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EXPERIMENTAL FIRE-SIMULATOR FOR POST-FLASHOVER COMPARTMENT FIRES

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ABSTRACT

The number of tall timber buildings around the world is rapidly increasing as a result of changes in regulations and the development of new engineered timber products. However, due to the combustibility of timber, the fire safety of tall timber buildings has been questioned. Building regulations for structural elements are based on fixed periods for which specimens shall resist standard fire exposure in a fire resistance furnace. Because no distinction is made between the exposure in fire resistance tests of combustible and non-combustible specimens, less conventional testing methods have been used for research of timber structures. This study aims to identify aspects that are important to simulate realistic fire conditions relevant to assess the structural performance of timber in post-flashover fires. A test method is developed aiming to replicate conditions in compartment fire tests using an experimental fire simulator that results in similar damage types and rates of damage in the timber specimen. Based on observations from these tests and results obtained using other testing methods, the applicability of standard fire resistance tests and other non-conventional tests for investigating the fire performance of timber are discussed.

Keywords: Cross laminated timber, compartment fires, fire resistance tests, simulation

1 INTRODUCTION

The number of tall timber buildings around the world is rapidly increasing as a result of changes in regulations and the development of new engineered , often glued, timber products; such as Cross Laminated Timber (CLT). This increase in building height creates new challenges for fire safety. Various methods have been used to study the performance of timber products in post flashover fires; such as standard fire resistance tests [1] and tests with a radiant heat source in an open environment (e.g. [2]). Differences in results from these tests have led to various hypotheses regarding the important aspects to achieve realistic fire exposures relevant for timber structures [3,4].

This paper focusses on key parameters that must be controlled to produce results relevant for the structural assessment of timber in post-flashover compartment fires. While full scale compartment

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fire tests can be used to represent real building fires, these tests can be time consuming and costly. Therefore, we present an intermediate scale method to replicate relevant conditions of a specific compartment fire test [5]. Successful replication of the compartment fire should result in similar damage to that observed in a comparable full scale test.

2 REFERENCE COMPARTMENT FIRE TEST

An extensive study led by the Fire Protection Research Foundation involved six full scale compartment fire experiments, performed by the National Research Council Canada and the National Institute of Standards and Technology to study the contribution of exposed Cross Laminated Timber (CLT) to the fuel load of the fire [5]. The study involved compartment tests with various configurations of exposed CLT surfaces and ventilation. Due to weakening of the CLT adhesive in the fire, fire induced delamination (hereafter *delamination*) occurred during the compartment fire tests with exposed CLT. In the compartment tests, delamination led to increased combustion and subsequent fire growth or continuation of the fully-developed fire [5]. Delamination depends on the adhesive used to produce CLT. To study whether delamination would have occurred had other adhesives been used, an intermediate scale fire testing method was developed as discussed herein. For this, compartment Test 1-4 described by Su et al. [5] was chosen for reference. A short summary of the test setup is discussed below.

The compartment was made of 175 mm thick 5-ply CLT walls and ceiling. The interior of the compartment was 9.1 m × 4.6 m × 2.7 m (depth × width × height) and there was an opening of 1.8 m × 2.0 m in one of the 4.6 m × 2.7 m walls. Three layers of 15.9 mm type X gypsum boards were applied on the CLT walls and the CLT ceiling was left exposed. Typical residential furniture with a fuel load density of 550 MJ/m^2 was used as fuel.

After ignition, flashover occurred after approximately 11 min and the exposed ceiling became fully involved in the fire. A significant fire plume was observed during the fully-developed stage of the fire. Two layers of the exposed CLT delaminated. Delamination of the second layer occurred during the decay phase of the fire, leading to a secondary flashover. The results from Test 1-4 are used in Section 3 to benchmark the fire conditions in the intermediate scale tests.

