J Wood Sci (2016) 62:109–115
DOI 10.1007/s10086-015-1516-5

NOTE

The effect of depth and diameter of glued-in rods on pull-out connection strength of bamboo glulam

Yan Yan[1] · Huanrong Liu[2] · Xiubiao Zhang[2] · Heng Wu[3] · Yun Huang[4]

Received: 19 April 2015 / Accepted: 8 September 2015 / Published online: 7 October 2015

Abstract In order to explore bamboo glulam utilization in structure construction, the adhesive bonded steel connection of bamboo glulam was investigated in this study. By carrying out both-end pullout tests on glued-in threaded rods in bamboo glulam, the effects of depth and diameter of embedded rods in bamboo glulam on the pullout strength and the failure modes were discussed. Results showed that threaded rods fracture and adhesive interface failure were the two main different failure modes in the tests. The pullout peak load of both-end glued-in rods in bamboo glulam increased with the diameter and the embedded length of the threaded rods. To satisfy tensile load of the glued threaded rods (quality 4.8) used in the connections between engineering structural materials, the slenderness ratio (λ, the ratio of depth and diameter of glued-in threaded rods) equal to 10 or over was necessary.

Keywords Bamboo glulam · Glued-in rods · Pullout strength · Failure mode

Introduction

As a non-wood natural bio-composite, bamboo has attracted worldwide attention in construction, transportation, stationery commodity and even daily articles due to its abundant resource, excellent mechanical performances and environmental protection [1]. Based on the better understanding of bamboo structural, physical and mechanical performance [2], bamboo is extremely potential to be utilized as an engineering structure material [3]. However, lack of strong and reliable connection restricts its further application in construction. At present, there are many types of connections used in timber structures in the residential or commercial houses, including nailed connections [4], bolted connections [5], dowel connections [6–9] and adhesive bonded steel connection. Epoxy bonded steel connection, which is used in bamboo timbers, is that a threaded steel bar is placed into predrilled holes in timber members and bonded with epoxy resin. The embedded steel bar with the epoxy bonding agent allow a strong connection to be made with increased stiffness of the joint and the structure could be also kept for its excellent esthetic appeal and fire resistance without any cover [10, 11]. So epoxy bonded steel connection has been extensively used in column-base, beam-column and elbow connections [12, 13] for quite a long time since the first study by Riberholt [14, 15]. There are two different types of the epoxy bonded steel connection classified by the different implant bar number: single bar connecting bar and multitude bar connection. However, there are studies on the epoxy bonded steel connection in bamboo glulam, better analyze the performance of epoxy bonded steel connection into bamboo glulam could explore its utilization [16]. The ratio of depth and diameter of glued-in rods are the main factors influencing pull-out connection strength of timber [17].

The present study focus on the single bar connection in bamboo glulam. Epoxy bonded steel was glued into bamboo glulam parallel to the grain of bamboo glulam; tensile tests were carried out on both-end. The effects of depth and

✉ Huanrong Liu
icbrliuhuanrong@sina.com

1 Anhui Taiping Experimental Station, Taiping, China

2 International Center for Bamboo and Rattan, No. 8, Futong Dong Dajie, Wangjing Area, Chaoyang District, Beijing, China

3 Anhui Agricultural University, Hefei, China

4 Anhui ZHONG-AO Institute of Technology, Hefei, China

the diameter of the embedded bar in the bamboo glulam on tensile performances were investigated, and the failure modes was discussed.

Materials and method

Materials

Four-year-old moso bamboo (*Phyllostachys pubescens* Mazei ex H. de Lebaie) culms were obtained from Zhejiang province. The bamboo strips were sliced from bamboo culm which is in dimension of 15 mm (thickness) × 4 mm (width) × 1800 mm (length). Bamboo glulam are made by bamboo strips in the process of bamboo strips impregnated into PF and then hot pressing. The production process of bamboo glulam in detail is shown in Fig. 1.

Steel rods with metric threads M8, M12 and M16 were zinc coated and corresponded to quality 4.8 (quality 4.8 refers to the threaded rod performance rating label, label is made up of two parts, respectively, represent the nominal tensile strength value and yield ratio of threaded rod. For example, 4.8 threaded rod, the meaning is: (1) threaded rod material nominal tensile strength: 400 MPa, (2) threaded rod material yield ratio: 0.8, (3) threaded rod material nominal yield strength: 400 MPa × 0.8 = 320 MPa). The diameter and embedment length of rods were shown in Table 1 ($\lambda = L_a/d$ represented by the slenderness ratio).

