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# INFLUENCE OF ELEVATED TEMPERATURE ON THE STRENGTH AND STIFFNESS OF TIMBER

Christoph Kurzer[1], Kilian Zeier[2], Norman Werther[3], Cvetanka Chifliganec[4], Katrin Nele Mäger[5], Alar Just[6], Andrea Frangi[7], Stefan Winter[8]

**ABSTRACT:** This paper presents the procedure and results of small-scale experiments on the effect of elevated material temperatures on wood's mechanical properties (strength and stiffness) for static loading in compression and bending. This includes three scenarios investigating the behaviour at elevated temperatures and the reversibility of these effects caused by heating the wood. The heated scenario investigates the mechanical properties at eight temperature levels up to 240 °C. The cooled-down scenario investigates material properties when the heated specimen is re-cooled for 24 hours. In the re-moisturised scenario, the specimen was stored in a climate chamber for 28 days after heating before the load tests were executed. The material temperatures were kept constant within the experiment series, unlike in a real fire scenario. While the compressive strength remains almost equal, the compressive stiffness varies over temperature. Strength and stiffness in bending decrease with rising temperatures. Generally, the effects are reduced by cooling down and further reduced by re-moisturing, showing apparent reversibility.

**KEYWORDS:** timber, material properties, strength, stiffness, elevated temperature

## 1 – INTRODUCTION

For the fire design of timber structures, knowledge about the behaviour of wood in fire and elevated temperature is essential. Besides charring and the temperature distribution within a fire-exposed cross-section, the temperature influence on the mechanical properties, like strength and stiffness, is crucial for precise analytical and numerical fire design methods. Also, this knowledge acts as a basis for developing future standards for timber structures, like EN 1995-1-2 [1] in Europe.

Therefore, the research project " Mechanical Properties of Wood for Fire Design" investigates the thermomechanical properties of wood exposed to fire. Aiming to provide a basis for revising or confirming the design methods in prEN 1995-1-2 [2], the Swiss Federal Institute of Technology Zurich (ETH Zurich), the Technical University of Munich (TUM), and the Tallinn University of Technology (TALTECH) joined in this research project and planned to carry out medium-scale fire tests on timber members, numerical examinations, and small-scale experiments on wood under elevated temperatures. The small-scale experiments aim to investigate whether a correlation exists between the behaviour of timber members exposed to fire and exposure to elevated temperatures without direct fire exposure.

This paper discusses the small-scale experiments that have been conducted until now. Like the medium-scale fire test, the small-scale experiments investigate the three main load types: compression, bending, and tension. This paper includes the compression and bending experiments on pre-heated wood up to material temperatures of 240 °C before applying load.

## 2 – BACKGROUND

### 2.1 STATE OF THE ART IN EUROPE

The current (EN 1995-1-2:2004-11 [1]), as well as the new generation (prEN 1995-1-2:2023-09 [2]) of the Eurocode 5, provides simplified relationships for mechanical properties of wood as a function of the temperature based on König's and Walleij's work [3]. Figure 1 shows those relationships as bi-linear curves with full strength at 20 °C, zero strength at 300 °C, and a breakpoint at 100 °C. The compression strength is

[1] Christoph Kurzer, Chair of Timber Structures and Building Construction, TUM, Munich, Germany, ORCID: 0000-0001-7559-7110

[2] Kilian Zeier, Chair of Timber Structures and Building Construction, TUM, Munich, Germany, ORCID: 0009-0003-9634-3234

[3] Norman Werther, Technical University of Applied Sciences Augsburg, Germany, ORCID: 0000-0001-9762-1329

[4] Cvetanka Chifliganec, Institute of Structural Engineering, ETH Zürich, Zürich, Switzerland

[5] Katrin Nele Mäger, Structural Engineering Research Group, TalTech, Tallinn, Estonia, ORCID: 0000-0002-6623-9263

[6] Alar Just, Structural Engineering Research Group, TalTech, Tallinn, Estonia, ORCID: 0000-0002-8001-401X

[7] Andrea Frangi, Institute of Structural Engineering, ETH Zürich, Zürich, Switzerland, ORCID: 0000-0002-2735-1260

[8] Stefan Winter, Chair of Timber Structures and Building Construction, TUM, Munich, Germany, ORCID: 0000-0002-5825-0710


