



Structural behavior of timber columns in wood crib compartment fire tests

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ARTICLE INFO

Keywords:

Natural fire tests
Timber columns
Glulam (GLT)
Structural failure
Cooling phase
Burnout resistance
Wood crib

ABSTRACT

Timber framing is increasingly used as a load-bearing structural system in mid-rise and high-rise buildings. While extensive data exists from standard furnace tests, there is a lack of data on the fire performance of loaded timber members in full-scale compartment fires. Compartment fire tests are crucial to investigate a structure's performance under conditions where the fire is let to grow naturally with the fuel and oxygen present in the room and then let to cool down as the fuel burns out. This paper presents the findings from six fire tests performed on glue laminated timber columns in a custom-built compartment. Wood cribs are used as fuel. The columns, 3680 mm long with a 280 × 280 mm² section, are subjected to constant axial loading during the whole fire duration. Column design and loading are based on a 60-min fire resistance. The tests vary in opening factor, fire load, and wood crib size. Column failure was observed in the six tests, with failure times ranging from 35 to 71 min. In four of the tests, failure occurred after the gas temperature had started to cool down. Comparisons with tests on similar columns made in a fire resistance furnace allow comparing charring rates observed in standard conditions and in natural fires.

1. Introduction

The use of timber as a primary structural material in building construction is gaining momentum, driven by the need to reduce greenhouse gas emissions embedded in construction materials [1]. As timber is increasingly used in mid-rise and high-rise buildings, it is crucial to understand and assess its behavior in the event of a fire. Specifically, it is recognized that standard fire ratings only provide a limited picture of the fire performance [2–4] and that the response of timber structures under real fire conditions requires further examination [5–9]. It is important to investigate a structure's performance under conditions where the fire is let to grow naturally and then let to cool down as the fuel burns out. Indeed, when considering high-rise buildings, the fire-fighters may not be able to intervene to fully extinguish the fire as there are practical challenges involved with a combustible structure [10]. To advance fire design methods, experimental research is essential to collect data on the performance of timber structural members subjected

to both mechanical loading and thermal exposure from natural fires.

Recently, research efforts have accelerated, with more experiments conducted outside of a laboratory furnace to assess the fire behavior of timber structures subjected to so-called natural fires. Most experiments have focused on the fire dynamics in timber compartments [11,12]. This included several tests with exposed cross laminated timber (CLT) surfaces in compartments designed for post-flashover fires [13,14] as well as tests in open-plan large compartments with traveling fires [7,15]. However, few fire tests in compartments have included structural loads on the timber members [16].

In a previous study, the authors conducted furnace tests on glue laminated timber columns under a controlled heating-cooling regime [6]. The findings confirmed that timber columns may fail during the cooling phase of the fire. Key factors influencing structural stability were the fact that the timber columns experienced a temperature increase for a significant time after the peak of the fire curve in the central zones of the section, and that timber strength and modulus were significantly

This article is part of a special issue entitled: SiF published in Fire Safety Journal.

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<https://doi.org/10.1016/j.firesaf.2025.104413>

Received 1 December 2024; Received in revised form 2 March 2025; Accepted 5 May 2025

Available online 13 May 2025

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affected even by a moderate temperature increase. Other authors have also shown structural failure of timber members during the cooling phase of a fire [17,18], but these tests were also in a laboratory furnace. Therefore, there is a need for further investigation of the response of loaded timber members under natural fires. There are very few full-scale experiments on loaded timber members in compartment fires. Crucially, the interaction of applied loading, natural fire exposure, and testing throughout the decay phase until complete cooling of the member is unique. Data from such experiments is needed to calibrate material models for numerical analysis of the response of load bearing mass timber structures under natural fires. For example, the data will be used to calibrate temperature-dependent effective thermal properties and strength retention factors applicable for non-standard fire exposure, including during the cooling phase. The calibrated models can then be used in parametric numerical analyses to develop simplified methods for burnout resistance design. [19]. The aim of burnout resistance is to assess the ability of structural elements to maintain their stability throughout a fire, including the cooling phase. Unlike traditional fire resistance, which focuses on the heating phase, burnout resistance considers the risk of collapse during or after the peak of the heating phase. This requires conducting natural fire tests on loadbearing timber columns for assessing the possibility of collapse after the compartment temperature has started to cool down. These tests involve different heating than the ISO curve, with higher or lower heat release rates and peak temperatures, with various nonlinear cooling rates, and various oxygen content. Compared to furnace tests, natural fire tests in compartments may provide conditions closer to real building fires.

This paper describes in detail the results of six experimental fire tests on timber columns with a section of $280 \times 280 \text{ mm}^2$ conducted in a compartment with wood cribs as the fire source. These 6 tests are part of a larger experimental program which includes larger columns (up to section of $400 \times 400 \text{ mm}^2$) and other fire scenarios including fire-fighters' intervention [20]. The timber columns were loaded during the tests and the objective was to investigate their thermal-structural behavior under natural fire exposure including during the cooling phase. These natural fire tests were performed in 2022 and 2023 at the Fire Testing Centre of CERIB in France.

2. Materials and methods

2.1. Timber column specimens

The columns were made of glued-laminated timber (GLT). The dimension of the section was $280 \times 280 \text{ mm}^2$. The length of the columns was 3680 mm. The columns were hinged-hinged. Steel plates were screwed to the columns at both ends to serve as connection plates. This resulted in a length of 3740 mm between the axes of the cylinders that formed the hinged-hinged (pinned-pinned) boundary conditions in one direction and fixed-fixed in the other direction at both ends.

The columns were designed to be representative of the load-carrying columns in a five-story building with a fire resistance requirement of 60 min. A load eccentricity of 20 mm in the hinged direction, perpendicular to the front wall of the compartment, was considered. The analysis of the building using the Eurocode load combinations [21] led to a total permanent load on the column $G = 250 \text{ kN}$ and an imposed load $Q = 252 \text{ kN}$ (3 kN/m^2 for current level and 1 kN/m^2 for roof). To calculate the load N_{Ed} , safety factors of 1.35 on the permanent loads and 1.5 on the imposed loads are used, resulting in a design axial load in the column $N_{Ed} = 715 \text{ kN}$ at ambient temperatures. With an imposed load factor of $\Psi_2 = 0.3$, ($\eta_{fi} = 0.45$), this led to a design axial load in the fire situation $N_{Ed,fi} = 322 \text{ kN}$. The section size was then determined as $280 \times 280 \text{ mm}^2$ from the fire resistance requirement, using the charring rate of 0.70 mm/min and zero-strength layer of 14 mm from the prEN 1995-1-2 (June 2021) [22]. The 322 kN load is therefore 100 % of the design capacity in fire situation. This load represents 40 % of the design capacity at ambient temperature and 26 % of the expected actual ultimate

capacity at ambient temperature. Strength and stiffness properties of GL 24 h [23] were provided by the manufacturer and adopted in the calculation. Detailed calculations are provided in Ref. [6]. The members were made of 40 mm thick spruce slats glued with MUF (Akzo Nobel System MUF 1247/2526/4426 "GripPro"). Temperatures inside the columns were measured with 1.5 mm thick type K Inconel sheathed thermocouples along the centerline at various depths with 10 mm increments (i.e., at 10 mm depth, 20 mm depth, etc.), with 6 thermocouples (2 in the lower part of the column (B, 1 m from the bottom of the column), 2 at mid height (M, 1.9 m from the bottom of the column), and 2 in the upper part (H, 2.8 m from the bottom of the column)) for each depth, see Fig. 1. For tests 9 and 10, two installation methods were used to place the thermocouples: on the glue line (GL) and by drilling inside the wood (Fig. 1 (b)). The accuracy of the thermocouple position where suspected to be low with the drilling method, hence for test 11 and later, the thermocouples were only installed on the glue line Fig. 1 (c).

2.2. Previous furnace tests

Furnace tests were conducted on the columns and have been reported in a previous publication [6]. Two specimens were subjected to fire resistance tests, i.e., exposure to the ISO 834 time-temperature curve until failure. The fire resistance of these two columns was measured as 55 and 58 min, respectively. These values are close but slightly shorter than the 60 min which were estimated by the simple model of Eurocode 5 with a charring rate of 0.70 mm/min and a zero-strength layer of 14 mm . Note that the estimations used for strength and stiffness values based on the declared resistance class.

Four other specimens were subjected to heating under ISO 834 curve for a set duration followed by cooling at a constant rate of -10.4 K/min . For two of the columns, the duration of the heating phase was 15 min, with a peak temperature of 754°C . The end of the theoretical decay phase (i.e., time when the compartment temperature is back to ambient) was 85 min, although furnace temperatures started to cool down slower than the theoretical rate after 70 min when the temperatures had dropped to about 150°C . These two columns collapsed after 98 and 153 min. For the two other columns, the heating phase lasted 10 min, and these two columns survived the complete fire duration and the long cooling phase which followed. These results are within the range estimated by the numerical simulations reported before the experiments [19]. Thermocouples inside the columns also confirmed the sustained temperature increases for hours after the end of the heating phase. This sustained temperature increase, due to the heat transfer process in the timber section that continues beyond the time of peak gas temperature, is also shown by numerical models. It results in a continued reduction of the load bearing capacity of the column, as the material strength and modulus degrade further in the core of the section.