3 EXPERIMENTAL FIRE SIMULATOR FOR POST-FLASHOVER FIRES

An experimental method to replicate fire conditions was needed to study whether other adhesives would have performed better under the conditions of Test 1-4 (discussed above). For the purpose of this study, a successful replication of the fire conditions of the compartment fire test in a furnace should lead to similar damage in both tests if the same product is tested. Recent studies have indicated that the oxygen concentration of ambient gasses has a significant influence on the rate of damage of timber exposed to fire. Timber tested in fire conditions involving oxygen concentrations over 10 % had significant char oxidation leading to the gasification of protective char layers and more thermal damage of the timber [6]. Therefore, oxygen concentrations, in addition to plate thermometer temperatures, measured in Test 1-4 were used to replicate the conditions of a flashover compartment fire in a furnace. This setup is referred to here as the ‘experimental fire simulator’.

To study whether delamination would occur for an arbitrary adhesive, the delamination induced temperature increase and the reduction of oxygen concentration after 120 min in Test 1-4 were ignored (Figure 1). The target oxygen content and temperature in the final stage of the test (from 120 min to 180 min) were extrapolated based on a similar compartment test without exposed CLT (Test 1-1 in [5]).

Two replicates (denoted A and B) of CLT panels constructed using five different adhesives were tested. In this paper, the results of two polyurethane adhesives (referred to as PU1 and PU2) are discussed. PU1 is the same adhesive as used in Test 1-4. The other polyurethane adhesive (PU2) was enhanced to avoid delamination.

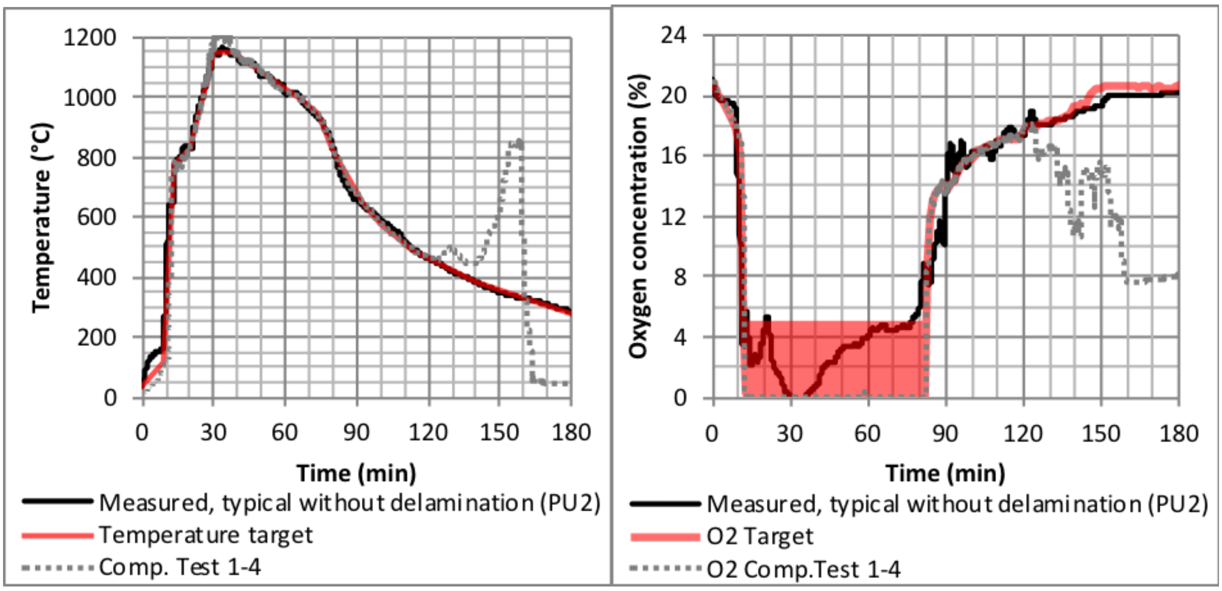

Figure 1: Target and typical temperature and oxygen concentration in fire simulator tests

The experimental fire-simulator had interior dimensions of 1.0 m × 1.0 m × 1.0 m (Figure 2). The CLT floor specimen was 1400 mm × 600 mm, of which 1000 mm × 600 mm was exposed. One of plate thermometers was positioned at 100 mm distance from the CLT surface directed away from the surface (similar to the plate thermometer in Test 1-4) and an additional plate thermometer was positioned 150 mm from the surface. The oxygen concentration was measured in the exhaust of the furnace. There was an inlet for air and nitrogen to control the oxygen concentration and the temperature during the cooling phase. Temperatures were measured in the adhesive bond line of the CLT in a similar fashion as was measured in the compartment fire tests discussed above. The incident radiant heat flux was determined in two different ways:

1. From the plate thermometer temperature and the gas temperature measured by a thermocouple near the plate thermometer.
2. From a water cooled heat flux gauge flush with the surface of the CLT specimen. The temperature of the cooled sensor was measured using a thermocouple. The heat flux was estimated for corresponding to different convection coefficients.

