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LONG-TERM BEHAVIOR OF RODS GLUED IN HARDWOODS UNDER STATIC LOADING, ELEVATED TEMPERATURE AND HUMIDITY ENVIRONMENT

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ABSTRACT: Glued-in rods (GiR) are nowadays an integral part of timber engineering's catalog of joints. While of widespread use, there are still open topics to be addressed, e.g., the behavior under elevated temperatures and humidity. First, the adhesives are tested for suitability by a dynamic mechanical analysis (DMA) and their glass transition temperature T_g is determined. Most adhesives in the industry exhibit a glass transition temperature close to the temperatures relevant for design. At temperatures close to T_g a significant drop in the load capacity of adhesives is to be expected. Afterwards, the pull-out strength of different hardwood-adhesive combinations is tested under laboratory conditions and higher temperatures. The results of the preliminary tests are then used to design testing rigs for the long-term investigations of the GiR. Service classes (SC) I to III are to be explicitly examined as part of the investigations to characterize the GiR's performance under increased environmental conditions.

KEYWORDS: glued-in rods, hardwood, material testing, long-term testing, temperature

1 – INTRODUCTION

Nowadays, the significance of green alternatives to traditional building materials (e.g., concrete) with a poor environmental footprint is more urgent than ever. Timber engineering stands as a cornerstone for fostering sustainability in construction. For years, the building industry has leaned on wood as a renewable and eco-friendly material, leading to its widespread adoption today [1]. Primarily, softwoods take precedence in this regard, as many applicable standards and approvals are tailored to them. However, with climate change increasingly evident, domestic forests are undergoing significant transformations [2]; as part of this, most trees will be hardwoods in a few years. The advantages of hardwoods concerning their use as structural elements include higher resilience against higher temperatures, longer dry periods, and insect attacks [3]. In addition, hardwoods possess a higher raw density, if compared to softwoods [4], leading to better mechanical properties [5].

Glued-in rods (GiR) are a commonly used adhesively bonded connection with good mechanical performance [6, 7]. Therefore, the influences of the geometric parameters that affect the short-term resistance of the axially loaded glued-in rod under laboratory conditions (usually 20°C and 65% r.h.) are well understood [8]. Because of the adhesive used to connect the rod to the hardwood, the mentioned joint type is sensitive to temperature [9], with the glass transition temperature T_g being the critical parameter [10, 11]. Regarding wood, it is known, that its strength is highly dependent upon the moisture content [12].

This paper investigates the long-term behavior of glued-in rods, focusing on both laboratory conditions (or service class (SC) I) and SC II and III. Currently, there is limited understanding in this area due to the challenges of testing and the time-consuming experimental procedures involved. The study will present results within the context of relevant material properties, particularly those of the

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adhesives used, providing valuable insights into the performance of glued-in rods over extended periods.

2 – STATE OF THE ART

Advancements in adhesive technology, from traditional natural sources to modern synthetics like Phenol-Formaldehyde (PF) and Urea-Formaldehyde (UF), have revolutionized timber engineering, facilitating the widespread use of engineered wood products [13] such as Glued-Laminated Timber (GLT), Cross-Laminated Timber (CLT) and Laminated Veneer Lumber (LVL), or adhesively bonded connections [14]. Davis [15] has outlined key factors to consider when bonding wood products, such as ensuring clear and uncontaminated surfaces, assessing wood wettability and surface polarity, as well as evaluating adhesive performance in on-site conditions. However, certain parameters like surface roughness and porosity remain debated [16, 17]. Most adhesives were optimized for softwoods, necessitating further investigations, particularly regarding their performance under environmental conditions and long-term behavior, especially when applied to hardwoods [14]. Both epoxies (EP) and polyurethanes (PUR) exhibit sensitivity to environmental conditions but in slightly different ways. EP's are more affected by temperature, with their glass transition temperature T_g (typically determined using dynamic mechanical analysis, DMA) causing a significant drop in stiffness and strength [10, 18]. In contrast, polyurethanes are more vulnerable to increases in humidity [19]. This is because polyurethanes are produced by the reaction of isocyanates, which are highly reactive towards nucleophiles like water. The reaction with moisture can disrupt the curing process and lead to issues like foaming. Lastly, all adhesives are prone to creep due to their viscoelastic nature, which allows for molecular rearrangement and deformation over time under constant stress [20, 21]. Environmental factors like temperature, humidity, and load levels can further exacerbate the creep behavior of adhesives, with the specific adhesive type and curing state also playing a role [22]. Besides the adhesives, wood is also sensitive to changes in environmental conditions [23]. While temperature changes in the range relevant for structural application in civil engineering do not significantly affect their mechanical properties, humidity, and the resulting equilibrium moisture content, impact wood's properties. Wood undergoes substantial deformations due to changes in moisture content [24]. Despite extensive research, results remain contradictory, with various factors like wood species, orthotropy, and structural anomalies complicating predictions. Differences in loading modes further complicate understanding, including recovery effects [25].

