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FIRE PROTECTION OF TIMBER MEMBERS – DETERMINATION OF THE FIRE PROTECTION SYSTEM CHARACTERISTICS FOR THE VERIFICATION OF THE LOAD-BEARING RESISTANCE BY MEANS OF CALCULATION MODELS

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Abstract. *Timber members appear in structural assemblies unprotected or protected by a fire protection system. Mostly passive fire protection systems are used which have the ability to delay the start of charring and decrease the charring rate as long the fire protection is attached to the structural element. Together with the failure time of a fire protection system the start of charring and the charring rate are crucial parameters for the residual cross-section which is the dominating parameter for the load-bearing capacity assessed in fire tests or calculation models as given in Eurocode. Calculation models are requested since they allow the variation of building components and are cost effective compared to fire tests. However, the accuracy of the load-bearing prediction under standard fire exposure is highly depending on the input factors (start of charring, failure of the protection system and charring rate) for the calculation of the residual cross-sections. Today no practical system is available to determine these input factors for fire protection system.*

1 INTRODUCTION

According to Eurocode 5 (EN 1995-1-2) [1] the load bearing capacity of any structural member has to be determined in two steps:

(1) Determination of the residual cross-section.
(2) Determination of the load-bearing capacity of the residual cross-section.

The reduction of the original cross-section by char has the largest influence on the load-bearing capacity in the fire situation (Figure 1). The large variety of claddings available on the market may be a challenge for designers since the diverse onset of charring as well as the specific charring rate has to be taken into account calculating the residual cross-section (step 1). A summary of failure times of claddings (gypsum plaster boards) applied to fire exposed timber frame assemblies was published previously [3, 4] and shows a wide range of results.

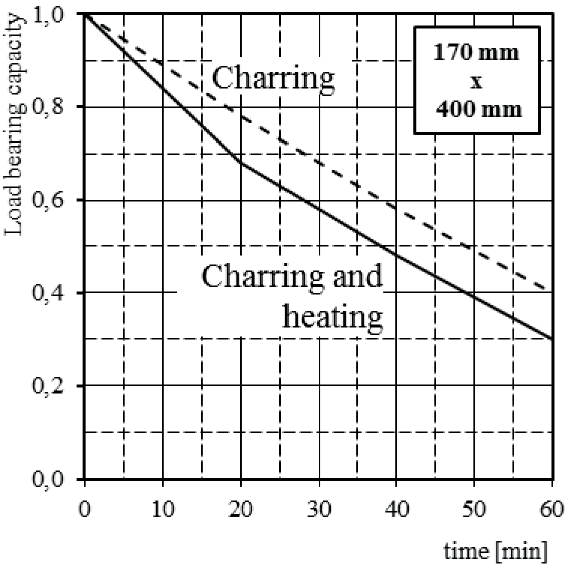


Figure 1. Load-bearing capacity according to Eurocode 5 of an initially unprotected beam 170 mm × 400 mm exposed to fire on three sides using the Reduced Cross-section Method.

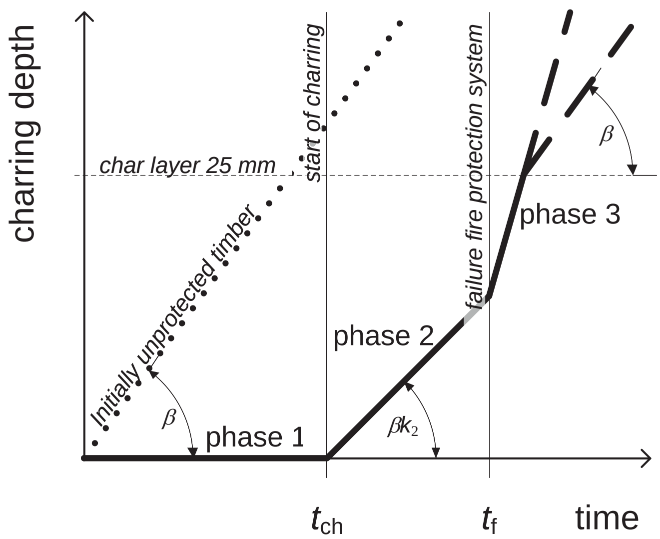


Figure 2. Charring of an unprotected timber member (dotted curve) and an initially protected member (continuous curve).

