World Conference on
Timber Engineering
Oslo 2023

NATURAL FIRE TESTS ON GLT COLUMNS INCLUDING THE COOLING DOWN PHASE

Fabienne Robert[1], Jean-Marc Franssen[2], Jochen Zehfuß[3], Sven Brunkhorst[4], Patrick Bamonte[5], Silvio Renard[6], Robert McNamee[7], Thomas Gernay[8]

ABSTRACT: This paper presents the data and the results of seven fire tests performed on glue laminated timber columns in a compartment built especially for the tests and in which timber wood cribs created a so-called natural fire. These tests are part of a research programme titled "burnout resistance" to establish a new methodology to better describe performance of structural elements during the whole duration of a fire. Comparisons with similar tests made in a fire resistance furnace allow comparing charring rates observed in standard conditions and in natural fires.

KEYWORDS: Fire, Column, GLT, timber, cooling

1 INTRODUCTION

The concept that has been used overwhelmingly for nearly one century to characterize and classify the ability of loadbearing members to withstand fire exposure is the concept of *fire resistance*. The element is loaded and then subjected to a standardised heating regime characterised by a time-temperature curve, for example the ISO 834 fire curve mentioned in Eurocode 1 [1] in Europe. If the fire resistance is determined by a test (as opposed to calculation), some prescriptions are also given about the pressure and the oxygen content in the furnace atmosphere [2]. The concept of fire resistance is a grading system. It is known that the duration which is the expression of the result must not be taken as the time during which the member, used in a real structure, would survive to a real fire that would develop in a real building. The underlying hypothesis of using the concept is that there is a monotonically increasing relationship between the fire resistance time and the performance level in a real fire; an element that has a higher fire resistance should perform better in a real fire, whatever the fire may be, than an element with a lower fire resistance. Similarly, if two different elements have the same fire resistance time, their performance in a real fire should be equivalent.

Although the concept of fire resistance has many shortcomings, there is some logic in that as long as the temperature of the fire is constantly increasing, as this will lead to constantly increasing temperatures in the elements and thus presumably to a constantly decreasing load bearing capacity.

Yet not all structures collapse during the heating phase of a fire. Some, if not most of them when the fire design was appropriate, are still standing when the fire temperatures start decreasing, either from firefighting intervention or from a lack of combustible material in the fire compartment. If the structure collapses during the cooling phase of the fire or even after the temperatures in the building compartment have gone back to ambient, this is a serious hazard for occupants that may not yet have evacuated the building but also for firefighters and rescue services who may still be fighting the fire or searching for occupants. There is a need for a new concept to allow evaluating the risk of collapse during or after the peak of the heating phase, as the current concept of fire resistance does not address this phase of the fire.

This paper first explains why the risk of collapse during the cooling phase of the fire may be particularly critical for timber elements, from theoretical considerations, then from some numerical examples and from experimental tests performed in a revised standardised environment. It then presents the results of seven tests performed in a room filled with a timber fuel load to generate a so-called natural fire with the first objective to check whether the observations and the conclusions derived from theoretical considerations, from numerical modelling and from standardised tests would remain valid when timber elements are subjected to a fire development more similar to a real fire. The final objective of the research is to provide appropriate tools to design non-protected timber elements which maintain stability during the whole duration of the fire including the cooling down phase.

2 THEORETICAL CONSIDERATIONS

Timber is a solid material in which heat transfer is predominantly by conduction when subjected to a

---

[1] Fabienne Robert, CERIB, France, f.robert@cerib.com
[2] Jean-Marc Franssen, Liege University, Belgium, jm.franssen@uliege.be
[3] Jochen Zehfuß, Technische Universität Braunschweig, Germany, J.Zehfuss@ibmb.tu-bs.de
[4] Sven Brunkhorst, Technische Universität Braunschweig, Germany, S.Brunkhorst@ibmb.tu-bs.de
[5] Patrick Bamonte, Politecnico di Milano, Italy. patrick.bamonte@polimi.it
[6] Silvio Renard, CERIB, France, s.renard@cerib.com
[7] Robert McNamee, RISE Research Institutes of Sweden and Lund University, Sweden, robert.mcnamee@ri.se
[8] Thomas Gernay, Johns Hopkins University, USA, tgernay@jhu.edu

