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PARAMETRIC EXPERIMENTAL STUDY ON GLT COLUMNS STABILITY DURING NATURAL FIRE TESTS INCLUDING THE COOLING PHASE

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ABSTRACT

This paper is about the behaviour of glue laminated timber (GLT) columns subjected to physically based fires which include a decay phase. A summary is first given of the results of numerical analyses, of furnace tests made in a controlled environment following the parametric fire model of Eurocode 1 and of a series of seven tests made in a naturally vented compartment with wood cribs used as fire load.

This paper then presents in detail the results of five additional tests performed in the same fire compartment with some variation of the parameters compared to the previously presented series. One test conducted with the same 280 × 280 mm² section as the previous series but with lower compartment temperatures, led to collapse after 45 minutes, not yet in the decay phase. Three tests were made on an increased section of 400 × 400 mm². These three specimens survived for more than 11 hours but collapsed thereafter due to localised zones of increased charring and combustion, essentially at the base of the columns. The final test investigated the effect of fire service intervention. In this test on the 280 × 280 mm² section, the column did not collapse owing to the intervention of fire fighters after 35 minutes of fire.

Keywords: Timber; loaded columns; Glue laminated timber; compartment fires; tests

1 INTRODUCTION

The ability of load-bearing members to withstand fire exposure is typically evaluated through the concept of fire resistance rating (FRR), as outlined in Eurocode 1 in Europe [1]. This grading system involves loading the element and subjecting it to a standardized, continuously increasing, temperature-time curve. It is well understood that the FRR, although it is expressed in minutes, must not be mistaken for the actual survival time of the structure to which the member belongs in a real fire. Notwithstanding all its limitations,

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this concept nevertheless forms the base of many fire regulations, probably because of the unwritten but accepted hypotheses that:

1) For a given type of member, either be it a steel, a timber, or a reinforced concrete member, increasing its FRR will result in a better performance in a real fire that may occur in the future, no matter what this fire may be.
2) Different types of members, either be it a steel, a timber, or a reinforced concrete member, which have the same FRR will have a similar performance in a real fire.

Whereas there is no reason to question the first hypothesis, the second one is already questionable if only the eventuality of collapse during the heating phase of a fire is considered. Real fires which are more severe or less severe than the standardized fire curve may affect different types of members in a different manner. Spalling in concrete, kinetics of the chemical reactions of intumescent products, charring rate in timber [2] may indeed be influenced differently by a variation of the fire temperature history compared to that of the standardized fire curve.

There are other reasons which may indicate that the second hypothesis is particularly questionable if the fire curve involves a descending branch, which is always the case in a real fire, and the structure has survived the heating phase of the fire:

- the fact that some types of members have their temperature decreasing nearly as soon as the fire temperature decreases whereas others experience a temperature increase for a significant time after the peak of the fire curve, at least in the central zones of the section [2, 3],
- the fact that some materials recover their strength or part of it when they cool down whereas others have an irreversible loss of mechanical properties [4],
- the fact that some materials are not severely affected when the temperature in the central zones of the section reach levels around 400°C whereas others may be severely affected or destroyed for much lower temperatures.

Because of these differences, the FRR may not give a good indication of the capability of a member to survive a fire that comprises a decay phase.

Yet, if the structure collapses during the decay phase or, even worse, during the cooling phase when the fire is completely down, this poses a significant hazard for both the occupants who may not have evacuated and for the firefighters and rescue services who may still be on the scene.

The concept referred to as "burnout resistance" addresses the challenge of load-bearing members having to withstand a complete fire event. This concept is the central focus of an international research program which aims to establish a methodology to describe the performance of structural members more accurately, namely throughout the entire duration of a fire. The goal of this research is to provide the necessary tools for designing non-protected timber members that maintain stability during the entire duration of the fire, until the end of the cooling phase.

This paper presents the result of 5 experimental fire tests performed in 2023 on full scale glue laminated timber columns in a compartment constructed at the Fire Testing Centre of CERIB in France where the fire source consisted of wood cribs.

2 PREVIOUS WORKS

2.1 Numerical simulations

To complement the concept of FRR, Gernay proposed an alternative normalised fire curve to characterise the behaviour of structural members subjected to a fire that comprises a heating and a decay phase [5]. This concept called DHP is based on the parametric fire model of Eurocode 1 in which the time factor Γ is taken as 1 (and the heating phase being thus very close to that of the ISO 834 curve). The DHP of a structural member is the duration of the heating phase of the longest parametric fire model that the member can be subjected to without collapse, even after an infinite duration. A parametric fire with a duration of the heating phase shorter or equal to the DHP will be survived by the member; whereas, if the duration of the heating phase is longer than the DHP, the member will collapse, either in the heating phase, in the decay phase or even in the cooling phase (when the temperature in the compartment is back to ambient).