GiR stand as a prevalent joining technology in the wood building industry. This popularity owes much to the numerous advantages inherent in GiR connections, including high performance, aesthetic appeal, and cost-effectiveness. In recent years, several experimental and numerical investigations have largely uncovered the most important aspects related to GiR. Extensive investigations into the performance of GiR have focused primarily on single rod glued-in joints under axial loading, employing various loading configurations such as pull-pull, pull-compression, pull-beam, and pull-pile foundation [26]. However, in most studies, GiR capacity is determined through pull-pull tests with a rod glued-in at one or both ends, with the capacity of the stronger end often remaining unknown—although it is in principle possible to account for both ends using statistical inference [14]. Despite the varied experimental setups, single glued-in joints exhibit different failure modes, including rod tension failure, adhesive-related failures (adhesive failure at the timber or rod interface, and cohesive failure of the adhesive), timber-related failures (localized timber shear failure around the bond and timber splitting), and failure of the timber member itself, with each mode associated with specific geometric joint parameters [8] and material properties [27, 28]. Recent review articles [29, 30] discuss different models for determining shear stress distribution along the bond line between rod and wood. They evaluate how these models affect stress distribution and strength of the glued-in rod, and consider methods for enhancing load-carrying capacity and achieving ductile failure behavior, including for engineered wood products as GLT and CLT [31, 32].

Most previous work focused on quasistatic and cyclic testing in service class (SC) I, thus excluding aspects related to environmental conditions and long-term loading. Fragiacomo et al. [33] reported long-term load tests on moment-resisting joints between glulam members, specifically examining the behavior of glued-in steel rods. The tests revealed time-dependent stress redistribution, joint creep, and timber-to-timber bearing surface crushing. Verdet et al. [34] investigated the creep behavior of joints with single glued-in rods under controlled and variable climate conditions. Steel rods in combination with black spruce and Norway spruce were joined with polyurethane (PUR) and epoxy (EPX) adhesives. Creep tests were conducted at 20°C / 65% RH and 50°C / 72% RH, with a load at 50% of the static breaking load. EPX joints exhibited lower creep and higher initial stiffness compared to PUR joints. At 50°C,

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Figure 1: Specimens for long-term testing with glued-in rods on both front sides, dimensions in mm.

EPX joints showed increased creep but no failures within 60 days, while all PUR joints failed within days. Varying climate conditions influenced creep, with humidification and drying cycles leading to higher creep and potential rupture. Wood drying caused damaging cracks at the wood-adhesive interface, reducing joint strength.

3 – EXPERIMENTAL SETUP

The specimens were designed following the normative standard DIN EN ISO 17334. This standard regulates the requirements and the testing procedure for rods glued into wooden materials in load-bearing function. **Figure 1** shows a representation of the small-scale specimens tested in the designed testing rigs.

The decisive factor in designing the specimens according to the standard is the diameter of the rod since all the other dimensions are defined in relation to it. For the specimens presented, a rod diameter of 6 mm was chosen. The embedment depth of the rods was chosen to be 6-times the diameter, leading to a depth of 36 mm. This led to an intended comparatively short adhesive length, supporting that the glue line was the weakest part of the material system. Thus, testing the adhesive layer could be more focused. The cross-section of the hardwood was chosen to have a square form with a side length of 7.5-times the rod`s diameter. This resulted in a hardwood body size of 45×45×122 mm³ for each specimen tested.

The experimental campaign (**Figure 2**) initially included mechanical characterizations of the individual components. First, the adhesives were examined utilizing the DMA. The most important material parameter was the glass transition temperature T_g of the different adhesives, which is crucial to their performance. With the surrounding temperatures approaching T_g, the adhesives are set to lose a major part of their strength.