https://doi.org/10.52202/069179-0244

temperature gradient. This is the case in a solid timber wall or slab when building physics considerations are at stake, for thermal insulation of a house in the winter, for example. This is also the case in timber or in the charred layer of a timber element subjected to the fire, although many chemico-physical phenomena which are much more complex than conduction occur in this case, such as evaporation of moisture, movement of moisture, pyrolysis, combustion of the char, formation of cracks and shrinkage leading to a change of geometry [3]. The subsequent considerations are based on a simple conductive model, the simplicity of which allows deriving interesting qualitative conclusions.

Starting from an initial condition when a section is at a low quite uniform temperature distribution, the thermal gradient during a fire is from the outside to the inside of the section as long as the fire temperature increases and, in the beginning of the cooling phase, as long as the fire temperature is higher than the surface temperature of the section. The heat transfer is thus also from the outside to the inside of the section and the temperatures are rising everywhere in the section.

When the fire temperature becomes lower than the surface temperature of the section, the heat exchange at the surface is from the section to the environment and the peripheral zones of the section start cooling down. Yet, there is still a positive temperature difference between these peripheral zones and the centre of the section. As a consequence, part of the energy of the peripheral zones does not travel toward the environment, but toward the centre of the section where the temperatures keep on rising for a certain time, to finally decrease when the whole section goes back to ambient temperatures.

Figure 1, for example, shows the temperature profile along the centreline of a 280 x 280 mm² timber section subjected to the parametric fire of Eurocode 1 [1] with a Γ factor equal to 1 (and, thus, a temperature evolution during the heating phase very close to the ISO 834 fire curve) and a heating phase of 60 minutes; see Figure 4 for curves with a Γ factor equal to 1. The curves of Figure 1 result from numerical modelling, see section 3, and the temperatures are given after 1, 2, 3 and 4 hours.

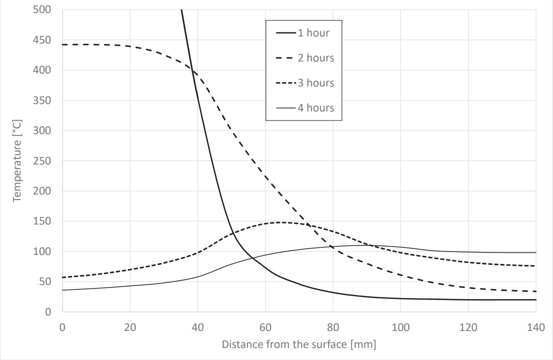

Figure 1: *Temperature evolution in a square timber section*

It can be observed that the temperature continues increasing in the zones of the sections long after the fire has reached its maximum temperature. A similar behaviour occurs in a human body member that has been severely burnt at the surface, hence the recommendation to keep the member under cold water for a long duration. What is specific to timber yet, is that the loss of mechanical properties with temperature is very fast, with all strength being lost at a temperature as low as 300°C according to Eurocode 5 [4]. Figure 2, for example, shows the evolution of the relative compressive strength of timber according to Eurocode 5 [4].

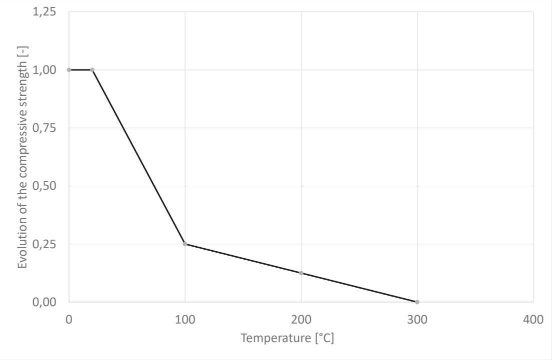

Figure 2: *Decrease of compressive strength according to EC5*

In addition to that, most of the phenomena that develop during heating, such as moisture evaporation, pyrolysis and combustion are irreversible (moisture may re-enter in the section in the long term, but not in the timeframe of a few hours) and it is thus unlikely that the mechanical strength can recover when char or heated timber cool down. Figure 3 shows, as a dotted line, the maximum temperature observed at any time along the centreline under the parametric fire discussed in Figure 1 and, as a full line, the residual compressive strength obtained from the curve of Figure 2 assuming that the residual strength is the same as the one determined at the maximum temperature.

