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SIMULATION OF THE TEMPERATURE DISTRIBUTION IN GLUED BUTT-JOINT TIMBER CONNECTIONS

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Abstract. *The end-grain bonding of timber components with the Timber Structures 3.0 technology (TS3) is an emerging construction method in timber engineering. For onsite applications at low ambient temperatures down to 0 °C, it is being investigated numerically and experimentally if it's possible to heat the butt-joint to above 17 °C during the curing process using a heating wire. The current research results show that this is basically possible.*

1 INTRODUCTION

With the TS3 technology, timber components are bonded together in a statically load-bearing manner at the end grain surfaces. This offers the possibility of creating biaxial load-bearing flat slabs made of Cross Laminated Timber (CLT) in any geometry and size [1]. For this purpose, CLT elements with pre-treated side surfaces are mounted next to each other with a 4 mm gap between. This gap is then filled with a casting resin so that a bonding takes place without lateral pressure necessary. For that, two-component polyurethane casting resin is used. However, to establish this technology internationally and thus provide a high-quality climate-neutral replacement for reinforced concrete slabs, the processing temperature of at least 17 °C required in accordance with the approval for glued in steel rods into load-bearing timber components [2] is currently still a challenge for the construction site application. The reason for this is that this temperature is hardly or at least only rarely reached in the colder season of the year. Accordingly, solutions must be found to extend the applicability without being limited to one season.

Therefore, the possibility of locally tempering the 4 mm thick casting resin joint during the curing process is being investigated numerically and experimentally. For this purpose, the opportunity of placing heating wires in the joint is being investigated. These heating wires are intended to heat the casting resin joint, or at least the load bearing lamellas to above 17 °C during curing at low ambient temperatures.

2 NUMERICAL AND EXPERIMENTAL INVESTIGATIONS

2.1 Material

Symmetrical 7-layer cross laminated spruce timber is chosen as the material for the investigations. The entire test specimen (Figure 1) consists of two CLT elements, each 500 mm wide and 250 mm long. The cross layers are 30 mm high and the longitudinal layers 40 mm, resulting in a total height of 240 mm. For one of these components, two grooves are milled into the surface to be cast, into each of which a heating wire is inserted. In the grooves, the heating wires do not hinder the subsequent casting and are nevertheless local in the joint. In relation to the cross-section height, these are in the third and fifth layer, that means in the not load bearing cross layers in each case (Figure 2). The grooves are 4 mm high and 5 mm deep. Simple insulated copper strands with a diameter of 3.4 mm are chosen as the heating wires. A 4 mm thick layer of 2-component polyurethane (TS3 PTS CR192) casting resin is applied between the two components and in the grooves around the heating wires.

Figure 1: casted overall test specimen with two heating wires

Figure 2: CLT element with heating wires in grooves in the cross layers

2.2 Methods

Figure 3 schematically illustrates the methodological procedure of the entire investigation. First, a transient thermal numerical simulation is carried out in Ansys® to investigate whether the heating wires cause a sufficient temperature in the joint. For this purpose, the symmetrical 7-layer cross laminated timber structure shown in Figure 1 is modelled in cadwork® and imported into Ansys® afterwards. The 4 mm thick casting resin layer between the two components is firmly bonded. The heating wires are exposed to an electrical power of 15 W/m in the simulation. For the required material parameters (thermal conductivity and specific heat capacity) of the timber (spruce) depending on the respective fibre direction and the wood moisture content (u), slightly different values can be found in the literature (e.g. Niemz 2005 [3]). The values used for the simulation are shown in Table 1. For the casting resin, however, the values are only known for the cured state according to the manufacturer's specifications (Table 1). Although these differ from those in the fluid respectively curing state, which is modelled here, they represent a first approximation. An assumption is also made for the exothermic reaction heat, based on manufacturer's data. The heat transfer coefficient (α), which characterises convective heat transfer [4], is estimated as a function of the orientation of the respective surfaces for enclosed spaces [4] (Table 2).With these input values and an initial- and ambient temperature of 0 °C, the temperature distribution in the joint is calculated over the cross-section for a time period of 29 hours.

Subsequently, an experiment with the same boundary conditions is carried out (Figure 4, Figure 5, Figure 6). In order to be able to record the temperature development over time and the cross-section, a total of seven temperature sensors were attached across the cross-section before casting (Figure 4) and connected to a data logger (Figure 5). The constant outside temperature of 0 °C was ensured by storing the test specimen in a climate chamber (Figure 6) and the heating wires were controlled with a power unit so that the previously simulated electrical power of 15 W/m was achieved (Figure 5). The numerical and experimental results were then compared with each other.

