



**HAL**  
open science

## Load-carrying capacity of timber joints with multiple glued-in steel rods loaded parallel to grain

Bo-Han Xu, Dong-Feng Li, Yan-Hua Zhao, Abdelhamid Bouchaïr

► **To cite this version:**

Bo-Han Xu, Dong-Feng Li, Yan-Hua Zhao, Abdelhamid Bouchaïr. Load-carrying capacity of timber joints with multiple glued-in steel rods loaded parallel to grain. *Engineering Structures*, 2020, 225, pp.111302. 10.1016/j.engstruct.2020.111302 . hal-04545467

**HAL Id: hal-04545467**

**<https://hal.science/hal-04545467>**

Submitted on 25 Apr 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial - NoDerivatives 4.0 International License

# **Load-carrying capacity of timber joints with multiple glued-in steel rods loaded parallel to grain**

Bo-Han Xu<sup>1</sup>; Dong-Feng Li<sup>2</sup>; Yan-Hua Zhao<sup>3</sup>; Abdelhamid Bouchair<sup>4</sup>

<sup>1</sup> Associate Professor, Dalian University of Technology, State Key Laboratory of Coastal and Offshore Engineering, Ocean Engineering Joint Research Center of DUT-UWA, Dalian 116024, People's Republic of China (corresponding author). E-mail: bohanxu@dlut.edu.cn

<sup>2</sup> Master Student, Dalian University of Technology, State Key Laboratory of Coastal and Offshore Engineering, Ocean Engineering Joint Research Center of DUT-UWA, Dalian 116024, People's Republic of China. E-mail: dongfengli@mail.dlut.edu.cn

<sup>3</sup> Associate Professor, Dalian University of Technology, State Key Laboratory of Coastal and Offshore Engineering, Ocean Engineering Joint Research Center of DUT-UWA, Dalian 116024, People's Republic of China (corresponding author). E-mail: yanhuazhao@dlut.edu.cn

<sup>4</sup> Professor, Université Clermont Auvergne, CNRS, SIGMA Clermont, Institut Pascal, F-63000 Clermont-Ferrand, France. E-mail: abdelhamid.bouchair@uca.fr

## **Abstract**

The joints with glued-in steel rods are efficient joints in the design of timber structures, due to their high stiffness, strength and fire resistance. The ductile behaviour of joints can be achieved through the yielding of steel rods prior to wood failure. In practice, joints are generally with multiple rods rather than single rod. In the case of multiple

glued-in rods, the yielding of single rod is designed as primary failure by using mild steel rod, and the load-carrying capacity of joints is expected to be equal to the yield capacity of single rod multiplied by the number of rods. However, the actual pull-out capacity of single rod in timber joints with multiple glued-in rods can be less than that in timber joints with single glued-in rod, due to the group effect of glued-in rods. Thus, the pull-out capacity of multiple rods is equal to the pull-out strength of single rod multiplied by the effective number of rods instead of the actual number of rods. It can result in the brittle failure of pull-out of rods prior to yielding of steel rods, though the yielding of single rod is designed as primary failure. Thus, it is necessary to determine the effective number of rods in the case of pull-out of rod.

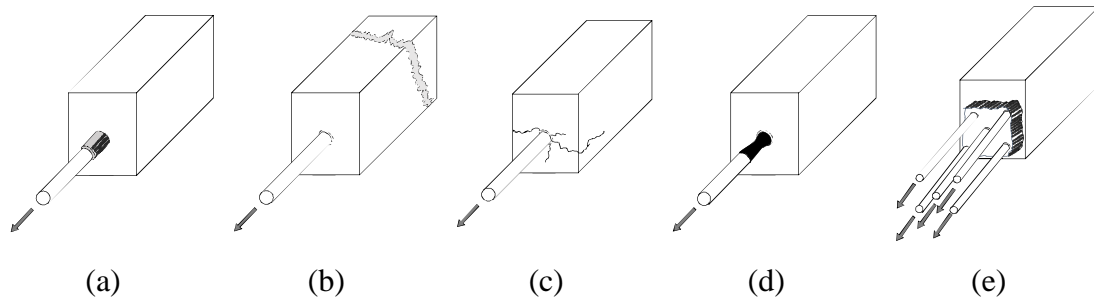
This paper presents an experimental investigation on joints composed of multiple glued-in steel rods (two and four rods with different spacing between rods) in glued-laminated timber with the pull-out failure mode. Then, the actual experimental results combined with those from literatures, are used to analyze the influence of main factors on effective number of rods. Afterwards, based on the diameter, slenderness ratio of rods, number of rods and rod spacing to rod diameter, an empirical expression of effective number of rods is derived. Finally, a model of load-carrying capacity for timber joints with multiple glued-in rods is proposed

**Keywords:** Glued-in rods; spacing between rods; group effect; effective number; load-carrying capacity.

## **Introduction**

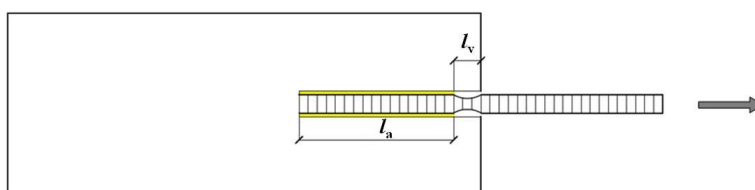
Timber joints with glued-in rods are stiff and high-capacity connections, which can be used for column foundations, moment-resisting connections in beams (Madhoushi and Ansell 2008; Xu et al. 2012) and frame corners (Bainbridge et al. 2002; Fragiaco and Batchelar 2011), as well as for strengthening structural elements loaded in the direction perpendicular to grain (Fueyo et al. 2010). In all cases, multiple rods are generally needed.

At present, the majority of the studies are focused on axial pull-out strength of a single glued-in rod (Tlustochowicz et al. 2011). There are four failure modes observed for timber joints with a single rod, such as pull-out of the rod caused by wood shear failure, tensile failure of the wood member, splitting of wood and yielding of the rod (Fig.1a-d). The splitting of wood is expected to be avoided by restricting the minimal edge distances  $e$ . Two and a half times the diameter of the rod ( $2.5d$ ) has been widely adopted as the minimal edge distances in the literatures (Blab and Laskewitz 1999; CEN 2003; Faye et al. 2004; DIN 2008). However, the splitting of wood may still occur when the requirement of minimal edge is met (Yeboah et al 2011), and it is considered more likely to be due to an imperfect axial loading than to a particular failure mode (Gardelle and Morlier 2007).



**Fig. 1.** Observed failure modes for timber joints with glued-in rods: (a) pull-out of the rod; (b) tensile failure; (c) splitting failure, (d) yielding of the rod, (e) shear block failure

The GSA-system (Fig. 2) is an efficient method to prevent early splitting of wood by removing the thread of rod within the length  $l_v$ , which leads to a shift of the anchoring zone to the interior of the wood (Widmann et al. 2007). It is an alternative way to achieve ductile behavior of the connection, where steel plasticization is assured by necking down the rods in high stress areas.