Generally speaking fire protection claddings are fire protection systems which cover single and multiple layers of one building material (e.g. gypsum plasterboards) or combination of fire protection materials (e.g. gypsum plasterboards and mineral wool). Typically fire protection systems for timber members are passive fire protection systems, however reactive materials such as reactive, intumescent coatings exist.

The reduction of the charring rate can be divided in different phases (Figure 2). The phases differ significantly and are divided by the start of charring (t_{ch}) and the failure time (fall-off) of the protection system (t_f). To determine the charring rates of protected members by means of calculation models in Eurocode 5 (EN 1995-1-2), input data are required with respect to the break-points at the start of charring and the failure time of the protection system. The actual testing standard in Europe to determine these data is ENV 13381-7 [5] which is referenced in EN 1995-1-2. ENV 13381-7 [5] is a pre-standard. This standard is rarely known by producers or test labs. Among others, since the standard requires testing of specimens with laminated members that are difficult to produce. The standard is also partly in conflict to EN 1995-1-2.

The claddings used for timber assemblies are typically gypsum plasterboards. However, the product standards EN 520 [6] and EN 15283-2 [7] do not define the data required for the verification of the load-bearing resistance by means of calculation models. Reasons are of many kinds, among others, that the failure time of the gypsum plasterboards is dependent on many variables, e.g. orientation, fixation, backing material.

This paper describes the principles of the new EN 13381-7 which shall replace the existing ENV standard.

Complementary to full-scale testing of protection systems attached to walls, floors or beams, testing in less than full-scale is intended for reactive fire protection materials which may not be activated in fires with slow grow.

2 STANDARD PROCEDURE FOR PROTECTION ABILITIES

Based on the need of input data to increase the use of calculation models CEN/TC 127/WG 1/TG 12 rewrote the EN 13381-7 standard to make it consistent with EN 1995-1-2 and make the test procedure more easy to understand and performable.

Aim of the standard is to allow testing of products for the fire protection systems and determine all needed input data in one single loaded test. Since observations of the behaviour and failure time of the cladding in longer fire tests may lead to difficulties only temperature measurements will be used.

The focus of the standard was

- to make testing less costly;
- to simulate the behaviour of timber members in an appropriate way;
- to formulate criteria in accordance to the other parts of the standard series.

The standardized procedure for determining fire protection system characteristics for the verification of the load-bearing resistance by means of Eurocode 5 is based on testing in standard fire according to EN 1991-1-2[8].

The actual draft of EN 13381-7 knows two types of tests. Tests of

- large-scale, using large scale test specimens and;
- model scale, using model scale test specimens.

2.1 Large scale tests

It is intended to collect all data relevant to assess the contribution of a fire protection system in a large scale test. Three different structures are specified for large scale tests – beams, walls and floors. Regarding the start of charring and the failure of the fire protection system, test results of beam tests are assumed to be corresponding to column tests.

The large scale beam test specimen consists of a load-bearing timber beam with attached fire protection system (Figure 3). The specimen is subjected to fire from three sides. The timber beam may be a solid timber member or a glued laminated member. The adhesive used for the production of the glued laminated beam shall be a certified adhesive according to EN 301 or EN 15425.