Gernay performed numerical simulations with the software SAFIR® [6] on timber columns, using thermal and mechanical properties of Eurocode 5 [7] assumed during cooling to be fixed at the value of the maximum temperature. His conclusion was that the DHP of timber columns varies from 20% to 50% of their FRR [3]. In other words, a timber column with a FRR of 60 minutes will not survive a parametric fire if the heating phase is longer than 30 minutes. In some conditions, collapse can occur during the decay or the cooling phase if the heating phase has been slightly longer than only 12 minutes.

2.2 Experimental tests under parametric fire curves

Experimental tests were performed at the Technische Universität Braunschweig on 8 similar 3.72 meters long glued laminated timber columns with a section of 280 × 280 mm² which were supported hinged-hinged (Euler case 2) [8]. The applied load of 322 kN amounts to 15% of the load bearing capacity of 2160 kN measured at ambient temperature on a companion specimen of the same production. The FRR was first determined by two tests as 55 and 58 minutes, slightly shorter than the 60 minutes which were estimated (on the base of declared resistance class) by the simple model of Eurocode 5 with a charring rate of 0.70 mm/min and a zero-strength layer of 14 mm. The other specimens were subjected to the parametric fire of Eurocode 1 with heating phase of various durations. Two columns subjected to a heating phase of 15 minutes followed by a decay phase with a constant rate of -10.4 K/min collapsed after 98 and 153 minutes. Two columns subjected to a heating phase of 10 minutes survived the complete fire duration and the long cooling phase which followed. These results are within the range estimated by the numerical simulations of reference [3].

2.3 Experimental tests under wood crib fires

Tests were performed on similar columns at the Fire Testing Centre of CERIB, in France, in a compartment built for this purpose, with dimensions L × l × H of 6.00 × 4.00 × 3.10 m^3, various opening factors and various fire loads. The length of the columns was 3.60 m, five of them with the same section as the tests performed in Braunschweig, one with the section increased to 340 ××× 340 mm², and one with the section increased to 360 x 360 mm². The load was maintained at 322 kN for all tests. The main results of the tests are presented in Table 1 in which T_{max} refers to the maximum in time of the average temperature in the compartment. More details are given in [9] (the value of 90 minutes given for Test 12 in [9] is a typing error).

Table 1. Main results of the previous tests with wood crib fires [9]

Test	A [mm²]	T_{max} [°C]	End of heating phase [min.]	Collapse [min.]
9	280 × 280	1 000	30	71
10	280 × 280	1 150	30	47
11	280 × 280	1 200	29	35
12	340 × 340	1 150	28	87
13	360 × 360	1 180	30	>98$^{(*)}$
14	280 × 280	600$^{(**)}$	36	66
15	280 × 280	1 250	40	37

$^{(*)}$Instability of the loading system, $^{(**)}$1 000°C during the first 7 minutes

Figure 1 presents the evolution of the average temperature (from 9 plate thermometers) in the compartment as a function of time, up to the moment of failure of the column in each test.

