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Effect of glue-line thickness and manufacturing defects on pull-out behavior of glued-in rods

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Abstract

Glued-in rods are offering to timber joints not only stiff and high-capacity performance but also aesthetical appearance and good fire resistance. However, there is not the uniform manufacturing process and quality control method in the literature. It's necessary to estimate the effect of possible manufacturing defects on pull-out behavior of glued-in rods. This paper presents experimental results on glued-in rods with two types of likely manufacturing defects on site: eccentric position of rod in hole and inclined setting of rod in hole. The effect of manufacturing defects was investigated with three different glue-line thickness.

Keywords: Glued-in rods, glue-line thickness, manufacturing defect, pull out strength, finite element analysis

1. Introduction

Connections with glued-in rods are made up of timber, rod and adhesive. Their mechanical behavior is not only related to the wood species, rod material and adhesive type, since different adherends may develop different bonding strength with different adhesives[1]; but also related to their geometrical parameters such as anchorage length, rod diameter, edge distance, glue-line thickness and load-to-grain load.

Though the technology of connections with glued-in rods has been developed more than 40 years, there are no design standards. It is primarily because there is still

not consistent conclusion about impact of a large number of parameters on the mechanical behavior of timber joints with glue-in rods.

In addition, the quality control in the manufacturing process is also important to guarantee a reliable performance of glued-in rods. Besides the special attention in terms of suitable curing temperature and moisture content for the adhesive, the manufacturing defects are noteworthy such as adhesive filling level, presence of voids and positioning of rod centrally in the hole [2]. However, the influence extent of manufacturing defects on performance of glued-in rods is relatively less studied.

Grunwald et al. [3] have reported the influence of adhesion defects on the capacity of adhesively bonded timber joints, in which joints with 50% amount of missing adhesion still achieve 70% amount of capacity of defect free joints. Similar results were also found for joints with glued-in rods with half the normal amount of adhesive, which resulted in decreased pull-out strength of between 20% and 39% [4]. Herefrom, the defects such as voids and lack of adhesion are less pronounced than commonly assumed by practitioners.

Gonzales et al. [5] presented that the influence of positioning defect of rod (inclined setting of rod in hole and eccentric position of rod in hole) with different anchorage length on the capacity of timber joints, in which these joints with sufficient rod anchorage (herein 10 times the rod diameter) do not exhibit a statistically significant loss of capacity, compared to defect free joints.

It should be noted that the glue-line thickness is an important parameter influencing the strength of timber joints with glued-in rods, which allows optimising the stress transfer and limiting stress concentration [6]. The larger thickness increases the net surface area of bond between rod and wood, therefore gives a more uniform stress distribution, which should lead to higher capacities. However, the current evidence back-up this conjecture. The pull-out strength slightly increases with increasing glue-line thickness in the range from 0.5 mm to 2 mm for epoxy adhesive [4]. Similar results were also found by Feligioni et al. [6], as brittle epoxy was used, the pull-out strength with 3 mm glue-line thickness is higher than that with 1 mm glue-line thickness. However, the pull-out strength with 5 mm glue-line thickness is

slightly less than with 3 mm glue-line thickness in the case of 10 mm and 12 mm rod diameter. Furthermore, their failure modes are also different, the cohesive wood failure appeared in joints with 3 mm glue-line thickness, and the cohesive glue failure appeared in joints with 5 mm glue-line thickness. Nevertheless, in the case of 14 mm rod diameter, the pull-out strength with 5 mm glue-line thickness is largest, and that with 1 mm glue-line thickness is least. Though the glue thickness shows a positive relationship with the pull-out strength for glued-in rods with ductile epoxy, the weak durability of ductile epoxy limits its application. Thus, at present a general conclusion about the influence of glue-line thickness has not been drawn.

Moreover, as rod is inclined or eccentrically positioned in hole, the rod positioning defect results in non-uniform adhesive distribution. The varying glue-line thickness around rod, particularly in the case of larger design glue-line thickness, could also mean uncertain pull-out strength and failure mode. The objective of this paper is to investigate the effect of the rod positioning defect with different design glue-line thickness on pull-out behaviour of glued-in rods.