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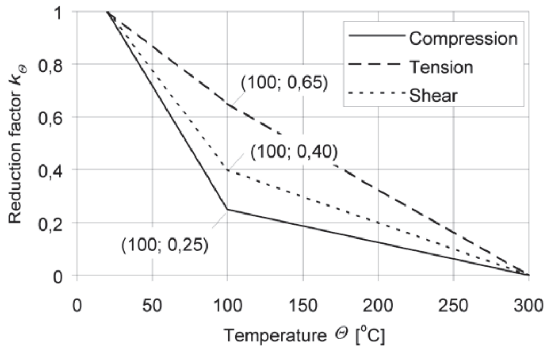
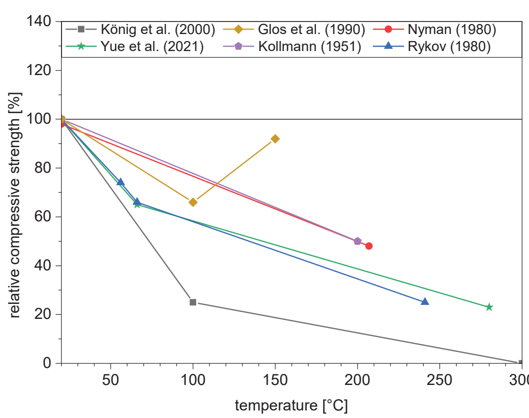



*Figure 1 – Reduction factor for strength parallel to the grain of softwood according to EN 1995-1-2 [1]*

reduced significantly from 100 % at 20 °C to 25 % at 100 °C, which raises the question of whether that represents actual material behaviour. Also, this question can be asked for the other load types and stiffness.

## 2.2 STATE OF SCIENCE

In the past, research has focused several times on the temperature-dependent material properties of wood since it is needed to estimate how a timber element performs structurally in a fire. Data from different studies enhance the existing uncertainty in this matter. Depending on differences in experimental procedure, wood species, dimensions of specimens, and exposure to fire or temperature, the research results indicate variability in the reduction factor for strength and stiffness. Figure 2 compares several research results, highlighting the uncertainty of those. Generally, König's results [3] are often the most conservative once compared to Nyman [4], Yue [5], Glos [6], Rykov [7], Kollmann [8], Young [9], Schaffer [10], Kaku [11], Kollmann [12], or de Moraes [13], which indicates a possibility to improve the reduction factors embedded in the standards when the reasons for the differences in the research results are known.

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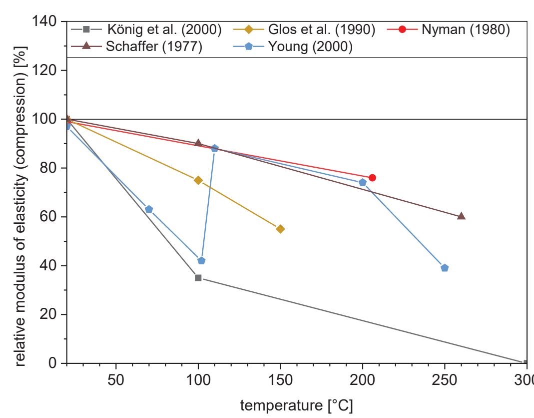


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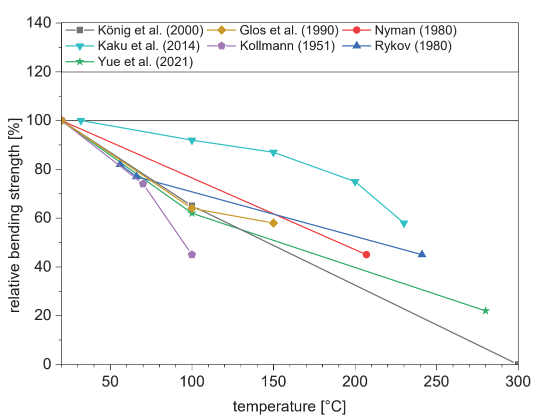


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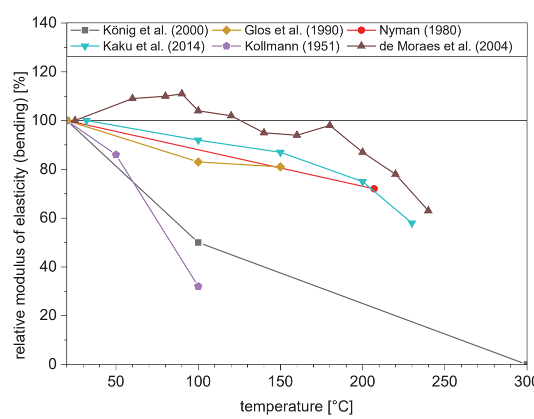



d)

*Figure 2 – Comparing research results on a) compression strength, b) compression stiffness, c) bending strength, and d) bending stiffness*

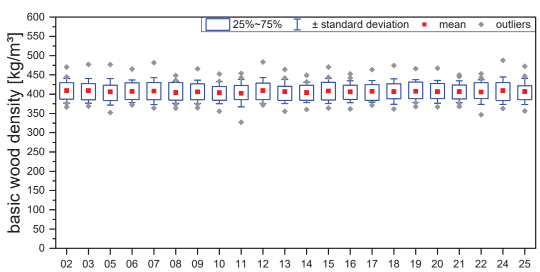
## 3 – PRODUCING SPECIMEN

### 3.1 RAW MATERIAL

As raw material for the specimens, Hasslacher Holding GmbH and Rubner Holding AG provided pre-planned lamellas 44 mm by 170 mm with a length of 4 m from their glued laminated timber production. Using machine grading, the parameters for the chosen lamellas are set to a grading class of T14 and a narrow density range between 420 and 440 kg/m³, aiming to select wood with a more homogeneous strength and stiffness.

