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The impact of defects on the capacity of timber joints with glued-in rods

E. Gonzales [a], T. Tannert [a,*], T. Vallee [b]

[a] University of British Columbia, Departments of Wood Science and Civil Engineering, Vancouver, Canada
[b] Fraunhofer-Institut für Fertigungstechnik und Angewandte Materialforschung IFAM, Adhesive Bonding Technology and Surfaces, Bremen, Germany

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ABSTRACT

Glued-in rods are an increasingly used technical solution for numerous structural applications in timber engineering, and demonstrate the potential of adhesively bonded connections. During the insertion process the adhesive fills a very narrow gap over significant anchorage contact area, raising concerns that manufacturing defects may impact the structural performance of the bonded joint, namely the possible lack of adhesion resulting from inadequate preparation of the joint on site. Previous studies on the effect of bonding defects on the capacity of bonded joints identified a nuanced relationship that depends on the ductility of the adhesive.

This paper presents experimental evidence that sheds light on the relationship between defects and capacity of glued timber joints. Joints composed of softwood glulam members and mild steel glued-in threaded rods were manufactured with two types of defects likely to be encountered on-site: i) rods placed at an angle inside drill hole instead of aligned with the joint axis, and ii) rod placed against the side of the drill hole instead of fully centered. To establish performance benchmarks a first phase studied the influence of the anchorage length and the rod diameter using three different adhesives. The effect of these defects on joint capacity was investigated with three different adhesives in combination with three different rod anchorage lengths. The investigations demonstrated that joints with sufficient rod anchorage (herein 10 times the rod diameter) do not exhibit a statistically significant loss of capacity, if compared to defect free joints. These results can contribute towards better understanding of the influence that the studied parameters have on the performance on timber joints with glued-in rods, as well as to translate this information to promote the development of further applications.

1. Introduction

1.1. Background

Joints between load-bearing members often constitute the critical elements when designing timber structures: the capacity and the overall stiffness of a timber structure may depend on the capacity and the stiffness of the joints. To connect timber elements practitioners have at their disposal a series of methods [1]: i) direct contact between timber members; ii) dowel type mechanical fasteners; and iii) load transmission by means adhesive bonding. The first category, carpentry type joints, represents the most traditional connection method and has seen a small-scale revival due to the advent of modern computer-numerically-controlled heavy timber machinery [2]. The second category, mechanical fasteners, represent the most common connection method and substantial research e.g. [3,4] allowed for contemporary standards such as EC 5 [5] to cover their design in much detail. The third category, adhesive bonding, provides an efficient method provided that: i) the joints are correctly designed; ii) suitable specifications are adopted; iii) the work is done by experienced operatives; and iv) strict quality control is exercised [6]. Furthermore, it is possible to combine joining methods into a "hybrid" joint [7–9].

Glued-in rods conceal the connector inside the wood member which is both an architecturally pleasing feature and provides the joint with excellent fire and corrosion protection if compared against conventional dowel-type timber connectors. Different types of rod materials can be glued into timber: steel, fiber reinforced polymers, and wood. Steel rods provide the advantage of attainable ductility and can be connected to other steel elements through nuts and washers; these are most commonly used. In addition, if threaded rods are used, mechanical interlocking between the threads and the adhesive are expected to eliminate

* Corresponding author.
E-mail address: Thomas.tannert@ubc.ca (T. Tannert).

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the dependence on the adherence between the adhesive and steel rod [10,11].

1.2. Mechanics of glued-in rods

Joints with glued-in rods are typically made up of three different materials (timber and steel as adherends and the adhesive) that have different stiffness and strength properties but are expected to transfer loads and deform simultaneously under loading. This complexity, along with the wide range of geometric and mechanical parameters that influence the performance of a glued-in rod joint, are amongst the reasons why a unique design model has yet to be agreed upon [11,12].

Although originally developed in the 1960s, it was not until the 1980s that extensive research was initiated on glued-in rods [11]. Research focused primarily on testing of single rod glued-in joints under axial loading: a practice that allows for isolation of parameters and their influence on the mechanical performance of the joint [11,12]. The parameters that have been investigated can be classified into three groups [13]: i) geometric parameters; ii) material parameters; and iii) boundary conditions. Amongst the geometric parameters, the impact of anchorage length of the rod into the timber member and the rod diameter on axial capacity were the main foci of research. Previous studies agree that joint capacity increases with larger anchorage length and larger rod diameters. These relationships are not linear and difficult to model due to the non-uniform distribution of shear stresses along the embedded length [6,10,14–20]. The influence of both parameters combined, rod diameter (d) and anchorage length (l_a) – assuming a constant and uniform adhesive line thickness – is handled using the term of slenderness ratio ($\lambda = l_a/d$) as design input parameter.

