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Enhancing glulam-fully threaded screw bond durability: The impact of transversal screw reinforcement on creep damage reduction

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Abstract

Glue laminated timber is preferred for its strength and aesthetics in construction, yet its anisotropic nature demands precise reinforcement techniques. Fully threaded screws, known for their durability and cost-efficiency, have become a widespread reinforcement method, though questions remain about their durability in timber structures over time. Research at RWTH Aachen Chair of Structure and Structural Design, as well as other researches, highlighted the reduced load capacity with screws parallel to wood grains under extended stress. To address this, a method using additional transversally oriented screws to the main loading direction (screw-axis) was used, significantly enhancing structural integrity by mitigating creep deformation and damage from environmental conditions. This technique, showed effective in preliminary research when screws are at a 0° angle to the timber grains, cuts creep deformation by almost half and offers a solution against the cracking and splitting of timber elements in outer or harsh climatic environments. This paper focuses on the study of this reinforcement type in a constant controlled climate, examining other angles to the main load and providing an overview of the outcomes.

Keywords: timber construction, fully-threaded screws, creep behavior, lifespan of structure, reinforcement

1. Introduction

Exploring the long-term effects of the bond between fully threaded screws and timber matrix under various climatic conditions and constant load reveals insights into how environmental factors influence the interface of the bond. This understanding is crucial for building practice, as it unveils potential retrofitting strategies aimed at mitigating climate effects, as well as enhancing the durability and safety of timber elements.

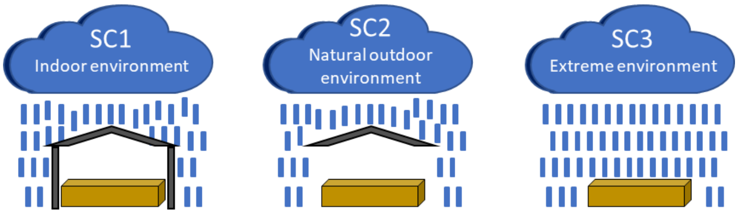


Figure 1: Simplified presentation of Eurocode 5 defined service classes.

The three service classes are defined in Eurocode 5 [1] and each is characterized by distinct levels of relative humidity. A simple presentation is shown in Figure 1. Service Class 1 (SC1) describes indoor environments where the temperature is stable around 20°C, and relative humidity consistently hovers around 65%, a condition that is rarely exceeded. This service class generally corresponds to interior spaces where climatic conditions are controlled. Service Class 2 (SC2) captures natural outdoor environments that experience seasonal variations, with temperatures around 20°C and humidity levels that may exceed 85% for several weeks each year, reflecting the fluctuating outdoor climate. Service Class 3 (SC3) pertains to extreme environments where there is a significant variation in moisture content, leading to frequent and drastic humidity changes. These conditions are typically more challenging and can significantly affect the durability and performance of timber structures. Investigating how bond screw-timber perform under each service class is necessary for designing durable timber structures.

Considering design of timber elements under different service classes where two materials are combined is rather complex. The interaction between the timber, being hygroscopic, that reacts significantly to humidity, and metal screws that respond to temperature changes, results in unique expansion and contraction behaviors. This differential movement can affect the bond's interface, potentially leading to additional displacements and, over time, weakening the bond itself. Such environmental stressors not only change the load distribution along the screws but can also accelerate creep displacements, jeopardizing the bond's long-term performance by reducing the bonding length and even altering failure modes [2].