2.3. Compartment fire tests

This paper describes natural fire tests conducted on the columns with wood crib fire in a compartment. The internal dimension of the compartment floor surface was 6.00 m by 4.00 m . The distance from the floor to the ceiling was 3.10 m for the tests 9 and 10 and 3.05 m for the following tests, see Fig. 2(a). The walls were made of 300 mm thick aerated concrete blocks. The concrete floor was insulated by a layer of mineral fibers covered by a 20 mm thick layer of plasterboard. The roof was made of 200 mm thick slabs of aerated concrete. For tests 11, 14, and 15, the ceiling was protected by 55 mm of mineral wool. As a result, the floor-to-ceiling distance was reduced to 3.05 m for these three tests.

Parameters varied between the tests included the opening factor, the fire load, and the size of the wood sticks, see Table 1. In the Table, the shaded cells show the parameter that is varied with respect to the reference case of Test 10. Note that the numbering of the tests is defined consistent with the complete experimental program [20].

The compartment had openings in one of the long walls, see Fig. 2(a).

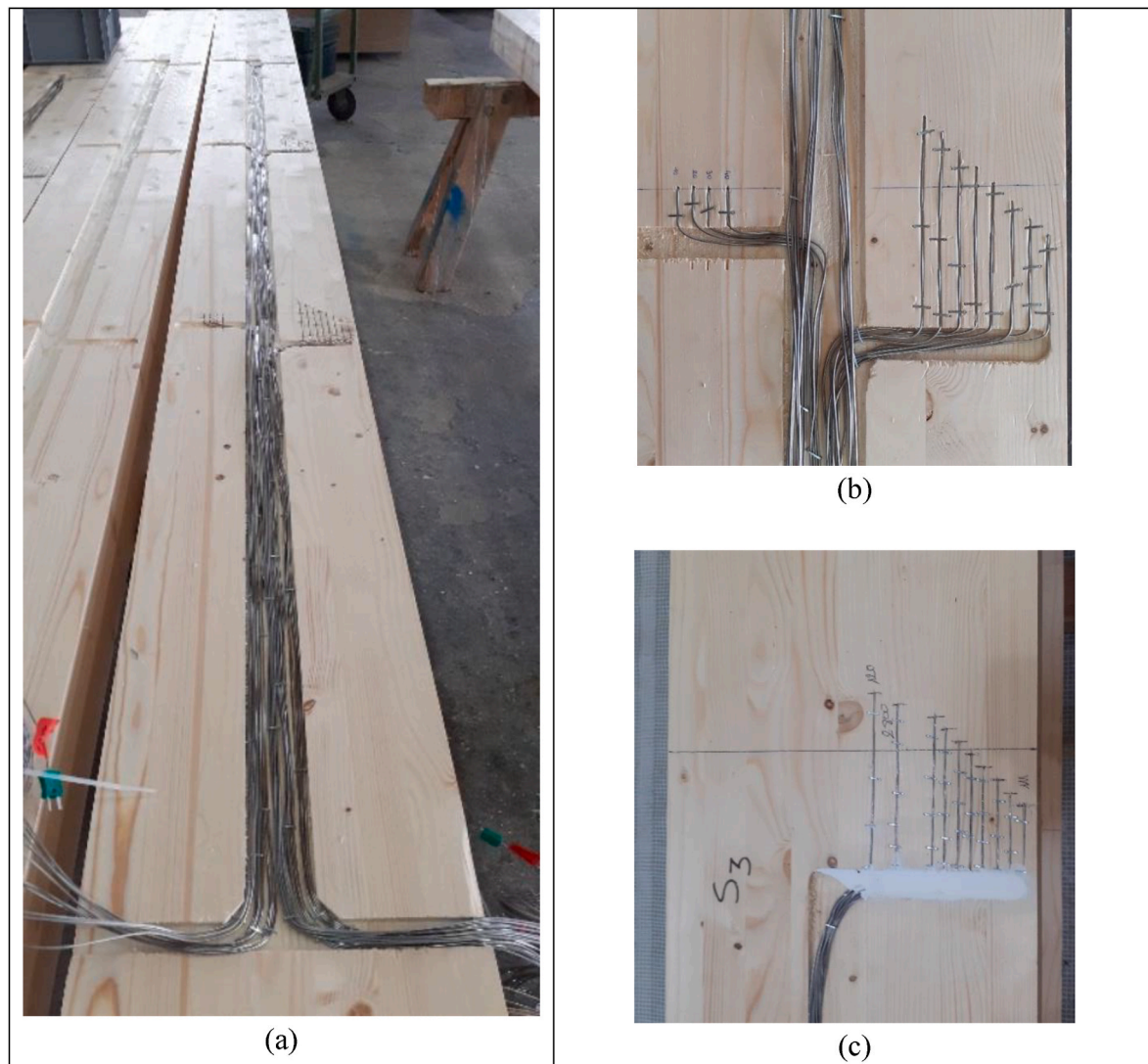


Fig. 1. Instrumentation details of one section (a) and the thermocouples installed perpendicular to the expected temperature gradient with a drilling method (b, left) and at the glue line (b, right). The machined gloves were filled before the final gluing of the two half sections (c).

The dimension of the openings was adjusted in each test to create the desired opening factor. The reference opening factor was $O = 0.065 \text{ m}^{1/2}$, obtained with three openings of dimensions $1.30 \times 1.50 \text{ m}^2$. In Test 9, there were three openings of $1.30 \times 2.50 \text{ m}^2$, for roughly doubling the opening factor. In Test 15, the opening factor was reduced to $O = 0.032 \text{ m}^{1/2}$, using a single opening of dimensions $0.95 \times 2.40 \text{ m}^2$.

The wood cribs used for the fire load were made of 10 layers of 5 sticks of $90 \times 90 \times 1000 \text{ mm}^3$ with 138 mm of clear distance between adjacent sticks. The amount of wood was adjusted in each test, taking into account wood density and moisture content, to generate the desired fire load density, with a value of 780 MJ/m^2 in the reference case, see Fig. 2(b) and Table 2. In addition, in Test 17, sticks with different thickness and arrangement were used to generate another fire development (the aim was to reduce the initial fire power and to obtain temperatures nearer from the temperatures of the ISO curve). The wood cribs were changed to 5 layers of 5 sticks of $120 \times 120 \times 1000 \text{ mm}^3$ spaced by 100 mm. This maintained the fire load constant but modified the burning rate of the fire [24,25]. In each test, the wood cribs were ignited simultaneously by heptane, with the aim to reach the fully developed phase of the fire (i.e., post-flashover) as quickly as possible. The quantity of heptane used in the initial phase of the fire was 18 L in all tests except for Test 17 for which it was 3 L. Fig. 2(c) and (d) show the fire development in Test 9 and 10, respectively. The two experiments

differ by the size of the openings.

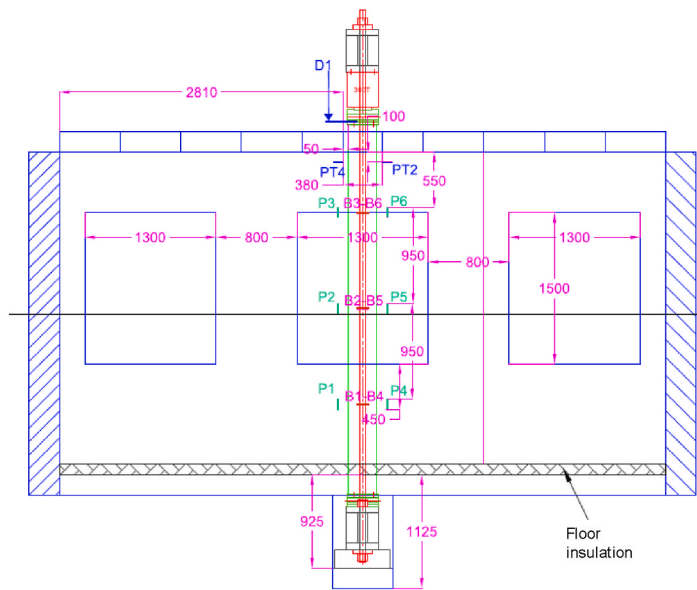
Temperatures in the compartment were measured with plate thermometers (PT) as defined in Ref. [30], as illustrated in Fig. 2(a) and (b). Twelve plates thermometers were positioned vertically, facing outward along the height of the column, on each side of the column at heights of 0.6 m, 1.55 m, and 2.5 m, with a distance from the column of $10 \pm 5 \text{ cm}$. Additionally, for Tests 9 and 10, four plates were positioned horizontally facing downward at $10 \pm 5 \text{ cm}$ of the ceiling.

The wind speed and direction were recorded during Tests 10, 11, 14, 15 and 17. The average wind velocity was between 0.5 m/s and 2.3 m/s, with maximum gusts between 3.7 m/s and 5.5 m/s (calculated with a peak gust duration set to 3 s).

