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PERFORMANCE OF PASSIVE PROTECTION OF CROSS LAMINATED TIMBER DURING STANDARD FURNACE TESTS AND NATURAL FIRES

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ABSTRACT: This paper presents the results of an experimental campaign designed to compare and understand the performance of passive protection under exposure to standard furnace tests and natural fires. As part of this campaign, five natural fire experiments were performed with partially protected cross-laminated timber (CLT) compartments under a range of ventilation conditions. In all the tests, only one side wall was left completely unprotected, and all other timber surfaces were protected with either two layers of 18 mm standard gypsum boards (GB) or two layers of 25 mm standard GBs. The structural CLT ceilings were subjected to a superimposed dead load of 1.35 kN/m² during the natural fire tests, and the fire load was (on average) 950 MJ/m²; chosen to represent the Eurocode 1991-1-2 characteristic value for dwellings. The performance of the passive protection was mainly evaluated with regards to the time to reach a protected timber surface temperature of 250°C. The testing confirms that the resulting fire protection performance of a given gypsum board layout depends on the ventilation conditions of the fire compartment, with more severe (and closest to ISO testing) outcomes when testing under ventilation-controlled scenarios. This paper provides data that sheds light on the co-dependency of the passive protection design and compartment fire dynamics and underlines the importance of considering the safety objectives of a building when defining the performance criteria of its structural elements.

KEYWORDS: Fire protection, Gypsum Plasterboard, Mass timber, Cross laminated timber, Natural fire

1 INTRODUCTION

“Too much fire protection is expensive, too little is dangerous” [1]. The use of structural passive fire protection (e.g. plasterboards) is often a key design approach – especially when designing for burnout of a compartment – to limit/prevent structural timber from contributing to a fire event and thus allow for successful compartmentation [2]. The thermal and physical properties of the plasterboards mitigate heat transfer to the structural timber elements in the event of a fire. For mass timber structures, the effectiveness of the protective plasterboards can be quantified in practice by tracking the temperatures at the interface of the plasterboard and the protected timber surfaces. This allows designers to compare the performance of such protective systems under various heating conditions.

Large scale compartment fire tests allow for the investigation of the fire protection instability depending on the natural fire dynamics combined with the application of structural load. Previous studies have demonstrated that flaming extinction in compartments can occur with limited amounts of exposed mass timber, and with the passive fire protection remaining in place. However, this has typically only been demonstrated for the designed fire duration (e.g. 4h [3]), after which experiments are usually terminated using manual suppression. In such prior test series, it has been shown that the total thickness of the necessary passive protection to prevent the contribution of timber to fire (for the constant fire load) varies depending on the ventilation conditions of the compartment. Since plasterboards are sensitive to the high incident heat fluxes (i.e., high heating rates may lead to accelerated deterioration), some natural fire scenarios may result in failure occurring earlier than in standard fire (i.e., furnace testing) conditions [4]. This was also noted by Hartl et al. [5] who tested small scale samples of gypsum plasterboards at heat fluxes of 50 and 100 kW/m².

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The tests presented in the current paper are part of a larger research programme: the Épernon Fire Tests Programme – Phase 2. The project seeks to understand the links between normative fire resistance ratings and real fire performance in buildings for combustible and non-combustible structures [6] [7] [8] [9]. The objective of the second phase presented herein is to investigate the performance of different passive fire protection layouts under both standard furnace testing and compartment fire scenarios. The impacts of various parameters are considered, such as the ventilation conditions and the proportion of exposed mass timber surfaces. The performance of the implemented passive protection solutions is evaluated with regards to *(i)* the surface temperature between the fire protection boards and the timber during the entire duration of the fire (including the decay phase) and *(ii)* the time at which the protection fails (see later).

2 CHOICE OF THE PASSIVE FIRE PROTECTION LAYOUTS

The layouts investigated under standard furnace and natural fire conditions were chosen based on existing French guidelines for a layout associated with a fire resistance time of 60 min ([10] [11]). The proposed layout consisted of two Type A 18 mm thick gypsum boards (GBs). An additional layout with a presumed higher fire protection time was also considered, which consisted of two layers of 25 mm GBs. The same mechanical fixing rules – as presented in Table 1 – were used for both the standard furnace and compartment tests. The joints between the boards were staggered from one layer to the other. Distance of fasteners to edges and joints was 10 mm approximately.

