ABSTRACT

This project has been carried out as a part of a European project - GIROD (Glued-in rods for timber structures). Two alternative production control test methods for glued-in rods for timber structures were studied: a destructive test method to be applied to specially designed specimens for production control and a non-destructive proof-loading method. For the proof-loading test method, different proof-load levels were tested. As the production control test method should reveal serious production errors, a series of possible production errors were singled out and imitated. Finally, tests were carried out to verify whether the proof-loading test method developed was adequate for error detection in production control. The following parameters were varied during the tests and analysed:
- two test methods: destructive (reference) and proof-loading
- two modes of load application (one-sided and two-sided tensile tests)
- three adhesives: two-component epoxy, polyurethane and phenol-resorcinol-formaldehyde
- two rod slenderness ratios ($\lambda = \text{glued in length/diameter of the rod}$): $\lambda = 10$ and $\lambda = 20$
- three glue line thicknesses: 0.5 mm, 1 mm and 2 mm
- four proof-load levels: 50%, 65%, 80%, 90%
- six implemented production errors

The results show that none of the tested groups of specimens, on the average, displayed a decrease in pull-out strength after proof-loading to high levels as 80% and 90%. Error detection was possible for some of the implemented production errors. Generally, no relationship between the density of the wood surrounding the glued-in rod and the pull-out strength was found.

INTRODUCTION

Glued-in rods are being used in several European countries, but the performance requirements and the design rules differ from country to country, a serious obstacle to trade. In previous work it was concluded that the existing knowledge was insufficient to draft the needed standards. Therefore, a 3-year partly EU-financed project named GIROD (Glued-in Rods for Timber Structures) was started in 1998. The project includes the following partners: Swedish National Testing and Research Institute (SP), University of Lund (Sweden), TRADA Technology Ltd (UK), University of Karlsruhe (Germany) and FMPA in Stuttgart (Germany).

The gluing-in of rods normally takes place at a factory. Threaded rods are preferred, in order to obtain a mechanical bond between the rod and the adhesive. Rods with a diameter of between 12 and 24 mm are common. The rods are glued-in either by injecting the adhesive, or by screwing in the rod. In the first case, the holes are normally larger than the outer diameter of the rod to give sufficient clearance for the injection of adhesive. In the second case, the hole is smaller than the rod diameter, normally by an amount equal to the depth of the thread. Adhesive is poured into the hole, and the rod is then screwed in.

One of the working packages dealt with in GIROD deals with the development of a production control test method for glued-in rods for timber structures. Since the mid-1970’s production control of glued-in rods has been carried out in Sweden.

1 Ph. D., Research Engineer, Wood Structures and Materials.
2 Research Engineer in Wood Adhesives, Wood Structures and Materials.
3 Head of Section, Wood Structures and Materials.
Swedish National Testing and Research Institute (SP), Box 857, SE-501 15 Borås, Sweden.
The objective of the work presented in this paper was to develop test methods which enable reliable and simple testing of glued-in rods for timber structures during production. The method should be capable of revealing serious production errors, e.g. insufficient adhesive application, insufficient hardening, and other gluing errors. Two alternative test methods have been studied: a destructive method, and a proof-loading method. This paper is focused on the results from the proof-loading tests.

**EXPERIMENTS**

**Preparation of specimens**
The specimens were made of Norway spruce (*Picea abies*) glulam. The cross section consisted of three laminations, visually graded to LT30 (INSTA 142), which corresponds to the C35 strength class (EN 338) as far as the tension parallel to the grain properties are concerned. All rods (threaded M16, galvanised of quality 8.8) were bonded in centrally, parallel to the grain, into the glulam blocks, see Figure 1. The dimensions of the different test specimens are summarised in Figure 1 and in Table 1. A total amount of 804 specimens was tested in this study. The wood blocks were equally divided into groups based on their weights, so that the average weight of the specimens in each of the groups was approximately the same.

![Design of test specimens](image)

**TABLE 1. Dimensions of test specimens**

<table>
<thead>
<tr>
<th></th>
<th>$\lambda=10$</th>
<th>$\lambda=20$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_s$ [mm]</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>$d_d$ [mm]</td>
<td>17/18/20</td>
<td>17/18/20</td>
</tr>
<tr>
<td>$a$ [mm]</td>
<td>115</td>
<td>115</td>
</tr>
<tr>
<td>$l_w$ [mm]</td>
<td>288</td>
<td>576</td>
</tr>
<tr>
<td>$l_s$ [mm]</td>
<td>260</td>
<td>420</td>
</tr>
<tr>
<td>$l_g$ [mm]</td>
<td>160</td>
<td>320</td>
</tr>
</tbody>
</table>

