

Gypsum plasterboards used as fire protection - Analysis of a database

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Abstract

A database with data from full-scale fire tests was assembled at SP Träteknik, to provide material for creating design rules for fire safety design of timber structures clad with gypsum boards. The database consists of results from more than 340 full-scale tests from different institutes all over the world, although mainly from Europe. Extensive evaluation of the available test data resulted in the development of easy-to-use rules for the start of charring times of timber studs and failure times of gypsum boards. The aim of the rules is to provide conservative data for calculating failure times of gypsum boards in wooden wall and floor assemblies in accordance with EN 1995-1-2. These conservative data are needed when manufacturers of gypsum boards do not provide necessary data for the design.

Key words:

Timber frame walls, standard fire, gypsum plasterboard, failure time, fall-off time, start of charring time

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Preface

This report describes the result of an analysis of a database of full-scale fire test reports, created to provide information for fire safety design of timber frame walls and floors with gypsum claddings. This conservative design approach is needed in order to establish intermediate times when manufacturers of gypsum boards are unable to provide necessary data for failure times of their products for use when designing in accordance with EN 1995-1-2.

The authors of this report would like to thank everybody who helped us with creating the database.

Summary

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

Gypsum boards are widely used for wall and floor structures, but very little information is given for the failure times of gypsum-based boards in EN 1995-1-2 or in standards for gypsum-based boards.

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

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

The aim of the rules provided in this report is to provide a conservative means of calculating the failure times of gypsum boards in wooden wall and floor assemblies in accordance with EN 1995-1-2. This conservative approach is needed when manufacturers of gypsum boards do not provide necessary data for design.

The start of charring of the wooden studs from the database was also analysed. The need to decrease the times given in EN 1995-1-2 is clearly seen. This is probably caused by less homogeneity of gypsum plasterboards nowadays, in comparison with the performance of boards in the past, due to optimising the cost and content of the boards.

1 Introduction

Timber frame assemblies are normally built up of the timber frame (floor joists or wall studs) and a cladding attached to each side of the frame (the cladding may be a lining or, in the case of floors, the decking or a sub-floor and additional layers). The cavities may be void or partially or completely filled with insulation. Since the timber frame is sensitive to fire exposure, it must be effectively protected against fire.

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

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

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

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

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

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

The aim of this report is to provide conservative design rules, covering a wide range of products.

As an alternative to the conservative equations, producers should declare protection times of their specific products to extend the protection phase given in EN 1995-1-2.

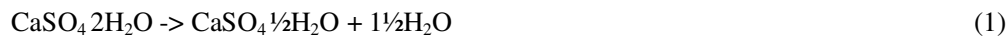
1.1 Symbols

GtA	gypsum board, Type A, in accordance with [2]
GtF	gypsum board, Type F, in accordance with [2]
t_f	failure time of gypsum board
t_{ch}	start of charring time
$t_{prot,i}$	protection time of cladding, layer i
$t_{prot,0,i}$	basic protection time of cladding, layer i
h_p	thickness of cladding, 1 layer
$h_{p,tot}$	total thickness of cladding
$h_{p,red}$	reduced thickness of cladding
$h_{p,1}$	thickness of outer layer of cladding
$k_{pos,exp,i}$	position factor that takes into account the influence of layers preceding layer i
$k_{pos,unexp,i}$	position factor that takes into account the influence of layers backing layer i
Δt_i	correction time for Type F gypsum plasterboards, (given by the producer)
$k_{j,i}, k_j$	joint coefficient
k_s	cross-section factor
k_2, k_3	protection factors
k_n	factor to convert the irregular residual cross-section into a notional rectangular cross-section
l_f	length of fastener
$l_{a,min}$	minimal anchorage length of fastener
β_0	one-dimensional design charring rate

2 Gypsum boards

2.1 Gypsum

Solid gypsum plaster and gypsum rock is calcium sulphate dihydrate $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, with two water molecules for each calcium sulphate molecule. The manufacturing process first involves driving the moisture out of the gypsum rock to create the powdery white material of calcium sulphate hemihydrate $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$. The dehydration reaction (calcination) is an endothermic decomposition reaction which occurs between 100 °C and 120 °C:



When the powder is mixed with water and formed into flat sheets of gypsum plaster, the reaction is reversed to become a hydration reaction again:



The resulting gypsum is 21 % water by weight. Moisture in gypsum plaster is very important because it contributes to the excellent fire-resistant behaviour. Gypsum plaster also contains about 3 % of free water, depending on the ambient temperature and relative humidity. When gypsum plaster is heated in a fire, the dehydration follows the reaction in Equation (1) as solid gypsum is converted back to a powdery form. Significant energy is required to evaporate the free water and make the chemical change which releases the water in the crystal structure. Complete dehydration does not occur until the temperature reaches about 700 °C, requiring additional energy input [3].

2.2 Industrial and natural gypsum

The gypsum core consists of natural gypsum, industrial gypsum and/or recycled plasterboards.

Gypsum, or calcium sulphate is a naturally occurring material, existing in large quantities all over the world. It is estimated that there are more than 2.500 billion tons in addition to the gypsum found as a natural ingredient in ocean water, approximately 1,6 kg per m³. Salt water contains dissolved gypsum. Deposits in closed ocean reservoirs, where the water slowly evaporated, created gypsum.

In addition to natural raw gypsum, industrial gypsum is used, which is manufactured as a by-product from the flue gas cleaning of power stations. This gypsum consists of crushed limestone mixed with water, air and sulphur dioxide. Using the sulphur dioxide to make plaster prevents acidification of the environment as well as providing pure gypsum material.

The difference between the two gypsum types is that the industrial gypsum has smaller crystals than the natural gypsum, because it has taken thousands of years to crystallize the natural gypsum, but both have identical chemical composition.

Producers of gypsum boards do not specify whether their boards are made of natural or industrial gypsum, but it may have affect their properties in fire.

2.3 Gypsum plasterboards

Raw materials for gypsum plasterboards are gypsum, paper and additives.

There are many types of gypsum plasterboards that comply with EN 520 [2].

Type A – regular common boards with porous gypsum core and no reinforcement except the paper laminated surface. This report uses the abbreviation GtA when referring to this board or similar.

Type F – fire protection board with improved core cohesion at high temperatures. The abbreviation GtF is used for this board in this report.

Fire-protection gypsum boards contain glass fibres which control shrinkage, causing a maze of fine cracks rather than a single large crack which can initiate premature failure of regular board. One of the most critical aspects of fire-resistant gypsum board is the extent to which the glass fibre reinforcement can hold the board together after the gypsum has dehydrated, to prevent the board pulling away from nailed or screwed connections when the board shrinks. Shrinkage can be reduced with various additives, such as vermiculite [3].

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.

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

In accordance with [2] there are also other types of gypsum plasterboards: examples include Type D, with a density over 800 kg/m^3 , and Type H with water-resistant properties etc.

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

2.4 Gypsum fiberboards

Gypsum fiberboards are high-performance building boards with cellulose reinforcement, complying with EN 15283-2 [4].

Gypsum fiberboards can be used as an alternative to plasterboards or for flooring. Gypsum fiberboard is made from 80-85 % burned gypsum (recycled gypsum recovered from industrial desulphurisation plants), 15-20 % cellulose fibres (recycled newsprint). The boards are impregnated with aqueous coating-based starch and silicone.