Table 1: *Fixing rules for gypsum boards*

2*18 mm GBs			
GB layer		1st (inner) layer	2nd (outer) layer
Screws (length)		35 mm	55 mm
Spacing *(in both directions)*	Ceiling	300 mm	150 mm
	Walls	600 mm	300 mm
2*25 mm GBs			
GB layer		1st (inner) layer	2nd (outer) layer
Screws (length)		45 mm	70 mm
Spacing *(in both directions)*	Ceiling	300 mm	150 mm
	Walls	600 mm	300 mm

Throughout this work, the temperatures at the interface between the mass timber and the inner GB are identified as “surface temperatures” and the temperatures between two GB layers are identified as “interface temperatures”.

3 STANDARD FURNACE TESTS

Intermediate scale furnace testing was performed to evaluate the performance of the chosen passive protection layouts under standard fire conditions. The performance has been assessed based on two parameters:
- the time at which the surface temperature reaches 250°C, and
- the time at which the inner GB layer starts to physically fall-off. This was evaluated through visual observation of the exposed face during the tests and the verification of the time at which the surface temperature differed by less than 50 K from the furnace temperatures.

For the performance of 2*18 mm GBs, three different sourcing of the gypsum boards were tested (S1, S2, S3). For the 25 mm GBs, only one sourcing of the boards was used. The tests were conducted under the ISO 834 standard fire exposure and were run until the GBs on all the timber surfaces started to detach from the timber. The GBs were fixed to horizontal CLT slabs (1,70 x 0,98 m²) and were exposed to fire over a surface of 1,30 x 0,98 m².

Table 2 summarizes the time at which the average surface temperatures reach 200°C (a temperature criterion suggested in the STA fire safety guidance to mitigate the onset of pyrolysis for the full duration of the relevant fire resistance period [12]), 250°C (a rise of 250 K is the temperature criterion according to EN 13501-2 and EN 14135 [13]) and 300°C (the temperature typically considered as representing the charring isotherm for timber [14]). In all cases, these temperatures were reached after 60 minutes, and only small deviations were observed between the three specimens. From the temperature criterion presented in Table 2, the difference between the 200°C and 300° criterion provides on average a difference of 12 minutes. For the remainder of the experimental programme presented in the current paper, all GBs correspond to S2.

Table 2. Inner interface temperature of the three 18mm GBs systems from different suppliers under ISO fire

	Interface temperature			Start of GB fall-off
	200°C	250°C	300°C	
S1	86 min *(±4 min)*	91 min *(±3 min)*	97 min *(±4 min)*	113 min
S2	81 min *(±2 min)*	87 min *(±3 min)*	93 min *(±4 min)*	118 min
S3	87 min *(±3min)*	93 min *(±3 min)*	99 min *(±4 min)*	132 min

An additional test has been performed to assess the performance of a thicker layer system, i.e. 2 x 25 mm GBs from supplier S2. The interface and surface temperatures of both layouts under the ISO exposure are shown in ***Figure 1***. Increasing the thickness of each individual GB layer by 7 mm postpones the time at which an average surface temperature of 250°C is reached by about 55 minutes.

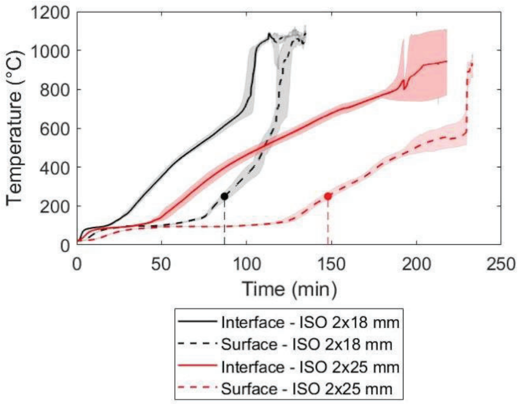

Figure 1. Comparison of ISO exposures with both 2x18 mm and 2x25 mm boards. The symbols indicate the time at which the surface reaches 250°C for each case.

