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EXPERIMENTAL ASSESSMENT OF THE BURNOUT RESISTANCE OF TIMBER AND CONCRETE COLUMNS

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ABSTRACT

Fire-exposed structures may collapse after the available fuel in the compartment has been consumed, while the enclosure is cooling or even after returning to ambient temperatures. But there is no standardized experimental method to study the stability of structural elements until full burnout. The standard fire testing method relies on continuous heating of the element to failure, and in some cases post-fire experiments measure residual load-bearing capacity, but neither of these methods assesses stability of loaded elements throughout the heating and cooling phases of a fire. This paper applies a new experimental method for evaluating the load-bearing capacity function of structural elements until fire burnout. The method adopts the Duration of Heating Phase (DHP) indicator for assessing the burnout resistance of the elements. Full-scale furnace tests on loaded columns are presented, including four on reinforced concrete columns and eight on timber columns, in which identical specimens were subjected to various heating durations followed by controlled cooling. For both the concrete and timber columns, failures occurred during the cooling phase after exposure to ISO 834 heating for a duration shorter than their fire resistance. The timber columns had a measured fire resistance of 55-58 minutes (two specimens) but, when exposed to heating for 15 minutes, failed during cooling after 98-153 minutes (two specimens). These experiments show that delayed thermal-mechanical effects can jeopardize structural stability in real fires and provide a systematic method to assess these effects.

Keywords: Fire tests; concrete columns; glued laminated timber; cooling phase; burnout resistance

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1 INTRODUCTION

Fire-exposed structures may collapse during the cooling phase of the fire, or even thereafter. This poses challenges for building occupants but also for firefighters who must evaluate on the spot whether it is safe to enter a burning building to fight the fire. Incidents of collapse after extinction of a fire have led to casualties [1]. However, currently the concept that is overwhelmingly used to characterize and classify the ability of loadbearing members to withstand fire exposure is the standard fire resistance, which relies on standardized furnace tests that measure the response under heating only. The method of standard fire testing does not include any evaluation of the effects of cooling phases on structural stability.

Researchers have long recognized that structural fire assessments need to go beyond the standard fire resistance rating [2-4]. To better inform about continued stability (or lack thereof) of loadbearing members throughout the different phases of a fire, there needs to be a framework, experimental protocol, and design methods to systematically assess resistance until burnout.

Recently, the concept of burnout resistance evaluated through a standard indicator named 'Duration of Heating Phase' (DHP) was proposed [5]. The DHP quantifies the longest duration of exposure to heating according to the standard ISO 834 fire that will not result in failure of a member when assessing stability throughout the entire fire event. Importantly, the aim of the concept is not to replace a performance-based analysis of the response of a structure under a realistic fire, but rather to adopt a standard method to investigate, measure, and compare the effects of cooling phases on the stability of structural members.

The concept of DHP was applied numerically by Gernay to concrete columns [6] and timber columns [7]. These numerical studies, and subsequent ones [8], showed the relevance and usefulness of the approach as they quantified the maximum thermal exposure that the structural members could withstand to burnout, which is shorter than the members' fire resistance time. But the next necessary step is to apply the concept experimentally and confirm the numerical findings with test data.

In this research, an experimental program was conducted to measure the burnout resistance of full-scale loaded columns in standard furnaces. The experimental program applied for the first time experimentally the concept and method presented numerically in previous research [5-7]. This demonstrates the feasibility and relevance of measuring the ability of columns to maintain stability until full burnout. Experiments were conducted at the University of Liege on four reinforced concrete (RC) columns and at the Technische Universität Braunschweig on eight glued laminated (glulam) timber columns. In both cases, several identical column specimens were tested under identical conditions of loading, in furnaces, but under varying durations of heating according to the ISO 834 time-temperature curve, followed by controlled cooling down phases. Temperatures inside the columns and displacements were measured throughout the tests, for a long duration after the end of the heating to measure possibility of delayed failure. The paper reports the test data from the RC and glulam column fire tests including cases of failure during cooling.

2 BURNOUT RESISTANCE AND DHP

To quantify the resistance to full burnout in furnace testing, this research builds on previous work in which the indicator of Duration of Heating Phase (DHP) [5] was proposed for investigation of delayed failures of structural members during the cooling phase of a fire. The DHP is a systematic measure of the longest heating phase which a structural member will be able to withstand until the end of the fire event, i.e., until the temperatures in the member are back to ambient. The DHP is evaluated by considering a standardized fire exposure with cooling phase and assessing the behaviour of the loaded member continuously throughout the different stages of the fire. The adopted standardized fire exposure, necessary to allow for systematic quantification and comparison between members, has the heating according to the ISO 834 curve followed by linear cooling with the cooling rate from the Eurocode parametric fire model when $\Gamma=1$ (it is close to -10 K/min for short durations of heating, and decreases for longer heating). The definition of the DHP is illustrated in Figure 1 and discussed in detail in previous publications [5-7].

Evaluating the DHP of a structural member requires to successively test the effect of various time-temperature curves on its stability, as illustrated in Figure 1. The DHP is eventually obtained by bounding the behaviour of the member, between a thermal exposure that can be survived to burnout, and one slightly longer that results in collapse during or after the cooling phase. In an experimental setting, this implies constructing several identical specimens and testing them under identical conditions except for the applied duration of the heating phase. This is the concept of the experimental program devised in this research.