2.5 Behaviour of gypsum boards in fire

Gypsum is a non-combustible material and makes no contribution to fire: it works, in fact, as a built-in sprinkler. One square meter of a 12,5 mm gypsum board contains approximately two liters of water of crystallisation in the gypsum core. Its high water content provides up to 90 % of the fire resistance protection of gypsum boards. The calcination process takes place when the gypsum is exposed to heat at a temperature of at least $80 \text{ }^\circ\text{C}$, and this water prevents the fire from penetrating the board while it is evaporating. The calcination process is mostly complete when the gypsum board reaches a temperature of $125 \text{ }^\circ\text{C}$ and becomes an anhydrate, CaSO_4 . This process requires much energy and time.

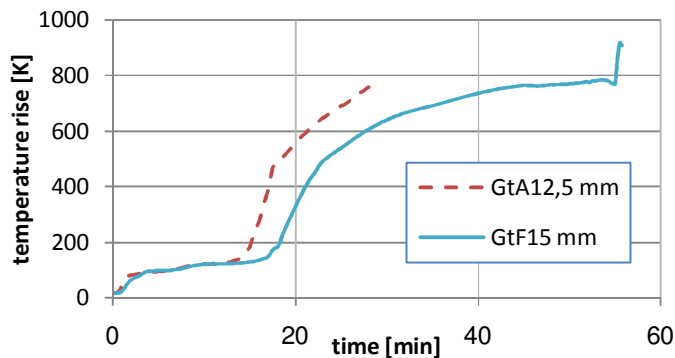


Figure 1 – Temperature rise behind Type A and Type F gypsum claddings in standard fire tests (example).

Figure 1 compares the temperature rise behind 12,5 mm thick Type A gypsum plasterboard and 15 mm thick Type F plasterboard. The calcination phase can be clearly seen. First, the temperature rises until $80 \text{ }^\circ\text{C}$ to $100 \text{ }^\circ\text{C}$ is reached behind the board. Water starts to evaporate and a plateau can be seen in the temperature curve (Figure 1). Evaporation time basically depends on the board thickness. After the evaporation process, the temperature rises again.

3 Protection phases and times

3.1 Charring of protected members

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

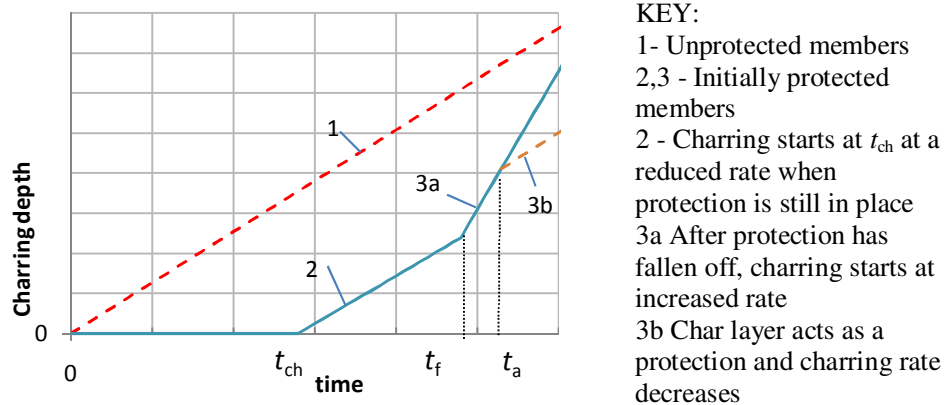


Figure 2 - Charring of timber studs with and without protection

Timber frame assemblies are normally built up in the form of the timber frame (floor joists or wall studs), with a cladding attached to each side of the frame.

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

Charring of protected wooden members can start before the failure of cladding. The charring rate of wood is much slower in this stage than the charring of initially unprotected wood, see Figure 2. After the claddings fall off, charring increases to a much higher rate than the charring rate of initially unprotected wood. The start of charring time and the failure time of gypsum boards are therefore important properties of cladding in the fire resistance design of wooden structures.

Since the thermo-mechanical properties of Type F gypsum plasterboard are not part of the classification given in EN 520 – the European product standard for gypsum plasterboards [2] - failure times of different makes may vary considerably. No generic failure times for gypsum plasterboard are known; but it is expected that the producer should declare failure times determined on the basis of tests, including information on spacing of joists, studs, battens etc. and edge distances and spacing of fasteners.

3.2 Start of charring time

Start of charring time is the time when charring of wood starts behind the cladding.

In this study, start of charring time is taken as time of reaching 300 °C on wooden surfaces behind cladding. The principle is in accordance with [1].

3.3 Failure time

Failure time or *fall-off time* of cladding is the time from the start of the test when at least 1 % of the board area has fallen off.

Regular gypsum board can fall off a wall or ceiling as soon as the gypsum plaster has dehydrated, at about the same time as charring of the timber studs begins. Boards with glass fibre reinforcement and closely spaced fixings will not fall off until the glass fibres melt, when the entire board reaches a temperature of about 700 °C. [3]

Sultan et al [5] have 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 from assembly to assembly with no identifiable correlation to assembly parameters.

In the present study, we have hardly any information about failure of the last piece. The fall-off of the first piece is counted as failure of the whole board.

Some findings of Sultan [6]

- Gypsum board fall-off time had a significant effect on the fire resistance of lightweight frame assemblies.
- The type of framing had no significant effect on gypsum board fall-off time
- Fall-off time was affected by the distance of the fasteners from the panel edges.
- The presence of insulation in floor cavities had an adverse effect on the fall-off time of gypsum board. When the cavity is insulated, the failure time is shorter.

Photos in Figure 3 to Figure 5 illustrate the development of failure of Type F gypsum board in a standard fire. The photos are taken on the fire-exposed side of the test wall through an observation window.

15 minutes after the test start, the joint filler has started to flake off. There are still no cracks in the gypsum board. See Figure 3.

30 minutes after the test start, some horizontal and vertical cracks appear on gypsum board, and shrinkage of joints takes place. Gypsum board is still protecting the structure from direct fire. Charring of the timber stud is still relatively slow. See Figure 3



Figure 3 – Fire test, 15 minutes



Figure 4–Fire test, 32 minutes



Figure 5–Fire test, 35 minutes



Figure 6–Fire test, 44 minutes

The first small piece of the gypsum board falls down 35 minutes after the test start (see Figure 5, upper middle part). Falling off of such a small piece does not noticeably change the fire conditions for wooden studs and is not counted as fall-off time yet.

Figure 5 shows that a piece with more than 1 % of the area of the board has fallen off. Final falling off of the remaining board then occurs after only a short time. From then on, the inside of structure is completely exposed to fire. The wooden stud is no longer protected from direct fire, and the charring rate of the stud increases. 44 minutes is the fall-off time of gypsum board in this particular test case.

The whole board falls off a short time after that, leaving no protection against the fire.

4 Design procedures

4.1 Design procedure by EN 1995-1-2

Start of charring time t_{ch}

The start of charring time for the narrow sides of floor and wall panels with void cavities, and for floor and wall assemblies with insulation, is counted as follows [1]:

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

$$t_{ch} = 2,8 h_p - 14 \quad (3)$$

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

$$t_{ch} = 2,8 h_p - 23 \quad (4)$$

Since gypsum plasterboard 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 calculation of start of charring of Types A or H gypsum plasterboard may be conservatively used for those types. Although not explicitly stated, the same applies to Type F gypsum plasterboard.