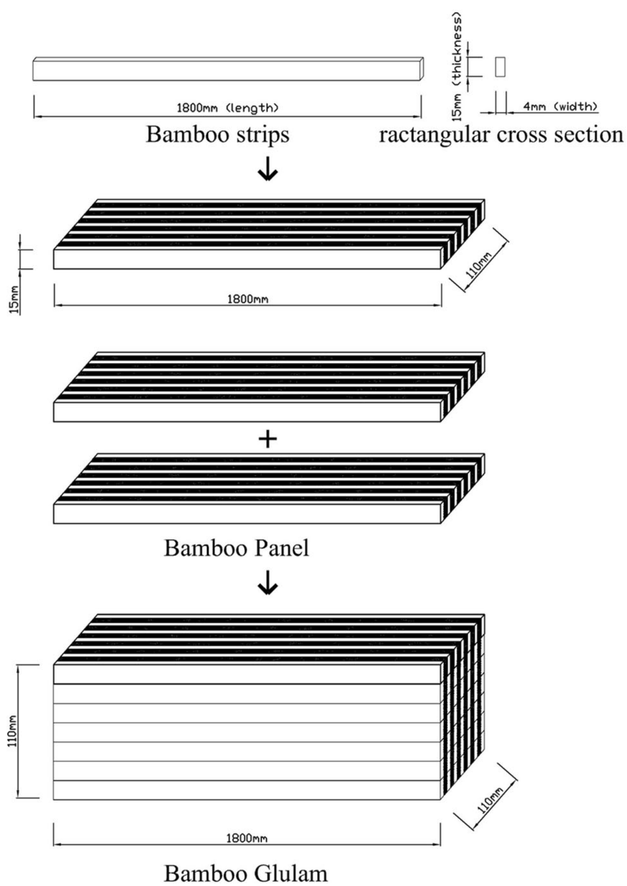

Fig. 1 Process of laminated bamboo glulam

Phenol–formaldehyde resin (PF) (Model 16L511) and polyurethane (Model PURBOND HB S709) were used to manufacture bamboo glulam which were purchased from Beijing DYNEA Chemical Industry Co. Ltd. The solid content and the viscosity of PF were, respectively, 49 % (3 g/135 °C/1 h) and 20–40 cP (at the temperature of 25 °C). And those of polyurethane were respectively 100 % and 24,000 MPa s. Fast-curing two-component epoxy resin (E-51) was used for glued-in rods which was supplied by Shanghai KAIPING resin Chemical Co. Ltd. The epoxy resin consisted of epoxy resin (epoxy equivalent weight of 184.3 g/eq) and amine curing agent, with a weight ratio of 4–1.

Sample preparation

1st—bamboo strips [1800 mm (length) × 15 mm (thickness) × 4 mm (width)] were impregnated into PF resin for 2 h, after air dried they were hot pressed to oriented panels.

2nd—the panels were cut and polished to regular panels in dimension of 15 mm × 110 mm × 1800 mm.

3rd—the panels were laminated to bamboo glulam (similar as typical LVL or solid wood boards to glulam) of in size of 110 mm × 110 mm × 1800 mm (Fig. 1). Every single specimen was cut from glued-laminated with a desired dimension respectively.

The holes for the rods were drilled using standard spiral bits. Its diameter *d*/*D* was 4 mm larger than the outer diameter of the rods. Epoxy resin was poured into the hole firstly, then the rebar was inserted slowly. At the same time, epoxy resin was pushed up and drained away air pocket [11]. The rebar was fixed at the centre of the hole (Fig. 2a). Aging time was 7 days.