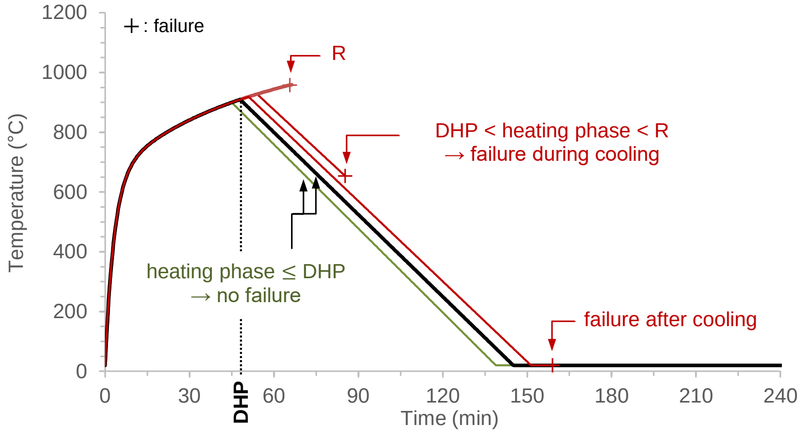


Figure 1. Definition of the DHP indicator to quantify a measure of burnout resistance.

3 DESCRIPTION OF THE EXPERIMENTS

3.1 Experimental method

The experiments are conducted in column furnaces. The columns are tested under heating exposure followed by a cooling phase while the load is maintained, and displacements are measured continuously until stabilization. This stabilization of displacements occurs hours after the end of the heating exposure due to the slow heat transfer across the column section. It is thus important to measure the response for many hours after the end of heating.

For any given test, possible outcomes are that the column: (i) fails during the heating phase, (ii) fails during or after the cooling phase, or (iii) survives the considered exposure. Several tests are conducted on identical specimens to explore the effects of different heating exposures. The heating-cooling exposures are selected with the aim to achieve the different outcomes and bound the behaviour to evaluate the columns' DHP. A priori modelling by the finite element method with SAFIR [9] is used to inform selection of the exposures. Details of the experiments are provided hereafter for the concrete and timber columns, respectively.

3.2 Concrete columns

The experiments on concrete columns were conducted at the Fire Testing Laboratory at the University of Liege, Belgium. The laboratory is accredited ISO 17025. The gas furnace for the column testing is 3.25 m in height. The loading is applied by two hydraulic jacks working in parallel. In each test, the columns were loaded with the same load. The tests varied by the applied time-temperature curve, see Figure 2.

Four identical reinforced concrete columns were cast. Siliceous concrete with a measured cylinder strength at 28 days of 31.3 MPa was used. The columns were designed according to Eurocode for a representative concrete building with five stories. The columns were 3.00 m long with a section of 300 x 300 mm². The longitudinal reinforcement, grade S500 steel, was made of 4 bars of 14 mm in the corners and 4 bars of 10 mm on the medians of the section, with a concrete cover of 20 mm over the 6 mm diameter stirrups. The columns were loaded at 1009 kN during the fire tests, with an eccentricity of 20 mm. This loading represents 56 % of the design load bearing capacity at ambient temperature (1814 kN) calculated according to Eurocode EN1992-1-1 [10]. The degree of utilization at ambient temperature is 90 %. The standard fire resistance rating of the column is 60 minutes according to Eurocode EN1992-1-2 [11] simplified method.

Test 1 was a standard fire resistance test with ISO 834 heating to failure. In Tests 2, 3, and 4, the columns were subjected to respectively 45 minutes, 55 minutes, and 72 minutes of ISO 834 heating followed by cooling, see Figure 2. Additional details on the specimens and experiments are provided in Ref. [12].

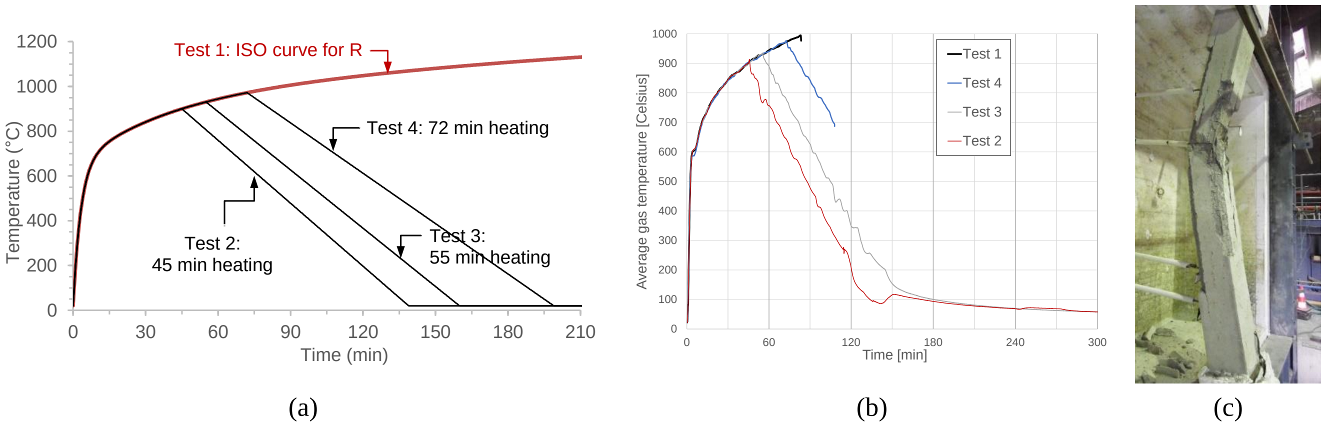


Figure 2. Concrete column fire tests. (a) Time-temperature curves, planned. (b) Measured furnace temperature. (c) column.