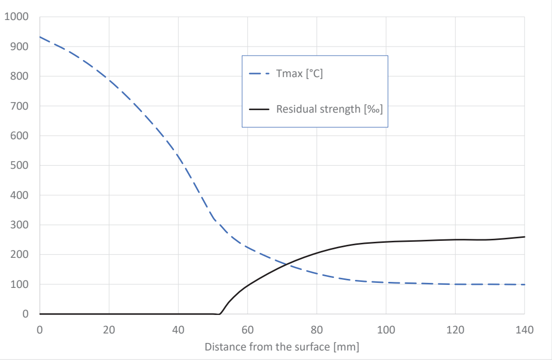

Figure 3: *Maximum temperature computed and corresponding residual compressive strength in a timber square section*

3 NUMERICAL SIMULATIONS

To quantify the theoretical considerations developed in section 2, Gernay made extensive numerical simulations on timber columns [5], deriving their ‘Duration of Heating Phase’ (DHP [6]). The DHP quantifies the *longest* duration of exposure to heating according to the standard ISO 834 fire that will guarantee stability of a member throughout the entire fire duration. Figure 4 shows, in addition to the ISO curve on which the fire resistance time R has been noted, four parametric fire curves, each characterized by a different duration of the heating phase. Only one of these curves, the black one, corresponds to the DHP.

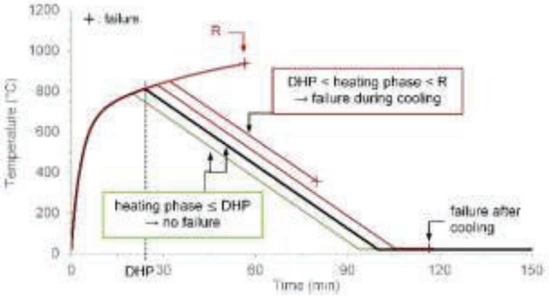

Figure 4: *Principle of the DHP*

In these simulations, the thermal and mechanical properties were taken as recommended by Eurocode 5 and it was assumed that all properties during the cooling phase keep the value they had at maximum temperature.

Gernay concluded that, depending on conditions, the DHP of timber columns varies between 20% and 50% of their standard fire resistance time. In other words, a column that is rated as R60 will collapse during or after the cooling phase if it is heated by the ISO curve for more than 30 minutes, followed by a linear cooling down phase of the fire temperature. In the worst situations, the heating phase of the fire cannot last for more than 12 minutes if stability after full burnout must be ensured.

4 EXPERIMENTAL TESTS IN MODIFIED STANDARD CONDITIONS

The numerical results mentioned in Section 3 are dependent on hypotheses on the material properties that, although they seem reasonable, have not been validated experimentally. The precise determination of all these properties in the cooling phase may be the topic of further fundamental research. In the meantime, researchers rely on experimental tests performed on timber elements to investigate the behaviour of these elements, such as the tests reported by Kinjo et al on GLT beams [7]. An experimental program was launched by CERIB with international partners to see whether the conclusions of the numerical simulations reported in [5] could be confirmed by tests on full scale timber columns.

A series of 8 tests were performed at the Technische Universität Braunschweig glued laminated timber columns with a section of 280 x 280 mm² [8]. The columns were pinned-pinned at the ends with a length between the support of 3,72 m and the load was applied with an eccentricity of 20 mm at each end. The columns were tested in a standard fire resistance furnace in which the heating according to the ISO 834 curve was applied for different durations, followed by a linear cooling down phase with a rate of -10.4°C/min.

The fire resistance of the columns was first determined as 55 and 58 minutes (two specimens). Two specimens were then subjected to a heating phase of 15 minutes and failed after 98 and 153 minutes. Two specimens heated for 10 minutes both survived the defined heating-cooling exposure. These furnace tests showed that timber columns can fail during the cooling phase when exposed to standard ISO 834 fire exposure for a duration significantly shorter than their standard fire resistance. In this particular case, the DHP between 10 and 15 minutes, is in the range of (18% ; 27%) of the average value of the fire resistance time (56.5 minutes), rather on the lower side of the range (20 % ; 50%) observed in the numerical analysis.

