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INFLUENCE OF LOW CURING TEMPERATURES ON THE STRENGTH DEVELOPMENT OF END-GRAIN BONDED TIMBER

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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 which various research projects are being conducted. For onsite applications, among other things, it is being investigated how low temperatures during the curing process affect the bonding. The current research results show that low curing temperatures have a negative impact on the mechanical properties of the bond. However, it also shows that low temperatures have a different effect on the pure casting resin strength (cohesion) than on the bonding strength (adhesion). It has turned out that the pure casting resin is neither the decisive factor for the tensile strength of the end-grain bonding nor for the curing time. Based on these findings, compensation measures for bonding at low temperatures can be determined and further research can be carried out.

KEYWORDS: Cross Laminated Timber, end-grain bonded timber, tensile strength, temperature effect

1 INTRODUCTION

With the TS3 technology, timber components are bonded together at the end-grain surfaces in a statically load-bearing manner. In particular, this offers the possibility of creating biaxial load-bearing flat slabs made of Cross Laminated Timber (CLT) in any geometry and size. 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. A two-component polyurethane casting resin is used, like that used for bonding steel rods into load-bearing timber components.

However, in order to establish this technology internationally and thus create a high-quality climate-neutral substitute for reinforced concrete slabs, the required processing or curing temperature of at least 17 °C according to the approval for bonded-in steel rods in load-bearing timber components [1] is currently still a challenge for construction site application. The reason for this is that this temperature is hardly or only rarely reached during the colder season in parts of the European sales market, especially in Scandinavia, which has a high affinity for timber constructions, but also in the Baltic States and Central Europe. Therefore, practicable solutions must be found to extend the applicability geographically without being limited to the summer season. For bonded-in steel rods, there have already been studies on the temperature dependence of the bonding and experiments on bonding at low temperatures have been carried out, for example using inductive heating (see [2]). The experiments described in this paper also address the question of temperature influence to be able to embed the TS3 technology as soon as possible in quality assuring design standards, as for universal finger joints [3].

2 MATERIAL AND METHODS

2.1 GENERAL

The curing process depends not only on the curing temperature but also on the curing time [1]. According to the approval, this is 14 days at 17 °C until the final strength is reached [1]. To determine whether the specified final strength is only achieved after a longer curing time at lower curing temperatures, or whether this remains significantly lower, the curing process is investigated experimentally as a function of the two parameters temperature and time.

In order to determine the curing characteristics of the casting resin, test specimens are cast at about 20 °C and then allowed to cure at different (lower) temperatures (20 °C, 15 °C, 10 °C, 5 °C, 0 °C) and tensile tests are carried out at different times. These tensile tests take place on the 1. / 2. / 3. / 6. / 10. / 15. / 20. / 30. day after casting. In addition, it is checked whether and, if so, to what extent post-curing takes place during post-storage at 20 °C. For this purpose, after 20 days of curing at low temperature, test specimens are subsequently stored at 20 °C for a further 7 or 14 days (see Figure 1) and then subjected to a tensile test.

According to the manufacturer's data, the tensile strength of the pure casting resin is approx. 45 N/mm^2, which is significantly higher than the previously determined strength of bonded timber (end-grain bonding).

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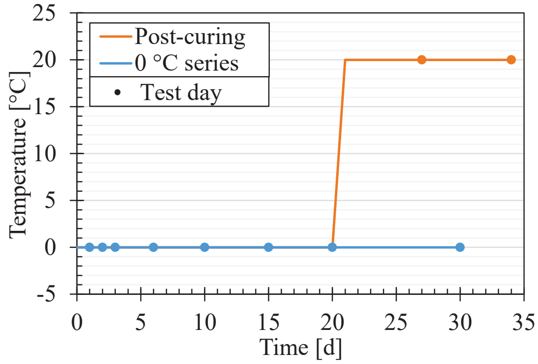


