FIRENWOOD

Improved fire design of engineered wood systems in buildings

Sub report D3.4
Test series 4

Editors/Authors:

Patrick Dumler

Norman Werther

Stefan Winter

Deliverable Number: D3.4

Date of delivery: 14/09/2022

Month of delivery: M42

Gefördert durch:

Bundesministerium für Ernährung und Landwirtschaft

aufgrund eines Beschlusses des Deutschen Bundestages

The FIRENWOOD project is supported under the umbrella of ERA-NET Cofund ForestValue by Germany (Federal Ministry of Food and Agriculture (BMEL); Agency for Renewable Resources (FNR) project number FKZ 2219NR120), Sweden (The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS); Swedish Energy Agency (SWEA); Swedish Governmental Agency for Innovation Systems (Vinnova) project number 2018-04989) and Norway (Research Council of Norway (RCN) project number 298587). ForestValue has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773324.

Coordinator: Tian Li at RISE Fire Research AS

Table of Contents

1 Introduction

Within the research project Firenwood, four different test series were carried out to investigate the adhesive behavior of glued in rods under temperature load. The final test series 4 described in this partial report includes fire tests. The specimens are made from glue laminated timber and are connected with glued in rods. During the fire tests the specimens are loaded with a constant tensile force. The specimens were planned according to the results from the test series 1 – 3. With these tests the proposed design model as well as the numerical model should be validated.

2 Materials and Test Methods

2.1 Experiment Overview

Within test series four fire tests with specimens with glued in rods under mechanical load (creep tests) under the Standard Fire Curve (SFC) were performed. Within the specimens there were configurations in the rod diameter, the adhesive type and the number of rods glued inside one specimen. The mechanical load level was based on the reference tests of test series 3 at room temperature. There were also four reference specimens placed inside the furnace for measuring the temperature inside the specimen during the test. In the specimens with the tensile load only the temperature at the rod was measured to avoid the weakening of the cross-section due to the insertion of thermocouples.

2.1.1 Materials

The test specimens were made from glued laminated timber (GLT) with strength class GL 24h. Before the gluing of the rods, the wood was stored for a minimum of 4 weeks in normal climate conditions (20 °C / 65% r. h.) until the equilibrium moisture content was reached.

Two different adhesive systems were used for the gluing of the rods:

• 2K-EP (Adhesive 1)

• 2K PUR (Adhesive 2)

The date of gluing for the different specimens is shown in Appendix A.

The timber specimens had a mean density of 448 kg/m³ with a standard deviation of 6,4 %. Drying samples showed an equilibrium moisture content of 13,1 %. The specific values of the specimens are shown in Appendix B.

Metric threaded rods with the strength class 8.8 were used, so that it could be guaranteed that the failure of the connection won`t happen in the steel rod.

2.1.2 Production

The cross-sections of test series 4 were planned on the basis of numerical analysis with the parameters and results of test series 2 and 3. In test series 3 a critical temperature limit was set for both adhesives which shouldn`t be exceeded to ensure the load-bearing capacity of the connection. The temperature limit determined for Adhesive 1 was 69 °C and for Adhesive 2 it was 79 °C. These values were derived from test series 3 and represent the 20 % quantile value of the failure temperatures that occurred for the specimens with adhesive failure. Based on numerical parameter studies described in report D2.4 the minimum wood coverage needed was calculated. The minimum coverage of the borehole edge is given in Table 1 for a fire load of 30 minutes and a glue line thickness of 1 mm.

Table 1: Minimum coverage needed based on numerical simulations for both adhesives with different rod diameters

	Minimum Coverage [mm]			
	20 % Quantile		5% Quantile	
	Adhesive 1	Adhesive 2	Adhesive 1	Adhesive 2
M12	46	43	48	44
M20	40,5	37	42,5	38,5

Based on these values the specimens were planned. The setup is shown in Table 2.

Table 2: Specimen setup in test series 4

Specimen	Cross-section [mm x mm]	Wood cover [mm]	Adhesive	Rod diameter [mm]	Embedment length [mm]	Load [kN]
SP1	120 x 120	53	1	12	162	17,06
SP2	100 x 100	43	2	12	162	16,03
SP3	180 x 180	46	1	4 x 12	162	61,42
SP4	120 x 120	49	1	20	150	26,53

The production of the test specimens followed the same procedure as in test series 3. One specimen was manufactured from two GLT beams with the specific cross-sections. The length was 1000 mm for each half. The two halves were bonded with a glued in rod with the same embedment length on both sides of 162 mm for the rod diameter of 12 mm and with 150 mm for the rod diameter of 20 mm (see Figure 1). To enable the insertion of the load on both ends of the specimen another rod with a diameter of 20 mm was glued in with an embedment length of 350 mm on each side. The minimum distance of 1,4 * l according to EN 17334 could be ensured.

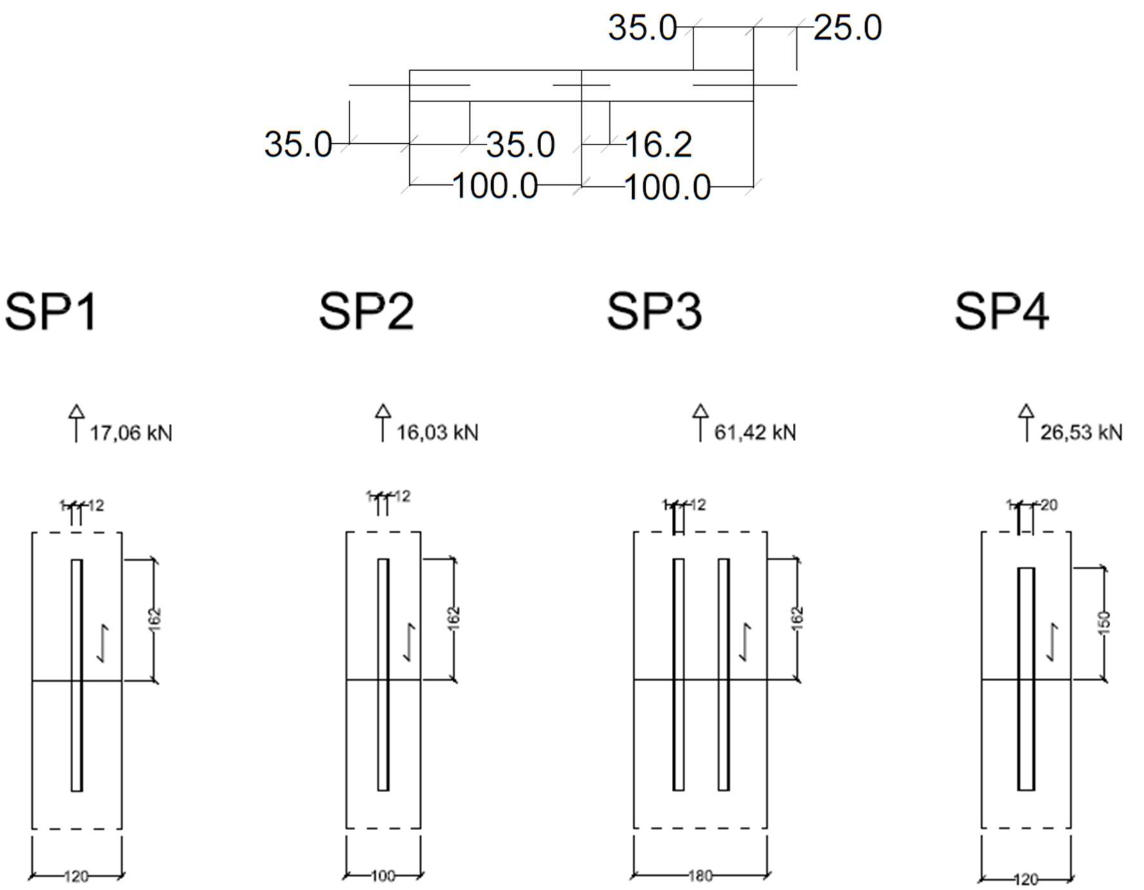


Figure 1: Dimensions and sections of the four specimens in test series 4

The rods were glued in the same order starting with the connection in the middle of the two GLT halves. The glue line thickness for each specimen was 1 mm. Therefore, a borehole with a 2 mm thicker diameter than the rod was drilled. Augerbits and a drill stand were used to ensure a borehole as straight as possible. After finishing the boreholes for the rods, additional holes with a diameter of 8 mm were drilled on the side of each specimen. These additional holes were placed 10 mm above each borehole end. For the middle connection one hole was to fill in the adhesive the other one was used as the ventilation hole. Before the gluing process could start, the boreholes were cleaned with compressed air. The two types of adhesives were mixed with the help of static mixers placed on double cartridges with resin and hardener, which guaranteed the mixing ratio specified by the manufacturer. In order to guarantee only a small joint between the two GLT halves, they were pressed together with screw clamps (see Figure 2). The bonding took place under normal climatic conditions. After seven days of drying time the top and the bottom rods were glued in. Only one side hole at the bottom of the borehole was drilled for the filling in of the adhesive. The opening of the borehole into which the threaded rod was inserted served as a ventilation opening.

Figure 2. Inserting of the middle rod (left), Gluing process of the outer rods (right)

There was a period of at least 28 days between the gluing of the specimens and the testing in order to ensure the maximum strength and temperature resistance of the adhesives as recommended by the manufacturers.

To measure the temperature inside the glue line two different methods were used. Since the test specimens were mechanically loaded, it was mandatory that no weakening of the cross section or glue line should appear. Therefore, only one sheathed thermocouple was installed perpendicular to the grain direction. It was inserted at the ventilation hole to measure the temperature of the rod during the test. The tip was in contact with the rod. The wire was guided along the surface of the specimen and covered by a gypsum plasterboard to prevent additional heat transfer through the thermocouple(see Figure 3).

Figure 3: Protection and position of the sheathed thermocouple for the measurement of the rod temperature

With the second method it was tried to measure the temperature development inside one specimen during the test. Therefore, structurally identical reference specimens were built.

The reference specimens were used to measure the temperature in the depths of 6 mm, 12 mm, 18 mm, 24 mm, 30 mm, 36 mm, 42 mm from the surface as well as in the glue line of the connection. They were produced from two GLT halves with a length of 500 mm each. The reference specimens were not mechanically loaded during the tests. To place the thermocouples alongside the isotherms the timber halves were cut in half along the long side with a table saw. The saw blade had a thickness of 2 mm. Therefore, after gluing one side length of the specimen is reduced by these 2 mm.

After the sawing process the two parts of each half were connected with screws. Two boreholes with a length of 150 mm for each side were drilled with an auger bit. These boreholes had the same dimensions as the test specimens and were intended for later insertion of the rods. Afterwards the screws were removed again.

Type K thermocouples were used for measuring the temperatures inside one half of the reference specimen. For this purpose, a 2 mm deep groove was sawn in the appropriate edge distances. The thermocouples were placed inside the grooves and fixated with staples. The drilled ends for temperature measuring were placed alongside the borehole. Above the end of the borehole the thermocouples were brought together and were guided centrally to the end of the specimen. The grooves were closed with Conlit afterwards (see Figure 4). The affected area then was sanded to ensure a good adhesion between the cut halves as well as a leveled surface. The two halves were glued together finally. The contact pressure was achieved by screws and clamps (see Figure 5). Excess glue that came out at the edges was removed. After a curing time of seven days the rods were inserted inside the boreholes and glued with the appropriate adhesive. The two halves were pressed together with screw clamps again to ensure a small joint gap. The channels and thermocouples in the production phase for each reference specimen are shown in Appendix C.

