Conference Paper

Timber under real fire conditions - the influence of oxygen content and gas velocity on the charring behavior

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TIMBER UNDER REAL FIRE CONDITIONS – THE INFLUENCE OF OXYGEN CONTENT AND GAS VELOCITY ON THE CHARRING BEHAVIOR

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ABSTRACT

As for any building material, verification of fire resistance is mandatory for separating and loadbearing timber members. While non-standard fire design for steel members has long tradition, the corresponding possibilities for timber members are limited. Reasons for this can be found in the degree of complexity of the material and the limited research done in the field. This paper summarizes selected outcomes of tests investigating the influences on the charring behavior varying the oxygen content and the gas velocity. Besides the charring rate the char layer depth was the focus of this study to investigate char contraction (consumption of the char layer). In general, measurements are in line with previous results reported in literature. Results show that charring is predominantly depending on the fire compartment temperature. Results show further that for gas oxygen contents below 15 percent the gas velocity has no influence on the charring. However, at higher oxygen rates char contraction was observed affecting the protective function of the char layer. Thus, the charring and the temperature distribution was affected and the residual cross-section was decreased. In fully developed fires increased charring due to char contraction may not be observed due to the low oxygen contents. Contrary, in travelling fires or in the decay phase char contraction may be considered. This may have significant impact to Performance Based Design using non-standard temperature fire curves where the complete fire duration has to be taken into account.

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INTRODUCTION AND BACKGROUND

Fire design of structural timber members is done in Europe according to rules given in the fire part of Eurocode 5 [1]. Design models are usually developed for standard fire exposure [2]. Very limited models are available for non-standard fires. In general, design of timber members considers the reduction of the cross-section by char as well as the reduction of strength and stiffness of the residual cross-section. While the charring rate in standard fires is normally observed to be constant [3], charring rate for non-standard fires varies and existing rules may be questioned.

The origin of this study is based on observations in fire resistance tests following the standard fire exposure (defined time-temperature and pressure curves as well as minimum oxygen content of 4% [2]) in different furnaces where different charring rates were observed for the same product. A further motivation can be found in observations of fire accidents where different residual cross-section of solid timber members inside a fire compartment depending on the air flow [4].

TEST PROGRAM

In total 12 tests with various test conditions were performed in a custom made gas-fired furnace; the tests lasted 60 minutes after ignition. After each test the specimen was removed from the furnace and any burning was extinguished with water; this procedure took less than 30 seconds to allow for accurate evaluation of the residual cross-section and the char layer depth.

Material

Tests were performed with CLT (Cross Laminated Timber) beams (150 mm x 150 mm x 1730 mm, C24 European wood grade) with 12% ±1% equilibrium moisture content. The five layer product (top layer 42 mm) is glued with PUR (Polyurethane) adhesive and all specimens were stored in a conditioning room before testing. CLT was used to have a homogeneous material with limited number of defects. The timber members with a width of 150 mm were insulated on both sides with stone wool (thickness 45 mm; 35 kg/m³). In four cross sections (A to D) the progression of char, temperatures and the oxygen content were recorded during the tests.
**Test Equipment**

The equipment used in the tests consisted of: (i) a gas supply unit in which a defined gas volume and the oxygen content of the supplied gas were controlled by means of mixing ambient air with nitrogen or oxygen; (ii) a heating device where the supply air was mixed with burning Gasol (95% Propane and 5% Butane); (iii) a fire compartment (insulated steel channel 200 mm x 160 mm x 2000 mm) and; (iv) an exhaust unit (part of the fire lab). Three sides of the fire compartment were designed to function as a large plate thermometer (PT) [2] comprising a steel plate at the exposed side and ceramic fiber insulation at the unexposed side. Temperatures were measured at sections A to D. Tests were performed in low under-pressure (ca. 10 Pa) to provide a good working environment in the laboratory. The air velocity was controlled in the inlet (cold condition) as well as in the fire compartment. Both measurements were in a good agreement. The oxygen content of the air was measured with a paramagnetic and an electrochemical method in five cross sections; at the beginning of the fire compartment (cross section zero) and sections A to D.

![Schematic cross-section view of the test set-up.](image)

**Test Conditions**

All fire tests aimed for a quick initial fire compartment temperature rise and a constant temperature during the test. During the early testing phases different temperatures of the cross-sections A to D were measured (compartment PT temperatures). Additionally to the PT temperature the gas temperature inside the fire compartment was measured using small thermocouples; the gas temperature was further used to determine the gas velocity in the fire condition in combination with a Pitot tube [5]. The temperatures (PT and gas) in the end of the tests varied between about 700°C and 900°C.

Air velocities were varied between about 1 m/s and 15 m/s in the fire compartment. The oxygen content was varied from 5% up to 15% (percentage by volume).
RESULTS

The documentation comprises the recordings gas concentrations, pressure, gas velocity, temperature and residual cross-section and char-layer after the tests. For the evaluation of variations of charring depth in longitudinal direction, residual longitudinal-sections at the center lines of the timber specimens were documented, see Figure 2.

Figure 2. Remaining cross-section (including the char layer) and residual cross-section in the length allocated to cross-section B thermal exposure (measurements at 700 mm).

Figure 3. Residual cross-section, and total depth after the fire test 9 (3 m/s gas velocity, 15% Oxygen).

To evaluate the residual cross-section at the corresponding temperature measurement stations (cross-sections A to D), as well as effects of the limited cross-section width of the beams, images of the residual cross-section were taken, see Figure 3.

