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Advancing Timber for the Future Built Environment

ENHANCING END-GRAIN BONDING OF TIMBER COMPONENTS UNDER LOW-TEMPERATURE CURING CONDITIONS

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ABSTRACT: Timber Structures 3.0 (TS3) technology developed during the last 10 years represents an emerging method in timber engineering, focusing on end-grain bonding of timber components. For a wider application, this study investigates the effects of low curing temperatures on tensile strength of the bond and explores optimization strategies. Results indicate that low curing temperatures adversely affect mechanical properties, while using heated casting resin significantly improves bonding strength. The findings provide design-relevant tensile strength values and effective bonding strategies for low ambient temperatures.

KEYWORDS: end-grain bonded timber; tensile strength; temperature effects; cross-laminated timber; flat slabs

1 – INTRODUCTION

The use of TS3 technology, originally developed in Switzerland during the last 10 years and subsequently approved in Germany [1], enables the load-bearing bonding of timber components on the end-grain surfaces. Therefore, a two-component polyurethane casting resin is used on the construction site without the need for lateral pressure. This innovation represents a significant advancement in the field of structural engineering, as it enables the first-time creation of biaxial load-bearing flat slabs made from Cross Laminated Timber (CLT) of any geometry and size.

However, to establish this technology on an international scale and to offer a high-quality, climate-neutral alternative to reinforced concrete slabs, the processing temperature of at least 17 °C, as specified in the approval [1], presents a significant challenge for onsite applications throughout the year. Initial investigations on that topic indicated a slower curing process and lower tensile strengths [2,3]. Nevertheless, these preliminary investigations were constrained by a limited number of test specimens and the use of defect-free wood samples. In contrast, this study examines representative wood qualities and statistically meaningful numbers of test specimens in order to provide design-relevant values. In addition, potential solutions are being investigated that would allow casting at low temperatures without loss of strength.

2 – MATERIAL AND METHODS

The study investigated the curing of end-grain bonded timber at low temperatures (20 °C, 5 °C, 0 °C; Table 1). To reflect construction site conditions, the wood was preconditioned to the target temperature before casting. Bonding was performed using casting resin at 20 °C (standard case) and 35 °C (wGH) as a compensation measure. Tensile tests (≥ 16 per series) were conducted on days 1, 2, 3, 4, 7, 10, and 15 after casting (Table 2) to assess tensile strength. The following tables summarize the climatic and boundary conditions of the experiments.

For all test specimen, spruce timber *(Picea abies)* belonging to strength class T14/C24 according to EN 338

Table 1. Overview climatic conitions per series

Series Name	Wood & Curing Temperature [°C]	Casting Resin Temperature [°C]
20 °C wGH	20	35
20 °C	20	20
5 °C wGH	5	35
0 °C wGH	0	35
0 °C	0	20

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Table 2. Boundary conditions of all series

Strength Class	T14 / C24
Density	420 kg/m³ ± 25 kg/m³
Target Moisture Content	12 M%
Tested Cross-Section	38 mm × 120 mm
Length	800 mm
Adhesive Layer Thickness	4 mm
Quantity	16 test specimen per test day and series
Test Setup	Uniaxial tensile tests according to EN 408+A1 (2012) [5] in conjunction with EN 14080, Annex E2 (2013) [6]
Test Speed	0.015 mm/s
Test Days	(1); 2; 3; 4; 7; 10; 15

(2016) [4] with a density of 420 kg/m³ ± 25 kg/m³ and a target moisture content of 12 % was used. Wood defects, such as knots, were not excluded to obtain relevant design values, but the knot percentage was recorded after the tensile tests. The adhesive was the two-component polyurethane “TS3 PTS CR192” without solvents or formaldehyde.

For the test specimen production, glued laminated timber (GLT) elements (800 mm length) were fabricated from 18 lamellae (43 mm × 132 mm) with uniform annual ring alignment. These were halved, pre-treated, and conditioned for two days in a climate chamber before bonding. Bonding was performed at room temperature with a 4 mm adhesive layer, ensuring different GLT origins per joint. Casting was performed through an injection hole in the middle of the outer lamella and the individual lamellae were numbered according to their distance from this injection hole. After casting, which took about 30 minutes, specimens remained in the climate chamber until testing. For tensile tests, one bonded GLT block per test day was removed, cut along glue joints, and trimmed (6 mm per side). Cover lamellae were excluded, yielding 16 specimens (38 mm × 120 mm). This elaborate test specimen production was necessary to ensure that edge effects like surface bubbles or incomplete casting, which could impact tensile strength in small specimens, could be minimized.