4 NATURAL FIRE TESTS

The natural fire compartments were constructed with an internal area of approximately 21 m² enclosed by mass timber elements which are then surrounded by walls of aerated concrete blocks (Figure 2). Protected walls had two layers of GBs. The inner dimensions of the compartment after the installation of the timber elements and the GBs were 5.6 m (length) x 3.8 m (width) x 2.5 m (height), with small deviations when changing the arrangement of the protected walls (Table 3) or the thickness of the GBs.

The compartment was made of two lateral (i.e. side) loadbearing walls 180 mm thick CLT (40/30/40/30/40) supporting the timber ceiling, and two non-loadbearing longitudinal walls made of 60 mm thick (20/20/20) CLT.

In each test, only one timber surface was left initially exposed to fire. Figure 2 and Table 3 show the distribution of the protected and unprotected surfaces for each test, the passive protection layouts that were used, and the opening factors according to EN 1991-1-2 [15].

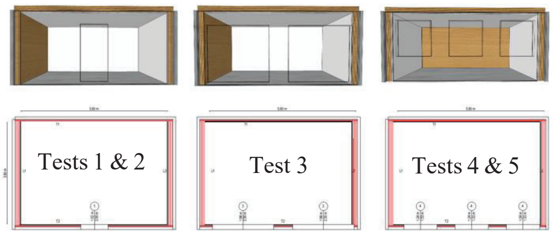

Figure 2: *Compartment plan with 3D view illustrating the opening configurations (W1: left wall, W2: right wall, W3: back wall, W4 : front wall with openings). Tests 1&2 (W1 exposed), Test3 (W1 exposed), and Test 4&5 (W3 exposed).*

The ceiling of the compartment used was a 180 mm thick CLT slab (40/30/40/30/40) for Tests 1 to 4 and a timber frame assembly (TFA) for Test 5 (Figure 3). The joists used in Test 5 were positioned on the spanning length of the ceiling and were spaced every 600 mm on centres. Noggins were also placed every 1,250 mm between the joists to allow additional fixing points for the GBs. The ceilings of the five tests were subjected to an imposed load composed of five dead weights for a total force of 29.5 kN, i.e., an average superimposed dead load of 1.35 kN/m².

Different ventilation openings were arranged in one of the long walls of the compartments to yield different ventilation conditions (i.e., fuel- or ventilation-controlled). Ventilation conditions ranged from an opening factor of 0.032 $m^{1/2}$ to 0.142 $m^{1/2}$.

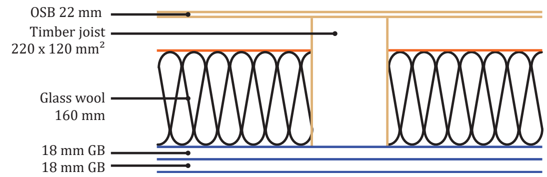

Figure 3: *Composition of the TFA ceiling (Test 5)*

Table 3. Description of the compartments for the 5 natural fire tests

	Test 1	Test 2	Test 3	Test 4	Test 5
Opening factor	0.032 $m^{1/2}$	0.032 $m^{1/2}$	0.142 $m^{1/2}$	0.065 $m^{1/2}$	0.065 $m^{1/2}$
Wall 1	180 mm CLT				
	2*18 GBs	2*25 GBs	2*18 GBs	2*18 GBs	2*18 GBs
Wall 2	180 mm CLT				
	-	-	-	2*18 GBs	2*18 GBs
Wall 3	60 mm CLT				
	2*18 GBs	2*18 GBs	2*18 GBs	-	-
Wall 4	60 mm CLT				
	2*18 GBs	2*18 GBs	2*18 GBs	2*18 GBs	2*18 GBs
Ceiling	180 mm CLT				220 TFA
	2*18 GBs	2*25 GBs	2*18 GBs	2*18 GBs	2*18 GBs

A total moveable fire load of about 950 MJ/m² (related to the floor area), consisting of six wood cribs (and a combination of heptane and gasoline for ignition) was adopted to represent dwellings as per EN1991-1-2 Annex E [4].

Gas phase temperature measurements were made with plate thermometers (PTs) installed 100 mm from the boundary surfaces of the compartment (11 PTs in front of the ceiling and 9 PTs in front of each wall). Surface and interface temperatures were measured with 7 Type K thermocouples (diameter 1.5 mm) per surface.