Based on this comparison between the results of the numerical simulation and the experimental investigation, a sensitivity analysis was carried out to determine the influence and the absolute values of the material parameters of the casting resin in the liquid or curing state (thermal conductivity, specific heat capacity, exothermic reaction heat), which have not yet been precisely determined. Likewise, the heat transfer coefficient (α) was included in the sensitivity analysis, as there was a clearly higher flow velocity than expected in the climate chamber and the dependence on the surface orientation was negligible. In the following, these parameters were adjusted in the simulation so that the simulation and experiment match.

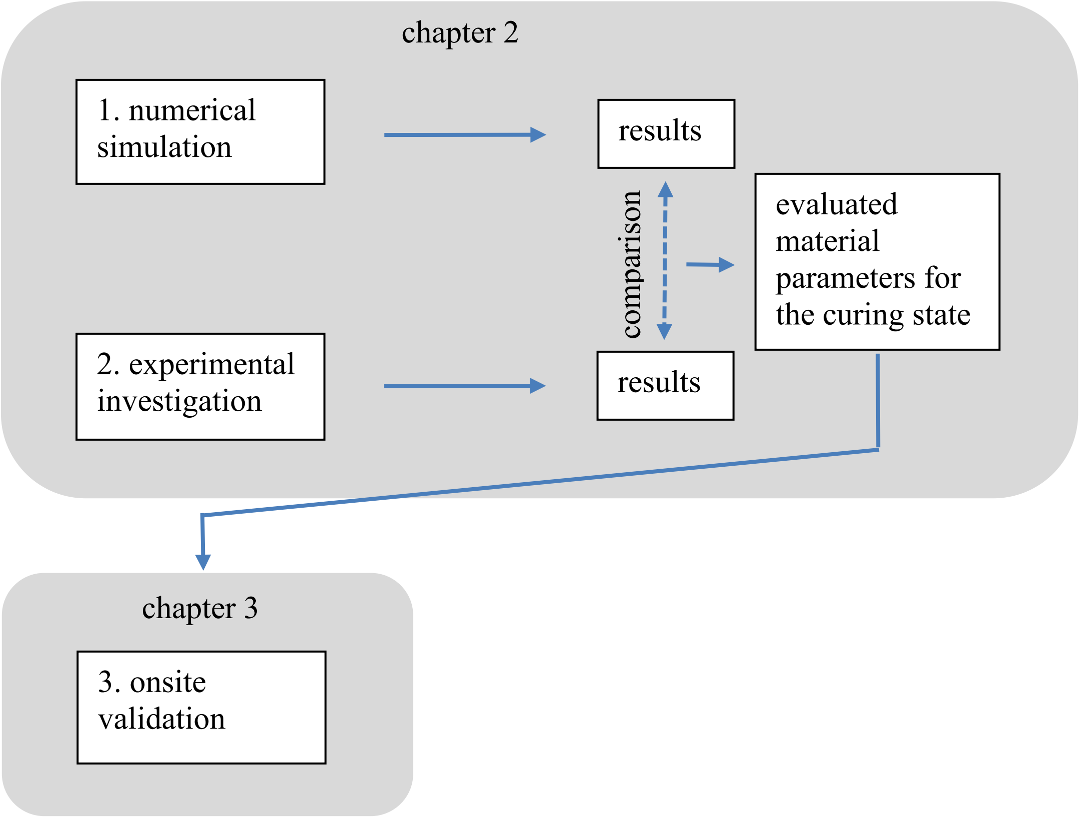

Figure 3: methodological scheme of the investigation

Figure 4: test setup: temperature sensors and heating wires before casting

Figure 5: test setup: data logger (left) and power unit (right)

Figure 6: test setup: casted test specimen in the climate chamber

2.3 Results

The numerically determined temperature distribution is completely plausible. Figure 7 shows this distribution after 29 hours at the interface between CLT and casting resin for the first simulation using the material parameters of the casting resin for the cured state. At this point, a constant temperature has already been established over time. The highest temperatures of about 100 °C occur at the heating wires and towards the top and bottom the temperatures drop to approximately 20 °C at the edges. The edge areas on the left and right also show lower temperatures than in the middle. Between the heating wires in the middle of the test specimen, a temperature of about 80 °C results.