Thermocouples inside the columns also confirmed the sustained temperature increases for hours after the end of the heating phase, as shown by the numerical models.

5 EXPERIMENTAL TESTS UNDER NATURAL FIRE CONDITIONS

5.1 INTRODUCTION

Although the tests mentioned in section 4 confirmed the theoretical considerations and the numerical simulations, these tests have some features which are different from those of a real fire such as, for example, the nature of the fuel, the oxygen content, the shape of the cooling phase curve and the procedure that was followed in the tests to control the temperature in the cooling phase.

A series of tests was thus performed in a compartment specifically built at the Fire Testing Centre of CERIB, in France, in condition supposed to represent as closely as possible the conditions which could prevail in a real fire.

.

5.2 THE COMPARTMENT AND THE FIRE LOAD

The compartment was made of 300 mm walls of aerated concrete blocks and the roof was made of 200 mm thick slabs of aerated concrete. The concrete floor was insulated by a layer of mineral fibres, covered by a 20 mm thick layer of plasterboards. The ceiling was made of 200 mm thick slabs of aerated concrete, protected for the tests 11 to 15 by 55 mm of mineral wool.

The distance from the floor to the ceiling was 3.10 m for tests 9 and 10 and 3,05 m thereafter, and the internal dimensions in the plan view were 6.00 m by 4.00 m.

Different openings were made in one of the long walls to create the desired opening factor as mentioned in Table 1. The fire loads was made of wood cribs of (0.75 m)³ made of 10 layers of 5 sticks with a section of 83 x 83 mm². The fire load was also varied from test to test to create the fire load density mentioned in Table 1. The wood cribs were ignited simultaneously to reach as quickly as possible a post-flashover fire.

https://doi.org/10.52202/069179-0244

The main characteristics of each tests are shown in Table 1, with the shaded cells showing the difference with respect to test 10 which could be seen as a reference from which variations have been made.

Table 1: *Conditions in the fire compartment*

Test	O ($m^{1/2}$)	q (MJ/m^2)	Section (mm^2)
9	0.144	780	280 x 280
10	0.065	780	280 x 280
11	0.065	950	280 x 280
12	0.065	780	340 x 340
13	0.065	780	360 x 360
14	0.065	420	280 x 280
15	0.032	780	280 x 280

5.3 THE COLUMNS

The tested columns were made of GLT with a section of 280 x 280 mm² for most of them, 340 x 340 mm² for test 12 and 360 x 360 mm² for test 13. The length of the timber columns was 3 680 mm. With the steel head plate and base plate, axes of the cylinders that formed the boundary conditions at both ends were at a distance of 3 740 mm.

5.4 THE LOAD

As for the tests made in Braunschweig, a load of 322 kN was applied with an eccentricity of 20 mm in one direction at both ends. The load was maintained for 15 minutes before the fire load was ignited and it was kept constant during the whole fire duration.

5.5 THE FIRE TEMPERATURES

The average temperature recorded in the compartment for all tests can been seen on Figure 5.

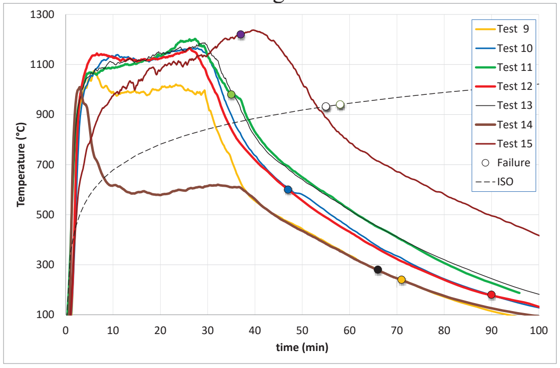

Figure 5: *Temperatures in the fire compartment*

Test 9 had a very large opening factor created by 3 openings of 1,30 x 2,50 m², see Figure 6, which led to the temperatures being limited to 1 000°C during only 30 minutes.