EN 1995-1-2 also provides information on the start of charring where two layers of gypsum plasterboard are attached to the timber member. Where both layers are of Type A

or Type H, the contribution of the inner layer is reduced by taking into account only 50 % of its thickness since, after failure of the outer layer, the inner layer is already preheated and has partially calcined and is exposed to a higher temperature.

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

Example

Two layers of 12,5 mm Type A gypsum plasterboard. No joints on timber stud.

$$h_p = 1,5 * 12,5 = 18,8 \text{ mm}$$

$$t_{ch} = 2,8 * 18,8 - 14 = 38,6 \text{ min}$$

Failure time t_f

The present design procedure is described in EN 1995-1-2.

The failure time t_f of panels with respect to pull-out failure of fasteners may be calculated in accordance with Equation [C.9] of EN 1995-1-2 [1]:

$$t_f = t_{ch} + \frac{l_f - l_{a,min} - h_p}{k_s k_2 k_n k_j \beta_0} \quad (5)$$

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 Types A and H gypsum plasterboard should be taken as

$$t_f = t_{ch}$$

4.2 Design procedure by ETH

Start of charring time t_{ch}

Research work has been carried out at ETH [7] to investigate the fire protection abilities of different materials. The method described in [7] can also be used for calculating the start of charring time.

$$t_{ch} = \sum t_{prot,i} \quad (6)$$

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:

$$t_{prot,i} = (t_{prot,0,i} k_{pos,exp,i} k_{pos,unexp,i} + \Delta t_i) k_{ji} \quad (7)$$

For gypsum plasterboards, the basic protection value is expressed as:

$$t_{\text{prot},0} = 30 \left(\frac{h_i}{15} \right)^{1,2} \quad (8)$$

where h_i is thickness of the board in mm.

Position coefficients are

$$k_{\text{pos,exp},i} = 1 - 0,6 \frac{\Sigma t_{\text{prot},i-1}}{t_{\text{prot},0,i}} \quad \text{if} \quad \Sigma t_{\text{prot},i-1} \leq \frac{t_{\text{prot},0,i}}{2} \quad (9)$$

$$k_{\text{pos,exp},i} = 0,5 \sqrt{\frac{t_{\text{prot},0,i}}{\Sigma t_{\text{prot},i-1}}} \quad \text{if} \quad \Sigma t_{\text{prot},i-1} > \frac{t_{\text{prot},0,i}}{2} \quad (10)$$

$$k_{\text{pos,unexp},i} = 0,5 h_i^{0,15} \quad \text{if the layer is backed by insulation}$$

$$k_{\text{pos,unexp},i} = 1 \quad \text{if the layer is backed by cladding}$$

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

$$k_{\text{j},i} = 1,0 \quad \text{for all other cases.}$$

Example:

Two layers of 12,5 mm Type A gypsum plasterboard. No joints on timber stud.

$$t_{\text{prot},0} = 30 \left(\frac{12,5}{15} \right)^{1,2} = 24,1 \text{ min}$$

First layer

$$k_{\text{pos,exp},i} = 1 ; k_{\text{pos,unexp},i} = 1 ; k_{\text{j},i} = 1,0$$

$$t_{\text{prot},1} = 24,1 \text{ min}$$

Second layer

$$k_{\text{pos,exp},i} = 0,5 \sqrt{\frac{24,1}{24,1}} = 0,5$$

$$k_{\text{pos,unexp},i} = 0,5 * 12,5^{0,15} = 0,73$$

$$k_{\text{j},i} = 1,0$$

$$t_{\text{prot},2} = (24,1 * 0,5 * 0,73) * 1 = 8,8 \text{ min}$$

Start of charring time for two-layer cladding is

$$t_{\text{ch}} = (24,1 + 8,8) = 32,9 \text{ min}$$

5 Database of gypsum boards

5.1 General

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

Numbers of data from full-scale test reports were collected from the different institutes. The data about the test numbers, producers etc. are confidential.

Parameters recorded in the database are as follows:

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

Part of the work of assembling the database was performed as a student thesis at the Royal Institute of Technology in Stockholm [8]. The database is still growing. Not all data from every test has been available.

There are 342 full-scale test results in the database, provided by the following countries:

Austria	22
Canada	62
Denmark	13
Germany	22
Estonia	6
Finland	3
France	42
Netherlands	2
New Zealand	6
Norway	5
Sweden	136
Slovenia	2
UK	32

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

Walls	189
Floors	153
GtA	72
GtF	233
others	37

5.2 Analysis of the database

5.2.1 General

Data in the database shows that gypsum plasterboards of the same types have a very large scatter of performance properties in fire.

Charring behind gypsum boards often starts earlier than stated in the present EN 1995-1-2 [1]. This is probably caused by less homogeneity of gypsum plasterboards compared than was the case in the past due to optimising cost and content of the boards. There is therefore a clear need to reduce the time for start of charring. Compare the different lines in Figure 20.

Since fall-off is a failure which cannot be calculated using finite element programs due to the complex failure mechanism, easy-to-use rules were developed as a result of extensive evaluation of the available test data. In addition, different build-ups and fixings were taken into account, since failure is not only a question of the cladding itself. The resultant rules are a worst-case approach to the failure times. The equations provide deliver failure times remaining the failure times from all the relevant tests, apart from those that differ very much from the rest, known as outliers.

The same procedure is used to produce the equations for the start of charring time of timber members.

The aim of the rules provided in this report from analysis of the database is to give conservative data for calculating failure times of gypsum boards in wooden wall and floor assemblies in accordance with EN 1995-1-2. These conservative data are needed when manufacturers of gypsum boards do not provide necessary data for design.

5.2.2 Failure time t_f

Failure times of gypsum boards from the full-scale fire tests are shown in diagrams and tables in Sections 5.3.1 and 5.4.1. Failure times of gypsum boards beneath floors are shorter than for walls, due to the effect of gravity.

The values given in this report are a conservative approach to the problem. If producers claim better performance for their products and longer failure times than for designs using the rules derived from the database, they must provide data which enables this to be confirmed.

Failure times of Type F gypsum plasterboards due to thermal degradation are missing from EN 1995-1-2 [1]. Some of the test results of failure times presented here may be caused by pull-out of fasteners. The reason for failure is not always clearly understood in test reports.

To find the design failure time, values in accordance with the proposed rules in accordance with this study and values due to pull-out of fasteners in accordance with [1] should be calculated, and the minimum selected.

There is a difference in failure times of gypsum plasterboards backed by insulation or by void cavity. In the worst case approach, used in the present study, the difference could be neglected. See test results in Figure 18.

The database consists of test walls with timber studs and steel studs. The difference in failure times is shown in Figure 9 and Figure 11. From this, it can be stated that the failure times of gypsum boards on steel studs and on wooden studs are similar.

In addition, the distance between floor beams or resilient channels can be neglected when creating worst-case equations. See Figure 17.

Failure times of Type A gypsum boards show a tendency that indicates that values in Eurocode 5 are overestimated. Full-scale tests in the database show that failure of Type A gypsum board often occurs earlier than the design values from EN 1995-1-2 [1].

There is insufficient data for failure times of claddings for floors, consisting two or three layers of Type A gypsum plasterboards.