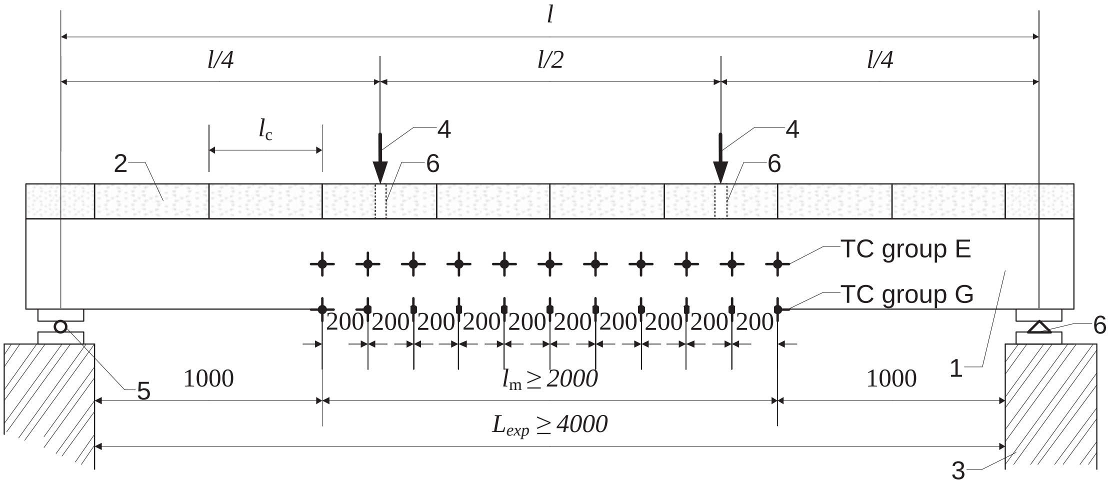
The test setup shall ensure that the entire construction deflects uniformly during the fire test taking into account the reduced heat impact to the outer joists. I.e. all load-bearing joists shall exhibit the same stiffness from the beginning of the test to its termination although joists may get charred.

The large scale wall or floor test specimen consists of load-bearing joists, stone wool insulated cavities, a decking on the non-exposed upper side and a fire protection system on the fire exposed lower side (Figure 4).

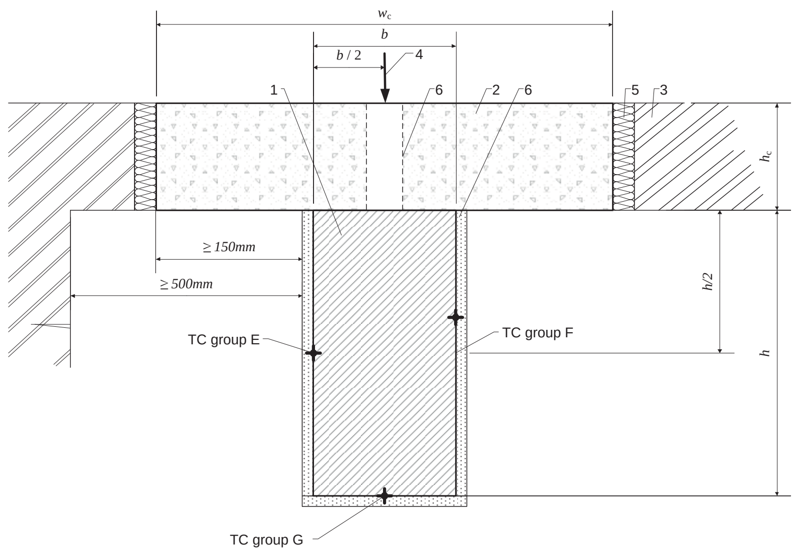
Fire protection systems comprising boards, slabs or batts, for the fire protection of flat, two dimensional, timber structures shall be arranged such that boards, slabs or batts of the largest practical size are used and that at least one longitudinal joint and one transverse joint, where applicable, are tested within the furnace.

The load of large scale tests is chosen to be 60% of the design load given in EN 1995-1-1 due to several reasons. On one hand due to the analogy with the standard series; On the other hand calculations for ambient design (EN 1995-1-1) show that the maximum utilization of beams/floors is normally lower than 50%. In some cases even lower due to the limitations of vibration behaviour in serviceability limit state (SLS). By using the 5% fractile value (characteristic value) for timber and disregarding the normal design procedure in fire using $k_{mod,fi}$ ($\geqslant 1,0$) an appropriate load can be computed for the large scale test.