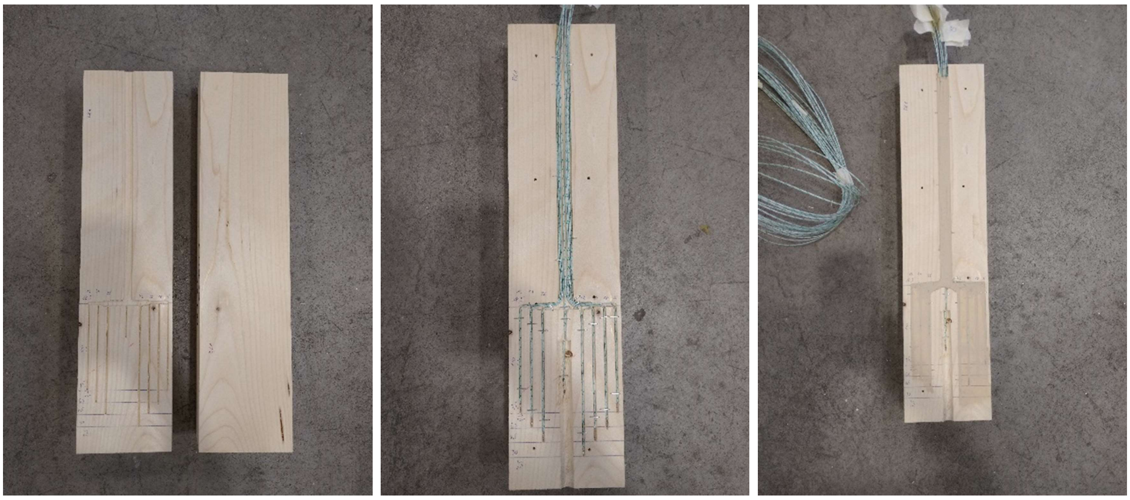


Figure 4: Reference specimen during the process of installing the thermocouples

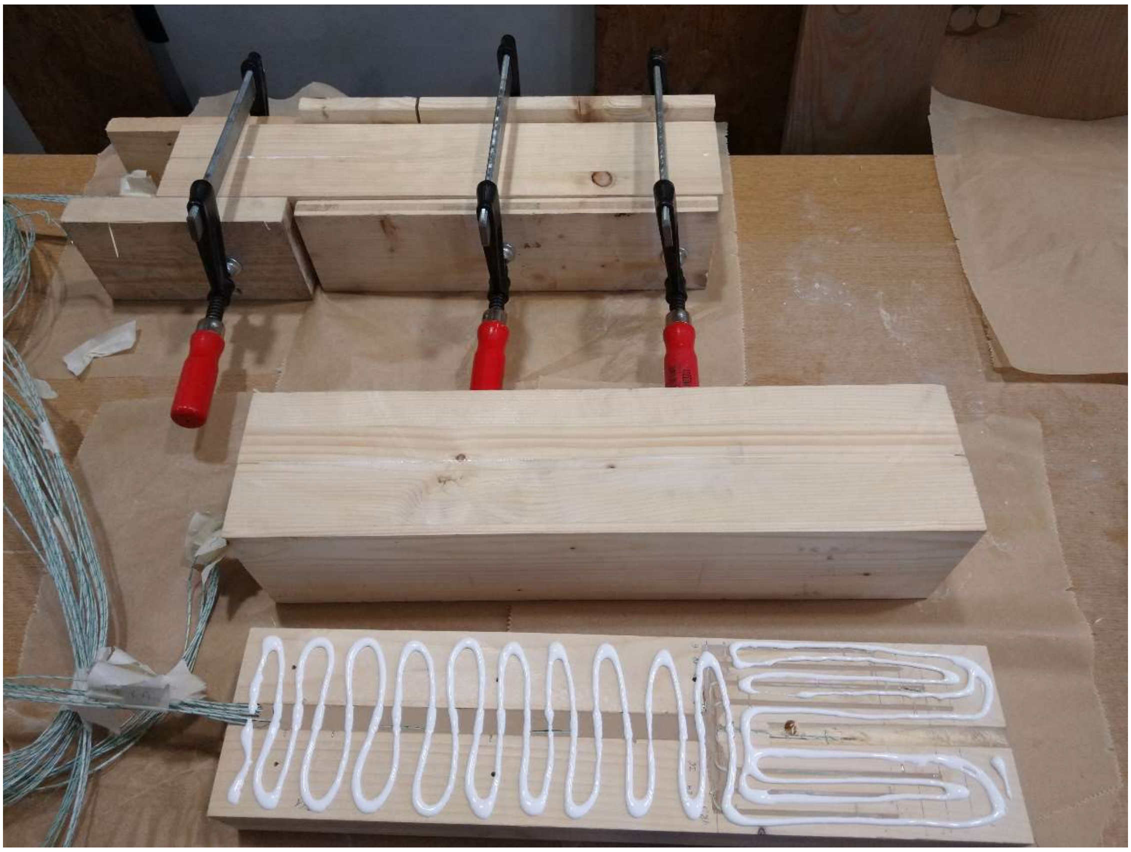


Figure 5: Inserting of thermocouples and Conlit in the reference specimen (top), Gluing of the two specimen halves of the reference specimen (bottom)

For the reference specimen 3 two different adhesives were used. Since Adhesive 2 has a higher temperature resistance only a smaller wood cover is needed. Therefore two different edge distances were used. These were 43 mm for Adhesive 2 and 46 mm for Adhesive 1. For the temperature measurement 2 layers of thermocouples were installed inside the specimen (see Figure 6).

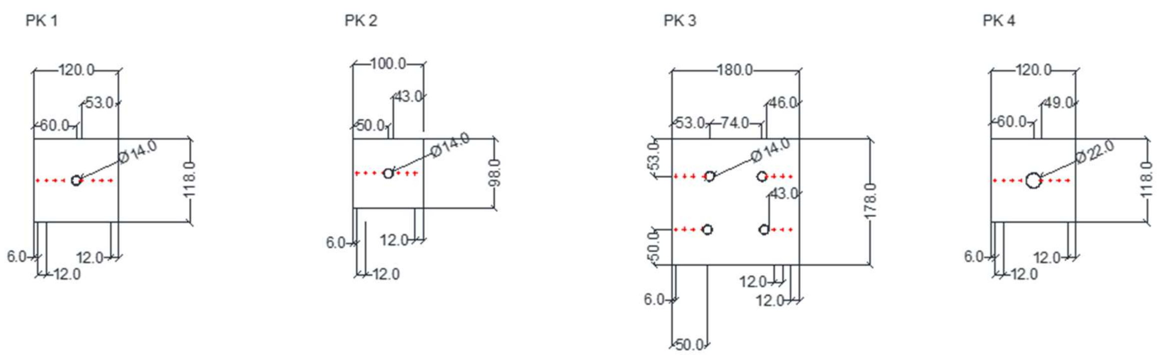


Figure 6: Cross-sections and positioning of the thermocouples (red) in the reference specimens

2.1.3 Test configuration

The specimens were tested under creep configuration with a thermal load. Therefore, the specimens were clamped into the testing machine and subjected to a constant mechanical tensile load (derived from test series 3.1 at 20 °C). The load level was set to 40 % of the mean load from the reference tests of test series 3.1. For the specimen with four rods the load was reduced by 10 % as stated in the 3rd draft for EN1995-1-1 since an equal load distribution between all of the rods can`t be guaranteed due to production inaccuracies and deviations. The mechanical load was applied at least 15 minutes before the thermal load. As a thermal load the Standard Fire Curve (SFC) was used.

To guarantee the failure in the middle rod of the specimen only this part was thermally loaded. Therefore, the other parts of the specimen had to be protected from the fire.

The furnace dimensions used for the fire tests were 3 m x 3 m x 4 m (width x height x depth). For the load application a portal steel frame was used (see Figure 7).

Figure 7: Positioning of the steel frame in the furnace

This frame was placed inside the furnace and had to be thermally protected. The plans are shown in Appendix D. For the fire protection of the steel frame aerated concrete blocks were used. They covered the bottom crossbeam as well as the vertical columns and were walled up to the ceiling of the furnace. The specimens were clamped between the two steel columns. The wall was bricked so high that only the middle part of the specimen with the intended rod was thermally loaded.

The reference specimens were placed next to the steel frame on a walled platform. On the left and the right side there were ventilation holes next to the frame to ensure a better air circulation during the test. But since the width was very small it was considered impractical to install the reference specimens in this area. It was assumed that only lower temperatures than for the area with the test specimen would be reached because of the small width and the location at the edge of the furnace (see also Figure 8).

Figure 8: Installed specimen 1 (left), View of reference specimen 3 (right)

The frame had a height of 4 m so the top crossbeam wasn`t inside the furnace and therefore unprotected. On the top crossbeam the measurement equipment could be installed.

2.1.4 Testing equipment and testing procedure

In order to measure the air temperature in the furnace two thermo plates were installed diagonally facing the specimen. The height was on the same level as the joint of the specimen. The distance for all tests was about 15 cm (see Figure 9) from the specimen surface. The temperature inside the furnace was controlled according to these plates.

Figure 9: Positioning of thermo plates

In addition, one sheathed thermocouple was placed near the surface of each test and reference specimen to measure the air temperature in the direct surroundings. These values were used in the numerical simulation as input variables for the thermal load. The thermocouples were connected via a measuring module to the multi-channel data logger midiLogger GL840 from Graphtec. The data could be retrieved in real time.

The mechanical load was applied with a hollow piston cylinder on the top crossbar. It was controlled via compressed air supply. The sensor 26K - 500kN (E 96060) was used to measure the applied load. During the tests a decrease in pressure was present. Therefore, the applied load had to be readjusted manually. The deviation amounted to a maximum of approx. - 0.4 and +0,7 kN. The aim was to stay within the range of the larger load in order to be on the safe side. With higher temperatures, the deformation in the connection rose which is why the load had to be readjusted more often.

The deformation of the whole specimen was measured using two WayCon SX50 draw-wire sensors. They were placed on the top cross-sectional area of each specimen. The edge distance in the diagonal was set to 2 cm. Here it should be verified simultaneously whether a misalignment occurs due to the deformation of the specimen. Due to the complicated structure of the test setup, an attachment for deformation measurements in the area of the fire exposed connection was not possible (see Figure 10).

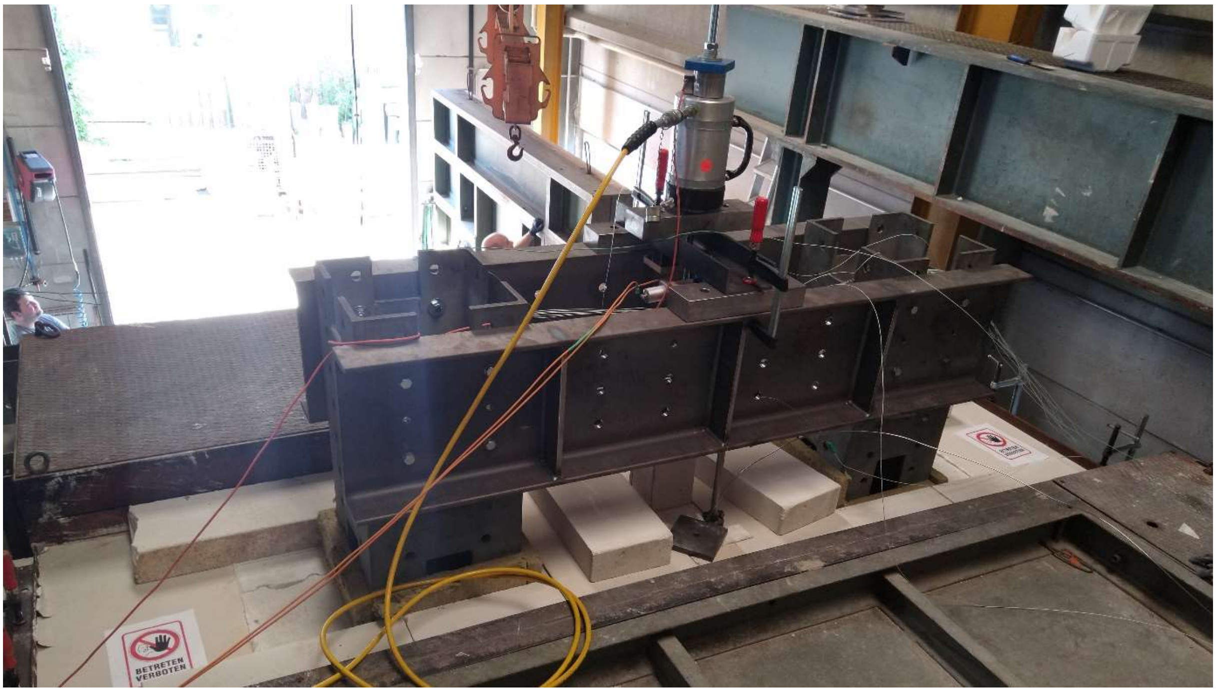


Figure 10: Top of the steel frame with measurement

After the failure of each specimen due to the high temperatures it was not possible to remove them from the furnace. Therefore, a check-up of the burnt specimen especially the connection right after the test could not be performed.

3 Results of test series 4

3.1 Air temperature

The air temperature in the furnace was regulated according to the measured temperature of the two thermo plates. It is known that they react slower to heating than sheathed thermocouples. Therefore, the air temperature was measured additional next to the surface of the specimen to get inputs for the numerical simulation. Also, the reference specimens weren`t placed in the same height as the mechanically loaded specimens. It was suspected that other temperatures (higher) were present for them. The following diagrams show the furnace air temperature curves for the four tests. The time is projected on the horizontal axis. The temperature is shown on the vertical axis. Five different temperature curves are compared with each other. The first two show the temperatures of the thermoplates. One curve shows the SFC which the control of the furnace was aiming at. The last two curves represent the measured air temperature for the specimen and the reference specimen using sheathed thermocouples.

For test 1 the temperature measured by the thermo plates shows a percentage deviation within the norm EN 1363-1. As expected the air temperature at the reference specimen shows higher values than the thermo plates since it was measured with sheathed thermocouples and the specimen was placed directly in the furnace. Lower temperatures are to be expected in the area of the test specimen, as the air circulation is hindered by the massive test frame (see Figure 11).

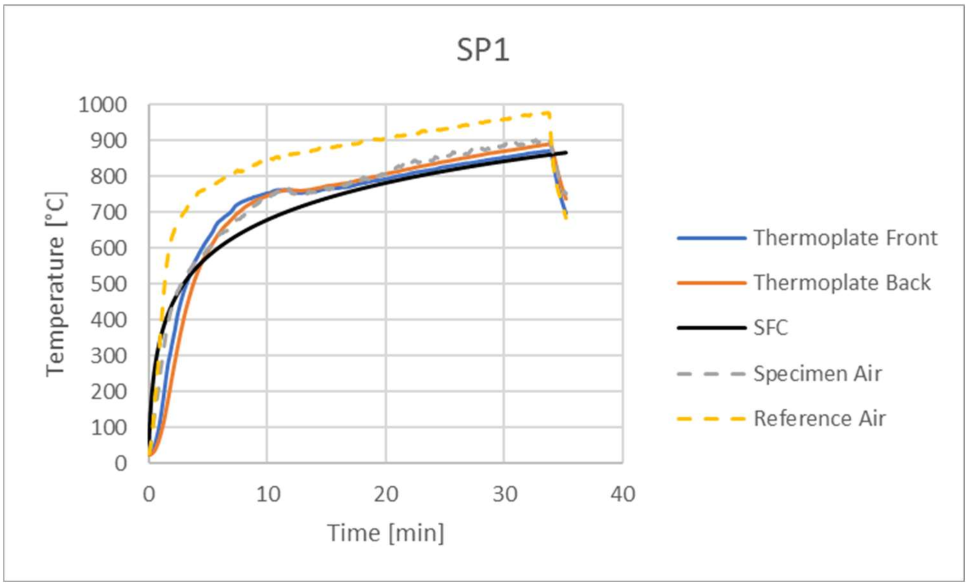


Figure 11: Air temperature measured for test 1 and in comparison to the Standard Fire Curve

For test 2 similar temperature curves are shown in Figure 12. The target temperature demanded by EN1363-1 is reached with the thermo plates. The deviations are within the permissible range. The measured air temperature with thermocouples is higher for both the specimen and the reference specimen.