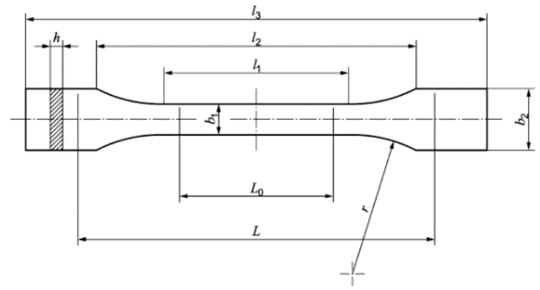
Figure 1: *Exemplary representation of the curing temperature for the 0 °C series incl. post-curing*

Furthermore, low curing temperatures may have a different effect on the curing characteristics of the bonding strength, than of the pure casting resin. Therefore, timber bonding specimens are additionally tested. The development of hardness for similarly stored casting resin samples was also investigated to derive a possible correlation between hardness and strength. This correlation could be used to introduce an additional option for quality monitoring. In this way, the simple and quick handling of the hardness test can be conducted on the construction site and thus conclusions can be drawn about possible curing deficits.

2.2 DETERMINATION OF THE CASTING RESIN STRENGTH

The casting resin strength is tested according to SN EN ISO 527 (Plastics - Determination of tensile properties) [4]. To produce the test specimens, TS3's own 2K-PUR casting resin "TS3 PTS CR192" is poured into a template to obtain the geometry according to Figure 3. This template is fixed in a casting device (see Figure 2). Immediately after casting, the test specimens together with the casting device are stored in a climate chamber at the respective low temperature. On the first test day, all test specimens of a series are taken out of the template and

Figure 2: *Casting device*



	Specimen type	1A	1B
l_3	Overall length[a]	170	≥150
l_1	Length of narrow parallel-sided portion	80 ± 2	60,0 ± 0,5
r	Radius	24 ± 1	60 ± 0,5
l_2	Distance between broad parallel-sided portions [b]	109,3 ± 3,2	108 ± 1,6
b_2	Width at ends	20,0 ± 0,2	
b_1	Width at narrow portion	10,0 ± 0,2	
h	Preferred thickness	4,0 ± 0,2	
L_0	Gauge length (preferred)	75,0 ± 0,5	50,0 ± 0,5
	Gauge length (acceptable if required for quality control or when specified)	50,0 ± 0,5	
L	Initial distance between grips	115 ± 1	115 ± 1

[a] The recommended overall length of 170 mm of the type 1A is consistent with ISO 294-1 and ISO 10724-1. For some materials, the length of the tabs may need to be extended (e.g. l_3 = 200 mm) to prevent breakage or slippage in the jaws of the testing machine.

[b] $l_2 = l_1 + [4r(b_2 - b_1) - (b_2 - b_1)^2]^{1/2}$, resulting from l_1, r, b_1 and b_2, but within the indicated tolerances.

Figure 3: *SN EN ISO 527-2:2012: Dimensions of type 1A and 1B test specimens [4]*

the thickness is calibrated on a wide belt sander (grit 100) to the specified 4 mm ± 0.2 mm (see Figure 3). Subsequently, the test specimens are again stored at the respective low temperature and removed from the climate chamber at the planned times and subjected to a tensile test. The tensile test also takes place according to EN ISO 527 and is displacement-controlled with a test speed of 2 mm/min. The test is carried out in a constant climate of 20 °C and 65 % r. h. Since the casting resin is a homogeneous material after mixing the two components and thus a low scatter is to be expected, only three test specimens are tested per test day and temperature.

2.3 DETERMINATION OF THE BONDING STRENGTH

The bonding strength of the end-grain bonding at low temperatures is determined following the TS3 approval tests of the MPA University of Stuttgart [5]. These in turn were carried out in close accordance with DIN EN 301 [6] and DIN EN 302-1 [7]. Just like the tensile tests of the pure casting resin, the timber bonding test specimens are also tested at 20 °C and 65 % r. h. with a displacement-controlled test speed of 2 mm/min.