2.4. Test program

The test program was designed to investigate the behavior of the loaded timber column under natural fires throughout the whole fire duration including the decay and cooling phase. Parameters influencing the fire growth were varied in a range deemed realistic for office and dwelling applications. The test program is described in Fig. 3.

All tests were performed on identical column specimens under identical mechanical loading conditions. The load was maintained at 322 kN for all tests, with an eccentricity of 20 mm in one direction. In the



(a) Elevation view of the column and compartment



(b) Wood crib (780 MJ/m²)



(c) Test 9, $O = 0.140 \text{ m}^{1/2}$



(d) Test 10, $O = 0.065 \text{ m}^{1/2}$



(e) Test 15, $O = 0.032 \text{ m}^{1/2}$

Fig. 2. Compartment fire tests.

Table 1
Conditions in the fire compartment.

Test	O (m ^{1/2})	q (MJ/m ²)	wood sticks (mm ²)
9	0.140	780	90 × 90
10	0.065	780	90 × 90
11	0.065	950	90 × 90
14	0.065	420	90 × 90
15	0.032	780	90 × 90
17	0.065	780	120 × 120

test procedure, the column was loaded first. The load was maintained for 15 min before the fire load was ignited. The load was kept constant during the whole fire duration including the cooling phase.

Test 10, the reference test, used an opening factor of $0.065 \text{ m}^{-1/2}$, fire load of 780 MJ/m^2 (representative of an average value for dwellings in Eurocode 1-1-2 [26]), and timber stick size of $90 \times 90 \times 1000 \text{ mm}^3$ with a 138 mm distance between sticks. The five other tests incorporated a modification in one of these parameters to investigate the column performance under a different natural fire, as mentioned in Table 1 and

Table 2

Wood crib used in the fire compartment. The values of mass and moisture content are extrapolated from a sample of 9 sticks. The heat of combustion is calculated taking into account the moisture content and the energy density is calculated including the contribution from heptane used for ignition.

Test	Wood sticks (mm ²)	Total mass (kg)	Moisture content	Heat of combustion (MJ/kg)	Calculated (target) energy density (MJ/m ²)
9	90 × 90	1055	15.7 %	17.1	776 (780)
10	90 × 90	1045	15.7 %	17.1	769 (780)
11	90 × 90	1299	14.3 %	17.4	964 (950)
14	90 × 90	560	15.1 %	17.2	425 (420)
15	90 × 90	1098	18.0 %	16.8	790 (780)
17	120 × 120	1102	16.5 %	17.0	793 (780)

Fig. 3.

During the tests, the collected data included the temperature in the compartment (16 plate thermometers (PT)), temperatures inside the timber column, and oxygen concentration. Oxygen measurements were

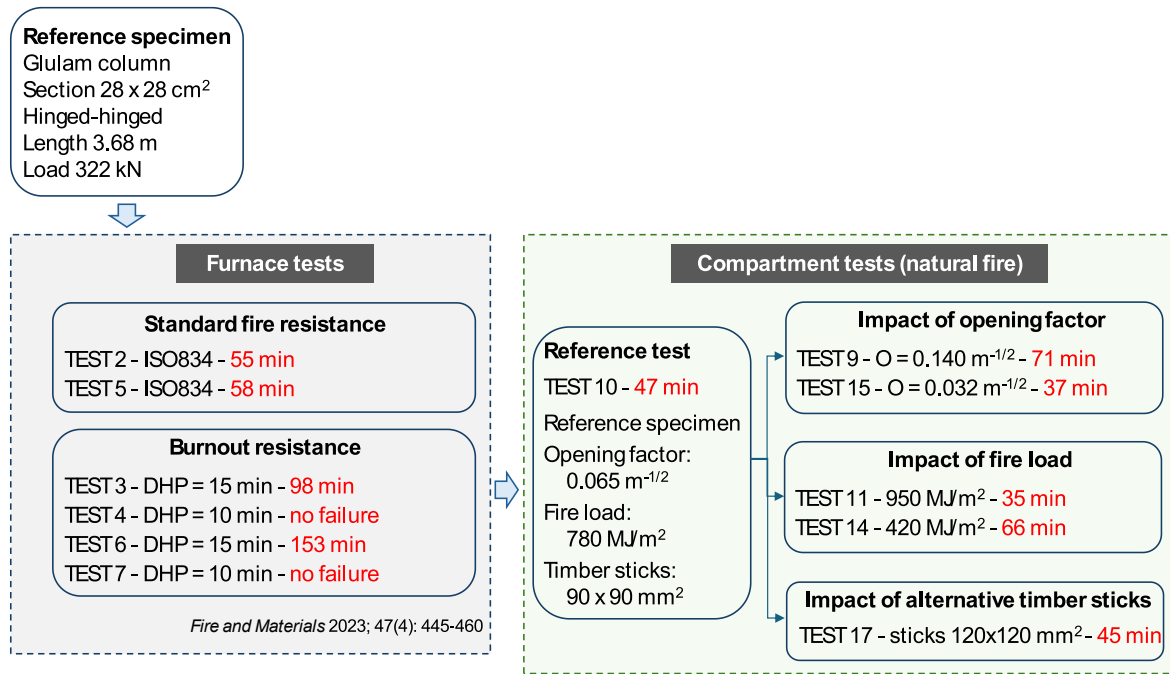


Fig. 3. Test program for compartment fire tests on timber columns with a section of 280 × 280 mm².

sampled at 2.88m, 1.10m from the left inner wall and 1.27m from the right inner wall. Time of failure was determined based on the drop in the value of the force applied on the column, as the column became unable to withstand the target load. The charring rate was also evaluated after the experiments from the temperatures measured in the sections.

3. Results of the fire tests

3.1. Reference test (Test 10)

In Test 10, the average value of the temperatures in the compartment

rose to exceed 1000 °C in about 3 min. It plateaued at about 1150 °C from 9 min to 30 min. The end of the time with peak gas temperature occurred at 30 min. The compartment temperature then cooled down at an average rate of about 30 °C/min over the next 20 min. The column failed after 47 min when the temperatures in the compartment were around 600 °C. The temperatures measured by 16 PT are plotted in Fig. 4 (a). The oxygen concentration is plotted in Fig. 4(b), showing a ventilation-controlled fire during the fully developed phase and a fuel-controlled situation thereafter.

The column is shown at the time of failure in Fig. 5(a). The wood crib had been consumed. Flaming combustion reappeared along the column

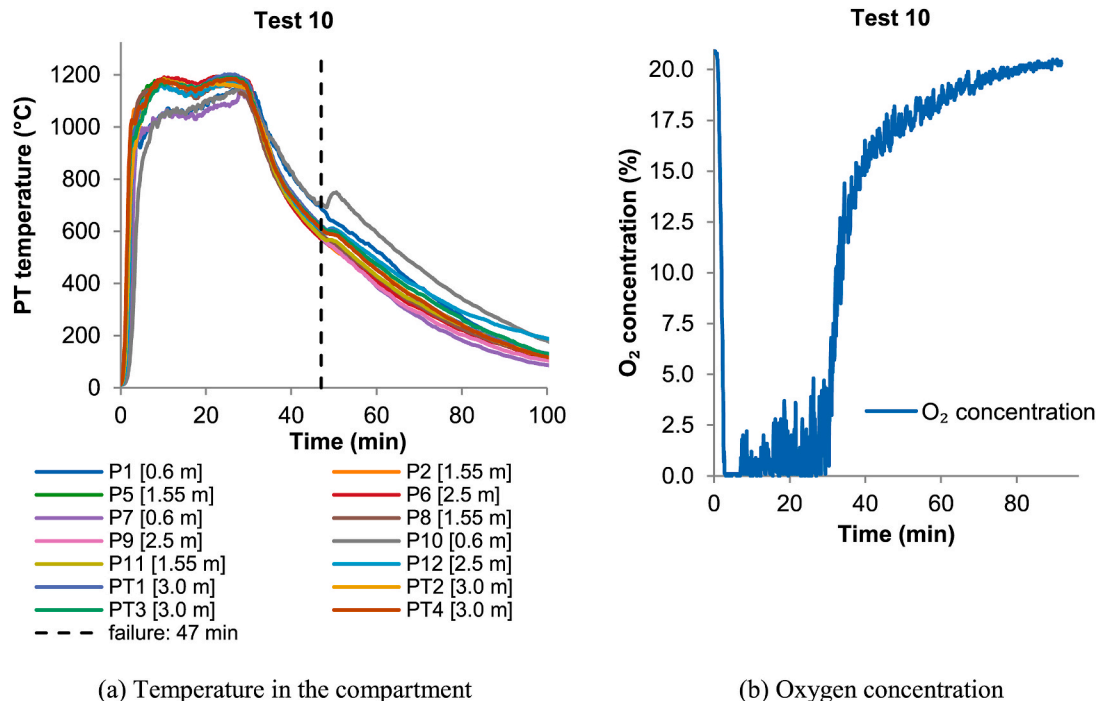


Fig. 4. Compartment measurements for Test 10.



Fig. 5. Timber columns at the time of failure.

due to the post-failure wood damage.