The aim of the large scale test is to deliver values for the start of charring, t_{ch} and the failure time of the protection system, t_f (failure of the protection system, end of stick ability) as well as the charring rate between t_{ch} and t_f.



Side elevation

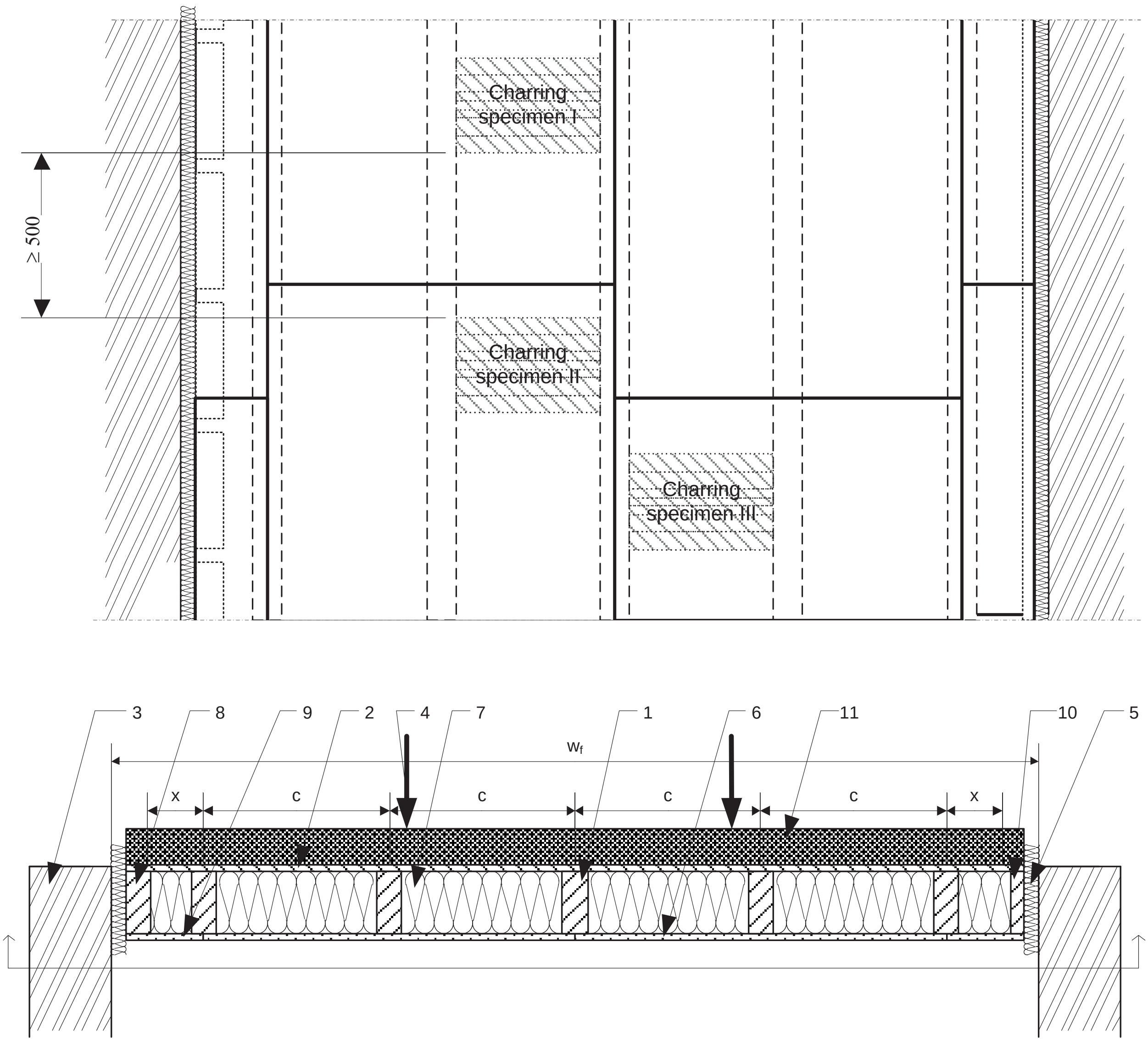


End elevation

Key

1	Instrumented timber beam	b	test specimen width
2	Aerated concrete member	h	depth of the test specimen
3	Test furnace	h_c	depth of the aerated concrete member
4	Load	w_c	width of the aerated concrete member
5	Insulation fitting part	l	span
6	Load spacer	L_{exp}	Fire exposed length
		l_m	Measurement length

Figure 3. Large scale beam test specimen with single layer fire protection system.



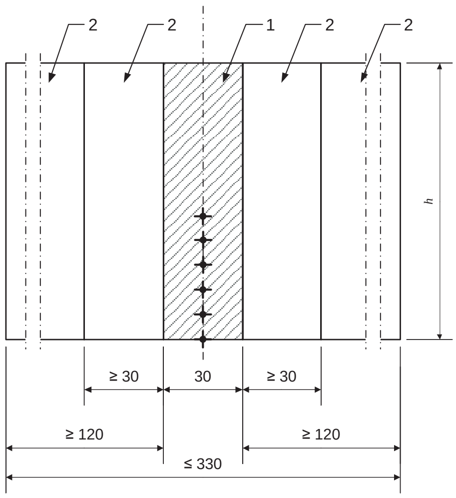
Key

1	Timber joist	7	Cavity insulation
2	Decking	8	Outer joist (example: cut)
3	Furnace	9	Fire protection board (fitting part)
4	Load	10	outer joist (example: half width)
5	Insulation fitting part	d	Board displacement
6	Fire protection board		

Figure 4. Large scale floor specimen.

In the large-scale test specimens and the model scale test specimens charring specimens are incorporated (Figure 5).