Figure 6: *Test 9 during the cooling phase*

The five subsequent tests were performed with an opening factor reduced by a factor of 2, with 3 openings of dimensions 1,30 x 1,50 m².

A similar situation developed in the compartment during tests 11, 12 and 13 although the fire load has been increased by 22% in test 11.

The fire load was reduced in Test 14 leading to a fuel-controlled fire with a lower power than the previous 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 were it was around 5% - until the cooling phase started). This resulted in the peak temperature of around 1 000°C to be observed only from minute 2 to minute 5, after which a plateau of 600°C lasted for about 40 minutes.

The opening factor was again reduced by a factor of 2 for test 15 which was performed with a single opening of dimensions 0,95 x 2,40 m². The temperature development was more severe in this test with average temperatures reaching 100°C after 10 minutes, increasing steadily up to some 1 250°C after 45 minutes when the cooling down phase started.

5.6 RESULTS

In test 9, the column failed after 71 minutes when the temperatures in the compartment were down to the range from 200 to 300°C. Figure 7 shows the evolution of the temperature measured at different depth from the surface on the centreline of the section, each curve being the average of 6 measurements, 2 in the lower part of the column, 2 at mid height and 2 in the upper part. Although these temperatures have been obtained for a different fire curve and they are presented in a different form, these results confirm the trend presented in Figure 1, 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.

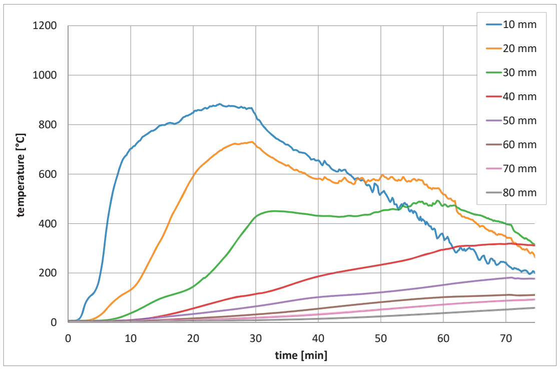

Figure 7: *Evolution of the temperature at different depth in the section for test 9*

At the time of failure, temperatures were at or above 300°C at 42 mm from the surface, 115°C at 60 mm and 55°C at a 80 mm. From the time it took to the 300°C isotherm to reach different depth, the average value of the charring rate can be calculated as 1.41 mm/min for the first 14 minutes, 0.83 mm/min from 14 to 26 minutes, and 0.28 mm/min from 26 to 61 min. These values can be compared to the quasi-constant value of 0.6 mm/min which was observed during tests 1 and 2 made under ISO curve in Braunschweig.

In test 10 where the opening factor had been reduced, the column failed after 47 minutes when the temperatures in the compartment were around 600°C. The temperatures in the peripheral zones increased faster, with average values of the charring rate varying from 1.78 mm/min during 11 min, 1.33 mm/min to 19 min and 1 mm/min up to 27 min. At the time of failure, a layer of 46 mm was at or above 300°C, the temperature was 115°C at 60 mm, but still at ambient at 80 mm.

In test 11 where the fire load had been increased but the compartment temperatures nevertheless followed the same evolution as in test 10, failure occurred after only 35 minutes, early in the cooling down phase with gas temperatures still around 980°C. This result, compared to the result of test 10, gives an idea of the variability inherent to the material.

Test 12 was made in the same conditions as test 10 but with a column that had a section of 340 x 340 mm². The objective was to see whether these additional 30 mm of “protection”, together with an initial load level reduced to 68% of the one of test 10, would allow the column to survive to the fire until complete burnout and after. Collapse occurred after 90 minutes when the temperatures in the compartment were down to 180°C.

The section was increased again to 360 x 360 mm² for test 13 made in the same conditions as tests 10 and 12. The column was still supporting the load after 98 minutes, when an instability of the loading system developed at one of the supports due to an imperfect insulation of this support.

For test 14, the 280 x 280 mm² section was used again, but with a reduced fire load and hence, significantly lower temperatures in the compartment, exceeding 600°C for only 7 minutes. Collapse occurred after 66 minutes, with gas temperatures around 280°C.