The temperatures measured in the section of the timber column are plotted in Fig. 6. The measurements were taken at different depths from the surface on the centerline of the section. At each depth, the average from five or six measurements along the column at that depth are plotted as bold lines. The temperatures in the peripheral zones increased fast, with the temperature at 10 mm depth reaching 300 °C in 5 min. Average

values of the charring rate are estimated based on the time to reach the 300 °C isotherm at different depths. This charring rate was 1.78 mm/min during 11 min, 1.33 mm/min up to 19 min, and 1.13 mm/min up to 27 min.

The compartment temperature starts cooling down at 30 min. The column failed at 47 min. Examination of the thermocouple measurements show that the temperatures in the section continue to increase

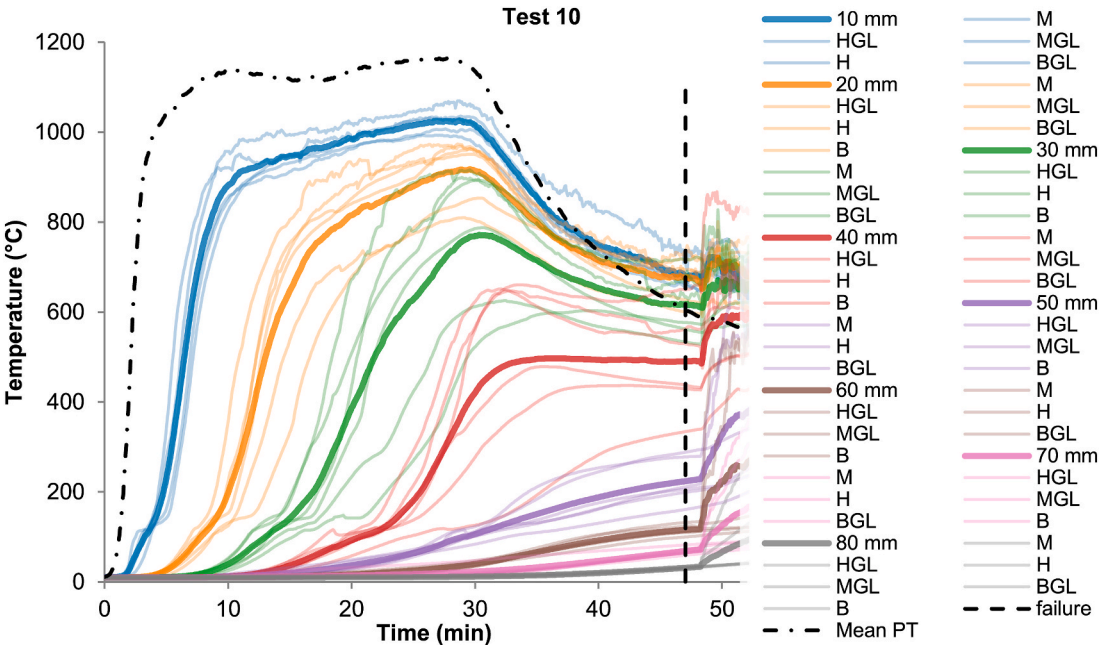


Fig. 6. Temperatures across the section depth of the timber column, the thin lines represent the individual thermocouple measurements, and the thick line represents the average of the measurements.

after the compartment temperature has started to cool down. For example, at 40 mm depth, the average temperature at 27 min was 270 °C, while it reached 490 °C at 47 min. At 50 mm depth, the average temperature at 27 min was 81 °C, while it reached 224 °C at 47 min. At the time of failure, a layer of more than 30 mm was at or above 300 °C. At that time, the temperature at 60 mm depth was 115 °C, while at 80 mm depth it was still only at 30 °C.

3.2. Varying the opening factor (Test 9 and Test 15)

Tests 9 and 15 included variations in compartment openings compared to Test 10. In Test 9, the opening factor was increased from of 0.065 m^{1/2} to of 0.140 m^{1/2}. This was achieved by increasing the height

of the openings from 1.5 m to 2.5 m, all the way to the floor. In Test 15, the opening factor was reduced to 0.032 m^{1/2} with a single opening of 0.95 × 2.4 m².

The temperatures and oxygen concentrations in the compartments are plotted in Fig. 7. In Test 15, the reduced opening factor led to a longer duration of the heating phase and to higher temperatures in the cooling phase. The levels of oxygen in the compartments differed significantly during the two tests. The fire in Test 9 had excess oxygen owing to the larger openings, while the fire in Test 15 was ventilation controlled for almost 50 min. This impacted the time at which the temperature peaked in the compartment, which was around 6 min for Test 9 and 40 min for Test 15. The peak temperature was higher for Test 15 (about 1250 °C) than for Test 9 (about 1000 °C).

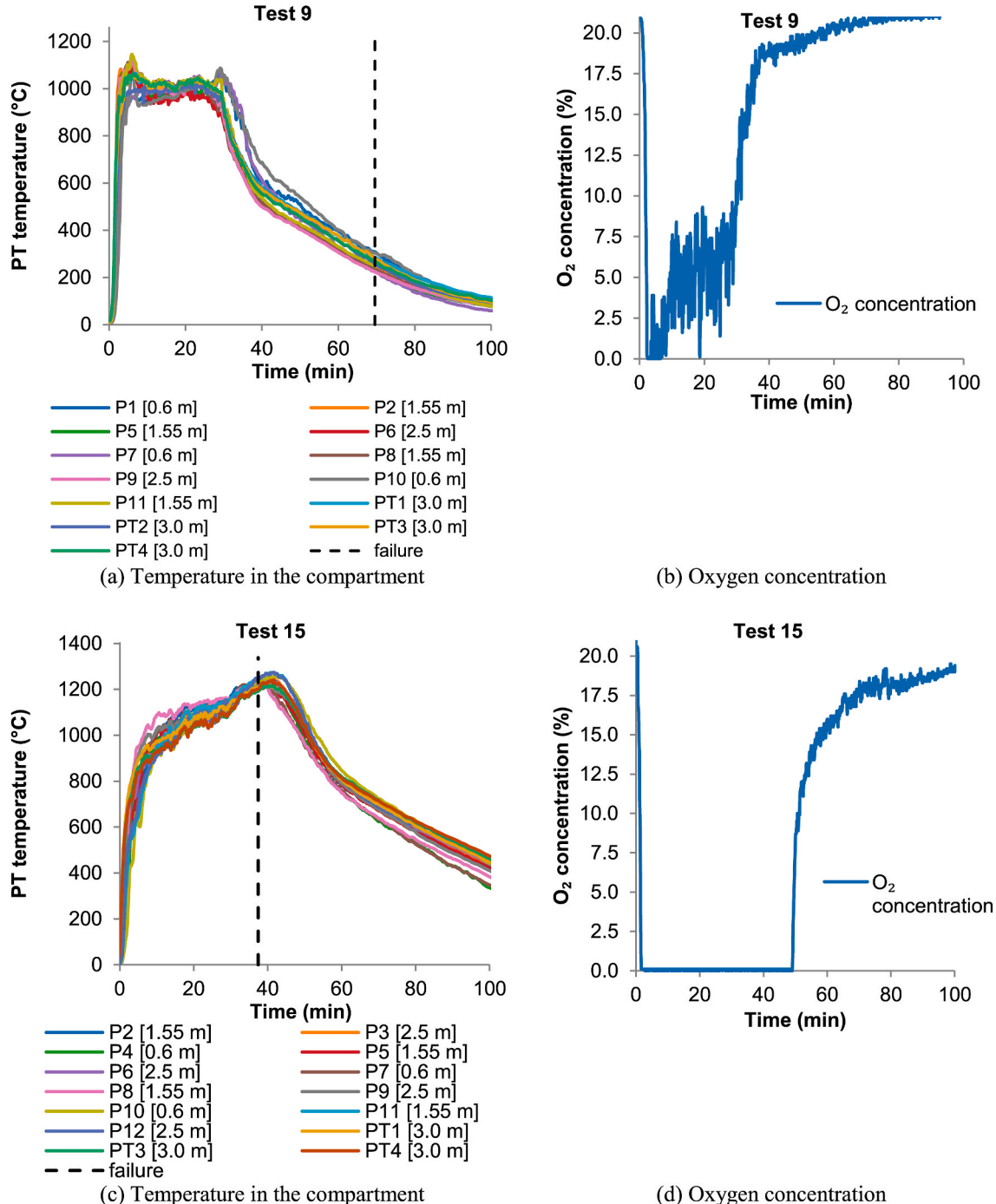


Fig. 7. Effects of the opening factor on the compartment fire development.

In Test 9, the column failed after 71 min when the temperatures in the compartment had cooled down to the range 200–300 °C. The column at failure is shown in Fig. 5(b).

The temperatures measured in the section of the timber column for Test 9 are plotted in Fig. 8(a). Each curve is the average of 6 measurements: 2 in the lower part of the column, 2 at mid height, and 2 in the upper part. These internal temperatures confirm the trend discussed above for Test 10, i.e., with temperatures decreasing very soon after the peak of the gas temperatures in peripheral zones of the section, while they keep on increasing during the cooling down phase in the central zones. At the time of failure, a layer of more than 40 mm from the surface was at or above 300 °C. Temperatures were at or above 110 °C over a depth of 60 mm. At 80 mm depth, the temperature was 55 °C. The average value of the charring rate was calculated as 1.41 mm/min for the first 14 min, 0.83 mm/min from 14 to 26 min, and 0.28 mm/min from 26 to 61 min.