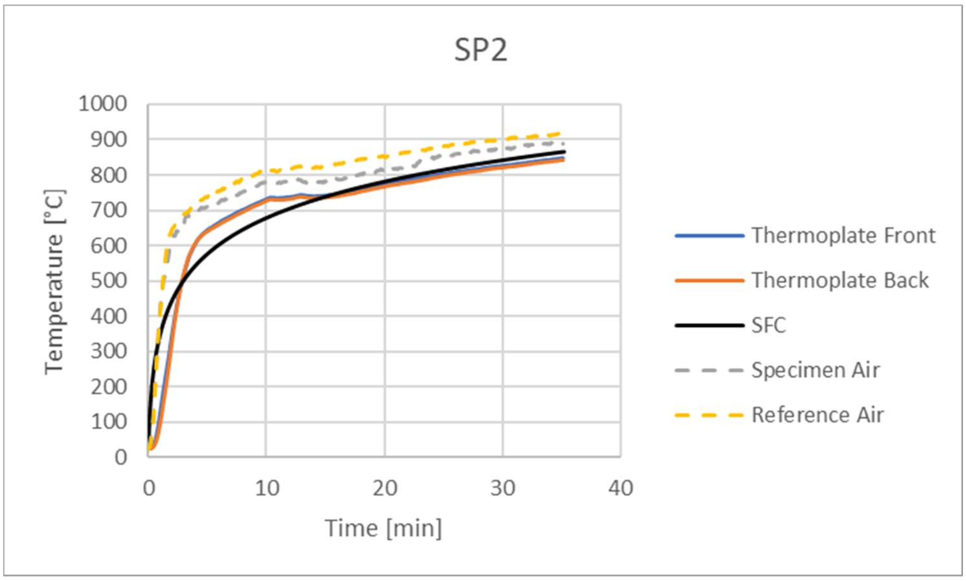


Figure 12: Air temperature measured for test 2 and in comparison to the Standard Fire Curve

In test 3 the measured temperature shows a slightly higher deviation from the SFC between minute six to minute eight. The specifications from EN 1363-1 are nevertheless met. The same temperature rise can be seen for the temperatures measured at the specimens. Both of them show slightly higher temperatures than the thermo plates. The reference specimen has the highest temperatures for the whole test duration (see Figure 13).

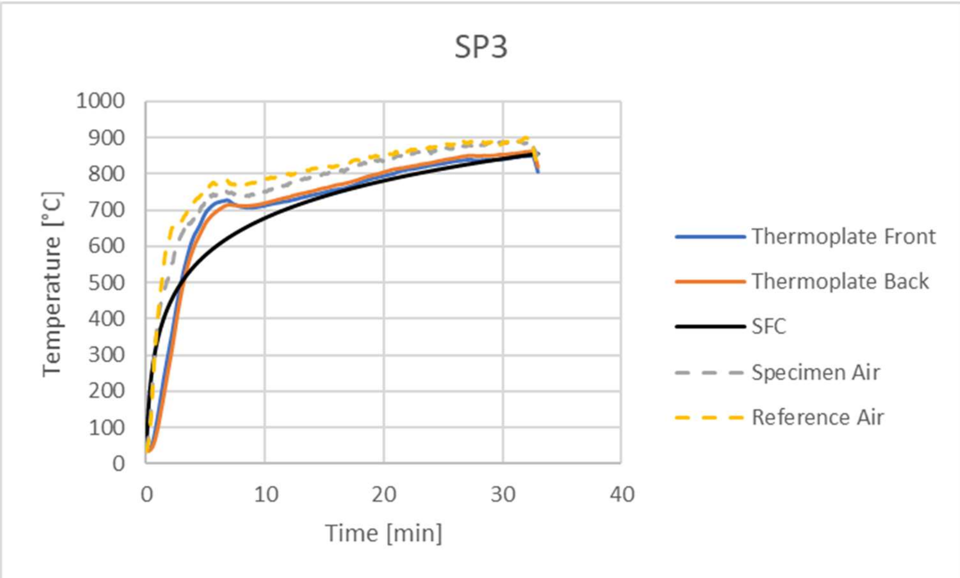


Figure 13: Air temperature measured for test 3 and in comparison to the Standard Fire Curve

Test 4 shows the same results as the other tests (see Figure 14). The only differentiation is the two curves of the reference specimen and the test specimen. The reference specimen shows after four minutes an approx. 100 °C higher temperature.

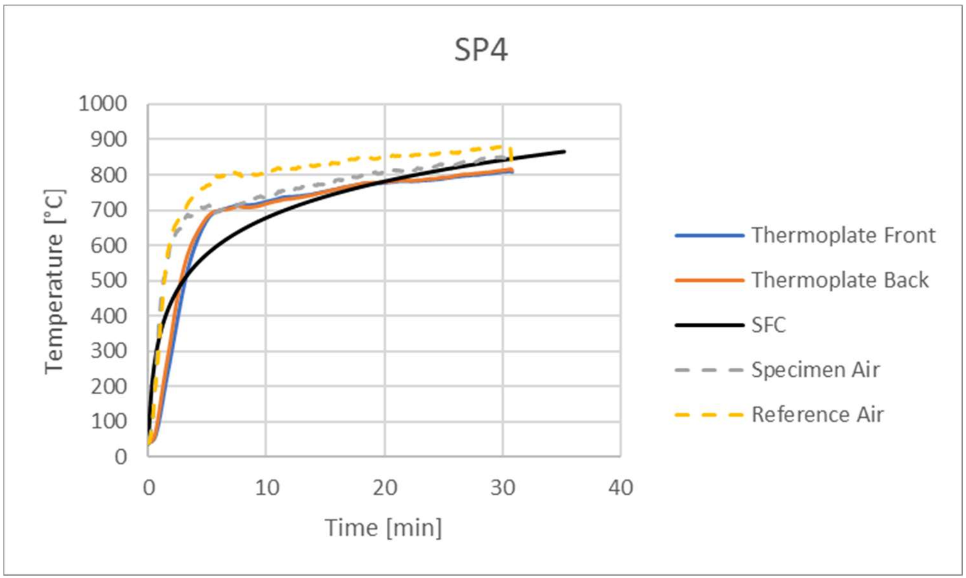


Figure 14: Air temperature measured for test 4 and in comparison to the Standard Fire Curve

All tests show higher temperatures for the measurement with sheathed thermocouples. Especially at the beginning of the tests, the thermo plates react slower to the temperature changes inside the furnace. Therefore, the values from the sheathed thermocouples are used for the numerical simulation, as these represent the real temperature load better.

Also, the reference specimen had a different positioning in the furnace than the mechanical loaded specimens which led to higher temperatures in all tests.

3.2 Temperature distribution

Within this chapter the measured temperature in the different depths of each specimen is compared with each other. During the tests within the time slot between approx. 7 and 15 minutes the measuring device showed a temperature rise for all depths and all specimens. Afterwards the temperature sank back to the original level. The reason for this could not be conclusively clarified. Changing the slots within the measuring unit returned the same error in the next test. The affected values were removed for the evaluation. For a detailed representation, the temperature range is only shown up to the 300°C – isotherm. Therefore, the time range for the depths of 6 mm, 12 mm and 18 mm is reduced. The plots for the whole time duration are presented in Appendix E. The reference specimen 3_1 shows results for a wood covering of 46 mm whereas specimen 3_2 shows the values for a wood covering with 43 mm.

For the depth of 6 mm reference specimen 2 showed serpent lines for unknown reasons. Therefore, this curve is excluded in Figure 15. Reference specimen 4 shows higher temperatures at the start. The reason for this was a previous test the day before. Due to the large mass that the brickwork brought into the furnace and only a small cooling opening, the temperature in the furnace could not be completely cooled down to ambient temperature. In the subsequent tests, the test specimens were wrapped with mineral wool during installation to protect them from the effects of heat before the test. On the other hand, the ceiling of the furnace was partially opened to enable a faster cooling process.

In the range of 100 °C a small flattening of the temperature curves is visible. The water bound in the wood evaporates and the temperature doesn`t rise until it is completely dry. All curves show a similar temperature rise for the specimens tested. The 300 °C - isotherm is reached between six and eight minutes.

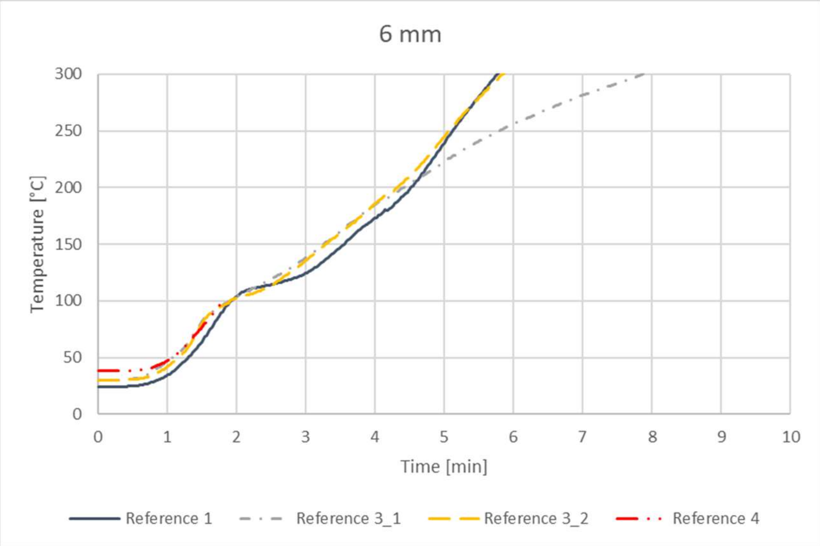


Figure 15: Temperature development for all reference specimens in a measurement depth of 6 mm

In the depth of 12 mm there are bigger deviations for all specimens visible (see Figure 16). Reference specimen 1 shows the slowest temperature rise in the beginning which is contrary to the air temperatures, as the largest was measured here. At 100 °C a small plateau is formed because of the water evaporation. The 300 °C - isotherm is reached approx. between eight and ten minutes for all specimens. Therefore, a charring rate between 1.5 mm/min and 1.2 mm/min was present.

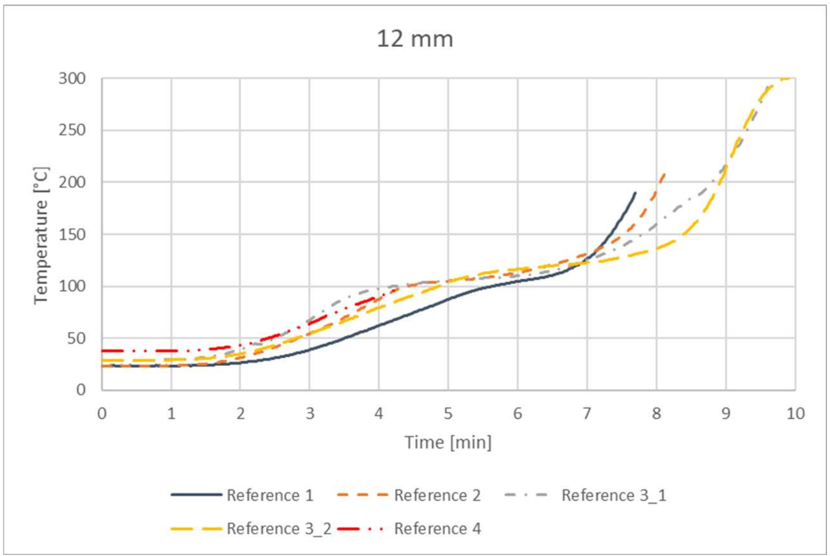


Figure 16: Temperature development for all reference specimens in a measurement depth of 12 mm

The depth of 18 mm shows the highest deviations for the specimens (see Figure 17). The temperature of 100 °C is reached within a time period of seven to nine minutes. Reference specimen shows no flattening in this area which may be caused by the measurement error described above. The 300 °C - isotherm is reached within 17 and 24 minutes. Reason for the deviations can be the irregular charring of the wood. In addition, an even layer of charcoal had probably not formed, which has a heat-insulating effect and protects the wood behind it.

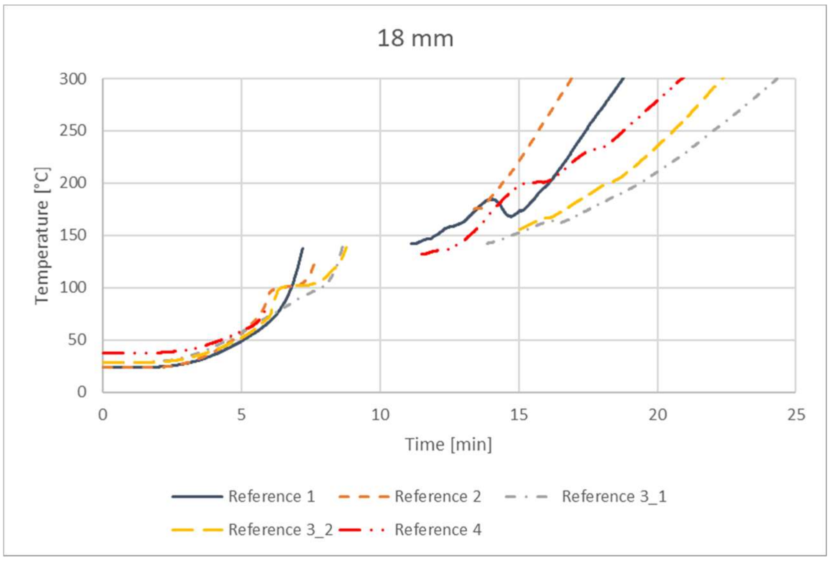


Figure 17: Temperature development for all reference specimens in a measurement depth of 18 mm

For the depth of 24 mm the temperature of 100 °C is reached after about 15 minutes for all specimens. After the evaporation phase specimen 1 and specimen 2 show the fastest temperature rise. For specimen 1 it was assumed to be a measurement error, which is why the following temperatures were excluded. The charring limit is reached after 25 to 31 minutes. The charring rate lies between 0,96 and 0,77 mm/min. The reason for the decrease in the charring rate is the growing charcoal layer, which slows down the combustion of the wood behind it (see Figure 18).