Likewise, the results of the experimental investigation show a similar temperature curve after 29 hours in the middle of the test specimen width (Figure 8). Here, the temperatures at the heating wires are around 85 °C and become lower towards the outside, down to 10 °C at a distance of 10 mm from the outer edge (outermost measuring point; see Figure 4). In the area between the heating wires, a temperature of about 40 °C develops.

Although both described temperature curves are plausible and at first glance even approximately parallel, a closer look reveals partly significant differences. In particular, the absolute temperatures differ greatly. For example, there is a temperature delta of approximately 15 °C at the heating wires, and even 40 °C in between the heating wires. A temperature difference of 20 °C to 30 °C can also be observed in the outer areas. These differences in the temperature delta also make it clear that the courses are not parallel.

Figure 9 shows the comparison of the temperature curve over the cross-section between the experiment and the adjusted numerical simulation as described in chapter 2.2. The calculated curves and the spot-measured temperatures now agree with only minimal deviations. The material parameters of the casting resin and the heat transfer coefficient (α) used for this can be seen in Table 1 and Table 2.

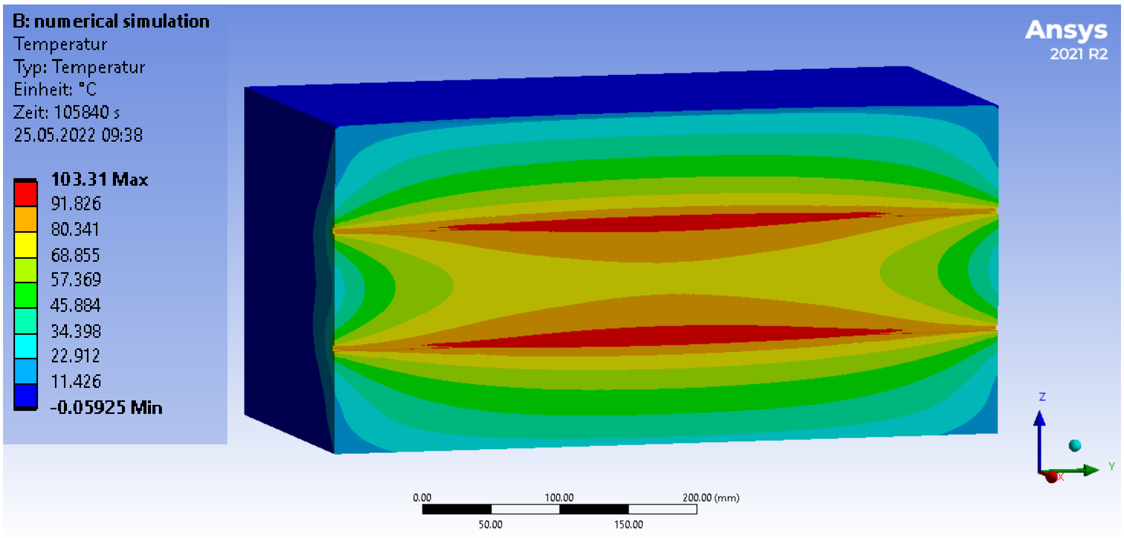

Figure 7: temperature distribution after 29 h

Table 1: material parameters for transient thermal analysis

Variable	Casting resin (cured state)	Casting resin (curing state) evaluated	Spruce Timber (u≈12 %)
specific heat capacity c	566.3 J/kgK	56.63 J/kgK	1680 J/kgK
thermal conductivity λ	0.5 W/mK	0.06 W/mK	0.13 W/mK (radial/ tangential) 0.24 W/mK (longitudinal)
reaction heat	4.15 * 10^{-5} W/mm^3	1.25 * 10^{-5} W/mm^3	-

Table 2: heat transfer coefficient (α)

Surface Orientation	Heat transfer coefficient (α) used before investigation	Heat transfer coefficient (α) evaluated after investigation
Vertical (Up)	$10.0 * 10^{-6}$ W/mm²K	$25.0 * 10^{-6}$ W/mm²K
Vertical (Down)	$5.9 * 10^{-6}$ W/mm²K	$25.0 * 10^{-6}$ W/mm²K
Horizontal	$7.7 * 10^{-6}$ W/mm²K	$25.0 * 10^{-6}$ W/mm²K