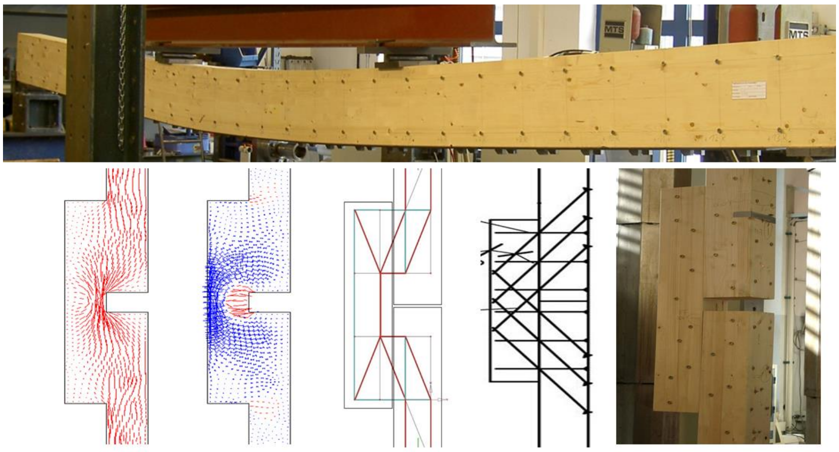
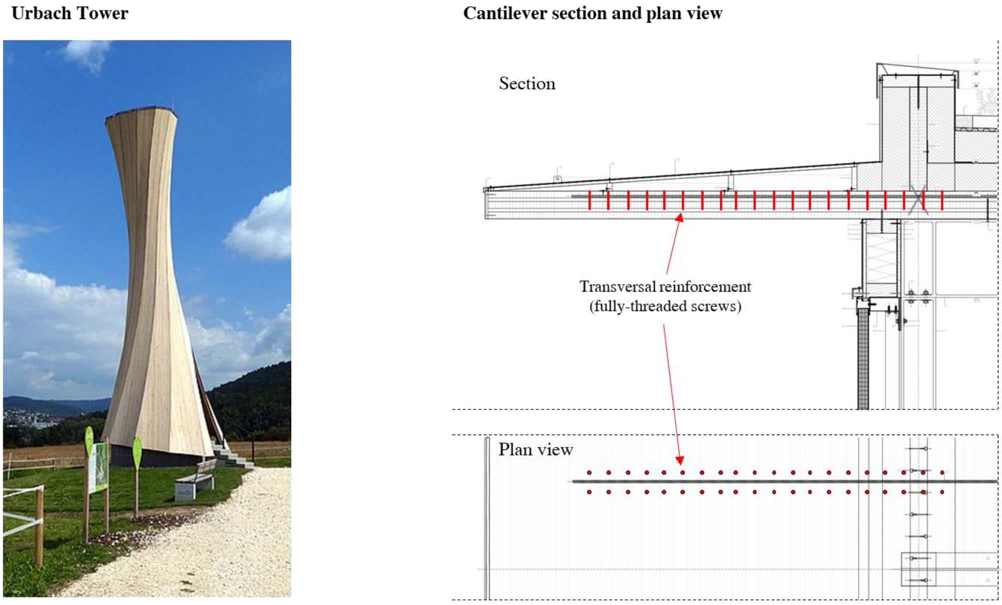


Figure 2: Main and additional transversal reinforcement in: Up – bending beam [8-9]; Down – Fish-plate joints [7-8]. Main reinforcement was calculated using strut-and-tie modelling approach and serves to increase stiffness and to canalize internal forces.

Approaches, such as inserting additional screws transversally to reinforce timber weaknesses in direction perpendicular to the grain in tension and compression, like for example in near dowel-type connections [3-4] or even as compressive support reinforcement [5-6], have demonstrated significant potential in enhancing structural integrity. This method has proven particularly effective in *a priori* reinforcing thin timber elements against splitting, in connection and in element itself (see Figure 2), systematically strengthening the timber's tensile strength orthogonal to the grain and improving shear resistance. This approach not only addresses timber's inherent vulnerabilities but also compensates for local material deficiencies. Extrodinary structures, like the Urbach Tower [10] (see Figure 3 left), crafted from curved cross-laminated timber (CLT), exemplify the challenges posed by thin, twisted, or curved timber elements, especially in connection design due to varying joint angles. Such outer exposed structures can benefit from additional reinforcement of the bond through the strategic use of fully threaded screws to reduce climatic effects on its connection. A theoretical example of such additional transversal reinforcement against climatic can be seen in the students design of the "B2-RWTH Multispace Hall," (see Figure 3 right). Here, students employed cross-laminated timber slabs reinforced with long, fully threaded rods for the cantilevered sections of the roof. By introducing additional transversal reinforcement with fully threaded screws, the intention was to reduce the potential for shrinkage cracks, thereby minimizing overall slab deflection and allowing for a thinner slab, which would otherwise need to be much thicker to accommodate deformations from long-term effects.