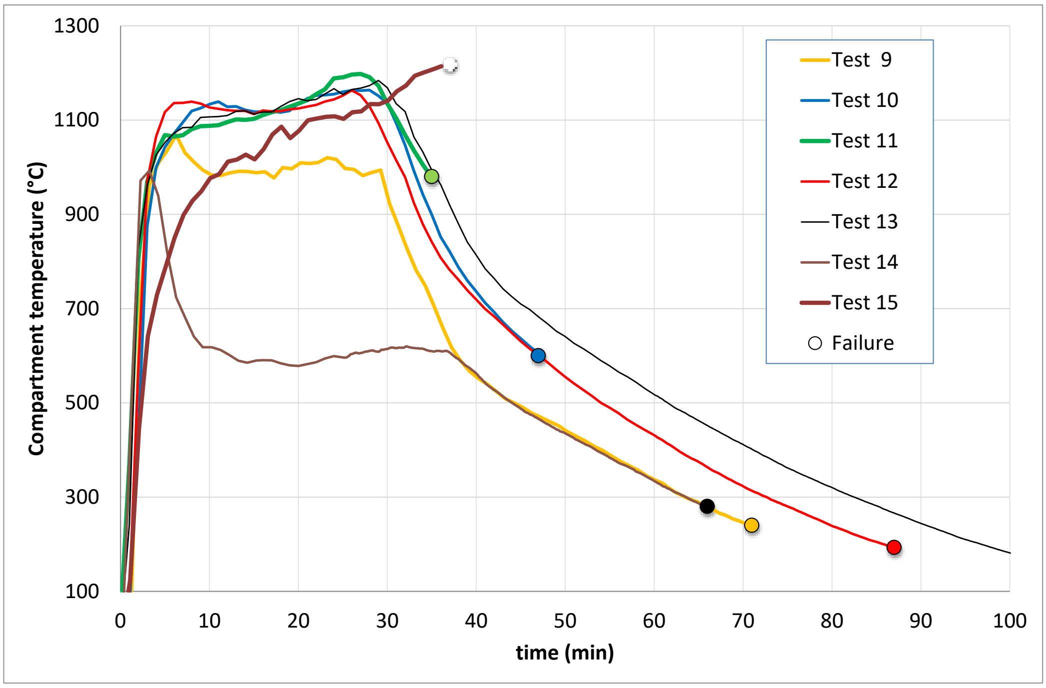


Figure 1. Evolution of the temperature in the compartment for 7 tests in timber columns

These tests confirmed that timber columns can fail during the decay phase of a fire, not only in the controlled environment of a furnace, but also in a naturally vented compartment in which the fire load is made of wood cribs. It has yet to be noted that, except for test 14 performed with a reduced fire load, the temperatures in the compartment in the heating phase were higher than those of the ISO curve. Nevertheless, failure in the decay phase was also observed for this test 14 and for test 12 where the section had been increased by 47%.

3 NEW SERIES OF TESTS

3.1 Modification of the compartment temperature

From the observation that the temperature in the heating phase was higher than the ISO curve in most of the tests described in Section 2.3, a new test (Test 17) was performed on the 280 × 280 mm² section with a modified fire load. Instead of wood cribs made of 10 layers of 5 sticks of 90 × 90 × 1 000 mm^3 spaced by 138 mm, the cribs were now made of 5 layers of 5 sticks of 120 × 120 × 1 000 mm^3 spaced by 100 mm, while the total fire load was maintained at 780 MJ/m² and the opening factor at 0,065 $m^{1/2}$. The total amount of heptane used in the initial phase of the fire was also reduced from 18 liters to 3 liters. In this Test 17, collapse occurred after 45 minutes, whereas the compartment temperature kept on increasing until 915°C, reached after 55 minutes when the decay phase started.

It would be interesting, from a fire dynamics point of view, to examine how the compartment temperature development was influenced by the type and amount of fire load and by the value of the opening factor, and eventually by the wind intensity and direction with respects to the openings. Yet, in this paper, the focus is on the structural behaviour of the timber columns. This is why Figure 2 shows the average compartment fire development for the 6 tests made on similar 280 × 280 mm² columns subjected to the same loading up to the moment of collapse of the specimen.