To be able to consider the temperature influence in isolation, all other parameters are excluded as possible influencing factors on the tensile strength as far as possible. For this purpose, spruce timber with a low scattering gross density of 350 kg/m³ ± 25 kg/m³ is defined for all test specimens. Secondly, the wood moisture content should be 12 % in all test series. For this purpose, the relative humidity is adjusted according to the respective temperature in such a way that a compensation wood moisture content according to Keylwerth and Noak [8] of 12 % is achieved. For monitoring purposes, the

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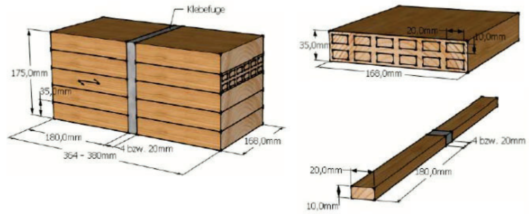
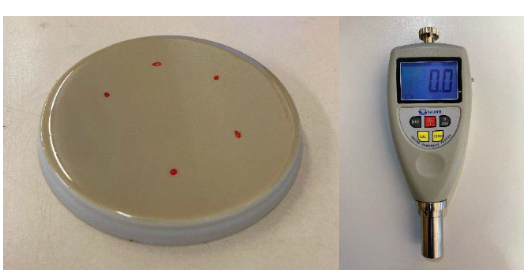


Figure 4: *Schematic representation of the axial composite tensile test specimen [5]*

temperature, the relative humidity as well as the wood moisture content are recorded during the entire test. The wood moisture content is measured in two separate ways on reference test specimens, which are also located in the climate chamber. On the one hand, the wood moisture content is continuously recorded using the resistance method, and on the other hand, several test specimens are weighed regularly, and oven dried at the end of the test series to determine the wood moisture content at the respective measurement times. Since wood defects, such as knots in particular, have a great influence on the tensile strength of the small, end-grain bonded test specimens, these are also excluded in order to be able to determine the temperature influence as accurately as possible.

To produce the timber bonding test specimens, glulam elements are first made from board lamellas, see Figure 4, left. These are then cast together on the end-grain surface according to the TS3 technology and stored in a climate chamber at the intended temperature. Analogous to the determination of the casting resin strength, the glulam elements are cut apart after the first day, so that the test specimens are produced with the dimensions 10 mm x 20 mm, see Figure 4. These are then stored again in the climate chamber and tested on the corresponding days. The aim of this complex test specimen production is to eliminate possible edge influences such as bubble formation or incomplete casting, because although these are negligible on the component scale, they can result in significant deviations in the small test specimen geometry. Since the timber and thus the bonding test specimens, despite the homogenisation approaches mentioned above, give rise to the assumption of greater scattering compared to the casting resin, five test specimens are tested per test day and temperature.



(a) Test specimen *(b) Durometer*

Figure 5: *Test specimen (a) and measuring device (b) for determining the casting resin hardness*

2.4 DETERMINATION OF THE CASTING RESIN HARDNESS

The hardness is determined according to EN ISO 868 [9]. According to the standard, the Shore-D hardness of the "TS3 PTS CR192" casting resin is tested with a corresponding durometer (see Figure 5). The test specimens are small round plates (see Figure 5), which are cast in corresponding templates and then stored with the tensile test specimens in the climate chamber. Five hardness measurements are conducted on different samples for each test day and temperature.

3 RESULTS

3.1 GENERAL

In Figure 7 to Figure 9, the mean value curves of the three measured variables (casting resin strength, bonding strength, casting resin hardness) including standard deviation are plotted against time and compared with each other for the different curing temperatures. This is shown individually for each measurand. In addition, a comparison of the curves of the three measured variables is shown as an example for 10 °C curing temperature in order to recognise the correlation between the casting resin hardness and strength. Furthermore, a proposal is made for a design concept that considers the influence of low curing temperatures on the tensile strength of end-grain bonded timber components.

