i-1}}} \qquad \text{if} \qquad \sum t_{prot,i-1} > \frac{t_{prot,0,i}}{2} \qquad (17)$$

$$k_{pos,exp,i} = 0,5 * h_i^{0,15} \qquad \text{if the layer is backed by insulation} \qquad (18)$$

$$k_{pos,exp,i} = 1 \qquad \text{if the layer is backed by cladding} \qquad (19)$$

Joint coefficient for gypsum plasterboard is

$k_{j,i} = 0,8$ if the layer is backed by void cavity and has joints

$k_{j,i} = 1,0$ for all other cases

3.4.3.2 Calculations

In order to compare the start time of charring by using this method with the results of the database, calculations were made using the component additive method. Five different types of constructions were chosen: assemblies with 1 layer and 2 layers of gypsum board type A; assemblies with 1 layer and 2 layers of gypsum board type F. The 2 layered type F gypsum construction was calculated using two variants, a wall and a floor construction. The results are described in Table 2.

Table 2 - Start time of charring according to the component additive method

Type of cladding	h_p, $h_{p,tot}$ [mm]	Σt_{prot} [min]
GtA 1/1	12.5	17.60
GtA 1/1	15	22.52
GtA 1/1	25	44.87
GtA 2/2	18	21.09
GtA 2/2	25	31.27
GtA 2/2	30	38.92
GtF 1/1	12.5	17.60
GtF 1/1	15	22.52
GtF 1/1	25	44.87
GtF 2/2 Wall	18	27.74
GtF 2/2 Wall	25	38.87
GtF 2/2 Wall	30	47.22
GtF 2/2 Floor	18	34.62
GtF 2/2 Floor	25	37.54
GtF 2/2 Floor	30	40.12

4 Fire testing

4.1 Designation of type F for gypsum plasterboards according to EN 520

4.1.1 General requirements

In order to get the designation of type F for a gypsum plasterboard, the test of determining core cohesion at high temperature according to EN 520 [9] has to be carried out. The principle of the test is heating a specimen with a bending moment applied between two burner flames. When deflection is complete the specimen will be examined for breakage. In order to get the designation of type F, none of the specimens tested shall break.

4.1.2 The test of determining core cohesion at high temperature

Testing requires 3 boards of each type and thickness. From each board 2 specimens 300±5 mm long by 45±1 mm wide are cut with the long edge parallel to the edge of the board.

The setup of the test apparatus can be seen in Figure 7. A specimen is placed in the supporting device and the load is applied to the unsupported end of the specimen (3). Two propane Meker burners are mounted with their nozzles facing each other and each nozzle 25±1 mm from the specimen (2). After lighting the burners the gas flow is adjusted to give a temperature of 1000±50 °C on each thermocouple. When the load reaches the platform or after 15 min the specimen is examined for cohesion. If any of the 6 specimens separates into two of more pieces the board is deemed to have failed.

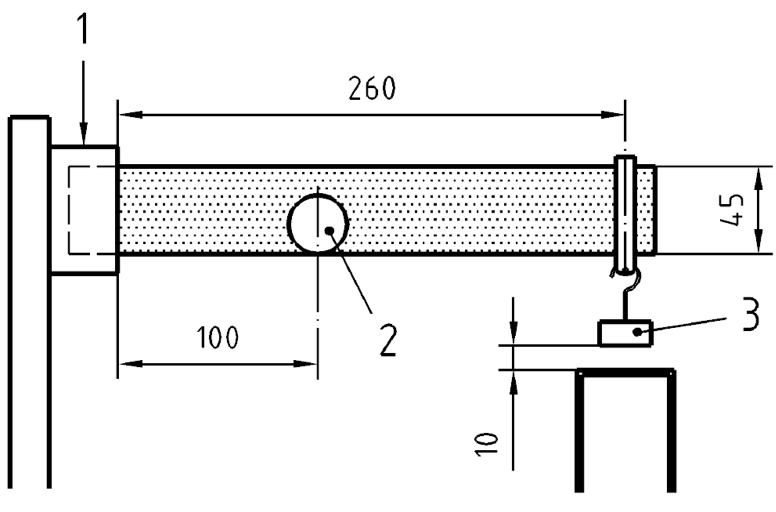


Figure 7 - Side view of the test apparatus for the test of determining core cohesion [9]

4.2 Fire testing of assemblies with gypsum boards

4.2.1 Testing methods

In order to evaluate the behaviour of a gypsum board in fire, fire testing of assemblies with gypsum boards shall be carried out. There are two ways of fire testing – model-scale and full-scale fire testing. Model-scale testing involves a model size furnace and model size test specimens. However, as the formation of cracks during fire exposure affects the fire performance of gypsum board membranes, gypsum boards should be viewed as material subject to „weak-link" failure. As the probability of the „weak-links" is significantly lower in smaller pieces of gypsum boards, the performance of assemblies that are finished with only a portion of a sheet of gypsum board in model-scale fire tests may not be representative of that in full-scale tests. Therefore, in order to eliminate the faults in the testing results due to defects in the materials, full-scale fire testing is used. For example there could be air bubbles in the gypsum board, bad quality of the wooden studs or other defects from the manufacturer. The database analysed in this project, is based on the results of full-scale fire tests. [20]

4.2.2 Model-scale fire testing

Model-scale testing enables to test pieces of a wall, joists or connections between them. Due to the furnace size, model scale tests are not sufficient for determining failure times of claddings, although they can be used to determine the start of charring. A model-furnace has all the components of a full-scale furnace such as burners, ventilation-, pressure- and temperature systems, thermocouples, peep hole, plate-thermometer, etc. The systems can be regulated manually or automatically with a computerized system. The test specimen is placed horizontally on top of the furnace in the case of testing a gypsum floor and vertically in the case of testing a gypsum wall. An example of a model-scale testing furnace can be seen in Figure 8.

Figure 8 - Model scale furnace at SP Technical Research Institute of Sweden [7]

4.2.3 Full-scale fire testing

4.2.3.1 General requirements

The general requirements of the full-scale fire testing are described in European Standard 1363-1 [33] and the requirements on the specific construction types in EN-1364 [34] and EN-1365 [35]. The test furnace has to be designed to employ liquid or gaseous fuels and shall be capable of heating of walls on more than one side. The furnace has to be capable of providing the standard fire exposure conditions with respect to thermal exposure and pressure. Equipment needed to carry out the tests involves a specially designed furnace to subject the test specimen to the test conditions; control equipment to enable the temperature of the furnace to be controlled; equipment to control and monitor the pressure of the hot gases within the furnace; a frame in which the test construction can be erected; arrangement for loading and restraint of the test specimen as appropriate; equipment for measuring temperature in the furnace; equipment for measuring the deflection of the test specimen; equipment for evaluating integrity; equipment for establishing the elapsed time and equipment for measuring the oxygen concentration of furnace gases.

Figure 9 - Full-scale fire testing furnace [36]

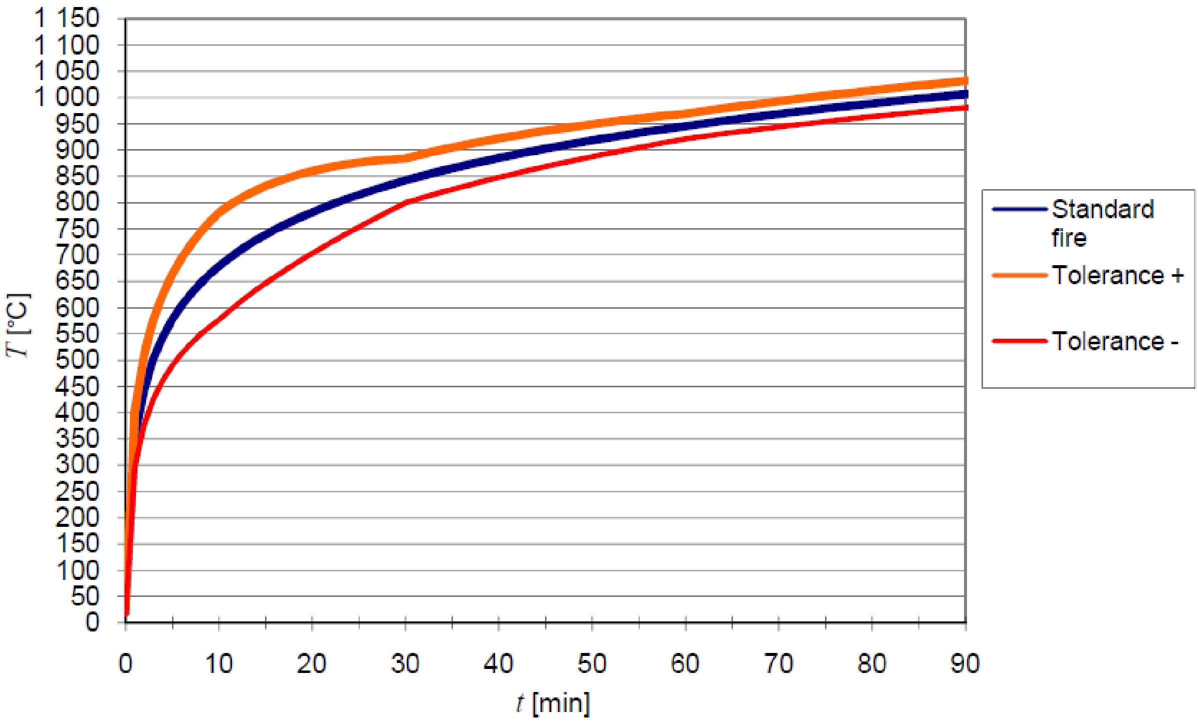
4.2.3.2 Standard fire curve

The average temperature of the furnace as derived from the furnace thermocouples has to be monitored and controlled such that it follows the relationship, known as the ISO standard fire curve (ISO 834)

$$T = 345 log_{10}(8t + 1) + 20 \quad (20)$$

Where T is the average furnace temperature in degree Celsius and t is the time in minutes.

The percentage deviation in the area of the curve of the average temperature recorded by the specified furnace thermocouples versus time from the area of the standard temperature/time curve shall be within the required values, described in EN-1363-1 (5.1.2). The standard fire curve with allowed tolerances of temperature change can be seen in Graph 4. [33]



Graph 4 - Standard fire curve with allowed tolerances [7]

4.2.3.3 Test specimen and testing construction

Materials used in the construction of the test specimen and the method of construction including the tolerances and the erection has to represent the use of the element in practice. At the time of the test, the strength and the moisture content of the test specimen has to be approximate to those expected in normal service.

Normally, the test specimen has to be full size. When the specimen cannot be tested full size, the specimen size shall be in accordance with the specific test method.

4.2.3.4 Temperature measurements

The furnace thermocouples are plate thermometers comprised of an assembly of a folded nickel alloy plate, a thermocouple fixed to it and insulation material and they measure the temperature of the furnace. The plate thermometer is set 100 mm below the test specimen in the furnace and is a slow changing thermometer which receives both heat radiation and heat conduction. They will be distributed so as to give a reliable indication of the average temperature in the vicinity of the test specimen.

The temperature of the unexposed surface of the test specimen shall be measured by means of disc thermocouples. One or more roving thermocouples shall be available to measure the unexposed surface temperature during a test at positions where higher temperatures are suspected.

If information concerning the internal temperature of a test specimen is required, it shall be obtained by means of thermocouples having characteristics appropriate to the range of temperatures to be measured, as well as suitable to the type of materials in the test. Thermocouples are small measuring points which can measure rapid change of temperature.

Figure 10 - Thermocouple located on fire exposed side [7]

To indicate the ambient temperature a thermocouple shall be used within the laboratory in the vicinity of the test specimen both prior to and during the test period. It is nominally 0,25 mm diameter, mineral insulated, stainless steel sheathed type K thermocouple specimen.

4.2.3.5 Testing with load

The load may be applied hydraulically, mechanically or by the use of weights. The loading equipment has to be able to simulate conditions of uniform loading, point loading, concentric loading, axial loading or eccentric loading as appropriate for the test construction.

When uniform loading is applied in the testing of gypsum boards, it is achieved using a hydraulic system, which presents even pressure on a large area. Normally the load is set to about 10 kN per stud. [7]

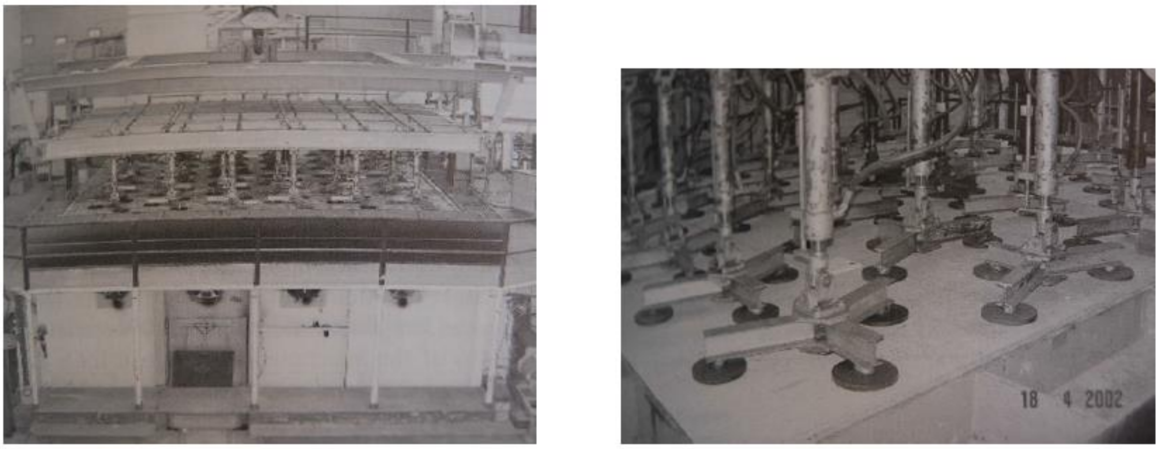


Figure 11 - Hydraulic load system [7]

When testing with loads, it is important that the corner build-up of the test piece is built correctly.

When the database of fire testing reports used in this study was assembled, a common problem was noticed in the corner build-up of the walls. While testing a wall with load it has to made certain that the two studs on the sides are not loadbearing. That is why a distance of around 50 mm is kept in the corners between the studs and the top member (Figure 13). Otherwise the construction would appear stronger than it is since the effect of charring will appear only on the inner sides of the studs, instead of appearing on both sides, as can be seen on (Figure 6). [3] [7]

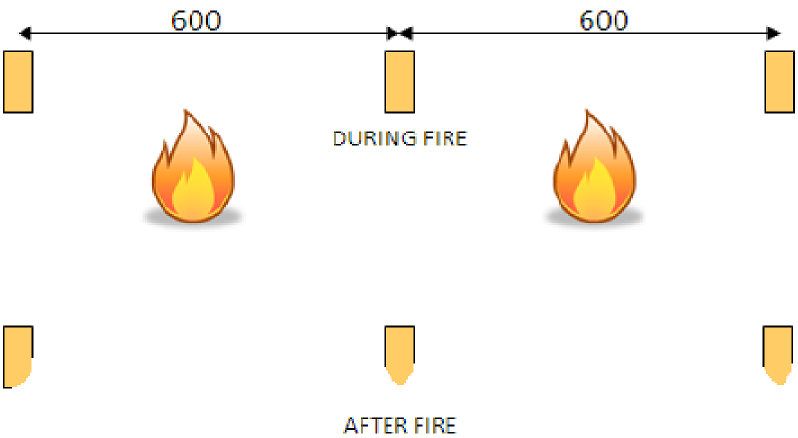


Figure 12 – The effect of charring [7]

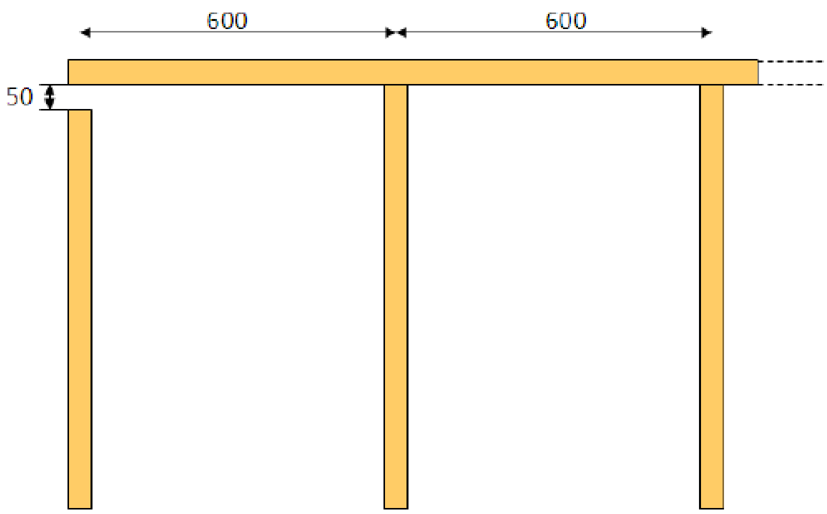
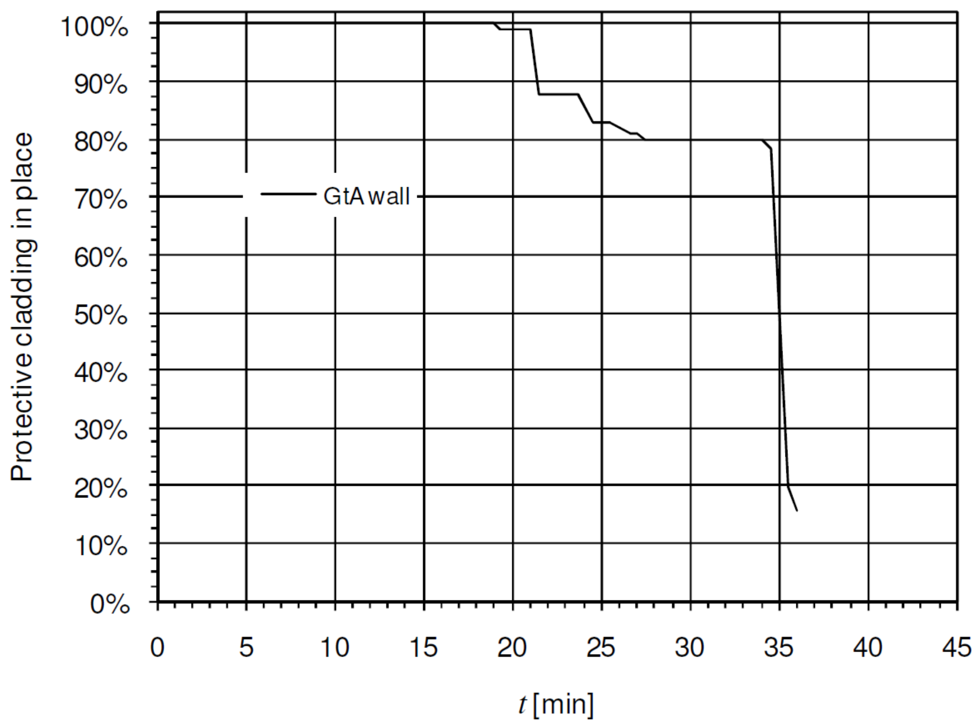


Figure 13 – Correct corner build-up [7]

4.2.3.6 Visual observations

Unlike the start of charring, which is measured by the thermocouples on the surface of the wood, the time of cladding failure in a fire test is acquired by visual observation. It is observed through the furnaces peep hole. The observer writes down the moment, when in their opinion the cladding has fallen off. As all kind of visual observations are subjective to some extent, the recorded time might not be exactly right. Especially considering the facts, that the observer might not be on their position behind the peep hole at all times during the fire test and the peep holes of the furnaces are small and might not give a clear look at the gypsum board in the furnace.

Thermal degradation of the board is a process starting with falling off of small pieces and developing during time. An example of the percentage of gypsum board in place in a fire test can be seen on Graph 5. That also leads to a question: which area of the gypsum board falling off is significant concerning the fire protection of wood studs? This question does not have an exact answer today.