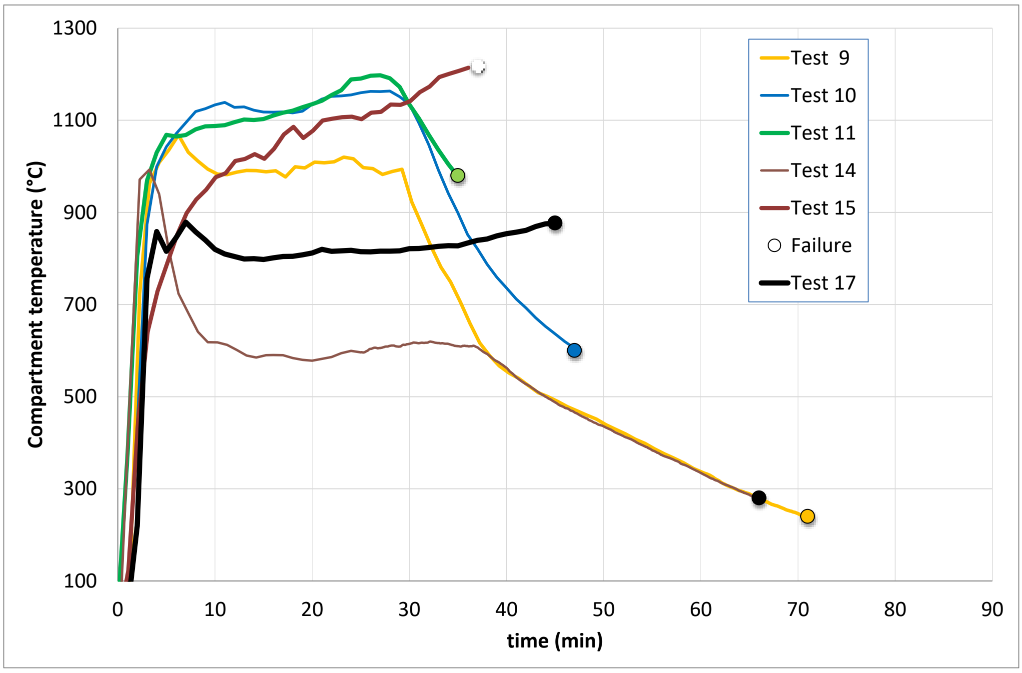


Figure 2. Evolution of the temperature in the compartment for the 6 tests on 280 × 280 mm² sections

These results form a unique set of results on similar specimens subjected to different compartment fire histories and should form a statistically meaningful base for the development of a calculation method for timber columns subjected to physically based fires. This is at least the case if the compartment temperature is the main driving parameter of the temperature development in the section and, hence, of the structural behaviour. The evolution of oxygen concentration has also been measured and is given for this test 17 in Figure 3. The detailed results for all tests are available on the web site “burnout-resistance.eu”.

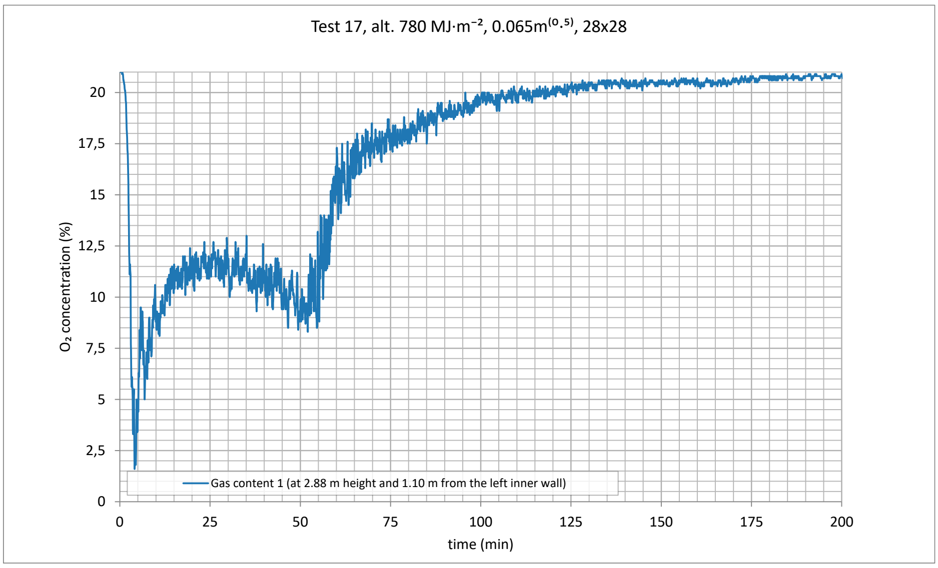


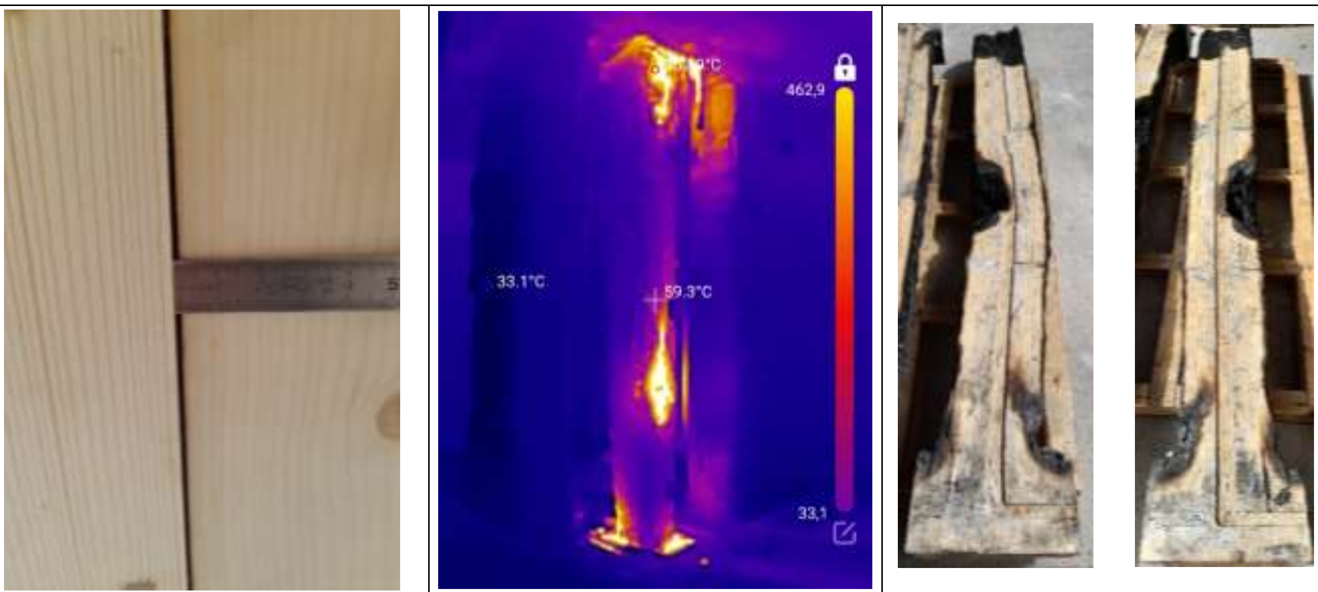
Figure 3. Evolution of the oxygen concentration in the compartment for test 17