2. Experimental investigation

2.1. Specimen description

Three groups of glued-in rods specimens were tested (Fig. 1): centric position of rod in hole (Group A), eccentric position of rod in hole (Group B) and inclined setting of rod in hole (Group C). The adhesive thickness usually varies between 0.5 mm and 3 mm, the specimens in each group were manufactured with 1 mm, 2 mm and 3 mm glue-line thickness. Therefore, there are 9 series of specimens in total and three repetitions for each series were prepared. Each series is identified by a letter and a figure, letter represents the position of rod in hole and figure represents the glue-line thickness. For example, A1 represents the specimen of Group A with 1 mm glue-line thickness.

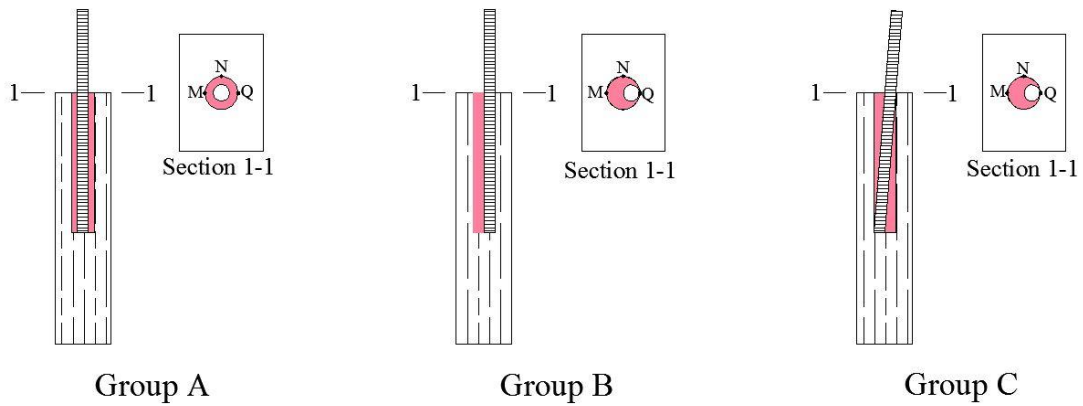


Fig. 1. Schematic diagram of test specimens

Due to the additional mechanical interlock, threaded or deformed bars are usually recommended in glued-in rod [7]. However, the deformed bars can lead to more splitting failures because their curve of the surface deformations produced more prying and wedging action [8]. Thus, the threaded rod was adopted in this study.

The threaded steel rod with nominal diameter of 10 mm was glued in glulam member with cross section of 100 mm× 70 mm. Though there are no design rules regarding the glued-in rods connection in the current version of Eurocode 5 [9], some guidance is given in some national European regulations such as the German DIN code [10]. In this work, the anchorage length is 100 mm, the edge distance and anchorage length meet the requirements of the current DIN code [10].

2.2. Materials

The glulam member was made of *Pinus sylvestris*. The measured mean density (ρ) was 495 kg/m³ and the average moisture content of timber measured in laboratory conditions before test was about 10 %. Its mechanical properties have been tested and shown in Table 1 and 2. L, R and T correspond to the parallel to grain direction, radial and tangential direction of wood, respectively. $f_{t,0}$ and $f_{t,90}$ are the tensile strengths parallel and perpendicular to grain, $f_{c,0}$ and $f_{c,90}$ are the compressive strengths parallel and perpendicular to grain, and f_v is the shear strength of timber.

Table 1

Modulus of elasticity and poisson ratio.

E_L (MPa)	$E_T=E_R$ (MPa)	$G_{LT}=G_{LR}$ (MPa)	G_{RT} (MPa)	$\nu_{LR}=\nu_{LT}$	ν_{TR}
11305	403	550	204	0.368	0.315

Table 2

Timber strength (MPa)

$f_{t,0}$	$f_{t,90}$	$f_{c,0}$	$f_{c,90}$	f_v
104.64	2.23	57.71	8.44	7.49

The high strength steel was chosen in order to avoid failure of the steel rod. Its properties are shown in Table 3.

