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Pull-out strength and bond behaviour of axially loaded rebar glued-in glulam

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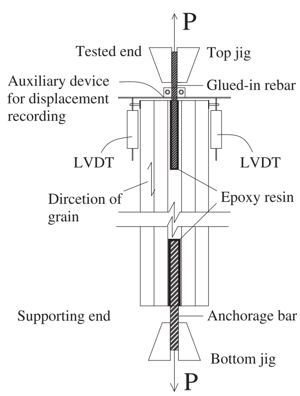
HIGHLIGHTS

- The mechanical properties of glued-in rebar timber joints were investigated.
- Four typical failure modes were observed during the testing.
- Bond stress–slip relationship of glued-in rebar joint was characterized by a two-branches model.
- The variation in glue-line thickness was within a reasonable range for glued-in rebar joint.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents an experimental program for testing glued-in rebar timber joints. Twenty five glulam specimens, each with a single glued-in rebar parallel to the grain were tested to evaluate the effects of anchorage length and glue-line thickness on pull-out strength and bond behaviour of glued-in rebar timber joints. Tests were conducted in pull-pull configuration. The test results showed that both the anchorage length and glue-line thickness had a significant influence on these two properties. Failure modes were characterized by pull out failure of the rebar, either alone or combined with the shear failure of timber along the glue line, longitudinal splitting of wood and bar yielding. For the same anchorage length, the average bond stress at both interfaces showed different variations (increasing by 11.6% at the bar/adhesive interface, and decreasing by 12% at the adhesive/timber interface) since the glue-line thickness increased from 2 mm to 6 mm. The load–slip relationship and initial stiffness of specimens were analysed in terms of anchorage length and glue-line thickness. An empirical bond–slip model for glued-in rebar timber joint was proposed by regression analysis based on the experimental data. It was observed that the proposed model fit the bond–slip relationship of glued in rebar timber joints with less than 15% deviation. Finally, the test results were compared with the design proposals reported in the literatures. It can be concluded that the prediction of Rossignon design proposal was more closely to the test results, and the Steiger design equation was unsafe, however, the Riberholt design equation was too conservative for the joint design.

1. Introduction

Glued-in rod technology has been widely used in concrete for strengthening and retrofitting, which is also becoming increasingly

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popular in the construction new timber structures and repairing of some pre-existing timber structures. Glued-in rod timber joints provide many improvements over traditional timber joints, including lower weight, greater strength and stiffness, improved aesthetic appearance and good fire resistance. The straight-forward method for manufacturing glued-in rod timber joint is to inject adhesive into the pre-drilled hole firstly and then insert and rotate the rod into the partially adhesive-filled hole until the rod reach the bottom of the hole to allow for a reliable bond between the rod and timber.

Over the past four decades, a large number of experimental and theoretical studies on glued-in rod timber joints have been carried out. Most of the experiments were pull-out tests, aimed to investigate the effects of geometrical and material properties on the pull-out strength and bond behaviour of glued-in rod joint [1–6]. The test results showed that the pull-out strength and bond behaviour of glued-in rod joint were influenced significantly by the key parameters, involving anchorage length, bar diameter and surface treatment, bar edge distance, timber density and adhesive type. Several design proposals of glued-in rod timber joint have been reported [7–11], which provide designers with useful design criteria and methodologies. Theoretical analysis of glued-in rod joints has also been conducted by several researchers [12–15]. Those works mainly focused on the analysis of interface bond mechanism and the finite element simulations of glued-in rod joints. Tlustochowicz et al. [16] published the state-of-the-art review on timber connections with glued-in steel rods, both the glued-in single rod and multiple rods joints are involved in, including manufacturing methods, mechanisms and parameters governing the performance of the joints, theoretical analysis approaches and the design proposals in the existing literatures.

Timber connections with multiple glued-in steel rods were also studied by several researchers [17–19]. Buchannan and Fairweather [17] tested timber connections with glued-in steel bars under simulated seismic loading for the recommendations for seismic design. Fragiacomo and Batchaler [18] proposed a methodology for joint design based on evaluating joint strength for moment and axial force with traditional mechanics theory adapted for use with timber, which has been successfully used in many projects. Parida et al. [19] conducted an experimental program on timber-to-steel connections with multiple glued-in rods. Finally, provisions for ductile behaviour of timber-to-steel connections with multiple glued-in rod were proposed.