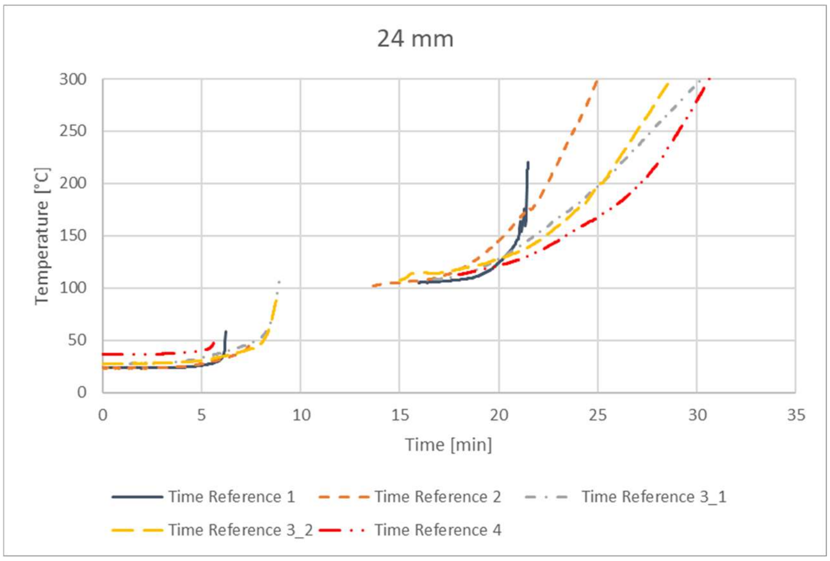


Figure 18: Temperature development for all reference specimens in a measurement depth of 24 mm

In a depth of 30 mm a plateau at the 100 °C - isotherm can be seen for all specimens for a time between 17 and 23 minutes (see Figure 19). Afterwards the temperature rises for specimen 1 and 2 are the fastest. It is plausible for specimen 1 since the measured air temperature was the highest. Reference specimen 2 shows no wood errors in the area of the thermocouples. Therefore, the reason for the faster temperature rise may be the uneven combustion of timber. Experience shows that there are always some fluctuations present.

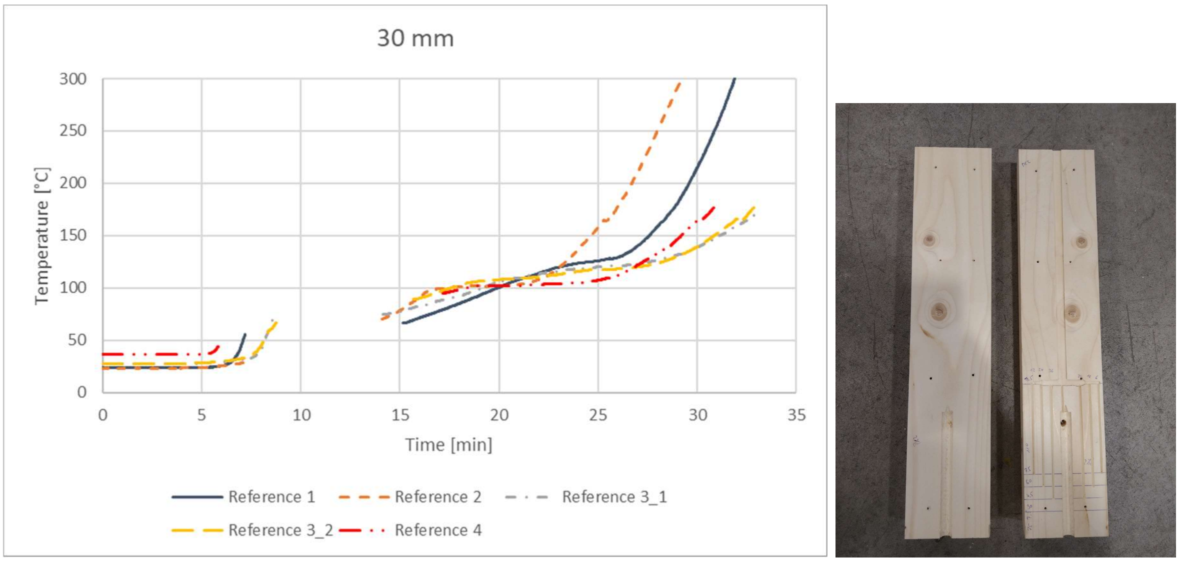


Figure 19: Temperature development for all reference specimens in a measurement depth of 30 mm and section of reference specimen 2

For a measurement depth of 36 mm most of the temperature curves show a slow heating to 100 °C until minute 25. Afterwards only reference specimen 2 reaches the 300 °C charring limit. Reference specimen 1 shows a rise of 50 °C until the failure of the respective test specimen. All other reference specimens didn`t show a rise of temperature above 100 °C. It can also be said that until reaching 100 °C the curves are quite uniform (see Figure 20).

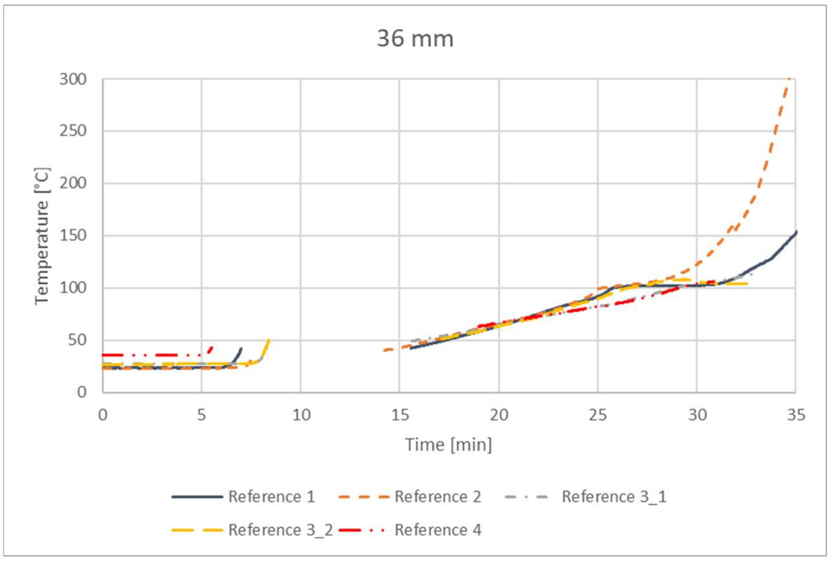


Figure 20: Temperature development for all reference specimens in a measurement depth of 36 mm

Due to the cross-sections of the specimens only reference specimen 1 and 4 had enough wood cover to install a thermocouple in the depth of 42 mm from the surface. Both specimens didn`t reach a temperature of 300 °C when the failure of the respective test specimen occurred (see Figure 21). Reference specimen 4 didn`t even reach 100 °C. For reference specimen 1 a plateau can be seen after 32 minutes. The temperature curves show a similar progression. For specimen 4 the higher temperature in the beginning of the test is due to the slow cooling process of the furnace.

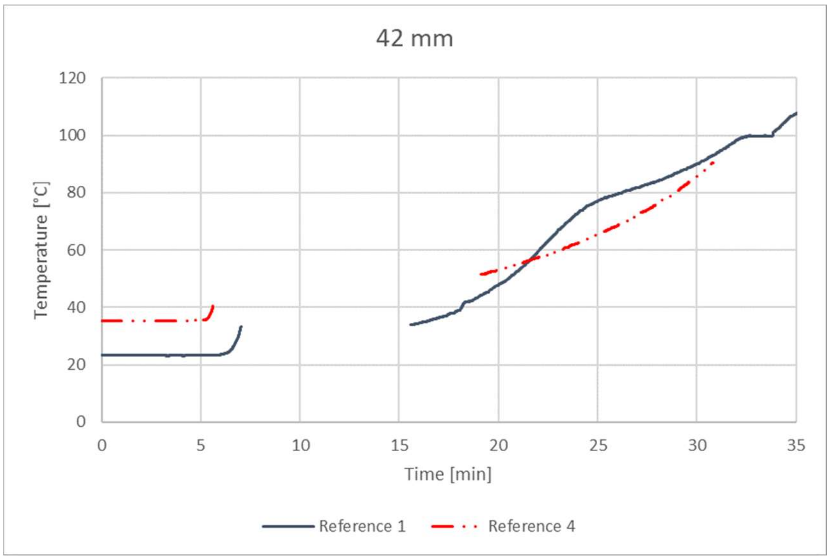


Figure 21: Temperature development for reference specimens 1 and 4 in a measurement depth of 42 mm

The reference specimens were used to measure the temperature development inside the specimen during the test. This wasn`t possible in the mechanically loaded test specimen in order to not weaken the respective cross-sections and glue lines. The temperature curves shall validate the proposed thermal and material parameters derived from test series 2 and 3 and were used in the numerical simulation in D2.4.

Furthermore, the measurements showed similar temperature curves for all reference specimens until the temperature of 100 °C is reached. Afterwards bigger deviations can be seen due to uneven burning and the resulting varying thickness of the charcoal layer. Specimen 1 showed higher temperatures in most of the cases since higher air temperatures were measured close to the surface. A subsequent assessment was not possible, as the reference specimens were completely burnt.

3.3 Failure temperature

In the following diagrams the failure times as well as the temperatures of the rods of each specimen are shown. In addition, the total deformation curves are displayed. Based on these graphs the failure temperatures of each rod were derived. The failure was reached when the mechanical load couldn`t be hold on the same level and therefore dropped abruptly. More detailed curves with focus on the deformation are shown in Appendix F. The time at which increased deformation occurred was determined when a change in the gradient was visible or the load application had to be readjusted more than three times a minute due to the increasing deformation.

For specimen 1 the failure temperature of 74,9 °C was measured (see Figure 22). The time of failure was after 33 minutes. The temperature curves of the rods of the specimen and the reference specimen are opposite to the air temperatures, as higher temperatures occurred with the reference specimen. Therefore, a faster temperature rise in the rod than in the reference specimen was expected. At the time of failure, a difference of approx. 14 °C occurred. The deformation curves show a linear rise until the temperature of 67 °C was reached after a fire exposure of approx. 31,5 minutes. After that, the deformation shows a greater increase for both measurement points. In this time slot, the tension load had to be recalibrated more often because of the increasing creep deformation of the connection.

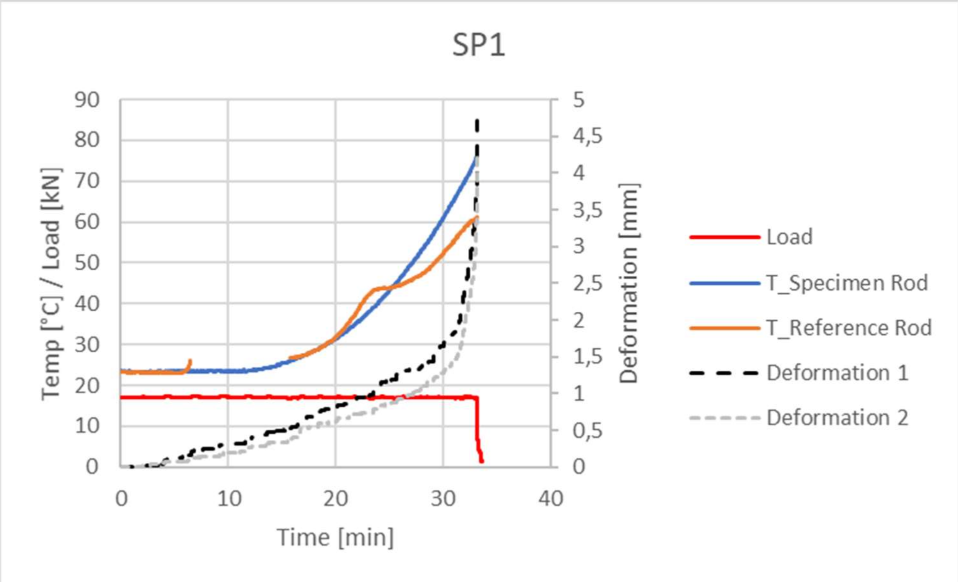


Figure 22: Load / Temperature / Displacement curves for test 1

Specimen 2 showed a similar behavior (see Figure 23). The failure time was 34.2 minutes. The specimen had the longest testing time in test series 4. Here, the specimen of the rod showed higher temperatures than in the reference specimen although the air temperature measured at the reference specimen was higher. The failure temperature at the rod was 106.9 °C and about 6 °C higher as the respective temperature in the reference specimen. For Adhesive 2 used in this test the deformation curves show a slightly longer creeping period than for Adhesive 1 as also observed in test series 3. After 28 minutes of fire load a higher rise in deformation can be seen at a temperature level of approx. 77 °C.