Table 3

E (MPa)	ν	f_y (MPa)	f_u (MPa)
210000	0.3	900	1000

Compared with polyurethane (PUR) and phenol-resorcinol-formaldehyde (PRF), epoxy (EPX) adhesives develop a strong bond with both steel and wood, resulting in the wood becoming the weakest link of the joint [11]. Thus, the two-component epoxy resin (HILTI HIT-RE 500) was adopted in order to achieve wood or the wood/adhesive interface failure, which are susceptible to rod positioning defect and glue-line thickness. The properties of adhesive used in the tests are shown in Table 4.

Table 4

Mechanical properties of adhesive

E (MPa)	ν	f_v (MPa)	Elongation at break (%)
5700	0.3	15.9	2.0

2.3. Manufacturing

The timber members with a length of 450 mm were firstly cut from the same batch of lager glulam beam. Then, holes with diameter of 12 mm, 14 mm, 16 mm were drilled parallel to the grain at one end of timber members, to realize 1 mm, 2 mm, 3 mm glue-line thickness. Three additional holes with 16 mm diameter were drilled into the lower sections of the specimens to attach the specimens to the testing apparatus by steel bolts. In addition, adhesive injection hole and overflow hole were also drilled to assure the complete and even filling of the embedment hole with adhesive and removal of air bubbles, see Fig. 2.

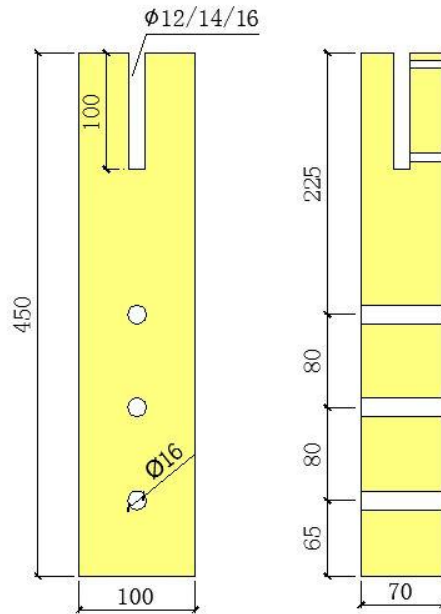


Fig. 2. Schematic diagram of bore holes

To ensure that the rod was centered in the hole of Group A specimens, the rod hole was sealed with a steel ring and the upper part of rod was fixed with a holder as shown in Fig. 3. Rods in specimens of Group B were placed completely off-set to one side of the hole by squeezing into a small rubber block between the rod and the hole. For Group C specimens, rods were placed at an angle inside the drill hole, and rods contacted with one edge of the hole by blocking a small rubber block at the top and the opposite edge of the hole by blocking a small glue droplet at the bottom. The angle to the grain is largest for the specimens with 3 mm glue-line thickness (3.4°), which results in a small but neglectable bending moment as the loads were applied parallel to the timber. All specimens were cured in a climate room with 20°C and a relative humidity of 65 % for fifteen days before testing.

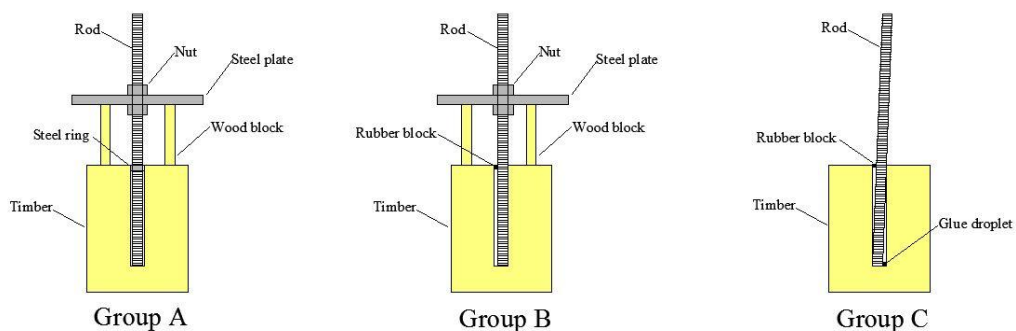


Fig. 3 Schematic diagram of auxiliary holder

2.4. Methods

Specimens were tested under the pull-pull loading at a constant rate of 2 mm/min according to the European Standard 26891 [12]. The set-up of these experiments is shown in Fig. 4. Two LVDT displacement transducers were used to measure the relative displacement between the rod and the timber. At the same time, a force sensor is used to record the bearing capacity.