3.3 Timber columns

The experiments on timber columns were conducted at the Institute of Building Materials, Concrete Constructions and Fire Safety (iBMB) of Technische Universität Braunschweig, Germany. The furnace has an inner floor area of 3.60 by 3.60 m² and an inner height of 3.50 m. The furnace uses six oil burners. The mechanical load is applied by a hydraulic press system.

Eight identical timber columns were constructed. The timber columns consisted of glued-laminated spruce made with melamine glue. The single lamellas were 40 mm thick and finger joints were used to produce lamellas of desired length. The strength class was GL 24h. A total of 48 thermocouples were installed at three different heights inside the timber column (16 per section). The measured moisture content for all columns was 9 % ± 0.5 % (in mass percentage) at 5 mm and 13 % ± 0.5 % (in mass percentage) at 30 mm on average. The design of the timber column was also defined to sustain a load representative of a building with five stories with a degree of utilization of 90% at ambient temperature. The cross-section of the timber columns was 280 by 280 mm². The length of the columns was 3.68 m. The columns were loaded at 322 kN during the fire tests, with an eccentricity of 20 mm. The columns were designed to achieve a target fire resistance of R60 according to the Eurocode EN1995-1-2 [13] with consideration of the revised value of the zero-strength layer in prEN1995-1-2 [14]. Details on the specimens and tests are provided in Ref. [15].

Tests 1 and 2 were standard fire resistance tests in which the columns were subjected to ISO 834 heating until failure. Test 1 was hinged-fixed while Test 2 was hinged-hinged; for the remainder of the test program, hinged-hinged conditions were used. In Tests 3 and 4, the columns were subjected to respectively 15 minutes and 10 minutes of ISO 834 heating, followed by a cooling at 10.4 °C/min. Tests 5 to 7 served to verify the repeatability of the previous tests, without inner thermocouples. The time-temperature curves applied in the timber column tests are plotted in Figure 3.

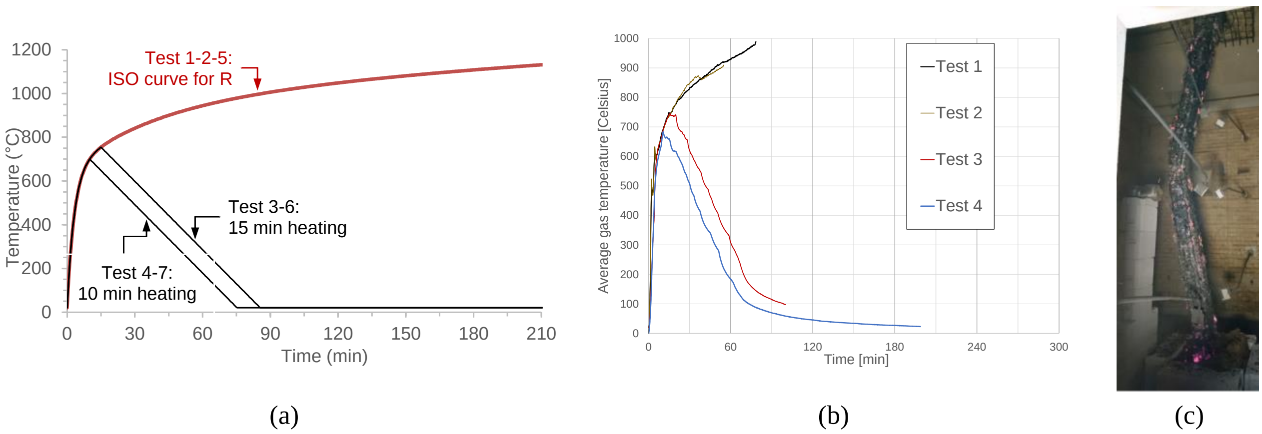


Figure 3. Timber column fire tests. (a) Time-temperature curves, planned. (b) Measured furnace temperature. (c) column.

4 EXPERIMENTAL RESULTS

4.1 Concrete tests

The tests were conducted at Liege in the summer of 2021. In Test 1, the column failed after 83 minutes of exposure to the ISO 834 time-temperature curve. In Test 2, an identical column was subjected to ISO 834 heating for 45 minutes followed by a linear cooling phase with a rate of -9.4 K/min. No collapse was observed. After 6 hours and 15 minutes, when all temperatures in the section were cooling and were below 150 °C, the load was increased until failure. The post-fire failure load was 1527 kN. In Test 3, the column was heated for 55 minutes followed by cooling at -8.9 K/min (cooling rates are from the Eurocode parametric fire model). No collapse was observed. The column was loaded until failure after 5 hours and 30 minutes. The failure load was 1497 kN. In Test 4, the column was subjected to 72 minutes of ISO 834 heating, followed by cooling at -7.5 K/min. The column failed during cooling after 108 minutes of testing. At time of failure, the temperature in the furnace had dropped from 973 °C to 700 °C.