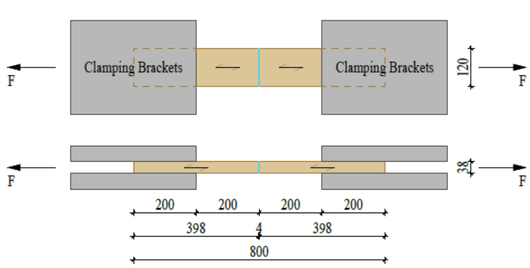

Figure 1. Schematic structure tensile tests; all dimensions in [mm]

The uniaxial tensile tests were conducted in a horizontal testing maschine and followed EN 408+A1 (2012) [5] in conjunction with EN 14080, Annex E2 (2013) [6]. The free specimen length was 400 mm (≥ 9 × width), see Figure 1. The temperature was between 17 and 29 °C and the relative humidity 35-65 % during the tests.

3 – RESULTS

Most specimens failed at the adhesive-timber interface (adhesive failure mode). To evaluate the effects of curing time and distance from the injection hole on tensile strength, initially only specimens without knots on the fracture surface are analyzed. Combined with the homogenization methods from *Material and Methods*, these influences are largely isolated.

Figure 2 displays the tensile strength versus time-averaged distance from the injection hole (with standard deviation). It can be seen, that at a curing temperature of 20 °C, the distance from the injection hole has no impact on tensile strength, as shown by the continuous line representing the overall average (Figure 2 top). However, at lower curing temperatures, this influence is clearly noticeable and is well-represented by third-degree polynomial functions for each test series. These functions were chosen because they closely correlate with the data (e.g., $R^2 = 0.95$ for the 0 °C series) and define inflection points for further analysis. Overall, both lower curing and casting resin temperatures amplify the negative impact of distance (see Figure 2 bottom). To mitigate this, reducing segment lengths proves effective. Thus, a maximum segment length is defined based on curing and casting resin temperatures, using the inflection points of the polynomial functions (red markings in Figure 2 bottom).

Figure 3 considers only specimens from the area between the injection hole and the inflection points (5 °C wGH ≈ 55 cm, 0 °C wGH ≈ 45 cm, 0 °C ≈ 40 cm). It depicts the mean tensile strength with standard deviation over curing time, modeled using the exponential function in equation (1). Here, ‘t_1’ represents the time at which ~63 % of the final strength (σ_∞) is reached. At 20 °C curing temperature, strength develops rapidly, reaching its final value within a day, regardless of casting resin temperature. Lower curing

$$\sigma(t) = \sigma_\infty[1 - e^{-t/t_1}] \quad (1)$$

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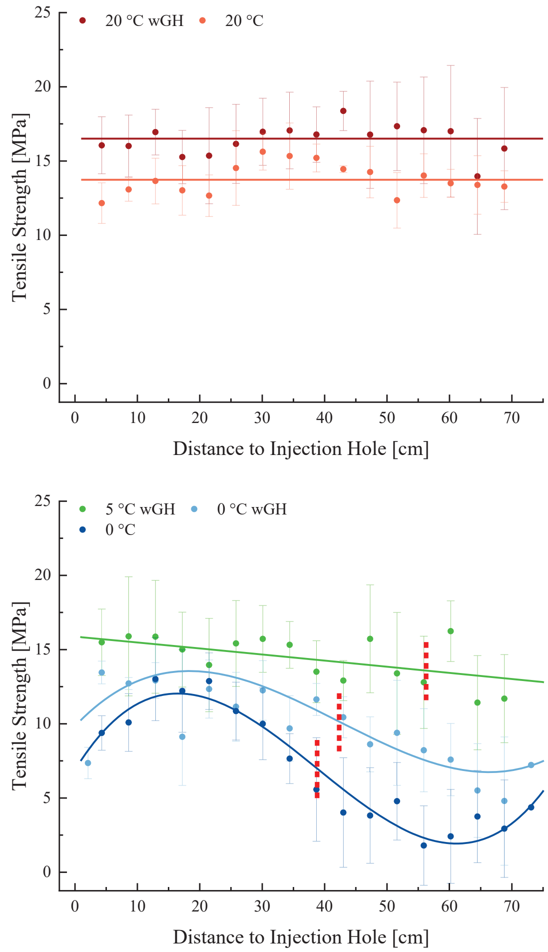

Figure 2. Tensile strength vs. distance to injection hole incl. standard deviation and trendlines

temperatures slow the process and result in lower final strength, while increasing casting resin temperature slightly reduces the curing rate but increases the final strength.