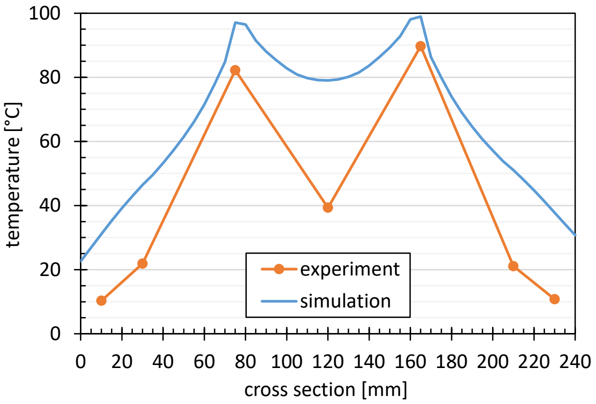

Figure 8: comparison of the temperature curves over the cross section after 29 h

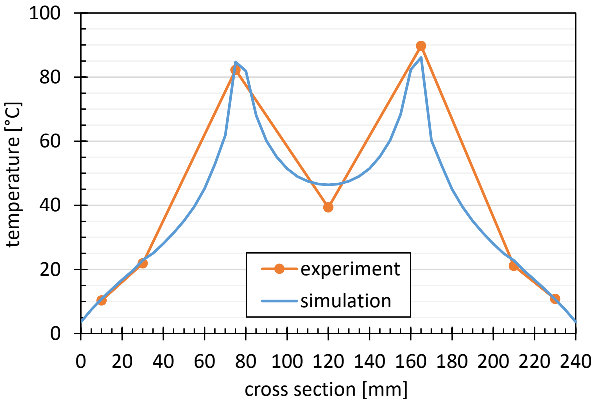

Figure 9: comparison of the temperature curves over the cross section after 29 h with adapted parameters

3 ONSITE VALIDATION

3.1 Material and Methods

In order to validate the parameters determined once again (see Figure 3) and also to be able to determine possible differences that arise between laboratory and construction site conditions, a numerical simulation was carried out using a real project with the parameters determined and the geometry and boundary conditions of the project. These were symmetrical 5-layer CLT elements with a height of 200 mm and only one heating wire inserted at the lower edge of the middle lamella (Figure 11). Figure 10 shows a ground floor plan of the building with the two TS3 joints marked with red dashed lines. The outside temperature was about 5 °C and the electrical power of the heating wire was 9 W/m. When pouring, the timber had the outside temperature of 5 °C and the casting resin 20 °C. In the simulation, the pouring process with the different initial temperatures of the materials was also modelled (Figure 13). In the first step, the initial temperature of 5 °C was assigned to the timber, the second step represents the pouring process in which the 20 °C warm casting resin is filled in and in the third step the heating phase begins in which the heating wire is operated for 29 hours. Similarly, temperature recordings were carried out (Figure 12) analogous to the laboratory experiment and the results were compared with each other.

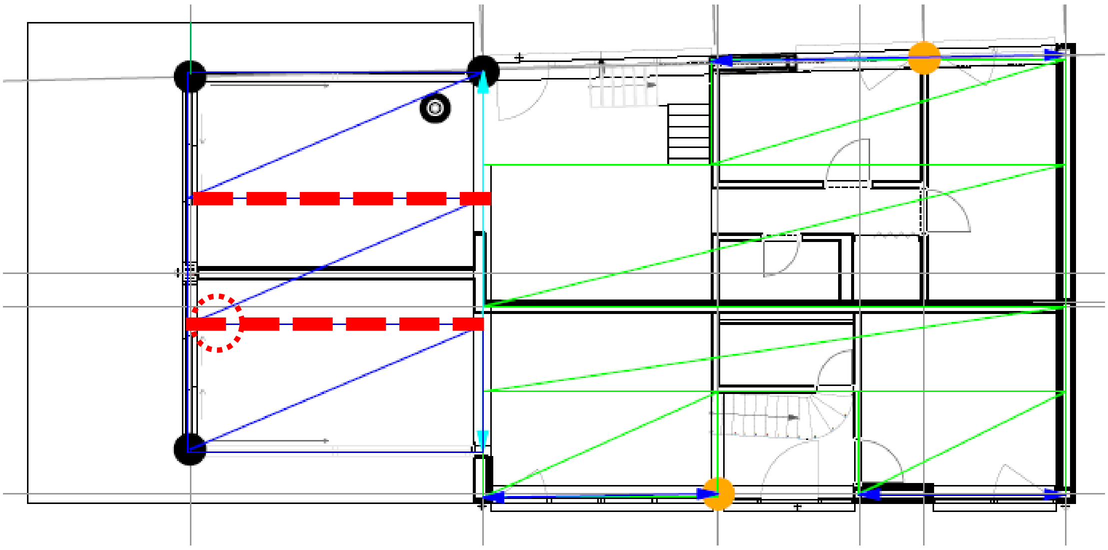

Figure 10: ground floor plan; red dotted circle: temperature measuring point (source: Timbatec Holzbauingenieure Schweiz AG)

