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Modelling of glued laminated timber joints with glued-in rod considering bond-slip location function

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ABSTRACT

It was frequently reported that the bond-slip relationships at different locations along the bonded length are different, which can be illustrated as bond-slip location effect. In order to reveal the influence of this effect on the bond behaviour between glue laminated timber (glulam) and glued-in rod, a 3D finite element model considering bond-slip location function is developed for the glulam joints with glued-in rod in this paper. Moreover, an experimental program conducted on the glulam joints with glued-in rod is also presented. The numerical and experimental results are compared and discussed in terms of withdrawal capacity, typical failure modes, load-slip behaviour, strain development of glued-in rod and the interface shear stress distribution. It is indicated that the non-linear spring elements can be used to simulate the bond behaviour between the glulam and the glued-in rod effectively. The numerical results obtained considering the bond-slip location function are generally in better agreement with the experimental results compared to that obtained neglecting the bond-slip location function. Finally, the withdrawal stiffness of the glued-in rod glulam joints is evaluated by a theoretical approach based on the Volkersen theory. The withdrawal stiffness calculated by the proposed model shows good agreement with the experimental results, which confirms that the calculation model is effective for predicting the withdrawal stiffness of the glulam joints with glued-in rod.

1. Introduction

Glued-in rod technique offers great potentials in new timber constructions as well as the maintenance of existing timber structures due to its obvious advantages, such as high strength-to-weight ratio, high joint stiffness, and aesthetical appearance. This type of connecting technique has been successfully applied in timber engineering, including the current world's tallest timber building - Brock Commons, which is a student apartment building located at UBC campus, Vancouver. In the past decades, many experts did great efforts on the investigation of glued-in rod timber joints, including the bond behaviour of glued-in single rod in timber [1–8] and the structural performance of moment-resisting timber joints with glued-in rods [9–15].

Glued-in rod timber joint can be regarded as a composite connecting system involving three types of materials, which are the timber, the glued-in rod and the adhesive. To some degree, the structural performance of this type of joint is greatly governed by the bond behaviour between the timber and the glued-in rod. The existing literature indicates that the bond stress-slip relationships at different locations along the bonded length are different [16–18], which was also confirmed by the investigation on FRP-to-timber bonded interfaces [19]. Finite element modelling is an effective way to understand the bond behaviour between different adherents. The following are several numerical studies on glued-in rod timber joints.

Serrano [20] created a 3D nonlinear finite element model for glued-in rods for timber structures and conducted finite element parameter studies. A strain-softening crack band model was used to characterize the behaviour of the adhesive layer between the rod and the wood. Senno et al. [21] investigated the most influencing parameters for the shear stress distribution of axial glued-in steel timber joints by finite element method, Xu et al. [22] established a 3D finite element model for beam-to-beam timber connections with glued-in ribbed steel bars considering the orthotropic elasto-plastic behaviour of timber. Perfect bonding was assumed between the glued-in steel bar and the timber. The numerical results show a good agreement with the experimental results. Martín et al. [23] conducted numerical simulation on glued-in threaded steel rod timber joint aiming to investigate the stress distributions and to develop design strategies to improve the effectiveness of these joints. Tannert et al. [24] developed a 3D FEA model for glued-in BFRP rod timber joints by using ANSYS to investigate the interfacial

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stress distribution between the BFRP rod and the timber. The interaction between the BFRP rod and the timber was simulated by contact pairs. Numerical results indicated that finite element method is an effective way to predict the failure load of glued-in rod timber joint. Coureau et al. [25] built a 2D finite element model of glued-in rod in timber in order to reveal the progressive damage and the crack propagation located at the wood-adhesive interface, aiming to separate the progressive failure due to modeI(Double-cantilever beam, DCB)and modeII (End-notched flexure, ENF). This study indicated that the mode Iinitiates the damage in the glued interface and the predicted pull-out strengths were estimated from the elastic properties of substrates (wood, adhesive, and steel) and the fracture properties of wood. It is found from the above studies that the effect of the locations along the bond line on the bond behaviour between timber and glued-in rod was neglected, which might cause errors between the numerical results and the real joint behaviour.

In order to understand the real joint behaviour, it is necessary to consider the location effect of bond-slip relationships along the bonded length when doing numerical modelling on the bond behaviour of glued-in rod timber joint. This paper presents a finite element model considering bond-slip location function for glulam joints with glued-in rod. In this model, the glulam was modelled as orthotropic materials. The mechanical behaviour of glulam was illustrated by the elasto-plastic Hill yielding criterion. The local bond stress-slip relationship between the glulam and glued-in rod was simulated by non-linear spring elements. An experimental program on glulam joints with glued-in rod is also presented to validate the efficiency of the finite element model considering bond-slip location function.