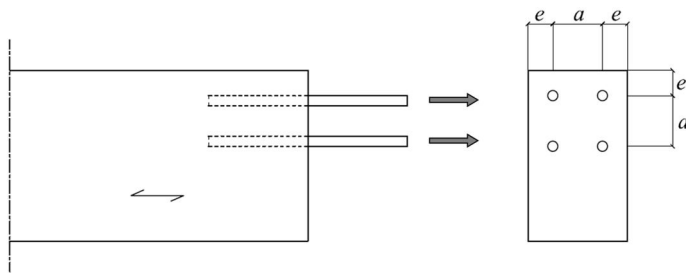


**Fig. 2.** GSA -system

It is easy to calculate the axial resistance in tension for a single rod corresponding to tensile failure of the wood member and yielding of the rod. However, there are still

no consensus on the design criteria for the axial pull-out strength of a single glued-in rod, which depends on various material and/or geometrical parameters, such as anchorage length  $l_a$  (Steiger and Gehri 2007; Rossignon et Espion 2008; Nie 2012; Ling et al. 2014), diameter of the rod  $d$  (Broughton et al. 2001; Gardelle and Morlier 2007; Otero Chans et al. 2009; Yan et al. 2016), glue-line thickness  $t$  (Otero Chans et al. 2010; Nie 2012) and density of wood  $\rho$  (Serrano 2001; Otero Chans et al. 2010; Konnerth et al. 2016), as well as adhesive type and wood species (Harvey and Ansell 2000).

Timber joints with single rod are not common in practice. For multiple glued-in rods, in addition to the four failure modes above mentioned, a shear block failure (Fig. 1e) can be observed. It is due to the insufficient wood volume around the rods that depends on the rod spacing ( $a$ ) (Broughton and Hutchinson 2001). Different values of minimum rod spacing ( $a$ ) for glued-in parallel to grain (Fig. 3) have been proposed:  $2d$  (Johansson 1995),  $3d$  (Faye et al. 2004),  $4d$  (CEN 2001) and  $5d$  (DIN 2008). To obtain a stress distribution as uniform as possible in the rods and the timber part, the axial stiffness of timber and rods needs to be equivalent (i.e.  $E_{\text{Timber}}A_{\text{Timber}}=E_{\text{Rod}}A_{\text{Rod}}$ , that gives, in case of steel rods,  $A_{\text{Timber}}\approx 16-20A_{\text{Steel}}$ ). It implies that rod spacing should be taken as  $4d$  to  $5d$ , and edge distance should be taken as  $2.5d$  (Steiger et al. 2015).



**Fig. 3.** Spacing and distance for axially loaded rods glued-in parallel to the grain

Ductility is an important requirement in timber structure design (Jorissen and Fragiaco 2011). Timber is a material inherently brittle in bending and in tension, ductile behavior of glued-in rod connections can most effectively be achieved through the yielding of steel rods as primary failure (Parida et al. 2013). However, in timber joints with multiple glued-in rods, pull-out of the rod and splitting of wood could still be the primary failure, although the yielding of a single rod is designed as primary failure (Parida et al. 2013; Gonzalez et al. 2016). It might be because of an uneven load

distribution and stress interferences between the rods, which is considered as group effect. Therefore, in order to ensure yielding of rods as primary failure in design, it's necessary to determine the pull-out capacity of multiple rods, which is less than the number of rods ( $n$ ) multiplied by pull-out capacity of a single rod.

At present, most investigations focused on single glued-in rod rather than multiple glued-in rods. Within the available literatures, a few of available experimental results on the timber joints with multiple glued-in rods have been summarized in Table 1. However, there are few investigations on predicting the pull-out of multiple glued-in rods. New Zealand Timber Design Guide (Timber Industry Federation Inc 2007) provides a reduction factor for groups of rods: 1.0 for 2 rods in a group; 0.9 for 3 or 4 rods in a group and 0.8 for 5 or 6 rods in a group, in which the influence of spacing is not considered. Based on the reference spacing of  $5d$ , Gehri (2009) proposed a reduction factor equal to  $(a/5d)^{0.35}$  for smaller spacing, thus, an effective number of rods can be given by Eq. (1).

$$\begin{aligned}
 a \leq 5d \quad n_{ef} &= n \frac{a}{5d}^{0.35} \\
 a > 5d \quad n_{ef} &= n
 \end{aligned} \tag{1}$$

**Table 1.** Summary of available experimental results from the literatures

Reference	$d$ (mm)	$t$ (mm)	$a$	$l_a$	$n$	Failure mode for single rod
Blaß et al. (1999)	16	0.5	-	20d	1	Pull-out of rod
			2.5d		2	Splitting of timber
			1.5d		2	
			2d, 2.5d, 3d, 3.75d		3	

Nie (2012)	8	2	-	15d	1	Rod tensile failure
	8		2d, 3d, 4d, 5d, 6d, 7d, 8d		2, 4	Pull-out of rod, rod tensile failure
	12		-		1	Pull-out of rod
	12		2d, 3d, 4d, 5d		2, 4	Pull-out of rod, splitting of timber
	16		-		1	Pull-out of rod
	16		2d, 3d, 4d, 5d		2	Pull-out of rod, splitting of timber
Gonzalez et al. (2016)	12.7	2	-	5d, 7.5d	1	Pull-out of rod
			-	10d, 15d	1	Rod yielding
			3d, 4d, 5d	5d, 7.5d 10d, 15d	2, 3, 4	Pull-out of rod, splitting of timber, rod yielding

Due to the lack of experimental results for greater distance between rods such as  $6d$ , in the case of pull-out of single rod as primary failure. This paper firstly describes experimental investigation on timber joints with multiple glued-in steel rods with the different rod spacing ( $4d$ ,  $5d$  and  $6d$ ) as a supplement to the current literatures. High quality steel threaded rods were used in order to promote pull-out of rod rather than rod yield. Timber joints with one, two, four rods were tested under uniaxial quasi-static tension loading. Then, using the experimental results of the present study combined with those from the literatures, the influence of rod diameter ( $d$ ), rod slenderness ( $l = l_a/d$ ), rod spacing to rod diameter ( $a/d$ ) and number of rods ( $n$ ) on effective number of rods are analyzed. The effective number is equal to pull-out capacity of multiple rods divided by pull-out capacity of a single rod. After that, an empirical formula based on main influence factors above mentioned is derived for effective number of rods in the case of pull-out of rod as primary failure. Finally, a model of load-carrying capacity for timber joints with multiple glued-in rods is proposed.

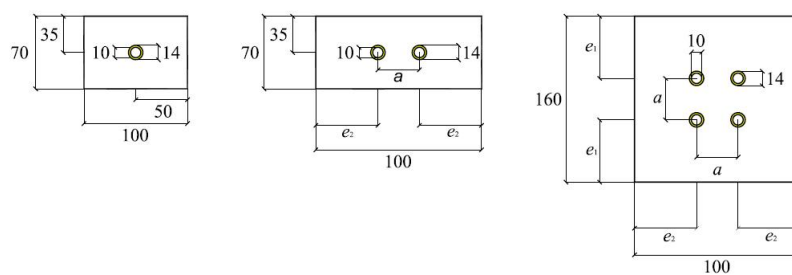
## Experimental Program

### *Specimen description*

In order to investigate the influence of rod spacing and number of rods on mechanical behaviour of timber joints with multiple glued-in rods, a total of 34 specimens of seven series were tested in tension. The parameters of test series are summarized in Table 2. The diameter of rod ( $d=10$  mm) and the anchorage length ( $l_a=10d$ ) are fixed for all the specimens. The rods were inserted into one end of the timber specimens and bolt holes were drilled into the other end to attach the specimen to a steel plate fixed to the testing machine. The geometry of specimens is shown in Fig. 4. The edge distance ( $e$ ) of at least 3.5 times the rod diameter ( $3.5 d$ ) meets the requirement of German standard (DIN 2008). For specimens with multiple rods, the rod spacing ( $a$ ) is taken equal to  $4d$ ,  $5d$  or  $6d$ .