Experimental method

The pullout tests were performed according to ASTM D1761-88 “Standard Test Methods for Mechanical Fasteners in Wood” [18]. Tensile tester (MTS810, USA, as shown in Fig. 2b) was equipped with a load cell with a capacity of 250 kN. The displacement rate was 1 mm/min. The nominal bond shear strength (f_v) was obtained by the following equation:

$$f_v = \frac{F}{S} \tag{1}$$

$$S = L_a \times \pi \times d_a \tag{2}$$

Table 1 Geometric properties and failure mode of specimens

Specimen code	Rod diameter, d_a (mm)	Rod effective stress cross sections (mm^2)	Rod embedded depth, L_a (mm)	λ	S (mm^2)	Number of specimens	Failure mode		Nominal bond shear strength, f_v (MPa)	F_{avg} (kN)
							Yield	Pull out		
8–1	8	35.77	40	5	1507.2	8	8	0	6.74	10.16
8–2	8		80	10	3014.4	8	8	0	3.25	9.8
8–3	8		120	15	4521.6	8	8	0	2.16	9.77
8–4	8		160	20	6028.8	8	8	0	1.59	9.59
12–1	12	82.47	60	5	3014.4	8	6	2	10.18	30.69
12–2	12		120	10	6028.8	8	8	0	5.11	30.83
12–3	12		180	15	9043.2	8	8	0	3.57	32.24
12–4	12		240	20	12057.6	8	8	0	2.45	29.6
16–1	16	153.86	80	5	5024	8	0	8	10.54	52.93
16–2	16		160	10	10048	8	8	0	5.56	55.89
16–3	16		240	15	15072	8	8	0	4.03	60.69
16–4	16		320	20	20096	8	8	0	3.03	60.96

where F is the pullout peak load; S is the gluing area; L_a is rod embedded depth; and d_a is the diameter of hole for rod after tests.

Results and discussion

The failure modes and the shear strength

At different rod diameters and ratios of length to diameter (λ), the typical pullout test curves and the statistical results are shown in Fig. 3 and Table 1. As the statistical results of failure mode in Table 1, there were two main failure modes in tests: threaded rod tensile fracture and threaded rod pullout. In threaded rod tensile fracture mode, rod necking and tensile fracture of the threaded rod were also found. However, in threaded rod pullout fracture mode, interface shear failure of the bamboo glulam around the anchoring zone of the threaded rod happened.

Failure modes were different in M8, M12 and M16. According to the failure mode statistical results in Table 1, when it was M8($5 \le \lambda \le 20$), only the threaded rod tensile fracture mode occurred and the peak load of series M8 had no difference which was due to the peak load of the metal material. When it was M12($\lambda = 5$), both of threaded rod pullout failure and threaded rod tensile fracture happened, and the number of specimens was, respectively, 2 and 6. The $F_{avg(M12,\ \lambda = 5)} = 30.69$ kN, $f_{v(M12,\ \lambda = 5)} = 10.18$ MPa. When it was M12($10 \le \lambda \le 20$), the failure mode of specimens was threaded rod tensile fracture. But the peak load of M12($10 \le \lambda \le 20$) was similar to specimens M12($\lambda = 5$), which was due to the stable peak load of the metal material was relatively. When it was M16($\lambda = 5$), the failure mode was threaded rod pullout failure, and the $F_{avg(M16,\ \lambda = 5)} = 52.93$ kN, $f_{v(M16,\ \lambda = 5)} = 10.54$ MPa. However, when M16($\lambda = 10$), the failure mode was threaded rod tensile fracture, and the peak load of the specimens M16($10 \le \lambda \le 20$) was greater than that of M16($\lambda = 5$).

The effect of the ratio of length to diameter of the threaded rod embedded in bamboo glulam on pullout strength

When the rods were in the same slenderness ratio λ but different threaded rod diameters d, the influence of the threaded rod diameter d on peak load was analyzed. As Fig. 3 showed that the peak load increased with threaded rod diameters. When $\lambda = 5$, as threaded rod diameters increasing, the failure mode of three series samples (M8, M12, M16) changed from threaded rod tensile fracture to pull out fracture. However, when $\lambda \ge 10$, the failure mode of three series samples (M8, M12, M16) was same which was threaded rod tensile fracture (Table 1). Therefore, to satisfy the utilization of glued threaded rods connection bamboo glulam in engineering and structure, $\lambda \ge 10$ was very necessary.

With the same diameter conditions, the peak load of M16 series samples increased with λ. Moreover, the peak loads was the limit load of metal rods and remained stable when the threaded rod tensile failure. And in the same way, the peak load of M8 and M12 series increased with λ.