Delamination was indicated using: (1) temperature measurements in the lamellae and in at the bond line of the CLT, (2) video recordings of the specimen surface during the test, (3) charring rates determined from temperature measurements, (4) final charring depth measured after the test, and (5) measurements of the mass loss.

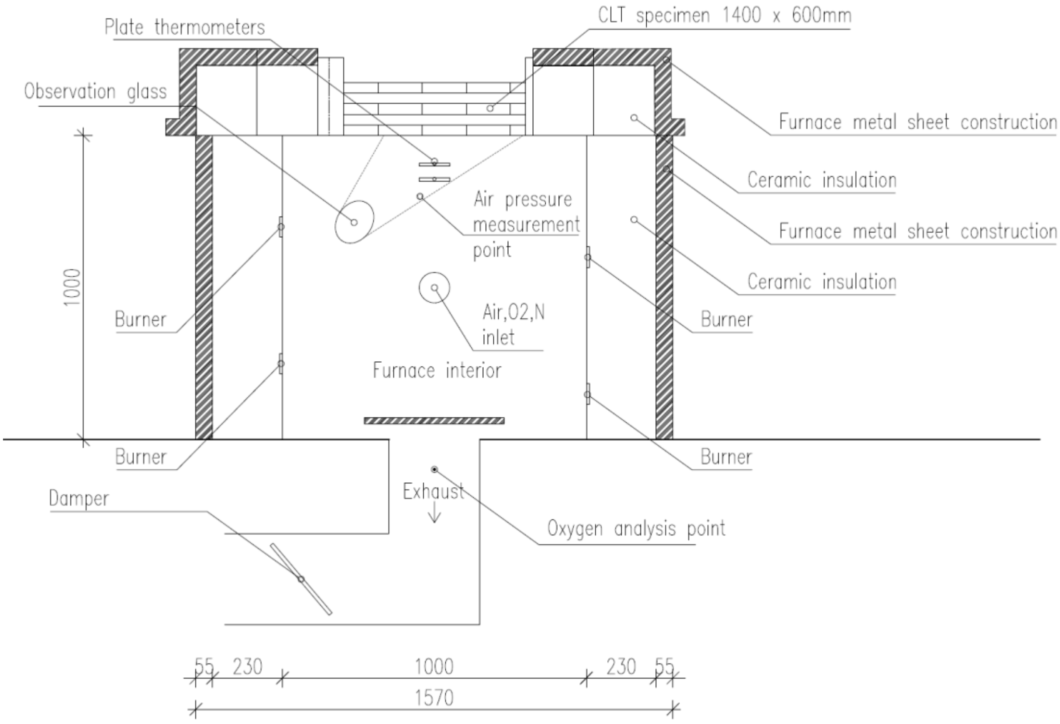

Figure 2: Cross section of the test setup

3.1 Results and evaluation of the furnace tests

In this section, the damage and temperatures for compartment Test 1-4 and the intermediate scale tests are compared. A successful replication of the fire conditions of a compartment test should lead to a similar rate of charring for the same CLT product.