**Table 2.** Specimen configuration and test results

Series	Number of rods $n$	Rod spacing $a$	Number of specimens	Dimension of timber member (mm)	Joint capacity	
					Average (kN)	COV (%)
1	1	0	4	520×100×70	40.06	1.37
2-4d		4d	5	520×160×70	62.68	17.56
2-5d	2	5d	5	520×160×70	69.07	10.50
2-6d		6d	5	520×160×70	70.40	9.60
4-4d		4d	5	520×160×160	91.80	15.85
4-5d	4	5d	5	520×160×160	89.14	16.33
4-6d		6d	5	520×160×160	100.26	16.90



**Fig. 4.** Geometry of specimens (dimensions in mm)



## ***Materials***

The timber member is glulam made of Mongolian Scotch pine (*Pinus sylvestris var. mongolica Litv.*) laminae bonded by water-based vinyl polyurethane adhesives. The mean density of timber member is equal to  $498 \text{ kg/m}^3$ , and the moisture content is equal to 9.6%.

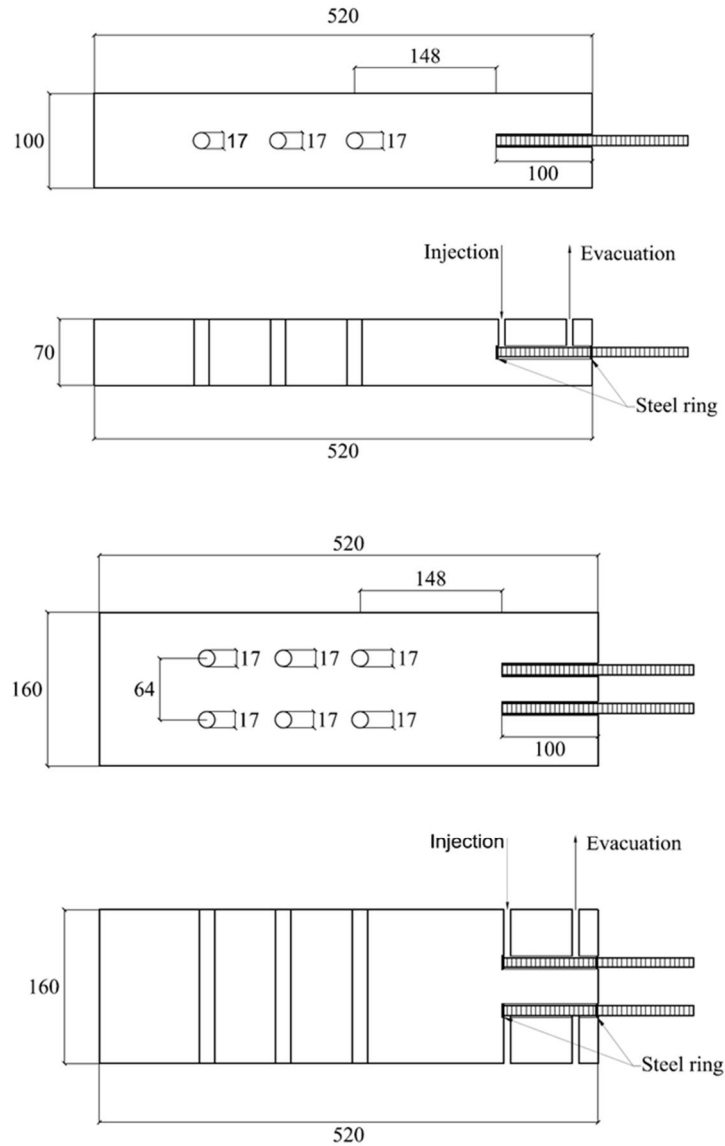
In practice, the timber joints with glued-in rods should be designed in such way that the ductile rod failure (yielding of steel rods) occurs rather than the brittle wood or adhesive failure. However, within the framework of this project, the desired failure mode of specimens tested is the pull-out of rod, which is a shear failure at the interface between the wood and the adhesive. Thus, high quality steel threaded rods were used, which correspond to strength grade 10.9 with a characteristic yield strength  $f_y = 900 \text{ N/mm}^2$  and a characteristic ultimate tensile strength  $f_u = 1000 \text{ N/mm}^2$ . In order to determine the real tensile strength of threaded steel rods, tensile test have been done on four specimens. The average yield capacity of rod is 43.0 kN, and the average ultimate capacity of rod is 46.8 kN.

Due to the good structural performance and durability, a two-component epoxy resin (HILTI HIT-RE 500) was adopted with 2% tensile elongation at break, which permits classifying the adhesive as brittle.

## ***Specimen Manufacture***

Firstly, the timber members were cut into their test dimensions from the same batch of glulam beam. Then, blind holes were drilled parallel to grain with a diameter of 14 mm, in order to maintain a glueline thickness of 2 mm. Additional holes were drilled into the other end of the specimens for attaching them to the testing apparatus using bolted connection in order to guarantee failure in the glued-in rod connection. After that, the rods were inserted into the timber member, and the adhesive was introduced through a small hole drilled close to one end of the embedment hole, perpendicular to it (Fig. 5). The other end of the embedment hole is drilled to assure the complete and even filling of the embedment hole with adhesive and removal of air bubbles. Two small circular

rings were placed into both ends of the embedment hole to center the rods. Finally, the specimens were left to cure in a constant climate room (20°C and 65% RH) for 15 days before testing.



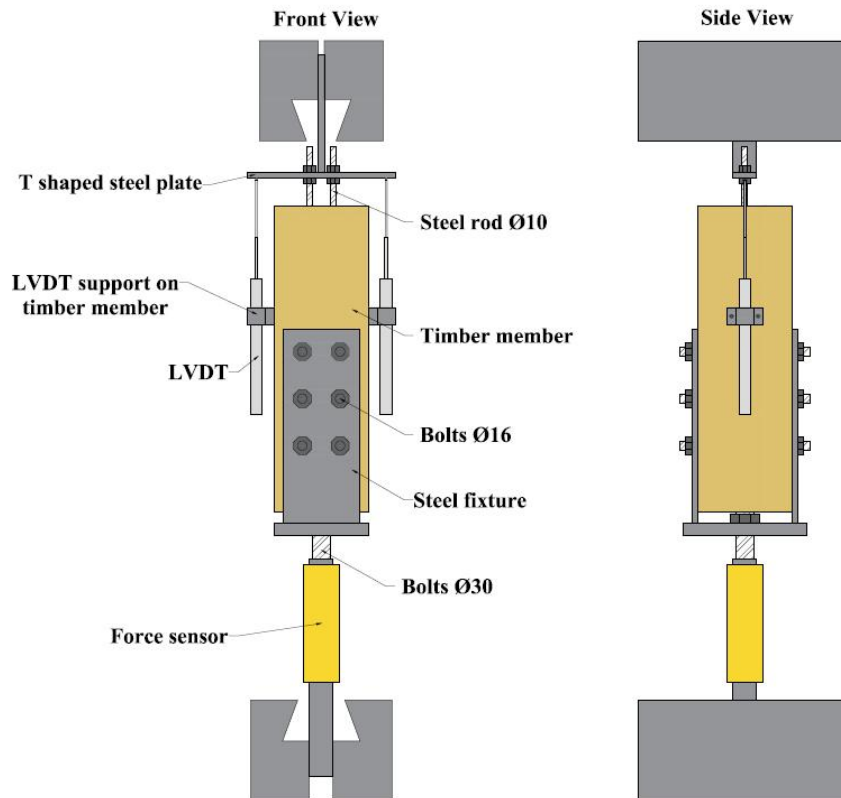
**Fig. 5.** Specimen geometry and method for gluing-in rods

### *Experimental Setup*

One end of specimen was attached, through bolts, to steel plates connected to the force sensor of the testing machine. In the other end of specimen, the rods were fixed using nuts on T shaped steel plate, which was connected to holding device of testing machine. All specimens were tested using a universal testing machine with a 1000 kN capacity

under a constant displacement rate of 2.0 mm/min. Two linear variable differential transformers (LVDTs) transducers were attached to the specimens to record the relative displacement between the rod and the timber member. The testing setup is shown in Fig. 6.