As shown in Table 1, f_v decreased with increasing λ due to the increasing gluing area S. The value $f_v = 10$ MPa was a cut-off point of the fracture modes. When $f_v < 10$ MPa, the fracture mode was the threaded rod tensile failure; but, when $f_v > 10$ MPa, the fracture mode was pull-out of

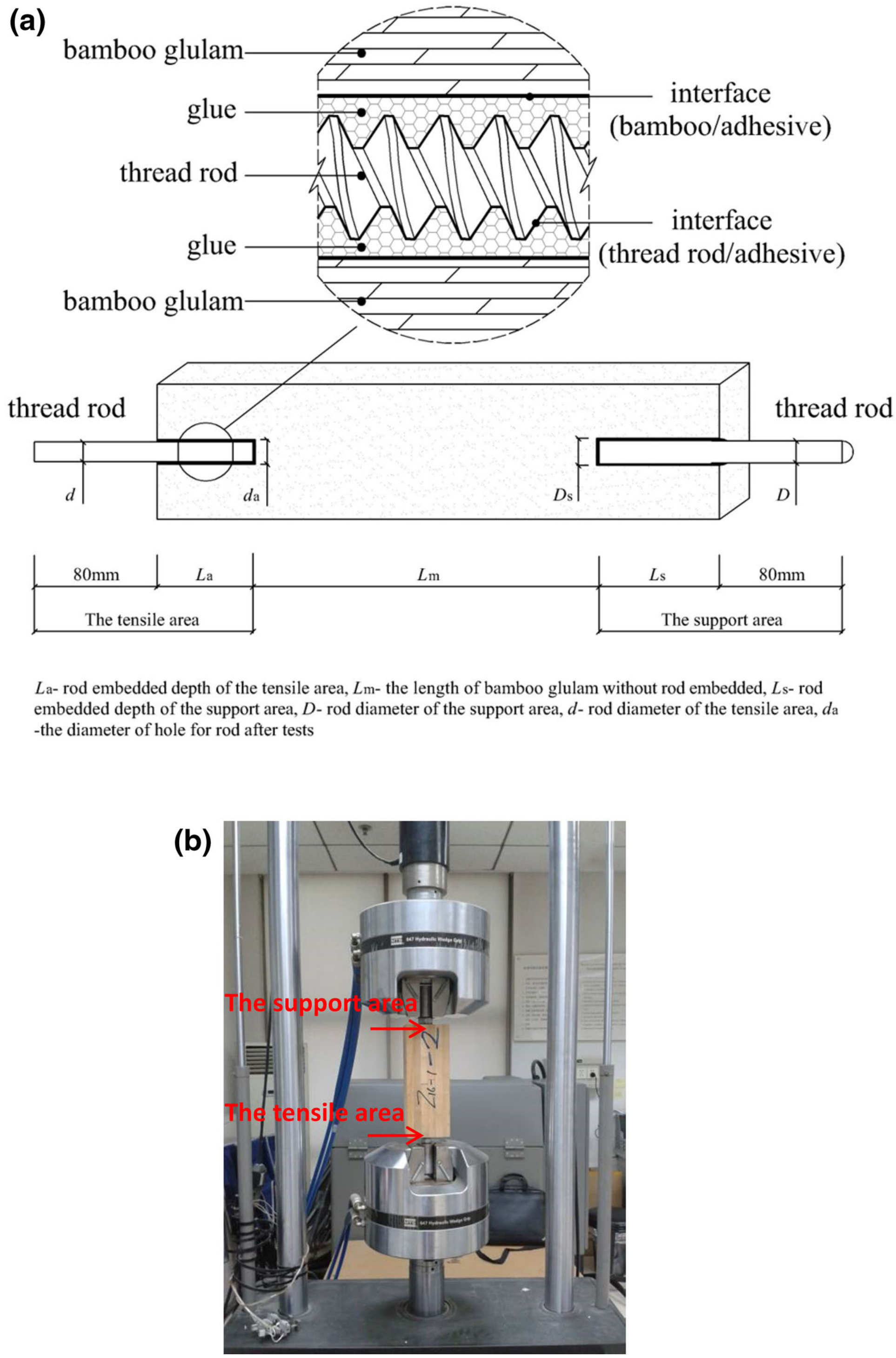

Fig. 2 **a** Schematic of sample and the key parameters. **b** Schematic of longitudinal tensile test

threaded rod and the glue-bamboo glulam interface fracture.