After the DMA was finished, the adhesives once more were solely tested for their performance in combination with the later used hardwoods (e.g., beech, ash, and oak). Therefore, specimens were bonded in a way, so that the adhesives were loaded with shear stress. It is known, that glue lines are especially weak to that type of loading, thus testing the minimum strengths of the adhesives.

In the next step, the material system containing the rod, the adhesive, and the hardwood were joined and the pull-out strength of the system was determined. The pull-out tests were conducted in pull-compression configuration with a testing speed of 2 mm/min. The identified load-bearing capacities of the different material combinations of adhesive and hardwood were then used to design and dimension the testing rigs. After these were built, the long-term static tests began for 1 to 18 months. During the static loading, the deformation of the specimens was recorded continuously. After 6 and 12 months some of the specimens were removed from the static load and their residual load-bearing capacity was determined.

4 – MATERIAL TESTING & RESULTS

4.1. Design of the testing rigs

Initially, the glass transition temperatures for the different adhesives were determined and all were within

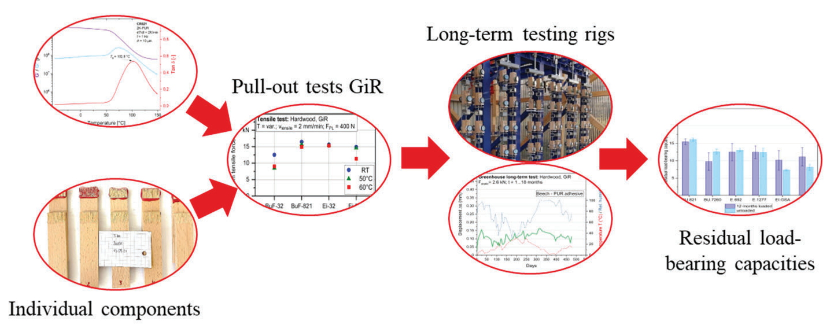

Figure 2: Experimental campaign for the design and operating of the long-term testing rigs.

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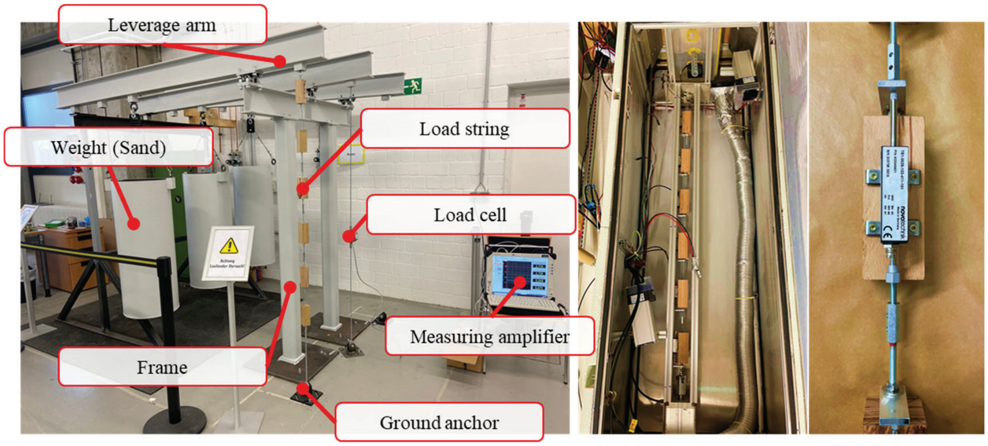

Figure 3: Long-term testing rig. Left: testing under laboratory climate; right: under elevated temperature and humidity environment in a climate chamber.

the range of 60 to 120°C. The lap shear strength of the adhesives in combination with beech wood, for example, varied strongly between 4 to 16 MPa. Based on the results, a preselection of adhesive was made for the following long-term tests. Afterwards, the small-scale specimens were tested regarding their tensile pull-out strength under different environmental conditions. The results for the tensile tests performed at laboratory climate (room temperature (RT), ~20°C and 60% RH) and elevated temperatures underline the influence of temperature on the GiR-system. The maximum load-bearing capacities in relation to the rod's diameter were around 18 to 25 MPa at laboratory conditions. While some of the combinations' tensile force did not decrease at 50°C and 60°C, respectively, the rest reacted distinctively to the increased temperatures. Two of the combinations forfeit nearly 30% of their initial strength due to the vulnerability of the adhesives described earlier. The results of the maximum pull-out force were then used to design the testing rigs for the long-term tests.