Urbach Tower

Cantilever section and plan view

Figure 3: Left – Urbach tower built for the Remstal Gartenschau 2019, Germany [10]. *Photo by Geak* [11]. Right - B2-RWTH Multispace Hall student Integrated project 2022 (*see Acknoledgement*). A detail example of using long screw as a reinforcement of tensional forces in the CLT cantilever and possible transversal reinforcement to reduce long-term effects

The motivation to strengthen transversally axially loaded bond (by 0° angle screw axis-timber grain) is supported by research results from previously made test of the long-term behaviour in natural outdoor climate [2, 12] and its necessity is confirmed by other researchers reports as well [13-14]. These studies consistently show that screws inserted parallel to the timber grain, under continuous load and exposure to climate, lead to rapid damage at the bond interface. As a result, specimens often fail under relatively low loads due to withdrawal.

Introducing additional reinforcement transversely to the main loaded screw axis effectively reduces crack width and subsequent displacements between the main loaded screw and the timber. This method ensures that timber elements maintain their original thickness, with screws embedded within the timber and invisible in the finished product. Other alternatives include increasing the thickness of the timber element to extend the bond length, using fiber polymer reinforcing strips, or creating composite concrete-timber slabs. By opting for additional transverse reinforcements, the structural integrity is enhanced without altering the aesthetic appeal of the timber elements. Additionally, this type of reinforcement can be inserted subsequently, providing flexibility in construction schedules. However, the disadvantages include increased labor and production time, which elevate the potential for errors and add complexity to the automation of manufacturing processes.

2. Background

This section presents a concise overview of key findings from the research on long-term behavior of screw-timber grain bonds conducted by the Chair of Structures and Structural Design. It highlights the crucial role of timber anatomy, particularly grain orientation, in influencing creep displacement. Notably, displacement is greatest when screws are inserted perpendicular to the timber grains and significantly lower when aligned parallel, with the stiffness of the timber grain orientation being a important factor [2,12,13,15].

Specimens subjected to high moisture variations and cyclic climate conditions exhibited greater displacements compared to those in a more controlled outdoor environment, even if they had lower load levels [12].

An interesting aspect of the research involved the addition of transversal reinforcement to specimens, which, when positioned parallel to the grain under a load factor of 40% of the withdrawal load, demonstrated a substantial reduction in creep displacement by up to 50% (see Figure 4 left). This was particularly evident when examining the specimens' residual load capacity after 435 days, where those with reinforcement showed significantly less bond damage compared to those without. Specimens with transversal reinforcement had a residual load to withdrawal load ratio of 91.5%, and those without reinforcement had 75.8% (see Figure 4 right).