Figure 4 plots the evolution of the axial displacement at the top of the RC columns. The columns first expand (negative values of axial displacement on the plot) under the effect of thermal expansion. Then, the displacement progressively shifts to a contraction as the column stiffness is reduced by temperatures, transient creep develops [16], and, in Tests 2-3, long cooling leads to partial recovery of the thermal strains.

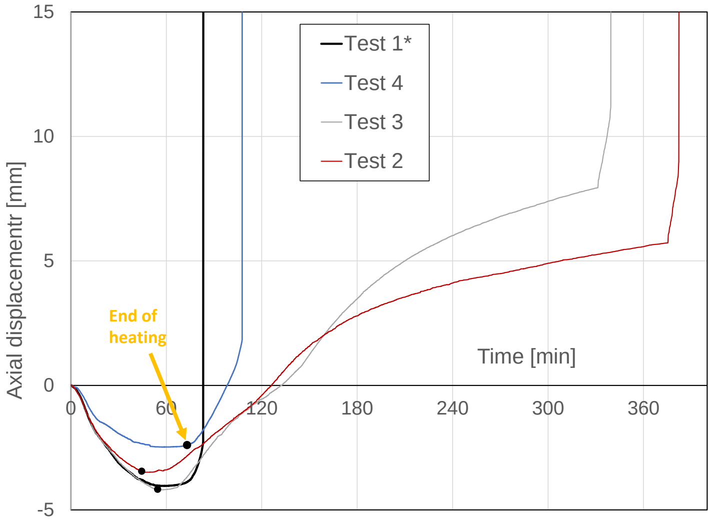


Figure 4. Concrete column tests: evolution of the axial displacement of the columns (negative values are for elongation). Test 1 fails in heating; Test 4 fails in cooling; Tests 2 and 3 are loaded to failure after the end of the heating-cooling sequence.

The experimental program achieved the intended outcome: the tests captured one failure in heating, one failure in cooling, and two cases of survival to burnout. Figure 5 plots the tests outcomes on a timeline. It shows that RC columns may fail during the cooling phase after exposure to ISO 834 heating for a duration shorter than their standard fire resistance. The DHP lies between 55 min and 73 min. The results from the RC column tests are summarised in Table 1.

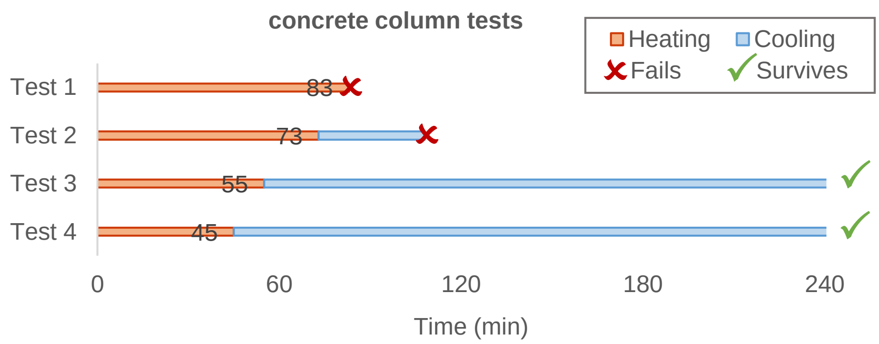


Figure 5. Results from the furnace tests on reinforced concrete columns under heating and cooling.

Test	Time of collapse in the heating phase	Start of the cooling phase	Time of collapse in the cooling phase	Failure load after cooling
	Minutes	Minutes	Minutes	kN
1	83	-	-	-
2	-	45	-	1527
3	-	55	-	1497
4	-	73	108	-

Table 1. Results of the fire tests on the reinforced concrete columns.

Figure 6 shows pictures of the RC columns after the fire tests. The column from Test 1 exhibited corner spalling, but it is unclear whether this spalling developed before the failure or was caused by the failure. The column from Test 3 was loaded to failure after the heating-cooling exposure to determine the residual loadbearing capacity. The column from Test 4 failed during the cooling phase.

Test 1 (failure at 83 min) Test 3 (loading at 330 min) Test 4 (failure at 108 min)

Figure 6. Pictures of the RC columns fire tests.

