# Influence of Glue-free Zones on the Withdrawal Capacity of Glued-in Steel Threaded Rods

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The hidden nature of a glued-in rod joint presents considerable challenges with regards to quality control, and there has been minimal research on the subject to fully understand the influence of defects on the joint performance. In this study, voids in adhesive line or glue-free zones were simulated in various depths of the embedded rod, and the results were compared to a reference sample population without defects. Withdrawal capacity of glued-in steel threaded rods were lower compared to reference group samples without gluing defects, when glue simulated voids or glue-free zones were positioned in the middle part and upper (closer to sample crosscut surface) part of the glued-in rods. And no difference was observed of simulated glue-free zones in the lower (the deepest) part, closer to the end of the glued-in rod, compared to reference group samples without gluing defects.

*DOI: 10.15376/biores.18.1.1206-1214*

*Keywords: Glued-in steel treaded rods; Defects; Glue-free zones; Withdrawal capacity; Destructive testing*

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## INTRODUCTION

These days, large-scale timber structures can be considered as normal because of various advances in materials, chief among them being glued-laminated timber (GLT) (Jones *et al.* 2016), cross-laminated timber (CLT) (Brandner *et al.* 2016), and laminated veneer lumber (LVL) (Ozarska 1999). This in many ways has paved the path to the state of the timber building industry as it is known and is projected in the future, wherein there is a prominent effort to shift to more emission-efficient production of construction materials (Hildebrandt *et al.* 2017).

The advent of new materials and changes in legislature are not the only driving forces for the timber construction field that have led it to the present state; a considerable number of advancements in fasteners and joint design are also highly important contributing factors. Proper design of the joints is often listed as one of, if not the most complex issue for parties involved in the timber building design process (Stepinac *et al.* 2018); hence, continued advancements in this field are paramount for future developments.

Connections using glued-in rods (GiR), as the name suggests, employ a metallic or composite rod embedded in timber *via* an adhesive. The GiR is a hidden connector that connects two timber elements or timber with another material. Most common modern applications include column foundations, moment-resisting connections, and beam connections loaded in different directions (Steiger *et al.* 2015).

There are a multitude of variables to experiment with in GiR, such as different rod types (dominant among which are: rebars (Ling *et al.* (2014), threaded rods (Chans *et al.* 2013), fibre-reinforced polymers (Zhu *et al.* 2017)), and different adhesives (Bengtsson and Johansson 2002). In addition, one can carry out tests with different wood species and wood products, including coniferous trees (Raftery and Whazelan 2014), deciduous trees (Chans *et al.* 2008), GLT (Grunwald *et al.* 2019), LVL (Myslicki *et al.* 2019), and many others regarding the geometry of the joint, loading properties, and environment, *etc*.

All the aforementioned variable factors theoretically would affect GiR performance, which would render these connections susceptible to a large number of potential defects and would impact the calculation process. Because thorough quality control of GiR joints in manufacturing is challenging, research regarding the impact of potential defects is a logical step in further understanding GiR joints and aiding their application in real-life scenarios.

In the research field on the subject of GiR, there have been a number of studies considering the performance of nearly ideal samples and their various properties. However, few publications have studied the effect of various imperfections and defects on the performance, which is a reality under factory circumstances (Karachalios *et al.* 2013; Markatos *et al.* 2013).

The material of the glued-in steel rods plays an important role in the design of the connection. Ideally, structural connections with glued-in steel rods should be designed in such a way that, in case of overload, the connection does not break in the glue seam or the wood layer, but during the plastic deformation or relative elongation of the bar (Steiger *et al.* 2007). Therefore, low-alloy steel is most often used as the material of the rods, in which, in case of overload, the fracture occurs due to plastic deformation rather than elastic deformation (Gattesco and Gubana 2006). Threaded rods with metric threads are commonly used because they have a larger contact area and also provide mechanical adhesion between the adhesive and rod surfaces (Yeboah *et al*. 2011). Threaded rods are also useful when joints are used to connect wood and metal elements or the free end of the rod is embedded in concrete structures (Tlustochowicz *et al*. 2011).

It is a logical assumption that any imperfections, whether in glue line or of the geometrical arrangement of the joint, would have substantial impact on the capacity of the GiR joint. However it has been concluded that GiR joints are considerably more robust than it would seem; rods do not need to be perfectly aligned or centered with the borehole (Kohl *et al.* 2018) and common defects, such as dirt or oil contamination or even rusting of the rod, has little to no influence on the mechanical behavior of the joint. Ratsch *et al.* (2019) also concluded that a type of defect, which does have significant impact on the performance of the joint, is glue-free zones or air bubbles within the glue line. This paper further explores this effect through positioning a simulated void in the glue line, “glue-free zones”, in various positions along (representing about 33% of the length) the axis of the threaded rod and comparing the results with a reference sample population with no defects.