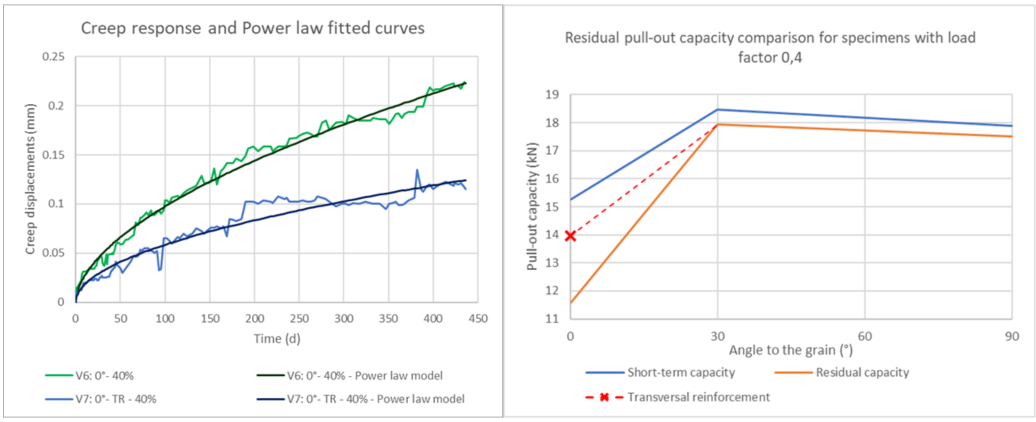


Figure 4: Left – Creep displacement development of 0° specimens (axially loaded screw paralle to timber grain) without additional reinforcement (green – specimen shown in Figure 5 right) and with additional transversal reinforcement (blue– specimen shown in Figure 5 left) in natural outdoor environment; Right – Comparison of residual load capaciy in natural outdoor environment [2]

These findings underscore the potential benefits of further investigating the reinforcement of timber connections transversally for long-term durability, exploring various screw-timber grain angles, and examining the effects of different climatic conditions. This comprehensive approach aims to enhance our understanding of these behaviors and contribute to the development of a damage model for such specimens.

3. Materials and method

This paper explores the use of transversal reinforcement to improve the long-term bond between screws and the timber matrix. It focuses on studying the effects of transversal reinforcement on creep development, under long-term loading conditions. These conditions span different climates defined as service classes by Eurocode [1]: constant (20°C/65% RH), sheltered natural outdoor, and harsh weekly cyclic climates (20°C/35%RH to 20°C/85%RH), all under constant load with load factor 0,4 for 12 months. This paper highlights the initial six months' results in a constant climate setting. The 12-month specimens and other climate conditions are part of ongoing research. All specimens were made from spruce glue-laminated timber, classified as Gl24h, with an average density of $\rho = 325$ kg/m^3. The fully threaded screws used in the study were supplied by SPAX [16].

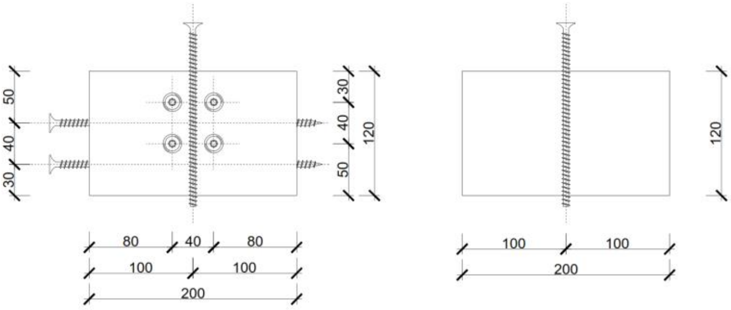


Figure 5: Specimens with and without transversal to main laod direction reinforcement

The specimen size was chosen to ensure comparability with previous research, facilitating direct validation and comparison of findings. Research focuses on exploring the fundamental effects of additional reinforcement through a single screw bond. As this study is still in the basic research phase, the primary objective is to understand the underlying phenomena, for which size effects are not yet the main consideration. Using small specimens allows for more efficient resource utilization and controlled experimental conditions, providing initial insights that can inform future research with larger specimens.

The study involves two types of specimen configurations: one with transversal reinforcement, labeled TR (see Figure 5 left), and one without, labeled S (see Figure 5 right). The preparation of the specimens is illustrated in Figure 6. The process included several steps: First, the specimens were cut to a size of 120x200x200 and then planed for uniformity. After cutting the specimens on size, fully threaded screws with a diameter of 8mm were inserted in the direction of the main load. For those specimens designated for transversal reinforcement, additional screws were inserted perpendicular to the main load axis. Finally, the specimens were stored in a room climate until the time of testing. Each configuration maintains the same bonding length and screw diameter. The variables include the screw to timber grain angle (0°, 30°, and 90°) and the test duration (6 months and 12 months). The aim is to examine the strength over time and therefore necessity for different time spans in testing. This approach helps in developing a model to predict failure time and probability. To ensure the tests are non-destructive, allowing for post-experiment examination of specimens, a load factor of 0.4 of the withdrawal capacities was selected, which also enables comparison with previous results.