Figure 3 shows the average char depth measured after Test 1-4 and the estimated average char depth from the intermediate scale furnace tests after the same time (160 min). Because the furnace test was 20 min longer, the corresponding average char depth was estimated using linear interpolation of measurements of the char depth at the end of the test and the depth at the time at which the thermocouples read 300 °C. A distinct difference can be seen between the charring depth of CLT with non-delaminating adhesives and CLT with a delaminating adhesive (PU1). The average char depth determined after Test 1-4 only deviates a few millimeters from the average charring depth determined from the furnace tests. Based on a study of the uncertainty of thermocouple locations and temperature measurements, the expanded total uncertainty for the interpolated char depth is estimated to be ±0.9 mm (95 % confidence). It should be noted that there was significant spatial (24 mm) variation in char depth across the ceiling, as measured after Test 1-4. For both intermediate scale tests of the same CLT product (PU1), the spatial variation of char depth measured was 9 mm. The spatial variation of charring depth measured in tests with non-delaminating polyurethane adhesives (PU2-A and PU2-B) was significantly less (2 mm).

Figure 4 shows the temperatures measured in the CLT of the compartment fire test together with the furnace tests. For the comparisons, only temperature measurements of the furnace tests with the same CLT product as the compartment test are shown (PU1). It can be seen that the temperature increased in the decay phase of PU1-A, despite the reducing furnace temperature. Due to delamination and the high oxygen content, the temperature could not be controlled in this phase. The temperature increase is, however, similar to that of the compartment fire. Test replicate PU1-B had the same specimen, but only had small parts of lamellae falling during the decay phase. At the end of the test, however, most of the second lamella fell-off.

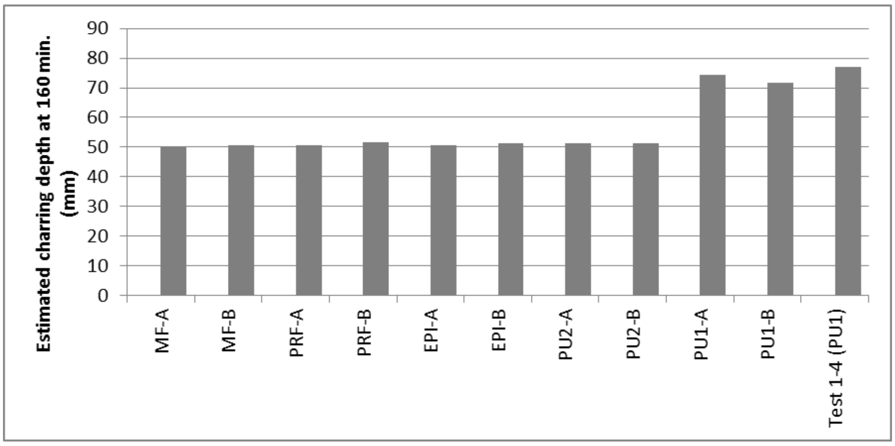

Figure 3: Estimated average charring depth at 160 min using linear interpolation

The temperature jumps measured by the thermocouple indicate delamination, which is confirmed by video recordings of the surface. The times at which delamination occurs is determined from temperature measurements in the adhesive bond line and in the falling lamellae. Times at which temperature increases of 100 °C within 1 minute were measured in the fully-developed phase and times at which temperature increases of 100 °C within 5 min were measured in the decay phase, were found to correspond well with the times of delamination determined from video recordings. Box plots of the times at which this temperature increase was observed in all thermocouples are shown in Figure 5. It can be seen that the time at which delamination of the second layer was observed in Test 1-4 is within the range of delamination times observed in the furnace tests.