Graph 5 - Gypsum board in place in a full-scale fire test [37]

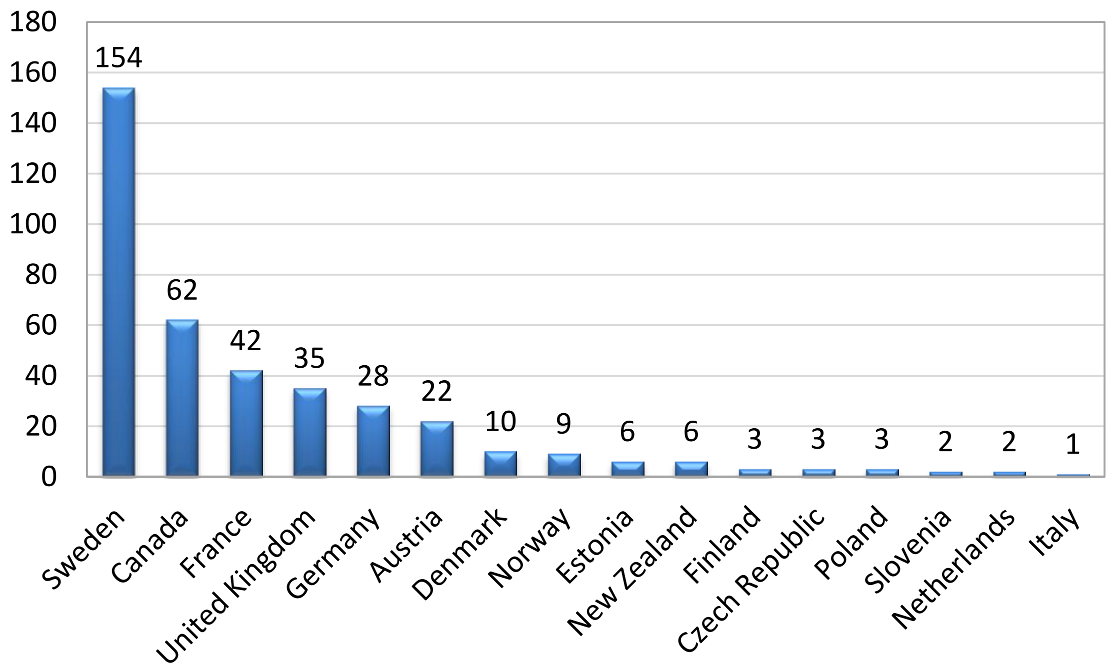
In this study, the failure times of gypsum boards are taken as a time when the failure of the board was fixed in the visual observations in the test report. However, in a full-scale fire test, European Standards do not require visual observations from the side of the fire. Therefore some test reports in the database of full-scale fire tests do not contain information about the failure time of the cladding. In this database, test results of assemblies containing type F gypsum boards in most cases contain the data about the failure time of the cladding, since those assemblies were usually tested for the type F gypsum board. In test assemblies with type A gypsum board, the purpose of the fire test in most cases was the fire resistance of the whole assembly. However, a representative organization for European organizations for fire testing, inspection and certification (EGOLF) has advised the member organizations to perform the visual observation for the failure time of the cladding in full-scale fire tests. This situation needs improvement in the future.

5 Database of full-scale fire tests

5.1 General

A database with data from full-scale fire test reports with assemblies including claddings made of gypsum plasterboards in accordance with EN 520 and gypsum fibre boards in accordance with EN 15283-2 was collected at SP Technical Research Institute of Sweden to provide necessary design rules for fire safety design of timber structures with gypsum boards. The database was performed as a student thesis at the Royal Institute of Technology in Stockholm in collaboration with SP Technical Research Institute of Sweden. [3] [7]

The database consists of results of 388 full-scale tests from different institutes all over the world, although mainly from Europe. The exact distribution of test reports by country can be seen in Graph 6, however the gypsum board itself might be of another origin. The number of test reports is not final and the database is still growing.



Graph 6 - Number of test reports by country

A great majority of the assemblies tested were timber frame assemblies with solid timber members and some with I-joists. In some cases, the frame was built of lightweight steel members. The data about the test numbers, producers etc. are confidential. Parameters recorded in the database are described in Table 3. [3]

Table 3 - Parameters in the database of fire tests of gypsum boards

General test data	Frame structures	Insulation	Cladding	Observations
• Report number • Date • Wall or floor assembly • Fire curve • Fire exposure • Loading	• Height • Span • Stud material and cross-section • c/c distance • Nogging structures	• Type • Density • Thickness	• Type • Orientation • Thickness • Density • Edge shape • Fastener parameter • Resilient channels	• Failure time • Thermocouple readings

Although, the database includes the test results of fire tests of several types of boards, in this research, only GtA and GtF (GtX) type of boards are analysed. The number of tests of other types of boards is too small to enable making conclusions based on the method used in this study.

5.2 Results of the previous analysis of the database

The first analysis of the results of the full-scale fire tests was carried out by A.Just *et. al.* [3] and the results of the analysis were published in the „Fire Safety in Timber Buildings. Technical guideline for Europe“ [1]. The first analysis stated, that gypsum plasterboards of the same type and thickness have a very large scatter of performance properties in fire. Since charring behind gypsum boards often starts earlier than stated in the present EN 1995-1-2, there is a clear need to reduce the time for start of charring. [3]

The available test data was evaluated and easy-to-use rules were developed to provide data about failure times of gypsum boards and the start time of charring of timber members, in case manufacturers do not provide it. The results of all relevant tests were included, except for the ones that differed very much from the rest. The relevant test data was inserted in a chart and the equation for the failure of the cladding or the start time of charring was found by drawing a line so that all the relevant test data would be upon it. Therefore, the developed equations are a worst-case approach to failure times and start times of charring of timber members. Since it would not be fair to other manufacturers to use the worst-case approach when designing, there is a need for the further analysis of the data, which would be in accordance with the 95% principal.

Analysis of the database confirmed, that due to gravity, the failure times of boards used in floor constructions are shorter than those used for wall constructions. It was also found that using either timber or steel frames does not affect in the failure times of the claddings. The analysis stated, that two layers of GtF cladding and a combination of GtF gypsum board backed by GtA board both showed the failure of two layers at the same time. Therefore, in this study both types are analysed together.

According to the analysis, the reason for failure of the boards is not always clear in the test reports, but some of the results might have shorter failure times due to the pull-out of the fasteners. This assumption is analyzed in this study. The analysis states, that there is a difference in the failure times of boards backed with insulation and boards with void cavity. In this study, this effect is also analyzed. [3]

6 Analysis and discussion of the database

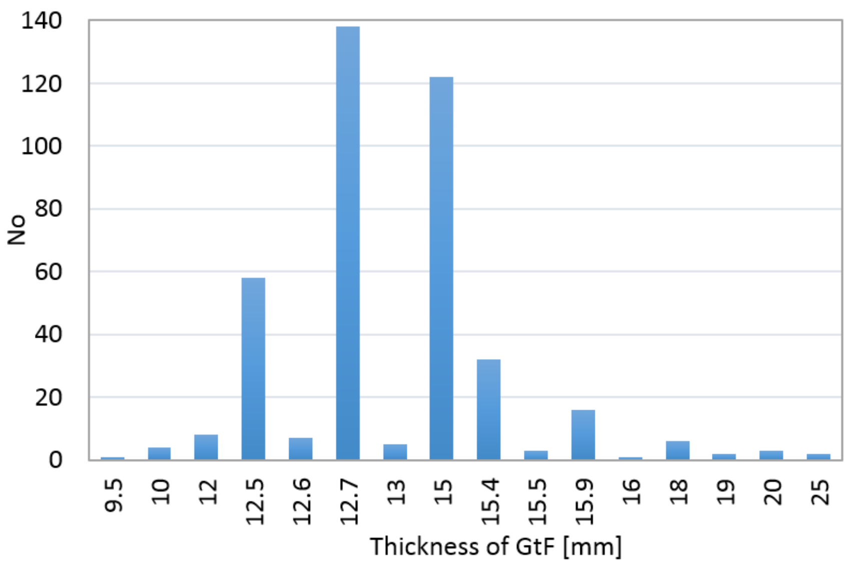
6.1 General

As a result of this thesis, an improvement of database was created. The previous database files of the results of full-scale fire tests of gypsum boards in EXCEL were reorganized, making it easier to find and read the information needed for further analysis and to enable the easy entry and processing of new data as more test results are added to the database in the future. The database files, which include information about the producers, dates of the test and other confidential data were separated from the files that include data about the set-up and the results of the full-sacle fire test.

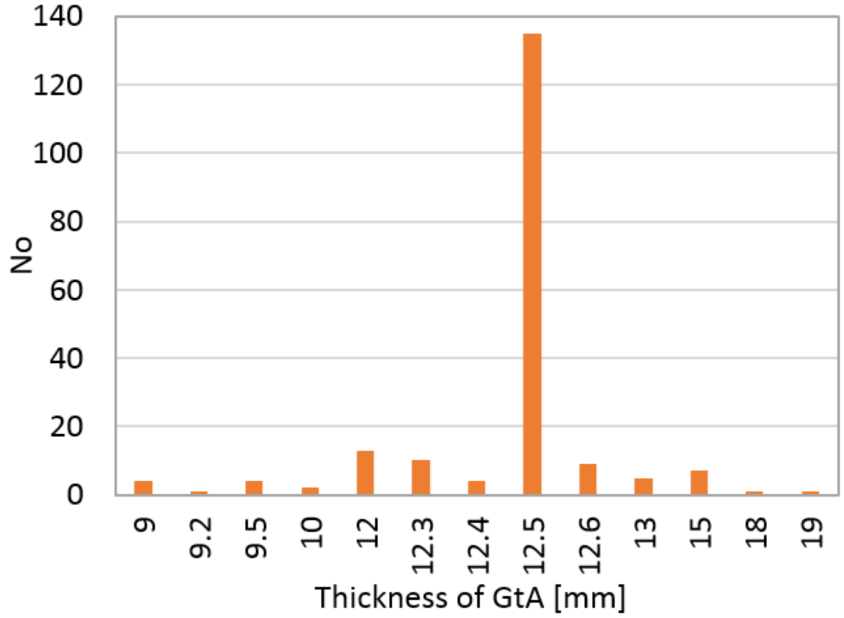
6.2 Methods of analysis

6.2.1 Grouping of results

Gypsum boards do not have a standardized value for the thickness of the boards. Every producer decides the thickness of their gypsum board and therefore the thickness varies to some extent by the producer and by the region the gypsum board is produced. The thickness of gypsum boards type F in this database can be seen in Graph 7 and the thickness of gypsum boards type A in Graph 8.



Graph 7 – Thickness of gypsum boards type F in the database



Graph 8 - Thickness of gypsum boards type A in the database

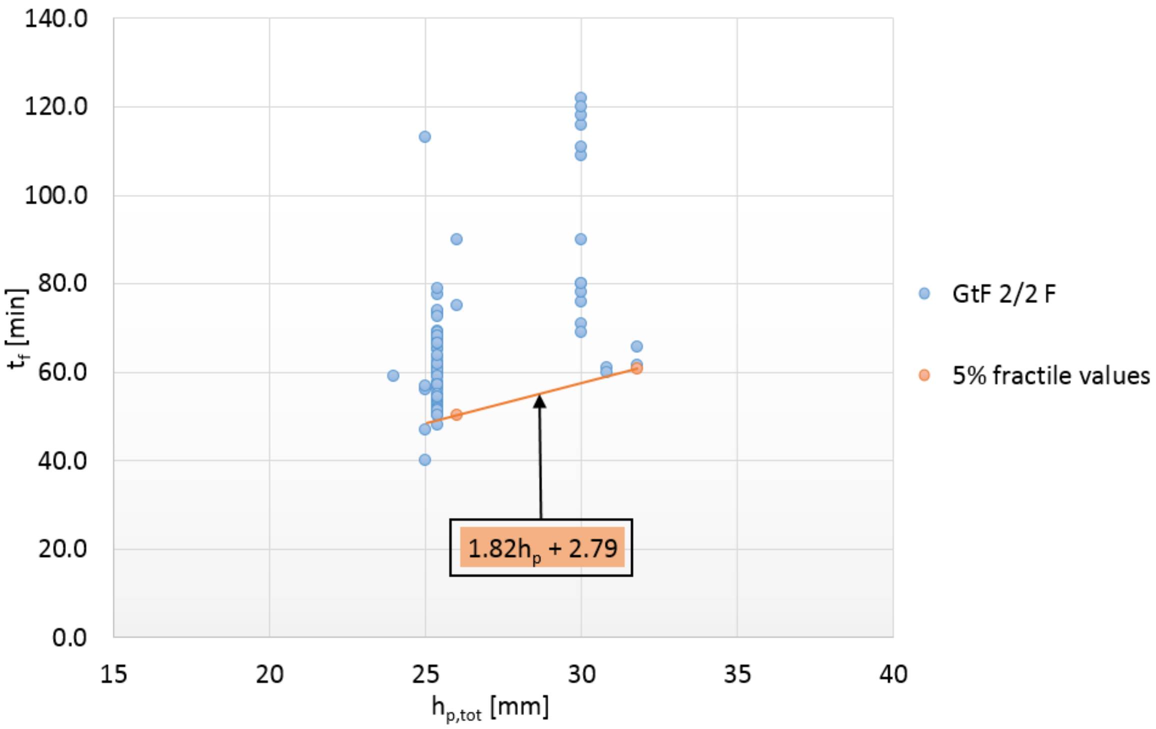
Some thicknesses of the boards are more common. In this study, thicknesses that deviate from the most common thickness ±2 mm, are analysed in the same group.

In case there are less than 6 values for a certain thickness group, the 5% fractile for this group is not found. Therefore, using this method of analysis no conclusion about the start time of charring or the failure time of the board could be made for some categories. Further analysis will be possible as more test results are added to the database in the future.

6.2.2 5% fractile

In order to eliminate 5% of the lowest values for the start time of charring and the failure time of the board in this study, the 5% fractile value was found. In order to use the 5% fractile value, the normal distribution of test results is assumed. A fractile is a point below which a stated fraction of the values lie. Therefore, 5% fractile is the point below which 5% of the values lie. In each category, the test results were sorted into groups by thicknesses as described in previous paragraph. For each group, which consisted of at least 6 test results, the 5% fractile value for failure time of the board was found using MS Excel function "PERCENTILE". Those values were inserted in a chart, where axis x describes the thickness of the board and axis y the start time of charring or the failure time of the board and a trend line was found for these values. In case a group of results consisted of gypsum boards with different thicknesses, the highest thickness was chosen as the value for the thickness of the board in the graph, in order to find the more conservative value for the failure time. The equation of the trend line is the equation, which describes the dependence of the start time of charring or the failure time of the board on the board thickness, taking into account the elimination of the 5% of the lowest values.

An example of finding the design equation can be seen in Graph 9. Most of the test results are of two thicknesses, 25,4 mm and 30 mm gypsum boards, therefore two groups are created for the analysis. The first group consists of test results of gypsum boards with thicknesses 25 mm, 25.4 mm and 25.9 mm. The second group consists of test results of gypsum boards with thicknesses 30 mm, 30.8 mm, 31.8 mm. In both groups, the 5% fractile value of all test results in the group is found. The values are displayed in the graph for the highest thickness value in this group.

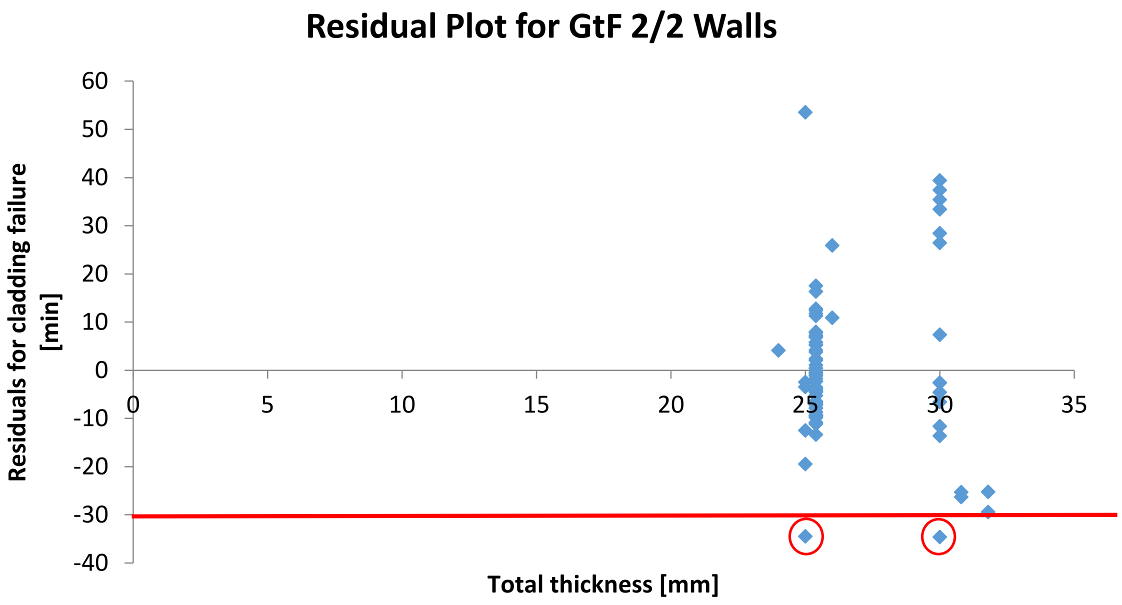


Graph 9 - Example of finding the design equation

6.2.3 Elimination of results differing from the rest

The results of the first analysis showed that gypsum plasterboards have a very large scatter of performance properties in fire. [3] In order to eliminate values for the start time of charring and failure time of the boards that differ a lot from the rest, the estimated mean value of the results and the residuals of each value were found in every category using the MS EXCEL data analysis “Regression”. A residual is the difference between the observable value and the estimated mean value of the results.

The values of residuals were analysed and the results with residuals lower than -30 minutes, were removed from the further analysis of the database. The difference of 30 minutes was chosen as it is the difference between commonly used fire classes in Europe. An example of a residual plot is presented in Graph 10. The values with red circles around them are removed from further analysis. The values with residuals higher than 30 minutes, were not removed, in order to not exclude fire tests, where the gypsum boards proved to have a good performance in fire. Those results proved to have an insignificantly small effect on the 5% fractile value.



Graph 10 - Example of residual plot

6.2.4 Failure due to the pull-out of fasteners

EN 1995-1-2 [22] states that failure times for gypsum boards of type F should be determined with respect to the thermal degradation of the cladding or the calculated time of the pull-out of fasteners. The minimal of those two should be selected. In the database, the „Cladding failure time“ is the visually observed moment written in the test report, when the observer noticed a piece of the gypsum board had fallen off. However, the reports do not specify, whether the board fell off due to thermal degradation or due to insufficient length or spacing of the fasteners.

In order to estimate the reason of the failure of the cladding, the failure time with respect to pull-out failure of the fasteners was calculated according to the formula EN 1995-1-2 C2.3 (5) for type F gypsum boards. The result was compared with the visually observed

„Cladding failure time“ of the test. In case the calculated time was about the same as the visually observed failure time of the cladding, the cladding failure might have happened due to the pull-out of the fasteners.

As a result, 14 test reports of the assemblies containing gypsum boards type F contained enough data for the calculation of the pull-out of fasteners and for 3 of those results the visually observed „Cladding failure time“ was available to compare to the results of the calculations. None of the 3 results gave comparable times for the cladding failure time. However, this method can be used in the future as more test results are added.

6.3 The start time of charring

6.3.1 General

The number of test results in the database for the start time of charring by number and type of cladding can be seen on Figure 14. Out of the 388 test results, 106 contained information about the time when 300°C was reached behind the gypsum cladding on the surface of the stud.