4.2 Timber tests

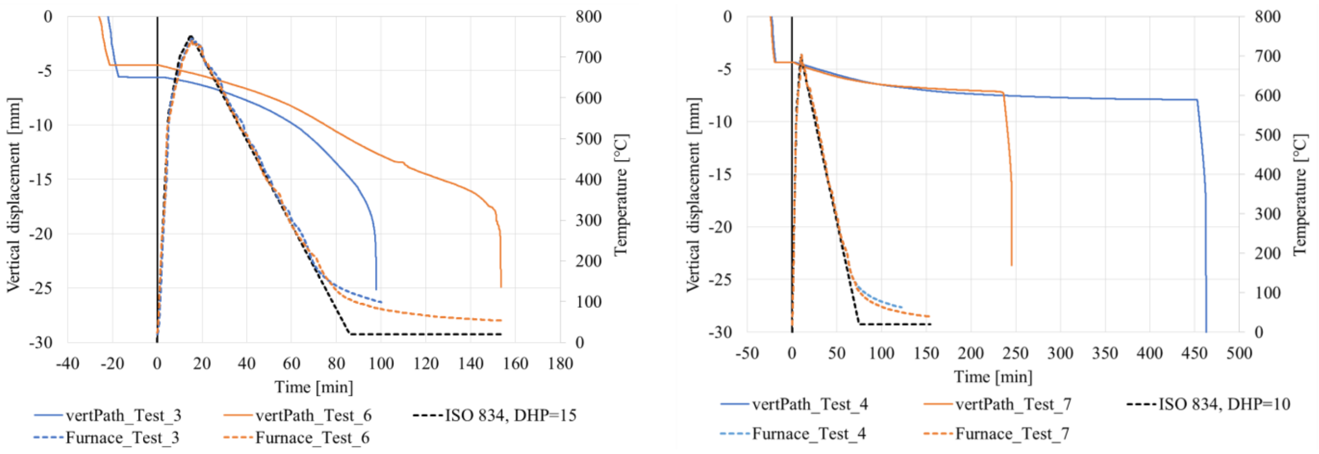
The timber tests were conducted at Braunschweig during the spring and summer of 2021. Tests 1, 2, and 5 were standard fire resistance tests under the load of 322 kN. In Test 1, which was hinged-fixed, failure occurred after 78 minutes of fire exposure. In Test 2, which was hinged-hinged, failure occurred after 55 minutes. Test 5 was identical to Test 2 except that no thermocouples were installed in the specimen of Test 5. The column of Test 5 failed at 58 minutes, indicating good repeatability of the fire resistance test. The average charring rate, under the assumption of a charring temperature of 300 °C, was 0.64 mm/min at the axis of the column.

In Tests 3 and 6, the timber column was subjected to the ISO 834 heating for 15 minutes followed by a linear cooling phase at a rate of -10.4 K/min. The tests were nominally identical but the specimen of Test 6 was without inner thermocouples. Both columns collapsed in the late decay phase under the constant load of 322 kN (Figure 7a). During the cooling phase, the temperature continued increasing inside the timber section. A self-extinguishing of flames on the surface of the timber columns in Tests 3 and 6 occurred after approximately 40 minutes, but local smouldering was visible until the failure in Test 3 and until 100 minutes in Test 6. The column in Test 3 collapsed after 98 minutes and that in Test 6 collapsed after 153 minutes.

In Tests 4 and 7, the duration of the ISO 834 heating was 10 minutes. This was followed by a cooling phase at a rate of -10.4 K/min. Visible flaming stopped after 35 minutes. Self-extinguishing of the visible smouldering occurred after 100 minutes. After 150 minutes, all measured temperatures were below 100 °C and decreased very slowly. The vertical displacement progressively increased until about 200 minutes, after which it stabilized. Both columns survived the fire exposure; the columns were then loaded to failure (Figure 7b). The ultimate load capacity was 893.3 kN for Test 4 and 864.9 kN for Test 7. A residual cross-section without discoloration of approximately 230 by 230 mm² was measured after the fire tests.

Test 8 was an ambient temperature test to measure the loadbearing capacity. The ultimate load capacity for Test 8 was 2159 kN. This exceeds by a factor 2.7 the design load-carrying capacity of 800 kN obtained from application of the Eurocode 1995-1-1 [17] equations for a column subjected to combined compression and bending with a strength values of GL 24h, which may be due to the use of the 5% strength fractile in the Eurocode and/or the fact that the producer may have used lamellas with a higher strength classification. From Tests 4 and 7, the residual load capacity of the column after exposure to the fire with a 10 minutes heating phase was 40% of the load-bearing capacity measured at ambient temperature in Test 8.

Figure 8 plots the tests outcomes on a timeline. The timber columns may fail long into the cooling phase after a relatively short exposure to ISO 834 heating. For these specimens which have a measured fire resistance of 55 minutes (Test 2) to 58 minutes (Test 5), the DHP lies between 10 to 15 minutes.



(a) Test 3 and Test 6

(b) Test 4 and Test 7

Figure 7. Timber column tests: evolution of the axial displacement of the columns (negative values are for contraction). Tests 3-6 fail in cooling with the 15 min heating; Tests 4-7 survive with the 10 min heating and are loaded to failure after.