In Test 15, collapse occurred after 37 min, shortly before the end of the heating phase. Contrary to Test 9, the temperatures in the section were thus still increasing across the whole depth when the column failed, see Fig. 8(b). At failure, the temperatures at 40 mm and 50 mm depth were 375 °C and 178 °C, respectively. It was also observed that, at given depth, temperatures exhibited significantly more variability from one side of the section to the other side compared with the other tests. This was observed consistently for all three heights along the column where the measurements were made [27]. This non-symmetrical temperature distribution in the section developed although the temperatures measured in the compartment did not display the same pattern, as can be seen in Fig. 7(c). This may be due to the fact that Test 15 had a unique opening on the right part of the front wall, which was not symmetrically located with respect to the column (Fig. 2(e)). This may have resulted in a different oxygen content on the side of the column which was close to the opening compared to the other side, thereby driving gradients in oxygen penetration and therefore differences in temperatures. It is noteworthy that this non-symmetry in the section temperatures during the fire amounts to a structural imperfection. It is a point of interest for future investigation whether asymmetry in opening layout in real fires may create differences in oxygen concentration and therefore

asymmetry in temperature developments and char penetration in the section of timber members, with possible effects on stability.

3.3. Varying the fire load (Test 11 and Test 14)

Tests 11 and 14 were performed to study the influence of the fire load. Test 11 used a fire load of 950 MJ/m², which would be representative of a 80 % fractile for dwellings in Eurocode 1-1-2 [28]. Test 14 used 420 MJ/m², representative of an average value for offices [28]. Pictures of the fire tests are shown in Fig. 9.

The temperatures in the compartments are plotted in Fig. 10. In Test 11, despite the increase in fire load, the temperatures nevertheless followed approximately the same evolution as in Test 10. The temperature peaked at 1200 °C at 28 min. The column failed after only 35 min, early in the cooling down phase with gas temperatures still around 980 °C. This can be compared to the failure time of 47 min obtained in Test 10 with 780 MJ/m².

For Test 14, the reduced fire load resulted in significantly lower temperatures in the compartment. Except for a short period between minute 2 and minute 5, the oxygen concentration measurement showed availability of oxygen in the compartment. Temperatures exceeded 700 °C for only 6 min, while the heating phase lasted 36 min. The column failed after 66 min, with gas temperatures around 280 °C.

The temperatures in the timber columns are plotted in Fig. 11. In Test 14, the slow penetration of the heat wave in the section led to structural failure of the column after 66 min, even though the fire temperatures remained moderate.

3.4. Varying the wood sticks size (Test 17)

It was observed in the previous tests that the temperature in the heating phase was higher than the ISO curve, except for Test 14. To investigate the effect of the kinetics of the fire, Test 17 adopted wood cribs made of 5 layers of 5 sticks of 120 × 120 × 1000 mm³ spaced by 100 mm and an amount of heptane reduced to 3 L. The other parameters including total fire load and opening factor were identical to the reference Test 10.

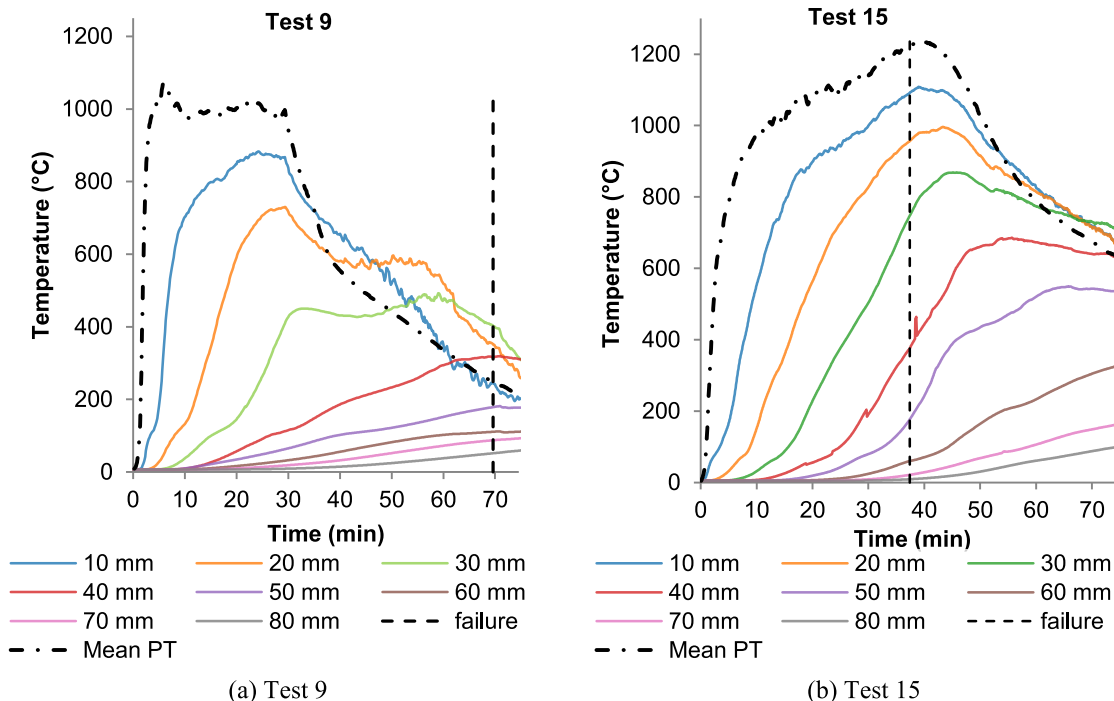


Fig. 8. Temperatures in the depth of the timber columns.

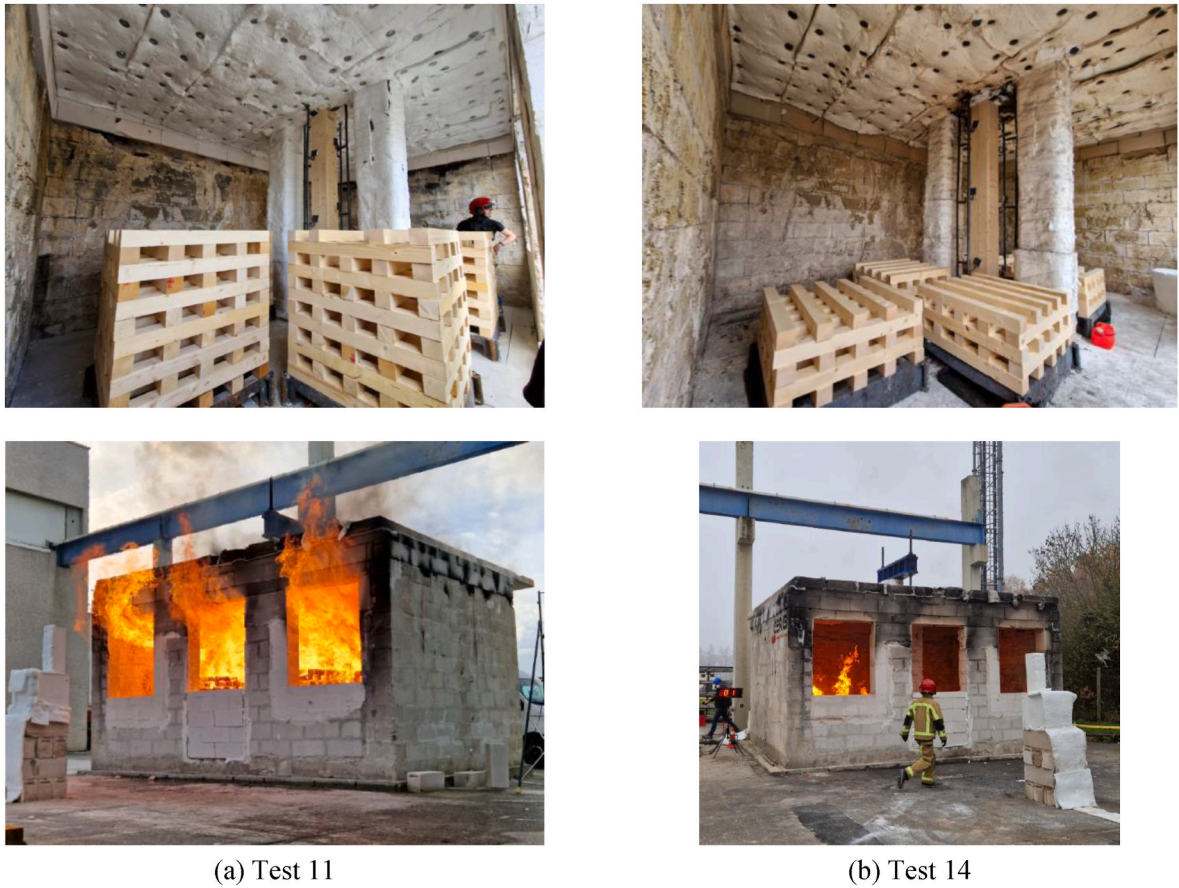


Fig. 9. Fire tests with different fire loads.