3.2 CASTING RESIN STRENGTH

Figure 7 shows the development of the tensile strength of the casting resin at the five different curing temperatures. It can be seen that lower curing temperatures result in significantly lower initial strengths. It can also be seen that the strength development is completed more quickly at higher temperatures than at lower ones. It can also be seen that the post-curing effect has a greater impact at lower curing temperatures and is no longer noticeable at 15 °C. The difference between the final strengths after post-curing is exceedingly small and the overall scatter is relatively low, as expected.

3.3 BONDING STRENGTH

Since knots were removed from the composite test specimens to isolate the influence of temperature, the absolute strength values are not directly representative for

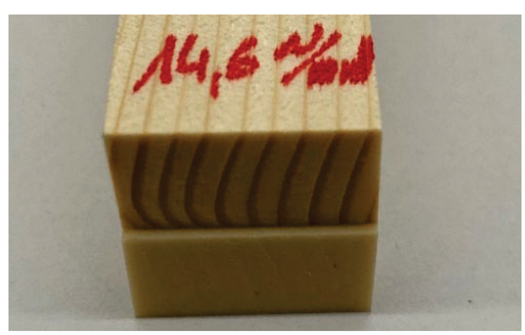


Figure 6*: Fracture pattern of timber bonding test specimen*

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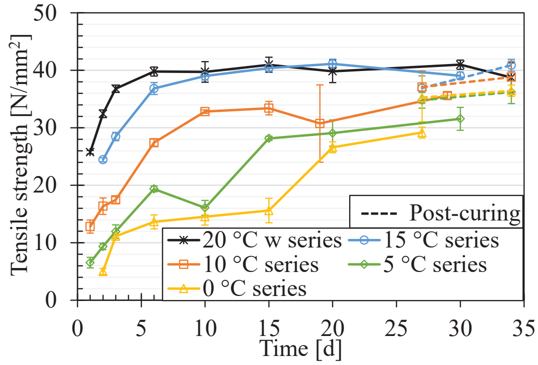

Figure 7: *Temperature comparison of the casting resin strength (mean values)*

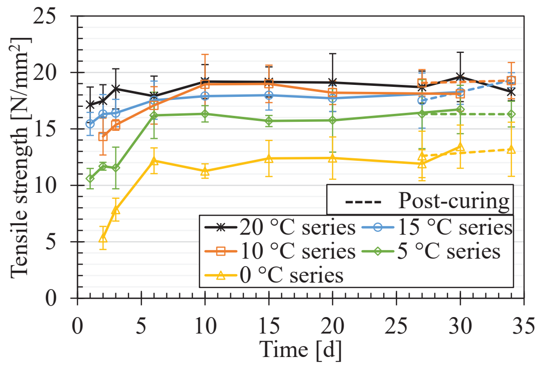

Figure 8: *Temperature comparison of the bonding strength (mean values)*

design; however, the temperature comparison provides an elevated level of information. Figure 8 shows, analogous to Figure 7, the development of the tensile strength of the timber bonding specimens at the different curing temperatures. Here, too, lower temperatures during curing result in lower initial strengths. However, regardless of the curing temperature, the final strength is reached earlier than with the pure casting resin, i.e., at the latest approx. 6 days after casting. Furthermore, there is no further increase in strength during post-curing, so that low curing temperatures also result in lower final strengths. It is also clear that the scatter in the bonding strength is, as expected, higher than with the pure casting resin. Furthermore, it is noticeable that in most cases the fracture appears to occur exactly in the area between the pre-treatment and the casting resin (see Figure 6).