The test data for walls and floors with two-layer claddings with Type F gypsum plasterboard on the fire-exposed side, backed by Type A gypsum plasterboard, have all shown the failure of two layers at the same time. See Figure 13 and Figure 19.

Data for gypsum fiberboard is shown in Figure 14. However, there is insufficient data for gypsum fiberboards consisting of more than one layer, and nor is there sufficient data for floor claddings of gypsum fiberboards. Data in the database show that failure times of wall cladding consisting of one layer of gypsum fiberboard are shorter than failure times of one layer of wall cladding of Type F gypsum plasterboard.

5.2.3 Start of charring time t_{ch}

Start of charring times of gypsum boards from the full-scale fire tests are shown in diagrams and tables in Sections 5.3.2 and 5.4.2.

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

If charring starts after the first layer has fallen off, the design rule time for start of charring should be the failure time of first layer.

In comparison with the safe design method based on the database, the methods given in EN 1995-1-2 [1] and ETH [7] are too optimistic for single-layer claddings to take the characteristics of the wide variety of products into account; see Figure 20.

The diagrams of the start of charring (Figure 20 to Figure 25) show the influence of joints. See Figure 7 for explanation of joint types. Unfortunately, there is not information on joints for every case.

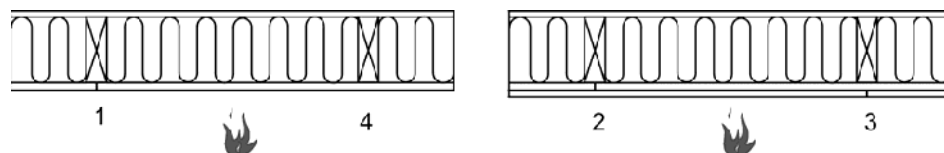


Figure 7 – Joint types as given in EN 1995-1-2 [1]

The summary of the safe design equations and diagrams for failure times of gypsum boards are shown in Table 1, Figure 27 and Figure 28.

The design equations for the start of charring times are shown in diagrams in Figure 20 to Figure 25 and in Table 2.

There are little data from which to draw conclusions about the start of charring behind gypsum fiberboards, although some values for gypsum fiberboards are given in Figure 26. The line of the equation for the start of charring time as given in EN 1995-1-2 is shown as an indicator.

5.3 Diagrams for safe design equations

5.3.1 Failure time t_f

5.3.1.1 Walls

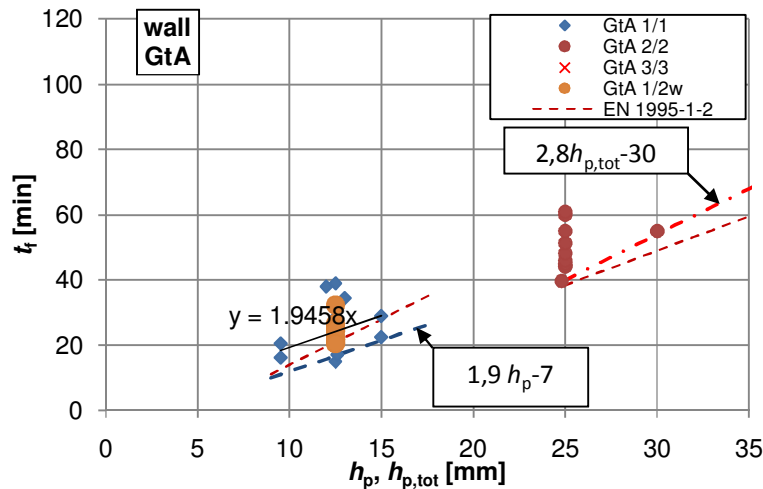


Figure 8 - Failure times of wall claddings of Type A gypsum plasterboards.

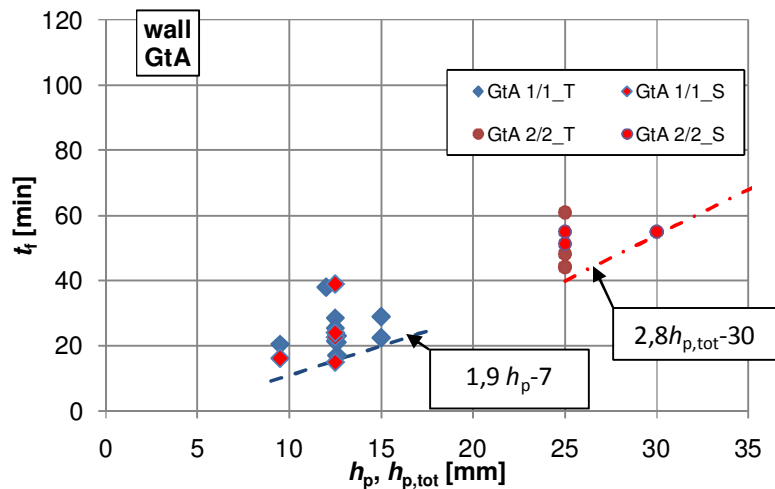


Figure 9 - Failure times of wall claddings of Type A gypsum plasterboards. Comparison of stud materials (S- steel, T-timber).

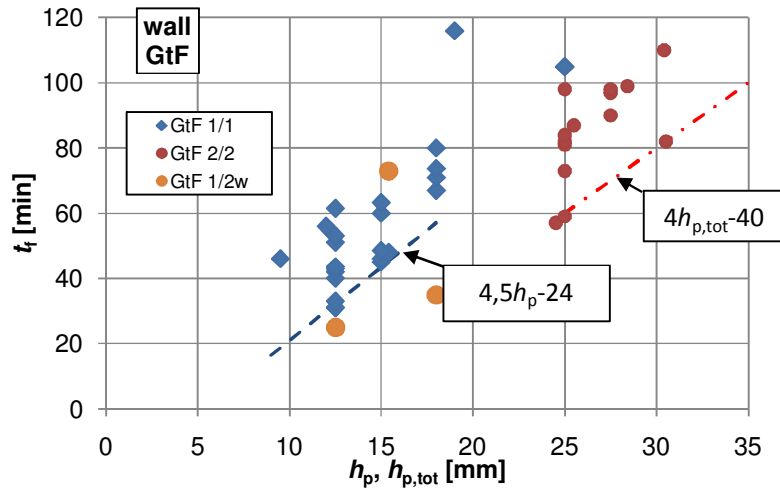


Figure 10- Failure times of wall claddings of Type F gypsum plasterboards.
a

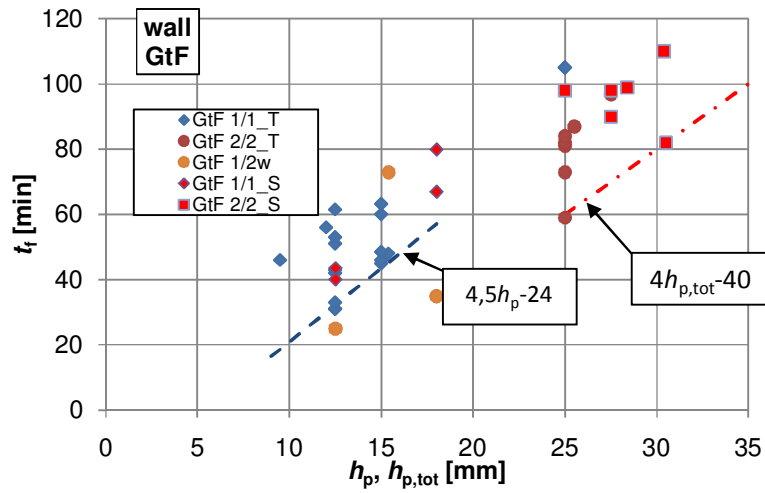


Figure 11 - Failure times of wall claddings of Type F gypsum plasterboards. Comparison of stud materials (S- steel, T-timber).