## EXPERIMENTAL

### General Sample Configuration

For the purposes of this study, four sample populations were made: reference group with no defects, and three test populations with equal length of one-third of the embedment length void in glue line positioned at the bottom of the joint, in the middle, and on the top side, as shown in Fig. 1. A total of 11 samples for each test population were manufactured to have sufficient amount of data even in the case of a terminated or otherwise impaired test.

The sample labeling was done according to the defect simulated in the population: "R" – reference sample population with no defects, "T" – void in the upper 1/3 portion of bonded rod, "M" – in the middle, and "B" – in the lower portion of the bonded rod, as seen in Fig. 1. Further, within each sample population, each sample was given a number 1 to 11, *e.g.*, sample R5 would be the 5$^{th}$ sample in the reference group (without defects).

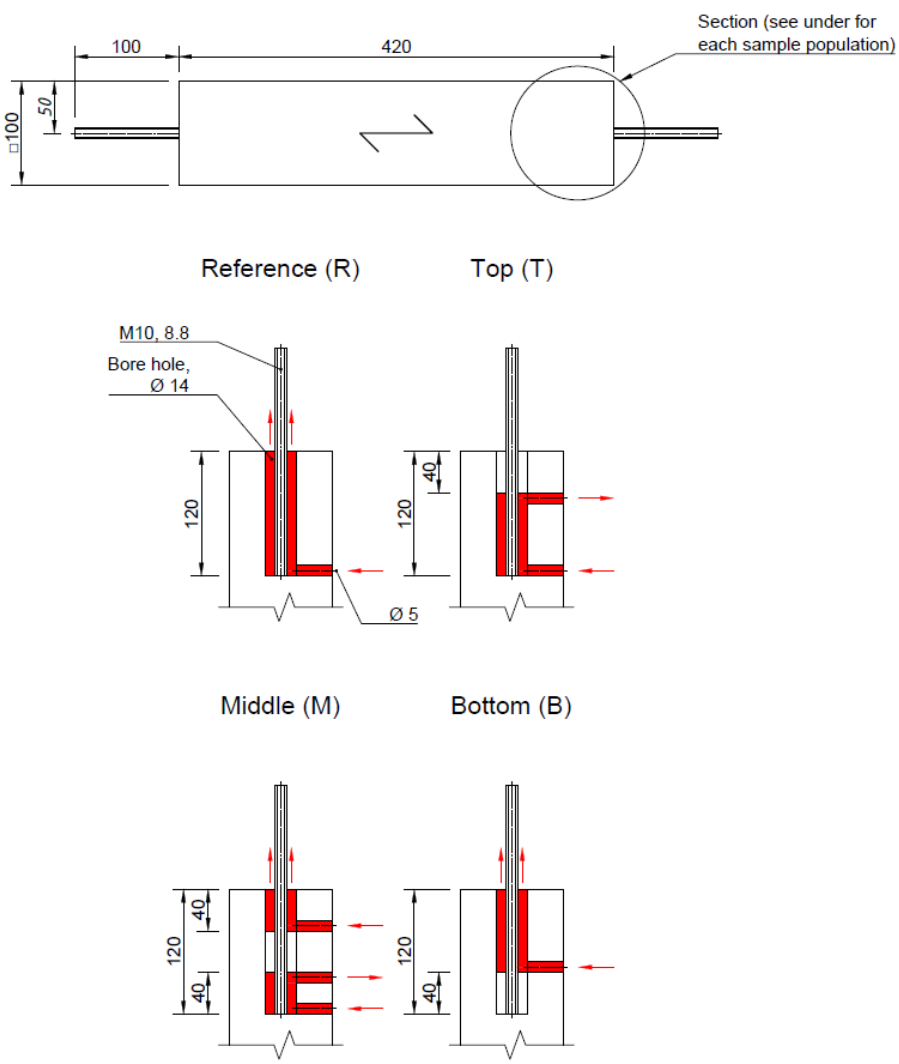


**Fig. 1.** Configuration of the test samples (adhesive thickness not to scale for better representation). Red hatching represents adhesive, dimensions in mm, R – reference (no defects), T, M, B – glue-free zones in top, middle, and bottom parts of the embedded rod, respectively. Note: symbol "□" indicates square cross section of test sample.