### 3.2 SELECTING SPECIMEN

Aiming to achieve almost defect-free specimens, over 450 pieces were produced for each experimental series of compression and bending, focusing on using only a suitable part of the provided material. Afterwards, only specimens that fit the wanted quality were selected, while the others were rejected. To form 36 test groups of ten specimens with a similar spread across the dry density, the dry density for each specimen was determined. Figure 3 illustrates the dry density spread of the testing group used for the compression and bending. The mean dry density of all groups is close to around 404 kg/m³. Assuming a wood moisture of 12 M.-%, the value of 452 kg/m³ is close to the given values of 460 kg/m³ in DIN 68364 [14] for the used wood types spruce or fir.

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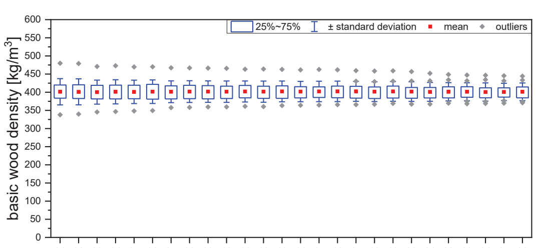


b)

*Figure 3 - Basic wood density spread of the test groups for a) compression [15] and b) bending [16]*

### 3.3 SPECIMEN DIMENSIONS

Based on the specifications of EN 408 [17], the specimens for compression have a cross-section of 30 mm by 30 mm and a length of 180 mm. For bending, the specimens have a cross-section of 35 mm in height by 70 mm in width and a length of 665 mm, which is visualised in Figure 4.

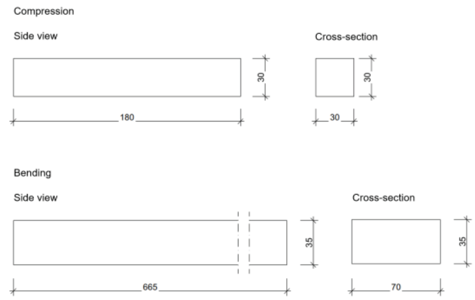


*Figure 4 - Dimensions of specimens*

### 3.4 CONDITIONING SPECIMEN

The produced test specimens were stored in a climate chamber, as shown in Figure 5, that maintained a standard climate with an air temperature of 20 ± 2 °C and a relative humidity of 65 ± 5 %, complying with the requirements of EN 408 [17].

a)

b)

*Figure 5 - Specimen storage in climate chamber for a) compression and b) bending experiments*


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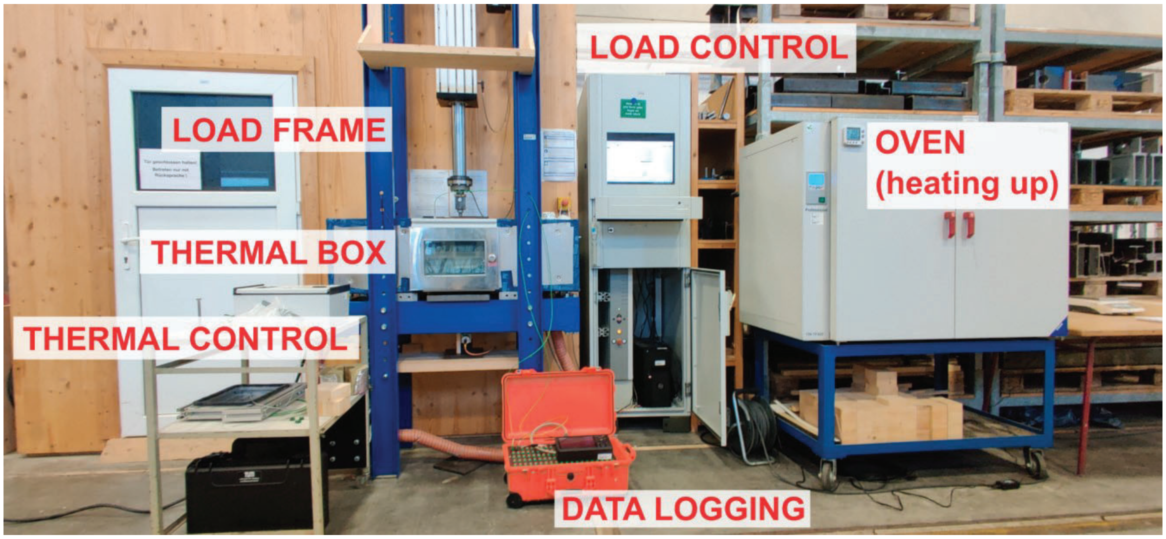