The results for start time of charring by number of layers of cladding and type of gypsum board can be seen in Graph 11. The test results for gypsum boards of 1 layer both type A and type F show similar scatter for the value of start of charring for gypsum board thickness 12,5 mm. Therefore, these two types are analysed together. For gypsum board thickness 15 mm there are only results of gypsum boards type F in the database, as this thickness is more common to this type. In the graph it is seen, that gypsum boards type F show a tendency for higher start time of charring. Therefore, the test results for type A and type F are analysed separately and start times of charring can be found separately for both types of gypsum claddings. In order to analyse claddings with external layer of gypsum board type F and inner layer of gypsum board type A, more test results are needed. The results of wall and floor cladding tests were not separated, as the effect of gravity influences the falling off of the board and not the temperature rise behind the gypsum board when the gypsum board is still in place.

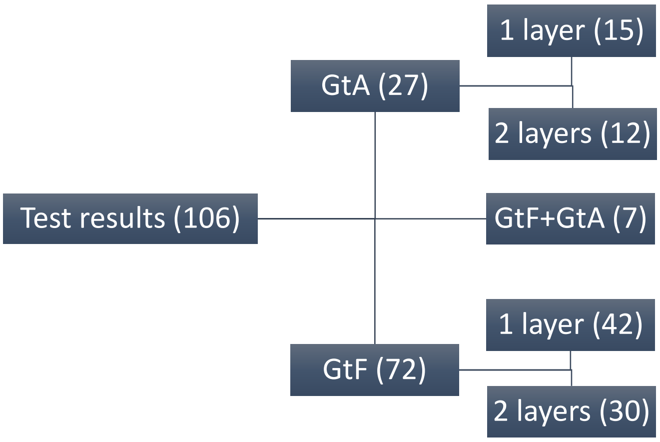
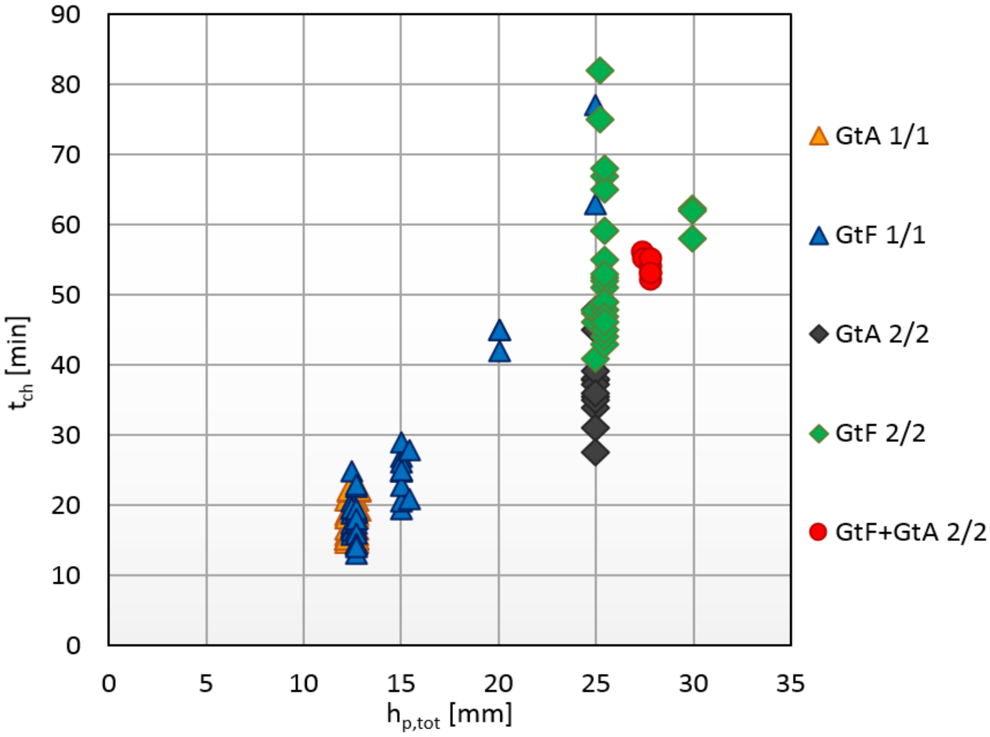
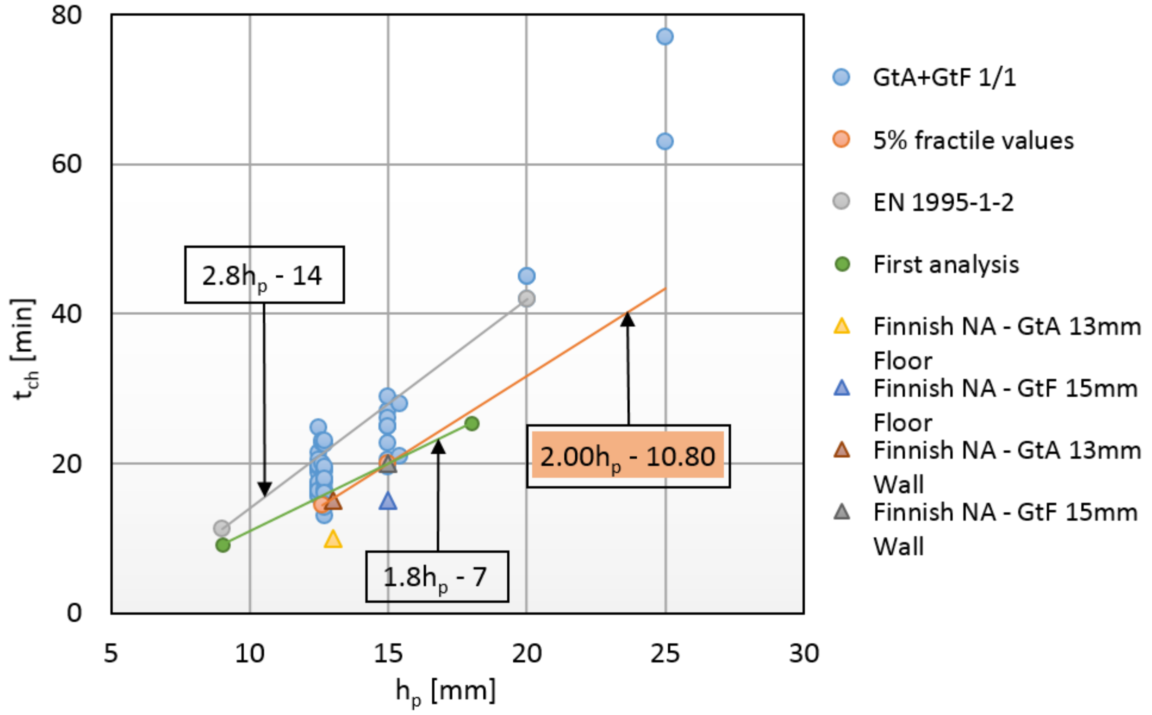


Figure 14 – Test results for the start time of charring in the database



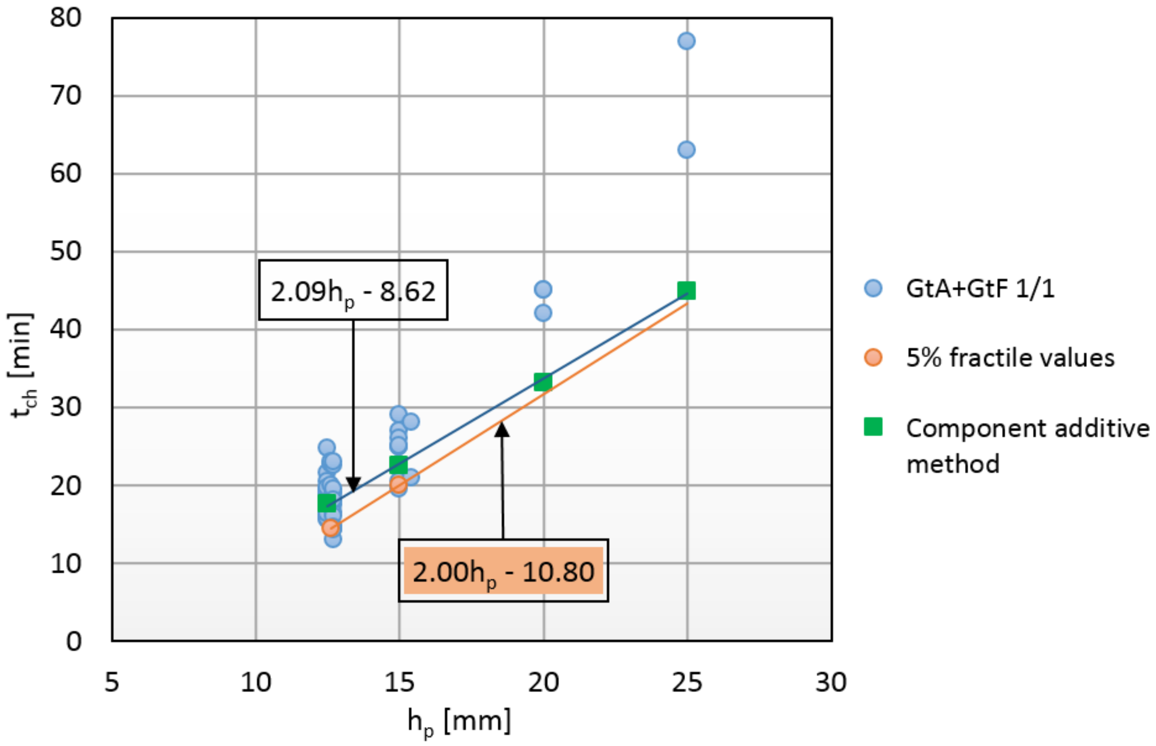
Graph 11 - Test results for start time of charring

6.3.2 Assemblies with 1 layer of gypsum board



Graph 12 - Start time of charring for gypsum cladding of 1 layer

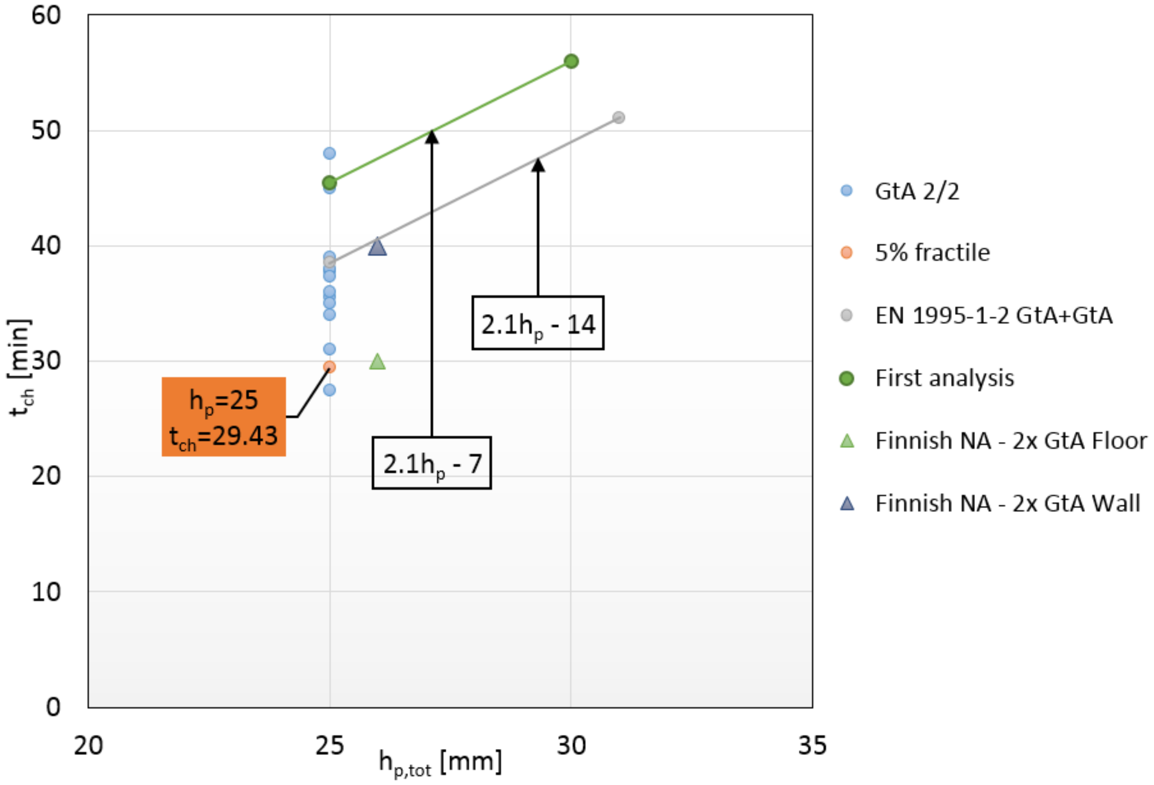
The results of start time of charring for gypsum cladding of 1 layer are presented in Graph 8. It can be seen in the graph, that most of the results for 12,5 mm and 15 mm gypsum boards are under the equation line given in EN 1995-1-2, which means that the equation in EN 1995-1-2 overestimates the start time of charring behind the gypsum boards. Comparison between the test results of this database and the Finnish National Annex of EN 1995-1-2 shows good correlation for wall assemblies. However, the Finnish National Annex underestimates the results for floor constructions. The results of the first analysis show good correlation with the results of this study.



Graph 13- Start time of charring for gypsum cladding of 1 layer. Comparison with Component Additive Method

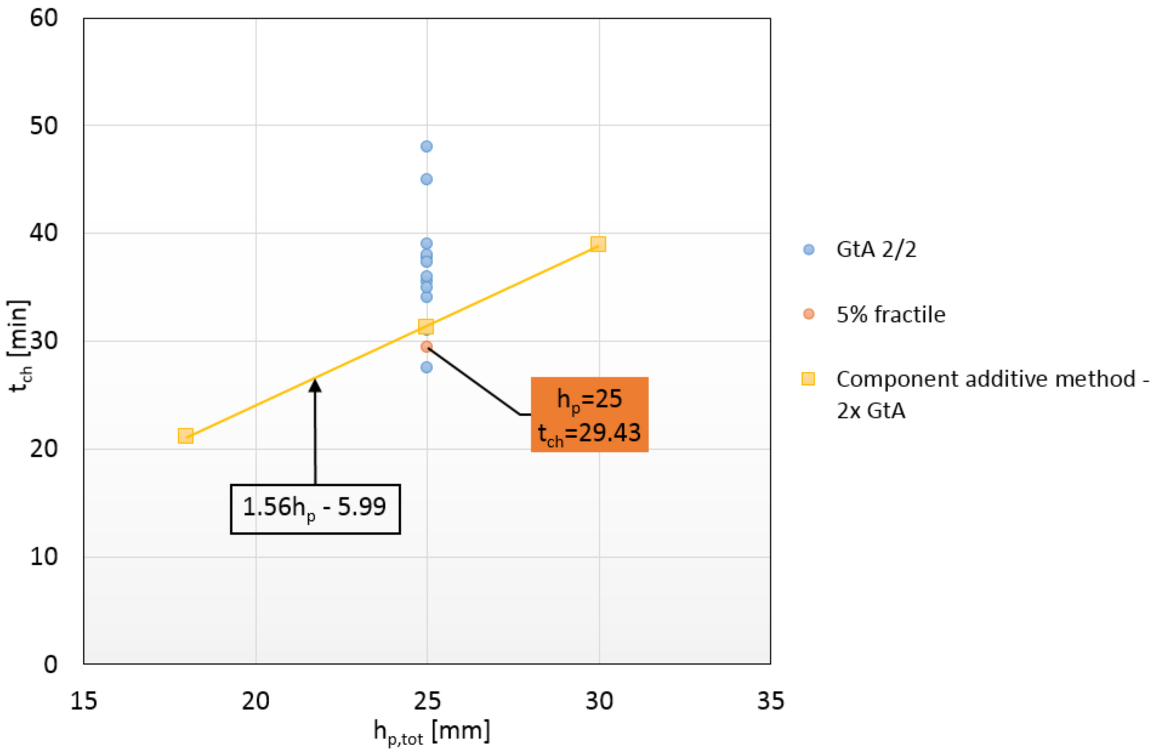
Graph 13 shows the comparison between the start time of charring based on the results of this analysis and the results calculated with the Component Additive Method. The results show good correlation.

6.3.3 Assemblies with 2 layers of gypsum boards of type A



Graph 14 - Start time of charring for 2 layers of gypsum cladding type A

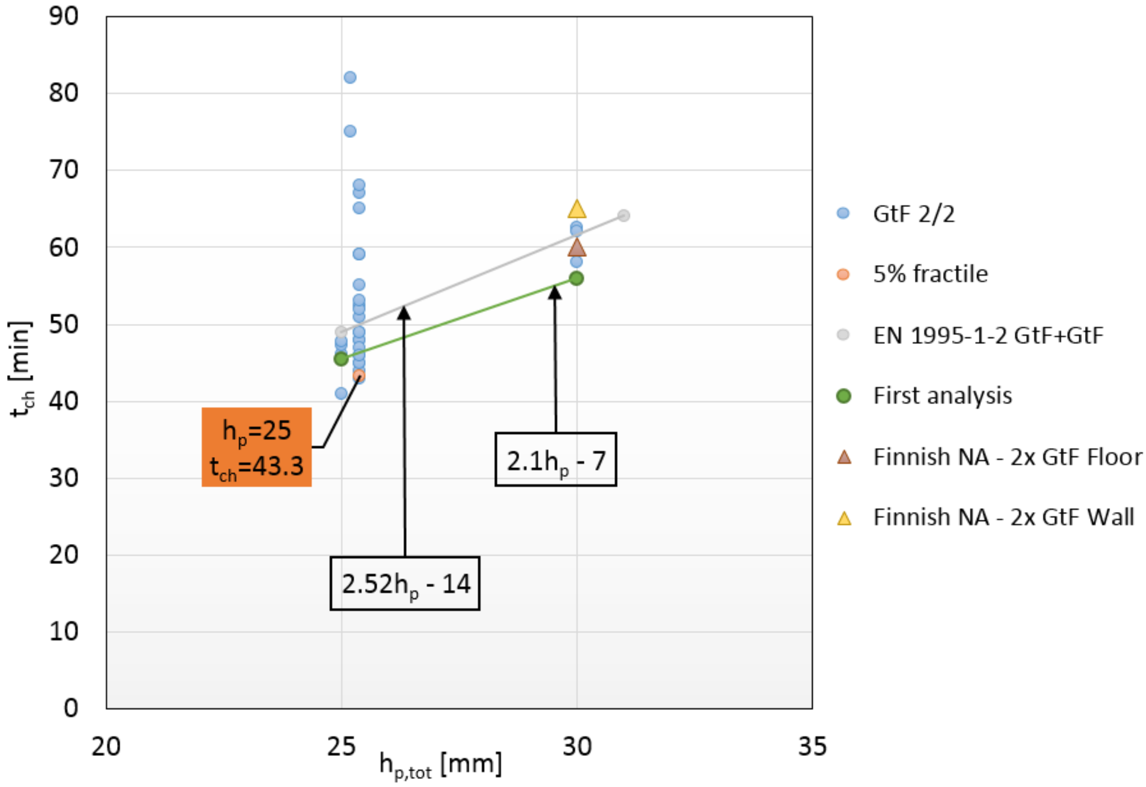
The results for the start time of charring for gypsum claddings type A of 2 layers are presented in Graph 14. Since there are test results only for gypsum claddings of 25 mm in the database, an equation for the start time of charring based on these results can not be given. The equation of the first analysis grouped both types of gypsum boards together, therefore compared to the results of this analysis, the design equation is overrated for gypsum boards type A, as most of the results stay under the equation line. The equation given in EN 1995-1-2 overestimates the value for start time of charring based on the results of this analysis. The value for floor claddings of gypsum boards type A in Finnish National Annex of EN complies with the start time of charring for gypsum boards with thickness 25mm. However, the start time of charring of wall claddings seems to be overestimated in the Finnish National Annex.