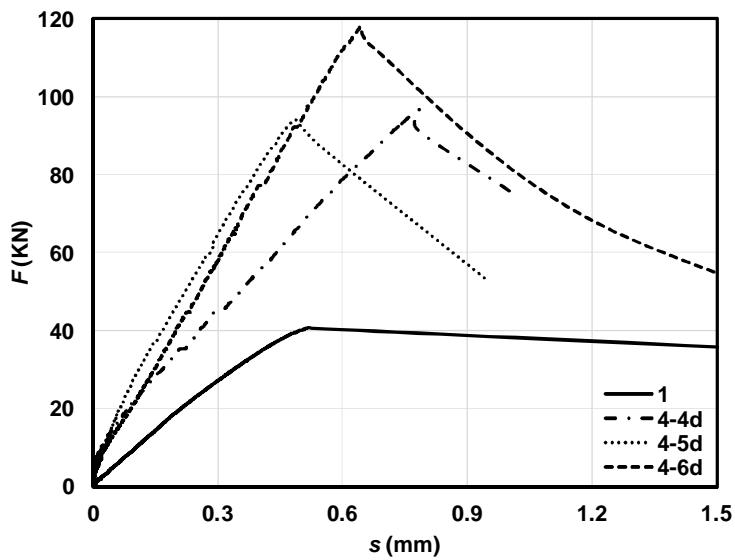
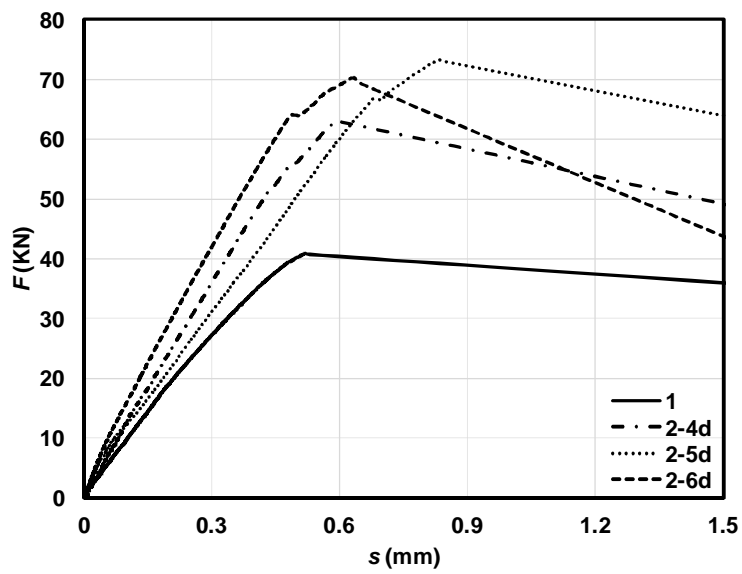
**Fig. 6.** Experimental setup

## Experimental results

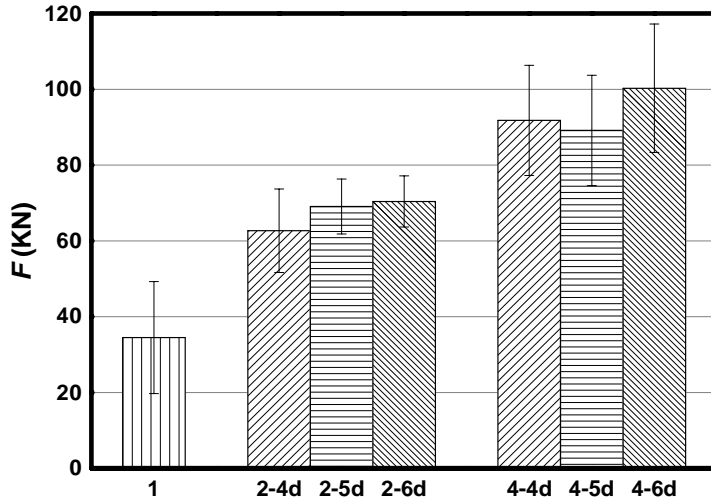
Only one failure mode was observed for all the tested specimens (single and multiple rods). It concerns the pull-out of a wood plug surrounding the individual rods as illustrated in Fig. 7. Figure 8 shows the typical load-slip curves for each series. It can be observed that the initial stiffness for joints with 4 rods, greater than those with 2 rods, is higher than 100 kN/mm. The average results and the respective coefficient of variation for joint capacity are listed in Table 1 and illustrated in Fig. 9.



**Fig. 7.** Failure of specimens



**Fig. 8.** Typical load-slip curves for each series



**Fig. 9.** Effect of number of rods and rod spacing on pull-out capacity

To evaluate the influence of the rod spacing and number of rods with regard to pull-out capacity, an analysis of variance (ANOVA) was conducted. If the significance of a test result called  $p$ -value is less than the significance level  $\alpha$  of 0.05 (Tannert et al. 2012), the result is considered statistically significant. The results are summarized in Table 3. The rod spacing has no significant differences when it varies from  $4d$  to  $6d$ , and the number of rods is statistically significant.

**Table 3.** ANOVA Summary

Factor	$p$ -value
$n$	0.014
$a$	0.293
$n' a$	0.654

## Discussion

Due to the group effect of glued-in rods, the pull-out capacity of multiple rods is less than the pull-out strength of single rod multiplied by the number of rods. The pull-out capacity of multiple rods should be considered as pull-out strength of single rod multiplied by the effective number of rods ( $n_{ef}$ ), as the effective number of fasteners for load-carrying capacity of multiple dowelled joints in Eurocode 5 (CEN 2004).

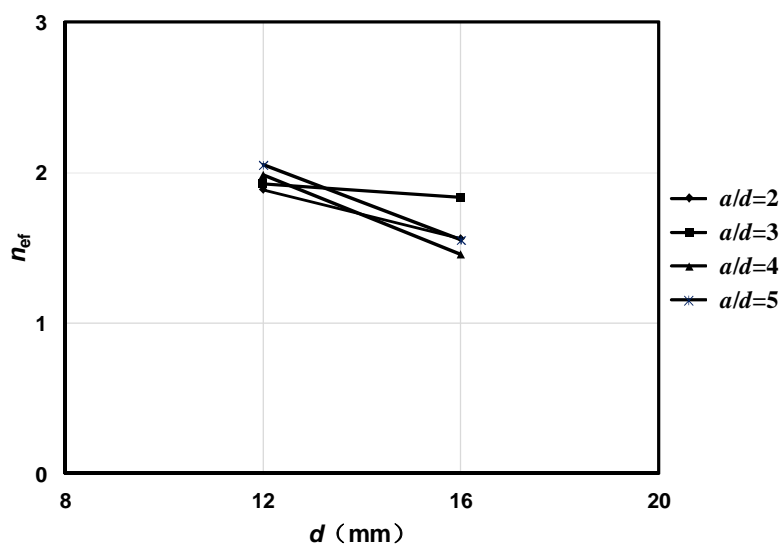
In order to determine the influence of main factors on effective number of rods,

the experimental results in this paper combined with other available experimental results from literatures were used. Figures 10-13 show the influence of diameter of rod ( $d = 10\sim 16$  mm), slenderness ratio of rod ( $l = 5\sim 20$ ), number of rods ( $n = 2\sim 4$ ) and rod spacing to rod diameter ( $a/d = 1.5\sim 6$ ).