3.2 Tests with increased section size

Three tests were then performed with a section increased to 400 × 400 mm², based on numerical modelling predictions made with SAFIR® indicating that this size would be sufficient for the column to survive the fire after the end of the decay and the cooling phase. The cross-sectional area was thus more than doubled compared to the reference section of 280 × 280 mm² while the intensity of the load was kept the same.

Test 18 was performed with the same fire load arrangement and fire load density (780 MJ/m²) and the same opening factor (0.065 $m^{1/2}$) as the reference case of test 10. The compartment temperature reached 1 080°C after 12 minutes, then increased to 1 200°C after 31 minutes when the decay phase started. The column seemed to be surviving the whole fire duration when collapse occurred suddenly 11 hours and 28 minutes after the beginning of the test, at a time when the compartment temperature was at 34°C.

It has yet to be mentioned that a defect in the construction of the specimen had been detected before the test in the form of a longitudinal gap between two halves of the column as can be seen in Figure 4-a. This gap, which was as much as 35 mm deep in some places was filled with an intumescent product for a length of 69 cm on one side and 197 cm on the other side. This did not save the situation as can be seen by the local glowing visible in Figure 4-b at mid-level of the column, and by the difference in residual sections visible on Figure 4.c when the two halves of the column have been separated after the test. In this Figure, the vertical dark line in the centre of each half is the groove which contained the wires of the thermocouples located inside the section.



a) Defect	b) Local glowing	c) Residual sections

Figure 4. Test 18 specimen before, during and after the fire test

It may be questioned whether any structural member would remain uninspected for more than 11 hours in a real fire event. Still, this test highlighted the detrimental influence that defects in gluing planes of GLT sections can have in case of fire, and the importance to have a deep inspection of the structure as soon as possible after a fire and not to neglect the dramatic consequences that local glowing may have on its stability; a fast extinction seems to be a must.

Test 19 was performed under the same compartment conditions as test 18 and on a 400 × 400 mm² section, but on a specimen that did not contain any thermocouple inside the section. This was to eliminate the possibility to have a defect in the gluing plane of the two halves of the column and to rule out the hypothesis that, even without any visible defect, this gluing plane may be different from the gluing planes that nevertheless exist between all lamellae of the GLT, and would perhaps be a weak point in the specimen. This also eliminated any possible negative influence of the groove and of the thermocouple wires.

The compartment temperature reached 1 050°C after 5 minutes, then increased to 1 170°C after 27 minutes when the decay phase started. The column seemed to be surviving the whole fire duration when collapse occurred suddenly 16 hours and 18 minutes after the beginning of the test, at a time when the compartment temperature was at 28°C.

After the test, it was observed that charring and combustion of the section have been much more severe at the foot of the column than in the rest of the column as can be seen in Figure 5 which presents the foot of the column before and after the test. Note that late failure of structural timber members due to continued smouldering have been reported by other authors; [10]: "*Scenario 2 collapsed 29 h after the onset of heating; this was attributed to continued smouldering within the slab after the fire had effectively burned out within the compartment* "; [11] "*Structural failures due to smouldering were studied, including the formation of holes in the ceiling and encapsulation, and the collapse of a column.* ".

a) Before the test	b) After the test

Figure 5. Foot of the column of Test 19

Figure 6 shows the residual section of the column after the test at different heights after the charred layers had been removed. Whereas around 0.08 m² of the initial section of 0.16 m² remained for most of the sections, there remained only 0.035 m² of it at the base of the column.