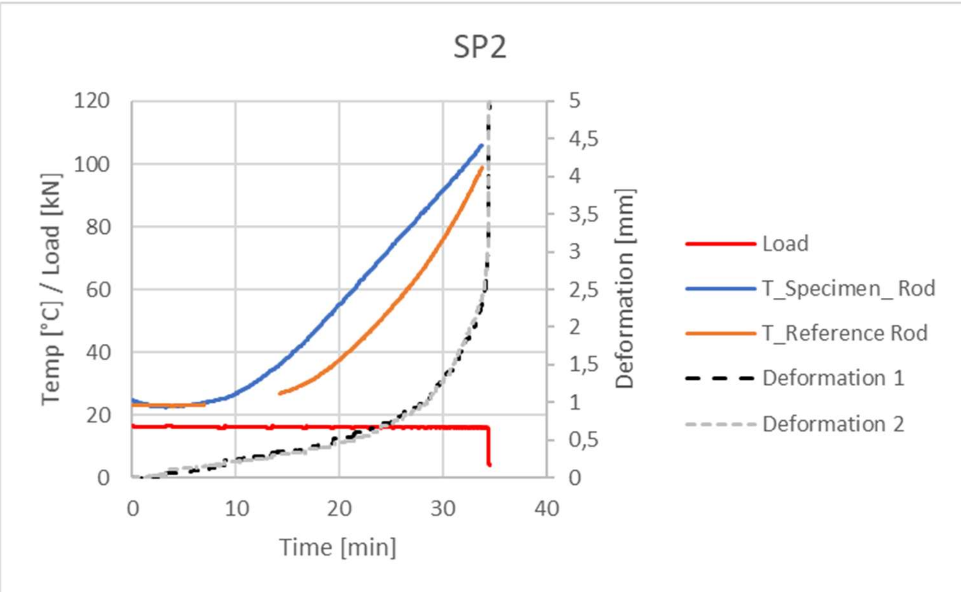


Figure 23: Load / Temperature / Displacement curves for test 2

In specimen 3 four rods were glued in the connection. The temperatures levels differed greatly when the failure occurred after 32 minutes. The failure temperatures lied between 62 °C and 109 °C (see Figure 24). Since no assessment of the specimen after the fire test was possible the reasons for the temperature difference of approx. 40 °C can only be speculated. One possibility for rod 1 is that the sheathed thermocouple has slipped out and was therefore lying closer to the surface. Also, during a fire test, a temperature difference of 40 °C is possible at any time due to gaps, wood defects, etc., which is why it is assumed that uneven combustion of the timber is mainly the cause.

In addition, the rods on the left side of the passage in the testing setup showed the smaller temperatures which were below the proposed critical temperature limit of 69 °C at the time of failure. Since one rod surpassed the limit temperature clearly it is assumed that there was hardly any load-bearing capacity left for the respective glue line and that the load was distributed over the other three rods, which is why lower failure temperatures occurred for them.

The deformation was almost linear until minute 28. At this time a first steeper rise was measured. After two more minutes the deformation was increasing in a faster pace until failure occurred. The temperature curves of the rod of the reference specimen 3 are given in Appendix G.

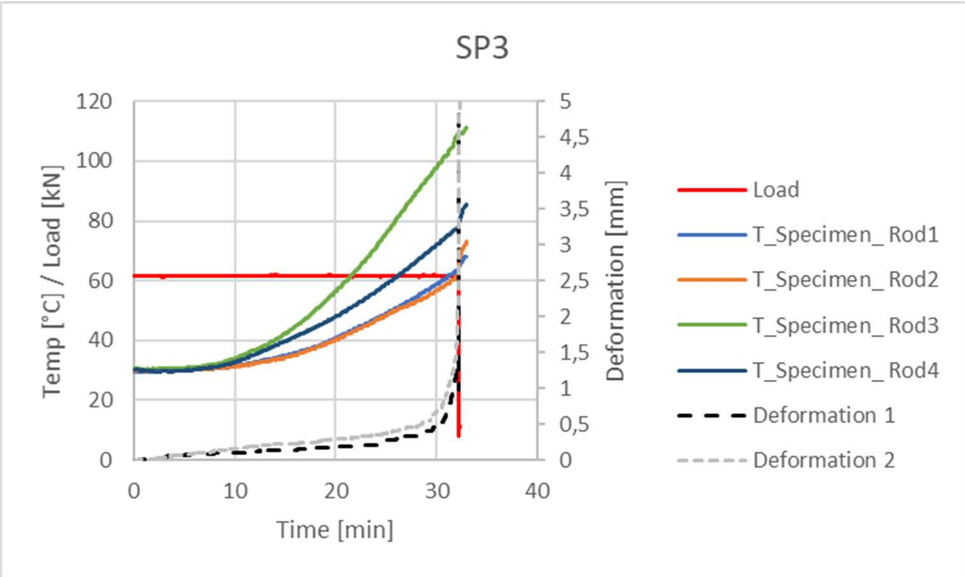


Figure 24 Load / Temperature / Displacement curves for test 3

Reference specimen 4 was the only test where higher temperatures were measured in the reference specimen than for the mechanically loaded specimen. The failure occurred after 30.1 minutes with a glue line temperature of 68.2 °C in the test specimen (see Figure 25).

The deformation is almost linear until minute 27. After that a steep rise was measured. The total deformation before failure occurred was rather big with about 4.5 mm. The reason for this could be the increased shear surface of the adhesive for the rod with a larger diameter of 20 mm. However, further tests would be necessary to prove a correlation between these parameters.

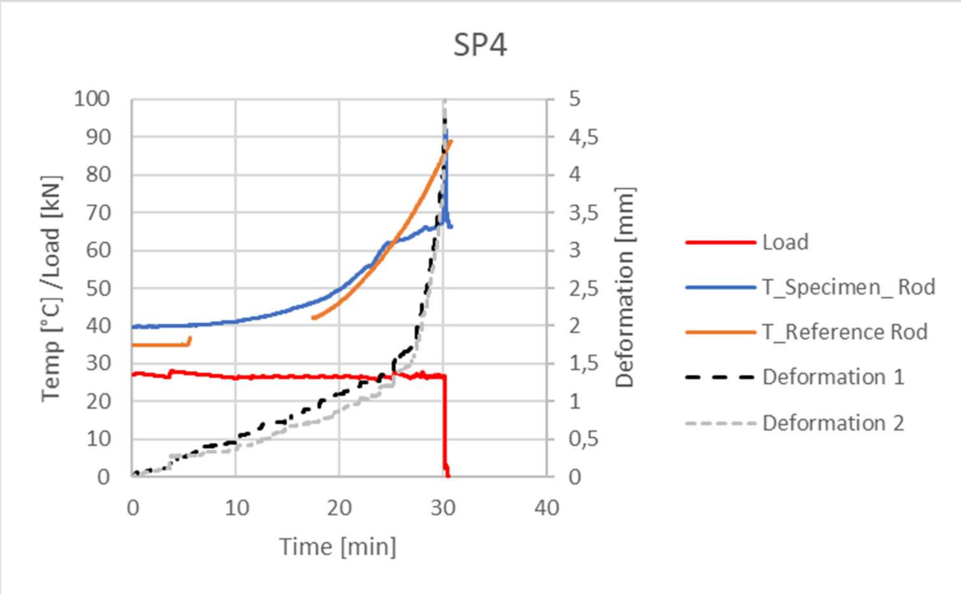


Figure 25: Load / Temperature / Displacement curves for test 4

In Table 3 the failure times and temperatures of each specimen and rod are shown. Also, the time when a rise in the deformation was identified with the respective measured temperatures are given.

Table 3: Failure and deformation temperatures at the rod according to the different tests

Specimen	Failure Time	Failure temp. Test		Deformation	
		Specimen	Reference	Start	Specimen
	[min]	[°C]	[°C]	[min]	[°C]
SP1	33	74,9	60,8	31,5	67,6
SP2	34,2	106,9	101,3	28	77,1
SP3	32,1	63,5	56,5	28,5	55,7
		61,7	59,8		53,6
		109	70,9		91,8
		75,4	59,1		67,9
SP4	30,1	68,2	85,1	27	63,8

4 Summary and conclusion

In the final test series 4 the results from the earlier tests (test series 1 – 3) as well as the derived parameters for the numerical simulations should be validated. Four specimens with different setups were tested under creep configuration. The specimens were mechanically loaded under a constant tension load and with a thermal load according to the Standard Fire Curve.

In addition, 4 reference specimens with the same design were tested without the mechanical loading. Thermocouples were installed in these at different depths to show the temperature development in the test specimens during the test.

The air temperature was measured next to the surface of the test specimen and the reference specimen to determine the thermal load for the numerical simulations afterwards.

The specimens were designed according to the previous results of test series 3 (see Sub report D3.4 – test series 3) so a failure in the glue line before reaching 30 minutes should not occur.

Adhesive 1 showed lower failure temperatures than Adhesive 2 as expected because the latter has a higher temperature resistance as could also be observed in the previous series of tests.

The deviations in temperature development are due to uneven combustion characteristics in the wood because of its anisotropic properties. In general, the temperature curves show similar progressions.

Four rods were glued in specimen 3. One of them showed higher temperatures than the other rods. Two of them had failure temperatures lower than the critical temperature limit of 69 °C. It is assumed that the adhesive had almost no load bearing capacity left for the rod with the high temperatures. The mechanical load was therefore redistributed on the other three rods which resulted in an earlier failure as the load bearing capacity reduces with rising temperatures in the glue line.

A Details gluing process

Table 4: Date of gluing for the middle connection

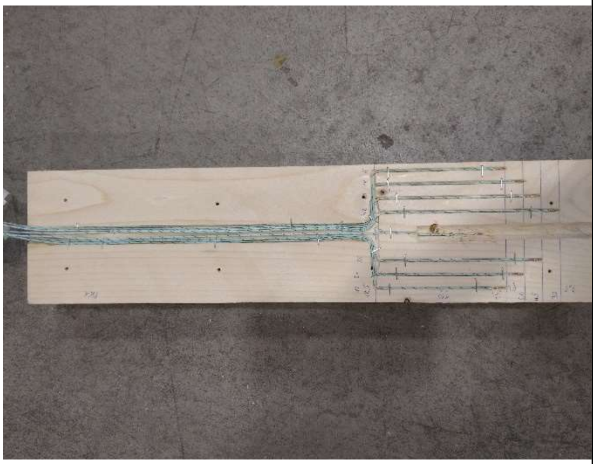
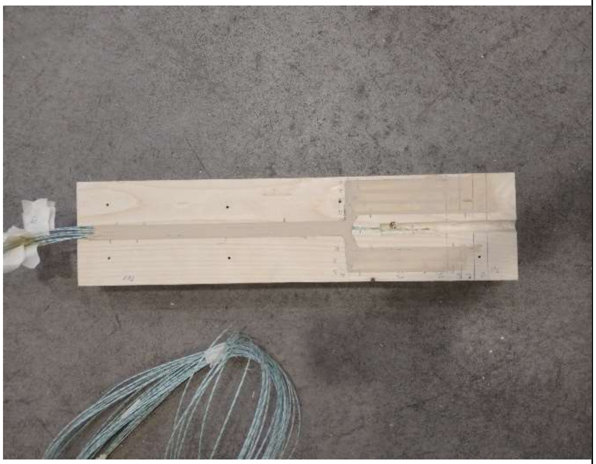
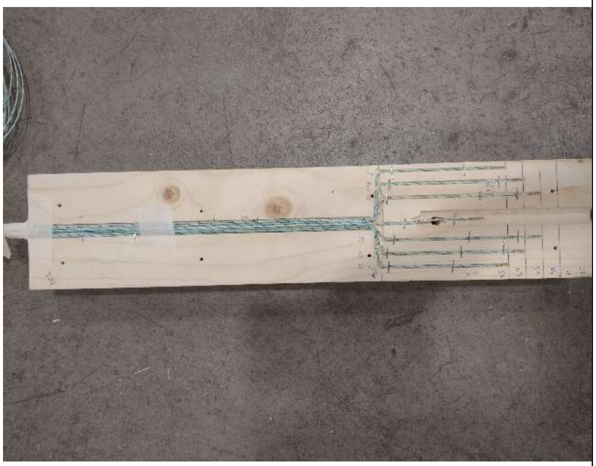
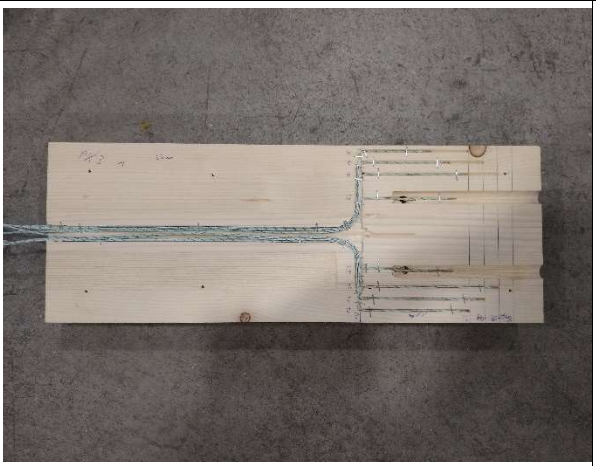
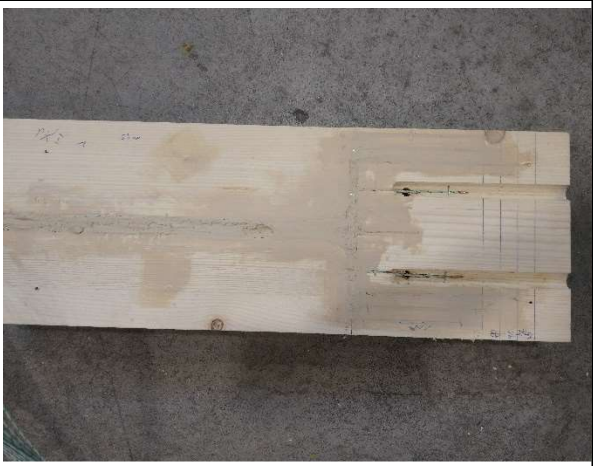
Date of gluing		
	Drilling	Gluing
	Test specimen	
13.06.2022	10:30	12:30
	Reference specimen	
13.06.2022	10:00	
07.07.2022		11:00