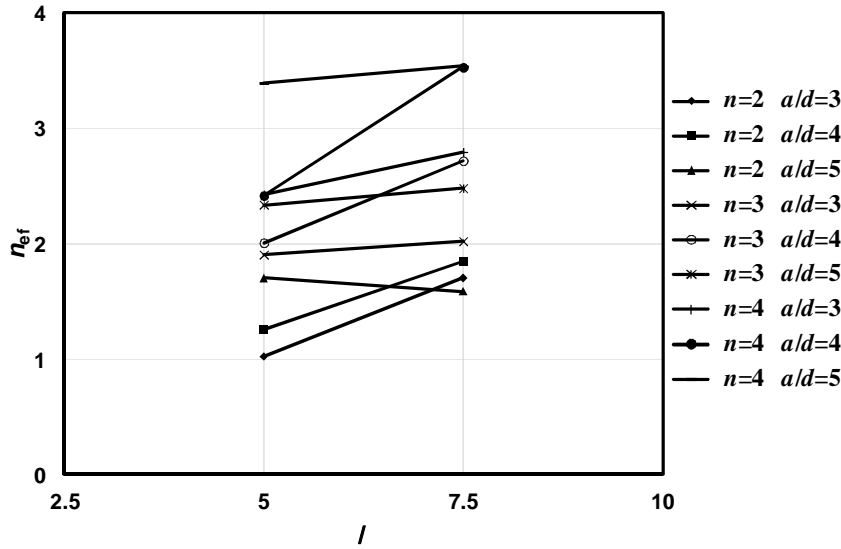
For fixed  $l = 15d$  and  $n = 2$ ; the diameter ( $d$ ) varying from 12 mm to 16 mm and the rod spacing from  $2d$  to  $5d$  (Nie 2012) influence the effective number of rods that decreases with the diameter increase (Fig. 10). For  $d = 12.7$  mm,  $a = 2d, 3d, 4d$  and  $n = 2, 3, 4$ ; and the slenderness ratio of rod ( $l$ ) varies from 5 to 7.5 (Gonzalez et al. 2016), the effective number of rods almost increases with the increase of the rod slenderness (Fig. 11).

In the German design code DIN 1052:2008-12 (DIN 2008), the minimum anchorage length is taken equal to the maximum value of  $0.5d^2$  and  $10d$ . Thus, as  $d \leq 20$  mm,  $10d$  should be adopted as minimum anchorage length. With anchorage length lower than  $10d$ , it can result in significant low pull-out strength of rod and high shear stress. In order to clearly illustrate the factors influencing the effective number of rods, the slenderness ratio of rod ( $l$ ) equal to  $10d$  is used as threshold.

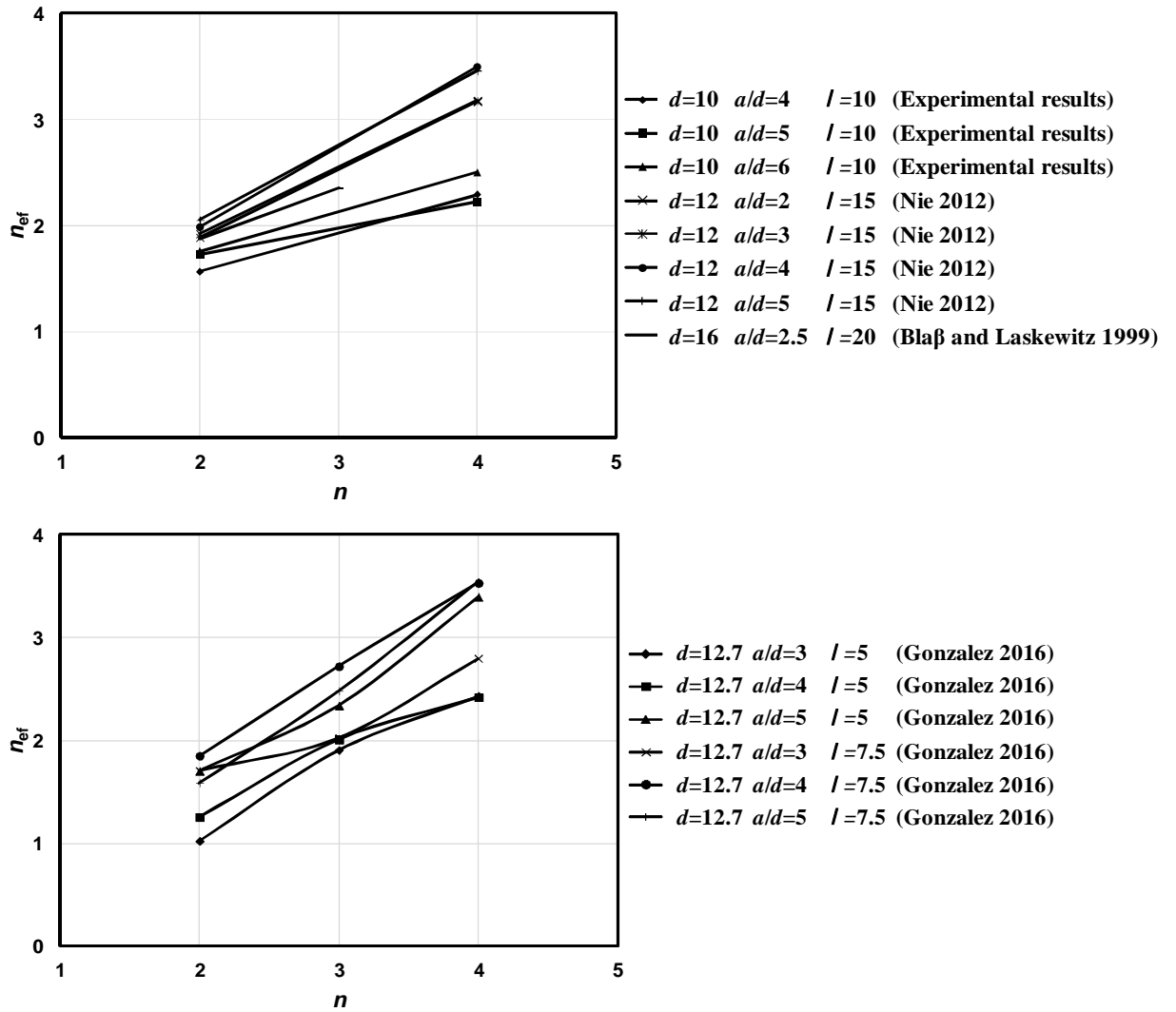
As shown in Fig. 12, the effective number of rods increases with the increase of number of rods. With the increase of the rod spacing to rod diameter ( $a/d$ ), the effective number of rods almost increases except for  $l = 7.5$  (Fig. 13).