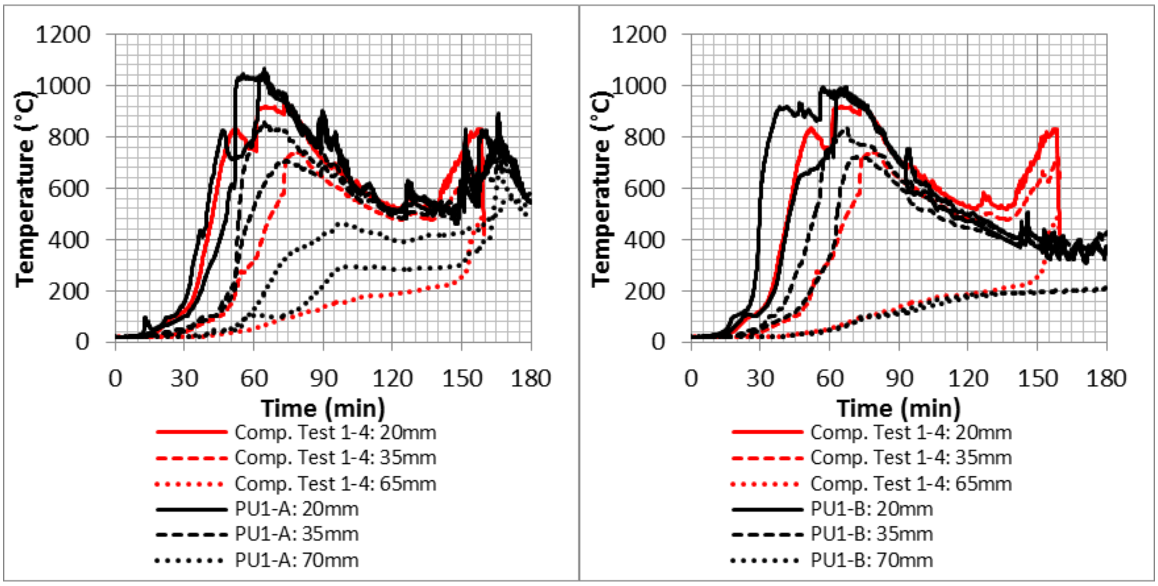

Figure 4: Temperature measurements at specified depths of PU1-A, PU1-B and compartment Test 1-4. In PU1-B thermocouples were installed at 50 mm instead of 70 mm depth

The incident radiant heat flux determined of the compartment and the replicating tests are shown in Figure 6. The incident heat flux was calculated using the following equation, assuming different convection coefficients of 0 W/m^{2}K and 25 W/m^{2}K (see Figure 6, “PT and TC h_c=0” or “h_c=25”):

$$\dot{q}_{inc} = \sigma T_{PT}^4 - \frac{h_c}{\varepsilon_{PT}}(T_g - T_{PT}) \qquad (1)$$

Where: σ is the Stefan Boltzmann constant; T_{PT} is the temperature measured by the plate thermometer; T_g is the gas temperature approximated by a thermocouple; h_c is the convection coefficient; ε_{PT} is the emissivity. The thermocouple probes measuring the plate thermometer temperatures were compliant with IEC 60584-2 requirements for class 1 K-type thermocouples, having a tolerance of 0.4 % of the measured temperature for temperatures exceeding 375 °C and ±1.5 °C for lower temperatures. The similarity between the incident heat flux of the compartment tests and the furnace tests, suggest that the incident heat flux can also be used to control the furnace test instead of the plate thermometer temperature.