*Figure 6 - Laboratory setup [15]*

## 4 – EXPERIMENTAL SETUP

### 4.1 LABORATORY SETUP

Figure 6 shows how the needed test equipment was assembled in the laboratory to minimise thermal losses while transporting the specimens from the oven to the load frame. A thermal box inside the load frame ensured a constant temperature environment while applying the load to the pre-heated specimens.

### 4.2 LOAD SETUP FOR COMPRESSION

Figure 7 shows the load setup with dimensions for compression. The feed rate was set to 0.01 mm/s to ensure the failure occurred within 300 ± 120 seconds, as specified in EN 408 [17].

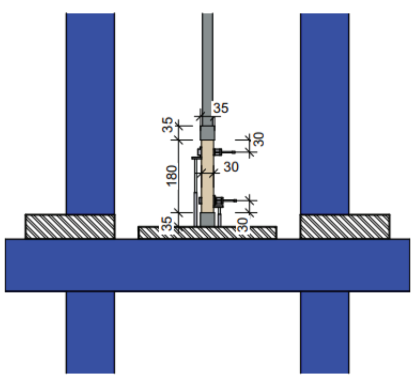



*Figure 7 - Drawing of the load setup for compression experiments [15]*

### 4.3 LOAD SETUP FOR BENDING

Figure 8 shows the load setup with dimensions for bending. The feed rate was set to 0.075 mm/s to ensure the failure occurred within 300 ± 120 seconds, as specified in EN 408 [17].

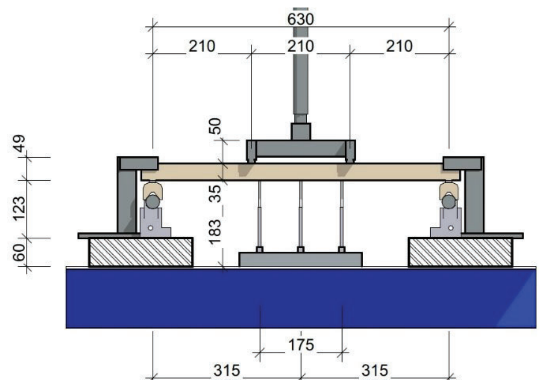



*Figure 8 – Drawing of the load setup for bending experiments [16]*

## 5 – EXPERIMENTAL PROCEDURE

### 5.1 GENERAL

For compression and bending, the same three experiment scenarios were performed to investigate how the strength and stiffness behave while heated, after cooling down for 24 hours, and after regaining wood moisture for a month. As documented in the test reports, compression was executed with a maximum material temperature of 210 °C [15]. In comparison, bending reached a maximum material temperature of 240 °C [16] due to an improvement in the experimental setup. A reference test for all scenarios was conducted with a material temperature of 20 °C. For all scenarios, the material temperature levels were 60 °C, 90 °C, 105 °C, 120 °C, 150 °C, 180 °C, 210 °C, and for bending 240 °C.

### 5.2 HEATED - SCENARIO

The heated scenario investigates how the thermo-mechanical properties of pre-heated wood behave at certain material temperatures. Therefore, the following workflow was executed:

1. The specimens were weighed before heating to conclude the wood moisture content after conditioning.
2. To heat the specimens, they were placed in the oven set five degrees above the tested material temperature level and equipped with thermocouples to measure the material temperature.
3. After heating, the specimens were immediately installed in the test stand equipped with a heated box to minimise thermal losses.
4. After the compression test, the specimens were reweighed to measure the mass loss from heating.
5. Cracks and deformations were marked, and the specimens were subsequently photo-documented.

### 5.3 COOLED DOWN - SCENARIO

The cooled-down scenario investigates how pre-heated wood's thermo-mechanical properties are reversible when, after heating, the wood is cooled down to standard temperature for 24 hours. Therefore, the following workflow was executed:

1. The specimens were weighed before heating to conclude the wood moisture content after conditioning.
2. To heat the specimens, they were placed in the oven set five degrees above the tested material temperature level and equipped with thermocouples to measure the material temperature.
3. After heating, the specimens were reweighed to measure the mass loss from heating and subsequently photo-documented.
4. 24 hours later, the specimens were weighed again to measure the weight changes due to the cooling and conditioning with standard climate at 20 °C and 65 % relative humidity.
5. Afterwards, the specimens were installed in the test stand and tested at standard temperature.
6. Cracks and deformations were marked, and the specimens were subsequently photo-documented.