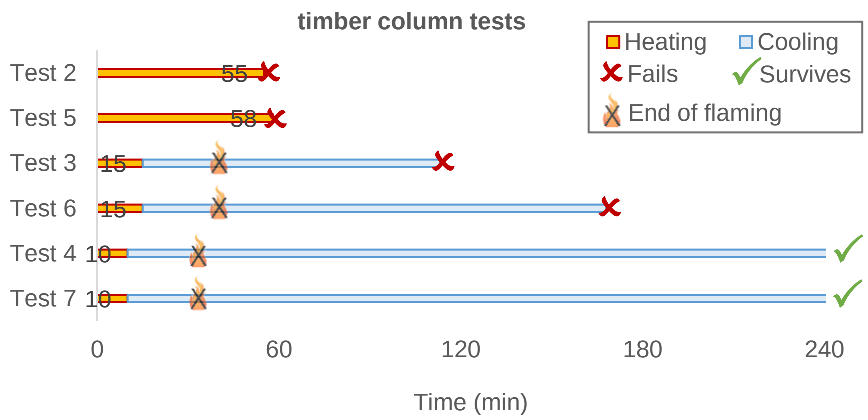


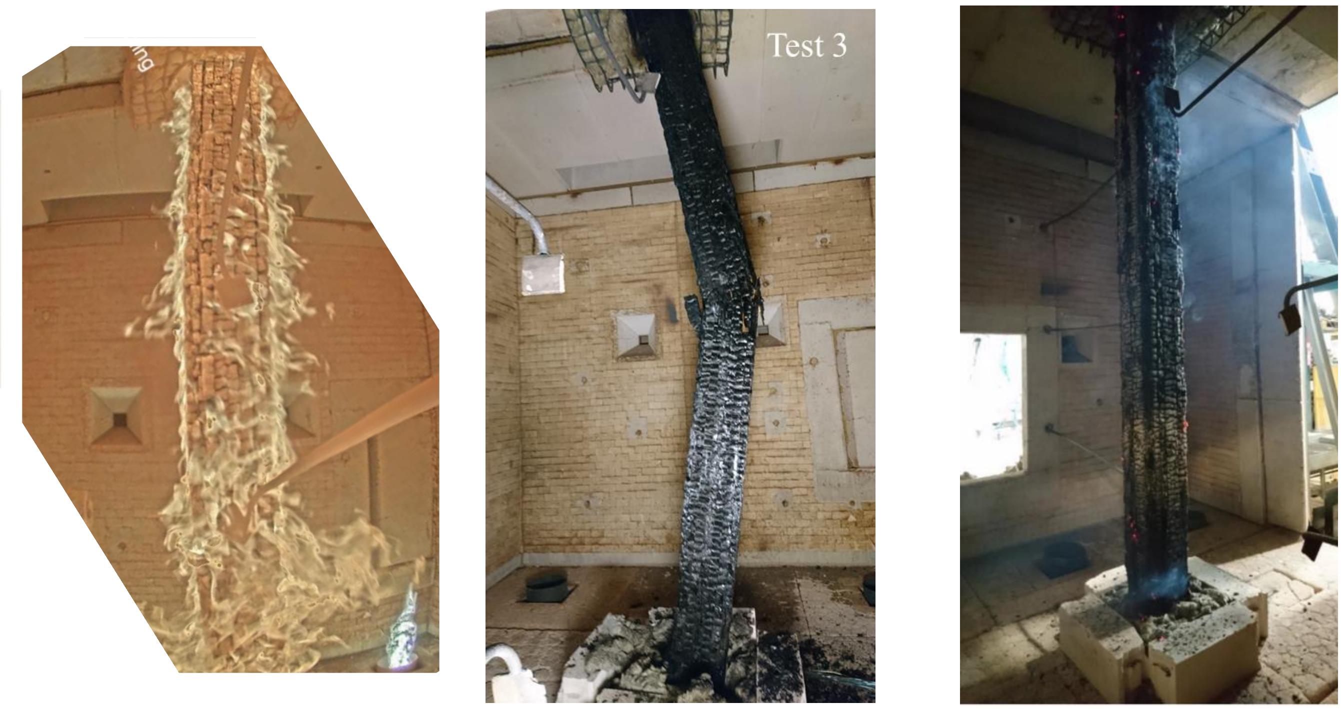
Figure 8. Results from the furnace tests on glulam timber columns under heating and cooling.

The results from the timber column tests are summarised in Table 2. A failure during the late decay phase of the heating-cooling gas temperature-time curve occurred in Tests 3 and 6. On the contrary, the columns of Tests 4 and 7 survived the heating-cooling sequence and were subsequently subjected to increasing load to assess their ultimate load capacity. The results show that there is good repeatability of the experiments and no significant influence of the milling grooves for the thermocouples on the load-carrying behaviour (Test 2 vs Test 5; Test 3 vs Test 6; Test 4 vs Test 7). The test program achieved the intended outcome, with data on failure during heating, failure in the late cooling stage, and survival to full burnout with subsequent loading to failure.

Figure 9 shows pictures of the timber columns from Tests 2, 3, and 4 in the furnace.

Table 2. Results of the fire tests on the glulam timber columns.

Test	Time of collapse in the heating phase	Start of the cooling phase	Time of collapse in the cooling phase	Failure load after cooling
	Minutes	Minutes	Minutes	kN
1	78	-	-	-
2	55	-	-	-
3	-	15	98	-
4	-	10	-	893
5	58	-	-	-
6	-	15	153	
7	-	10	-	865
8	-	-	-	2159 (ambient)



Test 2 (failed during heating) Test 3 (failed during cooling) Test 4 (survived the fire)

Figure 9. Pictures of the timber columns fire tests.