## Materials

European spruce (*Picea abies* L.) GLT samples (strength class GL24h according to EN 14080 (2013)) with dimensions as shown in Fig. 1 was used.

Dense, two-component epoxy resin adhesive "XEPOX D" (mixture doesn't contain any reinforcing particles) produced by "Rothoblaas" was developed and used for this application in the form of cartridges. This was chosen due to its viscosity properties. It is a highly viscous adhesive that is user-friendly for manufacturing, where it is not possible to vertically position bore holes. Hardening time, according to the manufacturer's recommendation, is at least 24 h.

Steel threaded rods with nominal diameter of 10 mm and strength class 8.8 in accordance with EN ISO 891-1 (2013) were used.

To simulate glue-free zones, 6 custom made cork wood washers (thickness 6 mm; inner diameter 10 mm; outer diameter 14 mm) per one void area were used. All six washers were fixed by thermo plastic glue from both sides. Cork was chosen because of its ability to provide sufficient sealing, thereby allowing consistent and reliable void dimensions and for its low strength values, which would not interfere with the test results. Cork contains a high proportion of suberin, which can account for its sealing behavior, but in this study it was not taken into account.

## Methods

After preparation, the samples were conditioned in a standard atmosphere (temperature 20 ± 2 °C, air humidity 65 ± 2%) until no changes in mass were observed. Special adhesive injection gun with mixing nuzzle produced by Rothoblaas was used. After gluing, the samples were kept under the above-mentioned conditions for 5 days (at least 24 hours according to the technical data sheet of the glue XEPOX D), until the mass of the samples remained steady or the moisture content of the wood was unchanged.

Bonding was completed in the same atmospheric conditions in compliance with the manufacturer's recommendations. To facilitate successful adhesive injection, side drillings with diameter of 5 mm were made perpendicular to the main bore hole and adhesive was injected after the rod was inserted. An adhesive line thickness of 2 mm was chosen according to the manufacturer's guidelines and to ease the manufacturing process.

The embedment length of the rod chosen was 120 mm (12 diameters of the rod), and extended 100 mm outside the GLT sample to facilitate clamping in the testing machine.

**Fig. 2.** Cork washers fixed of the rods for each sample population shortly before being embedded in samples: R – reference (no defects), T, M, B – glue-free zones in top, middle, and bottom parts of the embedded rod, respectively

To simulate glue-free zones, custom cork washers were made, using a laser Computer Numeric Control (CNC) machine, and fixed on the rod using minute amounts of hot-melt glue as shown in Fig. 2. This method was determined adequate for this experiment beforehand, as well as after the experiment, when no noticeable adhesive overspills in the simulated void area were observed and the cork washers do not offer notable mechanical resistance. The void size chosen was 1/3 of the embedment length in all cases. The rods were embedded symmetrically in both sides of the sample, duplicating the defects.

Samples were tested in a pull-pull configuration (Fig. 3), where rods at both ends of the sample were fixed in a universal testing machine ZWICK Z100 (Zwick Roell GmbH, Ulm, Germany) and failure of the sample in all cases was achieved within requirements of EN 17334 (2021), which also dictated the choice of loading properties and sample geometry.