In a next step, the final strengths were analyzed. Therefore, only the lamellae within the defined limit distances (see Figure 2) are considered. In addition, the time to reach ≈ 99 % of σ_∞ is calculated for each test series using equation (1) and only specimens tested thereafter are included in the evaluation (20 °C wGH & 20 °C = day 1; 5 °C wGH & 0 °C = day 7; 0 °C wGH = day 10). Furthermore, test specimens with knots in the fracture surface, previously excluded, are now incorporated. No other outliers are excluded, ensuring that relevant tensile strength values for design purposes are provided. The results, shown in Figure 4, are categorized by test series using boxplots, which include all individual data points. Mean values are presented alongside the boxes. The boxplots confirm that lower curing temperatures at the same casting resin temperature significantly reduce mean final strength values with approximately 20 % reduction between 20 and 0 °C curing temperature. Furthermore, higher casting resin temperatures lead to higher average final strengths (around 20 % increase at both 0 and 20 °C curing temperatures), with these differences being statistically significant (confirmed in t-tests). The variability between the test series also differs, but no clear correlation between curing or casting resin temperature and this variability is observed. Notably, the 0 °C wGH series shows a relatively low coefficient of variation (COV) of 13 %, as detailed in Table 3.

Finally, the final strengths were assessed at a characteristic level. To calculate the characteristic tensile strength values according to EN 14358 (2016) [7], it was first necessary to determine the distribution function, which corresponds to a normal distribution. The characteristic final tensile strength values, as shown in Table 3, are graphically presented in Figure 5. These 5 % quantile values are plotted against curing temperature (asterisks) and distinguished by casting resin temperature (35 °C = red, 20 °C = blue). Idealized normal distributions based on empirical mean values and standard deviations are also displayed. The characteristic tensile strength established during the approval process by MPA University of Stuttgart [8] is shown as a green dashed line. This value, determined for board lamellae with similar dimensions, is only applicable for curing temperatures of at least 17 °C but serves as a benchmark for lower curing temperature

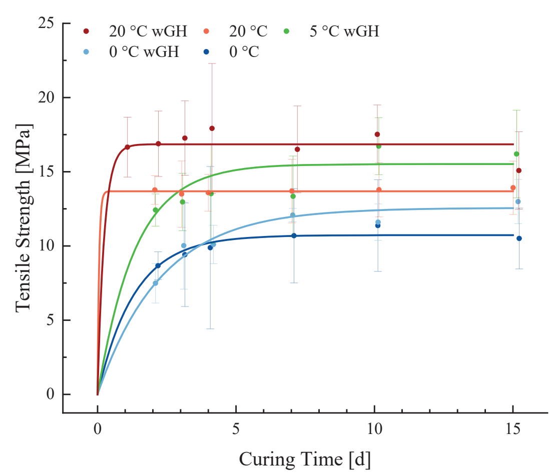

Figure 3. Tensile strength vs. curing time incl. standard deviation and trendlines

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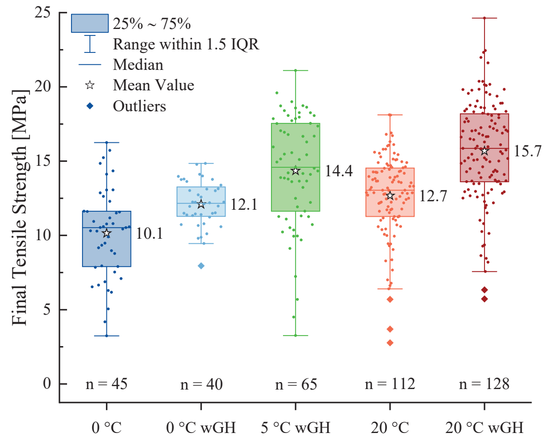

Figure 4. Boxplots of the final tensile strengths

scenarios. Consistent with the mean values, the characteristic strengths show that higher casting resin temperatures lead to significantly increased characteristic tensile strengths under identical curing conditions. Additionally, a curing temperature of 0 °C results in a 40 % reduction in characteristic strength compared to 20 °C curing temperature, assuming a 20 °C casting resin temperature. However, at a casting resin temperature of 35 °C, the characteristic strength at 0 °C curing temperature nearly matches that at 20 °C and exceeds that at 5 °C. This is mainly due to the low statistical dispersion in the 0 °C wGH series. Comparing with approval data, the 20 °C series from this study aligns with the approval conditions, and the 5 % quantile is consistent with the approval data, enhancing the reliability of the results. The 0 °C series shows significantly lower strength, while the