One of the testing rigs (**Figure 3 left**) was built to test the long-term behavior under the previously mentioned laboratory conditions. The static load was applied using weights suspended from a leverage arm. In metal cones, the weight was increased using sand. Due to the leverage effect, the weights were not too heavy and could be handled easier. The testing rig was designed for maximum loads from 10 to 12 kN. In addition, the length of the leverage arm could be varied from 3- to 5-times the length. This led to an enlargement of the covered force range. Thus, the testing rig was ultimately able to apply static forces from 2 to 12 kN. In **Figure 3 left** the load string of the described GiR specimens can be seen. One load string contained from up to 6 specimens. This enabled testing a total of 18 specimens simultaneously. The load strings were divided in accordance with the testing time. This allowed the removal of the whole load string after a defined amount of time (e.g., 6 or 12 months). The load string itself contained different hardwood-adhesive combinations. For the described geometry of the specimens, a load of 2.6 kN was set.

The second test rig (**Figure 3 right**) was designed to investigate the creep behavior of the wooden specimens under elevated temperatures and humidity. It was

Figure 4: Long-term testing rig for testing under cyclic climate conditions ("Greenhouse" testing rig)

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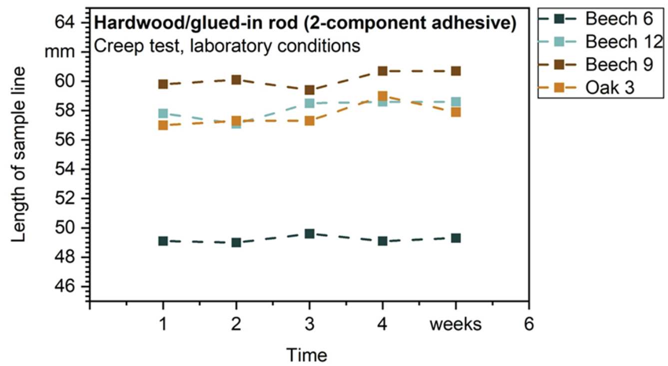

Figure 5: Results of the long-term tests under laboratory conditions.

designed to be placed in a climate chamber to obtain the opportunity to test the specimens under various climate conditions. Therefore, a pneumatic cylinder was attached to the load string of specimens once more arranged in a series connection. To apply the increased environmental conditions on the specimens, the load string was placed in a climate chamber. The displacement of the GiR was recorded via inductive displacement sensors that were screwed to the hardwood body of the specimens.

In addition to the two previously mentioned testing rigs, a greenhouse was built to test the specimens under the climatic conditions occurring over a year between the 45th and 60th latitudes. The greenhouse and the testing rig placed inside are shown in **Figure 4**. The static load was once more applied with a weight and a leverage arm. The creep deformations of the GiR were recorded utilizing mechanical dial gauges, that were read out continuously after a defined time interval.

4.2. Static long-term tests

The results under laboratory conditions are shown in **Figure 5**. The diagram shows the length of the sample line attached to the previously described testing rig for laboratory conditions in the first 9 months of static testing. The length was measured regularly and the elongation of the sample line as a result of creep deformation was recorded. It can be seen that the beech and oak specimens did not show a significant material reaction to the applied load. The elongation of the single specimens is within the range of a millimeter. Hence, all material combinations investigated were capable of withstanding the applied load under laboratory conditions.

The first hours of the creep tests of GiR glued into beech laminated veneer lumber (LVL) with increased temperature and humidity environment showed a different result. The adhesives failed cohesively after a short time and thus the rods got ripped out of the glue line. The diagram in **Figure 6** shows the abrupt increase of the deformation leading to failure. It can be seen, that the failure occurred after around 2.5 hours into the static loading when the temperature was close to reaching the desired 60°C. The other material combinations also showed a creep deformation at the beginning of the static long-term tests. After a combination-dependent amount of days, the creep deformation stopped and in the residual load-bearing determination, no significant influence of the passed through static testing could be observed.