### 5.4 RE-MOISTURISED - SCENARIO

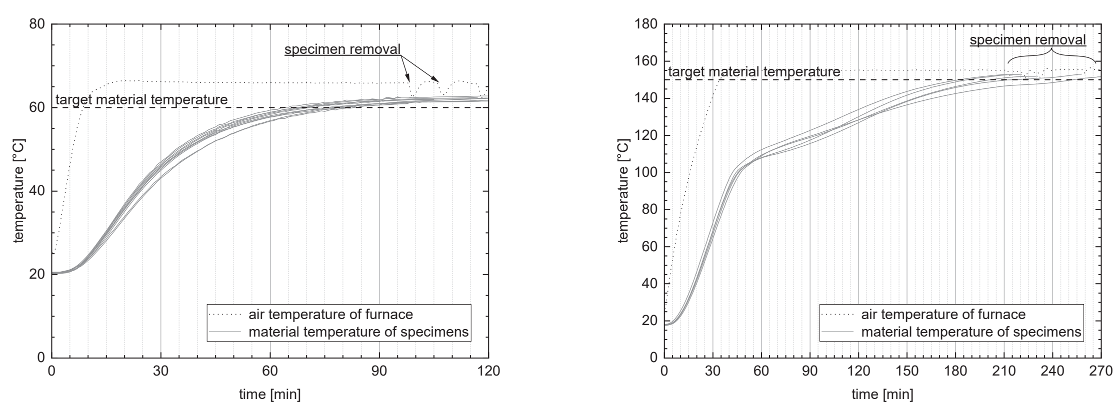
The re-moisturised scenario investigates how pre-heated wood's thermo-mechanical properties are reversible when, after heating, the wood is stored for 28 days in a standard climate to enable a possible re-gain of wood moisture. Therefore, the following workflow was executed:

1. The specimens were weighed before heating to conclude the wood moisture content after storage.
2. To heat the specimens, they were placed in the oven set five degrees above the tested material temperature level and equipped with thermocouples to measure the material temperature.
3. After heating, the specimens were reweighed to measure the mass loss from heating and subsequently photo-documented.
4. During the 28 days of conditioning, the specimens were weighed continuously every other day to measure the weight changes.
5. After 28 days, the specimens were installed in the test stand and tested at standard temperature.
6. Cracks and deformations were marked, and the specimens were subsequently photo-documented.

## 6 – RESULTS

### 6.1 TEMPERATURE DEVELOPMENT

During the heating of the specimens in the oven, the core temperature was measured to ensure that the specimen reached the target material temperature. For the bending experiments with specimens that have a crosssection of 35x70 mm, the two core temperature developments for target material temperatures of 60 °C and 150 °C in Figure 9 display how the heating process differed due to the wood moisture vaporising in the specimens at material temperatures above 100 °C. Table 1 provides an overview of the heating time needed for the different target material temperatures of the bending experiments.




a) b)

*Figure 9 – Specimen Core Temperature Development for a) 60 °C and b) 150 °C target material temperature of the bending experiments [16]*


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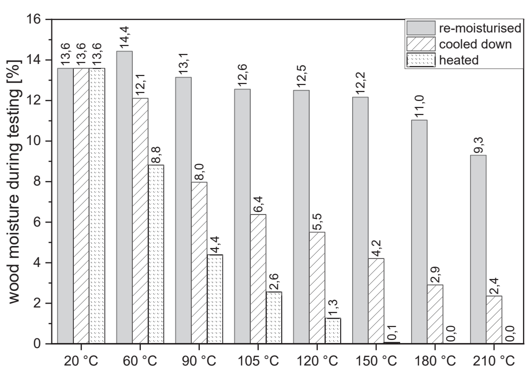
*Table 1 – Needed heating time to reach target material temperatures of the bending experiments*

| Material temperature | Heating time [min] | | |
|---|---|---|---|
| | ***min*** | ***mean*** | ***max*** |
| 60 °C | 64 | 75 | 91 |
| 90 °C | 165 | 244 | 165 |
| 105 °C | 233 | 292 | 350 |
| 120 °C | 230 | 280 | 320 |
| 150 °C | 178 | 223 | 280 |
| 180 C | 135 | 174 | 135 |
| 210 °C | 110 | 139 | 178 |
| 240 °C | 93 | 115 | 144 |

## 6.2 Moisture Content

The wood moisture content was determined for every specimen before load testing. Figure 10 shows the mean wood moisture content for each target material temperature, which is differentiated by the scenarios. In the heated scenario, the wood moisture content drops with the rising material temperatures, reaching a dry specimen with material temperatures over 150 °C.