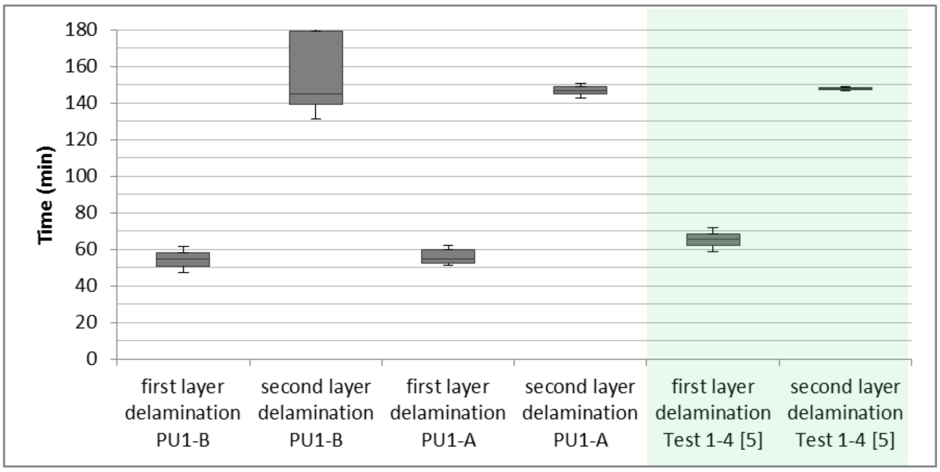

Figure 5: Time of delamination determined from thermocouple measurements

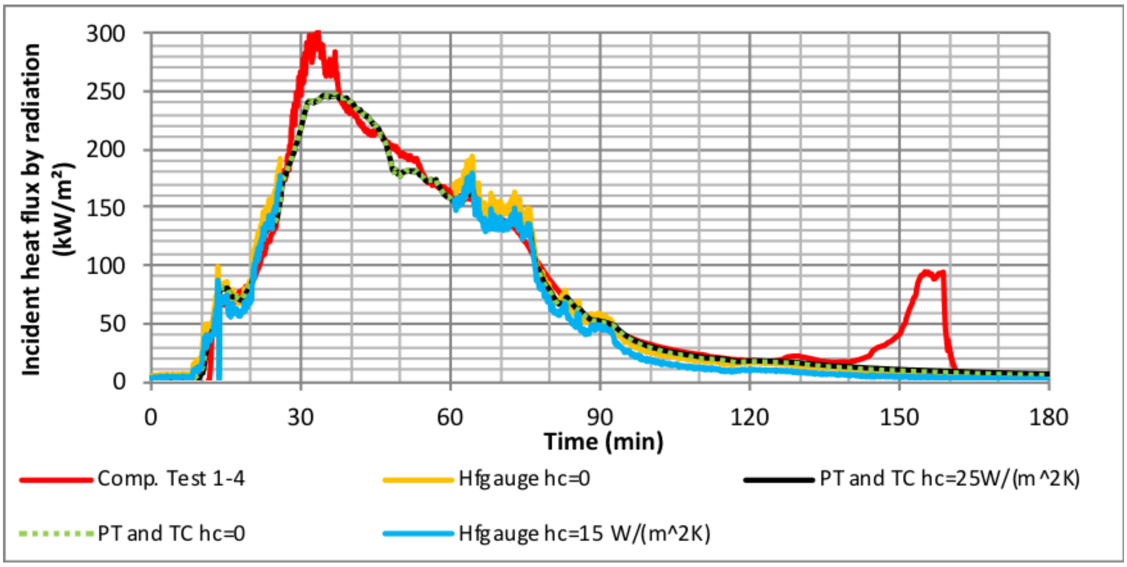

Figure 6: Incident heat flux by radiation corresponding to non-delaminating CLT with PU2 adhesive

4 DISCUSSION OF OTHER TESTING METHODS

Results of Section 3 suggest that certain relevant fire conditions of compartment fire Test 1-4 can be replicated in a furnace in which the oxygen concentration is controlled. The results of this paper indicate that this can be done by replicating the plate thermometer temperature or the incident radiant heat flux as well as the oxygen concentration of the compartment test in the furnace. In this section, the relevance of test methods in which the oxygen concentration is not similar to that of post-flashover compartment fires is discussed.

4.1 Test setups in open environments

Recently, new test setups have been introduced in which the thermal exposure is controlled by a radiant heat source in open environments with atmospheric oxygen concentration. A test published in [3] involved a testing method developed in [8] and had significantly lower incident radiant heat fluxes than those measured during Test 1-4. If the incident heat flux alone would be enough to describe reasonable fire exposure, the test with a significantly lower incident heat flux should show lower charring rates (less damage). However, despite that the incident heat flux was more than twice as high in the compartment for approximately most of the first 30 min, it was found that the charring rates corresponding to this period of both tests were similar. Due to the high oxygen concentration, the char oxidizes significantly in the radiant panel test. Additionally, surface flaming occurs which causes additional radiation and convection to the timber, which does not occur in the fully developed phase of a compartment fire due to the low oxygen content. Therefore, results of tests in which the oxygen concentration does not correspond to a post-flashover fire condition, should be considered with care for the assessment of timber in post-flashover fires.