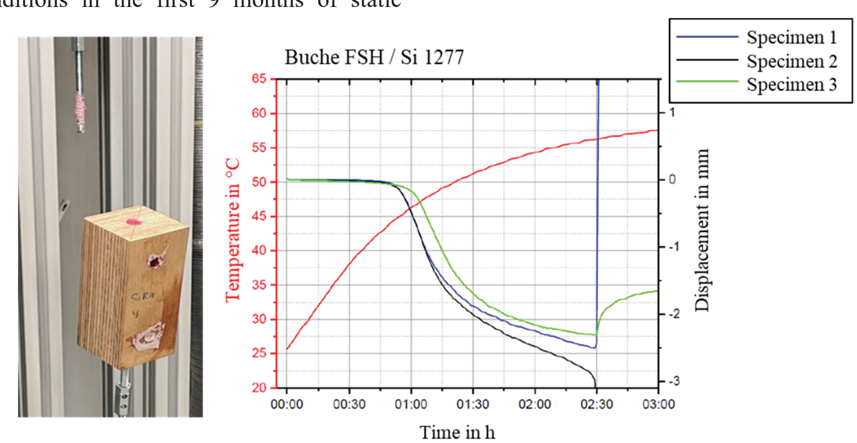

Figure 6: Results of the first hours of the creep tests of beech laminated veneer lumber overlayed with higher temperature and humidity environment.

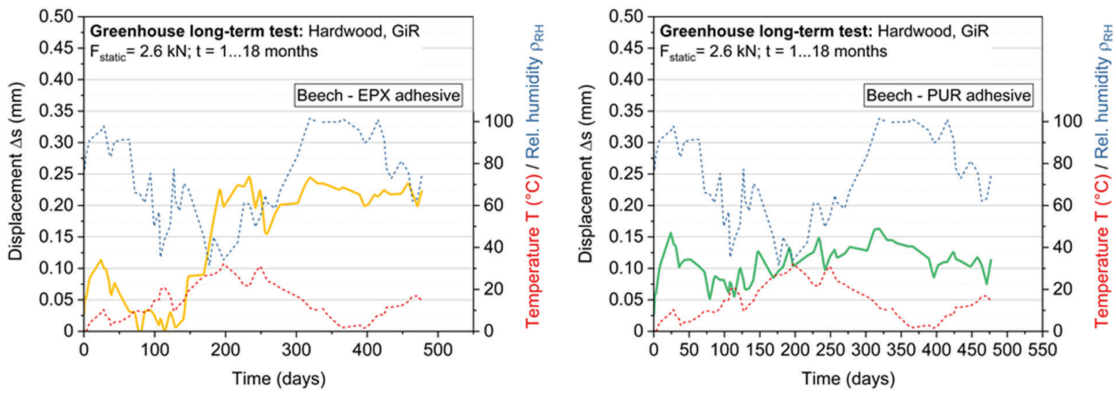

Figure 7: Results of the static long-term tests under cyclic environmental conditions in the greenhouse testing rig; beech laminated veneer lumber with left: EPX adhesive and right: PUR adhesive.

Figure 7 shows the results of the 18-month static tests performed in the greenhouse environment exemplary for beech LVL and EPX/PUR adhesive. Temperatures and humidity change over the course of a year due to the seasons and their typical weather conditions. The tests were started in winter when the temperatures were around 0°C and the humidity was high around 80-95%. In the first days of the static loading, the specimens showed a slight creep deformation. The average deformation was around 0.1 to 0.15 mm for the different material combinations. The cold temperatures did not seem to have a noticeable effect on the beech LVL combinations presented. In spring and summer, the temperatures rose and the humidity thereby decreased. In the summer with temperatures around 25 to 30°C and humidity of 40 to 50%, the material combination of beech LVL with EPX adhesive showed a rash in the measured deformation. Three specimens failed during the hot and dry period of summer. Since the adhesives are more sensitive to elevated temperatures, the assumption of a failure of the adhesive can be made. Since in the diagram the deformation of the GiR specimens is shown on average, the upward deflection of the curve can be explained by the nearly simultaneous failure of the three same combined specimens. The combination of beech LVL and PUR adhesive showed a slight increase in deformation during the summer months as well. However, the material reaction did not lead to a failure of the specimens. In the upcoming colder seasons, the deformation curves again did not show a significant progression and the deformation has tended to decrease.

The other material combinations investigated have shown different reactions to the changing climate conditions in the greenhouse. The oak specimens for example, During the cold months of the testing time, some oak specimens proved to be very susceptible to the low temperatures and especially the high humidities around 90%. Thus, during both winter seasons oak specimens failed prematurely due to the high humidity.