The charring test specimen is intended to measure the charring rate behind a fire protection system. It consists of an instrumented timber beam with surface and internal thermocouples. The charring test specimen is based on comprehensive tests performed [2]. These test results have been also confirmed in a numerical finite element (FE) computer simulation. In addition, (FE) parametrical studies were conducted to examine the influence of dimension and number of non-instrumented beams and the thickness of exposed lining to the temperature development in the instrumented beam and exclude any two-dimensional heat flux for the measurement points in the uncharred beam section during fire exposure. Temperature dependent material properties of timber, gypsum plasterboard and thermal insulation were taken from EN 1995-1-2 [1] and the literature [9] and implemented in the transient simulation together with the boundary thermal conditions of EN 1991-1-2 [8].



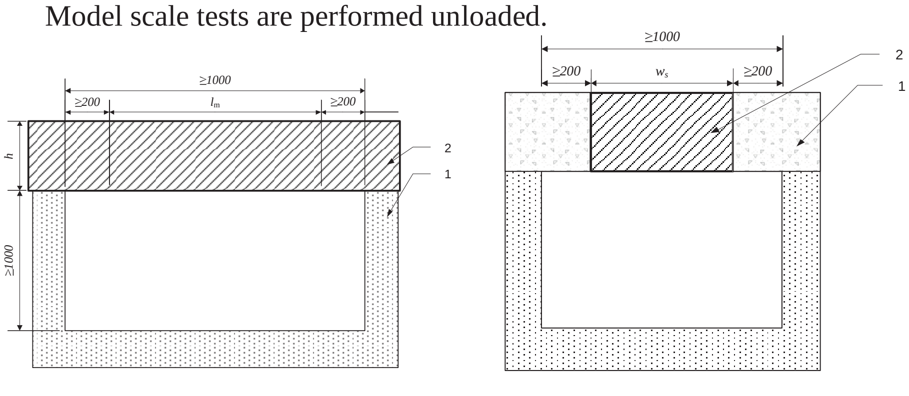
Key
1 Instrumented timber beam
2 Non-instrumented beam

Figure 5. Charring specimen with instrumented beam protected by outer beams.