Graph 15 - Start time of charring for 2 layers of gypsum cladding of type A. Comparison with Component Additive Method

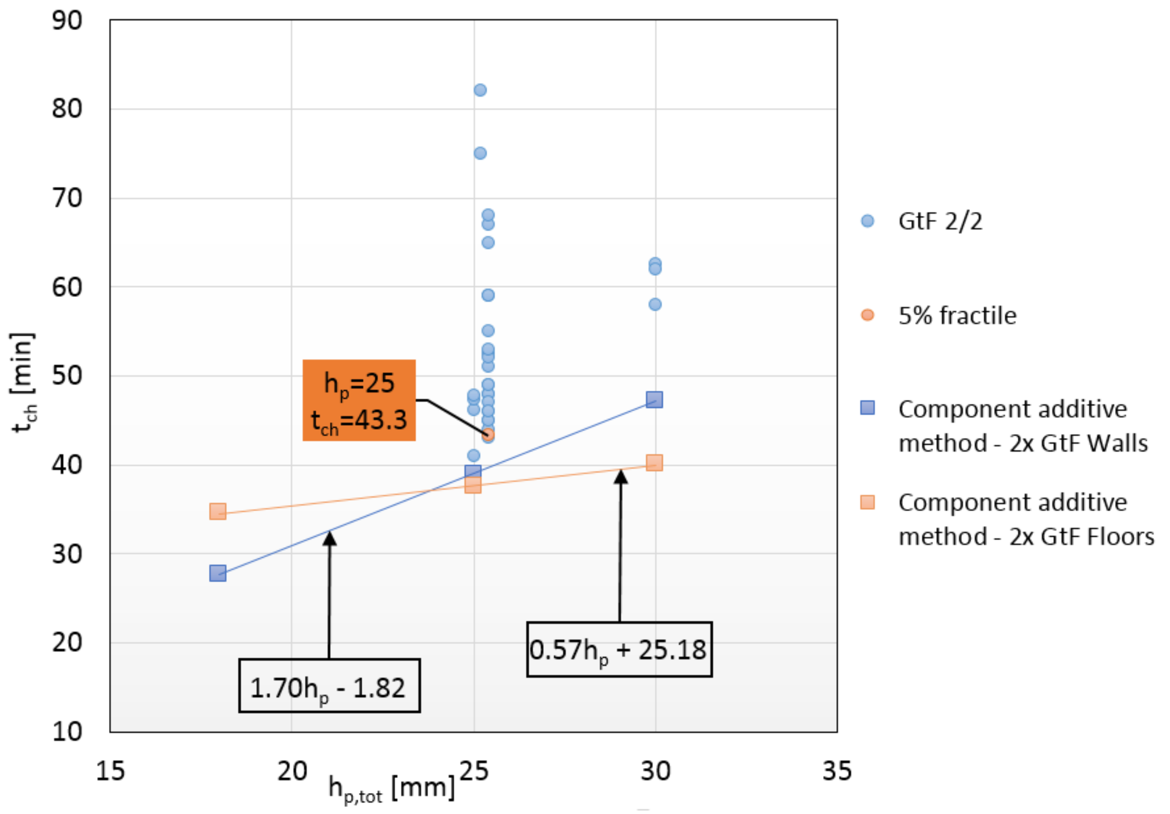
In Graph 15, it can be seen that the value for start of charring based on the component additive method slightly overestimates the value for start time of charring based on the results of this analysis.

6.3.4 Assemblies with 2 layers of gypsum boards of type F



Graph 16 - Start time of charring for 2 layers of gypsum cladding type F

Graph 16 displayes the results for the start time of charring behind 2 layers of gypsum cladding type F. Since most of the results represent gypsum board thickness about 25 mm, no equations for the start of charring can be given using the method of this study. The value for the thickness of 25 mm of gypsum cladding given in EN 1995-1-2 is overestimated, based on the results of this analysis. Same can be said about the equation that is based on the first analysis.



Graph 17 - Start time of charring for 2 layers of gypsum cladding of type F. Comparison with Component Additive Method

The comparison of the value for the start of charring based on this analysis and the values calculated with the component additive method show can be seen in Graph 17. The component additive method slighty underestimates the results for the start of charring for this type of assembly.

6.4 The failure time of the gypsum cladding

6.4.1 General

In order to analyse the influence different set-ups of the assemblies might have on the failure time of the boards, the test results were divided into different categories. The categories can be seen in Figure 15. Out of the 388 full-scale fire test results, 236 contained information about the failure time of the cladding.

Graph 18 and Graph 19 show all the results for the failure times of the gypsum claddings. For gypsum boards type A, the database contains more results about wall claddings. Claddings consisting of three layers of gypsum boards type A were not analysed, since the database contains only 6 results for wall claddings. For gypsum boards type F, the database contains more results about floor claddings. In order to analyse wall claddings consisting of three layers of gypsum boards type F, more test results of this type of assembly are needed.

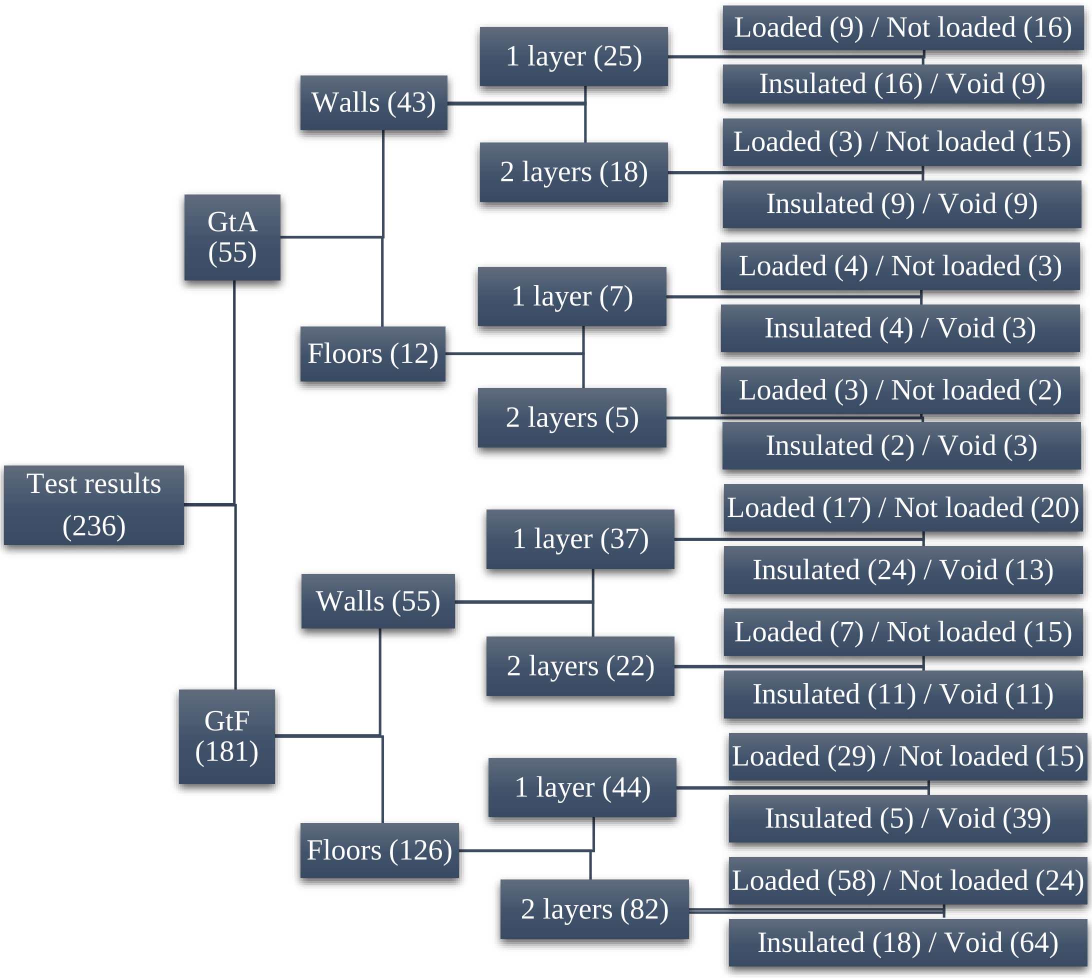
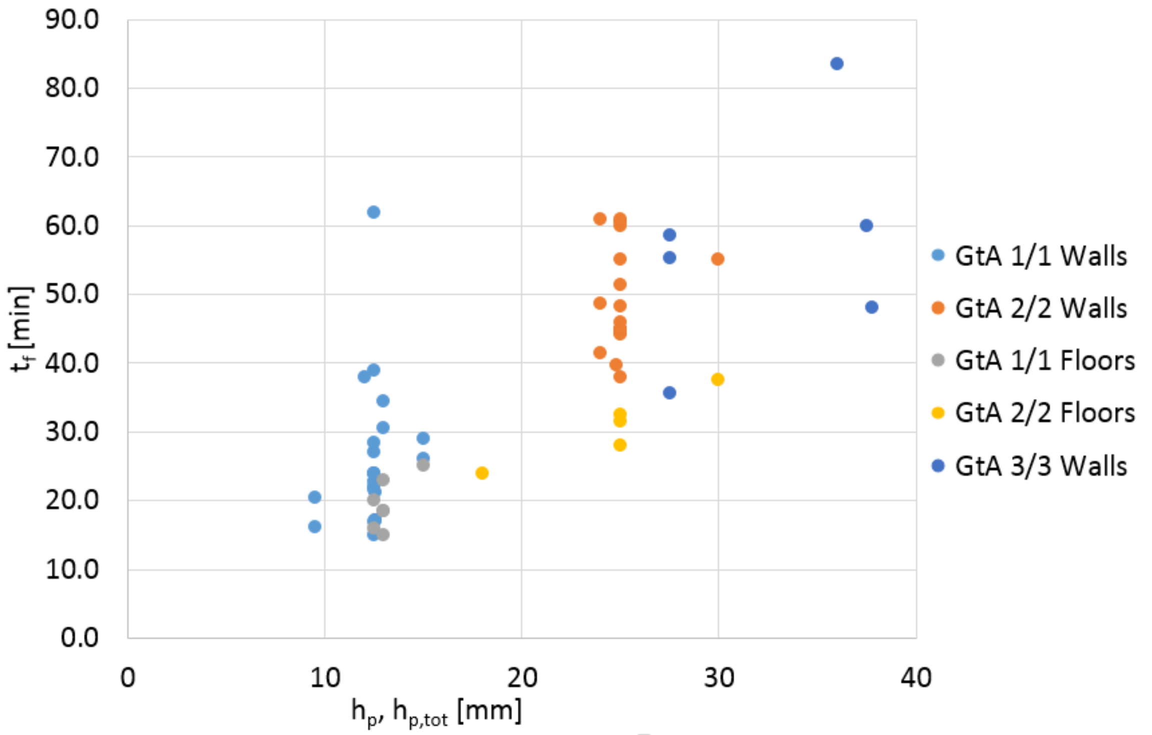
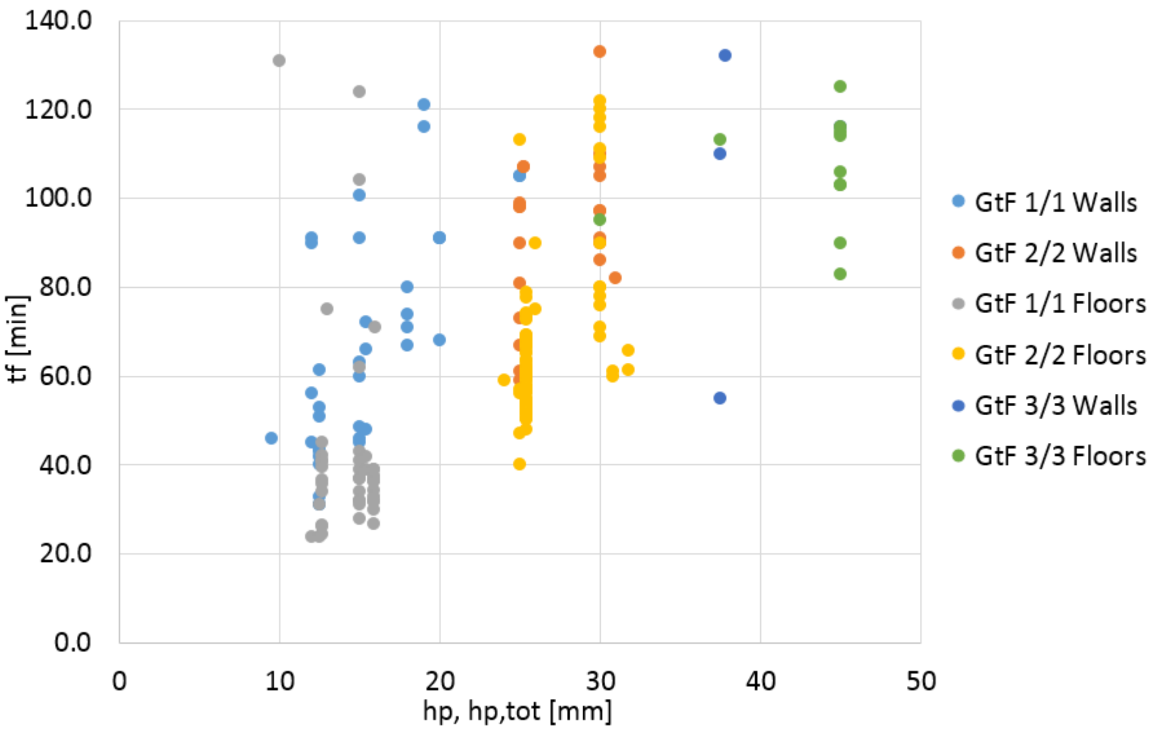


Figure 15 – Test results for the failure time of the cladding in the database



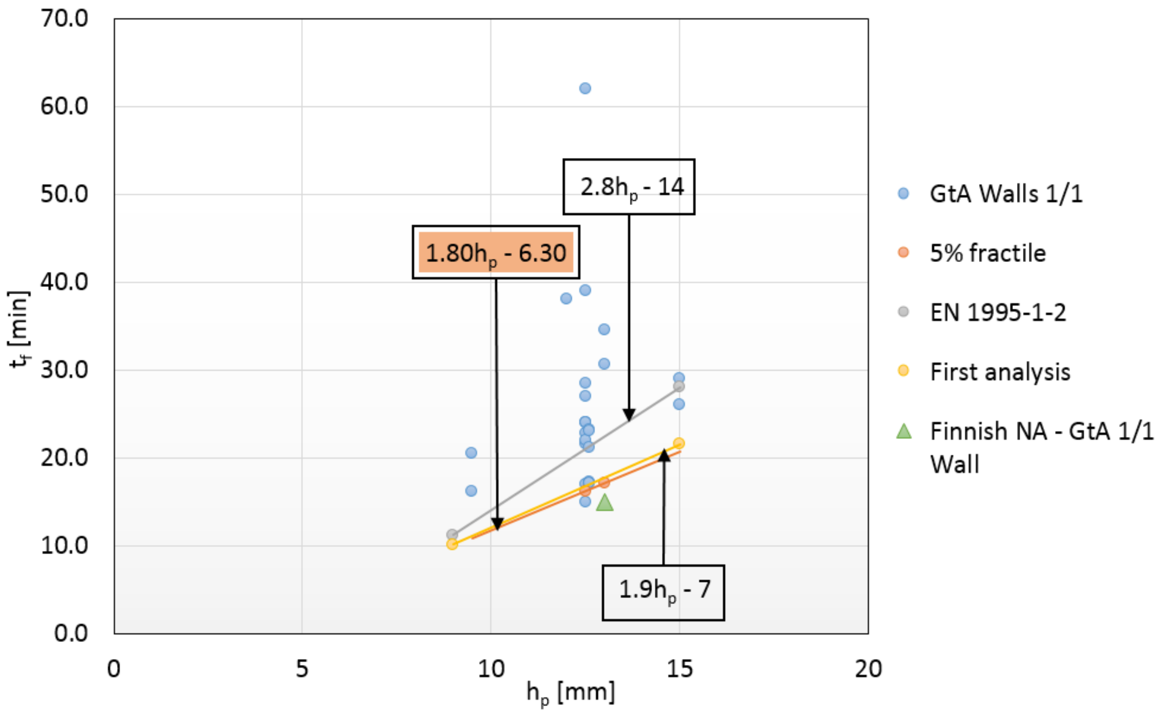
Graph 18 - Failure times of gypsum boards type A



Graph 19 - Failure times of gypsum boards type F

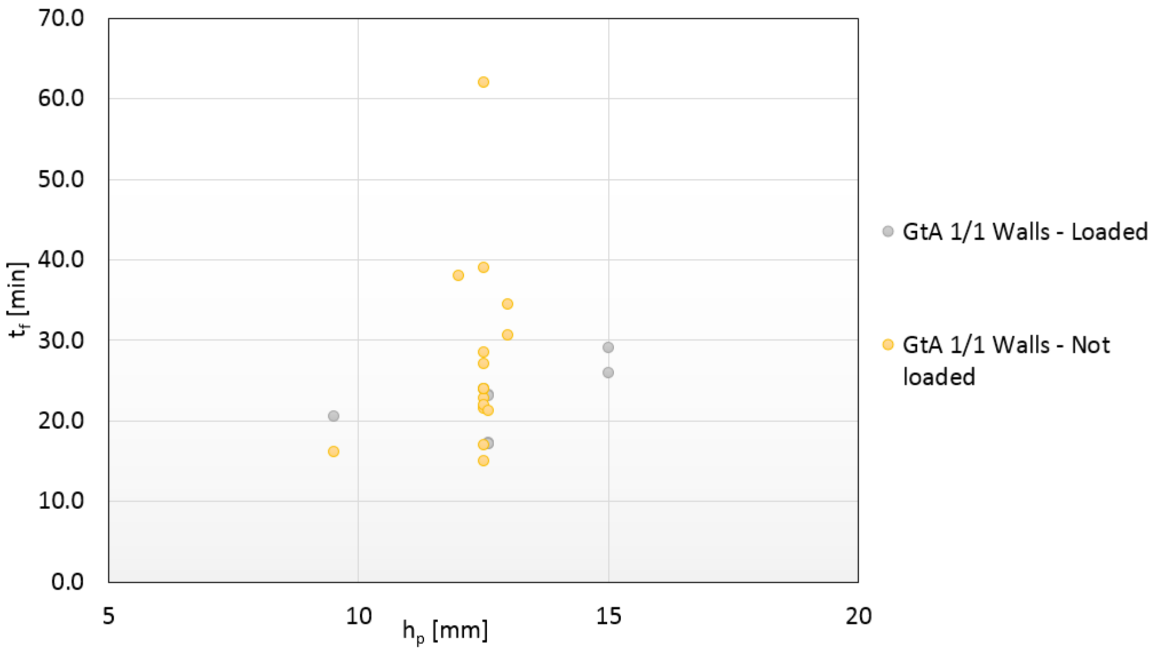
6.4.2 Gypsum boards type A

6.4.2.1 Wall assemblies with 1 layer of gypsum board type A



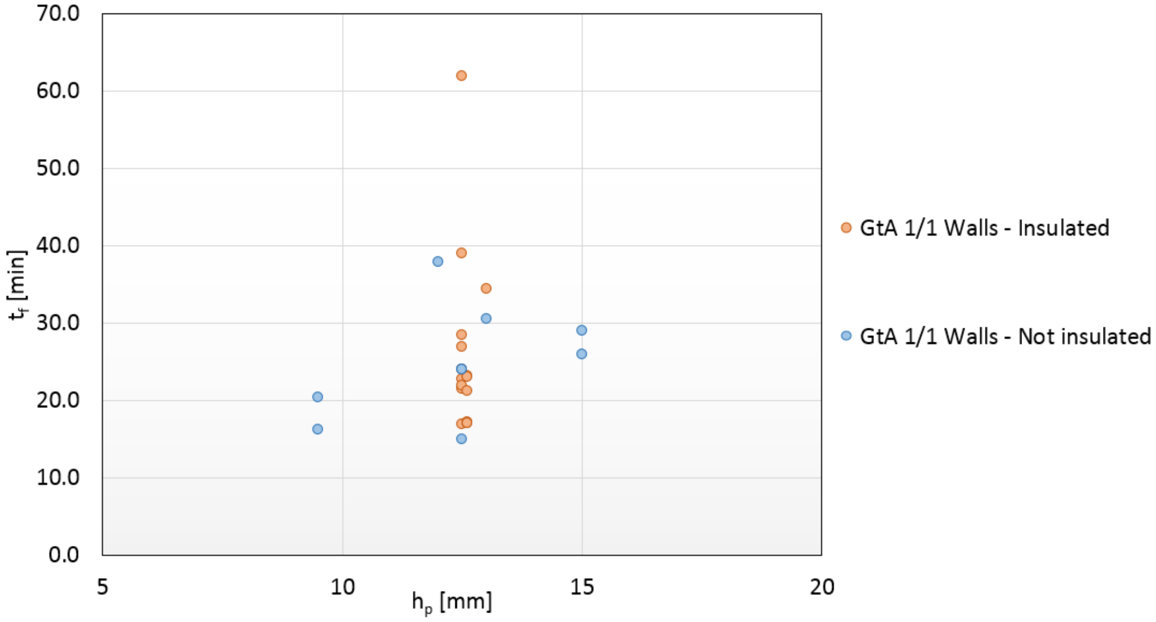
Graph 20 - Failure times of wall claddings of 1 layer of type A gypsum boards

In Graph 20, the failure times of 1 layer of type A gypsum boards used in wall assemblies can be seen. Some of the failure times of 12,5 mm gypsum board are under the equation given in EN 1995-1-2, which indicates that EN 1995-1-2 overestimates the failure time. Compared to the results of this database, the Finnish National Annex of EN 1995-1-2 slightly underestimates the failure time for gypsum boards type A in wall assemblies, as all test results remain above the the failure time given in the Finnish National Annex. The results of the first analysis show slightly higher time for failure of the gypsum boards. This might be due to the fact, that more results have been added to the database compared to the number of results the database had during the first analysis.