In the following subsections, the gas phase compartment and surface/interface temperatures are illustrated for a duration of 130 minutes to interpret the growth and decay phases of the fires. Only the temperatures under the ceiling are presented in this paper; the complementary data will be presented elsewhere.

4.1 VARIATION IN PASSIVE PROTECTION THICKNESS: 2x18 mm | 2x25 mm

Tests 1 and 2 were intended to represent ventilation-controlled fires (opening factor 0.032 $m^{1/2}$), with an exposed load bearing CLT wall positioned on the left from the opening. The two tests employed different thicknesses of the passive fire protection installed on all other surfaces: 2x18 mm for Test 1, and 2x25 mm GBs for Test 2.

Plasterboard Performance

Figure 4 presents the gas phase compartment temperatures at the ceiling for the two thicknesses of GBs tested. The results seen in ***Figure 4*** are also compared against the ISO 834 temperature-time curve. Performance is analysed in three representative stages for Test 1: <80min (growth), 80-100 min (decay) and >100min (re-growth); and two stages for Test 2: <80min (growth), >80min (decay). Visual representation of the stages is also presented in ***Figure 5*** and ***Figure 6***.

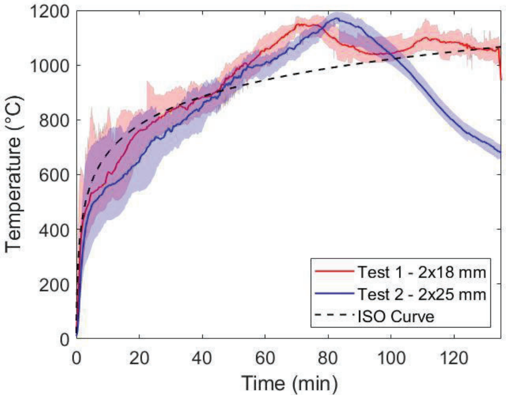

Figure 4: Compartment temperatures (from 11 PTs) under the ceiling for Test 1 (GB 2x18 mm) and Test 2 (GB 2x25 mm) compared to the ISO standard time-temperature curve (shaded areas show the extents of temperature variability).

As indicated in ***Figure 4***, after approximately 40-50 minutes the compartment temperatures in the natural tests 1 and 2 rise above the standardised test curve. The second stage marks the beginning of a decay phase at around 80 min for both natural fire scenarios. However, the onset of mechanical failure of the thinner (18 mm) layer of fire protection boards in Test 1 then led to the third stage, with fire regrowth at around 100 minutes. The temperatures inside the compartment remained approximately steady (at around 1000-1100°C). Conversely, in Test 2, the GBs remained in place for the full duration of the fire, and temperatures decreased in the compartment as a result.

In Test 1, the fire was manually suppressed after 135 minutes due to the severe fire regrowth and safety concerns. In Test 2, the temperatures continued to decay and the fire was manually suppressed after 225 minutes (when average temperatures were about 460°C). Moveable fuel was effectively consumed before the manual suppression in each case. Localised continuous flaming of the exposed load bearing wall was observed independently of the burn-out of the moveable fuel load, as shown in ***Figure 6***-3. This localized flaming continued up until the point of manual suppression (***Figure 6***-4). Continuous burning of the exposed CLT wall, as well as continuous smouldering in the other mass timber elements, were observed in both tests.

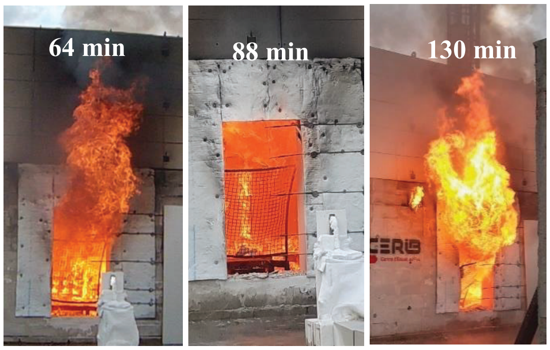

Figure 5. Test 1 stages: growth (l), decay (2), re-growth (3).