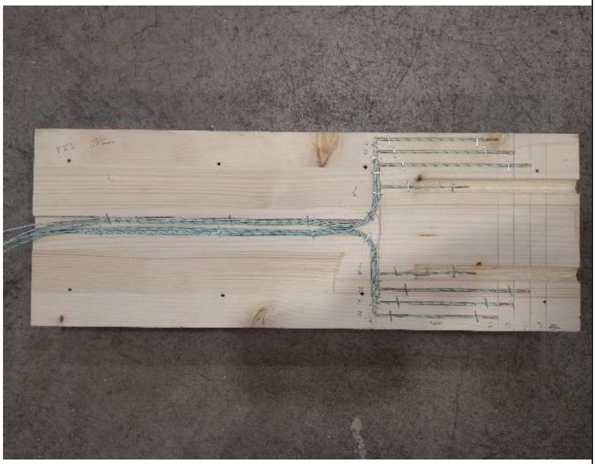
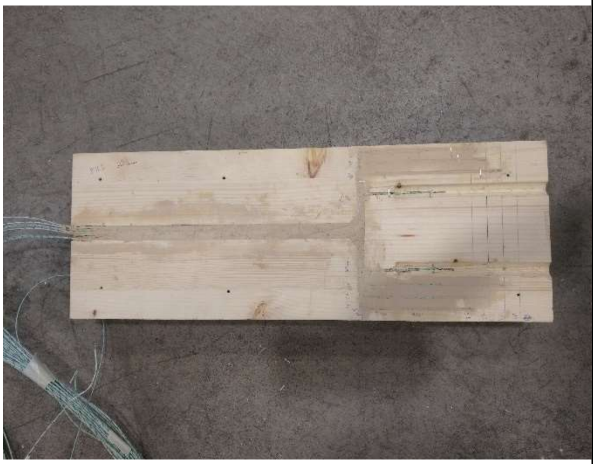
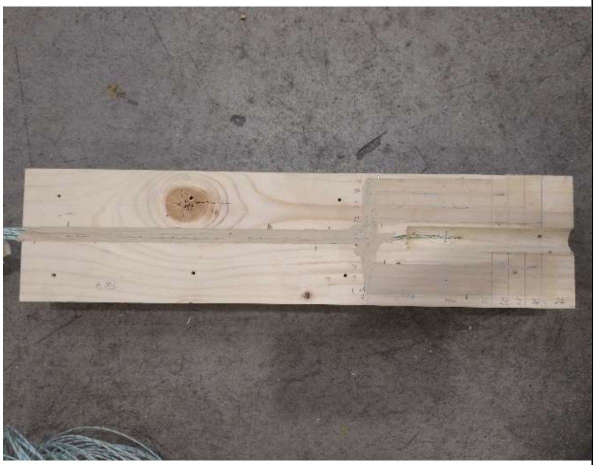
B Density specimens

Table 5: Densities of the specimen halves used

Test series 4	Density 1	Density 2
	[kg/m³]	[kg/m³]
SP1	425,8	449,7
SP2	487,1	500,6
SP3	457,4	475,6
SP4	419,6	424,4
Ref1	426,6	415,8
Ref2	475,8	471,8
Ref3	443,6	461,0
Ref4	416,7	415,8

C Reference specimen production

 Reference 1	 Reference 1
 Reference 2	 Reference 2
 Reference 3 - 46 mm	 Reference 3 - 46 mm

 Reference 3 - 43 mm	 Reference 3 - 43 mm
 Reference 4	 Reference 4

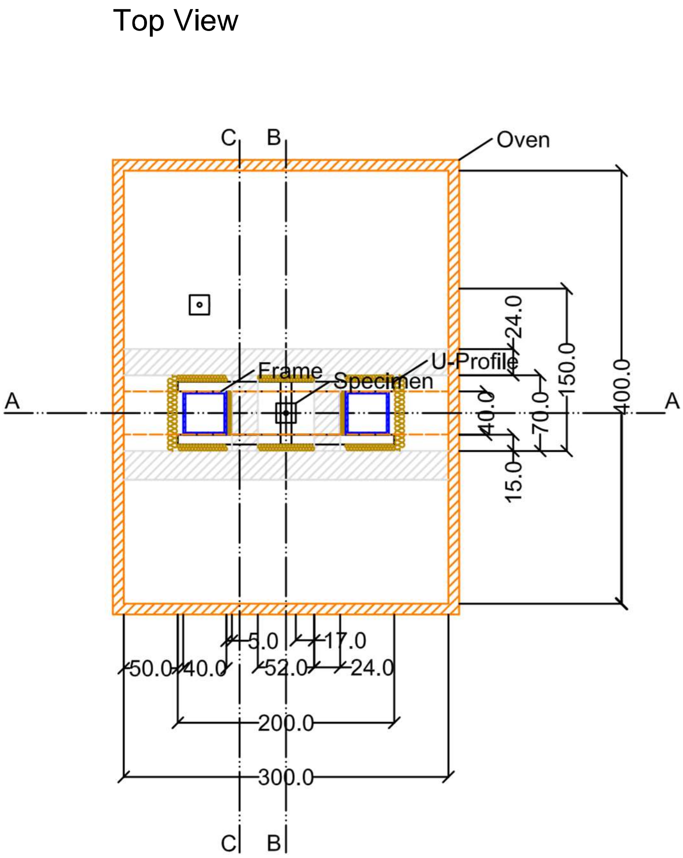


Figure 26: Top view of steel frame in furnace (M: 1:20)

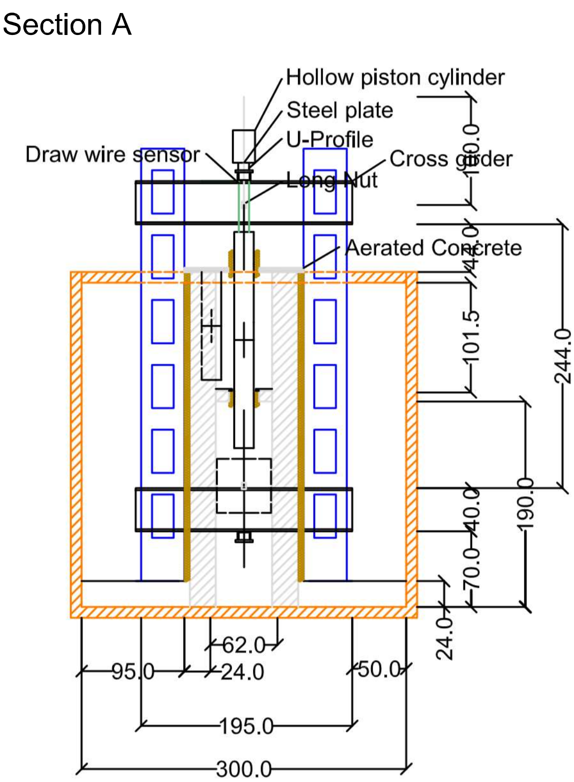


Figure 27: Section A of steel frame in furnace (M: 1:20)

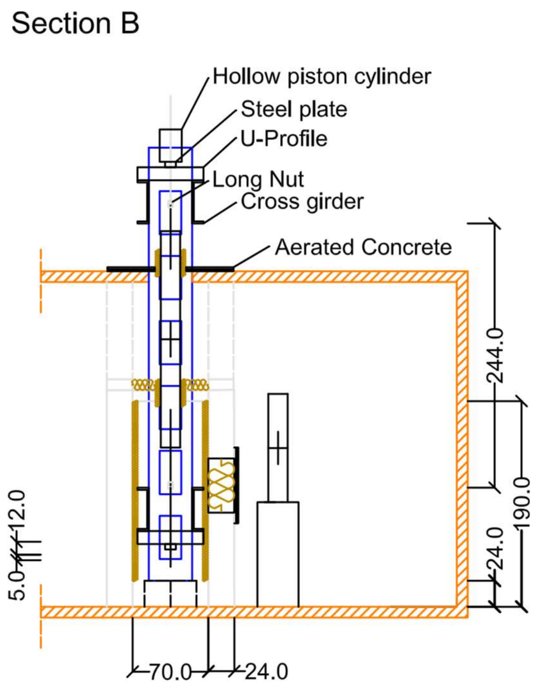


Figure 28: Section b of steel frame in furnace (M: 1:20)

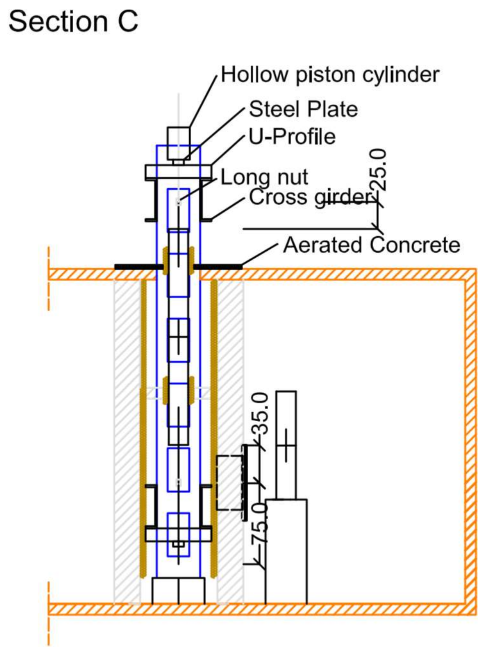


Figure 29: Section C of steel frame in furnace (M: 1:20)

E Temperature curves

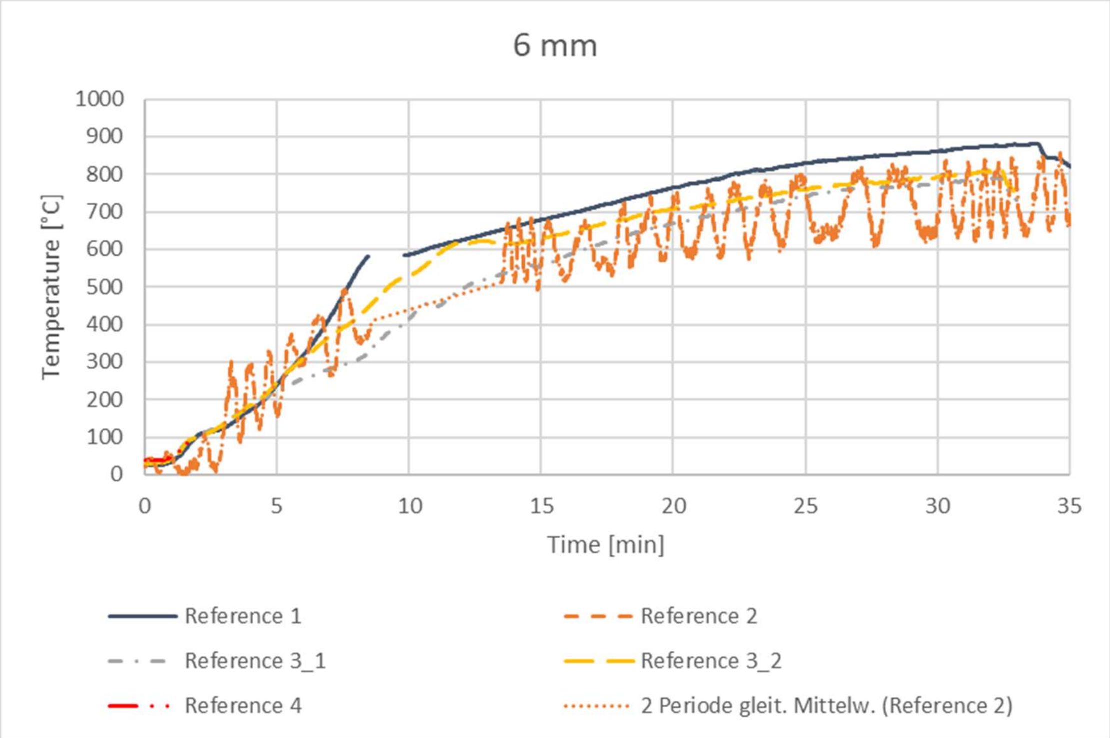


Figure 30: Temperature development for all reference specimens in a measurement depth of 6 mm

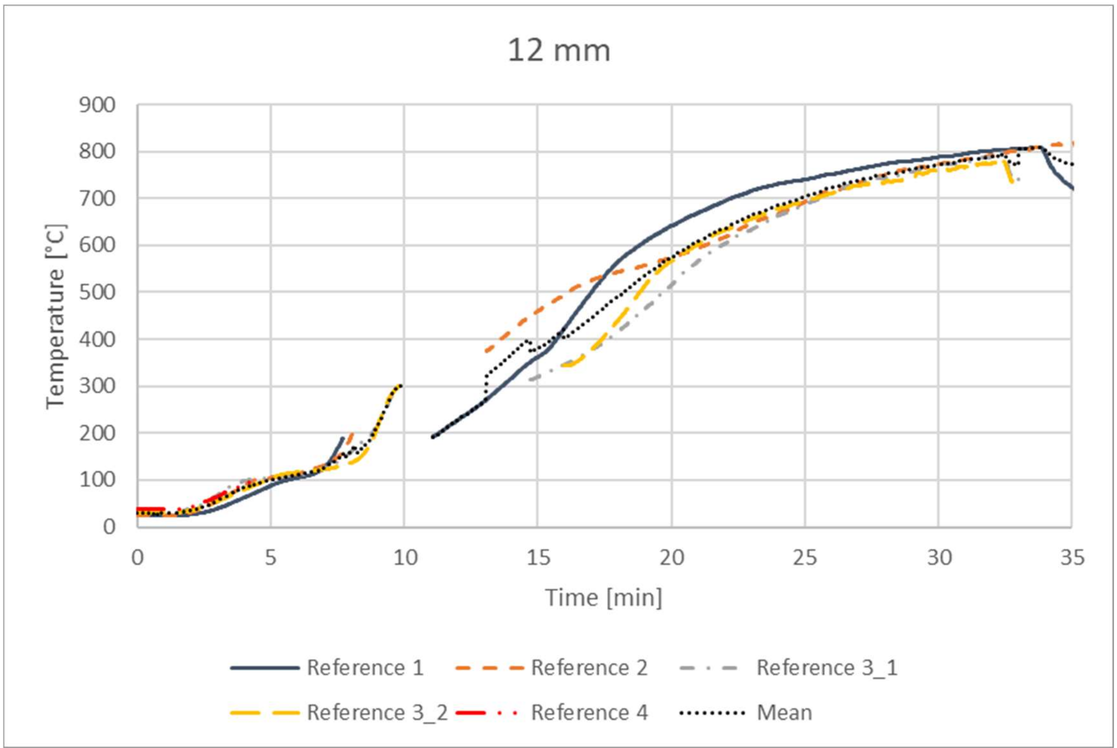


Figure 31: Temperature development for all reference specimens in a measurement depth of 12 mm