Graph 21 – Failure times wall claddings of 1 layer of gypsum board type A. Loaded and not loaded assemblies

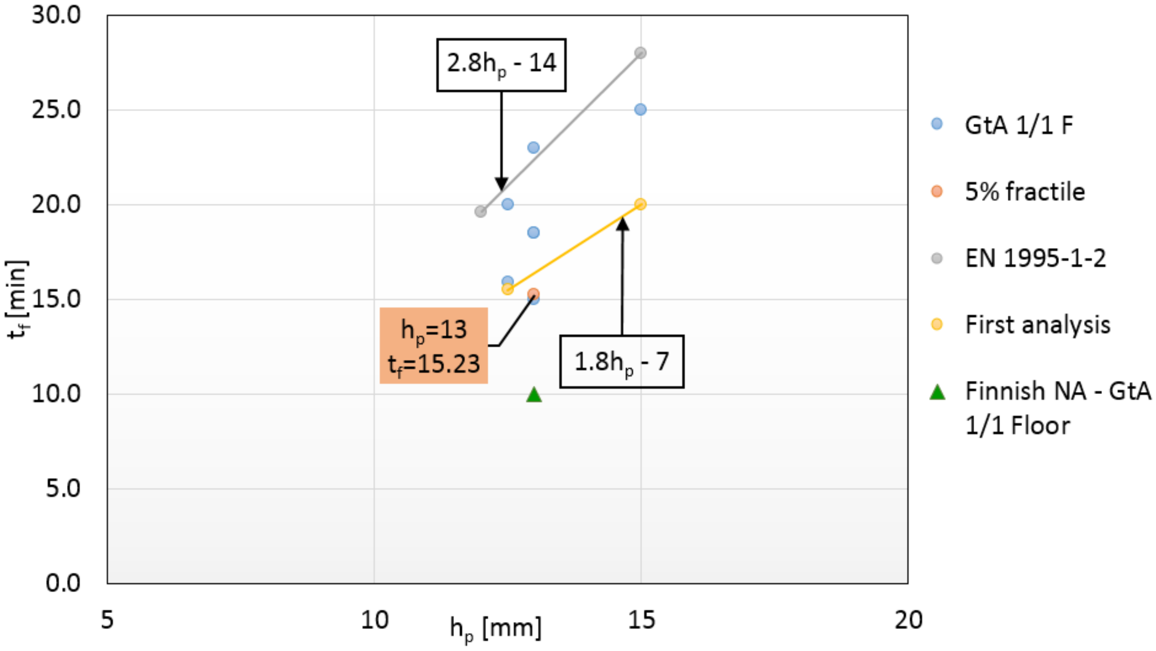
The number of test results for loaded and not loaded wall assemblies of gypsum board of 1 layer are presented in Graph 21. The results for the not loaded assemblies should have higher failure time of the cladding and most of the test results agree with that. However, the number of the test results for each type is too small to give equations for the failure times of the claddings depending on the loading conditions. The test results in the database are failure times of different assemblies. In order to find out how exactly applying of the load affects the failure time, same type of assembly should be tested without load and with load.



Graph 22 - Failure times wall claddings of 1 layer of gypsum board type A. Insulated and not insulated assemblies

Graph 22 displays the failure times of gypsum wall cladding type A of 1 layer by insulated and not insulated wall assemblies. Previous studies have confirmed that having a resilient channel behind the gypsum board shows down the temperature rise behind the board. However, there are too few results for each type of assembly in the database to confirm this.

6.4.2.2 Floor assemblies with 1 layer of gypsum board type A

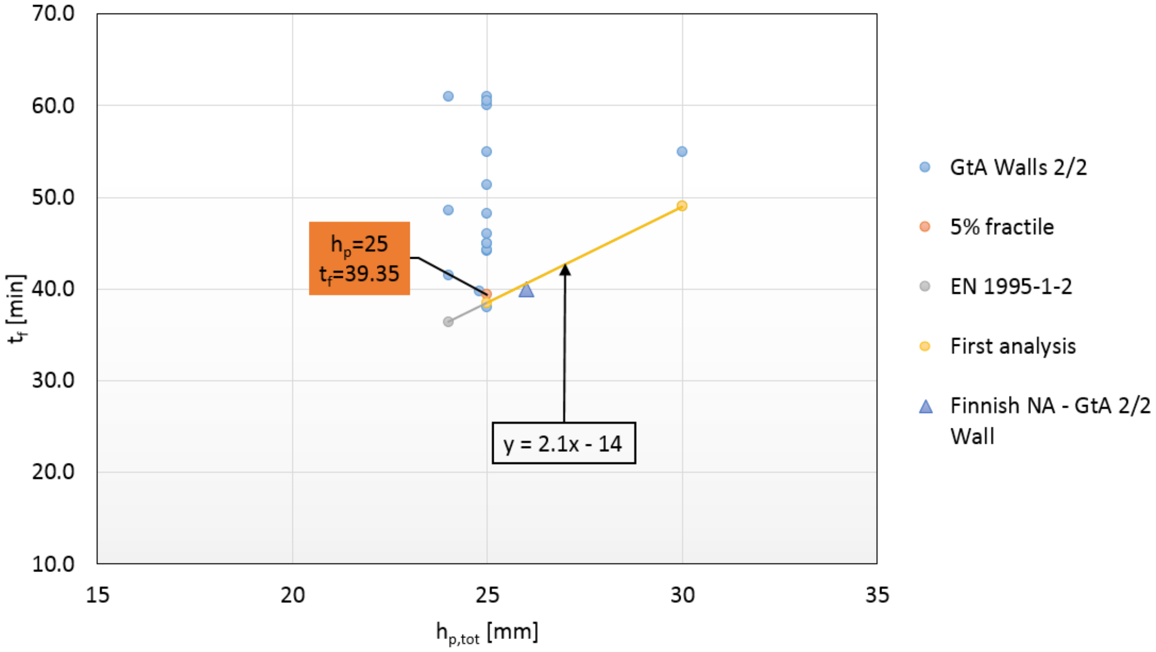


Graph 23 - Failure times of floor claddings of 1 layer of type A gypsum board

The results for failure times of floor claddings of 1 layer of gypsum boards type A are displayed in Graph 23. There are 7 results for this type of assembly in total, 6 of the results are for the gypsum board with a thickness of 12,5 mm to 13 mm. The failure time for this thickness is given in the graph. In order to give an equation for the failure time of this type of assembly, there are more results needed. Based on the results of the database, the failure time in EN 1995-1-2 is overestimated and the failure time in Finnish National Annex of EN 1995-1-2 is underestimated.

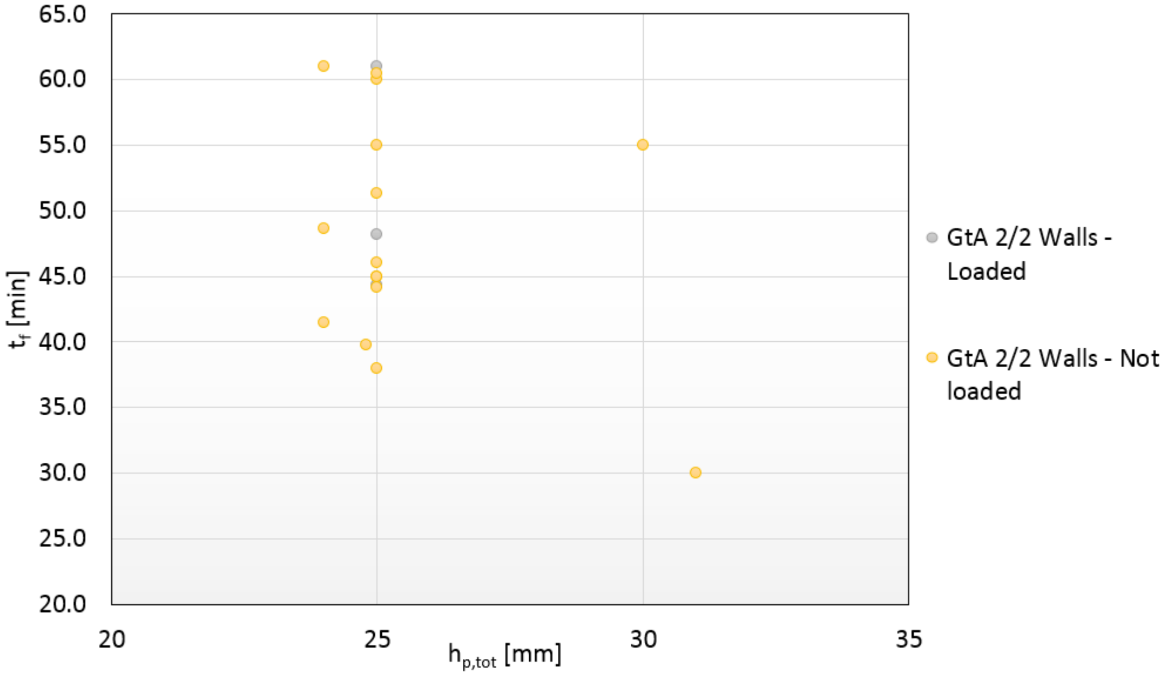
In order to present failure times considering the load arrangement and the insulation in the assembly, more results of full-scale fire tests need to be added into the database.

6.4.2.3 Wall assemblies with 2 layers of gypsum board type A



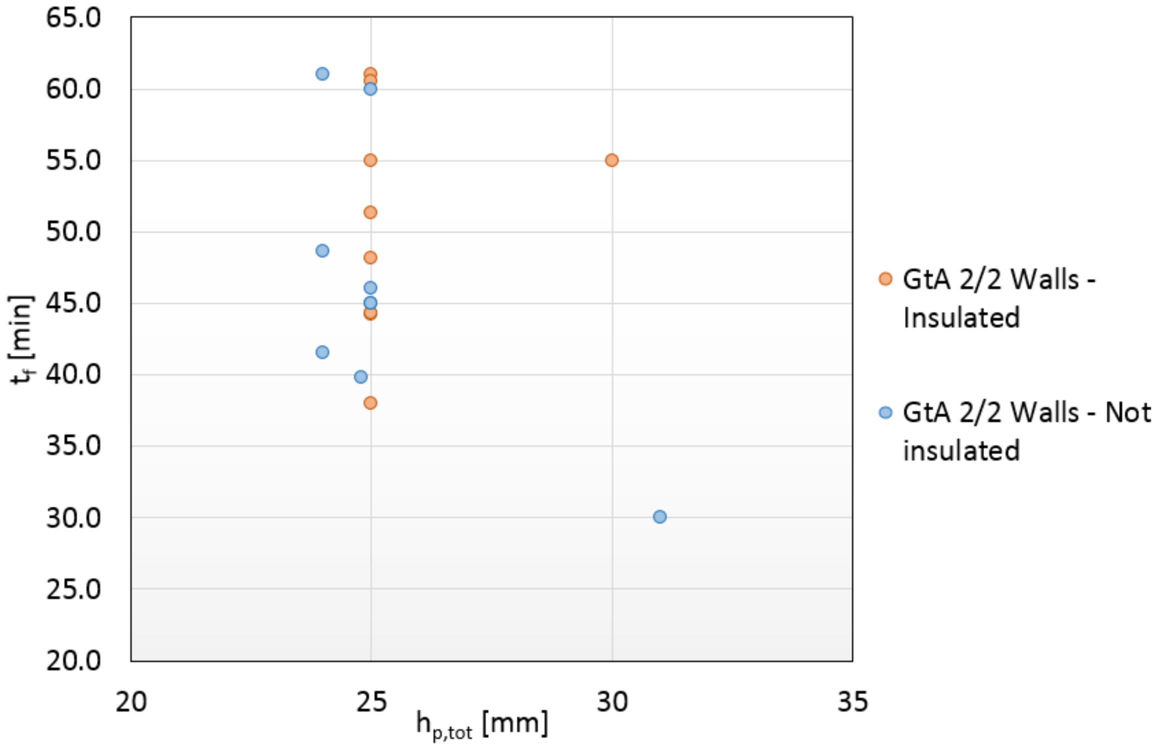
Graph 24 - Failure times of wall claddings of 2 layers of type A gypsum board

Failure times of wall claddings of 2 layers of type A gypsum boards are presented in Graph 24. As there are 12 values for gypsum board thickness 12,5mm, the 5% fractile value can be given for this thickness of gypsum boards type A. That value also complies with the equation given in EN 1995-1-2 and the result of the first analysis of the database. The value of failure time given by Finnish National Annex aslo complies with those equations.



Graph 25 - Failure times of wall claddings of 2 layers of type A gypsum board. Loaded and not loaded assemblies

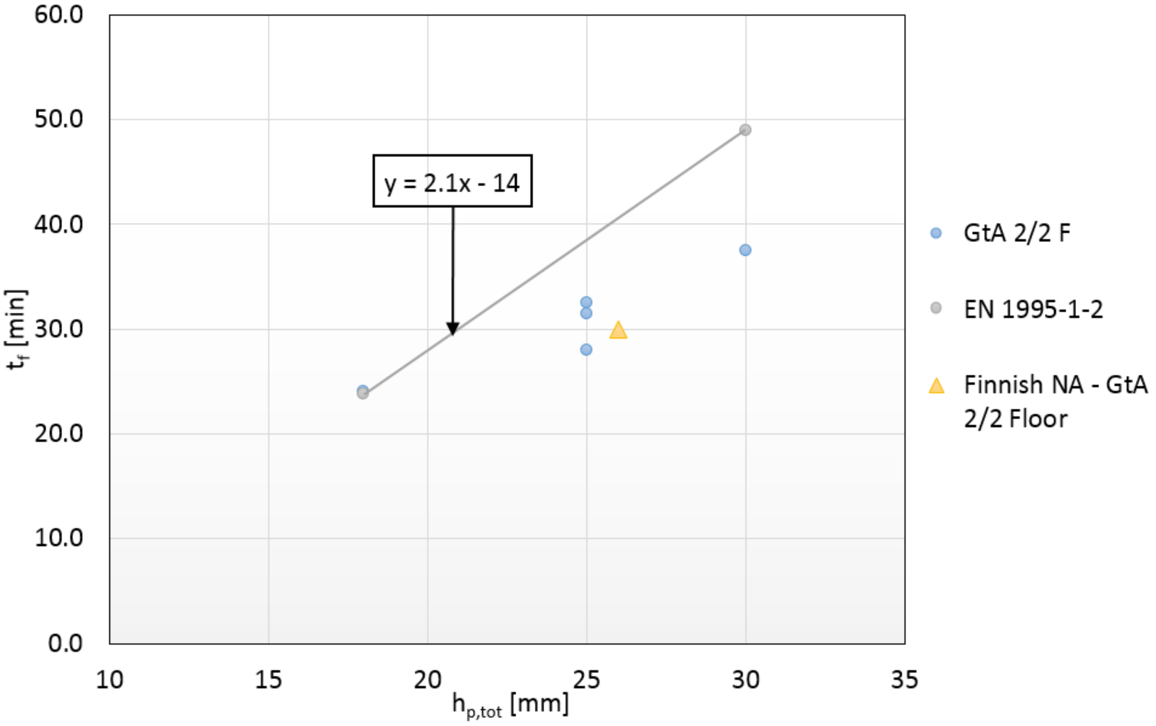
The failure times for different type of load arrangement are shown in Graph 25. Previous studies have confirmed that applying a load to the assembly has a negative effect on the failure time of the cladding. However, the results of this study can not confirm that, since there are too few test results for loaded and not loaded assemblies.



Graph 26 - Failure times of wall claddings of 2 layers of type A gypsum board. Insulated and not insulated assemblies

The test results for insulated and not insulated wall assemblies are presented in Graph 26. However, the negative effect of insulation on the failure time of the cladding can not be confirmed based on these results.

6.4.2.4 Floor assemblies with 2 layers of gypsum board type A

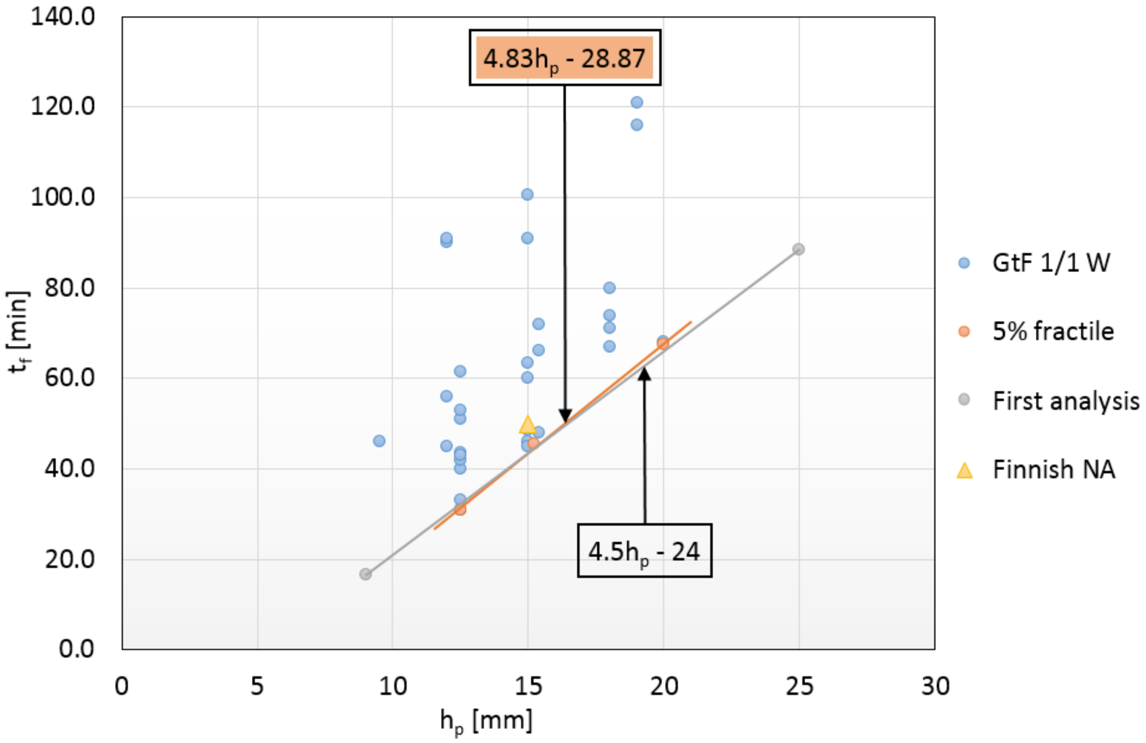


Graph 27 - Failure times of floor claddings of 2 layers of type F gypsum boards

Failure times of floor cladding of 2 layers of type F gypsum boards are presented in Graph 27. The number of results is too small to make any conclusions about the failure time of this type of claddings. Therefore, more results of full-scale fire tests need to be added to the database.