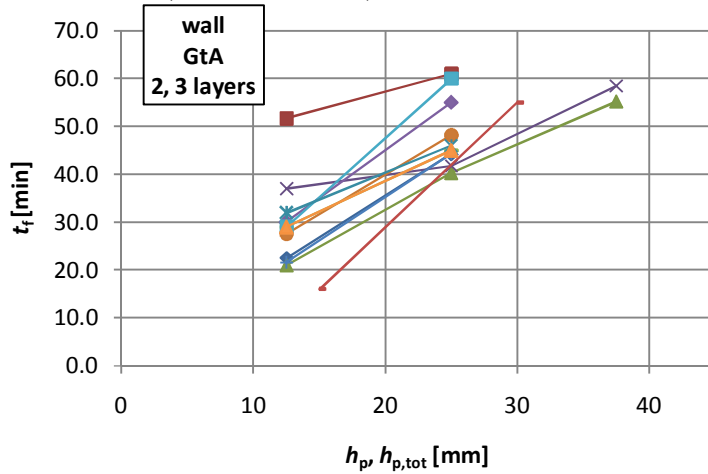


Figure 12 - Failure times of each layer of two-layer or three-layer wall claddings of Type A gypsum plasterboards.

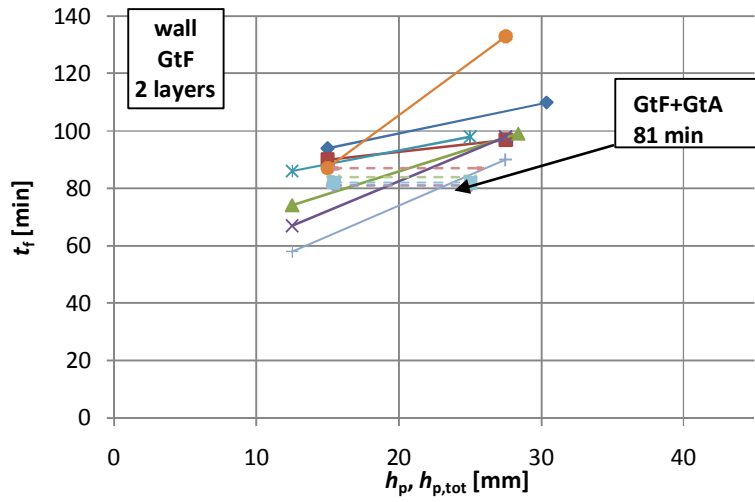


Figure 13- Failure times of both layers of two-layer wall claddings of Type F gypsum plasterboards and Type F combined with Type A.

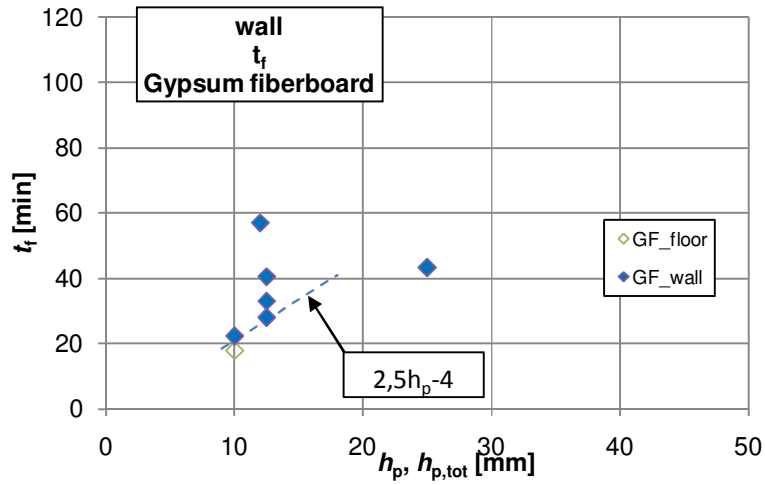


Figure 14 – Failure times of gypsum fibreboards.

5.3.1.2 Floors

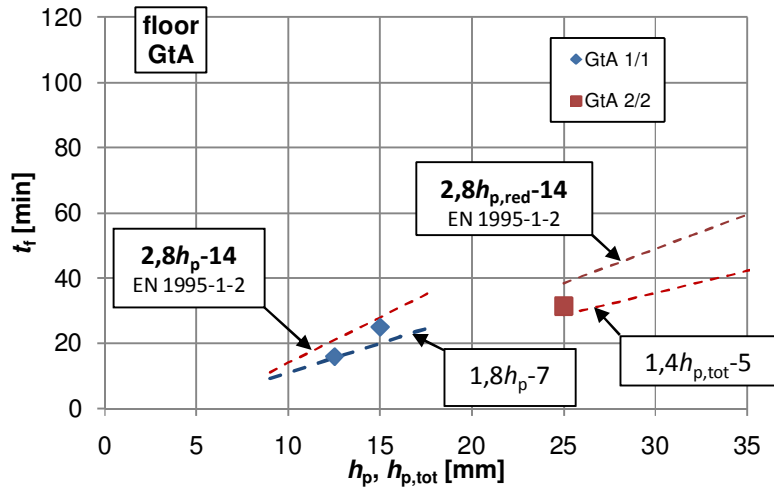


Figure 15 - Failure times of floor claddings of Type A gypsum plasterboards.

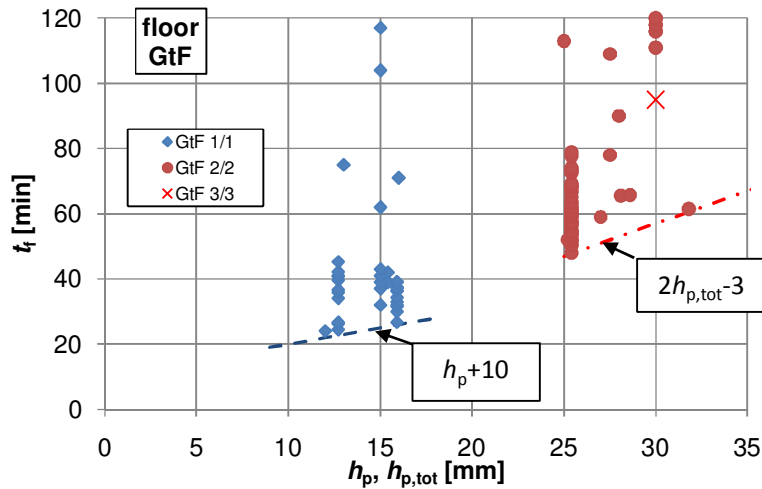


Figure 16 - Failure times of floor claddings of Type F gypsum plasterboards.