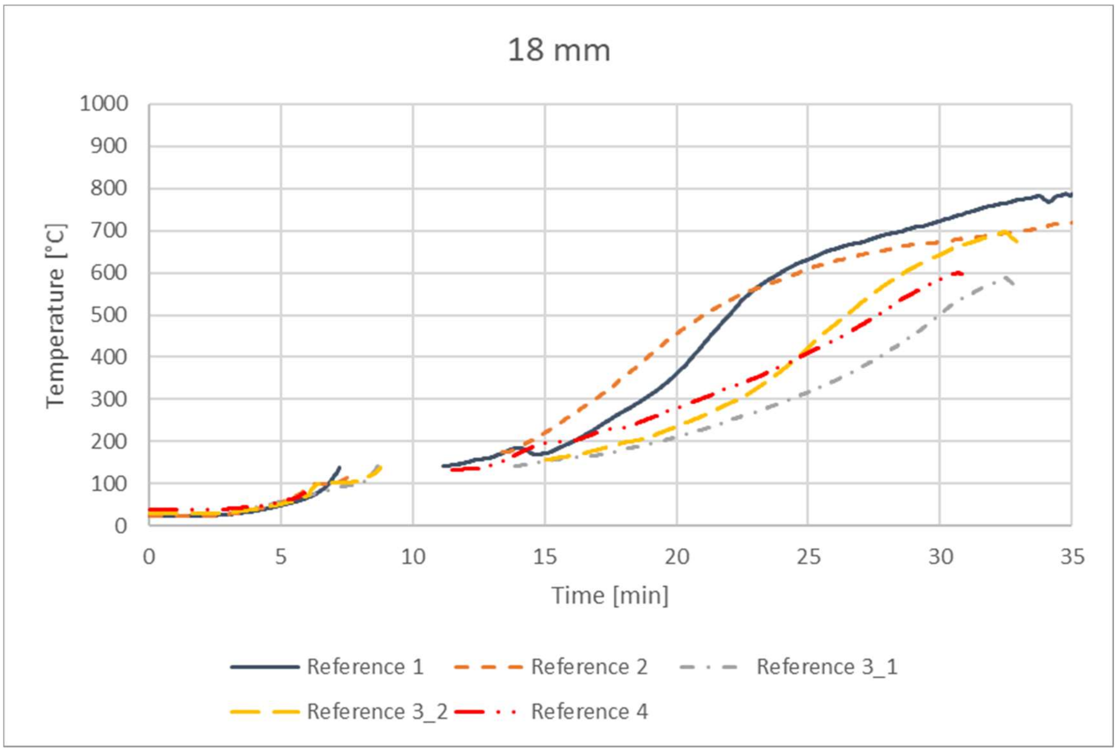


Figure 32: Temperature development for all reference specimens in a measurement depth of 18 mm

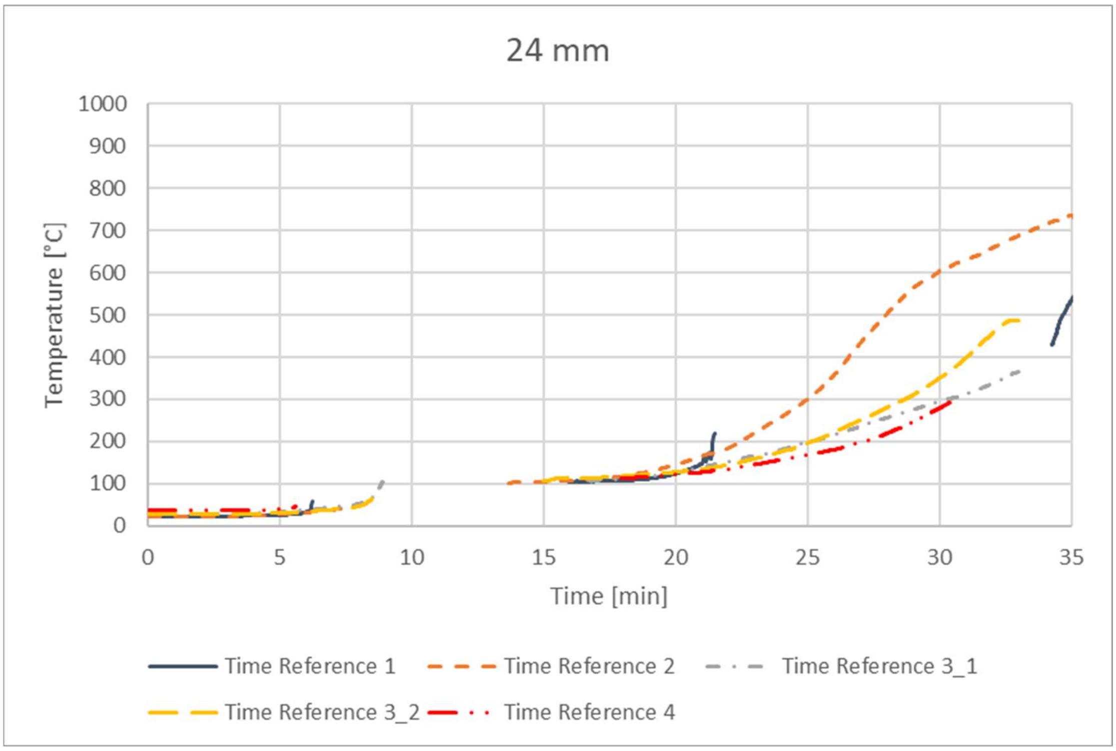


Figure 33: Temperature development for all reference specimens in a measurement depth of 24 mm

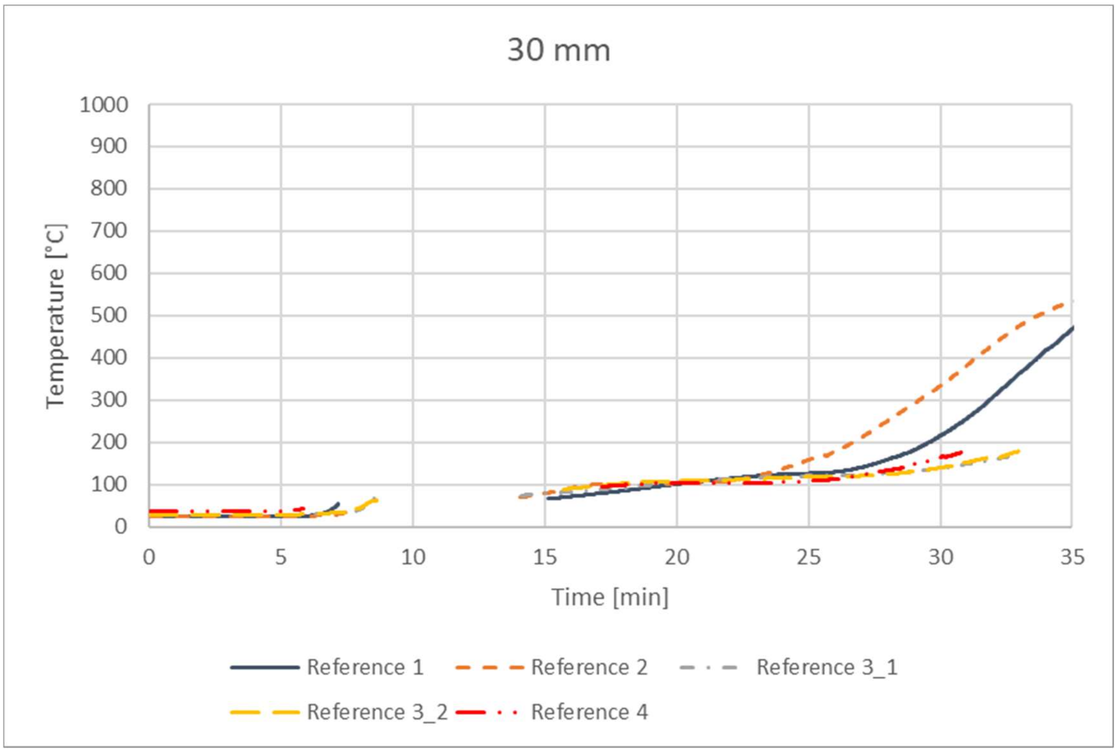


Figure 34: Temperature development for all reference specimens in a measurement depth of 30 mm

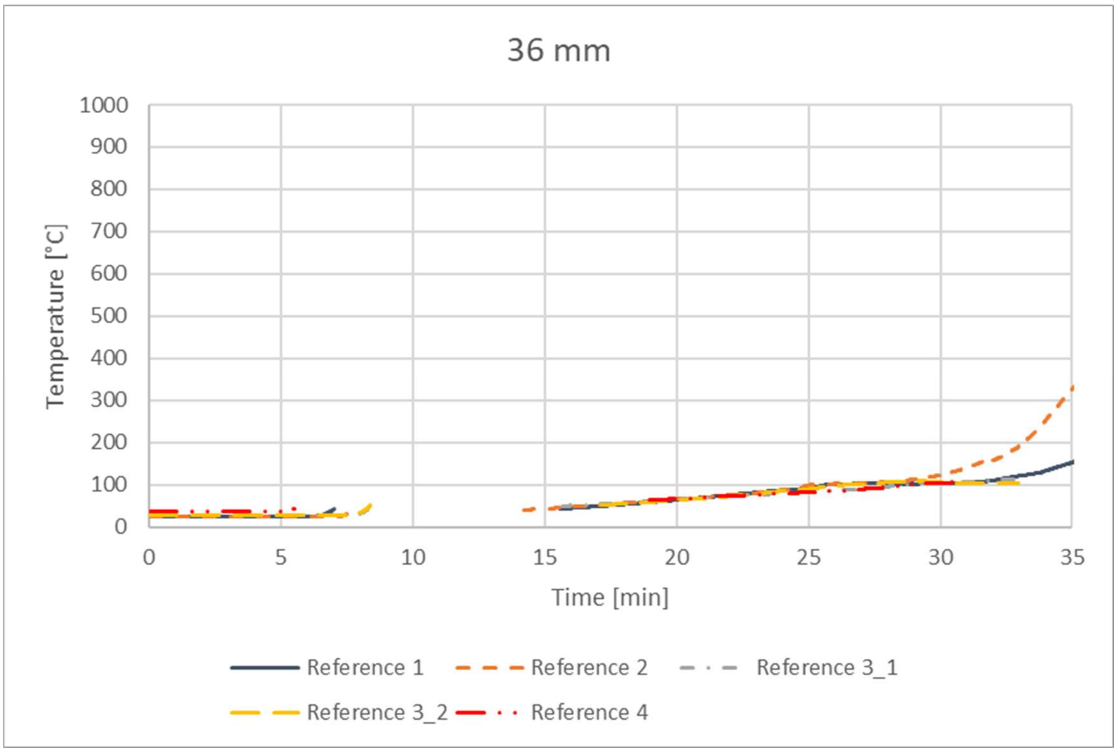


Figure 35: Temperature development for all reference specimens in a measurement depth of 36 mm

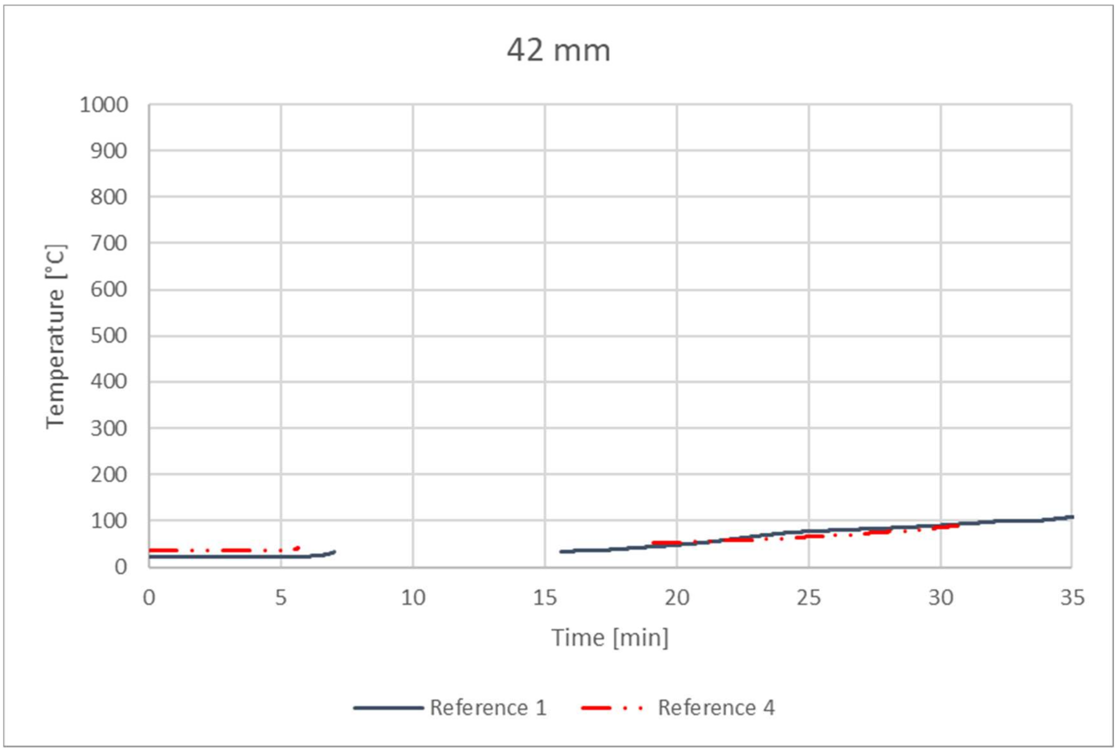


Figure 36: Temperature development for all reference specimens in a measurement depth of 42 mm