The tensile mechanism of glued-in rods

Glued-in rod connection strength is determined by two different interfaces: one is the interface between glue and threaded rods which is enhanced by the increasing contacting area; and the other is the interface between base materials and inherent bonding (Fig. 2a).When the glued-in rods are strong enough, the interface is critical to the connection strength. In terms of bamboo glulam, the glued rods with λ should be above the critical ratio.

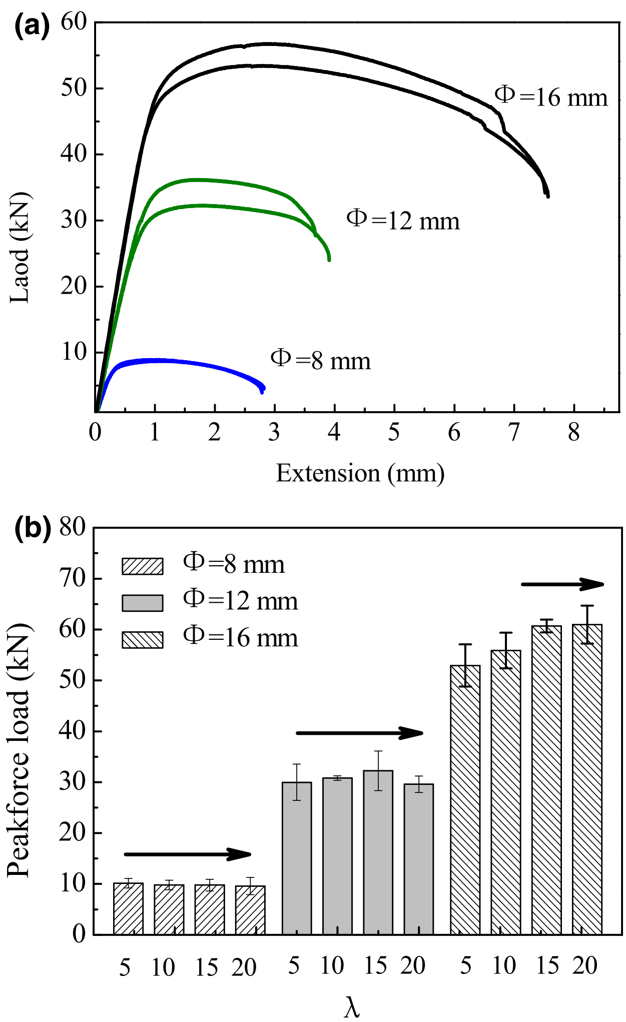

Fig. 3 Typical pullout test curves and statistical figures at different rob diameters (Φ) and ratios of length to diameter (λ). **a** Typical pullout test curves at different rob diameters (Φ) and ratios of length to diameter (λ). **b** Typical pullout statistical figures at different rob diameters (Φ) and ratios of length to diameter (λ)

The normal shear strength of threaded rod glued-in bamboo glulam was completely determined by the shear strength of interface between glue and materials, which was caused mainly by the poor permeability of glue into the bamboo. A typical threaded rod pullout curve was presented in Fig. 4. And a representative surface morphology of threaded rods pull out from bamboo glulam was showed in Fig. 5a. The interfacial failure between glue and base materials is found in Fig. 5a. Instead, the interface between glue and threaded rods kept intact. Therefore, enhancing the contacting surface roughness and permeability to increase the contacting area between glue and base materials could be an efficient way to improve the connection strength.