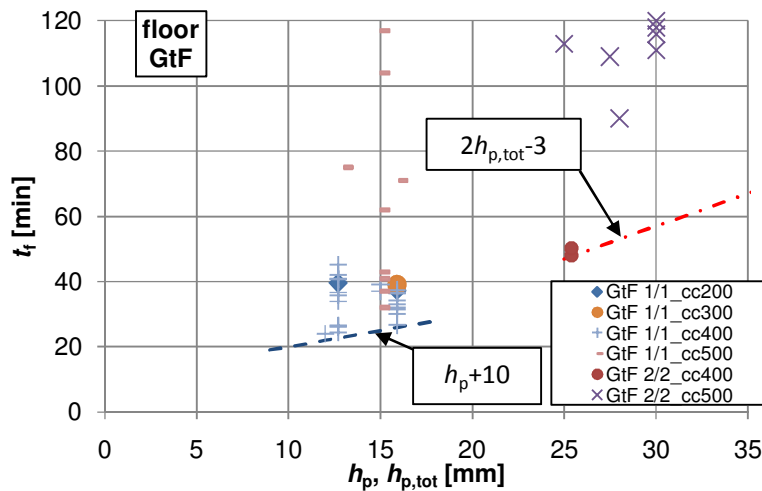


Figure 17 - Failure times of floor claddings of Type F gypsum plasterboards. Comparison of different spacings of battens.

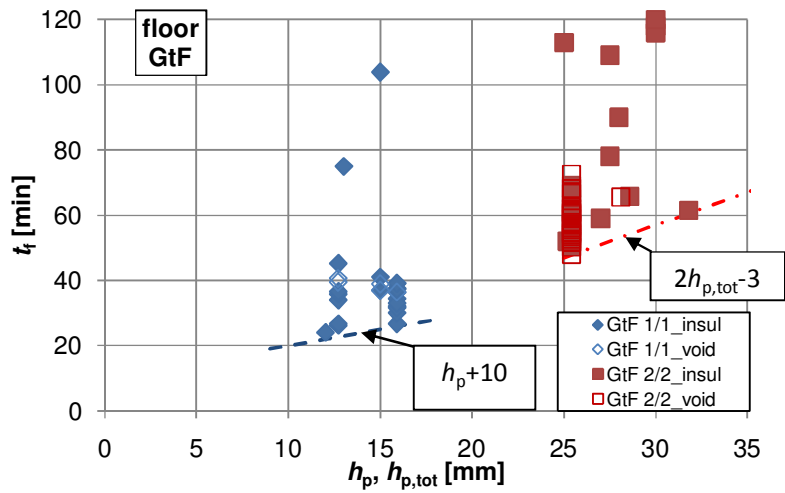


Figure 18 - Failure times of floor claddings of Type F gypsum plasterboards. Comparison of structures with insulated and void cavities.

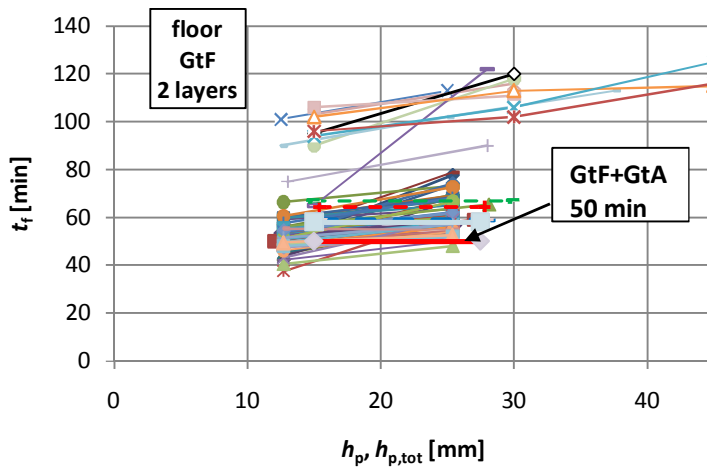


Figure 19 – Failure times of both layers of two-layer floor claddings of Type F gypsum plasterboards and Type F combined with Type A.

5.3.2 Start of charring time t_{ch}

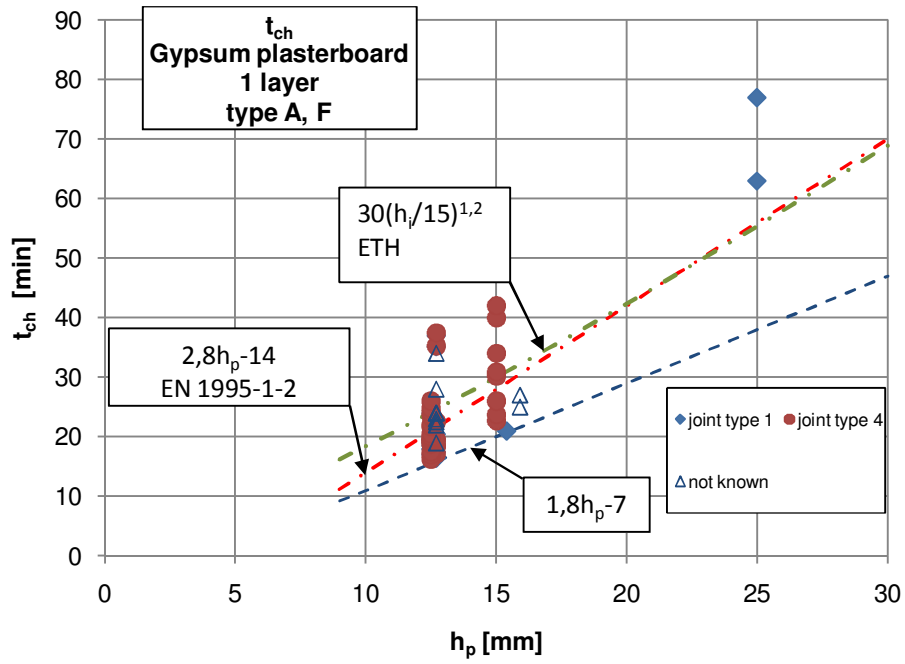


Figure 20 – Start of charring time for cladding of one layer of gypsum plasterboard.

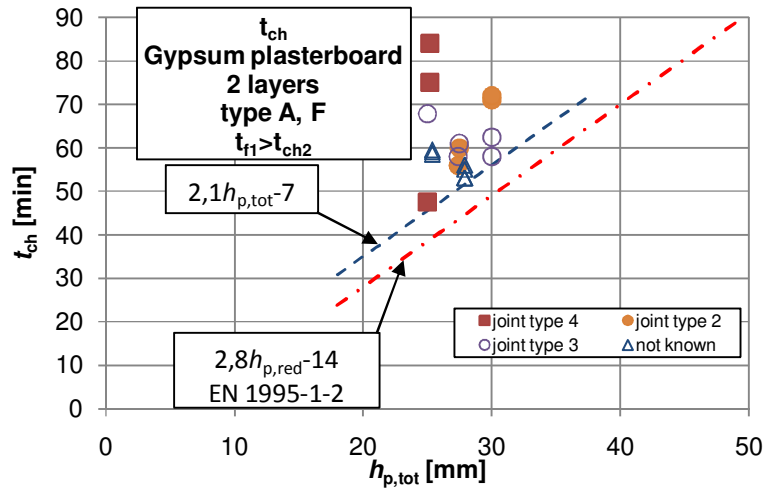


Figure 21 – Start of charring time for cladding of two layers of gypsum plasterboards when first layer does not fall off before charring starts