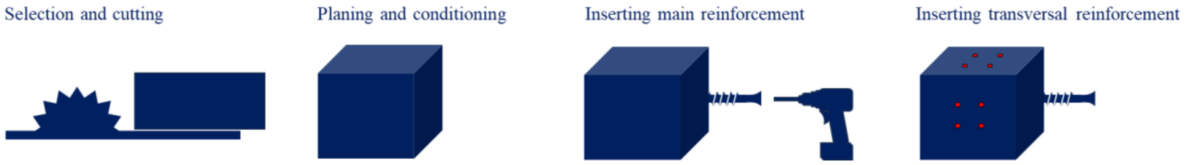


Figure 6: Specimens preparation for the long-term experimental setup

The experimental setup in the climatic chamber followed the same design as in previous studies [2, 12]. It included three steel frames. A dead load factor of 0.4, based on the five percentile fractile value of the withdrawal capacity, was applied using a lever mechanism. This setup is depicted in Figure 7, showing the test preparations. The chosen conditions for the climate were a constant 20°C and 65% relative humidity. Both preliminary/control tests and residual load assessments involved pull-out tests on a ZwickRoell machine. These tests were conducted at a displacement-controlled velocity of 1.5mm/min. For measuring relative displacements in both short- and long-term tests, inductive displacement transducers (LVDTs) were used at the loaded and free ends of the screw.

Figure 7: Experimental setup preparation for the constant cliamte long-term tests in climatic chamber

4. Results

This part of paper details the outcomes of experimental tests conducted. It covers preliminary pull-out tests, long-term tests under constant climate conditions with load factor 0.4 and residual load tests. The data collected, including relative displacements and force values, has been averaged and mean values are presented.

4.1. Influence of transversal reinforcement on short-term behaviour

Figure 8 displays force-relative displacement diagrams from preliminary/control pull-out tests for screw axis-timber grain angles of 0°, 30°, and 90°. The diagrams, along with mean values shown in Table 1, indicate minimal difference between specimens with and without transversal reinforcement.

However, for the 90° angle specimens (as seen in Figure 8 - down or Table 1), a slight variation in post-peak behavior is noticeable. This is rather important for understanding the residual load capacity, ductility, energy absorption and realistic failure analysis. Even after initial damage, structures can retain significant load-bearing capabilities, informing safety margins and design redundancy. Referencing the debonding mechanism stages by Pranjic [17] and Trautz [18], the 90° specimens reach maximum force slightly earlier. This shortens the grain distortion stage due to the orientation of the transversal reinforcement parallel to the timber grain. It likely induces additional cracks at the bond interface, damaging the bond and abbreviating its grain distortion behavior. This effect is also observed in the degressive friction phase, which, despite having the same rate of decrease, occurs sooner. In the short term, the withdrawal capacity difference isn't markedly noticeable. The only exception is for specimens aligned perpendicular to the grain, where the bond shows slight damage. The full extent of this phenomenon is expected to be more apparent in long-term tests, where the bond interface undergoes extended periods of stress.