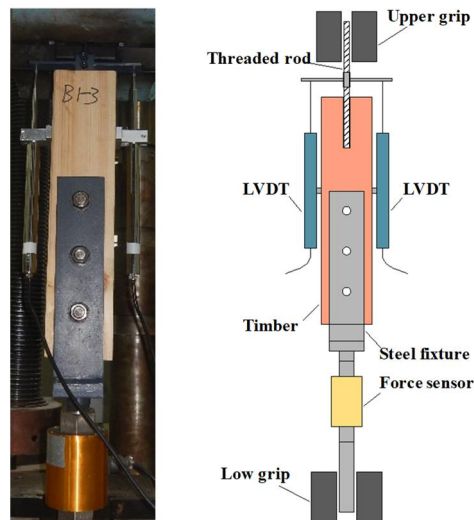


Fig. 4 Test set-up

2.5 Results

The load-slip curves of specimens are shown in Fig. 5. The load almost linearly increased with slip, and then a sudden decline appeared at a low relative displacement with audible cracks. The failure mode is shown in Fig.6. Failure mostly appeared at the timber-adhesive interface and accompanied with pull-out of wood plug. The splitting failure of the timber was only found in the specimen B3-2 (the second specimen in Group B with 3 mm glue-line thickness).

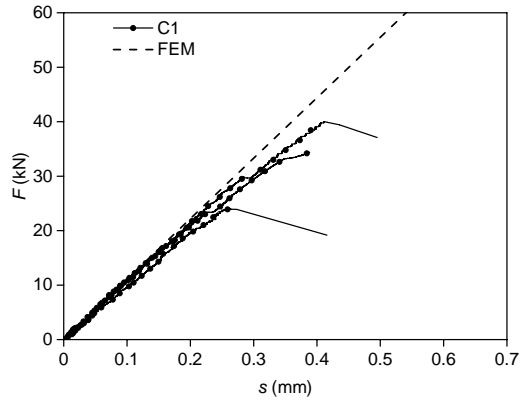
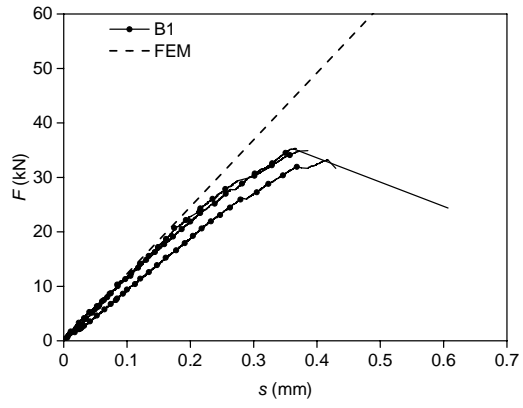
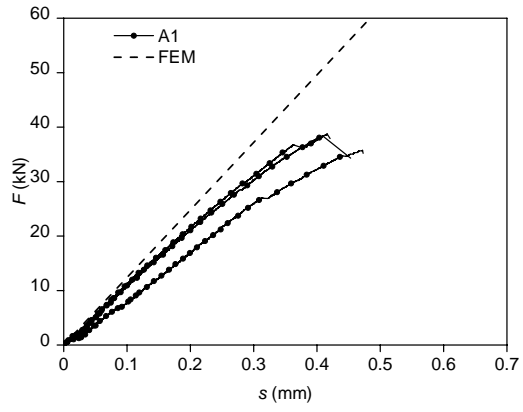


Fig. 5 Experimental and numerical load-slip curves



Fig. 6 Failure mode: timber-adhesive interface failure (left) and splitting failure (right)

Table 5

Experimental results.