Test 15 was also made with the 280 x 280 mm² section, with the same fire load as in test 9, 10, 12 and 13 but with a reduced opening factor leading to a longer duration of the heating phase and to higher temperatures in the cooling phase. Collapse occurred after 37 minutes, shortly before the end of the heating phase. It has yet to be mentioned that the temperatures measured differed significantly from one side of the section to the other side. Figure 8 showed that this was observed consistently for all three levels in the compartment where the measurements were made.

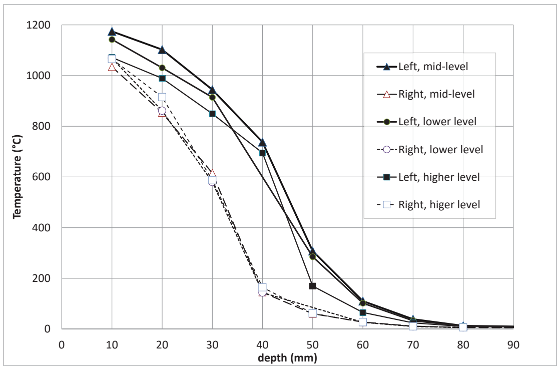

Figure 8: *Temperature distribution in the section at the time of collapse in test 15*

This may be due to the position of the unique opening which was not symmetrically located with respect to the column, as can be seen on Figure 9.

Figure 9: *Position of the opening in test 15*

This non symmetrical temperature development in the section developed although the temperatures measured in

https://doi.org/10.52202/069179-0244

the compartment did not display the same pattern, as can be seen on Figure 10. This may be due to a different oxygen content on the side of the column which was close to the opening compared to the other side.

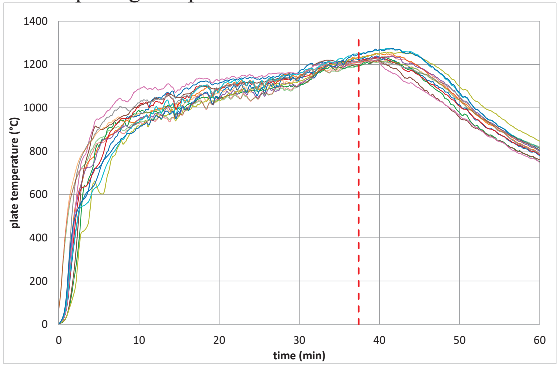

Figure 10: *Temperatures in the compartment in test 15*

Timber is indeed a material in which the physical phenomena that develop in case of fire are driven not only by the temperature but also by oxygen penetration.

This non symmetry in the section has created a structural imperfection that may have influenced the stability of the column. Although this makes it more difficult to compare the results of this test with those of the other tests in this scientific campaign, there is also a lesson to be learnt in the sense that nothing will guarantee a perfectly symmetrical development of the temperatures and of the char penetration in a real fire. Other materials would also be affected by differences in temperatures whereas timber may be the only material affected by differences in oxygen concentration.

5.7 CHARRING RATES

In was not possible, in these destructive tests, to measure the charring rate by direct visual observation. If charring is defined as reaching a temperature of 300°C, temperature measurements at different depth from the exposed surface allowed to observe the time at which each thermocouple reached this temperature and, hence, the average charring rate for the zone between two thermocouples.

Table 2: *Average charring rate for different zones along the depth.*

	0 - 10 mm	10 - 20 mm	20 - 30 mm	30 - 40 mm	40 - 50 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	0,28	
Test 10	1,82	1,74	1,33	1,13	
Test 11	1,69	1,82	1,17	0,92	
Test 12	1,74	1,69	1,05	0,78	
Test 13	2,00	2,14	1,05	1,29	1,24
Test 14	1,88	0,47	0,32		
Test 15	1,52	1,48	1,11	0,85	1,11

Table 2 shows the average value of the charring rate for different zones of 10 mm. Results from test 1 and 2 [8] 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, there is no zero strength layer of constant depth pushed ahead of the charring front, as assumed in the simple method of Eurocode 5. In the cooling phase of natural fires, the isotherms at 200°C and 100°C continue their progression long in 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 for the constant charring rate and constant zero strength layer.