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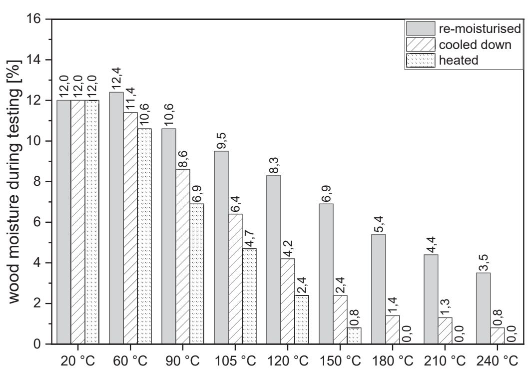


b)

*Figure 10 – Mean wood moisture content of specimens at load testing a) for compression and b) for bending*

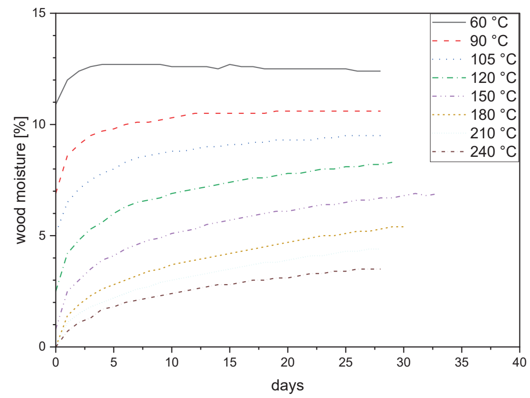


*Figure 11 – Wood moisture content during re-moisturising*

Comparing the mean wood moisture content of the compression and bending experiments, the decline and increase of the wood moisture is faster with the smaller cross-section of 30x30 mm against the larger cross-section of 35x70 mm. In the compression experiments, wood moisture content reaches its initial value in the re-moisturised scenario after approximately four weeks for material temperatures up to 150 °C.

## 6.3 Re-Moisturing Process

Figure 11 displays the change in mean wood moisture content over the storage period of approximately four weeks for the re-moisturised scenario of the bending experiments. The climate conditions were set to an air temperature of 20 ± 2 °C and a relative humidity of 65 ± 5 %, standard climate.

## 6.4 Visible Change of Color

Figure 12 shows the colour change of the surface of the specimens after heating, depending on their target material temperature. Starting with material temperatures of 150 °C, a colour change is noticeable. With material temperatures of 210 °C and 240 °C, the wood colour turns dark brown and the haptic changes, too.


*Figure 12 – Change of surface colour due to heating to different material temperatures*

### 6.5 Compression strength

In calculating the relative compression strength, the mean value of each test group was used, and the reference test group's mean value was considered 100 %. Table 2 and Figure 13 oppose the results of the three scenarios to each other. In general, the influence of the rising material temperature on the compression strength is small, with a maximal decrease of 9.0 %. Especially in the heated scenario, the influence of wood moisture loss seems more dominant, causing a maximal increase in compression strength by 16.1 % at 150 °C material temperature. In the cooled-down and re-moisturised scenarios, with the regain of wood moisture, the increase of compression strength in the heated scenario goes back down, and a slight loss of compression strength occurs.

### 6.6 Compression stiffness

In contrast to the compression strength, the compression stiffness is more temperature-dependent. Besides unwanted deformations, decreasing compression stiffness is crucial for highly compressed timber elements because it negatively influences the element resistance against buckling. Especially in the heated scenario, as Figure 14 and Table 3 show for the mean modulus of elasticity (MOE), the loss of compression stiffness at lower material temperatures up to 90 °C is significant, reaching a minimal MOE of 61.4% compared to the mean reference MOE. In the cooled-down scenario, the temperature-dependent loss of compression stiffness seems temporarily permanent, with only slight differences in the mean MOEs compared with the mean MOEs of the heated scenario at the same material temperatures. Considering the re-moisturised scenario, the compression stiffness seems to recover when the wood moisture gradually increases as time goes by.