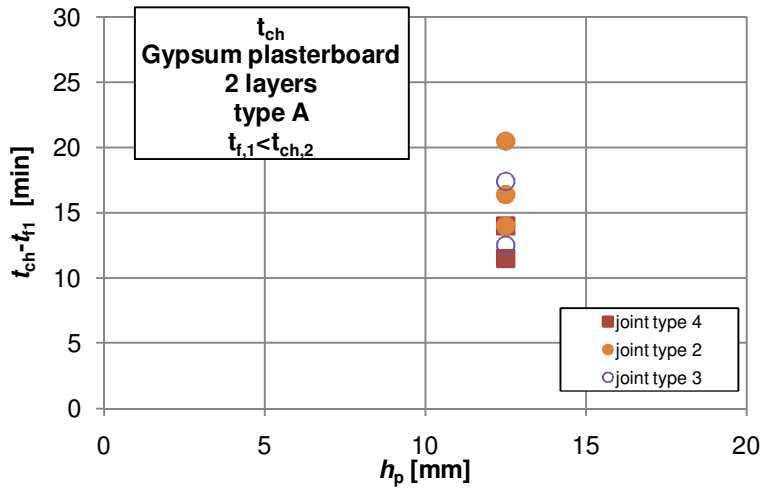


Figure 22 - Start of charring time after fall-off of first layer for Type A gypsum plasterboard

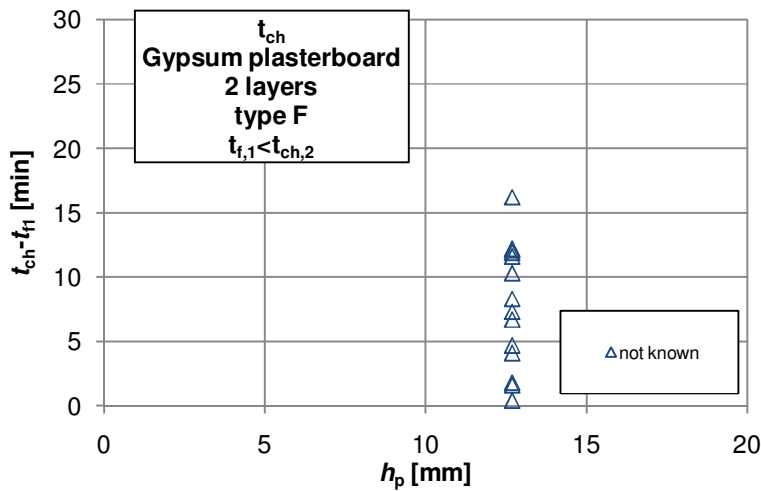


Figure 23- Start of charring time after fall-off of first layer for Type F gypsum plasterboard.

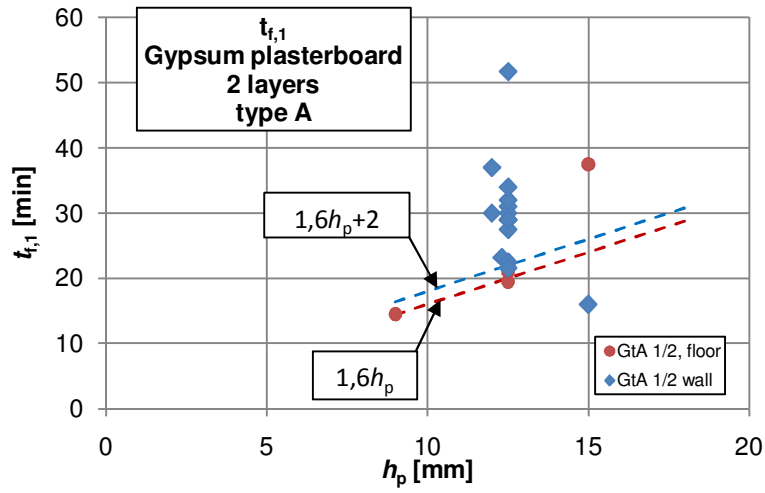


Figure 24 – Fall off of first layer of two for gypsum plasterboards type A

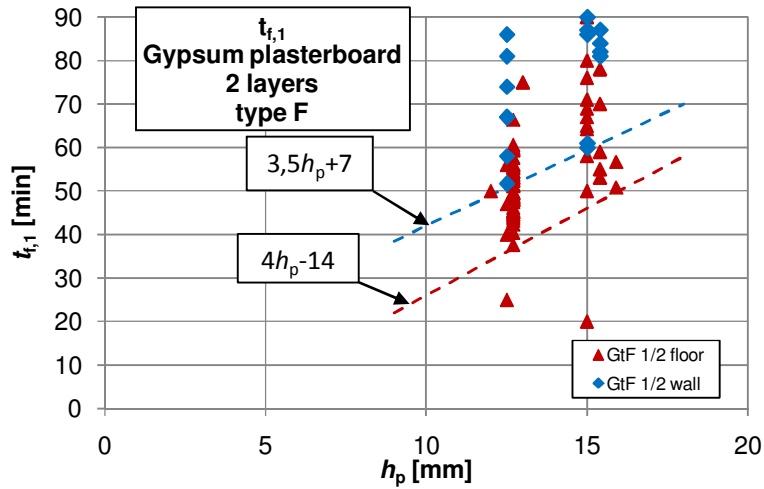


Figure 25 - Fall-off of first layer of two for Type F gypsum plasterboards

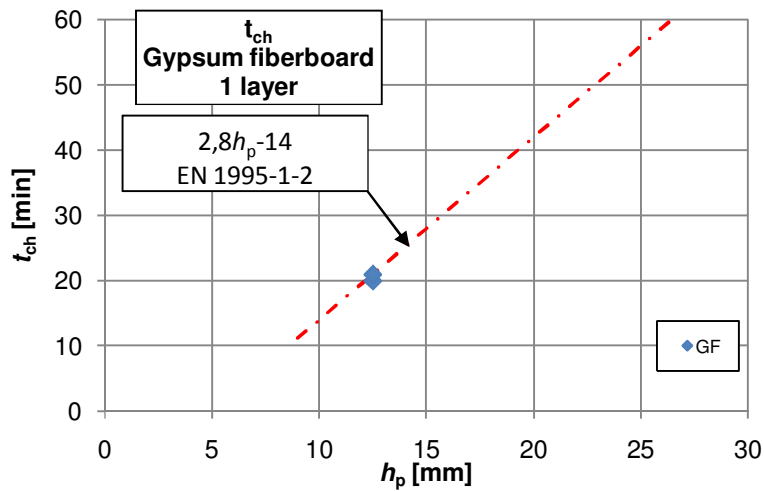


Figure 26 – Start of charring time of gypsum fibreboards.

5.4 Design equations

5.4.1 Failure time t_f

Based on the results of analysis of the database, Table 1 shows the safe design equations and their associated limitations of use. The limitations come from the available test data.