**Fig. 10.** Effect of diameter on effective number of rods

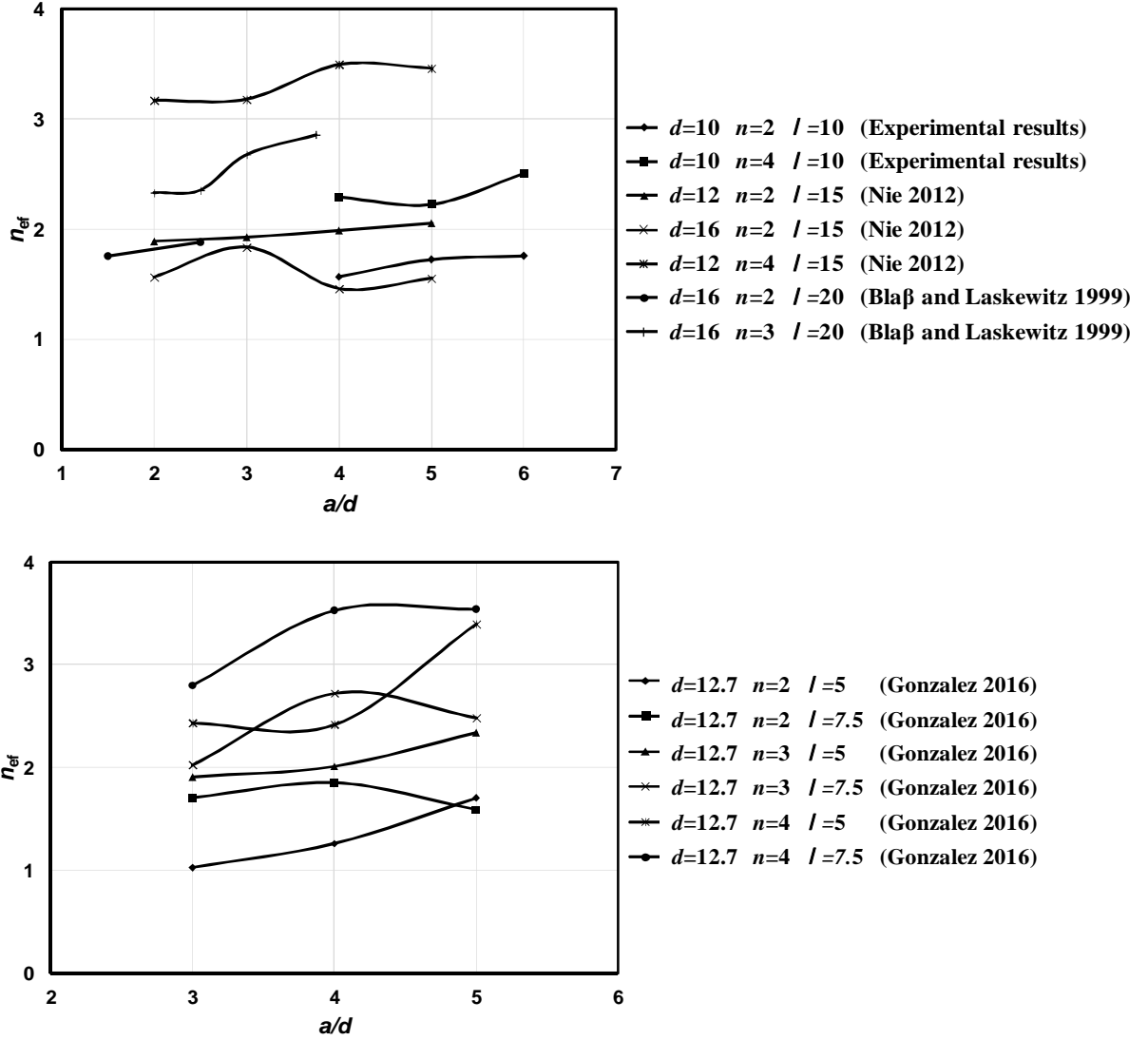


**Fig. 11.** Effect of rod slenderness on effective number of rods



**Fig. 12.** Effect of number of rods on effective number of rods





**Fig. 13.** Effect of spacing between rods to rod diameter on effective number of rods

Based on the four main factors observed hereabove, an empirical expression of effective number of rods [Eq. (2)] was proposed by data fitting with a reasonable correlation. The integral absolute error (IAE) expressed as Eq. (3) was adopted for the deviation assessment between experimental and predicted results. The effective number of rods shall be not greater than the actual number of rods, therefore, the effective number of rods can be defined in Eq. (4).

$$n_{ef} = 0.193n^{0.892}d^{0.390}l^{0.136}\frac{\pi d^2}{4}^{0.164} \quad (2)$$

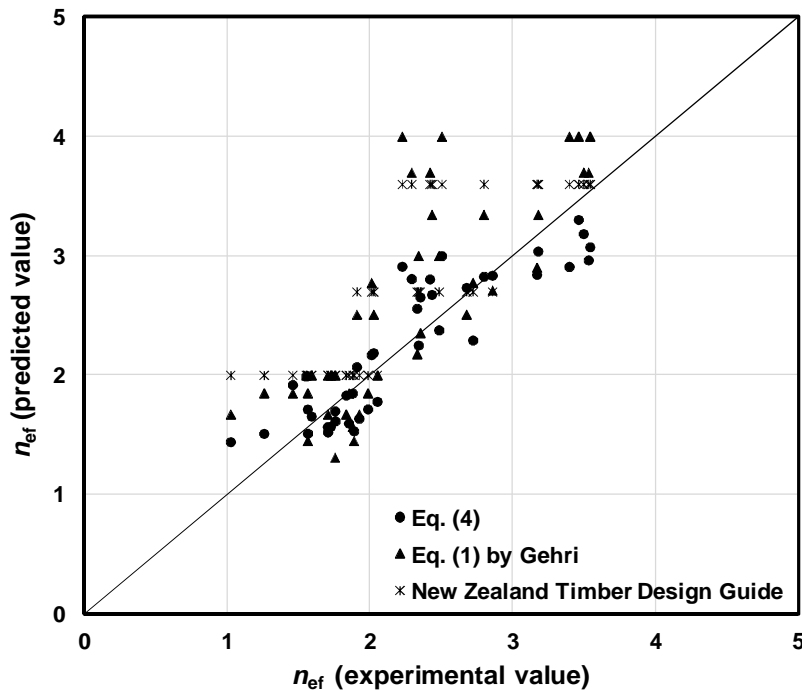
with  $R^2 = 0.764$ , IAE = 11.2%.

$$IAE = \frac{[(E_i - P_i)^2]^{1/2}}{E_i} \quad (3)$$

$E_i$  is the experimental value and  $P_i$  is the predicted value.

$$n_{ef} = \min \left\{ \begin{array}{l} n \\ 0.193n^{0.892}d^{0.390}l^{0.136} \frac{\sigma}{E_d} \frac{d}{\phi}^{0.164} \end{array} \right. \quad (4)$$

The proposed empirical expression shows better predictive ability of effective number of rods than current available predicted formulas, such as by New Zealand Timber Design Guide (Timber Industry Federation Inc, 2007) and Gehri (2009), as shown in Fig.14.



**Fig. 14** Comparison between experimental and predicted effective number of rods

The load-carrying capacity of timber joints with multiple glued-in rods can be calculated using Eq. (5)

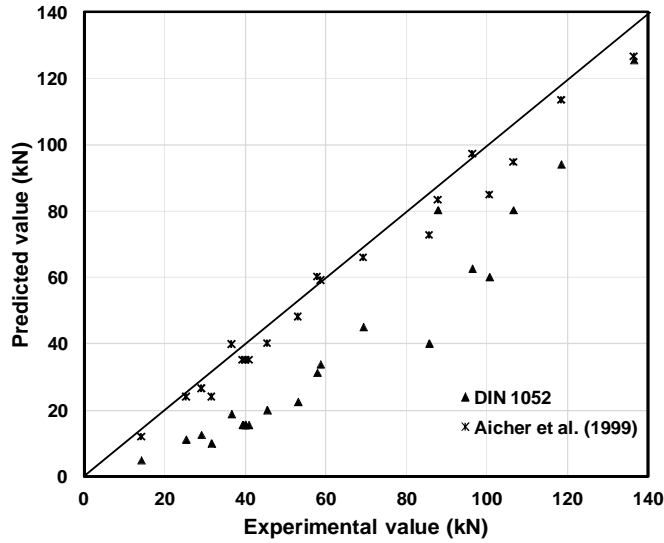
$$F = \min \left\{ \begin{array}{l} nF_y \\ n_{ef}F_p \end{array} \right. \quad (5)$$