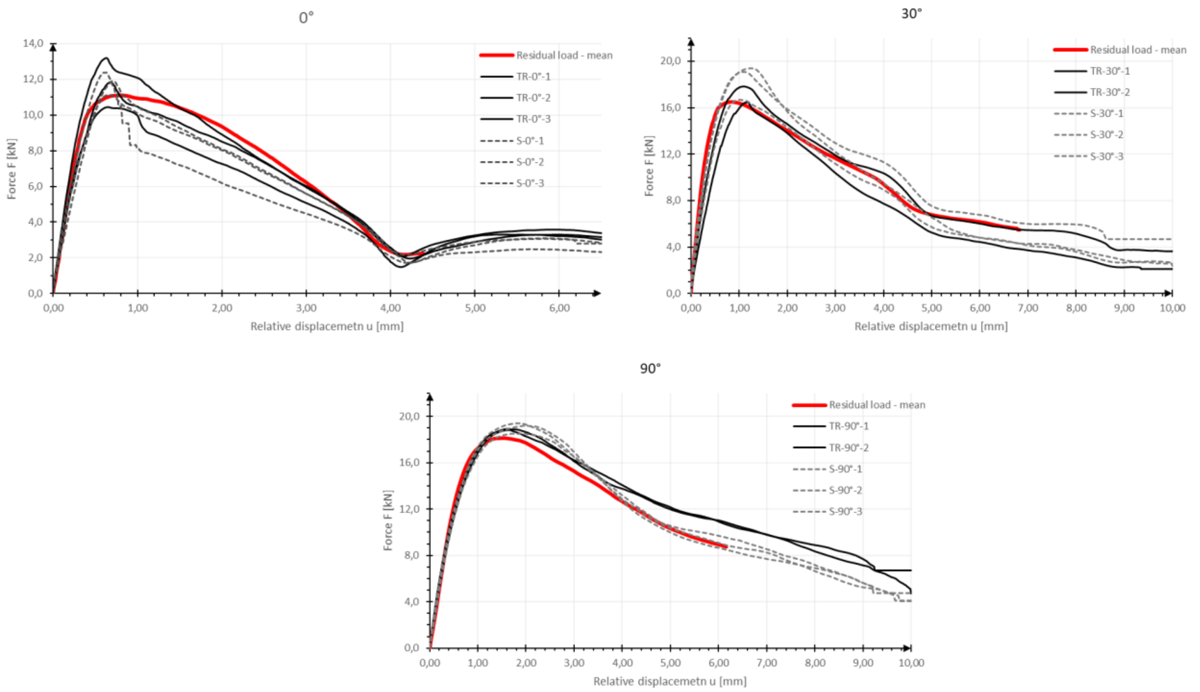


Figure 8: Force-relative displacement diagrams where black line are specimens with transversal reinforcement (TR) and grey dashed line are without reinforcement. With thick red lines is residual load capacity presented (see chapter 4.3). Up left are specimens with the angle screw axis – timber grain 0°, up right 30° and down 90°.

Table 1: Force and relative displacements mean values comparison

	without transversal reinforcement (S)			with transversal reinforcement (TR)					
	0°	30°	90°	0°	S/TR ratio	30°	S/TR ratio	90°	S/TR ratio
Fmax [kN]	11,80	18,38	19,05	11,82	0,998	17,15	1,072	18,88	1,009
u (Fmax) [mm]	0,66	1,12	1,91	0,65	1,016	1,14	0,984	1,65	1,154

4.2. Long-term behavior under the constant load and climate

Figure 9 showcases the average creep displacement observed over a six-month period under a constant load of 40% withdrawal capacity (based on 5% fractile value) and constant climate conditions (20°C/65 rel.H.) for screw configurations with (TR) and without transversal reinforcement (S). This pattern mirrors trends identified in previous research, highlighting consistent phenomenology in behavior across studies [2,12,13,15]. Notably, specimens with loaded screw positioned at a 90° angle in timber matrix exhibit the most significant displacements compared to those at lesser angles, indicating that creep development decreases as the angle between the loaded screw axis and timber grains narrows. This phenomenon can be attributed to the anisotropic nature of timber, which is significantly more rigid when loaded parallel to the grain. At higher angles, screws induce more extensive distortion of the timber grains.