Table 1 – Design equations for failure time t_f

Cladding	Walls		Floors	
	Equation	Limits	Equation	Limits
Gypsum plasterboards Type F, one layer	$4,5 h_p - 24$	$9 \text{ mm} \leq h_p \leq 18 \text{ mm}$	$h_p + 10$	$12,5 \text{ mm} \leq h_p \leq 16 \text{ mm}$
	57	$h_p > 18 \text{ mm}$	26	$h_p > 16 \text{ mm}$
Type F, two layers	$4 h_{p,\text{tot}} - 40$	$25 \text{ mm} \leq h_{p,\text{tot}} \leq 31 \text{ mm}$	$2 h_{p,\text{tot}} - 3$	$25 \text{ mm} \leq h_{p,\text{tot}} \leq 31 \text{ mm}$
	84	$h_{p,\text{tot}} \geq 31 \text{ mm}$	59	$h_{p,\text{tot}} \geq 31 \text{ mm}$
Type F + Type A ^a	81	$h_p \geq 15 \text{ mm}^b$ $h_{p,\text{tot}} \geq 27 \text{ mm}$	50	$h_p \geq 15 \text{ mm}^b$
Type A, one layer	$1,9 h_p - 7$	$9 \text{ mm} \leq h_p \leq 15 \text{ mm}$	$1,8 h_p - 7$	$12,5 \text{ mm} \leq h_p \leq 15 \text{ mm}$
	21,5	$h_p > 15 \text{ mm}$	20	$h_p > 15 \text{ mm}$
Type A, two layers	$2,1 h_{p,\text{tot}} - 14^c$	$25 \text{ mm} \leq h_{p,\text{tot}} \leq 30 \text{ mm}$		
	49	$h_{p,\text{tot}} \geq 30 \text{ mm}$		
Type A, three layers	55	$h_{p,\text{tot}} \geq 37,5 \text{ mm}$	– ^d	
Gypsum fibreboards, one layer	$2,5 h_p - 4$	$10 \text{ mm} \leq h_p \leq 12,5 \text{ mm}$	– ^d	
^a Outer layer Type F, inner layer type A ^b Thickness of first layer (Type F) ^c Same as EN 1995-1-2 Clause 3.4.3.3(3) ^d No data available.				

Figure 27 and Figure 28 show the failure time equations in graphical form.

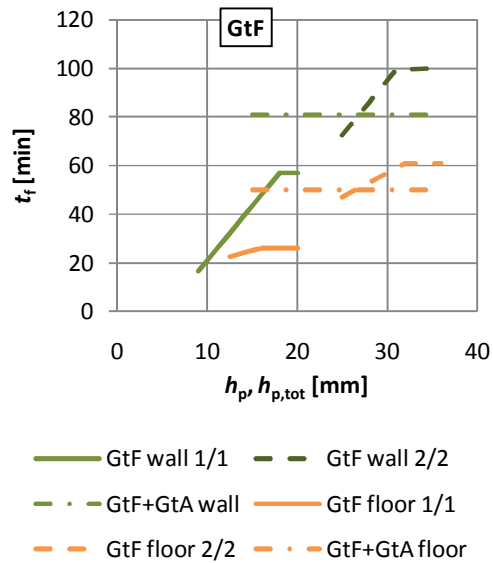


Figure 27 – Design equations for Type F gypsum plasterboard

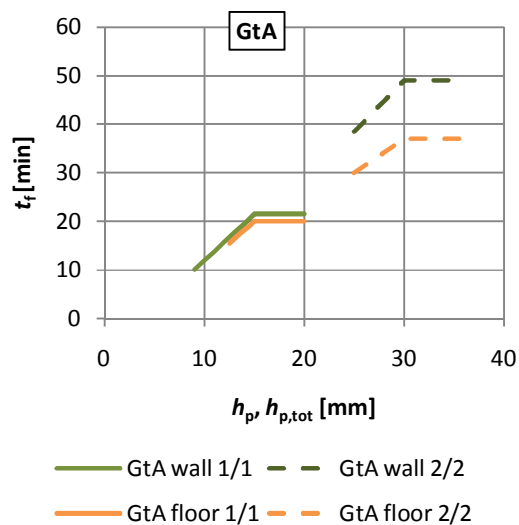


Figure 28 – Design equations for Type A gypsum plasterboard

5.4.2 Start of charring time t_{ch}

Table 2 and Table 3 show the safe design equations, as based on the database, with their associated limitations of use, as determined by the available test data.

For structures with two layers, the important issue is the fall-off of first layer. If charring behind the second layer starts before the first layer has fallen off, similar design rules can be applied for GtF and GtA. If charring starts after the first layer has fallen off, then the design rule for start of charring time depends on the failure time of the first layer.

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

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

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

Cladding	Walls		Floors	
	Equation	Limits	Equation	Limits
Type F $t_{f,1}$	$3,5h_{p,1} + 7$	$9 \text{ mm} \leq h_p \leq 18 \text{ mm}$	$4h_{p,1} - 14$	$9 \text{ mm} \leq h_p \leq 18 \text{ mm}$
Type A $t_{f,1}$	$1,6h_{p,1} + 2$	$9 \text{ mm} \leq h_p \leq 18 \text{ mm}$	$1,6h_{p,1}$	$9 \text{ mm} \leq h_p \leq 18 \text{ mm}$

5.4.3 Use of equations

Tables 1 to 3 show the safe design equations and their associated limitations of use. The limitations come from the available test data. No extrapolation is used. In some cases the limitations can result with bigger start of charring time compare to failure time of the same cladding. In this case there is no protected phase (Phase 2 in Figure 2) and failure time equation is to be used. Charring starts with the failure of cladding in those cases.

$$t_{ch} \leq t_f$$

6 Conclusions

The variety of properties influencing the fire protection ability of different products of gypsum plasterboards is very large. No significant influence of stud material or insulation has been found that can indicate the expected minimum failure times.

Design equations presented in this report give information on failure times and the start of charring times for design of timber-frame assemblies in accordance with EN 1995-1-2.

Producers should state the failure times of their specific products if their products have better values. There is a need for common procedure for this.

The start of charring times for gypsum plasterboards given in EN 1995-1-2 should be decreased for one-layer claddings, and can be slightly increased for two-layer claddings.

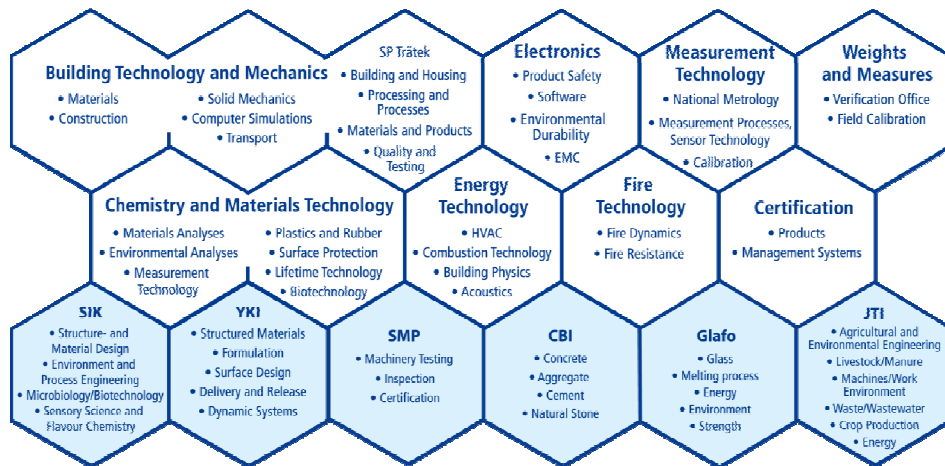
The work with the database continues.

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