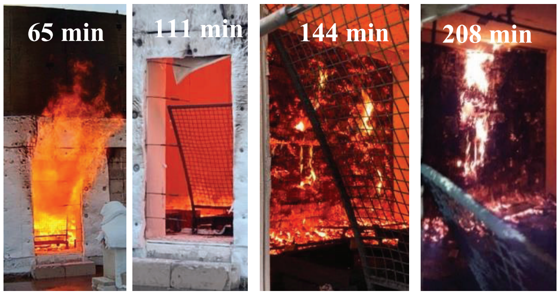

Figure 6. Test 2 stages: growth (l), decay (2); Continuous localised combustion of the exposed wall (3 & 4).

Interface and surface temperatures

Figure 7 shows the ceiling interface (i.e. between two layers of GBs) and surface (i.e. between timber and the inner GB) temperatures in Tests 1 and 2. During the first fire growth stage (<80min), the temperature plateau at 100°C is characteristic of the GB dehydration reaction in both tests, with a notably longer dehydration plateau seen in Test 2. The increased plateau duration was a result of the added thickness (i.e., increased volume of water in the GBs) from the 2*25 mm GBs compared to the 2*18 mm GBs.

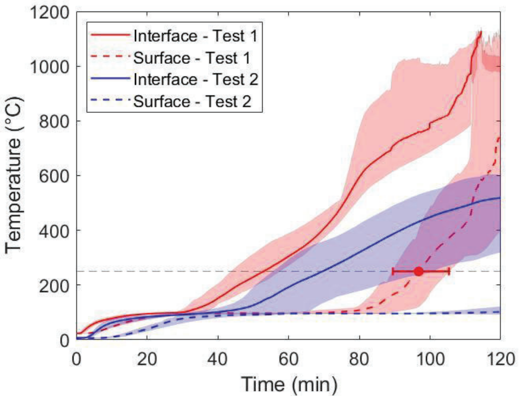

***Figure** 7*. Test 1 and 2 – Ceiling interface and surface temperatures. The symbol indicates the time at which the surface of Test 1 reaches 250°C (error bars indicating the range of times observed).

In Test 1, thermally induced cracks lead to mechanical failure of the boards at about 100 minutes followed by rapid increases in interface temperatures. It should also be noted that after such mechanical failures these temperature measurements may be significantly influenced by gas phase temperatures and may no longer represent the interface temperatures. CLT surface temperatures reach 250°C as early as 90 minutes (an average time of 97 minutes). In Test 2, where thicker GBs are used, interface temperatures between the GBs enter a steady phase from 110 minutes onwards. The surface temperature of the CLT remains below 250°C for the full duration.

4.2 EFFECTS OF VENTILATION CONDITIONS

Tests 1 and 3 include compartments with the same boundary conditions (i.e. applied GBs and orientation of the exposed timber wall) and fuel loads, but a different size of the openings. Two ventilation conditions have been used, whereby an opening factor of 0.032 $m^{1/2}$ leads to ventilation-controlled conditions whereas 0.142 $m^{1/2}$ to fuel-controlled conditions.

Fire development is described in three stages for both experiments. Stages for Test 1 were explained in ***Figure* 5**. Test 3's stages are: fire growth (<5minutes), steady state (<30min), and decay (>30minutes) as shown in ***Figure* 8** and ***Figure* 9.** The ventilation conditions resulted in faster fire growth in Test 3, reaching a maximum temperature of 1100°C within 10 minutes. The initial fire growth rate in Test 1 is lower, however it leads eventually to maximum temperatures of approximately 1100°C at 80 minutes.

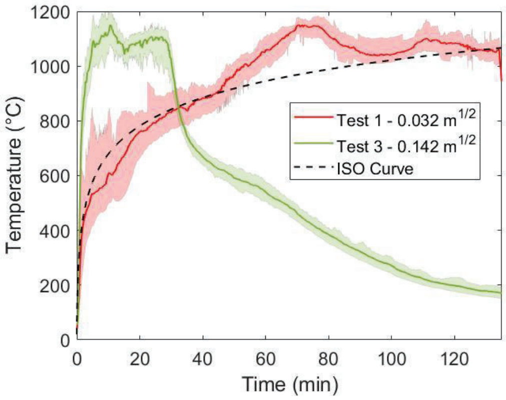

Figure 8: Compartment temperatures for Test 1 (opening factor 0.032 $m^{1/2}$) and Test 3 (opening factor 0.142 $m^{1/2}$) compared to the ISO 834 temperature-time curve.