As can be seen in Table 1, two different glued-in lengths were studied, $l_g=160$ mm and $l_g=320$ mm. This resulted in two slenderness ratios $\lambda=10$ and $\lambda=20$ ($\lambda=l_g/d_s$). Three glue line thicknesses were studied, 0.5 mm, 1 mm and 2 mm and three different adhesives were used. These were a two-component epoxy (EP), a two-component phenol-resorcinol (PRF) and a two-component polyurethane (PUR). The adhesives were mixed and handled according to the manufacturers' recommendations and they were injected into the bottom of the drilled holes. Thereafter, the rods were inserted by hand under continuous pressure and rotation. The rods were centred visually in the hole. The specimens were stored in a climate room (20°C and 65% relative humidity) during at least two weeks before they were tested. Closer details on the test specimens are given by Hausmann and Reil (1999).

**Test set-up**
The tests were carried out as one-sided pull-compression tests, see Figure 2. The test-method is newly developed. This test
set-up was chosen with regard to the test set-up practicality. The pull-out load was determined with a load cell and the pull-out displacement of the rod in relation to the wood surface was measured by two transducers. In order to make this test set-up as compact and stable as possible, the load cell was screwed to the hydraulic cylinder with the help of two steel plates, see Figure 2. On the top of the hydraulic jack, a thin steel plate was fixed in order to get a plane surface against which the pull-out displacement was measured. This test apparatus was put onto a stand to facilitate handling. Both transducers were assembled with a small metal sheet for simplified handling. As the jutting-out part of the glued-in rod was only 100 mm, an elongation was necessary to fix the rod to the hollow hydraulic jack. A higher steel quality was chosen for this extension (quality 10.9 according to DIN 18 800). The elongation was screwed on the top of the rod and put through the hollow hydraulic jack. Further description of this test set-up can be found in (Hausmann and Reil 1999).

Two-sided pull-out tests were also performed to verify the newly developed test-method described above. These tests were performed with a glue line thickness of 0.5 mm, all three adhesives were tested as well as the both slenderness ratios. The pull-out loads shown in Figure 3 are mean values of ten specimens. The two-sided pull-out tests gave higher loads.

**FIGURE 2.** Details of the test set-up.

**FIGURE 3.** Comparison between pull-out loads obtained from one-sided and two-sided pull-out tests. The showed pull-out loads are mean values of ten specimens.

a) Specimens with slenderness, $\lambda=10$.

b) Specimens with slenderness, $\lambda=20$. 

Two-sided pull-out tests were also performed to verify the newly developed test-method described above. These tests were performed with a glue line thickness of 0.5 mm, all three adhesives were tested as well as the both slenderness ratios. The pull-out loads shown in Figure 3 are mean values of ten specimens. The two-sided pull-out test specimens bonded with EP and PUR produced higher pull-out loads than the specimens tested one-sided. For EP and PUR specimens with $\lambda=20$ the difference in pull-out loads between the two test methods was considerable. The two-sided tests gave higher loads.


EXPERIMENTAL RESULTS

Destructive tests
For all destructive tests, the failure occurred within three to five minutes. All failures were sudden. Figure 4 shows examples of load-slip curves for three specimens bonded with different adhesives. The shape of these three curves was rather similar but among all the test results there are also load-slip curves with steeper slopes. Steeper load-slip curves were found mainly for specimens bonded with EP and PUR. The non-linear beginning of the load-slip curve was possibly caused by irregularities between the wood surface and the adhesive.

To analyse the failure modes precisely the failed specimens were opened and the failure was examined and quantified in percentage of wood failure. The specimens bonded with PRF displayed a uniform type of failure which can be classified as cohesive. There was poor adhesion to the steel. The EP-bonded specimens mostly displayed solid wood failures. Also the PUR-bonded specimens displayed a high percentage of wood failures but also cohesive failures occurred due to bubbles in the adhesive. Different failure modes are illustrated by Kemmsies (1999).

Three different thicknesses of the glue line, 0.5 mm, 1 mm and 2 mm, were investigated. For specimens bonded with EP and PUR an increased glue line thickness leads to increased pull-out strengths. For specimens bonded with PRF the pull-out strength decreased with increasing glue line thickness. The decrease was drastic. The decreased pull-out strength of PRF-bonded specimens is partly caused by shrinkage of the PRF adhesive.