Where  $F_y$  is yielding capacity of a single rod, which is equal to the steel yield strength multiplied by the area of the rod's cross section; and  $F_p$  is pull-out capacity of a single rod, which can be calculated using the expression [Eq. (6)] presented by Aicher et al. (1999). Their model shows a better agreement with experimental results in this paper and from available literature (Blaß1999, Nie 2012, Gonzalez et al. 2016) than German design code DIN 1052 (2008) (see Fig. 15).

$$F_p = \rho d_h l_a f_{v,\text{mean}} \quad (6)$$

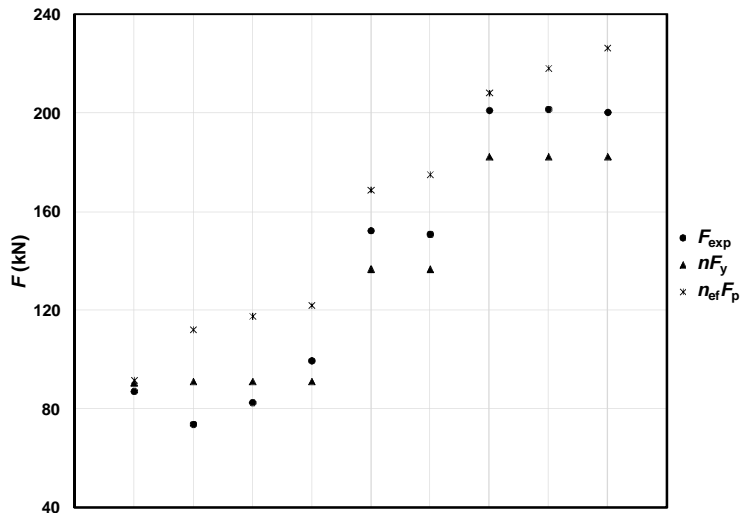
where  $d_h$  is diameter of the hole and the shear strength  $f_{v,\text{mean}}$  for brittle PUR (polyurethane) and EPX (epoxy) adhesives is given by

$$f_{v,\text{mean}} = \min \left\{ \begin{array}{l} 8 \\ 129d^{-0.52} l^{-0.62} \left(\frac{r}{480}\right)^{0.45} \end{array} \right. \quad (7)$$



**Fig. 15** Comparison between experimental and predicted results for pull-out capacity of a single rod

Figure 16 shows the load-carrying capacity of multiple rods from experimental results (Gonzalez et al. 2016) and predicted values using Eq. (5). Due to yielding capacity of multiple rods less than pull-out strength of multiple rods, the dominant failure mode is rod yielding, which is consistent with observed failure mode.



**Fig. 16** Comparison between experimental and predicted load-carrying capacity

Table 4 summarize the predicted results and experimental results (Gonzalez et al. 2016) for pull-out strength based on the design values of single rods primary failure. In fact, no rod yielding was observed in the case of multiple rods. The proposed model shows a promising predictive ability for the load-carrying capacity of multiple rods and failure modes, such as pull-out of rod and rod yielding, except for splitting failure, which is a premature failure.

**Table 4** Experimental and predicted results

$d$ (mm)	$n$	$l$	$a/d$	Experimental results			Predicted results		$\frac{F_{pre}}{F_{exp}}$	
				Failure mode	$F_{exp}$	$nF_y$	$n_{ef}F_p$	Failure mode		$F_{pre}$
12.7	2	10	3	Splitting	83.4	90.6	84.4	Pull-out	84.4	1.01
12.7	2	10	4	Pull-out	73.6	90.6	88.5	Pull-out	88.5	1.20
12.7	3	10	3	Splitting	108	135.9	121.2	Pull-out	121.2	1.12
12.7	3	10	4	Pull-out	115.8	135.9	127.0	Pull-out	127.0	1.10
12.7	3	10	5	Pull-out	112.2	135.9	131.7	Pull-out	131.7	1.17
12.7	3	15	3	Splitting	133.8	136.8	161.1	Yielding	136.8	1.02
12.7	4	10	3	Splitting	136.4	181.2	156.6	Pull-out	156.6	1.15
12.7	4	10	4	Pull-out	149.6	181.2	164.2	Pull-out	164.2	1.10
12.7	4	10	5	Pull-out	156	181.2	170.3	Pull-out	170.3	1.09

**Conclusions**

This paper firstly presented the experimental results on timber joints with multiple glued-in steel rods with different values of spacing between rods ( $4d$ ,  $5d$  and  $6d$ ). the main idea is to provide additional data complementing the current available results in the literature for greater distances between rods such as  $6d$ . In fact, the available data provides few experimental results in the case of pull-out of single rod as primary failure.

Due to the group effect, the pull-out capacity of multiple rods is less than the pull-

out strength of a single rod multiplied by number of rods. In order to obtain the pull-out capacity of multiple rods, an effective number of rods is needed, which is related to the joint geometry. Based on the experimental results of the present study and from the literatures, main influence factors were analyzed such as diameter of rod, slenderness ratio of rod, rod spacing and number of rods. An empirical formula based on main influence factors was proposed for effective number of rods in the case of pull-out of the rod as primary failure. The proposed expression shows better predictive ability than those from literatures. However, it should be noted that this expression was derived by data fitting using the experimental results with the diameter between 10 mm and 16 mm. The proposed expression needs to be further validated as it is used for rod with smaller or larger diameter.

Although the yielding of a single rod is designed as the primary failure, the pull-out failure may still occur in the case of multiple rods. The load-carrying capacity of timber joints with multiple rods should be calculated as the minimal value between yielding capacity of a single rod multiplied by the number of rods and pull-out capacity of a single rod multiplied by the effective number of rods. The proposed model in this paper has been proven to be promising capable of predicting the failure mode and load-carrying capacity for multiple rods.

## **Acknowledgments**

The authors gratefully acknowledge the support of “National Natural Science Foundation of China (No. 51878114)” and “Creative Research Groups of the National Natural Science Foundation of China (Grant No. 51421064)” and “Fundamental Research Funds for the Central Universities” (Grant No. DUT19LK48”).

## **References**

Aicher, S., Gustafsson, P. J., and Wolf, M. (1999). “Load displacement and bond strength of glued-in rods in timber influenced by adhesive, wood density, rod slenderness and diameter.” *Proc., Int. RILEM Symp. On Timber Engineering, RILEM Publications S.A.R.L., Cachan Cedex, France*, 369–378.