After this test 19 had shown the detrimental effect of the extensive charring at the base of the column, examination of pictures from test 18 showed that this effect may have been present also in this test, see Figure 4-b, although it was overwhelmed in this case by the more severe influence of the local defect at mid height of the column.

The reason for this extensive charring and combustion at the foot of the columns are not known. Possible leads are:

- Extensive radiation from the ambers of the fire load laying on the floor.
- Radiation from the floor surface (although the same effect should exist from the ceiling, which was not the case).
- Gravity current of fresh air containing oxygen flowing on the floor.

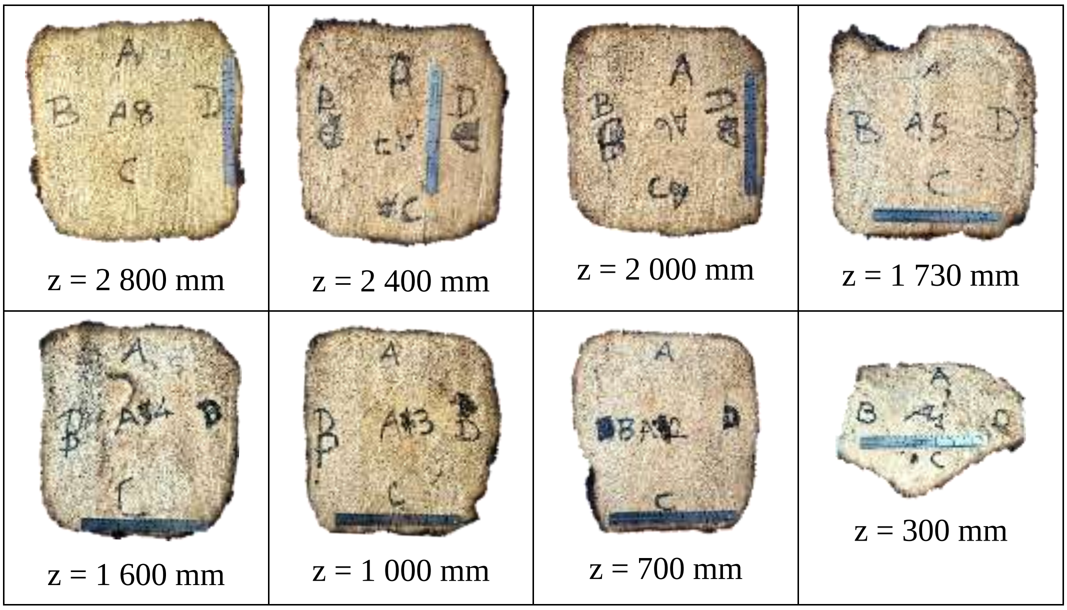


Figure 6. Residual sections of Test 19 at different heights

Test 20 was performed in an attempt to reach survival to the complete burnout. The effect of an increased cross section of 400 × 400 mm² and of reduced compartment temperatures by using thicker sticks of 120 × 120 mm² were combined, while the opening factor of 0.065 $m^{1/2}$ and fire load of 780 MJ/m² were maintained.

The average temperature in the compartment varied between 770°C and 850°C for 59 minutes when, at 780°C, the decay phase started. The column seemed to be surviving the whole fire duration when collapse occurred suddenly 12 hours and 18 minutes after the beginning of the test, at a time when the compartment temperature was at 34°C with, again, a severe reduction of the section at the base of the columns, as can be seen in Figure 7.

Figure 7. Foot of the column of Test 20 after the test

Figure 8 shows as full lines the compartment temperature evolution in the three tests to which the 400 × 400 mm² sections survived for more than 11 hours before collapsing due to local intense charring and combustion.