Proof-loading
Four different proof-load levels (PLL) were tested to try to find the maximum load that does not cause structural damage of the bond line. The levels selected were: 50%, 65%, 80% and 90% of the maximum pull-out loads obtained from the destructive tests. Both slenderness ratios were tested and a glue line thickness of 0.5 mm was used for all cases. Seven test pieces in each group were loaded up to the determined proof-load level (loaded during 30 seconds), then the load was held for 15 seconds. Thereafter, the specimens were unloaded and reloaded until failure within five minutes. Below (Figure 5), the mean values of the pull-out loads for each of the tested group of seven specimens are shown together with the mean value of the maximum loads for the group of ten specimens tested destructively.

Table 2 shows the mean pull-out loads and the coefficients of variation (CV) for the destructive tests and for the groups of proof-loaded specimens. For the EP-bonded specimens, the coefficients of variation were largest for the largest slenderness ratio. For the PRF-bonded specimens it was the other way around; the groups of specimens with the smallest slenderness ratio displayed the largest coefficients of variation.

For the specimens bonded with EP, it is remarkable that the specimens loaded to the proof-load levels 80% and 90%, on the average, reached higher pull-out loads than the specimens only tested destructively. The effect was most pronounced for the specimens with the longest glued-in length ($\lambda=20$). The pull-out loads were approximately 20% higher for the proof-loaded specimens. Additional tests with EP-bonded specimens loaded to the proof-load levels 80% and 90% were performed. These new tests confirmed the original effect. The reason for this behaviour is still unknown. One speculation can be that proof-loading to high load levels leads to redistribution of stresses along the glue line. Such a redistribution seems to be advantageous for the pull-out strength of EP-bonded rods.
FIGURE 5. Mean values of the pull-out loads for the groups of specimens tested at different proof-load levels and for the group of specimens tested destructively.
   a) Specimens bonded with epoxy.
   b) Specimens bonded with phenol-resorcinol.
   c) Specimens bonded with polyurethane.

For PUR-bonded specimens, with $\lambda = 20$, there seemed to be no pronounced effect on the pull-out loads of the proof-loading. For all specimens proof-loaded at the 65% level there was a decrease in pull-out loads (except for PUR with $\lambda = 20$). For PRF and for EP ($\lambda = 10$) this decrease was statistically significant compared to the destructive tests. This decrease in mean pull-out load, after proof-loading to 65%, is not yet explained.

TABLE 2. Mean values and coefficients of variation (CV) of the pull-out loads for the destructive tests (dest) and the proof-loaded specimens (PLL50 = proof-load level of 50%,…)

<table>
<thead>
<tr>
<th></th>
<th>EP, $\lambda=10$</th>
<th></th>
<th>EP, $\lambda=20$</th>
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<tr>
<td></td>
<td>dest. PLL50 PLL65 PLL80 PLL90</td>
<td>dest. PLL50 PLL65 PLL80 PLL90</td>
<td>dest. PLL50 PLL65 PLL80 PLL90</td>
<td></td>
</tr>
<tr>
<td>Mean [kN]</td>
<td>62.6 62.2 54.3 57.3 63.2</td>
<td>77.4 76.3 73.3 91.2</td>
<td>96.6</td>
<td></td>
</tr>
<tr>
<td>CV [%]</td>
<td>4.7 9.1 15.6 14.2 15.2</td>
<td>14.7 19.5 16.0 19.9</td>
<td>19.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PRF, $\lambda=10$</td>
<td>PRF, $\lambda=20$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean [kN]</td>
<td>63.8 64.6 53.8 56.6 59.9</td>
<td>98.4 93.9 88.8 94.0</td>
<td>99.6</td>
<td></td>
</tr>
<tr>
<td>CV [%]</td>
<td>7.3 13.1 14.5 10.5 11.7</td>
<td>6.4 7.9 7.4 6.8</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PUR, $\lambda=10$</td>
<td>PUR, $\lambda=20$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean [kN]</td>
<td>59.0 58.9 51.4 63.5 59.4</td>
<td>74.1 71.8 78.9 75.4</td>
<td>75.5</td>
<td></td>
</tr>
<tr>
<td>CV [%]</td>
<td>16.8 20.5 9.1 9.3 11.8</td>
<td>13.2 11.0 8.8 13.9</td>
<td>16.5</td>
<td></td>
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</tbody>
</table>

Based on the test results shown above the objective was to determine a proof-load level suitable for production control of glued-in rods. In addition to the results shown above, the density and the moisture content of the wood surrounding the glued-in rod was registered. A total amount of 196 specimens were proof-loaded to the different load levels. Of these specimens, 21 failed before reaching the proof-load level, and approximately ten specimens failed during the re-loading
very near the actual proof-load. None of the specimens failed before reaching the 50% proof-load level and only one specimen failed before reaching the 65% load-level. The amount of failures were equally distributed between the three types of adhesive. Not surprisingly, 16 of the specimens that failed before reaching the proof-load level were loaded at the 90% level. The average middle lamella density for all tested specimens in the study was 419 kg/m³ (density at 12% moisture content). For some specimens the wood surrounding the glued-in rod was relatively low, around 370 kg/m³. However, also specimens with high density, around 450 kg/m³, in the middle lamella failed. Furthermore, as will be shown below, the correlation between density and pull-out load was poor in present study and therefore it is not possible to draw any conclusions based on the value of the density.