Figure 9. Test 3 stages: growth (1-upper left), steady-state (2-upper right), decay (3-lower left); Continuous combustion of the exposed wall (4-lower right); Cracks after burnout of the moveable fuel load (5- last).

Rapid fire growth in Test 3 leads to a period of approximate steady temperature conditions where the temperature difference ranges between 200 to 600°C higher than compared to Test 1 or standardised furnace test during the first 30 minutes. The third stage of Test 3 is a decay phase where most of the moveable fuel is consumed; after which localised smouldering and flaming combustion of the combustible wall continues (***Figure 9-4***). All of the GBs remained fixed to the ceiling and walls

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in Test 3, however many pronounced cracks were visible (***Figure 9-5***). Manual suppression was *not* performed, and eventually continuous smouldering combustion resulted in collapse of the unprotected wall at some unknown point during the following night.

Interface and surface temperatures

Figure 10 illustrates a more rapid increase in the interface temperatures early into Test 3 compared to Test 1. Test 3 also displays a shorter 100°C temperature plateau due to the more sever heating conditions. Interface temperatures continue to rise 30 minutes into Test 3, after which the compartment temperatures decay (see ***Figure 8***).

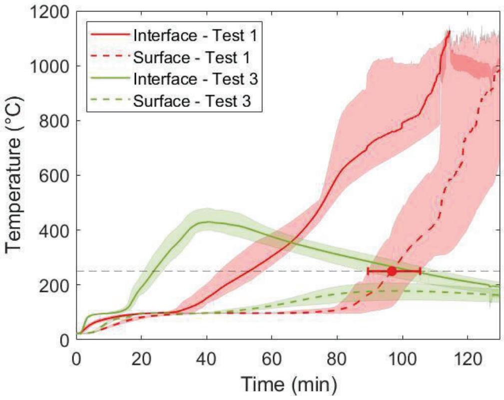

Figure 10. Test 1 and 3 – Ceiling interface and surface temperatures. The symbols indicate the time at which the surface reaches 250°C for each case.

The interface temperature data presented in ***Figure 10*** illustrates an earlier increase in the temperature at the interface compared to Test 1 but the surface temperatures for Test 3 were maintained below 200°C throughout the test. These results suggest that the rapid period of fire growth resulted in an earlier thermal wave through the first plasterboard, but the time scales of burning prevented the thermal penetration to significantly affect the second layer of plasterboard.

In Test 1 both surface and interface temperatures continued to rise at the similar rate once the GBs were dehydrated. Whilst the influence of the heating rate on the performance of the plasterboards was discussed previously [5], premature failure of the front exposed GBs was not observed for the fire conditions in Test 3. This result this confirms the importance of the exposure duration in addition to the heating rate [5].

Interface and surface temperatures: Test 1 and standard furnace fire test

The under-ventilated fire scenario (Test 1) and the ISO 834 furnace test show similar trends in the temperature developments. The average interface temperatures for the standard fire test and Test 1 follow similar heating rates up to 60 min. At about 75 minutes, a local rapid increase of temperatures was observed in Test 1, leading to local temperatures of 1000°C as early as 90 minutes (***Figure 11***).

Surface temperatures for Test 1 are comparable to the ISO 834 standard fire results. An average surface temperature of 250°C was reached at 87 minutes for the ISO 834 test and 97 minutes for Test 1, while this was never reached for Test 3.

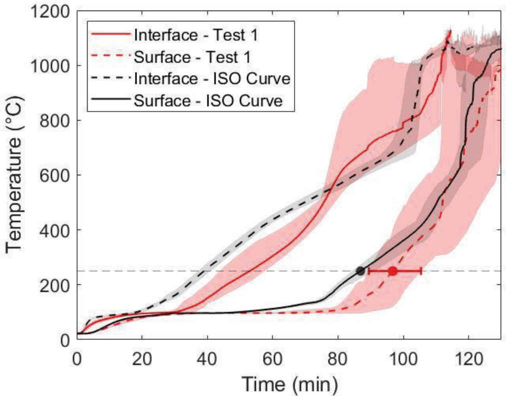

Figure 11. Surface and interface temperatures for Test 1 and furnace test (2*18 mm GBs). The symbols indicate the time at which the surface reaches 250°C for each case.