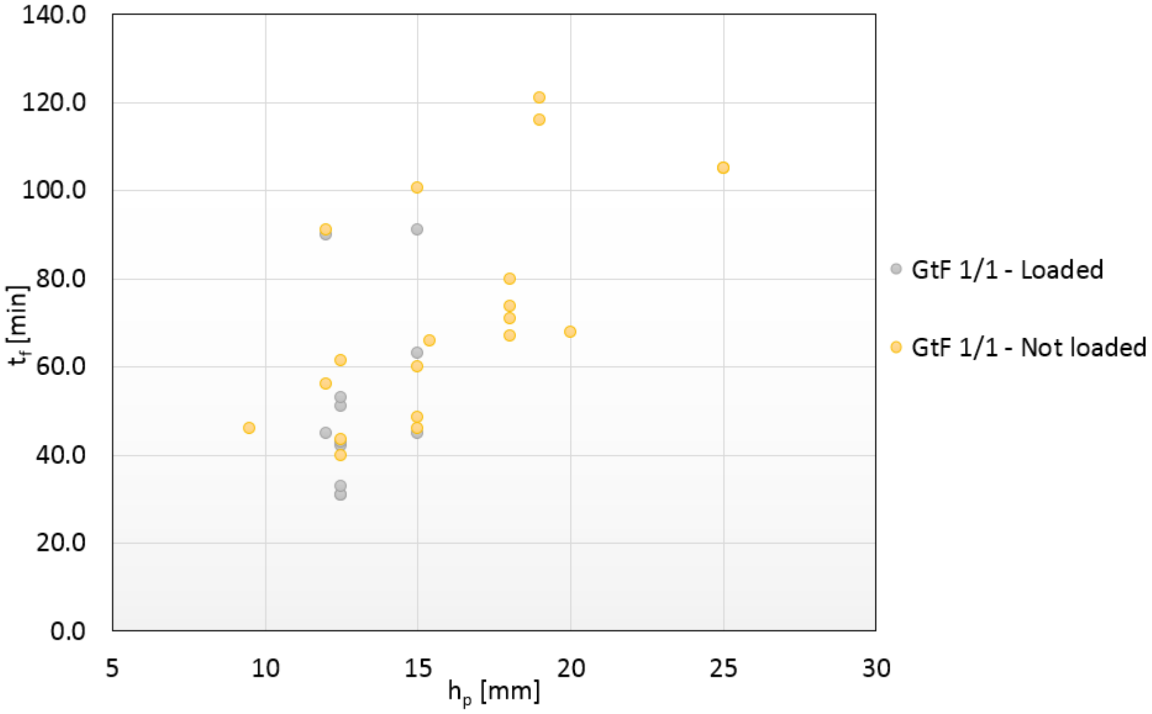
6.4.3 Gypsum board type F

6.4.3.1 Wall assemblies with 1 layer of gypsum board type F



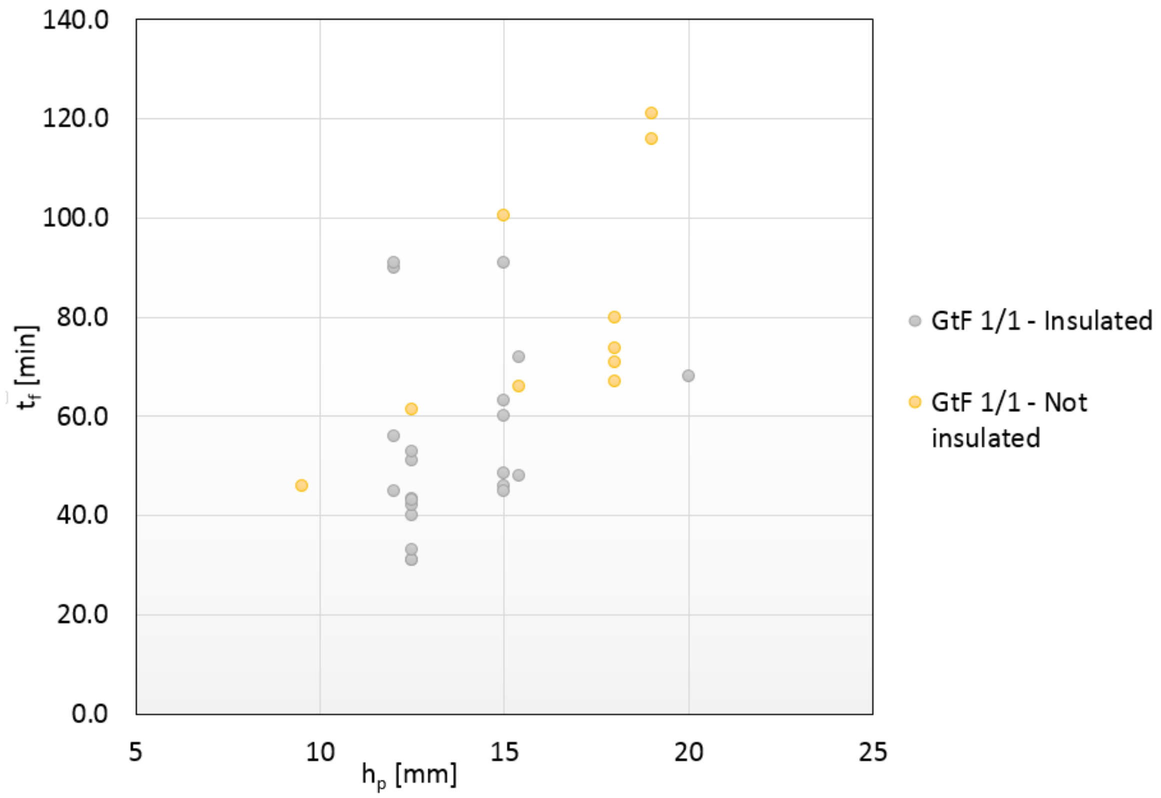
Graph 28 - Failure times of wall claddings of 1 layer of type F gypsum board

The results for the failure times of wall cladding of 1 layer of gypsum board type F are presented in Graph 28. The results in the database show a very large scatter of performance properties in fire. The results of the first analysis of the database show good correlation with the results of this study. Finnish National Annex of EN 1995-1-2 gives a slightly bigger value for the failure time than the equation developed in this analysis.



Graph 29 - Failure times of wall claddings of 1 layer of type F gypsum boards. Loaded and not loaded assemblies

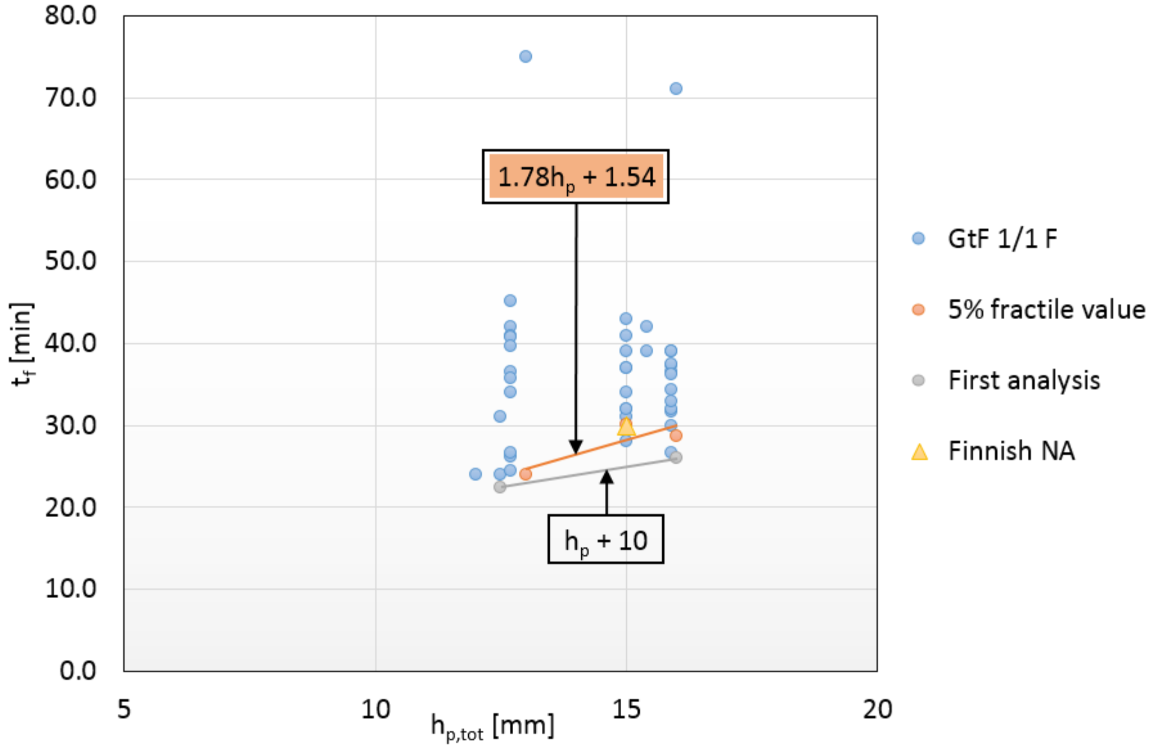
The results for the failure times by loaded and not loaded assemblies are displayed in Graph 29. Based on the previous studies, there is a tendency of not loaded test assemblies having higher values for the failure times of the claddings. This effect should be further investigated in the future.



Graph 30 - Failure times of wall claddings of 1 layer of type F gypsum board. Insulated and not insulated assemblies

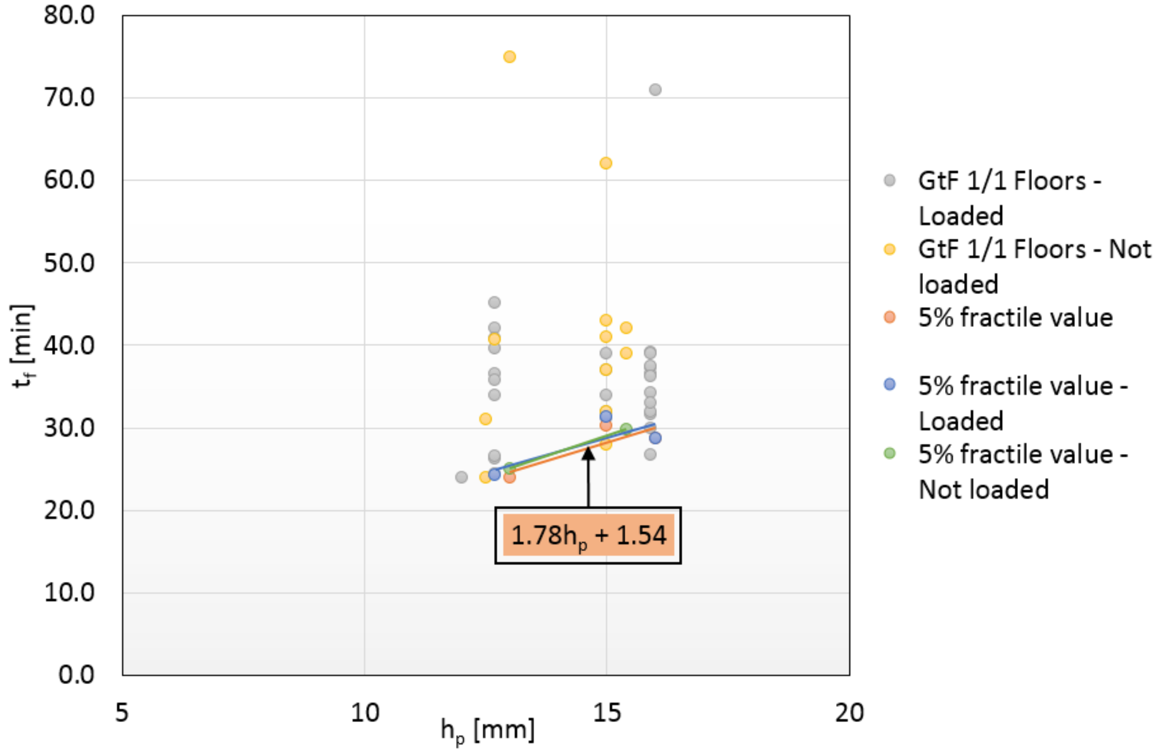
As can be seen in Graph 30, assemblies with insulation tend to show lower times for the failure of the gypsum cladding. However, this effect can be investigated more in the future as more test results are added.

6.4.3.2 Floor assemblies with 1 layer of gypsum board type F



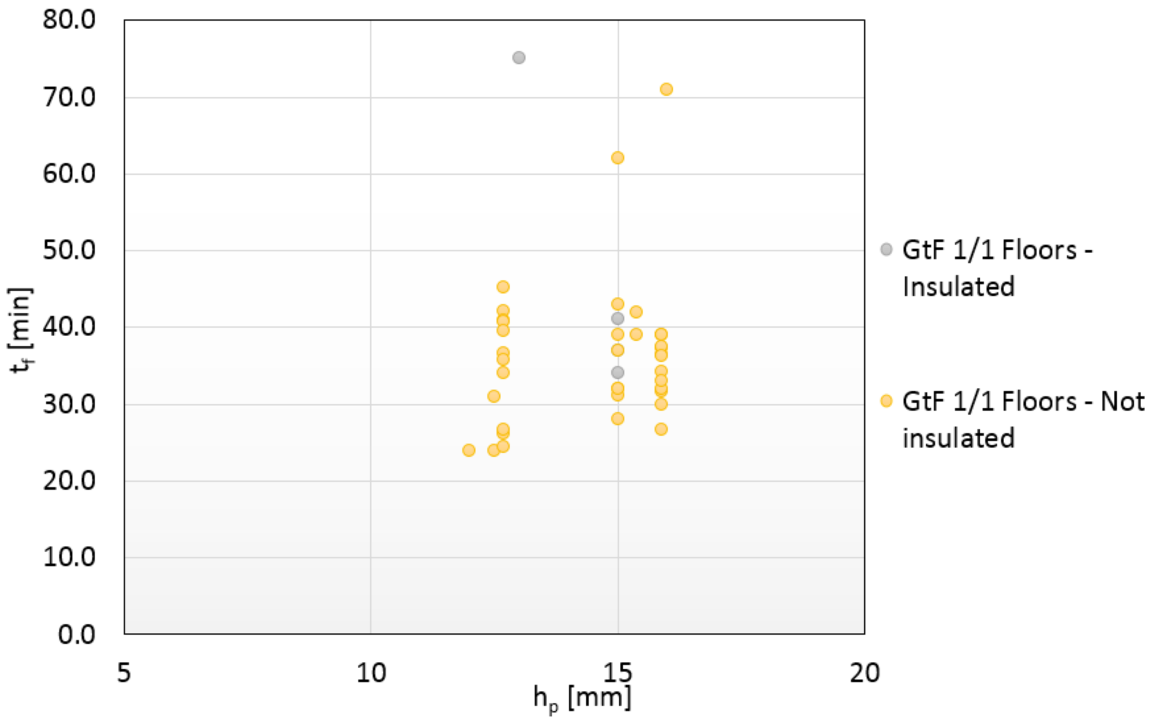
Graph 31 - Failure times of floor claddings of 1 layer of type F gypsum boards

The results for the failure times of floor cladding of type F gypsum boards of 1 layer presented in Graph 31, show a good correlation between the results of this analysis and the results of the first analysis of the database. The failure time for gypsum board type F of 15mm given in Finnish National Annex of EN 1995-1-2 also complies with the test results of this database.



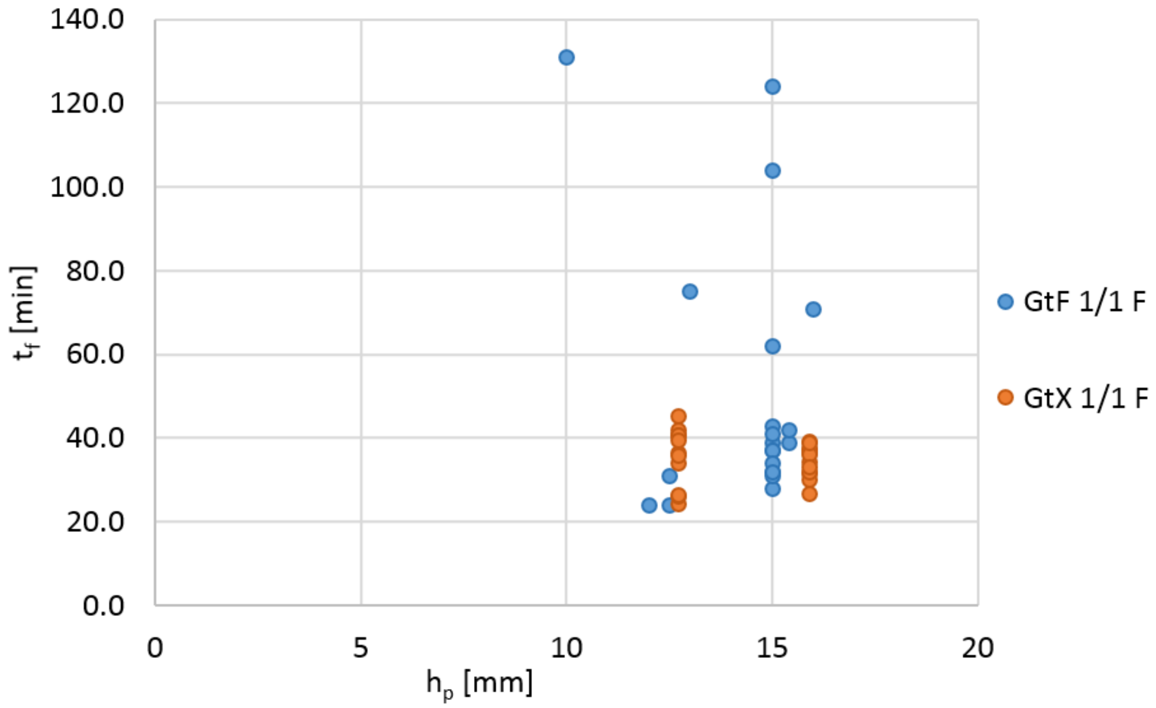
Graph 32 - Failure times of floor claddings of 1 layer of type F gypsum boards. Loaded and not loaded assemblies

The results for loaded and not loaded assemblies are presented in Graph 32. The 5% fractile values for loaded and not loaded assemblies are similar. The negative effect loading has on the failure time is not clearly seen based on the results of this database. In order to develop equations for both assemblies, more results for not loaded assemblies are needed.