Series	ρ (kg/m ³)	F_u (kN)	s_u (mm)	K (kN/mm)
A1	503	37.62	0.43	107
A2	450	35.76	0.43	108
A3	549	46.09	0.53	113
B1	464	34.49	0.39	107
B2	522	40.55	0.47	101
B3	499	46.9	0.55	109
C1	472	32.79	0.35	105
C2	483	35.57	0.39	120
C3	503	40.87	0.45	130

The experimental results are summarized in Table 5. Joint capacities (F_u) are defined as the load at failure. Ultimate slip (s_u) is slip corresponding to “ F_u ”. It can be found that the joint capacity and ultimate slip almost increase with the increase of the glue-line thickness. The capacity of series A2 is slightly less than that of A1, possibly because the mean density of A2 is less than that of A1. Density has been proven to be an influencing parameter on capacity of joints with glued-in rods [13, 14]. In order to normalize the comparison of capacity, the effect of density was eliminated by using Eq. 1, in which n may be assumed as 0.69 referred to [15]. Figure 7 shows the normalized capacities of joints \bar{F}_u versus glue-line thickness.

$$\bar{F}_u = F_u / (r / 480)^n \quad (1)$$

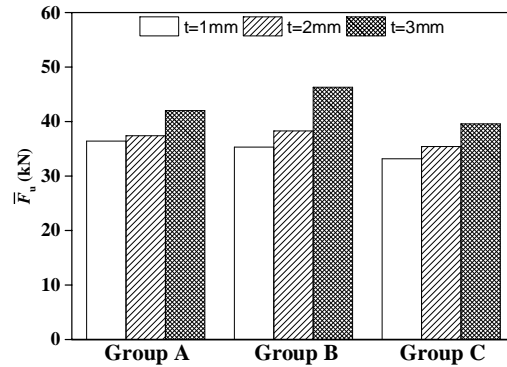


Fig. 7 Influence of glue-line thickness on joint capacity

Table 6 shows the normalized capacity of joints and capacity ratio between with positioning defect and without defect. The joint capacity of series B3 is highest, in which the rod is positioned off-centre in hole with 3 mm glue-line thickness. The inclined setting of rod in hole results in the decrease of joint capacity. However, the change in bearing capacity caused by positioning defect is less than $\pm 10\%$.

Table 6

Joint capacity.

Glue-line thickness (mm)	\bar{F}_u (kN) DIN	\bar{F}_u (kN) EC5draft	\bar{F}_{uA} (kN)	$\bar{F}_{uB} / \bar{F}_{uA}$	$\bar{F}_{uC} / \bar{F}_{uA}$
1	12.57	18.52	36.42	0.97	0.91
2	12.57	18.52	37.39	1.02	0.95
3	12.57	18.52	42.01	1.10	0.94

The stiffness in service (K_s) is also calculated according to EN-26891 [12], which is much larger than the value (2.78 KN/mm) calculated according to Eurocode5 draft [16]. The stiffness in service is not significantly related to glue-line thickness and positioning defect, however, it has a relatively weak correlation with density, see Fig. 8.

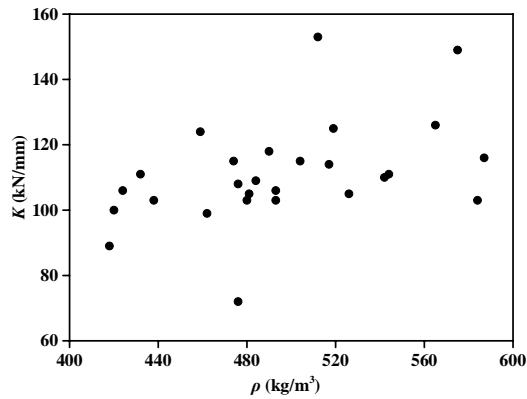


Fig. 8 Relationship between density (ρ) and joint stiffness (K)

3. Finite element modelling

To characterize the stress distribution of glued-in rods with and without positioning defect, a 3D finite element method model (FEM) is developed using the ABAQUS Software package. The meshing of the tested specimens, based on 8-noded hexahedral elements, is shown in Fig. 9. Considering the symmetry, only an half of specimen was modeled.