3.4 CASTING RESIN HARDNESS

Figure 9 shows the development of the casting resin hardness at the different curing temperatures. As in the two previous diagrams, it can be seen that a lower curing temperature results in a significantly lower initial hardness. Analogous to the casting resin strength, it can also be seen with the casting resin hardness that curing proceeds more slowly at lower temperatures, since the final hardness is reached significantly later than at higher temperatures. As with the casting resin strength, the post-

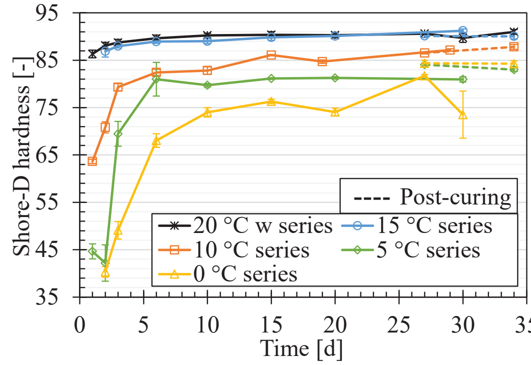

Figure 9: *Temperature comparison of the casting resin hardness (Shore-D hardness; mean values)*

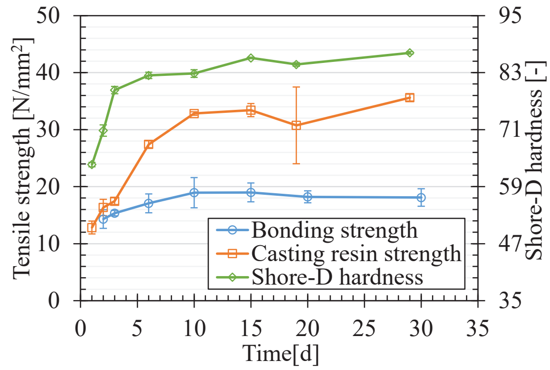

Figure 10: *Comparison of the casting resin strength, the bonding strength, and the casting resin hardness at 10 °C (mean values)*

hardening effect is also greater at lower temperatures than at higher temperatures. Here, however, this effect is no longer significant at 10 °C. Accordingly, the final hardness after post-curing is at a similar level despite the different curing temperatures, but with greater differences than for the casting resin strength. The scatter of the casting resin hardness is also very low, analogous to the casting resin strength.

3.5 COMPARISON CASTING RESIN STRENGTH – BONDING STRENGTH – CASTING RESIN HARDNESS

The comparison between the casting resin strength, the bonding strength, and the casting resin hardness in Figure 10, shown exemplarily for 10 °C curing temperature and without the post-curing, shows that the three measured variables basically correlate with each other over the period of 30 days. However, this fundamental correlation is not very surprising, as all the measured variables mentioned inevitably increase due to the chemical reaction after casting. However, a closer look at the graphs reveals that the casting resin strength and hardness in particular show approximately parallel curves. This can also be confirmed by the correlation coefficient according to Pearson [10] of 0.91 (r above 0.8: "high to perfect correlation"). Compared to the bonding strength, the deviations of the curves are significantly greater since the bonding strength increases less strongly between initial and final values and also reaches its final values considerably faster.

3.6 DESIGN CONCEPT

In the following, based on the findings on the curing characteristics of the bonding strength, a proposal for a design concept is developed which considers the temperature influence on the tensile strength of the TS3 joint. For this purpose, the results of the timber bonding series are first presented in a different form. The final tensile strengths of the individual series, i.e., the respective values from the 10th day after casting, are summarised and evaluated for each series. The mean value is formed, and the standard deviation is calculated. Then the tensile strength is plotted against temperature instead of time (see Figure 11). As already described in chapter “3.3 BONDING STRENGTH” it can be seen that the tensile strength also increases with increasing curing temperature. However, this relationship is not linear. The additionally drawn green dotted trend line corresponds to a third-degree polynomial.