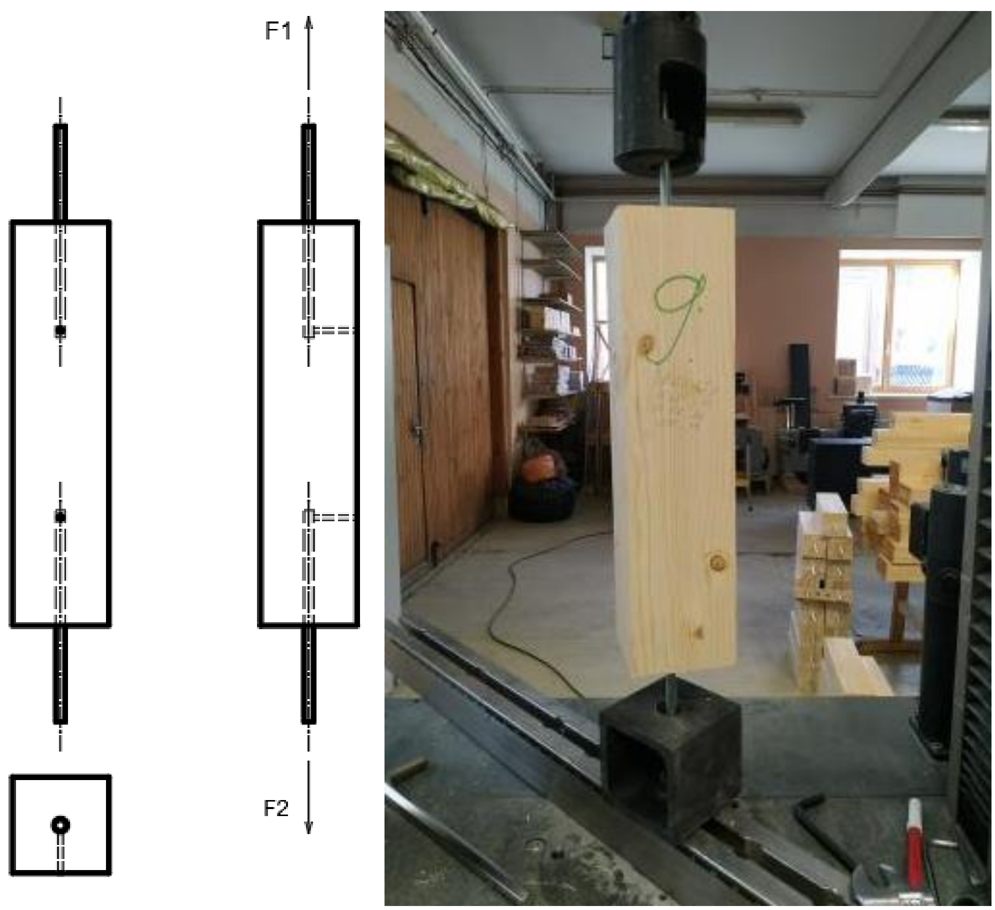


**Fig. 3.** Principle of testing of the specimens and in real conditions

A test speed 0.25 mm/min was used, and the test was continued until the applied force by machine dropped down within 10% of the maximum load. After testing, a piece of sample was cut out to determine density and moisture content according to EN 13183-1 (2003).

## RESULTS AND DISCUSSION

The results of the experiment are given in Table 1.

**Table 1.** Withdrawal Capacities of the Samples

| Sample No. | Withdrawal Capacity (kN) | | | |
|---|---|---|---|---|
| | Reference (R) | Top (T) | Middle (M) | Bottom (B) |
| 1 | 27.48 | 30.78 | 23.61 | 19.27 |
| 2 | 22.26 | 31.83 | 21.20 | 20.30 |
| 3 | 33.77 | 24.68 | 18.70 | 15.59 |
| 4 | 33.57 | 20.62 | 22.87 | 20.26 |
| 5 | 31.07 | 30.51 | 26.40 | 24.91 |
| 6 | 34.93 | 24.10 | 22.74 | 14.20 |
| 7 | 26.10 | 28.90 | 4.41 | 21.40 |
| 8 | 27.21 | 24.40 | 21.39 | 21.97 |
| 9 | 26.18 | 23.79 | 7.75 | 20.08 |
| 10 | 30.63 | 29.40 | 21.75 | 19.94 |
| 11 | 25.59 | 30.52 | 17.38 | 27.90 |
| Average | 28.98 | 27.23 | 21.78 | 20.53 |
| Standard deviation | 4.06 | 3.78 | 2.65 | 3.78 |

Two values from the results stand out. In the "Middle" sample population, values for samples M7 and M9 were considerably lower than the rest. While no visible problems were detected, these values were determined as outliers *via* an interquartile rule and thus were excluded from further statistical analysis.

For better representation, a graph of withdrawal capacity values is given in Fig. 4.