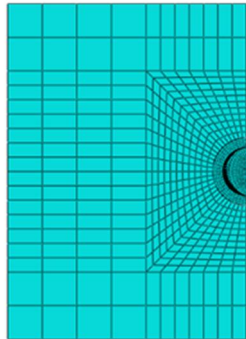


Fig. 9 Meshing of the tested specimens

The wood is modelled as being a linear elastic orthotropic material. The steel rods are modelled as being elastic and isotropic and the threading of rods is not modelled in detail in this paper. The epoxy adhesive is also modelled as being linear elastic and isotropic [17].

The adherence at both interfaces (rod-adhesive and timber-adhesive) are modelled using “tie” procedure. The loading is introduced by using controlled displacement applied on the nodes of the rod.

The load-slip curves from numerical simulations are shown in Fig. 5. The

stiffness of the finite element model is slightly higher than the experimental value. It may be because the threading of rods is not modelled, which reduces the axial stiffness compared to a smooth non-threaded rod of the same diameter [18].

Fig.10 shows the distribution of shear stress parallel to grain and stress perpendicular to grain along the glue-line for group A at the load of 30 kN. The origin of abscissa coordinate “0” corresponds to the bottom of the bore. Shear stress peaks appear near both ends and the highest tensile stress perpendicular to grain appears on top of bore. Stress decreases with increasing glue-line thickness, it explains the joint capacity increase with the increase of the glue-line thickness

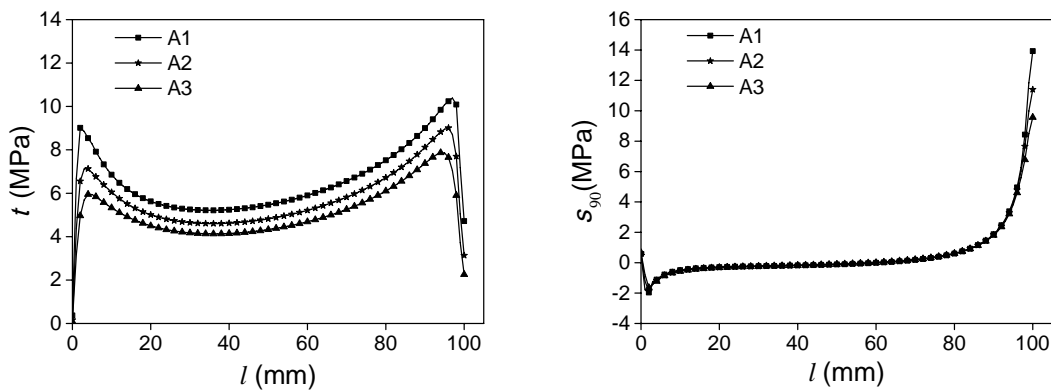


Fig. 10 Distribution of shear stress parallel to grain (left) and normal stress perpendicular to grain (right) along the glue-line

Figs.11-13 show the distribution of shear stress parallel to grain and stress perpendicular to grain along the glue-line through point “M”, “N” and “Q”, respectively, for the specimens with 2 mm glue-line thickness at the load of 30 kN. Due to additional bending moment, shear stress near the loaded end through point “M” in series C2 is less than that of the two other series, stress perpendicular to grain turns into compressive stress. The distribution of stress through point “N” is similar in three series. However, shear stress and tensile stress perpendicular to grain near the loaded end through point “Q” in series C2 is much greater than those of the two other series. It explains that the joint capacity of series C2 is less than that of the two other series.