The design concept is conceived based on DIN EN 1995-1-1 [11] so that it can be integrated as well as possible into the existing standardisation. Accordingly, the design value of the tensile strength of timber in fibre direction is calculated as in equation (1):

$$f_{t,0,d} = k_{mod} * \frac{f_{t,0,k}}{\gamma_M} \qquad (1)$$

The following condition must then be fulfilled for the dimensioning (equation (2)):

$$\sigma_{t,0,d} \leq f_{t,0,d} \qquad (2)$$

To take into account the temperature influence on the tensile strength of the TS3 joint, a coefficient k_t is proposed, which is included in the design specification as follows (equation (3)):

$$\sigma_{t,0,d} \leq k_t * f_{t,0,d} \qquad (3)$$

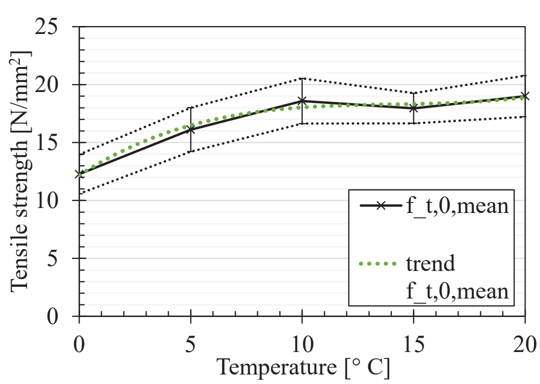

Figure 11: *Temperature comparison of the bonding strength (mean values)*

This coefficient must be dimensionless, lie between 0 and 1 and describe the temperature range between 0 °C and 20 °C to which its application is initially restricted. For the dimensionless determination of the coefficient k_t the ultimate tensile strengths of the different temperatures are normalised so that the tensile strength at 20 °C corresponds to 100 %, i.e., 1.0 (see Figure 12).

In contrast to the cubic trend line in Figure 11, the following bilinear approach for k_t (equation (4) and (5)) is chosen for simpler calculation in engineering practice (see Figure 12):

$$0\,°C \leq t < 10\,°C\colon\ k_t = 0.65 + 0.033 * t \qquad (4)$$

$$10\,°C \leq t < 20\,°C\colon\ k_t = 0.98 + 0.002 * t \qquad (5)$$

The concept presented is only a first proposal for the consideration of the temperature influence on the tensile strength of the TS3 joint in the design. Apart from the fact that the concept in its described form is on the unsafe side in the range of 15 °C, the introduced coefficient refers to the mean values of very small samples where timber features such as knots were sorted out. For the actual applicability, it is indispensable to generate a representative sample length with a commercially available timber sorting as a basis for the coefficient k_t and to define the ratios of the characteristic tensile strengths as a basis.

4 DISCUSSION AND CONCLUSION

The test results presented provide important findings for TS3 bonding at curing temperatures below the 17 °C specified by the manufacturer. The investigated properties (casting resin strength, bonding strength, casting resin hardness) initially show lower values at lower curing temperatures. However, the curing characteristics of the bonding strength and the casting resin strength differ significantly in some cases. Worth mentioning here is the fact that the final strengths of the timber bonding specimens are achieved significantly faster than those of the pure casting resin, regardless of the temperature. In addition, in contrast to the casting resin strength, there is no discernible post-curing effect in the timber bonding specimens, which means that the final strengths after post-

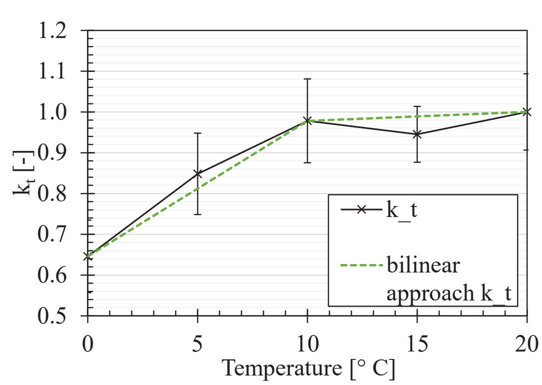

Figure 12: *Coefficient k_t*

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curing of the timber bonding specimens differ significantly as a function of temperature, whereas they are at a similar level with the pure casting resin. These observations can be justified based on the bond fracture pattern: Since the fracture apparently occurs in the area between the pre-treatment and the casting resin, it can be assumed that the adhesion between the pre-treatment and the casting resin is the decisive factor for the bonding strength and reaches its final strength approx. 6 days after casting. The further curing of the casting resin therefore no longer has any influence. The following conclusions can be drawn from this:

- An extension of the curing time does not result in a higher bonding strength.