ANALYSIS BY SIMULATIONS

The aim of the simulations was to estimate the effect of the gas velocity in comparison to temperature on the specimen. Thus, in the following, two tests (test 09 and test 14) are compared where equal temperature time curves were achieved. The oxygen content was set to 15% and the gas velocity was 3 m/s and 15 m/s respectively. The temperature exposure showed a logarithmic temperature rise (ca 30 min) up to a plateau with about 800°C; the test lasted 60 min. Fire exposures are specified Figure 4. Results show different cross-section depths for both tests with respect to the remaining cross-section (total depth including the char layer) and the residual cross-section. The length profile was observed to be most steady in cross-section B at about 700 mm length position, see Figure 4. In the following, the residual cross-section and temperature measurements in cross-section B, about 400 mm in length, are further analyzed.
Simulation of Char Contraction One dimensional thermal simulations were performed with elements of 1 mm depth. Simulations used the effective material properties available in Eurocode for fire design of timber structures [1] for standard fire exposure as deviations are limited, see Figure 5.

At standard fire exposure, charring depth after one hour can be expected to about 40 mm according to the simplified, linear charring rules in [1] and literature. In the following, the temperature rise in 40 mm depth is analyzed with respect to different conditions investigating char contraction. Char contraction was observed to be 10 mm after 60 min in the fire test 14. Char contraction was assumed to occur linearly which was realized in the simulations by deleting elements in equal steps of 6 min; every 6 min simulations were stopped, one element deleted and simulations continued using the before obtained temperature field. The following cases were investigated:

(i) Standard fire exposure and no char contraction as basis for the following comparison.
(ii) Standard fire exposure and char contraction to document the importance of the char layer as insulating layer.
(iii) Actual fire exposure and char contraction

Simulation Results and Conclusions

Results show that case (i) would lead charring of 40 mm at about 63 min which is slightly later than the conservative rules of Eurocode. In corresponding fire tests performed in this study the corresponding charring depth was 35 to 38 mm.

Results for case (ii) show that the temperature increase in 40 mm deviates significantly after 30 min resulting in charring at this depth about 8 min earlier than in case (i). This shows that the char layer provides significant protection of the virgin wood in the inner part of cross section. The significance of the char layer has been investigated
in many tests with cross-laminated timber where char ablation (e.g. for Cross-Laminated Timber) lead to a significantly increased charring rate.

Results for case (iii) show that considering the slightly lower fire exposure measured in test 14 charring would not reach 40 mm depth. This is in contradiction to the observations where the residual cross-section was significantly below 110 mm (corresponding 40 mm charring depth) which would be more appropriate for standard fire exposure.

Considering the actual difference of the char layer depth (10 mm) and of the charring depth (42 and 35 mm) it can be assumed that the only varying parameter, the gas velocity is responsible for the char oxidation and subsequently the smaller residual cross-section. It is assumed that the actual gas velocity in combination with the oxygen content leads to glowing combustion which causes char contraction. The effect is corresponding increased fire compartment temperature up to 200°C.

**ESTIMATION OF THE HEAT RELEASE BY THE TEST SPECIMEN**

To estimate the fire development in a fire compartment the fire load from the construction has moved into the focus of many authorities and researchers especially since solid timber products, e.g. CLT appeared on the market. With the actual test setup it was possible to estimate the contribution of the test specimen by two alternative methods. Firstly, (a) based on the charring rate, and secondly, (b) by means of the oxygen consumption.

(a) Cone calorimeter tests have previously been conducted to determine the heat release rate of different materials under certain exposures of constant incident heat flux. In this test, a specimen is exposed to a homogeneous incident heat flux. It can be concluded that the following ratio is valid:

\[
\text{Heat Release Rate : Charring Rate} = \text{Heat Release : Char Depth} \quad (1)
\]

As a basis for a compartment fire model, a relationship between the charring rate and the heat release rate was determined from cone calorimeter test results. Investigations of heat release rates and corresponding charring were investigated in [6]. At 75 kW/m² incident radiant heat flux, a heat release of 5385 kJ/m² per millimeter of charring depth, for charring depths exceeding 10mm was determined. For simplicity, the heat release rate is taken as constant for the whole period of the fire.

(b) The heat release rate can be performed from the oxygen consumption using calorimetry [7]; it can be assumed that the heat release per consumed mass of oxygen is 13.1 MJ/kg for most bio-based materials. This has been used as a basis for calorimetry in previous test setups, such as the cone calorimeter [7].

In the test setup the oxygen concentration was measured in section 0, A, B, C and D, further the gas velocity of the air was determined. The mass of oxygen passing each section can be determined in a similar way as is done using a cone calorimeter. For this study, the heat release rate was estimated is determined using the volume percentage of oxygen in dry air and the estimated volume flow of air excluding water vapor.
**Results of the Heat Release Estimation** Results using the two methods are in rough agreement. However, the results are not accurate enough to determine the difference in heat release rates between tests, as indicated in Table I. In the ongoing study the methods will be revised in order to improve the estimations of the heat release rate. The following improvements are planned for further tests: (I) A method should be developed to increase the frequency and the reliability of the oxygen measurements. (II) The water that is extracted from the sample gas prior to the gas analysis will be quantified in order to confirm the quantity of water vapor in the fire compartment.

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**METHODS FOR SAMPLE GAS AND GAS VELOCITY ANALYSIS**

The study used redundant systems to estimate the (i) gas velocity and the (ii) oxygen content. The gas velocity was estimated using a Pitot tube [5] combined with a small thermocouple wire which was found to be more reliable than measurements with an anemometer considering the thermal expansion of the gases. The electrochemical gas analysis gave similar results as the more expensive paramagnetic analysis. In contrast to cone-calorimetry, it seems that the electrochemical electrodes provide sufficiently accurate results for the test set-up presented here.

**REFERENCES**