Figure 10 shows the residual cross-section of the column from Test 3 at the end of the test. The residual cross-section without discoloration was approximately 220 by 220 mm² for the specimens of Tests 3 and 6. This means that, for the fire with a 15-minute heating duration, approximately 30 mm was consumed on each side over the whole fire exposure. From the standard fire resistance tests (Tests 1, 2, 5), the average charring rate under ISO 834 exposure was 0.64 mm/min. Accordingly, the 15 minutes of exposure to ISO 834 would have resulted in approximately 10 mm of charring depth at the end of the heating phase in Test 3 and Test 6. This shows that, under a fire exposure with a cooling phase, the depth of the section consumed by the thermal exposure (herein, about 30 mm when the column fails at 98 minutes) increases well beyond the charring depth determined at the time of maximum gas temperature (herein, 10 mm at the end of the 15-minute heating).

Figure 10. Residual cross-section for Test 3 of about 220 by 220 mm² (initial section: 280 by 280 mm²).

Figure 11 plots the evolution of the temperature inside the cross-section of the timber column during Test 3. The temperature data that is plotted is an average value of the thermocouple measurements over the three sections at the respective depth. The temperature inside the timber section continues increasing long after the end of the heating phase. It takes 90 minutes for the temperature inside the timber column to decrease below 200 °C.

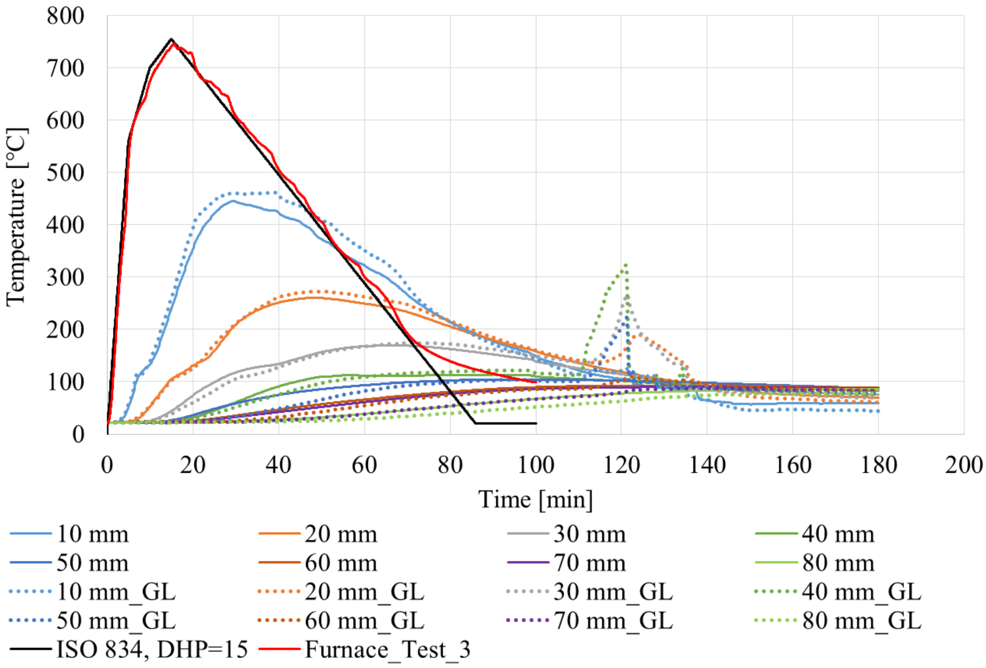


Figure 11. Time-temperature development inside the timber column at different depths under exposure to the 15 minutes heating fire (DHP = 15 min), Test 3.

5 COMPARISON WITH NUMERICAL MODELS

The test program allowed evaluating experimentally the burnout resistance of the RC column and the timber column, based on the DHP indicator [5]. The DHP of the RC column is between 55 and 73 minutes, see Figure 5, because the RC column survived the standardized heating-cooling sequence with a heating phase of 55 minutes but failed under the one with a heating phase of 73 minutes. The DHP of the timber column is between 10 and 15 minutes. Previous FEM studies had been conducted on columns to evaluate their DHP numerically. The new test data can thus be compared with the numerical predictions.

For the RC column, the new test data from this study is compared with the numerical results from the analysis of 74 reinforced concrete columns [6]. The comparison is shown in Figure 12. The experimental fire resistance is 83 minutes (from Test 1), so the “Test data” in Figure 12 shows an interval for R=83min and DHP=[55-73]min. The DHP equation proposed in [6] yields a DHP of 57 min based on the experimental fire resistance of 83 min, which is consistent with the experimentally obtained DHP. The experimental results obtained in this research agree well with the numerical predictions.

For the timber column, the test data from this study is compared with numerical results on 49 glulam timber columns analysed with SAFIR [7] in Figure 13. Two intervals are provided for “Test data” corresponding to the measured values of R equal to 55 and 58 minutes, respectively. The experimental DHP lies between 10 and 15 minutes. Very good agreement is obtained between the experimental data obtained in this study and the numerical predictions of R versus DHP published previously.