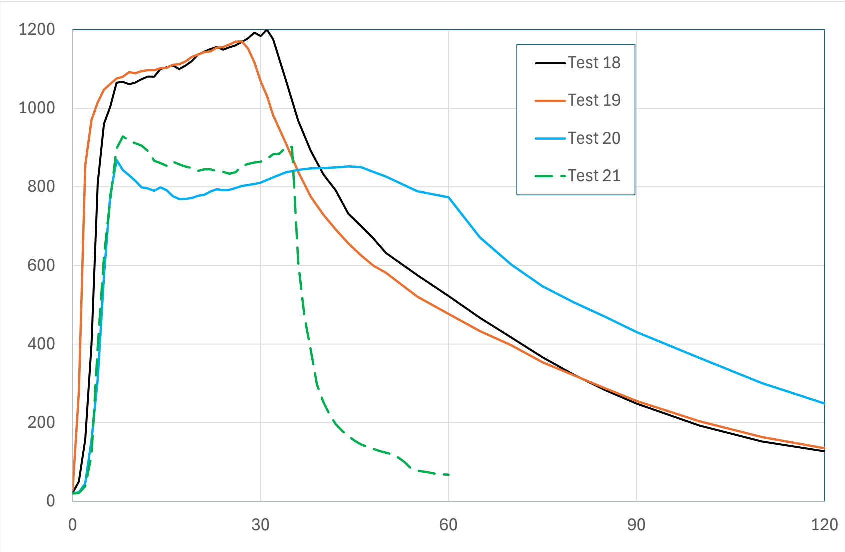
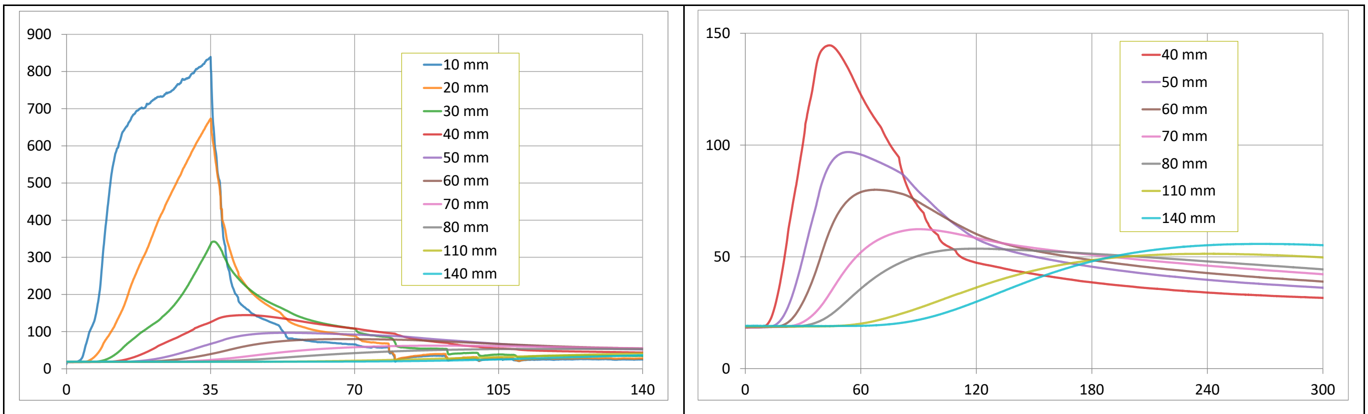


Figure 8. Compartment temperature for tests on 400 × 400 mm² sections (full lines) and for Test 21 (dotted line)

3.3 Fire fighters intervention

Test 21 was performed as a repetition of test 17 in which failure occurred after 45 minutes, but with an intervention of fire fighters planned after 35 minutes. At this time, fire fighters sprayed water in the compartment from the outside with a water hose to extinguish the wood cribs, then sprayed the column and finally entered in the compartment to scratch the charred layers away from the column. The amount of water used in the intervention was 1 m^3. Figure 8 shows, as a dotted line, the rapid decrease of the compartment temperature that was measured immediately after the beginning of the intervention. The column did not collapse.



a) Peripheral zones	b) Central zones

Figure 9. Temperature evolution in the section of tests 21 at different depths

Figure 9 shows the evolution of the temperature inside the section with each curve being the average of 6 measurements, two at three different heights. Figure 9-a shows that the temperatures inside the section at a depth of 10, 20 and even 30 mm from the surface decrease nearly immediately after the intervention. It must be noted that these distances are with respect to the initial geometry of the section and the section may have shrinked and the surface have cracked during the first 35 minutes of the fire. Figure 9-b shows that, on the contrary, temperatures continued to increase in the central zones of the section, and the time of the maximum value was all the more important that the depth was important. At the centre of the section, at a depth of 140 mm, it took more than 4 hours for the temperature to reach its maximum, notwithstanding the fact that a layer of char estimated (from Figure 9 a) at 30 mm had been removed, taking away with it the thermal energy that it contained, and reducing the distance from the central zones to cold air. Despite this continued heating of the inner part of the section, this test showed that the intervention of the fire fighters was successful in achieving resistance to full burnout of the timber column.