Graph 33 - Failure times of floor claddings of 1 layer of type F gypsum boards. Insulated and not insulated assemblies

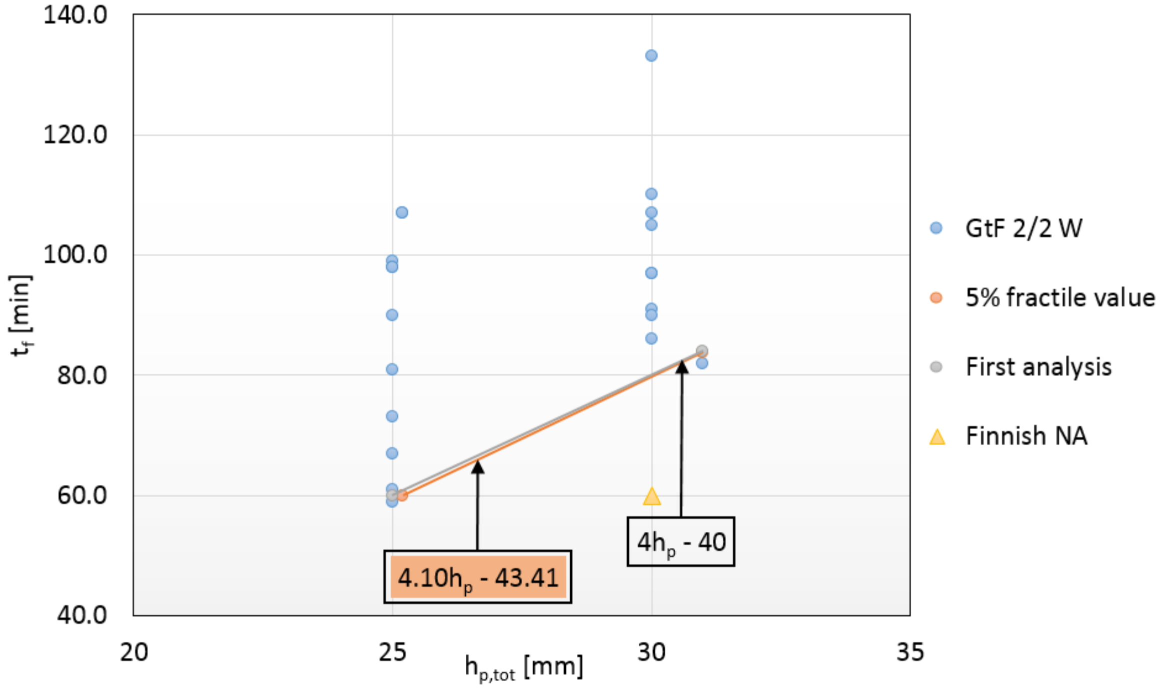
The failure times of insulated and not insulated assemblies can be seen in Graph 33. No conclusions about the effect insulation has on the failure times of the boards can be made based on the database, since the number of insulated assemblies of this type is 5. In order to analyse this effect, more test results for insulated assemblies are needed.



Graph 34 - Failure times of floor claddings of 1 layer of type F and type X gypsum boards.

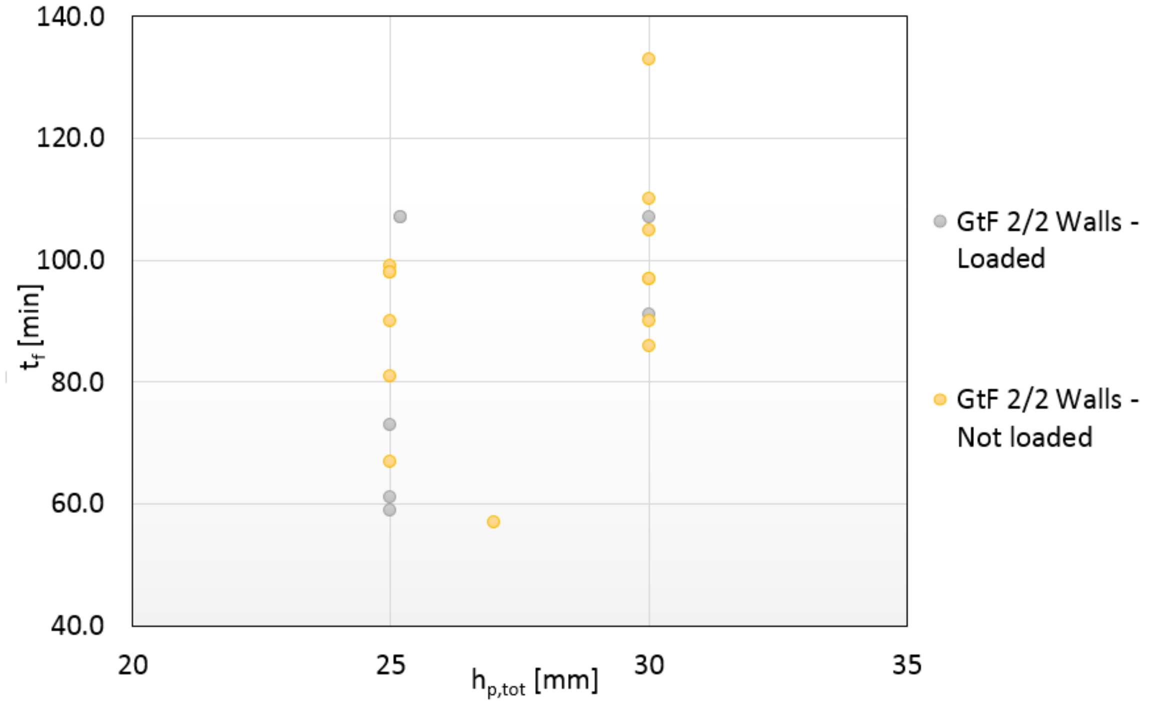
The test results of floor claddings of 1 layer, presented in Graph 34, consist of failure times of gypsum boards of type F and type X. There is a small difference in the measurements of the boards, due to the different measurement systems in Europe and North America. However, both types show similar scatter of results for the failure time of the board.

6.4.3.3 Wall assemblies with 2 layers of gypsum board type F



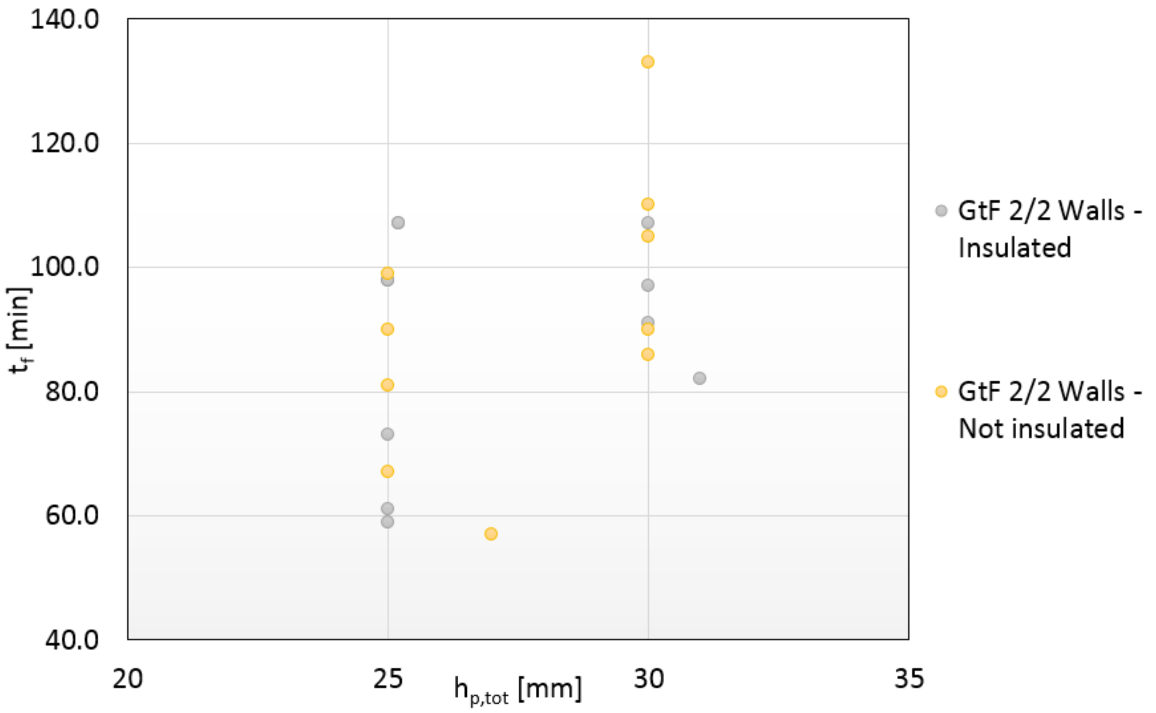
Graph 35 - Failure times of wall claddings of 2 layers of type F gypsum boards

In Graph 35, it can be seen that the results for wall claddings of 2 layers of type F gypsum boards in this analysis are in good correlation with the results of the first analysis. The result of Finnish National Annex of EN 1995-1-2 underestimates the time of the cladding failure for gypsum boards type F based on the results of this and the first analysis.



Graph 36 - Failure times of wall claddings of 2 layers of type F gypsum boards. Loaded and not loaded assemblies

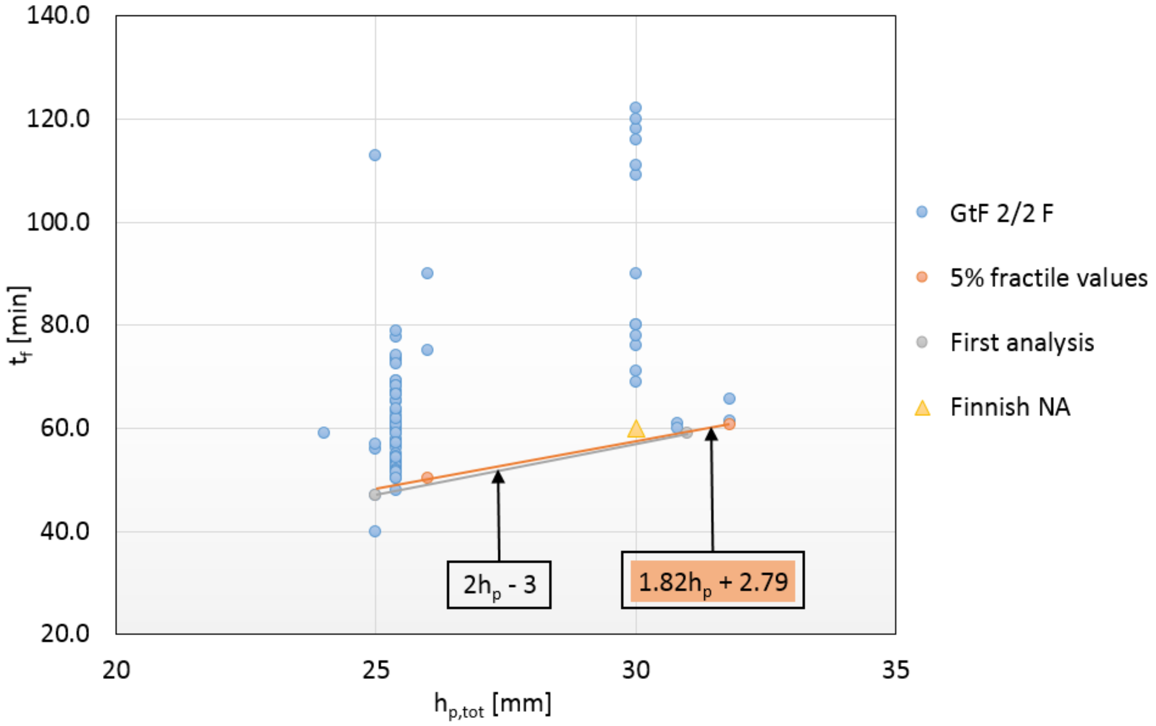
The failure times for loaded and not loaded assemblies are presented in Graph 36. Any conclusions about the effect that the applying of the load has on the failure time can not be made based on the results of this analysis. In order to investigate it further, more test results for both types of assemblies are needed.



Graph 37 - Failure times of wall claddings of 2 layers of type F gypsum boards. Insulated and not insulated assemblies

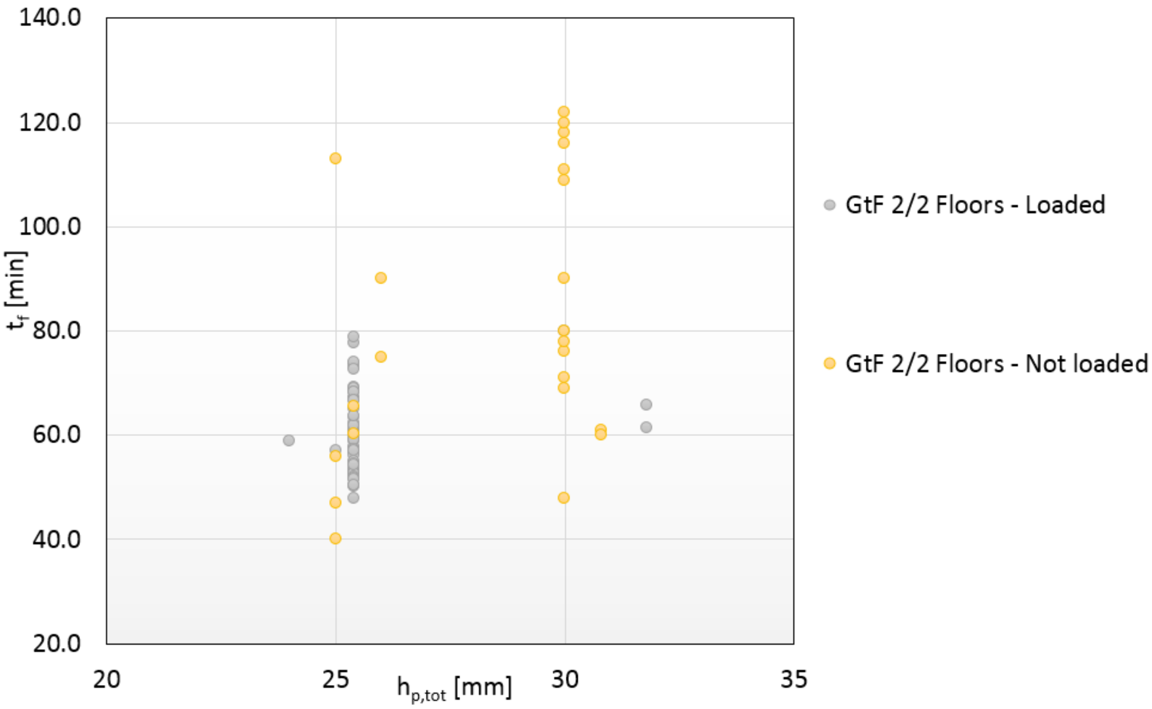
Based on the test results of insulated and not insulated assemblies for wall assemblies of 2 layers of gypsum boards type F presented in Graph 37, no conclusions about the failure time of the cladding can be made. In order to investigate the effect insulation has on the failure time of the cladding, more test results need to be added to the database.

6.4.3.4 Floor assemblies with 2 layers of gypsum board type F



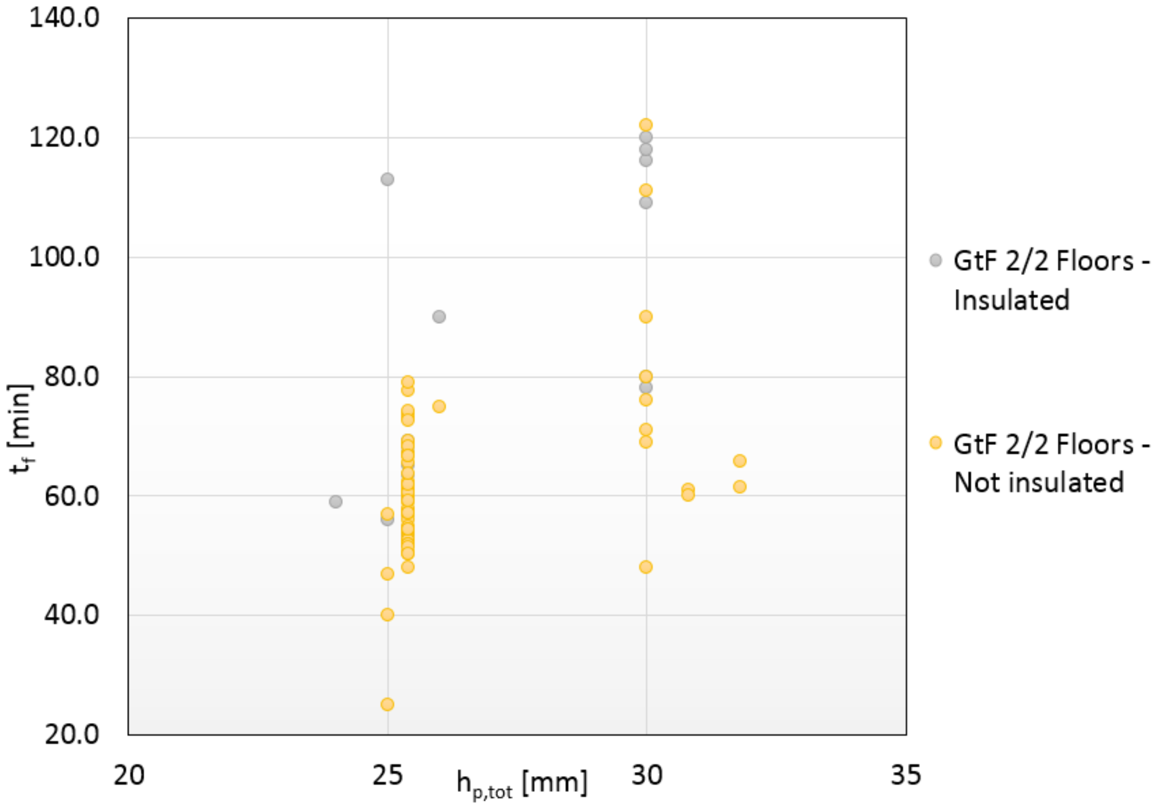
Graph 38 - Failure times of floor claddings of 2 layers of type F gypsum boards

It can be seen in Graph 35, that the results for wall claddings of 2 layers of type F gypsum boards in this analysis comply with the results of the first analysis. The value of failure time for 30 mm type F gypsum boards in Finnish National Annex of EN 1995-1-2 also complies with the results of this database.



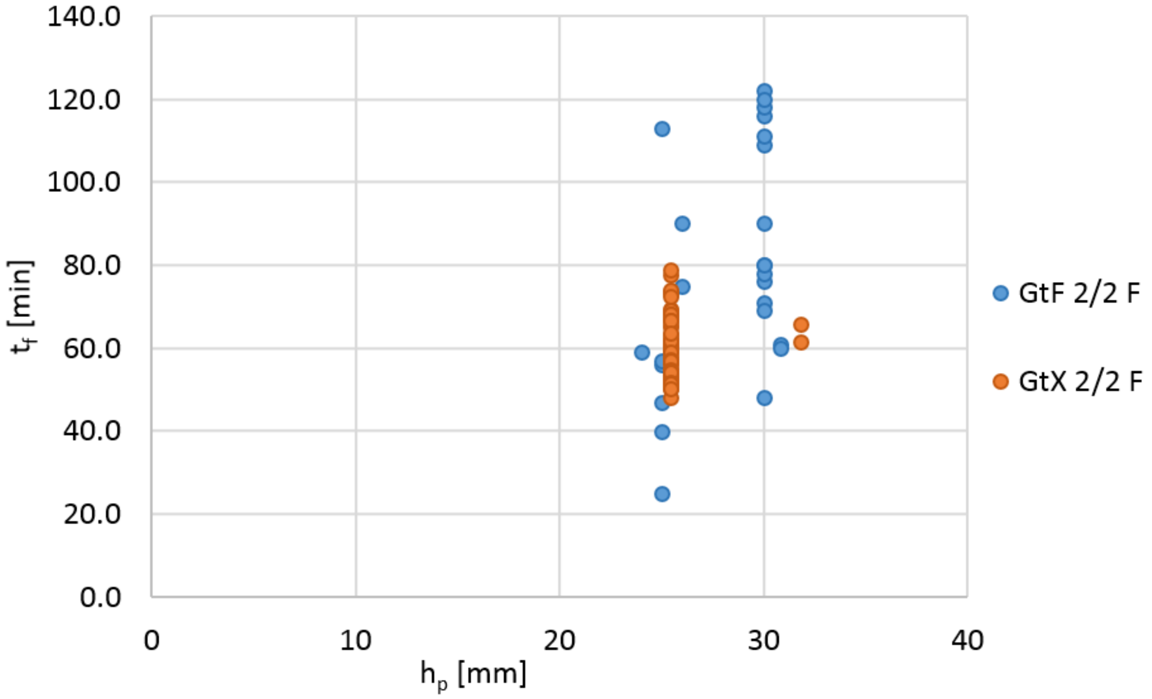
Graph 39 - Failure times of wall claddings of 2 layers of type F gypsum boards. Loaded and not loaded assemblies

The failure times for loaded and not loaded assemblies of 2 layers of gypsum board type F are presented in Graph 39. The 5% fractile value equation cannot be given for loaded assemblies, since most of the results are of thickness 25 mm and there is not enough data for other thicknesses. More test results for not loaded assemblies and loaded assemblies of other thicknesses than 25 mm are needed in order to develop equations for the failure time of the cladding.