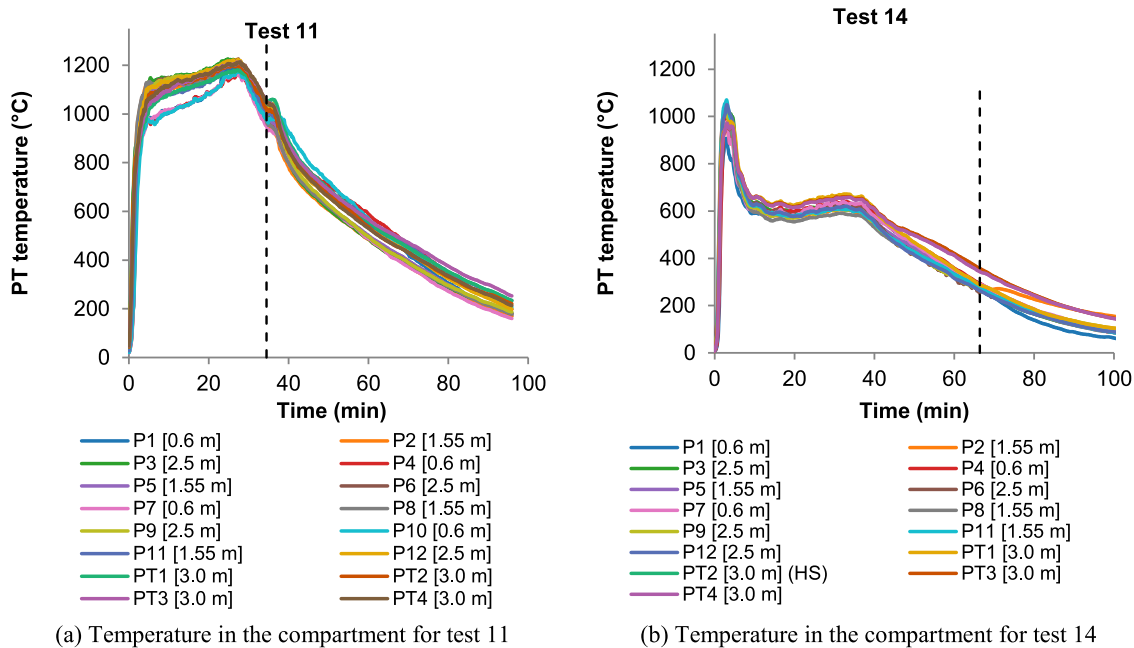


Fig. 10. Effects of the fire load on the compartment temperatures.

The temperatures in the compartment are plotted in Fig. 12. The temperatures in the column are plotted in Fig. 13. The compartment temperatures kept on increasing for 55 min, with a peak at 915 °C. The column failed after 45 min, thus still in the heating phase.

3.5. Summary of results

The results from the six compartment fire tests are summarised in Table 3. The fire tests were conducted on identical columns made of 280

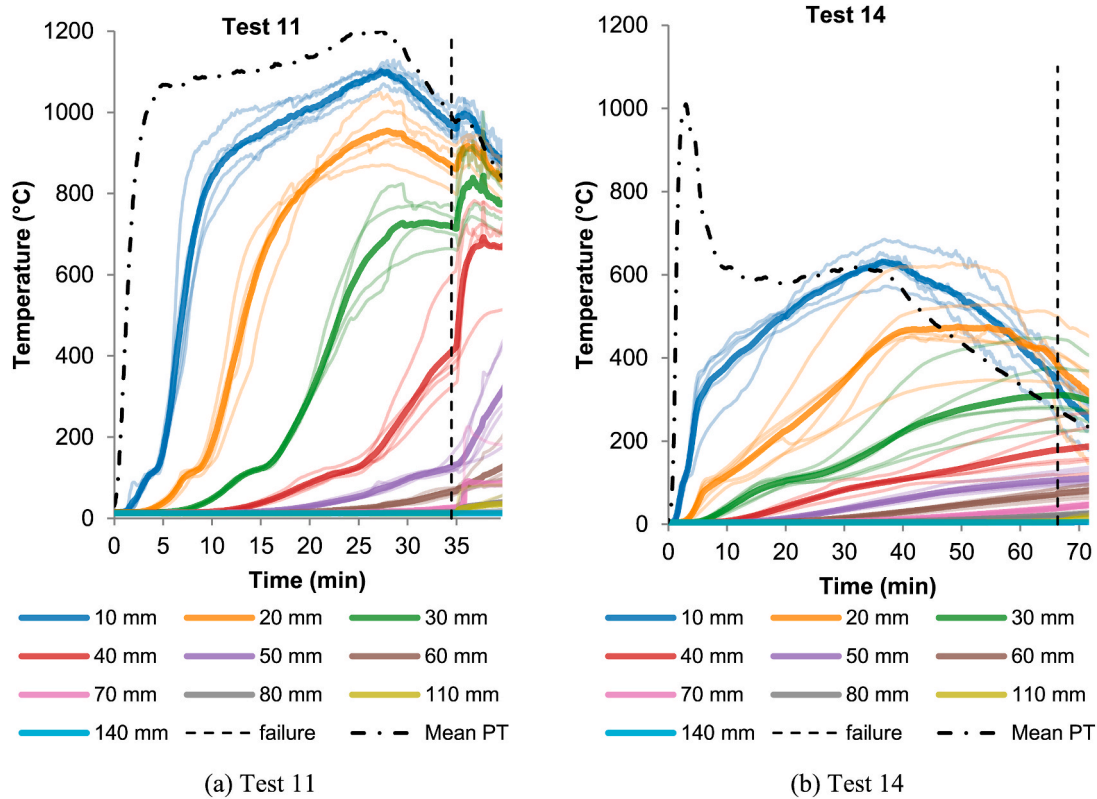


Fig. 11. Temperatures in the timber columns, the thin lines represent the individual thermocouple measurements, and the thick line represents the average of the measurements.

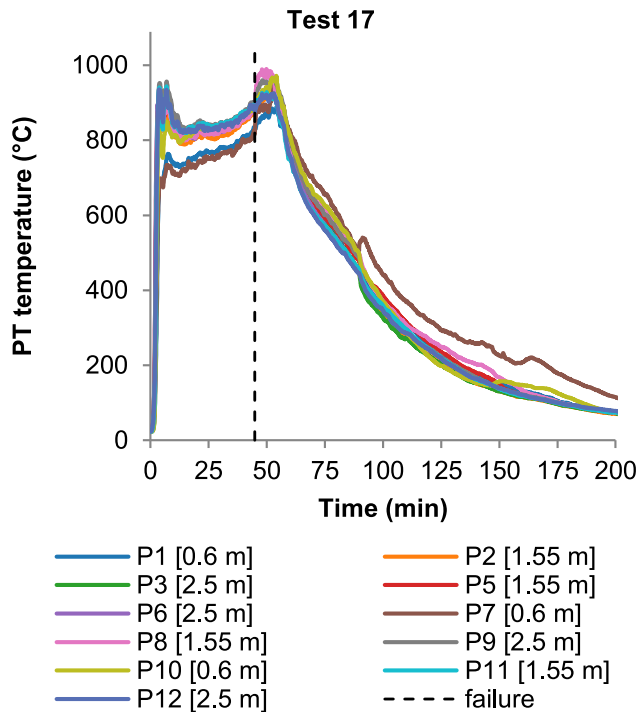


Fig. 12. Compartment temperatures for Test 17.

× 280 mm² section glued laminated timber, with identical length, boundary conditions, and loading. All six columns failed under the natural fires. Four of the columns failed after the end of the heating phase (i.e., the time at which the compartment temperatures start to

cool down), while two columns failed during the heating phase.

4. Discussion

4.1. Fire temperatures and effects of compartment parameters

The average temperature recorded in the compartment for the six tests are plotted in Fig. 14. The curves are interrupted at the time of failure of the column.

Test 10 and Test 11 had similar compartment temperatures. The only difference between the two tests was in the fire load, which was increased by 22 % in Test 11. However, this increase in fire load had minimal effect on the temperature development in the compartment.

In Test 9, the opening factor was multiplied by approximately a factor of 2. This led to lower temperatures than for the reference Test 10, with a similar duration of heating phase. In contrast, in Test 15, the opening factor was reduced by a factor of 2 compared to Test 10. This resulted in a more severe temperature development in this test with average temperatures reaching 1000 °C after 10 min and increasing steadily up to some 1250 °C after 45 min. The reduction in opening factor thus extended the heating phase (from 30 to 40 min) and, notably, led to the highest peak temperatures (1250 °C) recorded in all the tests.

The lowest temperatures were observed in Test 14. This test had a reduced fire load leading to a fuel-controlled fire with a lower power than the other tests as soon as the heptane used as an ignition source was consumed. Oxygen concentration in the compartment indeed remained around 15 % from minute 7 to minute 40 and increased in the cooling phase (oxygen concentration was around 2 % for all other tests - except Test 9 where it was around 5 % - until the cooling phase started). This resulted in the peak temperature of around 1000 °C to be observed only from minute 2 to minute 5, after which a plateau of 600 °C lasted for about 36 min.