*Table 2 - Relative compressive strength*

| | Material temperature | Experimental Scenarios | | |
|---|---|---|---|---|
| | | ***Heated*** | ***Cooled down*** | ***Re-moisturised*** |
| **Relative mean compression strength [%]** | 20 °C | 100 | | |
| | 60 °C | 93,0 | 94,4 | 96,3 |
| | 90 °C | 98,0 | 102,5 | 94,4 |
| | 105 °C | 112,4 | 102,5 | 92,4 |
| | 120 °C | 115,8 | 93,2 | 91,0 |
| | 150 °C | 116,1 | 98,9 | 97,5 |
| | 180 °C | 97,7 | 108,2 | 94,9 |
| | 210 °C | 94,1 | 109,9 | 100,8 |

*Table 3 - Relative modulus of elasticity in compression*

| | Material temperature | Experimental Scenarios | | |
|---|---|---|---|---|
| | | ***Heated*** | ***Cooled down*** | ***Re-moisturised*** |
| **Relative mean modulus of elasticity [%]** | 20 °C | 100 | | |
| | 60 °C | 86,3 | 77,7 | 114,9 |
| | 90 °C | 61,4 | 83,6 | 93,6 |
| | 105 °C | 75,8 | 72,4 | 77,1 |
| | 120 °C | 74,5 | 82,7 | 95,5 |
| | 150 °C | 57,9 | 68,6 | 105,4 |
| | 180 °C | 68,6 | 81,4 | 91,4 |
| | 210 °C | 96,4 | 72,2 | 106,1 |

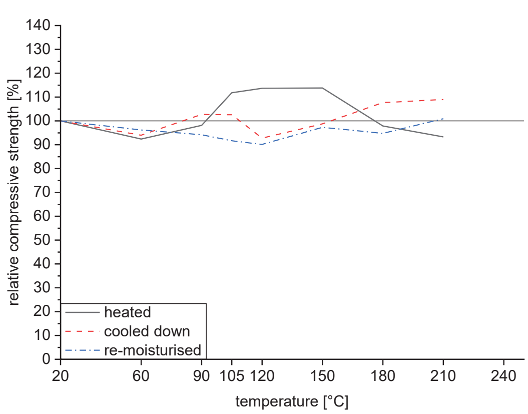


*Figure 13 - Relative compression strength [18]*

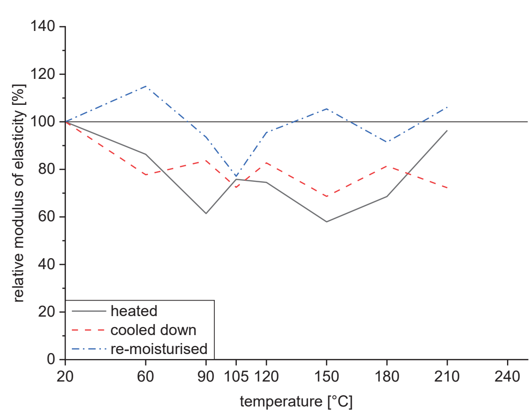


*Figure 14 – Relative modulus of elasticity in compression [18]*


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## 6.7 Bending strength

Table 4 and Figure 15 show the mean bending strength values for the three scenarios. With rising material temperatures in the heated scenario, the bending strength generally decreases, besides a slight increase in the material temperature range between 90 °C and 120 °C, where the wood's moisture vaporises. After a significant initial loss of bending strength up to a material temperature of 60 °C with a percentual loss of 23.1 %, the decrease of bending strength slows down. It reaches almost a plateau between 90 °C and 180 °C material temperature when ignoring the increase of bending strength in this temperature range. At material temperatures over 180 °C, the decrement of bending strength rises with rising material temperatures. In the cooled down and re-moisturised scenario, the bending strength generally regains and exceeds its reference strength for material temperatures up to 210 °C. At 240 °C material temperature, the mean bending strength in the cooled down and re-moisturised scenarios does not reach the mean reference bending strength, indicating permanent damage in the wood structure.

## 6.8 Bending stiffness

Regarding bending, the temperature-dependent loss of stiffness is less than the loss of strength due to rising material temperatures. Table 4, Figure 16 and Figure 17 show the mean global and local modulus of elasticity in bending for the three scenarios. The global and local MOEs generally behave similarly and decrease with increasing material temperatures. The mean global and local MOE of the cooled down and re-moisturised scenario are higher than the mean values of the heated scenario except for the low material temperatures (< 100 °C) in the local MOE. However, at higher material temperatures, the cooled down and re-moisturised MOEs are always lower than the MOE of the reference, indicating that the wood experienced permanent changes due to the heating.

*Table 4 – Relative bending strength*

| | **Material temperature** | **Experimental Scenarios** | | |
|---|---|---|---|---|
| | | ***Heated*** | ***Cooled down*** | ***Re-moisturised*** |
| **Relative mean bending strength [%]** | 20 °C | 100 | | |
| | 60 °C | 77,0 | 98,7 | 101,8 |
| | 90 °C | 77,2 | 111,8 | 110,4 |
| | 105 °C | 78,5 | 124,7 | 117,6 |
| | 120 °C | 87,6 | 126,5 | 112,4 |
| | 150 °C | 73,5 | 128,2 | 116,7 |
| | 180 °C | 68,3 | 107,7 | 113,6 |
| | 210 °C | 57,9 | 106,3 | 88,6 |
| | 240 °C | 39,0 | 71,3 | 58,7 |