However, for the continuation of the present study it was decided to use 80% as a suitable proof-load level.

**Error-detection**

To ensure that the proof-loading method can detect possible defects of the bonded connection, specimens with six different defects were prepared. The premeditated defects were:

1. Too little adhesive
2. Burnt wood surface in the drilling hole
3. Incorrect mixing proportions of the adhesive components
4. Rod temperature at -10°C
5. Too large drilling diameter
6. Oily rod

In addition, a control series (with no defects) was tested at the same occasion. Each group of specimens consisted of seven specimens and a total amount of 308 specimens was tested. The hardening time for all specimens tested in this test series was seven days.

The results of the proof-loading to 80% of the defect specimens are shown in Figures 6-8. The number of errors detected are marked black. It can be seen that the number of detected errors varies with type of adhesive, slenderness ratio and type of error. In the case of too little adhesive the amount of adhesive was reduced by a factor two. This defect resulted in decreased mean pull-out loads of between 20% and 39% compared to the control test series. All PRF-bonded specimens and a majority of the EP- and PUR-bonded specimens, with this defect, failed before reaching the 80% proof-load level.

Burnt wood affected the PRF-bonded specimens most seriously. The pull-out loads were decreased by, on the average, 10% to 24%.

The incorrect mixing of the adhesives was detected in all cases. The amount of hardener was strongly reduced ($\geq$ 40%). It is possible that this incorrect mixing was too coarse to act as an indicator for determining whether 80% is a suitable proof-load level. Incorrect mixing of the adhesives components lead to a reduction of the pull-out loads by 31%-55% for PRF- and PUR-bonded specimens. The EP adhesive did not harden and therefore these specimens were not possible to test.

The frozen rod and the oily rod only had a small influence on the pull-out loads for the bonded connections and, consequently, this error was only detected in a few cases.

Producing the hole diameter too large gives the same results as increasing the glue line thickness, i.e. increased pull-out strength for the EP- and the PUR-bonded specimens (by 5% to 29%) and decreased pull-out strength for the PRF-bonded specimens (by 27%-45%).
Influence of density on the pull-out strength
The correlation between the density of the wood surrounding the glued-in rod and the pull-out strength was examined for the different groups of tested specimens. In some cases there was no correlation at all between density and pull-out strength, see as example Figure 9a. Relationships showing decreased pull-out loads for increased density are not rare within the studied material. However, for a few groups of specimens the correlation between density and pull-out strength was stronger, see for example Figure 9b. This strong correlation was caused by one low density value. In general, no relationship was found between wood density and pull-out strength of the glued-in rod.

**FIGURE 9.** Density of the wood surrounding the glued-in rod versus pull-out strength of the rod.

a) Specimens bonded with EP, $\lambda=10$ and a glue line thickness of 2 mm.
b) Specimens bonded with PRF, $\lambda=10$ and a glue line thickness of 0.5 mm.

**CONCLUSIONS**

A newly developed test method, suitable for production control by proof-loading, was used for testing glued-in rod connections. The method is a one-sided pull-out test. Specimens bonded with epoxy, phenol-resorcinol and polyurethane were examined. Four different proof-load levels, 50%, 65%, 80% and 90% of pull-out loads obtained from destructive tests, were tested to try to find the maximum load that does not cause structural damage of the bond line. Specimens bonded with epoxy, on the average, reached higher pull-out loads after proof-loading until 80% and 90% than the specimens tested destructively. None of the tested groups of specimens displayed a decreased pull-out strength after proof-loading to such high levels as 80% and 90%. The groups of specimens proof-loaded to 65% displayed a decreased pull-out strength. The reason for this behaviour was not explained in the present study.

Error detection was possible for coarse errors by proof-loading up to the 80% level. The induced errors in the present study were sometimes extreme errors. The selection of 80% as a suitable proof-load level is, however, still uncertain and must be further evaluated.

Generally, no relationship between density of the wood surrounding the glued-in rod and pull-out strength was found. This fact needs to be further investigated.

**ACKNOWLEDGEMENTS**

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**REFERENCES**