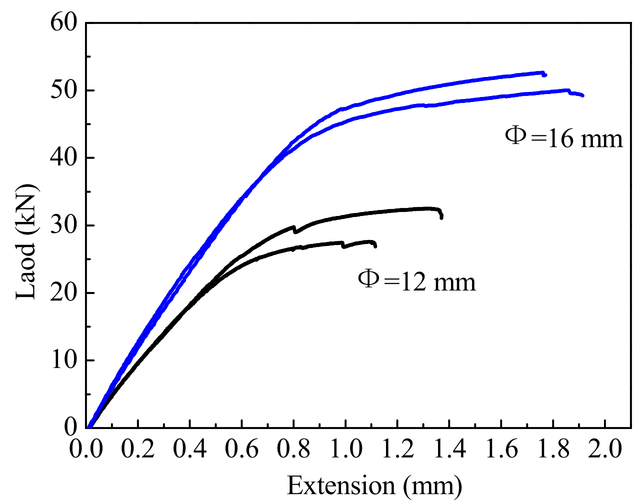

Fig. 4 The typical threaded rod pullout curves

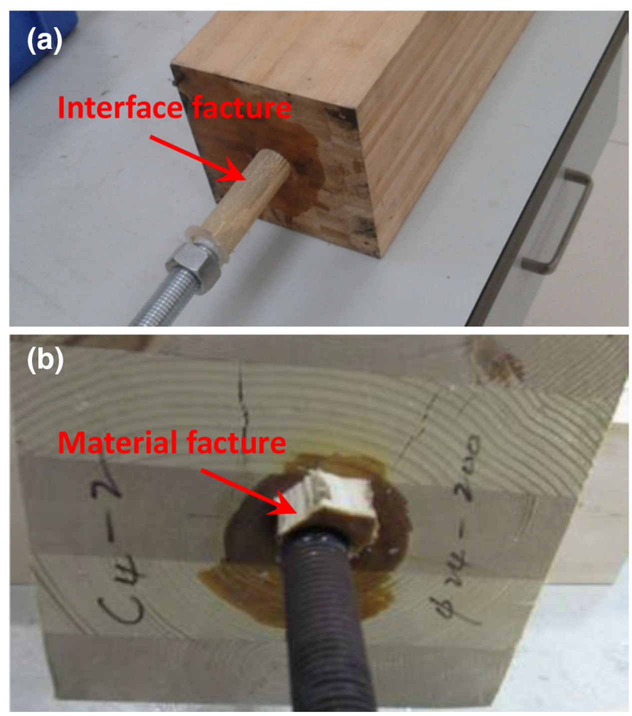

Fig. 5 **a** The typical surface morphology of threaded rods pull out from bamboo glulam. **b** The typical surface morphology of threaded rods pull out from glulam

Comparison of ultimate pull-out strength and failure mode between the wood connection and bamboo connection

Figure 5a, b showed the different pullout failure modes of bamboo-base materials and wood-base materials. The failure manner of wood was the material fracture which

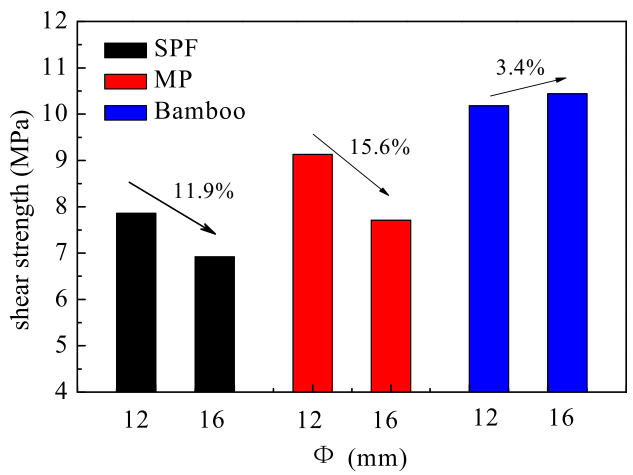

Fig. 6 The normal interfacial shear strength between different matrix materials and the adhesive

was different from bamboo glulam failure in resin–bamboo interface. Therefore, the mechanical performances of the glued-in rod materials are mainly determined by the base materials.

The normal interfacial shear strength between bamboo glulam and the adhesive is, respectively, 10.18 and 10.54 MPa at different diameters of threaded rods (M12, M16) with the same ratio of length to diameter ($\lambda = 5$), which is higher than those of SPF (Spruce-pine-fir), MP (Masson pine) and the adhesives. Besides, the interfacial shear strength between bamboo glulam and the adhesive slightly increases with the rise of the diameter and the embedded length of the glued-in threaded rods, contrary to those of SPF and MP (as shown in Fig. 6). It could be partly explained by the excellent tensile strength parallel to grain of bamboo (216.7 MPa) [17], which is far higher than those of SPF (124.4 MPa) and MP (111.3 MPa) [16].