After six months, the measured relative displacement for 90° specimens without reinforcement stands at 0.293 mm, whereas it is 0.082 mm for 30° specimens and 0.064 mm for those at 0°. Despite the similar ratio between different angle configurations to those specimens tested in a sheltered natural outdoor climate in 2017 [12], the current specimens exhibited values that were 2.6 (0° and 90° specimens) to 4.5 times (30° specimens) lower. This variance was anticipated, given that the specimens from 2017. were subjected to the same load factor but experienced natural climate conditions with seasonal variations and significant humidity fluctuations.

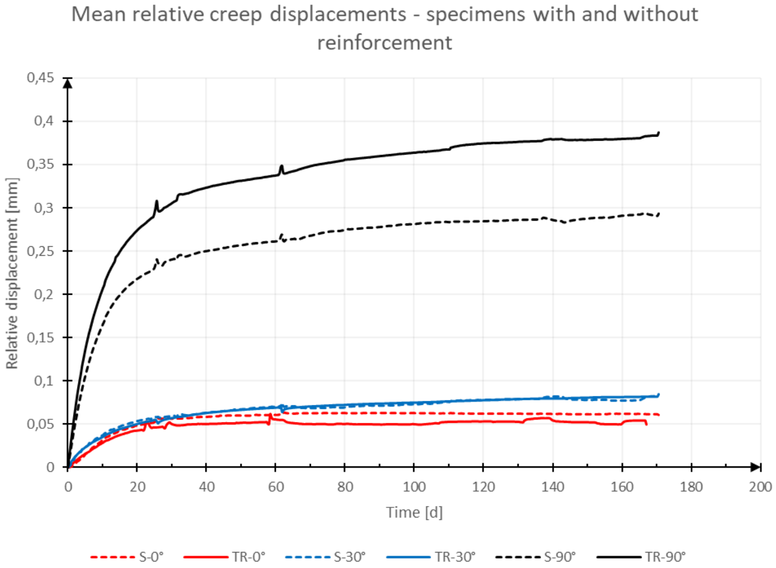


Figure 9: Mean relative creep displacements distribution in time of the long-term bond behavior under constant climate and a load factor of 0.4 for 6-months specimen series with and without additional transversal reinforcement.

The relative displacement values for specimens with transversal reinforcement after six months are as follows: 0.387 mm for those at a 90° angle, 0.084 mm for 30°, and 0.049 mm for 0°. This data indicates that specimens at a 0° angle benefit significantly from the additional transversal reinforcement, exhibiting a 30% slower creep development compared to those without reinforcement, as illustrated in Figure 9 (full and dashed red lines). The beneficial impact of transversal reinforcement on the long-term behavior of specimens at a 0° angle, observed in the current study, echoes findings from a 2017 research conducted in an outdoor climate setting [12,13]. In that study, specimens with transversal reinforcement exhibited approximately 50% less creep displacement compared to their non-reinforced counterparts. This reduction in creep displacement also resulted in higher residual loads after the long-term tests, underscoring the effectiveness of transversal reinforcement in enhancing the structural integrity and longevity of the specimens parallel to timber grains.

However, this positive effect is not noticed in specimens at a 30° angle in these 6-months testing. Furthermore, for specimens at a 90° angle, the reinforcement appears to have a detrimental effect, as stated in the previous chapter on short-term behavior. In these cases, transversal reinforcement seems to harm the bond at the interface by screwing in additional reinforcement, inducing crack widening and consequently reducing the timber's distortion resistance.

4.3. Residual load

After the long-term tests were done the specimens were prepared for the pull-out tests to investigate their residual load capacity. The data, presented in Figure 8 (thick red lines) and Table 2, indicated notable differences in mechanical behavior although the differences in capacity were minimal. At a 0° angle, the screw insertion parallel to the grain led to a 10% reduction in capacity. The post-peak behavior was more ductile, suggesting that wood's cellular structure in bonding interface suffered from humidity-induced softening. It is clear that the preloading and humidity negatively affected the timber grain, making the cell walls more flexible and less rigid.