Graph 40 - Failure times of floor claddings of 2 layers of type F gypsum boards. Insulated and not insulated assemblies

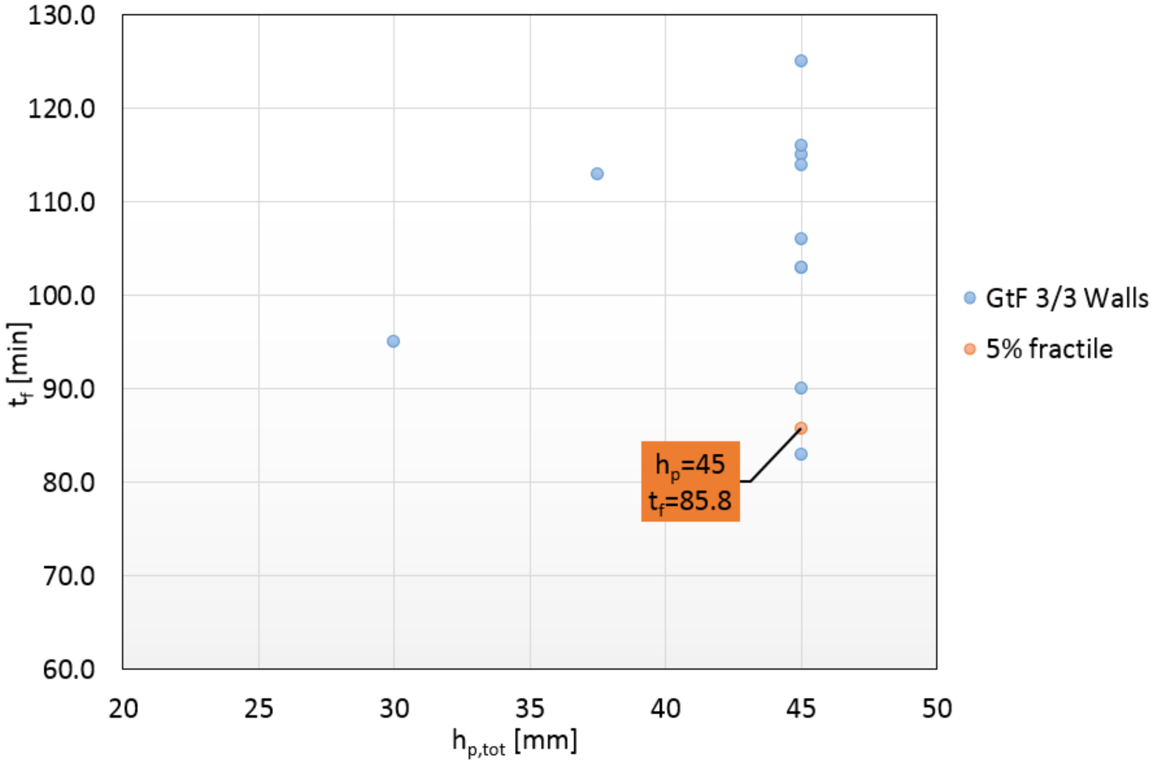
Graph 40 describes the failure times of insulated and not insulated wall assemblies with 2 layers of gypsum boards type F. There is not enough data to give the 5% fractile value equation for insulated assemblies. Therefore, more data for the insulated floor assemblies of this type is needed in the future.



Graph 41 - Failure times of floor claddings of 2 layers of type F and type X gypsum boards

The failure times for gypsum boards type F and type X can be seen in Graph 41. Based on the results in the database, there is no distinct difference in the failure times of gypsum boards type F and type X.

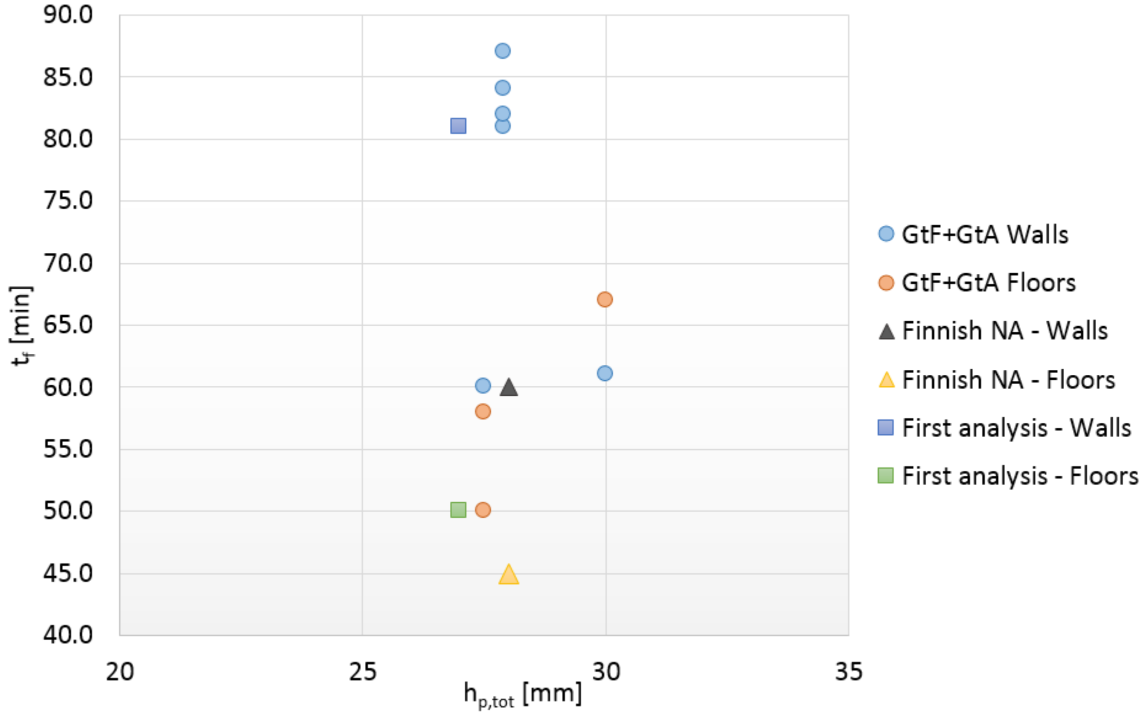
6.4.3.5 Floor assemblies with 3 layers of gypsum board type F



Graph 42 - Failure times of wall claddings of 3 layers of type F gypsum boards

The test results for failure times of wall claddings of 3 layers of type F gypsum boards are presented in Graph 42. Since most of the test results are of gypsum cladding thickness 45 mm, it is not possible to give a design equation for this type of cladding.

6.4.4 Assemblies with type F and type A gypsum boards



Graph 43 - Failure times of claddings of gypsum board type F as the outer layer and type A as the inner layer.

The failure times of gypsum claddings consisting of gypsum boards type F as the outer layer and type A as the inner layer are presented in Graph 43. As the number of results is small, 6 results for walls of this type and 3 results for floor of this type, any conclusions about the failure time of this type of cladding can not be made.

6.5 Design equations for the start time of charring

Table 4 gives an overview of the recommended design equations for the start time of charring developed based on this analysis.

Table 4 - Design equations for start time of charring

Number of layers in cladding	Type of gypsum plasterboard	Walls and floors	
		Equation for t_{ch}	Limits
1	Type F	$2{,}0h_p - 10{,}8$	$12{,}5\ mm \leq h_p \leq 15{,}4\ mm$
	Type A		
2	Type F	43,3	$h_p \geq 25\ mm$
	Type A	29,4	$h_p \geq 25\ mm$

6.6 Design equations for the failure time of gypsum boards

Table 5 and Table 6 give an overview of the design equations for the failure times of the gypsum boards developed based on this analysis.

Table 5 - Design equations for failure time of wall claddings of gypsum plasterboards

Type of gypsum plasterboard	Number of layers in cladding	Walls	
		Equation for t_f	Limits
Type F	1	$4{,}8h_p - 28{,}9$	$12{,}5\ mm \leq h_p \leq 20\ mm$
	2	$4{,}1h_p - 43{,}4$	$25\ mm \leq h_p \leq 31\ mm$
	3	85,8	$h_p \geq 45\ mm$
Type A	1	$1{,}8h_p - 6{,}3$	$12{,}5\ mm \leq h_p \leq 15\ mm$
	2	39,4	$h_p \geq 25\ mm$
	3	-	-

Table 6 - Design equations for failure time of floor claddings of gypsum plasterboards

Type of gypsum plasterboard	Number of layers in cladding	Floors	
		Equation for t_f	Limits
Type F	1	$1{,}8h_p + 1{,}5$	$12\ mm \leq h_p \leq 16\ mm$
	2	$1{,}8h_p + 2{,}8$	$24\ mm \leq h_p \leq 31\ mm$
	3	-	-
Type A	1	15,2	$h_p \geq 12{,}5\ mm$
	2	-	-
	3	-	-

6.7 List of test results needed

In order to provide design equations for all types of timber frame assemblies with gypsum boards analysed in this study, more test results need to be added. These results are described in Table 7.

Table 7 - Test results needed for the design equations

Gypsum board	Assembly	Number of layers	
Type A	Wall	1	15 mm
		2	30 mm
		3	
	Floor	1	
		2	
		3	
Type F	Wall	1	
		2	
		3	
	Floor	1	
		2	
		3	

- the number of test results of this type is sufficient (more than 6)

- more test results of this type are needed for all thicknesses of gypsum boards

12,5 mm - more test results of this type are needed for this certain thickness of gypsum board

In order to analyse the effect that insulation and loading have on the fire performance of timber frame assemblies, more test results are needed. The test results needed are described in Table 8.

Table 8 - Test results needed for further analysis

Gypsum board	Assembly	Number of layers	Loaded	Not loaded	Insulated	Not insulated
Type A	Wall	1	9 mm, 15 mm		9 mm, 15 mm	
		2		30 mm	30 mm	
		3				
	Floor	1				
		2				
		3				
Type F	Wall	1	15 mm, 20 mm			
		2				
		3				
	Floor	1		12,5 mm		
		2	30 mm	25 mm		
		3				

- the number of test results of this type is sufficient to clearly see the influence

- more test results of this type are needed for all thicknesses of gypsum boards (clear influence of the effect can not be seen)

12,5 mm - more test results of this type are needed for this certain thickness of gypsum board (clear influence of the effect can not be seen)

6.8 Future research

In order to continue the research in the field of fire resistance of timber frame assemblies, the database used in this study should be improved. Analysis of existing fire test reports seem to be the most straightforward way to extend the database and get reliable failure times for gypsum boards. Therefore, more test data should be added in order to find design rules for all types of timber frame assemblies. In order to study the effect that insulation and loading have on the fire resistance of a timber frame assembly, an assembly of the same set-up should be tested applying different conditions. The assumption of normal distribution should be analysed, as more test results are added.

The new design rules should consider the effect fasteners have on the failure time of the gypsum board. At the moment, EN 1995-1-2 enables to calculate the failure time of the gypsum boards due to the pull-out of the fasteners. However, it does not take into consideration the distance of the fasteners from the edge of the board, which can significantly changes the failure time of the gypsum board.

Another possibility would be to develop a small scale method for testing the fire resistance of the gypsum boards, as full-scale fire tests are time consuming and expensive. However, as many factors influence the outcome of a fire resistance test, it is difficult to assess the performance of the gypsum board independently of other wall system influences. In the fire testing of gypsum boards in EN 520, core cohesion of the gypsum board is the only criterion based on what, the gypsum board is assigned type F and no full-scale testing is required for the definition of the type of the gypsum board. Therefore the results for the failure time of the boards vary in a big extent. That on the other hand, makes developing a method based on the test results more complicated. The new testing methods should also include the thermal insulation test of the gypsum board, as one of the primary functions of the thermal barrier is to insulate the structure and unexposed surface from the fire, and the shrinkage of the gypsum board in high temperature, which would make it possible to assess the degree and severity of cracking. [9] [38]

7 Summary

The aim of this thesis was to analyse the protective effect claddings of gypsum plasterboards have on timber frame assemblies based on the results of the database of full-scale fire tests of timber frame assemblies.

As a result of this thesis, an improvement of the database was created. New test results were added into the database and the EXCEL files of the database were reorganized making it easier to find and process the data in the further analysis of the database. The database files, which include information about the confidential data were separated from the files that include data about the set-up and the results of the full-scale fire tests, making it easier to work with the confidential data.

Based on the test results of the database in those groups that include enough data for this certain type of timber frame assembly, design equations for the start time of charring and the failure time of the gypsum cladding were developed for different types of gypsum claddings using the 5% fractile method. The aim of the design rules in this thesis is to provide a conservative approach to calculating the start time of charring and failure time of gypsum boards in timber frame assemblies in accordance with EN 1995-1-2. These design rules could be used in case the manufacturer of the gypsum boards does not provide necessary data for their product.

The comparison between the results of this database and the method used in EN 1995-1-2 shows, that for most types of gypsum claddings, EN 1995-1-2 overestimates the start time of charring and the failure times of gypsum boards, which may lead to unsafe constructions in fire. The results of this analysis were also compared to the results given in Finnish National Annex of EN 1995-1-2 and in most cases, the values for start time of charring and the failure times given in Finnish NA were on the conservative side compared to the test results of this database. The equations for start time of charring and the failure time of the gypsum boards presented in „Fire safety in timber buildings. Technical guideline for Europe“, that are based on the first analysis of this database, did not exclude 5% of the lowest values and are therefore more conservative than the equations developed in this thesis.

The values for the start time of charring calculated using the component additive method in „Fire safety in timber building, Technical guideline for Europe“ show good correlation with the results of this database. Therefore, this method can be recommended to be used when designing start time of charring.

In order to provide the design equations for the start time of charring and for the failure time of the gypsum boards based on this database for all types of assemblies described in chapters 6.5 and 6.6, more test results of these types of assemblies need to be added into the database.

One of the objectives of this study was to analyse the effect that insulation loading of the assembly have on the failure time of the cladding. However, the number of tests results for each type of assembly was too small to make conclusions about the effects insulation and loading might have on the failure time of the cladding. In order to analyse those effects, more test results need to be added into the database. Furthermore, these effects should be studied by comparing similar constructions with and without insulation, with and without loading the assembly. The list of the test results needed is given in chapter 6.7.

In order to provide simple design rules for the fire safety of timber frame assemblies, research in this field has to be continued. One of the most important issues is considering the thermomechanical properties of type F gypsum boards. Recommendations on future research are given in chapter 6.8. At the moment, European standards give insufficient information about the thermal properties for heat transfer calculations and mechanical properties in fire. Therefore, the values for failure times for different gypsum plasteboards type F vary in a big extent. As long as the manufacturers of gypsum boards are not obliged to perform such tests, the conservative values for the failure time of the boards have to be used.

8 Resümee

Käesolevas lõputöös käsitleti puitkonstruktsioonide tulepüsivust. Täpsemaks eesmärgiks oli uurida kipsplaatidega kaetud puitkonstruktsioonide täismõõdus tulekatsete tõrketekkeaegu ja söestumise algusaegu kipsplaatide taga. Selleks analüüsiti andmebaasi, mis koosneb vastavalt Eurokoodeksile läbi viidud täismõõdus tulekatsetest, milles katsetatud konstruktsiooni tulepoolne külg on kaetud kipsplaatidega.

Käesoleva töö tulemusena andmebaas korrastati ning andmebaasi lisati juurde täismõõdus tulekatsete andmeid. EXCEL-i formaadis andmebaas jaotati kaheks. Üks failidest sisaldab tulekatsete konstruktsioonide kirjeldust ja tulemusi, mis on vajalikud andmebaasi analüüsi jaoks ning teine sisaldab konfidentsiaalseid andmeid tulekatsete kuupäevade, testijate ja kipsplaatide päritolu kohta. Töö tulemusena valmis andmebaas uuel kujul, mis muudab edaspidise töö andmebaasiga efektiivsemaks.

Andmebaasi analüüsi tulemusena antakse arvutusjuhised söestumise algusaja ja kipsplaatide tõrketekkeaja arvutamiseks sõltuvalt kipsplaadi tüübist ja kipsplaatidest koosneva katte kihtide arvust, jättes välja 5% madalaimatest tulemustest. Kuna teatud tüüpi konstruktsioonidele oli katsetulemusi arvuliselt vähe, pole nende tüüpide kohta 0,05-fraktiilväärtuse meetodit kasutades usaldusväärseid arvutusjuhiseid võimalik anda. Lisaks polnud katsete arvulise vähesuse tõttu võimalik anda eraldi arvutusjuhiseid isoleeritud või õhkvahega ning koormatud või koormamata konstruktsioonidele. Edasise analüüsi jaoks vajalike katseandmete nimekiri on kirjeldatud alapeatükis 6.7.

Antud töö käigus võrreldi saadud tulemusi Eurokoodeksis pakutud söestumise algusaja ja kipsplaatide tõrketekkeaja valemitega. Eurokoodeks EN 1995-1-2 annab arvutusjuhised söestumise algusaja ja tõrketekkaja leidmiseks A-tüüpi kipsplaatidele. Analüüsi käigus selgus, et Eurokoodeksi arvutusjuhised ülehindavad oluliselt nii söestumise algusaega kui A-tüüpi kipsplaatide tõrketekkaaega. Seega Eurokoodeksis pakutud arvutusjuhiste kasutamine praktikas võib tähendada tulepüsivuse mõttes oluliselt aladimensioneeritud konstruktsioone. Eurokoodeksi EN 1995-1-2 Soome Rahvuslik Lisa pakub väärtused söestumise algusaja ja kipsplaatide tõrketekkeaja leidmiseks 13 mm A-tüüpi kipsplaatidele ja 15 mm F-tüüpi kipsplaatidele. Võrreldes neid väärtusi andmebaasi analüüsi käigus saadud tulemustega selgus, et Soome rahvuslik lisa vastupidiselt Eurokoodeksile enamikul juhtudel alahindab kipsplaatide tulepüsivust. Võrdlus andmebaasi esimese analüüsiga, kus võeti arvutusjuhiste väljatöötamisel arvesse kõik katsetulemused, andis konservatiivsemad valemid kui praegune 0,05-fraktiilväärtuse meetod. Andmebaasi analüüsi tulemusena saadud arvutusjuhiseid söestumisaja arvutamiseks võrreldi ka tulemustega, mis arvutati käsiraamatus „Fire safety in timber buildings. Technical guideline for Europe“ antud komponentide liitmise meetodit kasutades. Arvutusjuhised näitasid omavahel head korrelatsiooni, seega võib antud komponentide liitmise meetodit soovitada söestumisaja arvutamiseks.

Puitkarkasskonstruktsioonide tulepüsivuse arvutamiseks lihtsate ja tegelikkusele vastavate arvutusjuhiste väljatöötamiseks tuleb antud valdkonnas uurimist jätkata. Üks olulisemaid teemasid on F-tüüpi kipsplaatide tuletehniliste omaduste määramine. Selleks, et vältida täismõõdus tulekatseid, mida eurokoodeks soovitab teha iga F-tüüpi kipsplaati sisaldava konstruktsiooniga, saab nende andmete puudumisel kasutada käesolevas töös pakutavaid konservatiivseid väärtusi. Käesolevas töös esitatud andmebaasi edasine analüüs on üks võimalustest, kuidas töötada välja arvutusjuhised puitkonstruktsioonide tulepüsivuse projekteerimiseks.

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