2. Experimental program

This section summarizes the experimental program on which the numerical modeling is based. A total of thirty-six glulam joints specimens with glued-in rod grouped by six are involved. It should be noted that the experimental works involving glued-in rebar has been reported in the previous study [7].

2.1. Materials and specimens

The glulam blocks in this study are made of North America Douglas fir lamellas with 30-mm thickness. The measured average density was 480 kg/m^3. The moisture content of glulam measured accordingly [26] ranged from 10% to 12%. The mechanical properties of glulam obtained by tests according to GB/T 50329-2012 [27] were reported in Table 1. Two types of steel rods, namely rebar and threaded steel rod were used as glued-in rod. By direct tensile tests, the yield strength of the steel rods was measured as 362 MPa for rebar and 695 MPa for threaded steel rod, respectively. The modulus of elasticity of the steel rods was recorded as 210 GPa. Two-component epoxy resin (MT-500) was used as the adhesive between glued-in rod and timber. The steel-to-steel bond strength of the adhesive was given as 22 MPa, which is a characteristic value at the laboratory conditions (20 ± 2 °C and a relative humidity of 65%) provided by the adhesive manufacturer (NJMKT, Nanjing, China). The modulus of elasticity and the shear modulus of the adhesive were set as 4000 MPa and 1500 MPa, respectively referencing Broughton and Hutchinson [28], because the similar adhesive was used.

Table 1
Mechanical properties of timber.

Wood designation	Douglas fir
Longitudinally compressive strength (MPa)	36.0
Longitudinally tensile strength parallel (MPa)	42.2
Longitudinally shear strength (MPa)	8.4
Longitudinally tensile modulus (MPa)	10,760

Currently, no unified design rules have been proposed for glued-in rod timber connections, though some design recommendations were proposed in Eurocode 5 [29]. The specimen configurations are shown in Fig. 1. The cross-section dimension of the timber blocks is 160 mm × 160 mm and the bond lined thickness is designed as 2 mm. The supporting end of the specimens was designed with more resistance than the testing end to ensure failure occurred firstly at the testing end. The distance between the two inner ends of the rods was designed to be 1.4 times the bonded length ($lm = 1.4la$) to reduce the interaction effect of the stress fields of the two opposite steel rods. In order to record the axial strain of the glued-in steel rods during loading, strain gauges were attached in the central groove of the steel rods with an interval ranging from 15 mm to 30 mm. In each group of specimens, three replicates were designed with strain gauges internally attached to the glued-in rod at the tested end.

2.2. Test setup and protocol

All specimens were tested on a universal testing machine with a 1000-kN capacity. The loading rate was set to 2.0 mm/min and kept constant throughout the loading process according to Broughton and Hutchinson [30]. The test set up and the arrangement of measurements were shown in Fig. 2.

2.3. Experimental results

Table 2 reports the experimental results in terms of the ultimate load, the corresponding relative slip between glued-in rod and glulam, and typical failure modes of specimens. The numerical results obtained by finite element modelling are also presented in Table 2. It should be noting that specimen group code was illustrated by S/R-rod diameter-bonded length-bond line thickness. The capital letter S and R in the group code mean rebar and threaded steel bar, respectively.

Typical failure modes of the specimens are shown in Fig. 3. Fig. 3(a)–(d) shows the failure modes of the specimens with glued-in rebar, namely pull-out failure of rebar, timber shear failure near the adhesive/timber interface, splitting failure of timber block and yielding of rebar, as reported in the literature [7]. Generally, the failure modes are related to the interaction mechanism between the steel rod and the timber. Those specimens with a short-bonded length (120 mm) failed by the pull-out failure of rebar (Fig. 3(a)), due to the interfacial bonding failure at the bar/adhesive interface. For the specimens with a bonded length of 160 mm, several specimens failed in timber shear failure near the adhesive/timber interface (Fig. 3(b)) and the other failed in timber splitting failure, as shown in Fig. 3(c). This is due to the prying and wedging action caused by the rib-roughened surface of the rebar. It can be seen from Fig. 3(d) that bar yielding occurred on glued-in rebar specimens, as the bonded length reach up to 200 mm, which indicates that the ductile failure mode of glued-in rod timber joint can be realized with reasonable design. Fig. 3(e) and (f) illustrates the timber plug shear failure, by which almost all the specimens with glued-in threaded steel rod failed. This is due to the perfect mechanical interlocking behaviour between the fine thread and the adhesive, so that these specimens always failed by timber shear failure.

3. Finite element modeling

3.1. General remarks

As illustrated early, the relative slip between timber and glued-in rod was existing during the pulling-out process of the glued-in rod, so that it is necessary to consider the bond-slip effect to perform the finite element modelling on the bond behaviour of the glued-in rod glulam joints. A finite element model for the glulam joints with glued-in rod was developed using ANSYS [31] and 1/8 vol of specimen was taken for saving computational time due to the symmetry. The selected volume