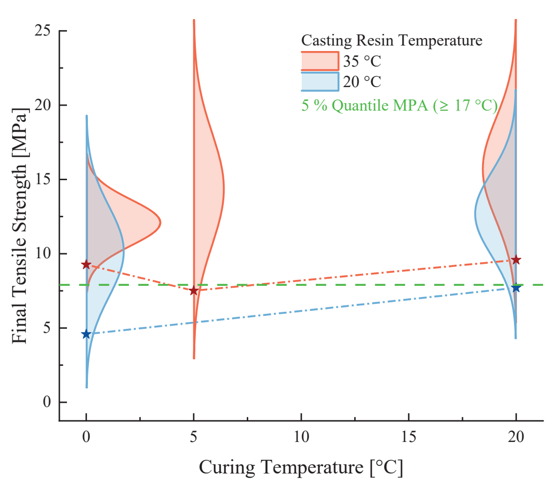

Figure 5. Final tensile strength vs. curing temperature incl. normal distribution & 5% quantiles according to EN 14358 (2016) [7]

35 °C casting resin temperature series either exceed (0 °C wGH and 20 °C wGH) or match (5 °C wGH) the benchmark strength.

4 – DISCUSSION

The observed impact of distance from the injection hole on tensile strength is plausible: the farther a lamella is from the hole, the longer the casting resin (warmer than the wood) takes to reach it, cooling as it passes the wood. Thus, tensile strength decreases with increased distance. In this study, the injection hole was located in the outer lamella of a glulam element, but in practice, it is typically centered in a CLT segment. The maximum distances observed here can be applied in both directions, doubling potential segment lengths. Additionally, real conditions likely result in less cooling from lateral edges than in laboratory settings, making the determined strengths conservative estimates.

Also plausible is the fact, that lower curing temperatures result in slower curing and reduced final strengths, while higher casting resin temperatures lead to higher strengths. However, especially at low curing temperatures, higher casting resin temperatures seem to slow down strength development, which is quite counter-intuitive.

The 0 °C wGH series has a notably low standard deviation, while the 5 °C wGH series shows a high variability. Therefore, in contrast to ecpectations, the characteristic strength at 5 °C curing temperature is lower than at 0 °C. Although the 5 °C wGH series has the highest knot percentage, this is not considered to be significant as it is less than 2.5 %. Even when analyzed without knots, the final strengths of the 0 °C wGH and 5 °C wGH series remain similar to those of the 20 °C series, with the positive influence of higher casting resin temperature still statistically significant.

In general, the curing characteristics of the pure resin [2,3], are not considered to have a significant influence on the TS3 tensile strength, as the cohesive tensile strength of the

Table 3. Determined values according to EN 14358 (2016) [7] for normal distribution

Series Name	**Mean Value [MPa]**	**Standard Deviation [MPa]**	**COV [%]**	**5 % Quantile [MPa]**
20 °C wGH	15.69	3.43	22	9.58
20 °C	12.68	2.79	22	7.71
5 °C wGH	14.36	3.80	26	7.51
0 °C wGH	12.09	1.54	13	9.26
0 °C	10.15	3.05	30	4.58

resin is notable higher than that of the TS3 joint at identical curing times and temperatures. This is further evidenced by adhesive failure being the predominant failure mode observed. Accordingly, it is assumed that influences on adhesion are decisive. Among other things, this could be the viscosity of the adhesive, which influences wetting.

5 – CONCLUSION AND OUTLOOK

The study on the impact of low curing temperatures on the tensile strength of end-grain bonded timber components offers key insights for on-site bonding using TS3 technology. The findings confirm the conclusions of Lins et al. [2,3] showing that the curing process is slower at lower temperatures. Furthermore, even with extended curing times, tensile strength remains lower at low temperatures compared to 20 °C. However, simple yet effective measures have been developed to mitigate the impact of low curing temperatures. These include limiting segment lengths and heating the casting resin to 35 °C before casting. The required curing times for achieving final strength were determined based on both curing and casting resin temperatures. These findings provide reliable characteristic tensile strengths, confirming that bonding at temperatures as low as 0 °C is feasible without strength loss if these measures are applied. This is especially relevant since the characteristic tensile strengths in the final approval are about 25 % lower than the benchmark values used in this study, ensuring a high safety margin. These measures are already being implemented on construction sites in Switzerland and have been validated through quality assurance tests. The results will also be used to extend the approval for TS3 technology. Future research will focus on analyzing the failure mechanism related to curing and casting resin temperatures, including microscopic studies of fracture interfaces, and exploring other factors like resin viscosity to further improve the TS3 joint's load-bearing capacity.

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