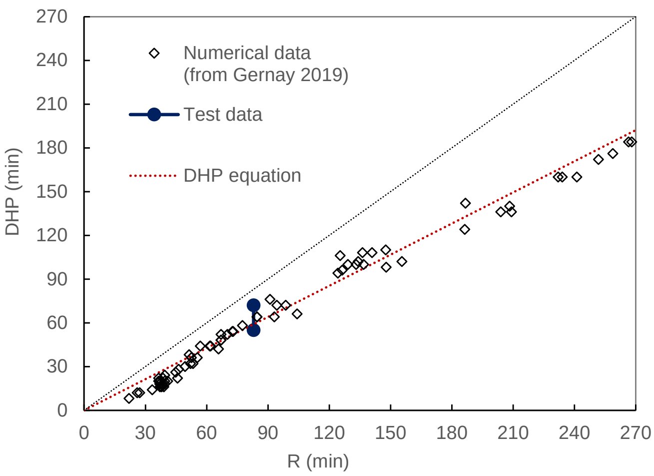


Figure 12. Fire resistance (R) and burnout resistance (DHP) of the concrete column specimen from this study compared with a previously published numerical dataset [6] for 74 reinforced concrete columns.

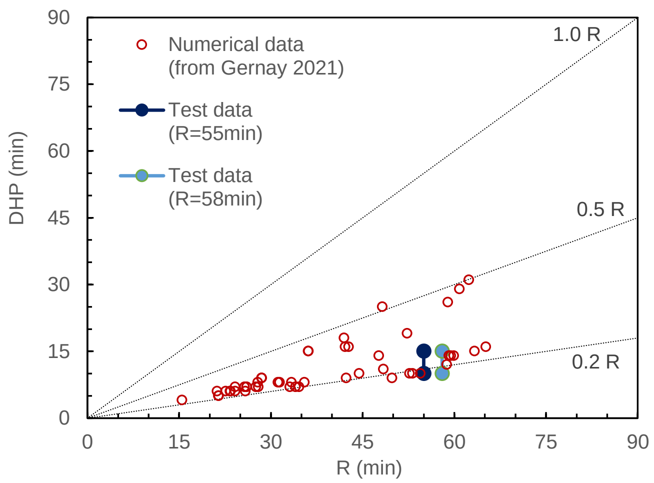


Figure 13. Fire resistance (R) and burnout resistance (DHP) of the timber column specimen from this study compared with a previously published numerical dataset [7] for 49 timber columns.

For both concrete and timber columns, the experiments demonstrate that loadbearing members may fail during the cooling phase when exposed to standardized ISO 834 heating for a duration shorter than their standard fire resistance. The physical phenomena that explain these delayed failures had been explained theoretically and discussed in papers presenting numerical results [6,7,18]. The delayed failures are primarily caused by delayed temperature increase (and charring in case of timber) inside the sections of the columns. As the heat is progressively transferred from the edge to the core of the section, the material strength in the core of the section reaches its minimum reduced value long after the end of the heating phase. The consequences depend on the material since different materials exhibit different laws of strength reduction with temperature. The experimental program presented in this paper confirmed these phenomena, not only qualitatively, but also quantitatively showing that advanced numerical models by the finite element method can be used to accurately assess the behaviour under heating and cooling.

6 CONCLUSIONS

This paper described the application of an experimental method to study the behaviour of columns subjected to fire until burnout. The method assesses the effects of heating-cooling exposure on the structural stability of the columns and determines what severity of fire exposure the columns can survive to full burnout. Application to loaded reinforced concrete columns and glulam timber columns provided new data on their response under controlled heating-cooling exposure. The main findings are:

- While the physical phenomena that explain failure during or even after cooling had been explained theoretically, and the concept of DHP had been introduced and quantified numerically for concrete and timber columns, this testing program brought an experimental confirmation to these theoretical and numerical developments, corroborating models on the prediction of structural failure during cooling.
- Besides qualitatively confirming the phenomena that explain delayed failure, the experimental results agree closely with numerical data previously published based on FE analyses with SAFIR. Numerical predictions of failure during the cooling phase are thus validated by the experiments, both for concrete and timber columns, supporting the validity of advanced analysis for studying burnout resistance.
- The new data include tests on four loaded reinforced concrete columns, 300 by 300 mm² and 3.0 m long, under various fire exposure. While the column had a tested fire resistance of 83 minutes, it failed during the cooling phase when the burners were shut off after 72 minutes while the load was maintained. The column survived a shorter fire exposure with 55 minutes heating.
- The new data also include tests on eight loaded glulam columns, 280 by 280 mm^2 and 3.7 m long. Under continuous ISO 834 heating, two column specimens failed at 55 and 58 minutes. Yet when testing identical columns under 15 minutes of ISO 834 followed by a cooling phase, two column specimens collapsed during the ensuing cooling phase after 98 and 153 minutes.
- Flame extinction was not an indicator of whether the timber column would survive to full burnout. The two timber columns subjected to 15 minutes of heating both exhibited self-extinguishing of flames after 40 minutes but failed after 98 and 153 minutes. Fire brigades should thus not take cessation of flaming of timber members as an indication of safety leading them to enter the building.

The findings from the experiments demonstrate that delayed thermal-mechanical effects can jeopardize structural stability in real fires, and they provide a framework to measure these effects in tests. Research is ongoing to further study the effects of different cooling rates, including in natural compartment fire experiments. Moving beyond fire resistance to quantify the response until burnout will support designs for safety of occupants and firefighters throughout the fire and promote repairability and resilience.

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