6 FUTURE TESTS AND FUTURE WORK

Two more tests should be performed by the time of the conference. Numerical simulations performed with the code SAFIR® [9] will also supplement the test results and will allow verifying whether the effective thermal properties of timber proposed in Eurocode 5 can be applied for computing temperatures in timber under nonstandard fires.

The last task will be to define a simple calculation method that ensures survival of timber columns during the whole duration of natural fire curves.

7 CONCLUSIONS

Seven tests have been performed under natural fire conditions on glue laminated timber columns for which the reference section of 280 x 280 mm² was shown to have a fire resistance of 55 and 58 minutes in standard testing conditions (two tests made).

In one test (test 15), collapse occurred after 37 minutes of the heating phase, but the temperatures in the compartment were higher than those of the ISO curve and a difference of temperature was observed between one side of the section and the other side, which induced a structural load eccentricity.

In one test made on a column with section increased by 65% (test 13), the columns had survived a heating phase of 30 minutes and was still supporting the load when a problem at one support of the loading system left to the premature termination of the test after 98 minutes, long into the cooling phase but not long enough to have all temperatures in the section back to ambient.

For the other 5 tests, failure occurred during the cooling down phase. For 3 of them with the same section (tests 9, 10 and 11), the temperature in the compartment had been higher than that of the ISO curve for the first 32 to 38 minutes and lower thereafter. For another one (test 12) the

https://doi.org/10.52202/069179-0244

temperature had been higher than that of the ISO curve during the first 35 minutes, but the fact that the section had been increased by 47% did not prevent it from collapsing after 90 minutes, when the temperatures in the compartment had significantly decreased. For one test (test 14) the section also 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.

These tests confirm the conclusion of previous numerical and experimental studies that a timber column can fail in a fire long after the fire temperatures started to decrease, and the fact that the structural element displays some “self-extinction” does not mean that its stability is ensured.

Some of the results tend to confirm that the influence from a fire on a timber member is not as directly linked to temperature as could be the case for other inert materials. Oxygen content in the vicinity of the element and other complex exothermic phenomena may probably also play a role. Temperature development and oxygen repartition in the compartment can be influenced by wind velocity and direction and, although the tests were performed with a maximum wind velocity in the order of 2 m/s (maximum gusts at 3 m/s), the direction varied from test to test.

The quantitative results should, with the results of the additional tests planned and with the help of numerical modelling, allow deriving a simple model for computing the behaviour of timber members under real fires including the cooling down phase. Also, using the DHP as a simple metric indicating real fire behaviour including the cooling phase will be further investigated.

ACKNOWLEDGEMENTS

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

REFERENCES

[1] Eurocode 1: Actions on structure – Part 1-2: General actions – Actions on structures exposed to fire, CEN Brussels, 2002.

[2] EN 1363-1:2020, Fire resistance tests – Part 1: General requirements, CEN, Brussels, 1999.

[3] Bartlett A. I., Hadden R. M. and Bisby L. A.: A Review of Factors Affecting the Burning Behaviour of Wood for Application to Tall Timber Construction. *Fire Technology*, 55:1-49, 2019.

[4] Eurocode 5: Design of timber structures Part 1.2: General – Structural Fire Design, CEN, Brussels, 2004.

[5] Gernay T.: Fire resistance and burnout resistance of timber columns, *Fire Safety Journal*, 122, 103350, 2021.

[6] Gernay T, Franssen J.-M.: A performance indicator for structures under natural fire, *Engineering Structures*, 100, 94–103, 2015.

[7] Kinjo H., Yusa S., Horio T., Hirashima T., Matsumoto T. and Saito K., Fire performance, including the cooling phase, of structural glued laminated timber beams, in: 8th International Conference on Structures in Fire, 593-600, 2014

[8] Gernay T., Zehfuß J., Brunkhorst S., Robert F., Bamonte P., McNamee R., Mohaine S. and Franssen J.-M.: Experimental investigation of structural failure during the cooling phase of a fire: Timber columns, *Fire and Materials*, 1-16, 2022.

[9] Franssen, J.-M., Gernay, T. Modeling structures in fire with SAFIR$^{®}$: Theoretical background and capabilities. *Journal of Structural Fire Engineering*, 8 (3), 300-323, 2017.

https://doi.org/10.52202/069179-0244