At a 30° angle, the capacity decreased by 4%, with grain distortion and friction occurring more quickly. The premature distortion resulted in a relative displacement at maximum that was 81% of what was seen in short-term specimens.

For screws inserted at a 90° angle to the grain, there was also a 4% decrease in capacity, accompanied by earlier distortion. The debonding mechanism here is primarily frictional, similar to that observed in non-reinforced specimens. But, the preloading of specimens in climatic chamber outlines inherent vulnerability of the perpendicular screw insertion, which disrupts the natural alignment of wood grains more extensively, causing degressive frictional rate much faster.

Table 2: Residual capacity results and comparison

Type	α [°]	F [kN]	F_{res} [kN]	F_{calc} [kN]	F_{res}/F [%]	F_{res}/F_{calc} [%]	$u(F_{max})$ [mm]	$u(F_{res,max})$ [mm]	$u(F_{res,max})/u(F_{max})$ [%]
TR	0	12,32	11,09	10,93	90,02	0,92	0,65	0,790	121,54
	30	17,15	16,49	15,89	96,13	0,93	1,14	0,925	81,14
	90	18,88	18,15	14,45	96,13	0,77	1,65	1,532	92,85
S	0	11,80	11,57*	10,66	98,05	0,90	0,66	0,863*	130,76
	30	18,38	17,93*	17,03	97,55	0,93	1,12	1,112*	99,29
	90	19,05	17,52*	16,13	91,97	0,85	1,91	1,564*	81,88

* values from the [12]
F – short-term withdrawal capacity
F_{res} – residual load withdrawal capacity
F_{calc} – residual load withdrawal capacity calculated with Equation 7 from [2]
$u(F_{max})$ – relative displacement at maximal short-term withdrawal capacity
$u(F_{res,max})$ – relative displacement at maximal residual load withdrawal capacity

5. Summary

The objective of this research is to investigate the effectiveness of adding transversal screw reinforcement to the main loaded screw in timber, particularly in terms of reducing creep-related displacement over time. The study is segmented into analyzing short-term and long-term behaviors under varying conditions.

In short-term loading scenarios, no significant change in withdrawal capacity was observed, except in post-peak mechanical behavior for specimens oriented at 90° to the main loaded screw axis. This orientation resulted in capacity being reached more rapidly, leading to earlier debonding.

For long-term behavior, tested over six months under a constant load equivalent to 40% of withdrawal capacity and a steady climate (20°C/65% relative humidity), the findings were as anticipated. Creep development follows the angle orientation and highest displacements had specimens with screw orientation 90° to timber grains (up to 7 times to 0° specimens). 30° specimens had around 2 times higher displacement as specimens with the angle 0° between screw and timber grains. Specimens reinforced transversally exhibited approximately 30% slower development of creep-related displacement compared to non-reinforced specimens, particularly when the main loaded screw was oriented at 0° relative to the timber grain. However, when the screw was oriented at 30° to the timber grain, results were similar to those of non-reinforced specimens. Notably, at a 90° angle between the screw and timber grain, the transversal reinforcement was disadvantageous, contributing to increased displacement development. This adverse effect was attributed to the orientation of the additional screws, which potentially widened cracks at the bond interface and reduced the mechanical interlocking of the main loaded screw.

Additional testing on residual load capacity, following earlier research, indicated a reduction in capacity across specimens. Pull-out testing revealed a variance in mechanical behavior, especially in specimens with a 0° angle, where behavior was more ductile due to humidity's effect on the wood's cellular structure. Preloading forces and climatic effects also led to earlier occurrences of maximum capacity and debonding in all specimens.

This research is ongoing, and a more comprehensive analysis is expected after completing 12-month tests and further testing under varied climatic conditions, including natural outdoor environments and harsh cyclic weekly climates. These future results aim to delineate the conditions, configurations, and quantities where transversal reinforcement could effectively support reinforced timber under long-term loading and diverse climatic conditions.

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