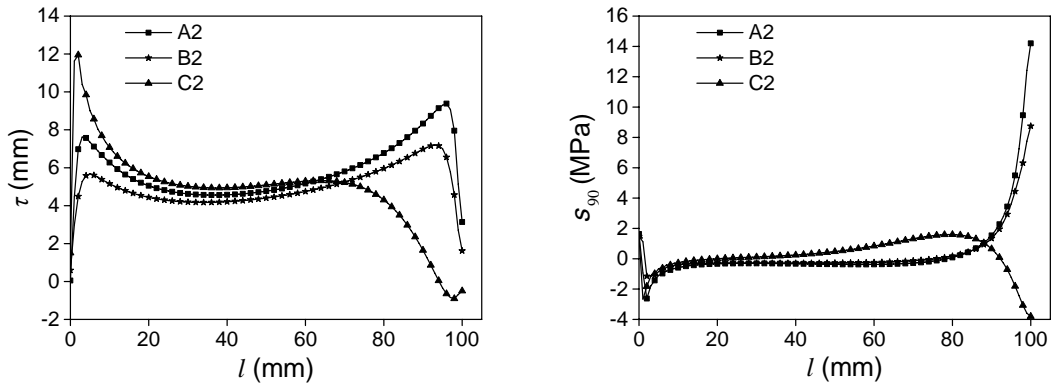


Fig. 11 Distribution of shear stress parallel to grain (left) and normal stress perpendicular to grain (right) along the glue-line through point “M”

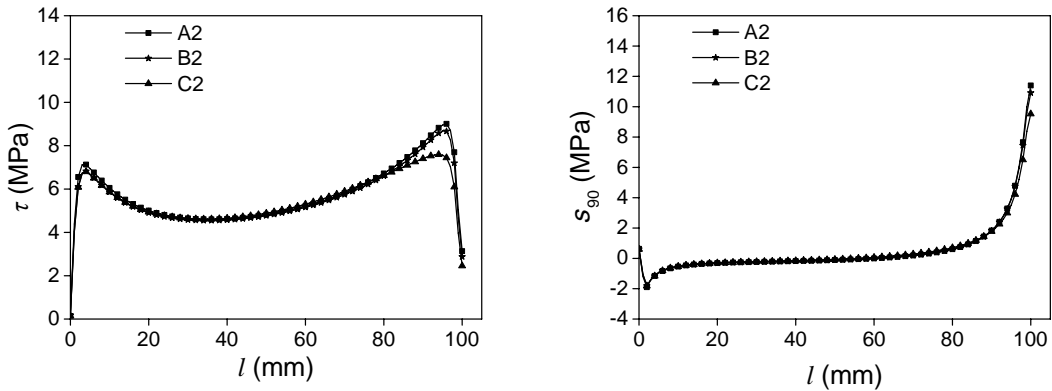


Fig. 12 Distribution of shear stress parallel to grain (left) and normal stress perpendicular to grain (right) along the anchorage length through point “N”

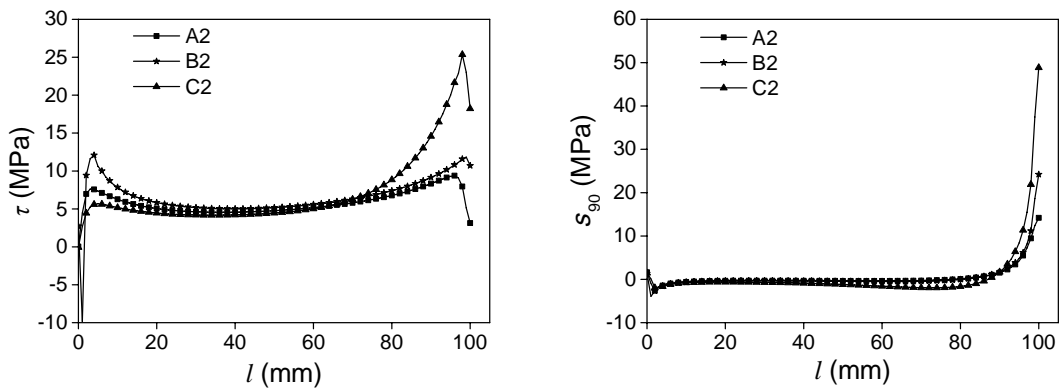


Fig. 13 Distribution of shear stress parallel to grain (left) and normal stress perpendicular to grain (right) along the anchorage length through point “Q”

Figs. 14 and 15 show the zone where the shear stress parallel to grain and stress perpendicular to grain exceeds their strength limit, respectively, for the specimens

with 3 mm glue-line thickness at the load of 30 kN. It can be seen that the brittle failure always initiate close to the top of the bore.