- Possible additional measures for tempering the TS3 joint are only required over a relatively brief period of time.

Furthermore, the assumption that there is a strong correlation between casting resin strength and hardness has been confirmed. This can be used to enable additional quality monitoring by means of on-site hardness tests. However, this can only be used to monitor the properties of the pure casting resin and thus detect possible negative influences (mixing ratio, curing temperature). However, it is not possible to draw a direct conclusion on the bonding strength without further ado, as the timber results in further influencing factors (wood moisture content, raw density, knottiness) that cannot be recorded by the curing characteristics of the pure casting resin.

5 OUTLOOK

To validate the previous findings on the curing characteristics of the bonding strength as a function of temperature, further test series are being carried out. For this purpose, a larger number of samples with larger timber cross-sections are evaluated, which already have the respective low temperature when casting, in order to represent the "worst case" that can occur on the construction site. The timber used corresponds to a commercially available sorting to be able to generate representative absolute tensile strength values. In addition to the distribution function, both the mean values and the characteristic values of the respective tensile strength must be determined. In particular, this is intended to further elaborate the design concept, because up to now this has been based on the mean values of relatively small samples. To be able to actually apply the concept in practice, it must refer to the characteristic values of representative samples. Furthermore, within the framework of these test series, random samples of the fracture patterns are analysed microscopically. In addition, the possibility of casting the resin at a temperature of 35 °C to obtain higher tensile strengths is being investigated.

Another approach to be able to conduct the end-grain bonding in the future even at low outside temperatures without loss of strength is the local tempering of the casting resin joint during the curing time with a heating wire. This possibility is also currently being researched at BFH so that it can be used as soon as possible.

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REFERENCES

[1] DIBt: 2K-PUR Klebstoff LOCTITE CR 821 PURBOND zum Einkleben von Stahlstäben in tragende Holzbauteile. Allgemeine bauaufsichtliche Zulassung Z-9.1-896, 2020-05

[2] Voss, M.; Evers, T.; Vallée, T.: Low-temperature curing of adhesives – Large-scale experiments. The Journal of Adhesion, 2022

[3] SN EN 14080: Holzbauwerke – Brettschichtholz und Balkenschichtholz – Anforderungen. SIA, 2013

[4] SN EN ISO 527-2: Kunststoffe – Bestimmung der Zugeigenschaften – Teil 2: Prüfbedingungen für Form und Extrusionsmassen (ISO 527-2:2012). SNV, 2012-06

[5] Aicher, S: TS3 Arbeitsplan 3 vom 18.09.2018. MPA Universität Stuttgart, 2018-09

[6] SN EN 301: Klebstoffe, Phenoplaste und Aminoplaste, für tragende Holzbauteile – Klassifizierung und Leistungsanforderungen. SNV, 2018-04

[7] SN EN 302-1: Klebstoffe für tragende Holzbauteile – Prüfverfahren – Teil 1: Bestimmungen der Längszugscherfestigkeit. SNV, 2013-05

[8] Keylwerth, R.; Noak, D.: Die Kammertrocknung von Schnittholz. Holz als Roh- und Werkstoff, 1964

[9] SN EN ISO 868: Kunststoffe und Hartgummi – Bestimmung der Eindruckhärte mit einem Durometer (Shore-Härte) (ISO 868:2003). SNV, 2003-09

[10] Sachs, L.: Angewandte Statistik. Springer Verlag, 2002

[11] DIN EN 1995-1-1: Eurocode 5: Bemessung und Konstruktion von Holzbauten - Teil 1-1: Allgemeine Regeln für den Hochbau. Beuth Verlag, 2016