F Deformation

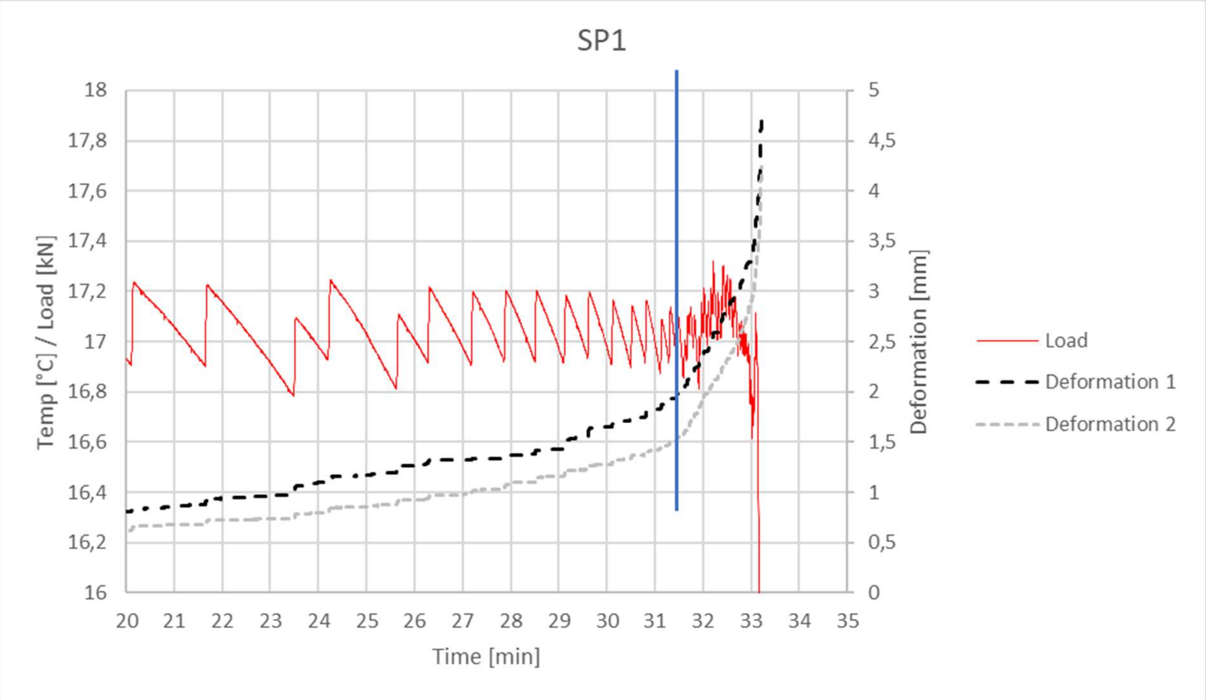


Figure 37: Load-deformation curves for specimen 1

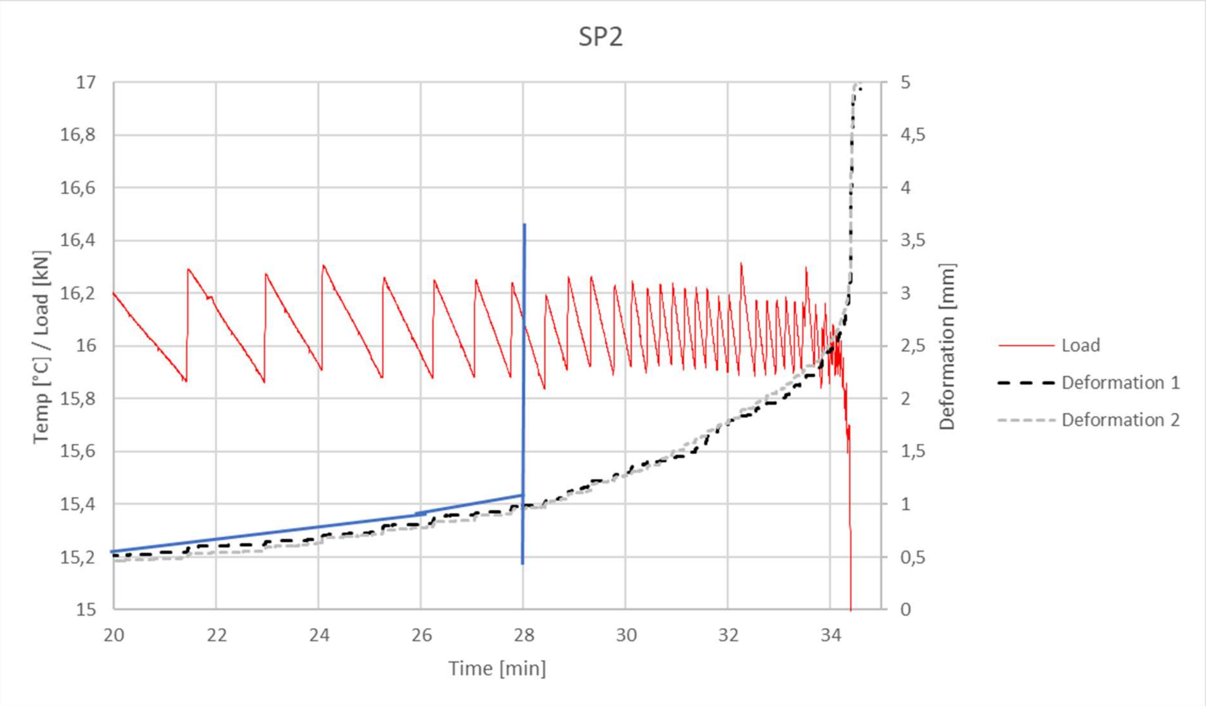


Figure 38: Load-deformation curve for specimen 2

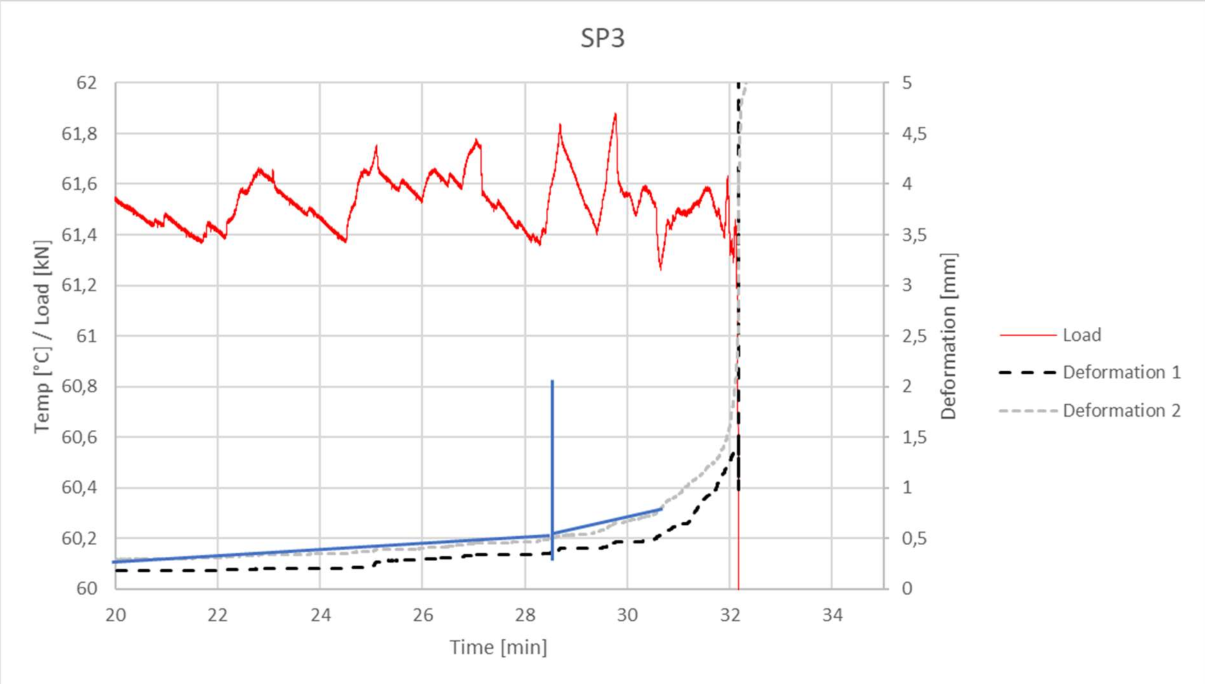


Figure 39: Load-deformation curve for specimen 3

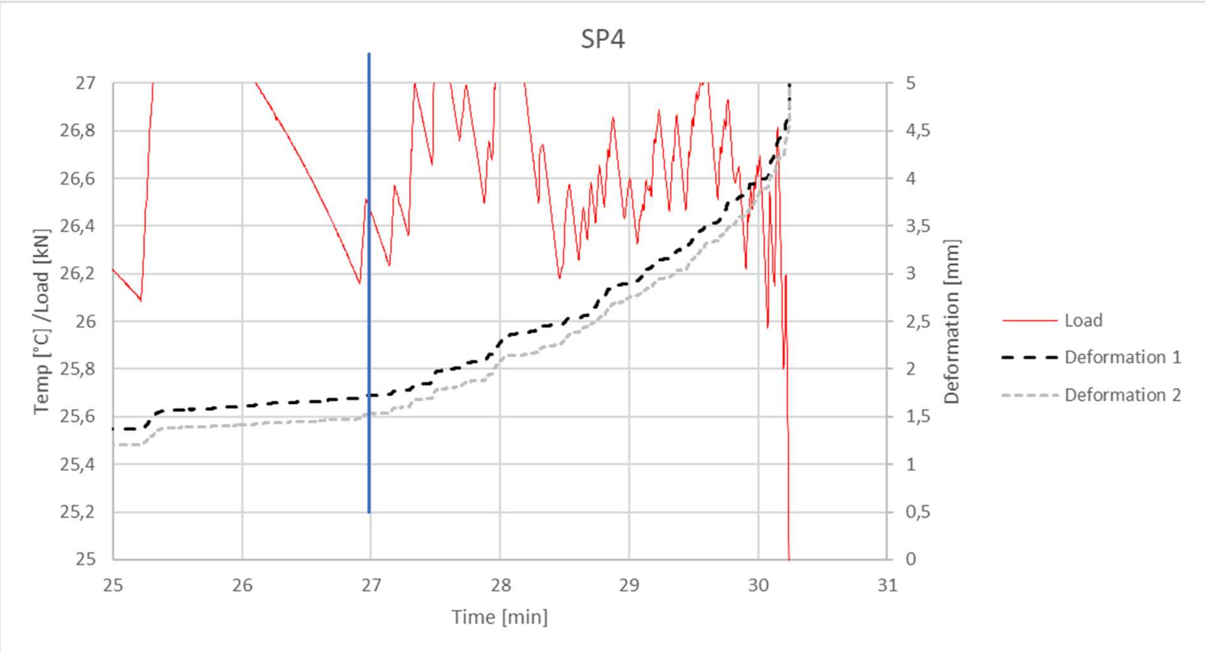


Figure 40: Load-deformation curve for specimen 4

G Temperature rod reference specimen

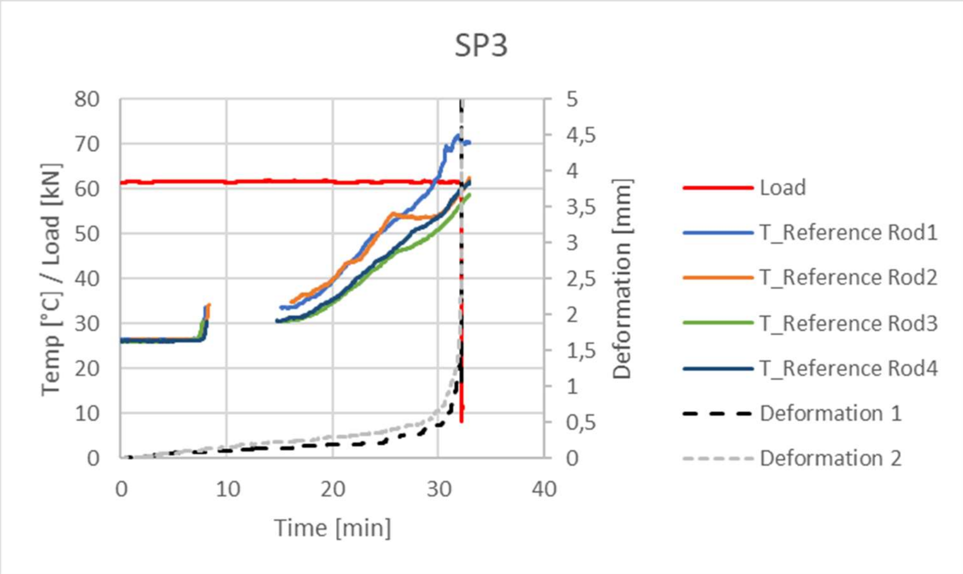


Figure 41: Tempearute curves for the glued in rods in reference specimen 3