2.2 Model scale tests

The model scale test is performed with a model scale test specimen and was mainly created to provide an alternative to large scale specimens to proof the protection ability of reactive fire protection materials when exposed to the smouldering fire curve (EN 1991-1-2). The model scale test specimen consists of three charring specimens and is tested unloaded (Figure 6).

Model scale tests are performed unloaded.



Key
1 Test furnace
2 Test specimen
l_m Measurement length

Figure 6. Model scale specimen.

The model scale test specimen(s) shall be installed horizontally on the furnace in an appropriate test frame. The furnace/test assembly interface shall be sealed with a non-combustible seal.

2.3 Temperature measurements

Plate thermometers of the type specified in EN 1363-1 shall be provided to measure the temperature in the furnace. They shall be uniformly distributed and positioned as specified in the appropriate tests.

The surface temperature of the timber members shall be measured with welded thermocouples (TCs) to have as small temperature measurement devices as possible.

Internal thermocouples are to be applied in charring specimens as well as the model scale test specimen.

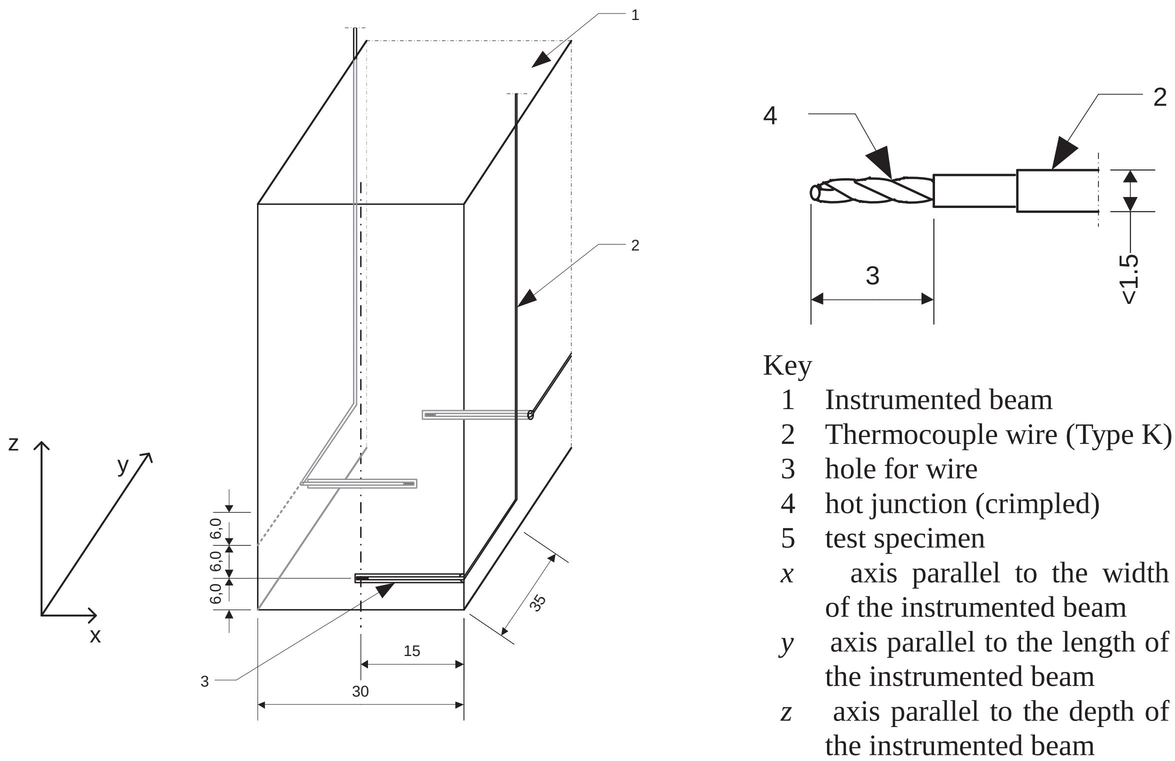


Figure 7. Arrangement of three adjacent internal thermocouples (left) and crimpled thermocouple junction (right).