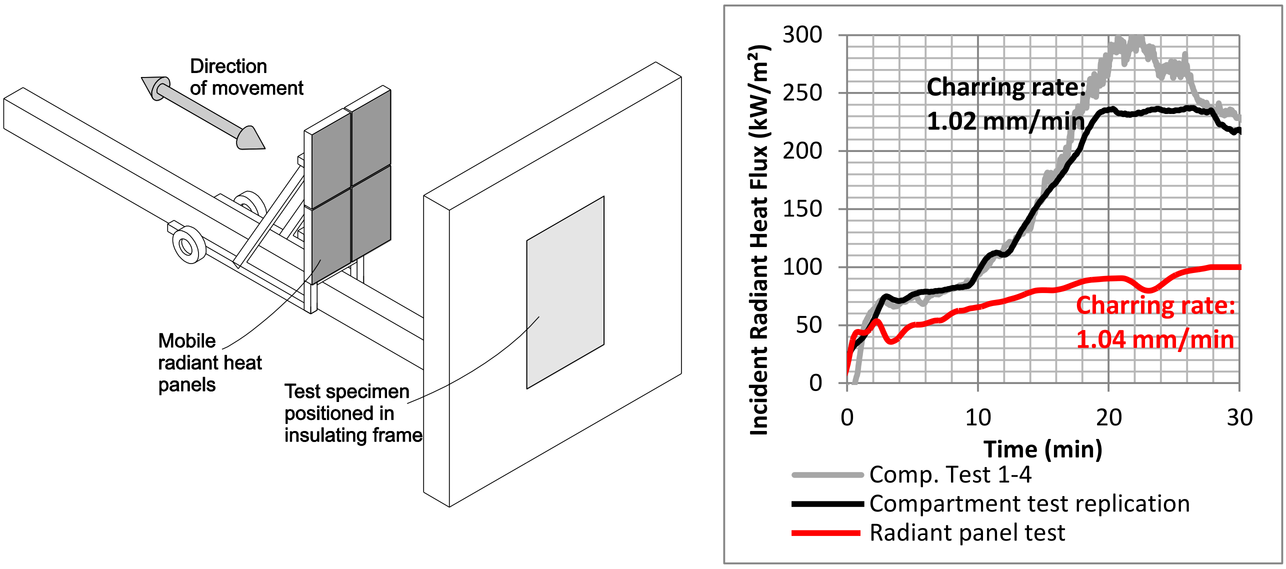

Figure 7: Setup of the position controlled radiant panel test [3] (left) & incident rad. heat flux of a radiant panel test, compartment test and replicating furnace test and corresponding charring rates

4.2 Standard Fire Resistance Tests

Standard fire resistance tests are performed in furnaces typically with low oxygen concentrations. This corresponds to the fully developed phase of compartment fire tests, which is often the most damaging phase of a fire for structures [10]. However, the decay phase with increasing oxygen concentration and increasing char oxidation of a compartment fire is, commonly, not represented in standard fire resistance tests. The validity of fire resistance tests is generally limited to a fully developed fire according to a recent publication [10], as the cooling phase cannot be described with standard fire resistance tests. It should be noted, that the temperatures of the ISO 834 time-temperature curve are significantly lower than temperatures measured during the fully developed phase of recent compartment tests [5]. Whether timber elements would allow for a cooling phase (including burn-out) is dependent on the interaction of the element with the fire compartment. It may be needed to require withstanding burn-out for tall buildings and buildings which the fire service cannot easily reach. If withstanding burn-out is required, it can be stated that the comparison of different materials in standard fire resistance tests can only be fair if the fire exposure (fire temperature to be measured by plate thermometer in front of the exposed surface or incident radiant heat flux, and oxygen concentration) of post-flashover fires of compartments, with these materials exposed, would be similar. Recent studies indicate that this is the case if (1) a limited amount of timber is exposed and (2) delamination of exposed engineered timber and fall-off of the base layer of gypsum boards are avoided [e.g. 5]. If that is not achieved using prescriptive regulations, performance-based methods such as proposed in [11] are needed.

5 CONCLUSIONS

This paper shows that relevant fire conditions of a post-flashover fire can be successfully replicated in fire testing furnaces. Hereby, a successful replication of a compartment fire in a furnace, should lead to the same rate of damage as was observed in the replicated compartment fire test. It was shown that controlling (1) the plate thermometer temperature or the incident heat flux and (2) the oxygen concentration, so that it resembles the conditions measured in the compartment test, leads to a successful replication. Fire tests of timber elements performed in an open environment with unlimited oxygen can lead to significantly higher charring rates than observed in compartment tests due to oxidation and surface flaming.

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