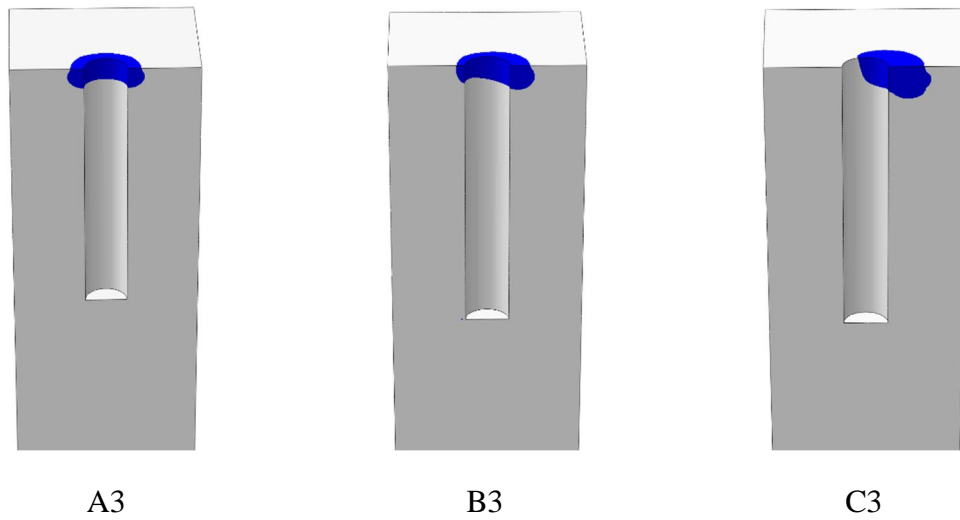


Fig. 14 Contour plot of tensile stress perpendicular to grain exceeding strength limit

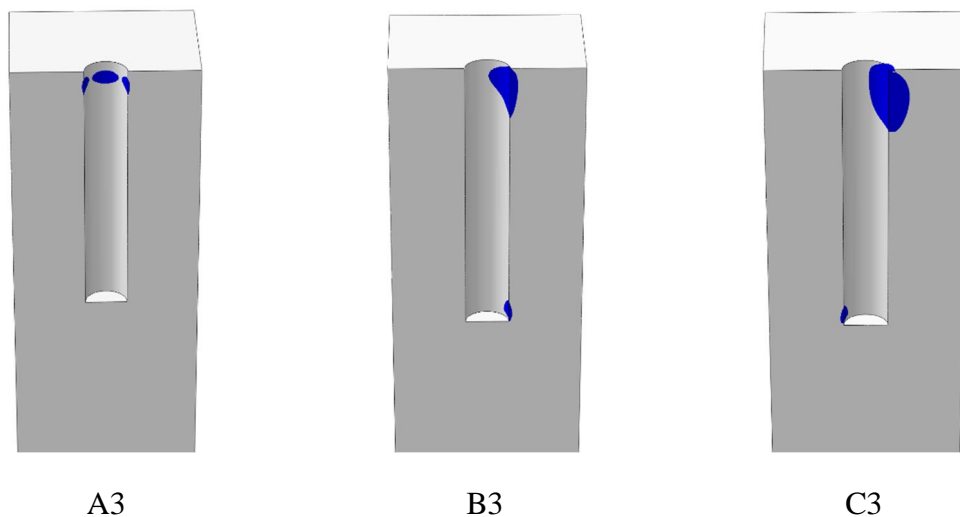


Fig. 15 Contour plot of shear stress parallel to grain exceeding strength limit

Conclusions

The stiffness in service is not significantly related to glue-line thickness and positioning defect. The joint capacity and ultimate slip almost increase with the increase of the glue-line thickness. The joint capacity of series B3 is highest, in which the rod is positioned off-centre in hole with 3 mm glue-line thickness. The inclined setting of rod in hole results in the decrease of joint capacity. The change in bearing

capacity caused by positioning defect is less than $\pm 10\%$.

The highest shear stress parallel to grain and tensile stress perpendicular to grain appears on top of bore. It implies that the brittle failure always initiates from the zone close to the top of the bore. In addition, shear stress parallel to grain and tensile stress perpendicular to grain near the loaded end through point “Q” in series C2 is much greater than those of the two other series. It explains that the bearing capacity of joints with inclined setting of rod in hole is lowest.

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