Thermocouples within the instrumented beam in the centre of the specimen shall have a diameter smaller than 1,5 mm to ensure that the cable can be inserted into a drilled hole of maximum ∅ 1,5 mm. The open end should be placed in the centre of the centre beam. The open end shall be 3 mm long and shall have crimped or welded junctions. The first 50 mm cable from the crimped or welded junction shall be arranged parallel to the isotherms within the specimens (parallel to the lower surface of the test specimen).

2.4 Fixation

The fire protection system shall be attached to the model scale test specimen in such a way that the fixations have no impact on the temperature measurements.

The fixations shall ensure that the fire protection system stays in place longer than during the full scale test performed. Fixations for the model scale test specimen may differ from the fixations used in the large scale test and/or in practice.

EN 1995-1-2 specifies the minimum anchorage length of fixations. Considering the charring depth behind a fire protection system a minimum length of the fixations has to be verified. In the direct applications, the verification is explicitly mentioned; this has to be done for the required time of fire exposure which is at least the failure time t_f assessed by means of EN 13381-7. Although it is assumed that staples can be exchanged with screws this is not given in the direct applications due to little information available.

3 ASSESSMENT OF CHARACTERISTICS

The assessment of the time of start of charring behind the fire protection system (t_{ch}) and the time of loss of stick ability (t_f) shall be done after a large scale test.

The assessment of the rate of charring behind the fire protection system (β_2) shall be done after a large scale test with incorporated charring test specimen (for multi-layer protection systems or single layer protection systems) or a model scale test (for single layer protection systems).

The start of charring shall be determined according to following equation:

$$t_{ch,charring-test-specimen} = \sum_{i=1}^{n} \frac{t_{300,TC1,i}}{n} \quad (1)$$

where

$t_{300,TC1,i}$ is the time when thermocouple reading achieves 300°C

n is the number of test specimens

For the assessment of the charring rate behind the fire protection system, the temperature recordings of all valid thermocouples (TC) of minimum 3 charring specimens exposed in the same fire test shall be used.

The charring rate shall be determined according to following procedure:

The time $t_{300,i,j}$ is the time when the charring of timber is reached i.e. when at the TCi,j for every temperature measurement station j, at the specific depth i, the temperature recording reaches 300°C. Linear interpolation between 2 time records of a TC is permitted.

Calculate the charring rates $\beta_{i,j}$ between 2 consecutive depths for each temperature measurement station j according to the following equation.