- Bainbridge, R. J., Mettem, C. J., and Ansell, M. P. (2002). “Bonded-in rod connections for timber structures—development of design methods and test observations.” *Int. J. Adhes. Adhes.*, 22(1), 47–59.
- Blaß, H. J., and Laskewitz, B. (1999). “Effects of spacing and edge distance on the axial strength of glued in rods.” *Proc., 32nd Meeting of the Working Commission W18-Timber Structures, CIB, Int. Council for Research and Innovation*, August, Graz, Austria, Paper No. 32-7-12.
- Broughton, J. G., and Hutchinson, A. R. (2001). “Pull-out behaviour of steel rods bonded into timber.” *Mater. Struct.*, 32(2), 100–109.
- CEN. (2001). “Eurocode 5-design of timber structures. Part 1-1: General rules and rules for buildings. Final draft” *ENV 1995-1-1*, Comité Européen de Normalisation, Brussels, Belgium.
- CEN. (2003). “Eurocode 5—design of timber structures. Part 2: Bridges. Final Project Team draft.” *ENV 1995-2*, Comité Européen de Normalisation, Brussels, Belgium.
- CEN. (2004). “Eurocode 5-design of timber structures. Part 1-1: General rules and rules for buildings.” *ENV 1995-1-1*, Comité Européen de Normalisation, Brussels, Belgium.
- DIN. (2008). “Design of timber structures. General rules and rules for buildings.” DIN 1052, Deutsches Institut für Normung, Berlin (in German).
- Faye, C., Le Magorou, L., Morlier, P., and Surleau, J. (2004). “French data concerning glued-in rods.” *Proc., 37th Meeting of the Working Commission W18—Timber Structures, CIB, Int. Council for Research and Innovation*, Edinburgh, Scotland, August, Paper No. 37-7-10.
- Feligioni, L., Lavisci, P., Duchanois, G., De Ciechi, M., and Spinelli, P. (2003). “Influence of glue rheology and joint thickness on the strength of bonded-in rods.” *Holz Roh-Werkst.*, 61(4), 281–287.
- Fragiacomo, M., and Batchelar, M. (2011). “Timber frame moment joints with glued-in steel rods. Part 1: design.” *J. Struct. Eng.*, 138(6), 789–801.
- Fueyo, J., Cabezas, J., Rubio, M., and Domínguez, M. (2010). “Reduction of perpendicular-to-grain stresses in the apex zone of curved beams using glued-in rods.” *Mater. Struct.*, 43(4), 463–474.
- Gardelle, V., and Morlier, P. (2007). “Geometric parameters which affect the sort term resistance of an axially loaded glued-in rod.” *Mater. Struct.*, 40(1), 127–138.
- Gehri (2009). “Influence of fasteners spacings on joint performance .” *Proc., 42nd Meeting of the Working Commission W18—Timber Structures, CIB, Int. Council for Research and Innovation*, Dübendorf, Switzerland, August, Paper No. 42-7-8.
- Gonzalez, E., Avez, C., Vallee, T., and Tannert, T. (2016). “Timber Joints with Multiple Glued in Steel Rods.” *J. Adhesion.*, 92(7-9), 635–651.
- Harvey, K., and Ansell, M. P. (2003). “Improved timber connections using bonded-in GFRP rods.” *Proc., 6th World Conf. on Timber Eng.*, WCTE 2000, Whistler, Canada.
- Johansson, C. J. (1995). “Glued-in bolts.” *Timber Engineering STEP 1—lecture C14.*, 1st Ed., H. J. Blass, ed., Centrum Hout, Almere, Netherlands, C14/1—C14/7.
- Jorissen, A., and Fragiaco, M. (2011). “General notes on ductility in timber

- structures.” *Eng. Struct.*, 33(11), 2987–2997.
- Konnerth, J., Kluge, M., Schweizer, G., Miljković, M., and Gindl-Altmutte, W. (2016). “Survey of selected adhesive bonding properties of nine European softwood and hardwood species.” *Eur. J. Wood. Wood. Prod.*, 74(6), 809–819.
- Ling, Z., Yang, H., Liu, W., Lu, W., Zhou, D., Wang, L. (2014). “Pull-out strength and bond behaviour of axially loaded rebar glued-in glulam.” *Constr. Build. Mater.*, 65, 440–449.
- Madhoushi, M., and Ansell, M. P. (2008). “Behaviour of timber connections using glued-in GFRP rods under fatigue loading. Part I: In-line beam to beam connections.” *Compos. Part. B. Eng.*, 39(2), 243–248.
- Nie, Y. J. (2012). “Study on pull-out strength and behavior of glulam glued-in rods.” Ph.D. thesis, Univ. of Chinese Academy of Forestry, Beijing, China.
- Otero Chans, D., Cimadevila, J. E., and Gutiérrez, E. M. (2008). “Glued joints in hardwood timber”. *Int. J. Adhes. Adhes.*, 28(8), 457–463.
- Otero Chans, D., Cimadevila, J. E., and Gutiérrez, E. M. (2009). “Influence of the geometric and material characteristics on the strength of glued joints made in chestnut timber.” *Mater. & Design.*, 30(4), 1325–1332.
- Otero Chans, D., Cimadevila, J. E., Vázquez Rodríguez, J. A., and Gutiérrez, E. M. (2010). “Influence of timber density on the axial strength of joints made with glued-in steel rods: An experimental approach.” *Int. J. Adhes. Adhes.*, 30(5), 380–385.
- Otero Chans, D., Cimadevila, J. E., and Gutiérrez, E. M. (2010). “Model for predicting the axial strength of joints made with glued-in rods in sawn timber.” *Constr. Build. Mater.*, 24(9), 1773–1778.
- Parida, G., Johnsson, H., and Fragiaco, M. (2013). “Provisions for Ductile Behavior of Timber-to-Steel Connections with Multiple Glued-In Rods.” *J. Struct. Eng.*, 139(9), 1468–1477.
- Riberholt, H. (1988). “Glued bolts in glulam - Proposal for CIB Code.” *Proc., 21st Meeting of the Working Commission W18-Timber Structures, CIB, Int. Council for Research and Innovation, Parksville, Canada, September, Paper No. CIB-W18/21-7-2.*
- Rossignon, A., and Espion, B. (2008). “Experimental assessment of the pull-out strength of single rods bonded in glulam parallel to the grain.” *Holz. Roh-Werkst.*, 66(6), 419–432.
- Serrano, E. (2001). “Glued-in rods for timber structures—an experimental study of softening behaviour.” *Mater. Struct.*, 34(4), 228–234.
- Steiger, R., Gehri, E., and Widmann, R. (2006). “Pull-out strength of axially loaded steel rods bonded in glulam parallel to the grain.” *Mater. Struct.*, 40(1), 69–78.
- Steiger, R., Serrano, E., Stepinac, M., Rajčić, V., O’Neill, C., McPolin, D., and Widmann, R. (2015). “Strengthening of timber structures with glued-in rods.” *Constr. Build. Mater.*, 97, 90–105.
- Stepinac, M., Hunger, F., Tomasi, R., Serrano, E., Rajcic, V., and Van de Kuilen, J. W. G. (2013). “Comparison of design rules for glued-in rods and design rule proposal for implementation in European standards.” *Proc., 46th Meeting of the Working*

- Commission W18-Timber Structures, CIB, Int. Council for Research and Innovation, Vancouver, Canada, August, Paper No. CIB-W18/46-7-10.*
- Tannert, T., Vallée, T., and Hehl, S. (2012). “Experimental and numerical investigations on adhesively bonded hardwood joints.’ *Int. J. Adhes. Adhes.*, 37, 65–69.
- Timber Industry Federation Inc. (2007). “New Zealand timber design guide”. Wellington, New Zealand.
- Plustochowicz, G., Serrano, E., and Steiger, R. (2011). “State-of-the-art review on timber connections with glued-in steel rods.” *Mater. Struct.*, 44(5), 997–1020.
- Xu, B., Bouchaïr, A., and Racher, P. (2012). “Analytical study and finite element modeling of timber connections with glued-in rods in bending”. *Constr. Build. Mater.*, 34, 337–345.
- Yan, Y., Liu, H., Zhang, X., Wu, H., and Yun, H. (2016). “The effect of depth and diameter of glued-in rods on pull-out connection strength of bamboo glulam.” *J. Wood. Sci.*, 62(1), 109–115.
- Yeboah, D., Taylor, S., McPolin, D., Gilfillan, R., and Gilbert, S. (2011). “Behaviour of joints with bonded-in steel bars loaded parallel to the grain of timber elements”. *Constr. Build. Mater.*, 25(5), 2312–2317.