Figure 8 shows the fractography for the specimens that failed throughout the static long-term testing in the greenhouse. An oak specimen that failed in the first months of the testing procedure can be seen in **Figure 8 (a)** and it can be stated, that the rod got pulled out of the glue line. This means that a cohesive failure of the adhesive can be assumed. The failure of the oak specimen that occurred in the second winter of the testing phase (**Figure 8 (b)**) can be described as an adhesion failure of the interface between the adhesive and the hardwood

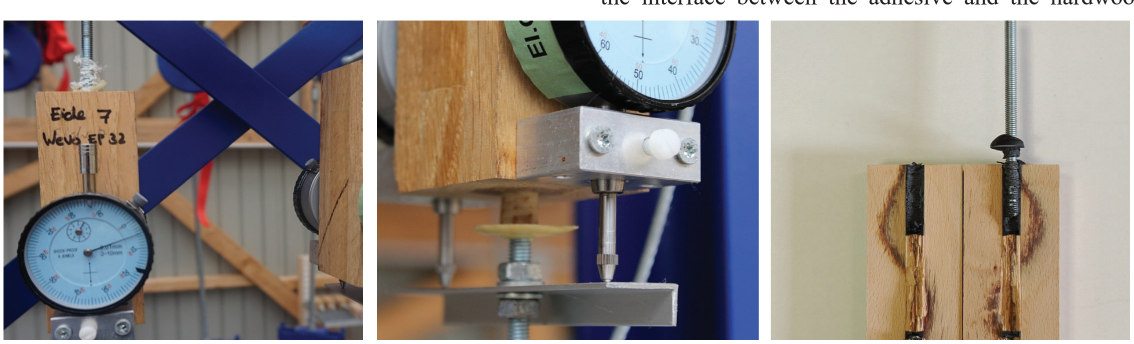

Figure 8: Fractography of failed specimens (a) and (b) oak specimens failed during winter and (c) beech specimen failed during summer.

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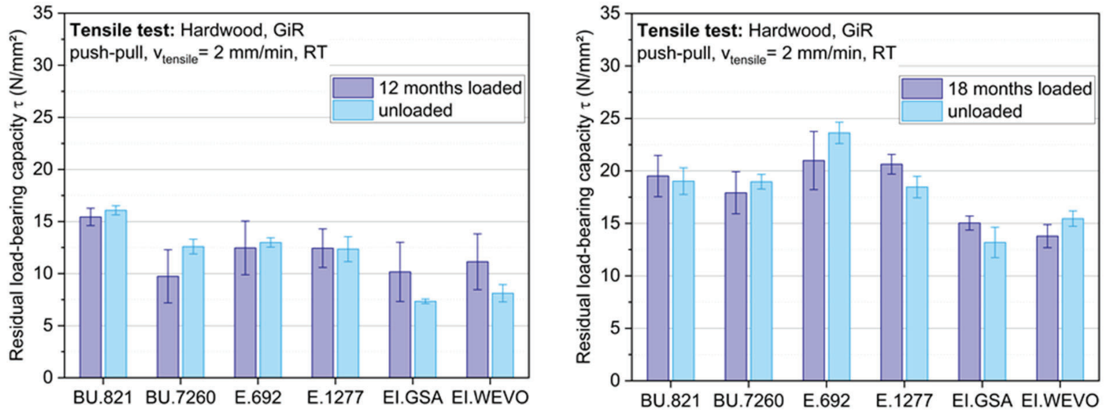

Figure 9: Residual load-bearing capacities for all investigated material combinations; left: 12 months and right: 18 months static loading.

material. **Figure 8 (c)** shows the failure observed during the summertime. Again, the rod got pulled out of the specimen and thus, the material system failed. This failure mechanism underlines the assumption of the elevated temperatures threatening the performance of the adhesives.

4.3. Determination of the residual load-bearing capacity

After defined time intervals under static loading, the specimens were tested regarding their residual load-bearing capacity following the experimental design previously described. An overview of the results for all material combinations investigated is shown in **Figure 9**. The average residual load-bearing capacity after 12 months of static loading was around 10 to 15 MPa for the beech LVL specimens, 12 to 13 MPa for the ash, and 10 to 12 MPa for the oak specimens, respectively. The tests after 18 months of static long-term testing showed an increase in the measured strengths of the GiR. For the beech and ash specimens, the load-bearing capacity was approx. 2-times higher than the value after 12 months. This remarkable increase in the pull-out strength of the GiR specimens can be explained by the differing wood moisture. Since the 12-month specimens were taken out of the testing rig during winter, meaning low temperatures and high humidity, the wood moisture was higher compared to those specimens tested in summer after 18 months. The difference for the ash specimens was 18% moisture in winter and 12% wood moisture in summer. Since wood is highly reactive to its moisture content, the stiffness drop seems plausible. Only the oak specimens were significantly weaker with a lower increase in the determined strength. This can be related to the adhesives not being approved in combination with oak, thus the possibility of the adhesive not working with the wood species cannot be excluded.