4.3 CLT VS. TIMBER FRAME CEILINGS

The last two tests of the series differ from Test 1 to Test 3 on two points:

- the use of an "intermediate" opening factor of 0.065 $m^{1/2}$ statistically representative of openings in many residential buildings (see e.g. [16]); and
- the modification of the exposed timber surface. In the first three tests, one lateral 180 mm CLT loadbearing wall was systematically exposed to fire, and continuous smouldering long after the end of the test led to eventual collapse. Thus, in the last two tests, it was decided to expose one long 60 mm CLT non-loadbearing wall (W3, in Figure 2).

Two additional tests were performed with intermediate ventilation conditions in order to compare a CLT and TFA ceiling in natural fire conditions. Test 4 and Test 5 are in all other respects identical except for the nature of the timber ceiling itself. Test 4 consisted of a CLT ceiling (identical to the one used for the previous tests) whilst the latter included a TFA ceiling. Whilst a detailed analysis of these two tests will be provided in a forthcoming paper, the main outcomes are presented here to illustrate differences that can be observed between the performance of mass timber and timber frame under natural fire conditions. Figure 12 shows the compartment temperatures for the two tests, with a reasonable similarity. Test 5 was, however, terminated at 250 minutes due to collapse of the TFA ceiling (see Figure 13).

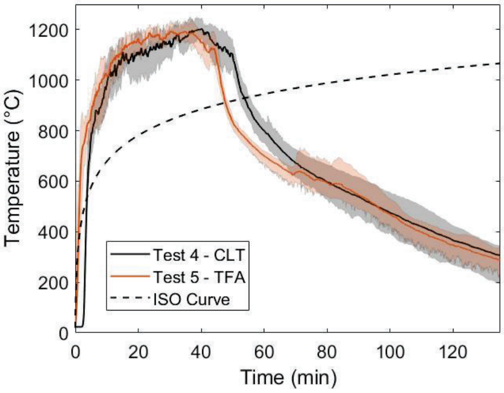

Figure 12. Compartment temperatures under the ceiling (measured with PTs) for tests 4 and 5.

Figure 13. Test 5 failure stages of the protected TFA ceiling.

5 DISCUSSION

Usually standardised pass/fail requirements for surface temperatures are representations of pyrolisis isotherms which indicate that timber is charring or has charred (i.e. 300°C in EN 13381-7 [17], or T_{amb}+250°C in EN 14315 [13] and as a threshold for K classification according to EN 13501-2 [18]). If one considers the *onset* of timber pyrolysis as a timber degradation criterion, this can be considered to occur from about 200°C [19]. The standard tests performed on three different sources of a 2x18 mm GBs layouts have shown that the difference in time to reach these different temperatures is about 10 minutes. Rather than discussing the temperature criteria themselves, an important question to answer is therefore the duration during which this temperature criterion should be delayed or prevented in a standard furnace test in order to limit the contribution of structural timber elements to a real fire – depending on the safety objectives and the fire safety strategy for any given building. If the temperature criterion is reached but the temperatures in the compartment remain high, the degradation of the GBs and the pyrolysis of the protected timber is likely to continue, which could then lead to fire regrowth and the prevention of burnout conditions [2] without fire service intervention. A single fire resistance rating (i.e., R60 or R90) could be associated with different safety objectives or fire safety strategies depending on the type of building (dwellings, offices ...). For some building categories (e.g. dwellings) a common strategy in some European jurisdictions is to limit the immediate evacuation to the floor (or even only the apartment) where the fire has started, while in other jurisdictions the strategy is instead that all people should leave the building alongside an assumption that the fire brigade *will* rapidly intervene. Such complexities warrant further investigation to observe the performance under a range of natural fire conditions.