3.4 Summary

The main parameters and results of the new series of tests are summarized in Table 2 whereas Figure 10 gives an overview of all tests made in this research work in a naturally vented compartment.

Table 2. Main results of the new tests with wood crib fires

Test	A [mm²]	Tmax [°C]	End of heating phase [min.]	Collapse [min.]
17	280×280	915	55	45
18	400×400	1 200	31	686
19	400×400	1 170	27	978
20	400×400	850	45	738
21	280×280	900	35(*)	-

*fire fighter intervention

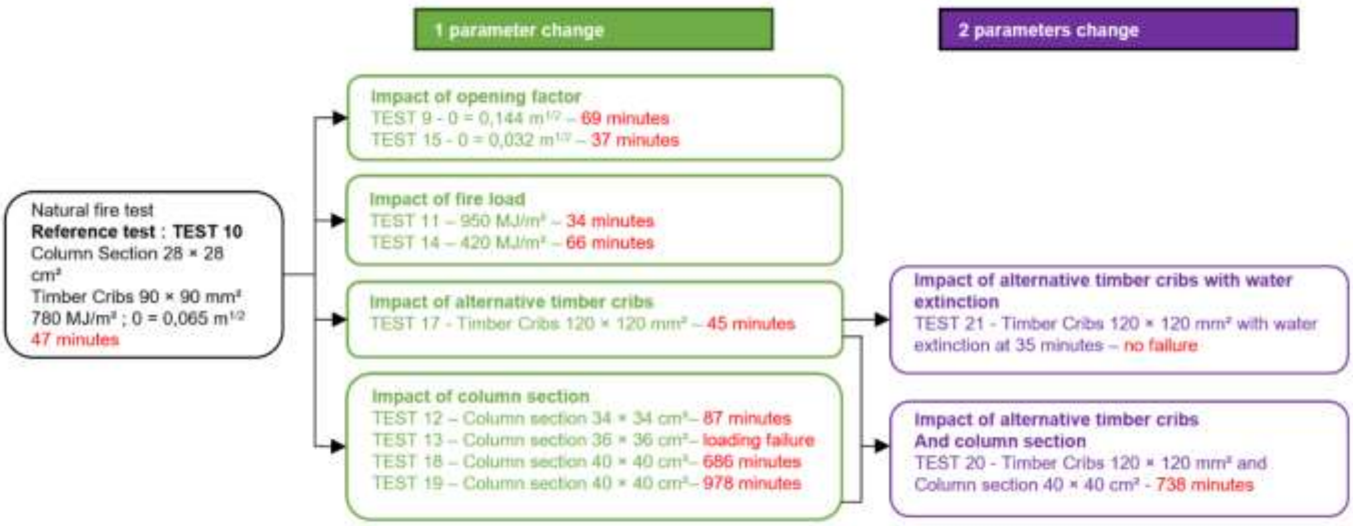


Figure 10. Overview of the tests made in a naturally vented compartment.

4 CONCLUSIONS

This paper describes five new experimental tests performed in a naturally vented compartment on full scale glue laminated columns.

Two tests were on specimens of 280 × 280 mm² cross-section. In the first test, the column collapsed after 45 minutes, still in the heating phase of the fire. In the other test, the fire was extinguished after 35 minutes and the column did not collapse.

Increasing the section from 280 × 280 mm² to 400 × 400 mm² allowed the three next specimens to survive for more than 11 hours, well after the decay phase of the fire. Yet, all three specimens collapse at a later stage, slightly after 11, 12 and 16 hours, due to an extensive charring and combustion that developed locally at the base of the columns and, in one test, at mid-level due to a defect in the construction of the specimen.

These experimental results form, with those previously reported, a significant and well documented basis for the development of design methods which should ensure that, when required, non-encapsulated timber columns can survive to the complete duration of a real fire or a physically based fire model.

The reasons for the intensive localised charring observed in three tests is still investigated. A point of great interest is whether such phenomena would occur in a real fire in a real building. These results nevertheless indicate that a thorough inspection of the whole structure should be undertaken without any delay after the decay phase of the fire and that any glowing area should be extinguished as soon as possible, which corroborates recent findings from other full scale experiments.

A rapid extinction of the fire and of the combustible structure is of course beneficial, although the optimum operational procedures still remain to be established if the amount of timber members involved is significant and it may not be possible to dedicated all required attention to all of them immediately as was the case here.

ACKNOWLEDGMENT

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