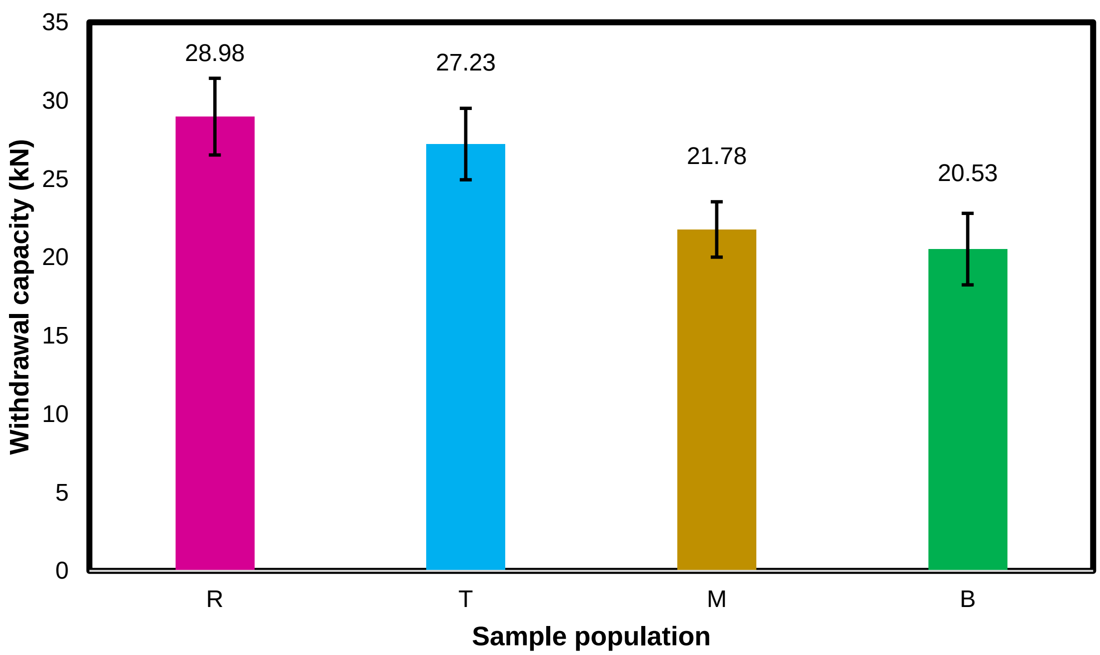


**Fig. 4.** Average withdrawal capacities of tested samples: R – reference (no defects), T, M, B – glue-free zones in top, middle, and bottom parts of the embedded rod, respectively, error bars – 2 standard error

The experimental data were first tested to verify that they were normally distributed and had a homogeneous variance. The subsequent analysis was started with a one-way analysis of variance (ANOVA) for all sample populations to determine whether or not withdrawal capacity is connected to the following factors: glue-free zones, density, and moisture content.

According to the results, it was determined that glue-free zones did have a significant impact on the withdrawal capacity ($P = 3.881E\text{-}06 \leq 0.05$), whereas density and moisture content did not cause statistically significant issues ($P_\rho = 0.557; > 0.05$, $P_{MC} = 0.111; > 0.05$).

After this, a *post-hoc* analysis was performed to determine the influence of void location (T, M, and B) on withdrawal capacity to R. A statistically significant difference was found for the following groups of specimens:

- R and M, $t_{stat} = 4.573 > t_{crit} = 2.101$; $P = 0.000236$;
- R and B, $t_{stat} = 5.053 > t_{crit} = 2.086$; $P = 0.0000608$.

A statistically insignificant difference was found for the following specimens' groups:

- R and T $t_{stat} = 1.05 < t_{crit} = 2.09$; $P = 0.308$.

As shown in Fig. 4, there was a drop in withdrawal capacity values in cases where glue-free zones were located in the bottom 2/3 of the embedment length, with no statistically significant difference between values in sample populations M and B ($P = 0.0045$) compared to reference group R, indicating and confirming the increase of axial strain in this area as simulated and measured by Ling *et al.* (2018).

In terms of failure modes, all samples failed due to pulling out of a small wooden plug around the adhesive as expected and no influence of defect location was observed.

## CONCLUSIONS

1. Within the scope of this study, there was a statistically insignificant ($P > 0.05$) impact of simulated glue-free zones in glue line in a lower (the deepest) part, closer to the end of the embedment length of GiR joints, compared to reference group samples without gluing defects.
2. There was statistically significant ($P \leq 0.05$) impact of glue-free zones in the glue line in the upper (closer to sample crosscut surface) and middle part of the embedment length of GiR joints, compared to reference group samples without gluing defects.
3. Differences were observed between the lower (the deepest) part (closer to the end of GiR) sample population group simulating glue defects compared to the sample population groups of the upper (closer to sample crosscut surface) and middle part of GiR.
4. Results were consistent with theoretical spikes in stress along the longitudinal axis – the embedded rod.

## ACKNOWLEDGMENTS

In accordance with the contract No. 1.2.1.1/18/A/004 between "Forest Sector Competence Centre of Latvia" Ltd. and the Central Finance and Contracting Agency, the study was conducted by “Meža un koksnes produktu pētniecības un attīstības institūts [Forest and Wood Products research and development Institute]” Ltd. with support from the European Regional Development Fund (ERDF) within the framework of the project “Forest Sector Competence Centre” and the project Z44 “Glue laminated timber structures for modelling at the factory conditions” (No. 3.2-10/124) co−financed by the strengthening scientific capacity at Latvia University of Life Sciences and Technologies.

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Article submitted: May 18, 2022; Peer review completed: August 21, 2022; Revised version received and accepted: December 16, 2022; Published: December 21, 2022.
DOI: 10.15376/biores.18.1.1206-1214