In addition to the specimens loaded during the long-term tests, specimens were aged without applying a load in the same greenhouse environment. The load-bearing capacities of these specimens were also determined and

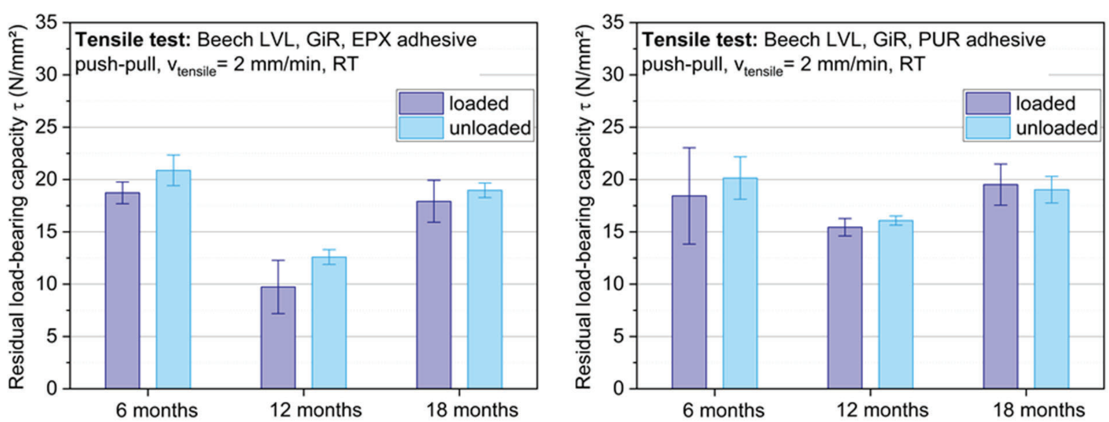

Figure 10: Residual load-bearing capacity of the material combinations (beech and left: EPX and right: PUR) after static loading for 6, 12, and 18 months.

the results are shown in **Figure 9** for all material combinations and testing durations. The unloaded specimens showed slightly differing strengths compared to the loaded ones. The occurring variance was in both directions and because of the small sample size of only two tests per material combination and time interval, a statement can only be made to a limited extent.

In **Figure 10** the results are shown for the two previously discussed material combinations of beech LVL and an EPX and a PUR adhesive. The described stiffness drop in conjunction with the increased moisture content in winter can be seen again. During summer (6 and 18 months) the residual load-bearing capacity of the two adhesives in combination with the LVL are nearly identical. In winter the EPX adhesive displayed some difficulties with a more pronounced decrease in stiffness. In comparison, the EPX is about 30-40% weaker than the PUR adhesive.

Afterwards, the specimens were investigated to identify fracture mechanisms of the connections. The following three main fracture mechanisms were observed in the tests performed. The interfacial wood fiber pull-out was the most commonly seen fracture mechanism in approx. 90% of the static long-term and pull-out tests. Other displayed fracture modes, namely the fracture of the GiR (steel failure) and the cohesive failure of the adhesive, were observed in about 5 percent of the cases each.

5 – CONCLUCIONS & OUTLOOK

The material tests conducted during this work showed the general suitability of the glued-in rods as connection elements for hardwoods in service classes II and III. At elevated temperatures, the adhesives were the weakest point of the connection. In contrast, the higher humidity environment led to higher wood moisture, which was responsible for the lower load-bearing capacities of the connection. This was particularly evident in the winter season during the static long-term tests, where the strength of the tested specimens decreased significantly. A wide range of different adhesives could be proven suitable for application with different hardwoods (e.g., ash and beech). The oak, however, showed a weaker performance, thus it is often not included in the approval of the adhesives. The beech LVL also showed some weaknesses during the long-term tests with additional climate impact assessment. Especially the combination of elevated temperatures and high humidity led to multiple failures of the material combinations during the first hours of static loading.

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