Finally, Test 17, with the alternative wood crib design, had lower

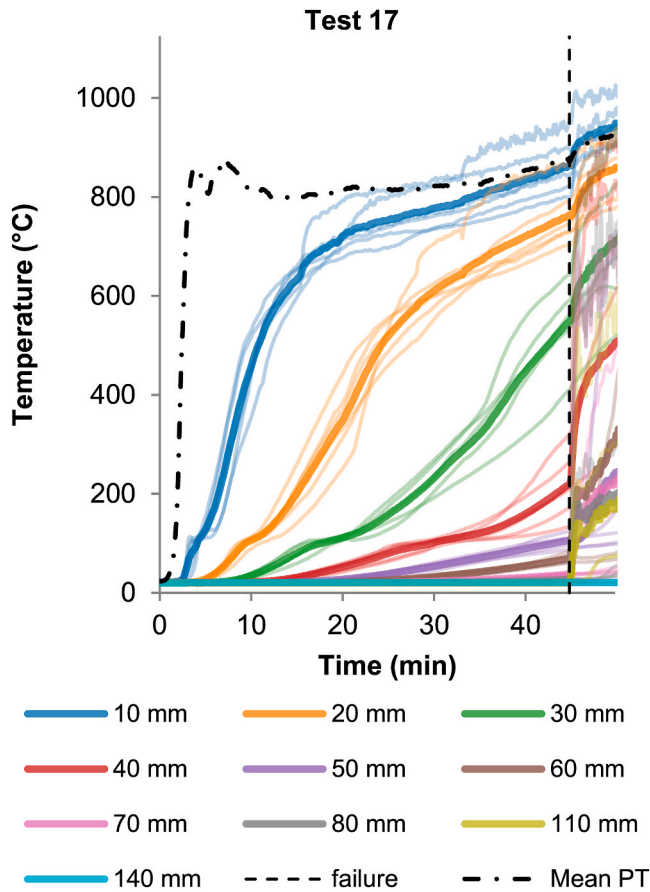


Fig. 13. Temperatures in the timber column for Test 17, the thin lines represent the individual thermocouple measurements, and the thick line represents the average of the measurements.

temperatures than the other tests with the same fire load. However, Test 17 had the longest duration of heating phase. The use of wood cribs with thicker sticks slowed the rate of heat release owing to their lower surface-to-volume ratio.

The test program thus provided data on the effects of opening factor, fire load, and type of wood sticks on the temperature and oxygen concentration in a compartment under a natural fire:

- The *opening factor* significantly impacted the temperature development and duration of the heating phase. Doubling the opening factor in Test 9 led to lower temperatures, while halving it in Test 15 resulted in extended heating phase and higher peak temperatures. Indeed, the larger opening factor allowed for more oxygen to enter the compartment, leading to a more fuel-controlled fire with lower temperatures. Conversely, the smaller opening factor restricted oxygen supply, resulting in a more ventilation-controlled fire that lasted longer and eventually reached higher peak temperatures.

- Regarding the *fire load*, increasing the fire load by 22 % (Test 11) did not noticeably affect the temperature development within the compartment. This may be attributed to the fact that the fire in the reference case (with 780 MJ/m²) was ventilation-controlled, so augmenting the fire load beyond this threshold had no significant influence on the heat release rate. However, reducing the fire load (Test 14) led to a substantial decrease in temperatures, resulting in a fuel-controlled fire with lower power and a plateau of 600 °C lasting for 36 min. This illustrates the fundamentally different regimes of fuel- and ventilation-controlled fires.
- The size and design of the wood sticks also influenced the compartment temperatures. The use of thicker wood crib sticks (Test 17) resulted in lower temperatures and a longer heating phase. This is attributed to the lower surface-to-volume ratio of the thicker sticks, which slows down the rate of heat release. This finding highlights the importance of considering the wood crib design in fire testing, as it can significantly impact the fire's behavior and temperature profile.

4.2. Comparison with standard fire resistance

The columns had been designed for a standard fire resistance of 60 min. Two standard fire tests on identical specimens showed an experimental fire resistance of 55 and 58 min. In these natural fire tests, the failure times ranged from 35 min to 71 min. The failure time of the timber columns is plotted in Fig. 15, showing also the duration of heating and cooling phases of the fire over the time preceding failure. Tests 2, 3, 5, and 6 correspond to the previously conducted furnace tests. As shown in Fig. 15, four of the columns failed earlier than 60 min in the compartment fire tests. This discrepancy is not surprising as the standard fire resistance does not intend to predict or represent the performance under a real fire. Thermal exposure conditions on the column vary widely between different fires, and it is noteworthy that most of the

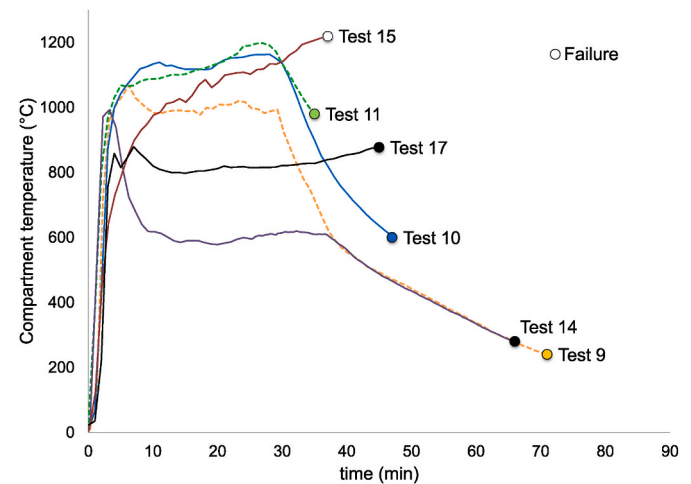


Fig. 14. Evolution of the average temperature in the compartment for the 6 tests.

Table 3

Summary of results from the 6 wood crib fire tests on timber columns. Shaded rows show timber columns that failed during the cooling phase.

Test	A (mm ²)	O (m ^{1/2})	q (MJ/m ²)	wood crib (mm ²)	T _{max} (°C)	End heating phase (min.)	Collapse (min.)
9	280 × 280	0.140	780	90 × 90	1000	30	71
10	280 × 280	0.065	780	90 × 90	1150	30	47
11	280 × 280	0.065	950	90 × 90	1200	28	35
14	280 × 280	0.065	420	90 × 90	600 ^(*)	36	66
15	280 × 280	0.032	780	90 × 90	1250	40	37
17	280 × 280	0.065	780	120 × 120	915	55	45

^(*)1000 °C during the first 7 min.

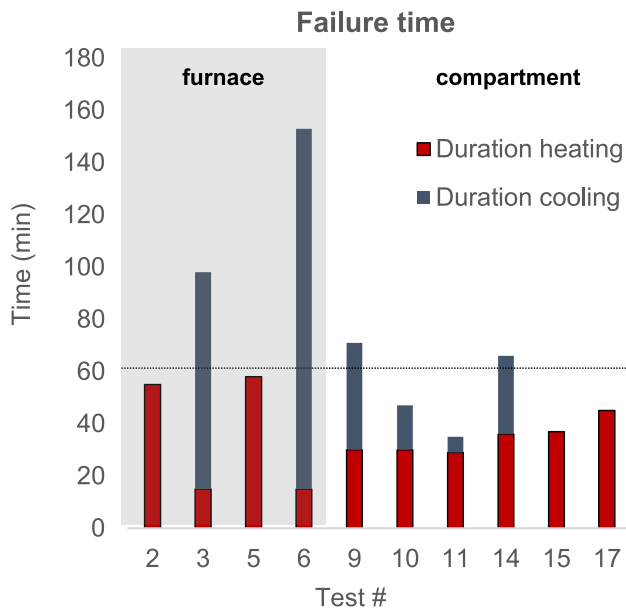


Fig. 15. Failure time of the timber columns for the four furnace tests and the six natural fire tests. Two of the furnace tests and four of the natural fire tests failed during the cooling phase.

compartment fires from this test series had a faster and more intense heating phase than the ISO 834 fire. Nonetheless, this shows the value of collecting data from compartment fire experiments on structural timber members as their performance proves to be highly dependent on the fire parameters.

4.3. Failure during the cooling phase

In four of the compartment fire tests, the columns failed during the cooling phase of the fire, see Fig. 15. In these four tests, the duration of heating phase ranged between 29 and 36 min. The duration that elapsed

between the end of the heating phase and the collapse (noted as “duration of cooling” in Fig. 15) ranged between 6 and 41 min. The latest collapse occurred after 71 min.

These experiments provide evidence that timber columns may fail after the compartment temperatures have peaked in real fires. This corroborates the concept of burnout resistance discussed in previous publications and supported by numerical [19] and furnace test data [6], this time under wood crib fire conditions. The data collected in the compartment experiments, notably the thermocouple measurements inside the timber sections throughout the natural fires, provide evidence of the delayed charring and temperature increase in the depth of the section during the cooling phase of the fires. When the failures occurred during the cooling phase, it was shown that the timber temperatures were still increasing in the core of the section at the time of failure.