*Table 5 - Relative modulus of elasticity in bending*

| | **Material temperature** | **Experimental Scenarios** | | |
|---|---|---|---|---|
| | | ***Heated*** | ***Cooled down*** | ***Re-moisturised*** |
| **Relative mean global (left) / local (right) modulus of elasticity [%]** | 20 °C | 100 | | |
| | 60 °C | 87,8 / 100,7 | 93,9 / 93,2 | 97,3 / 89,2 |
| | 90 °C | 84,8 / 94,7 | 93,1 / 84,4 | 98,6 / 88,6 |
| | 105 °C | 84,8 / 82,9 | 96,9 / 86,6 | 96,8 / 90,9 |
| | 120 °C | 81,9 / 88,1 | 98,6 / 94,2 | 98,2 / 95,5 |
| | 150 °C | 79,4 / 81,0 | 93,9 / 86,5 | 96,3 / 93,2 |
| | 180 °C | 76,5 / 74,2 | 93,5 / 86,5 | 97,9 / 91,2 |
| | 210 °C | 69,0 / 67,6 | 91,2 / 83,6 | 91,4 / 90,6 |
| | 240 °C | 52,7 / 56,2 | 82,8 / 76,1 | 81,8 / 80,1 |

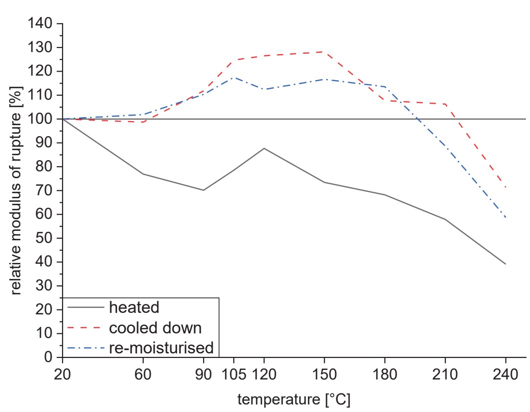


*Figure 15 – Relative bending strength [18]*

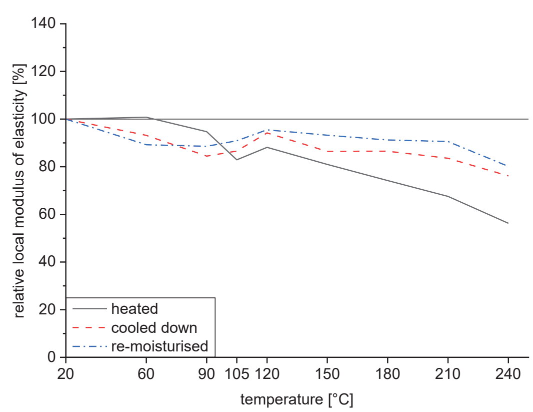


*Figure 16 – Relative local modulus of elasticity in bending [18]*

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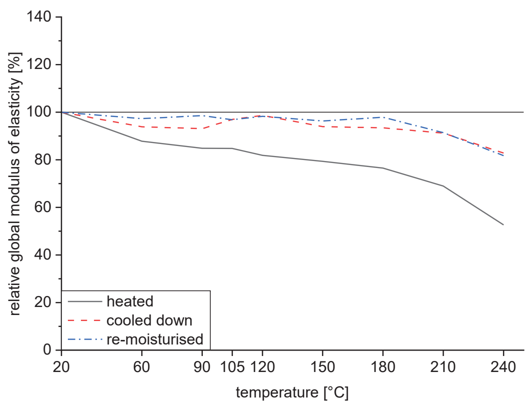


*Figure 17 - Relative global modulus of elasticity in bending [18]*

## 7 – CONCLUSION

Elevated temperatures significantly impact timber's mechanical behaviour, with distinct effects on compression and bending. Interacting effects of wood moisture changes and thermal wood decomposition need to be considered, as the results of the experiments show. Additional effects should be looked at when the results are referenced to a real fire scenario. This will be examined in future thermal creep tests.

The compressive strength remained largely unchanged until 210 °C, even increasing at the intermediate. However, this gain was temporary, disappearing once moisture was restored. In contrast, compression stiffness was highly temperature-sensitive, dropping to 60%. While cooling alone did not restore stiffness, re-moisturising substantially recovered it, suggesting stiffness reduction was mostly moisture-related.

Bending strength and stiffness were more vulnerable to heat. Strength declined steeply but regained between 90 and 120 °C. At 240 °C, timber retained around 40 % of its strength. However, the effects were largely reversible, as cooling and re-moisturising restored most mechanical properties. Only above 200 °C did irreversible damage occur, likely from thermal decomposition.

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