Commonly used adhesives are phenol-resorcinol (PRF), epoxy-based (EPX) and polyurethane based (PUR) adhesives. The adhesives' function in a glued-in connection is to provide the bond to transfer the loads from the rod to the timber. Design usually aims at not making the adhesive the weakest link; therefore, adhesive strength, glue-line thickness, drill diameter, rod diameter, anchorage length are taken into account to avoid a brittle failure mode [18]. In the context of the European Glued-in Rods for Timber Project (GIROD), extensive studies on the performance of PRF, EPX and PUR adhesives concluded that, if all other parameters were the same, joints with EPX exhibited the highest axial capacity, followed by PUR and then PRF [21]. More recent studies have shown that one of the most important characteristics of PUR based adhesives is their gap-filling ability [22].

The glue-line thickness has been studied without reaching complete consensus upon its impact on joint capacity [22,23]. Increasing the bond line thickness increases the net surface area of bond between rod and wood, and is therefore expected to more uniformly distribute stresses and should result in higher capacities. Research performed on these parameters, however, has not yielded consistent evidence to back-up this conjecture; and no code acknowledges the influence of bond line thickness. When it comes to practical applications, due to the dimensions of all elements (rod diameters from 6 to 30 mm, typical minimum anchorage lengths from 50 to 450 mm), adhesive layer thicknesses usually range from 1 mm to 3 mm; it was thus decided to carry out all experiments with a bondline thickness of 2 mm.

1.3. Design proposals

Five principal failure modes associated with glued-in steel rod connections are recognized [11,12]: i) shear along the steel rod (brittle); ii) tensile failure of the wood member (brittle); iii) shear block failure in the wood member (brittle); iv) cracking of the wood member (brittle); and v) yielding of the steel rod (ductile). Brittle failure modes are generally more difficult to accurately predict due to the high variability of wood strength properties; for this reason only the ductile yielding of the rod is considered to be a desirable failure mode.

In a traditional engineering approach, capacity prediction relies on the determination of stress or strain distribution through the use of analytical or numerical models, followed by a comparison with a failure criterion where the combined stresses reach the material resistance. Herein, only two prominent design methods are considered: the GIROD proposal [21] and the informative Annex to Eurocode 5 [24]. For other models, e.g. those proposed by Riberholt [14], Gerold [10], or Steiger et al. [18], and provisions within DIN 1052 [25], the reader is kindly referred to Stepinac et al. [26]. The GIROD Project presented a design formula, loosely based on the generalized Volkersen [27] theory:

$$P_u = \tau_f \cdot \pi \cdot d \cdot \ell_a \cdot (\tan\omega/\omega) \tag{1}$$

where:

P_u characteristic axial capacity of a single rod;
τ_f bond line shear strength;
d rod diameter;
ℓ_a rod anchorage length;
$\omega = \sqrt{(\ell_{geo}/\ell_m)}$.
$\ell_{geo} = ½\,(\pi \cdot d \cdot \ell_a)^2 \cdot (1/A_r + (E_r/E_w)/A_w)$
$\ell_m = E_r . (G_f/\tau_f^2)$
A_r cross sectional area (mm^2) of rod;
E_r modulus of elasticity of rod material;
A_w cross sectional area (mm^2) of timber host;
E_w modulus of elasticity of timber host;
G_f calculated from l_m with the assumption E_r=2,05,000 MPa.

The proposal presented by the GIROD project, which is subsequently used for comparison of the experimental results, provided the foundational discussion for inclusion into Eurocode 5. Annex C in pre-standard prEN 1995-2, [24] included a more simple design provision:

$$R_{ax,k} = \pi \cdot d_{eq} \cdot \ell_a \cdot f_{ax,k} \cdot (\tanh\,\omega/\omega) \tag{2}$$

where:

$R_{ax,k}$ characteristic failure load of joint;
d_{eq} min [D or 1.25d];
D hole diameter;
$f_{ax,k}$ characteristic shear strength 5.5 N/mm^2;
ω $0.016 \cdot l_e/\sqrt{d_{eq}}$

Despite their proven performance and a multitude of suggested design approaches [26], the ongoing discussion on appropriate design guidelines on glued-in rods keep them currently outside the scope of major timber engineering design standards. The struggle for an appropriate design rule, to cite Larsen [28], is (still) a "sad story".

1.4. Bonded timber joints with defects

The manufacturing process of connections with glued-in rods, as is the case for all structural adhesive joints, requires special attention. Quality control was viewed as one of the biggest limitations for the use of glued-in rods for on-site applications since quality control regulations for factory/in-house manufacturing of glued-in rod connections did not exist [29]. The current assumption is that very stringent quality control during the manufacturing process is essential to guarantee specific curing