In two of the tests, the heating phase lasted longer than 36 min, and in these two tests the timber columns failed in the heating phase. Specifically, the two failures during the heating phase occurred after 37 and 45 min, respectively.

4.4. Temperature in the section at failure

For each test, the measured temperature in the section at the time of failure was determined from the thermocouple measurements at different depths across the centerline. The average of six measurements at each depth was calculated. These temperatures in the section at the time of failure are plotted in Fig. 16.

The “failure temperature profiles” plotted in Fig. 16 vary between columns. Indeed, heat transfer in the sections was influenced by the different thermal exposure conditions resulting from the different fires (Fig. 14). These measurements highlight the role of the thermal wave heating the section of the timber column at different rates and over different duration, including throughout the cooling phase, for the different tests. This is also in line with recent numerical studies [29]. Test 15, which has the highest peak temperature in the compartment and failed in the heating phase, had a steep thermal profile gradient characterized by a relatively deep penetration of the 300 °C isotherm and the lowest temperature in the section depth (e.g., still ambient at 60 mm from the centerline). In contrast, Test 9, which failed the latest in

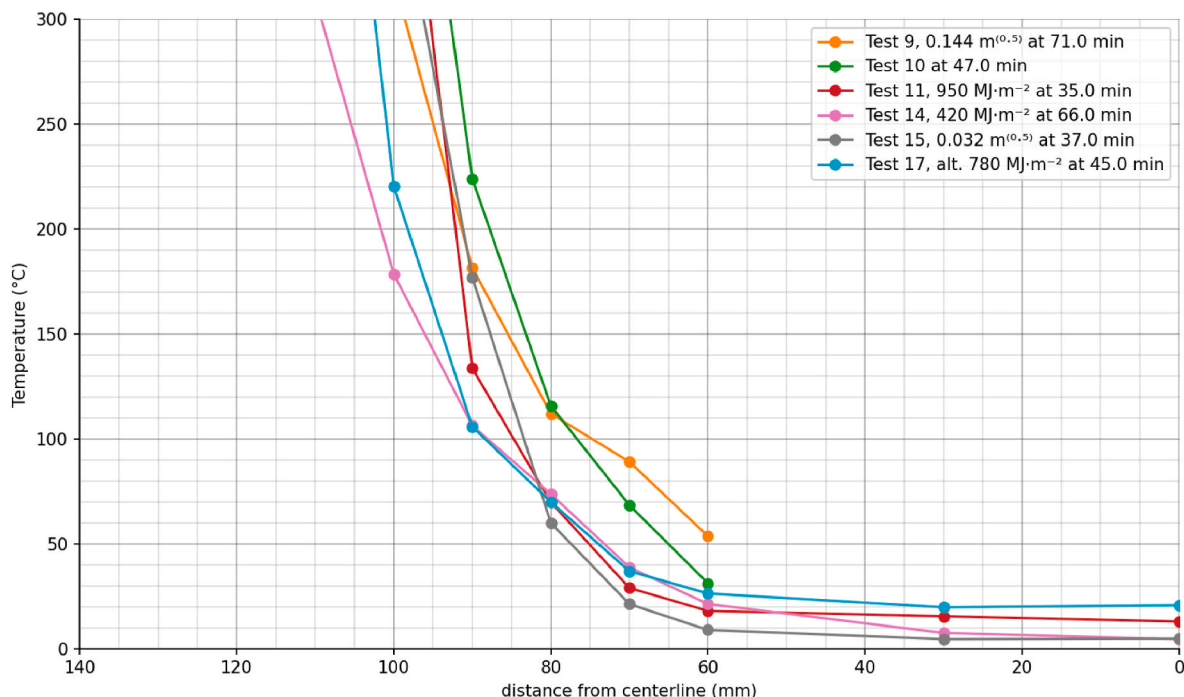


Fig. 16. Maximum temperature reached at different depths in the section at failure.

the cooling phase, had a thermal profile at failure characterized by a smoother gradient with a deep penetration of the thermal wave (reaching 50 °C at 60 mm from the centerline). Test 14, with the lowest peak temperature in the compartment, also has a significantly flatter gradient and a temperature increase deeper in the section compared with Test 15.

4.5. Charring rates

The charring rate was evaluated for each of the compartment fire tests and compared with the charring rate in furnace tests on the same specimens. The charring rate could not be measured directly by visual observation, since these were destructive tests on the columns. Therefore, determination of the charring rate was done based on the temperature measurements from the thermocouples inside the sections. Charring was defined as reaching a temperature of 300 °C. The temperature measurements at different depth from the exposed surface allowed observing the time at which each thermocouple reached this temperature and, hence, the average charring rate for the zone between two thermocouples. These average values of the charring rate are reported in Table 4 for different zones of 10 mm. The reported values on the charring rate only pertain to measurements before column failure time, as post-failure temperature measurements may have been affected by the structural failure.

In furnace tests [6] under the ISO 834 curve, a quasi-constant value of about 0.6 mm/min was observed for the charring rate, see the rows for Test 1 and Test 2 in Table 3. However, in the compartment fires, the charring rate exhibited much larger variations during the fire. The results show that the logarithmic increasing character of the ISO curve ensures a charring rate that is more constant than the one produced during the phase of the natural fire where the fire temperature was quasi constant. The charring rate in the natural fire tests decreases constantly during the period of quasi constant gas temperature, to finally drop down to 0 or very low values during the cooling phase.

Another difference is that, in natural fires, the zero-strength layer pushed ahead of the charring front does not have a constant depth, as assumed in the simple method of Eurocode 5 [26]. In the cooling phase of natural fires, the 300 °C isotherm may stop its progression shortly after the time of peak compartment temperature while the isotherms at 200 °C and 100 °C continue their progression long into the cooling phase.

This seems to indicate that a simple method to design timber elements under natural fire curves cannot result from a simple adaptation of the two values used in the simple method for the constant charring rate and constant zero strength layer.

5. Conclusions

This study presents the results of six compartment fire tests on loaded timber columns. The focus of the study was on the structural stability of timber columns subjected to natural fires with a cooling down phase. The glue laminated timber columns had a section of 280 × 280 mm² and were designed for a standard fire resistance of 60 min (R60). Two furnace tests showed a measured fire resistance of 55 and 58 min.

In the compartment fire tests, the six columns failed, with failure time ranging from 35 min to 71 min. This shows the influence of compartment fire parameters on the performance of structural timber members. In addition, two columns failed during the heating phase while four columns failed during the cooling phase. This validates the burnout resistance concept in real compartment conditions, confirming that a timber column can fail in a fire after the fire temperatures started to decrease. For one test (Test 14) the column collapsed in the cooling phase although the temperatures in the compartment had been significantly lower than those of the ISO curve for most of the test. The fact that the structural element displays some self-extinction does not mean that its stability is ensured. Indeed, temperatures in the section continue

Table 4

Average charring rate for different zones along the depth.

	0–10 mm	10–20 mm	20–30 mm	30–40 mm
Test 1 (ISO)	0.67	0.63	0.55	0.51
Test 2 (ISO)	0.67	0.70	0.63	0.50
Test 9	1.71	1.20	0.83	
Test 10	1.82	1.74	1.33	1.13
Test 11	1.69	1.82	1.17	0.92
Test 14	1.88	0.47	0.32	
Test 15	1.52	1.48	1.11	0.85
Test 17	1.29	0.94	0.64	

increasing through heat conduction throughout the cooling phase, causing a delayed reduction of load carrying capacity.

In the wood crib fires, the opening factor significantly influenced temperature development and heating phase duration. Increasing the fire load had a minimal effect for the considered ventilation-controlled fire, however, reducing the fire load led to a substantial decrease in temperatures, resulting in a fuel-controlled fire with lower power. Additionally, the size and design of the wood sticks affected the fire development and compartment temperatures.

Finally, charring rates were shown to differ significantly in the natural fire tests compared with the quasi-constant rate of 0.6 mm/min found in the companion furnace tests. In the natural fire tests, the charring rate was initially much faster and then exhibited a continuous decrease during the fully developed phase of the fire. The concept of zero-strength layer of constant depth was also found not applicable. This suggests that a simple method for designing timber elements under natural fire curves cannot be derived from a straightforward adaptation of existing approaches.

Further studies will focus on additional compartment fire tests with bigger sections and/or firefighters' intervention to achieve stability during the whole fire duration, as well as on numerical modeling of the experiments. The works aim to support the derivation of design methods for evaluating the behavior of loadbearing timber members under real fires including the cooling down phase.

CRediT authorship contribution statement

Silvio Renard: Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Fabienne Robert:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Jean-Marc Franssen:** Writing – review & editing, Software, Methodology, Investigation, Conceptualization. **Jochen Zehfuß:** Validation, Methodology. **Robert McNamee:** Validation, Methodology. **Patrick Bamonte:** Validation, Methodology. **Thomas Gernay:** Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Fabienne Robert, Silvio Renard reports financial support was provided by France Assureurs. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The support from the French Federation of insurers FRANCE ASSUREURS is gratefully acknowledged.

Data availability

Data will be made available on request.

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