Fiber reinforced polymer (FRP) bars show good resistance of corrosion, light weight and high performance of connections compared to steel bars, which result in FRP bars might be used as well as steel bars in timber connections with glued-in rod. Harvey and Ansell [20] carried out pull-out tests on bonded-in GFRP rods in timber blocks in order to investigate the influences of the bar surface preparation, glue-line thickness, anchorage length, adhesive type, moisture content and wood type on the pull-out strength of the joints. Lorenzis et al. [21] studied bonded-in CFRP bars in glulam timber by analytical and experimental methods. The bond–slip behaviour of CFRP bars bonded in timber both parallel and perpendicular to the grain was modelled numerically to determine the ultimate load of bonded-in CFRP bar timber joint. Yeboah et al. [22] studied the pull-out behaviour of basalt fiber reinforced polymer (BFRP) loaded perpendicular to glulam timber elements. The results showed that the bond stress of the theoretical model (at the ascending and descending branches) of the stress–slip curve was approximately 5–10% lower than that of the experimental value.

Rebars/deformed bars have also been used to instead of threaded bars in some early investigations [2,3]. The structural performance of glued-in rebar timber joints is significantly governed by the bond behaviour between timber and glued-in rebar with adhesives, and actually, the effectiveness of the glued-in rebar joints depends on the stress transfer mechanisms at the interfaces. Several researchers have investigated the bond–slip behaviour between glued-in rod and timber, for example, Serrano [23] proposed a test method which makes it possible to record the complete stress–displacement response of small test specimens. While the rebars probably show differences on bond behaviour in glued-in rod timber joint compared to threaded bars, because of the differences on their surface situation. So it is significant to conduct some researches to investigate the bond stress–slip relationship of glued-in rebar timber joints. This paper presents an experimental study on the pull-out strength and bond behaviour of glued-in rebar in glulam with epoxy adhesive. The varying parameters were anchorage length and glue-line thickness. Tests were conducted in the pull–pull configuration. The experimental bond–slip constitutive laws were established with a consideration of a uniform distribution of bond stress along the anchorage length of the glued-in rebar.

2. Materials and methods

2.1. Materials

2.1.1. Timber

The properties of the timber used in the tests are reported in Table 1.The timber blocks were cut from glued laminated timber composed of 30 mm thick lamellas, which was glued together in a conditioned environment with resorcinol resin adhesive. The moisture content of the specimens ranged from 10% to 12%, which was obtained by the oven-drying method according to the British Standards (BS EN13183-1:2002) [24]. The average density of timber was 480 kg/m^3.

2.1.2. Rebar

Rebars were adopted in this study due to its common using and price advantage compared to the threaded steel bars. The material properties of rebars were obtained by directly tensile testing according to Chinese Standard for tensile tests of metallic materials (GB/T228-2010) [25]. Table 2 presents the material testing results of rebars.

2.1.3. Adhesive

The adhesive used in this study was two-component epoxy resin produced by the manufacturers (NJMKT). This type of adhesive has been widely used for post-installed anchors in concrete and repairing the existing structures because of its good structural performance and durability. It has also been reported that the epoxy adhesive possess better shear strength than other types of adhesive, such as polyurethane (PUR) and phenol–resorcinol–formaldehyde (PRF) [26]. Meanwhile, it does not require high pressure during their application and curing. Material properties of the adhesive, provided by manufacturer, are listed in Table 3.

2.2. Specimens and fabrication

2.2.1. Geometry

Fig. 1 shows the design and configuration of specimens. To better understanding the load transfer and bond mechanism of the joint, glued-in single rod was adopted in this study. Moreover, it is more convenient to test glued-in single rod compared with testing on glued-in multiple rods. Thus, the specimens were designed with glued-in single rod at the double ends for testing.

It was indicated that the minimal hole-to-edge distance affected the strength of glued-in rod joints since the specimens failed by wood splitting due to the transversal stress concentration [27]. Broughton and Hutchinson [4] and Gardelle and Morlier [28] suggested that using the hole diameter d_h to instead of the bar diameter d_r in the edge-distance ratio (e/d_r) was much more effective. To prevent the premature splitting of specimens, in this study, the hole-to-edge distance e was designed to range from $2.85d_h$ to $4d_h$, which was higher than the minimal edge distance ($2.5d_r$) presented in Eurocode 5 [8], where d_r is the diameter of the bar.

Table 1
Mechanical properties of glulam timber specimens.

Wood designation	Douglas fir
Compressive strength parallel to grain (MPa)	36.0
Tensile strength parallel to grain (MPa)	26.1
Shear strength parallel to grain (MPa)	10.3
Tensile modulus parallel to grain (MPa)	11000