Figure 11: Excerpt of the CLT elements with heating wire in the groove

Figure 12: temperature sensors onsite

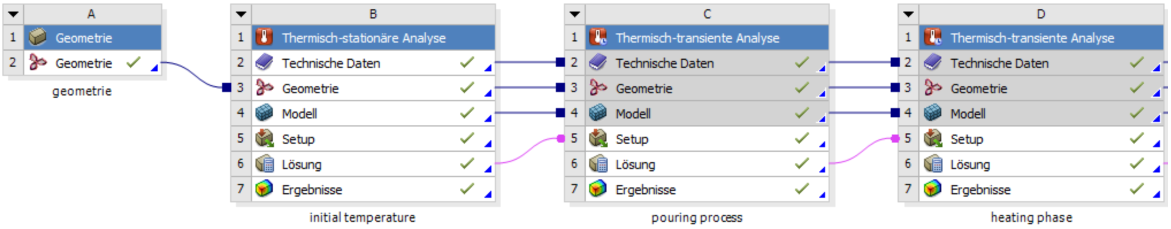

Figure 13: calculation structure in Ansys for onsite validation (incl. pouring process)

3.2 Results

In the renewed comparison between simulation and experiment, it becomes apparent that the latter also provides very satisfactory agreements under construction site conditions (see Figure 14). The temperature is highest at the heating wire at approximately 50 °C and decreases towards the outside. Since the heating wire was not inserted exactly in the middle of the cross-section, a slightly asymmetrical temperature distribution results. The deviations between simulation and onsite validation amount to only a few Kelvin.

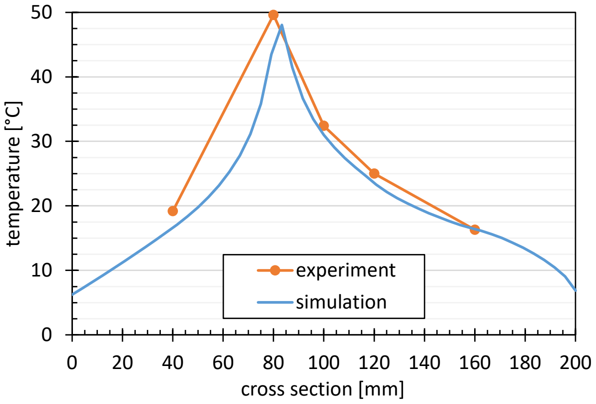

Figure 14: comparison of the temperature curves over the cross section after 29 h for onsite validation

4 CONCLUSIONS

The results of the adapted numerical simulation show that it represents reality very well. This is not only true for laboratory conditions but has also been confirmed with satisfactory accuracy on the construction site. Therefore, this model is suitable for carrying out temperature simulations in the given working environment in the future and thus being able to determine the temperatures as a function of time and the cross-section for the casting resin joint without having to carry out time-consuming measurements. Thus, it is now also possible to reliably determine and specify the necessary settings for the joint heating system (heating wires) depending on various parameters (geometry, outside temperature etc.) for the individual construction site situation by means of the numerical simulation and thus achieve the necessary temperature distribution.

5 OUTLOOK

Since the simulation provides very good results, in the next step this serves as the basis for developing a tool with which the necessary settings of current and voltage for the joint heating system can be determined quickly and easily on the construction site. For this purpose, certain boundary conditions as diameter and the specific electrical resistance of the heating wire are specified, but in addition, the corresponding values can be read off for the individual construction site situation. The panel thickness can be selected in 40 mm steps from 160 mm to 400 mm, and it must also be entered whether the outer lamella is load bearing or not. Furthermore, the outside temperature during curing must be estimated in 5 °C steps. All possible combinations of these input values are going to be calculated with the help of a parameterised simulation in Ansys® in order to subsequently output the target power of the heating wires of the joint heating system. By additionally specifying the heating wire length, the necessary current and voltage can be read off in an Excel tool.

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