$$\beta_{i,j} = \frac{d_{i+1} - d_i}{t_{300,i+1} - t_{300,i}} \quad (2)$$

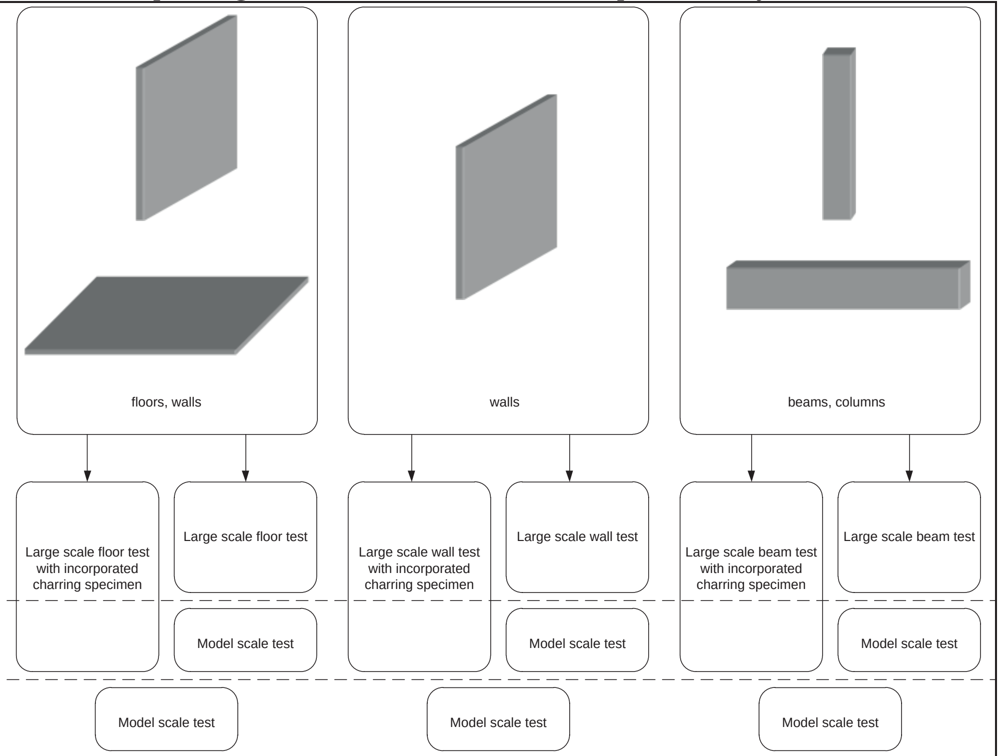
The standard procedure gives the charring rate for the protection phase only. The protection coefficient k_2 according to Eurocode 5 (EN 1995-1-2) [1] can be found as

$$k_2 = \frac{\beta_{i,j}}{\beta_0} \quad (3)$$

The failure of a protection system is assessed in a large scale test. Failure of the fire protection system is detected if the measurement of any TC located at the timber surface (for timber frame assemblies additionally in the field) when one TC rises steep towards the furnace temperature and the deviation between the TC measurement and the mean value of the furnace measured by plate thermometers is equal or less than 50K or when observation detect the loss of stickability of in total more than 0,25 m^2.

Overview of the possible routes for necessary tests is shown in Table 1.

Table 1. Fire tests depending on the intended use of the fire protection system.

<table>
<tr><td>The fire protection system will be attached to</td><td rowspan="4">
</td></tr>
<tr><td>Determination of the stickability</td></tr>
<tr><td>Determination of the charring rate</td></tr>
<tr><td>Determination of the protection ability of fire protection systems comprising reactive fire protection materials</td></tr>
<tr><td colspan="2">NOTE: If the model scale test is used for the determination of the charring rate behind the fire protection system, the determined charring rate β_2 is only valid until the failure of the first layer of the fire protection system.</td></tr>
</table>

4 DISCUSSION

The characteristics determined according to the procedure described here are valid only for tested construction configurations.

The charring test specimen is built up with 120 mm side members to ensure the one-dimensional charring rate at the protected phase. The effect of corner roundings is avoided. Two dimensional charring rate is not determined by these tests.

Failure time of claddings is measured by the thermocouples. Sudden rise of temperature is the criteria. Thermocouples measurements avoid the subjective results by visual observations.

Failure time of protection could also be influenced by spacing of fasteners including edge distances. This effect is not taken into account by the procedure described on this paper. There is an approach needed for the influence of fastener types and fastener spacings as well.

The failure time of protection is also influencing charring rate of timber element at the post-protection phase. The methods described in this article do not consider the post-protection phase. Conservatively the charring rate at post-protection phase should be taken as double value compared to the charring rate for initially unprotected member.

5 CONCLUSIONS

This article gives a possible route for a determination process of fire protection system characteristics for the verification of the load-bearing resistance by means of Eurocode 5.

The new standard allows assessing the time when charring starts, the failure time of the cladding and the charring rate for various types of claddings in a practical way.

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