Five natural fire tests have been performed in timber compartments of 21 m² with one exposed CLT wall and all other surfaces protected by either 2x18 or 2x25 mm GBs. It should be noted that different outcomes could result from exposing more timber surfaces or from changing the orientation of the exposed timber surfaces (e.g., ceiling instead of a wall). Three ventilation conditions were used, ranging from a ventilation-controlled fire (one opening, O=0.032 $m^{1/2}$) to a fuel-controlled fire (two openings, O=0.142 $m^{1/2}$). The variable of the ventilation factor in a realistic fire scenario assumes airflow through an available opening area (e.g., windows). However, toughened and fire rated glazing may not ultimately break, which could lead to a ventilation-limited fire even when large amounts of glazing are present. Hence, this paper analysed performance of the gypsum boards as a product and their influence on the compartment performance (i.e. fire dynamics) assuming all available openings allow for ventilation.

The compartment temperatures leading to manual fire suppression (Tests 1, 2 and 5) or without manual fire suppression (Tests 3 and 4) are given in Figure 14.

In the under-ventilated fire scenarios, the failure of the protection layouts in Test 1 (with 2x18 mm GBs) did not appear for the first 60-80 minutes, but the GBs failure ultimately led to fire regrowth and termination of the test by manual suppression (135 minutes). In Test 2, increasing the thickness of the two GBs by 7 mm each (25 mm layouts instead of 18 mm) significantly reduced the surface temperatures, keeping them below 250°C for the entire duration of the test up to manual suppression. Test 3 was more representative of a fuel-controlled fire and was characterised by a rapid growth and comparatively short fully developed phase. Thus, the interface temperatures in Test 3 were observed to decrease after approximately 40 min and the surface temperatures were found to remain below 250°C for the duration of the experiment. Results for tests 4 and 5, where three openings were used (O=0.065 $m^{1/2}$), are not part of this discussion but are noted to inform that the results obtained on CLT structures cannot strictly be applied to TFA structures. In the performed tests, an earlier failure of the TFA ceiling was observed compared to the CLT ceiling.

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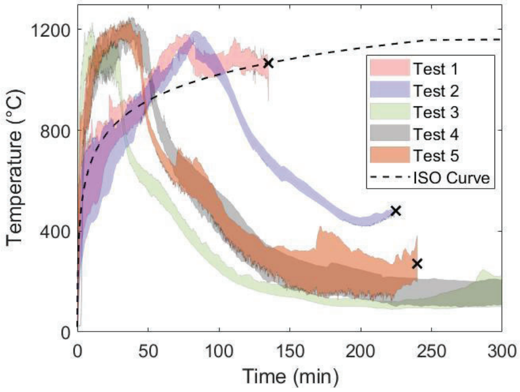

Figure 14. Overview of the compartment temperatures of the five natural fire tests up to 300 minutes with indication of manual suppression times (Tests 1, 2 and 5)

Each compartment was observed to collapse in the night following the experiment. Even the trials in which the CLT surface was measured to remain below the pyrolysis temperature were observed to ultimately fail (e.g., Test 3). In Test 1, following fire suppression at 135 min, the compartment temperatures were observed to steadily increase over a period of approximately 250-500 min. While the time of the structural failure is difficult to predict with certainty from temperature measurements alone, a collapse was observed approximately 6 hours following manual fire suppression. This underlines the importance of properly suppressing continued flaming and smoldering. In-depth heating of the timber may result in ongoing smouldering of mass timber structural elements, and potentially in re-ignition at a later stage. Understanding the mechanisms that may lead to delayed collapse, as observed in these experiments, requires further investigation.

6 CONCLUSIONS

A series of furnace and natural fire tests has been performed to study the performance of two passive fire protection schemes in various standard and natural compartment fire scenarios, and with the presence of one exposed CLT wall. It should be noted that different outcomes may result from exposing more timber surfaces or from changing the orientation of the exposed timber surfaces (e.g., ceiling instead of a wall). The experimental campaign confirmed that the performance of a given GB layout depends on the ventilation conditions of the fire compartment, with more severe outcomes when testing under ventilation-controlled scenarios for the given fuel loads used. This paper and the overall Épernon Fire Tests Programme Phase 2 suggest that GB passive protection applied to CLT appeared to perform about as well as it did in furnace tests (for the chosen performance criteria and the configurations tested). The data confirmed that ongoing smouldering and localised burning, if not fully supressed after the steady burning phase of a severe fire, have the potential to result in reignition and/or structural collapse at some time after the fire *appears* to have been extinguished. The conducted tests provide data that underline the importance of considering the safety objectives of the concerned building when defining performance criteria of a structural element.

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