Conclusion

By carrying out both-end pullout tests on glued-in threaded rods in bamboo glulam, the effects of depth and diameter of embedded rods in bamboo glulam on the pullout strength and the failure modes were significant, which provide an efficient way to study connection strength of glued-in threaded rods in bamboo glulam. The conclusions are as follows:

- There are two different failure modes (threaded rod tensile fracture and threaded rod pullout fracture) for glued-in rods on connection strength of bamboo glulam. In threaded rod tensile fracture mode, rod necking and tensile fracture of the threaded rod also were found. However, in threaded rod pullout fracture mode, interface shear failure of the bamboo glulam around the anchoring zone of the threaded rod happened. The mechanical performances and the failure modes of the glued-in rod materials are mainly influenced by the inherent base materials.
- The normal shear strength (f_v) of threaded rod glued-in bamboo glulam is completely determined by the interfacial shear strength between glue and materials. Therefore, an efficient way to improve connection strength is to increase the contacting area between glue and base materials.
- For the interface stability and base material transfer load to the metal, the quality 4.8 threaded rods with $\lambda \geq 10$ is propitious to bamboo glulam.

Acknowledgments The authors are grateful for the financial support of the Fundamental Research Funds for the International Center for Bamboo and Rattan (No. 1632015013 and No. 1632011002) for financially supporting this research.

References

1. Jiang Z (2007) Bamboo and rattan in the world. China Forestry Publishing House, Beijing, pp 3–5
2. Jiang Z, Wang H, Tian G, Liu X, Yu Y (2012) Sensitivity of several selected mechanical properties of moso bamboo to moisture content change under the fiber saturation point. Bioresources 7(4):5048–5058
3. Zhang B, Liu Z (2010) Study on bamboo buildings of bamboo-wood cup joints with wooden tenon-mortise joints. J Jiamusi Univ Nat Sci Ed 31(4):490
4. Johnsson H, Stehn L (2004) Plug shear failure in nailed timber connections. Eur J Wood Prod 62(6):455–464
5. Foces A, Garrido JA, Moreno (2006) A finite element model for beam to column bolted connections with semi rigid behaviour. III European conference on computational mechanics solids, Lisbon, June 5–8 2006, p 112
6. Cointe A, Rouger F (2005) Improving the evaluation of multiple-dowel-type connection strength. Wood Sci Technol 39(4):259–268
7. Jensen JL, Sasaki T, Koizumi A (2002) Plywood frame corner joints with glued-in hardwood dowels. J Wood Sci 48:289–294
8. Jensen JL, Koizumi A, Sasaki T, Tamura Y, Lijima Y (2001) Axially loaded glued-in hardwood dowels. Wood Sci Technol 35:73–83
9. Jensen JL, Gustafsson PJ (2004) Shear strength of beam splice joints with glued-in rod. J Wood Sci 50:123–129
10. Pedersen MU, Clorius CO, Damkilde L (1999) Strength of glued-in bolts after full scale loading. J Perform Conste Facil 13:107–113
11. Wiktor R (1994) Glulam connections using epoxy glued-in rebars. A thesis submitted in partial fulfillment of requirements for the degree of master of applied science, The University of British Columbia, Vancouver, p 20
12. Madhoushi M, Ansell MP (2008) Behaviour of timber connections using glued-in GFRP rods under fatigue loading. Part II: Moment-resisting connections. Composites Part B 39:249–257
13. Turkowskij S (1991) Prefabricated joints of timber structure on inclined glued-in bars. Proceeding of the international timber engineering conference, TRADA, London, pp 212–217

14. Riberholt H (1986) Glued bolts in glulam. Department of Structure Engineering, Technical University of Denmark, series R, number 210
15. Riberholt H (1988) Glued bolts in glulam. International Conical for Building Research Studies and Documentation Working Commission W18-Timber Structures Meeting 21, Vancouver, paper 21-7-2
16. Nie Y (2012) Study on pull-out strength and behavior of glulam glued-in rods. Doctoral dissertation, International Center for Bamboo and Rattan, Beijing
17. Liu Y, Gui R, Yu Y, Chen C, Fang W (2008) A preliminary study on the physical and mechanical properties of different provenances of moso bamboo. J Bamboo Res 27(1):50–54
18. ASTM D1761-88 (1998) Standard test methods for mechanical fasteners in wood. ASTM International, West Conshohocken