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DIFFERENT GLUELINE THICKNESSES PULL-OUT BEHAVIOUR OF MENGKULANG GLULAM

Tengku Anita Raja Hussin[a*], Oon Vincent[a], Rohana Hassan[b]

[a]Infrastructure University Kuala Lumpur (IUKL), Kajang, Selangor, Malaysia
[b]Universiti Teknologi Mara (UiTM), Shah Alam, Selangor, Malaysia

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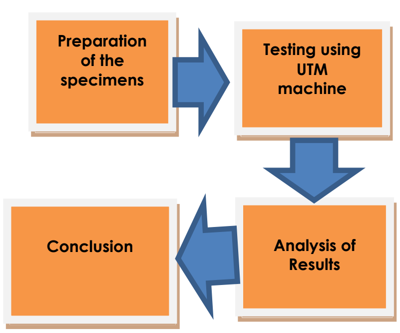
*Corresponding author
anita@iukl.edu.my,

Graphical abstract



Abstract

Timber connection is still facing inadequacy of engineering studies. Mechanical and adhesive joints are the two main types of connections being used for timber connection. In this study, pull-out strength test is carried to determine the best glue line thickness and the failure modes occur. Three different glue-line thicknesses of 2mm, 3mm and 4mm was tested with holes thicknesses of 14mm, 16mm and 18mm respectively were drilled on 9 with 3 specimens of each thickness. This test is carried out until failure in the specimen by using the Universal Testing Machine with load capacity of 1000kN and at the rate of 2mm/min. Phenol-resorcinol-formaldehyde (PRF) is the adhesive used for the strengthening purposes with ratio of PRF hardener and resin of 1:5 was used in this experiment. The dowel glued-in steel dowel is 10 mm in diameter from S 235 steel type. For the results; The data shows that glue line thickness of 2mm does generate the highest maximum load compared to 3mm and 4mm of glue line thickness with the value of 2.394kN compared to 2.223kN and 1.789kN respectively. However, glue line thickness of 3mm shows highest breaking load of 1.714kN compared to 1.631kN of 2mm glue line thickness and 1.454kN of 4mm glue line thickness. Therefore, it is proven that the 2mm glue line thickness is more superior in strength and shear stress than 3mm and 4mm of glue line thickness.

Keywords: Pull-out, glulam joint, thickness

1.0 INTRODUCTION

Glued laminated timber (glulam) is a highly engineered product and the timber is bonded with waterproof adhesives. Glulam is two or more layers of individual laminated graded sawn timber structurally glued up parallel to one another and each individual lamination must be less than 50mm of thickness [1]. Malaysian Timber Council (MTC) has been working on and promoting the usage of glulam for construction in Malaysia [2].Glulam has more than a handful of beneficial characteristic that is crucial in structural behavior. It has a higher strength-to-weight ratio than steel, along with its laminating process which enables it used in a longer span without the support from column and producing variety of shapes such as curved arches due to its versatility [3]. The most recent project using mainly glulam from various types of local timber as the load bearing structure in Malaysia is the "Galeri Glulam" located in Johor which officiated on 22 May 2012.

Joints are very important for structures to hold onto each other, transferring static and dynamic forces between structure members. One of the common technical causes of damage or failure in structure is inadequate behavior of joints, especially for larger and more complex structures. Joints amplify the bonding strength between structures and enabling the structure to withstand higher loads. Design of glued-in rods joint in timber or glulam is very problematic where the stress transmission in rod joints is complex [4].

Glued-in rod is one of the joint systems where rods and adhesive are used to be bonded-in in timber structure. The types of rod used are mainly steel rod. Glued-in steel rods joint system is dependent on the type of rod, dimension of rod, adhesive use and the glue-line thickness of adhesive.

In this research, with dimension and type of rod and adhesive used being constant, the glue-line thickness was a variable factor and testing to obtain the best glue-line thickness. This glue-line thickness was applied on the structure to optimize the joint and glulam properties. Bonding is crucial in structural elements where it can greatly affect the ultimate capacity of the structure and also its serviceability [5]. Glued-in rod timber connection has many benefits such as higher strength and stiffness, lower weight, good fire resistance and better aesthetic value [6]. Glued-in rods method has also been used to reinforce timber around the edges where the weak zones are and also to enhance the compression resistance in perpendicular to the grain in timber [7].

The glued-in rods transfer forces between the structural elements such as frame corner and also transferring forces into a structure or part of a structure such as column foundation joint [8]. Application of glued-in rods is advantageous, for example, good fire properties, low material and production cost, high aesthetics value, lightweight connectors, a very stiff connection and a high local force transfer [9].

There are numerous of experimental and theoretical studies carried out on glued-in rod timber joints over the past decades. Fragiacomo and Batchaler [10] presented a method for joint design on evaluating the joint strength for moment-resisting and axial force, where adjustment for various types of construction and geometries has been made. This method proposed has been successfully applied in many projects. It is based on modifying the section method at the interface of beam and column to evaluate the distribution of stress in both the timber and rods [10].

Yeboad *et al*. [8] carried out the experimental studies of the pull-out behaviour of basalt fiber reinforced polymer, BFRP which is loaded perpendicular to the grain in glulam [6].The studies shown that the pull-out strength of single glued-in rebar in glulam was greatly influenced by the anchorage length and thickness of glue-line. For shorter and longer anchorage length, the failure modes were the pull-out failure of rebar and longitudinal splitting of wood respectively. In addition, initial stiffness of the glued-in rebar joints did not appear to be affected by anchorage length, but it was clearly affected by the glue-line thickness [6].

The design of glued-in rods joint system is based on Eurocode 5 [11]. Design of timber structures of bolted and dowelled joint. Based on the Eurocode 5 design, the minimum spacing and distances for both dowelled joints are in Figure 1 which must be obeyed in the design.

Spacing and end/edge distances (see Figure 8.7)	Angle	Minimum spacing or distance
a_1 (parallel to grain)	$0^\circ \le \alpha \le 360^\circ$	$(4 + \lvert\cos\alpha\rvert)\, d$
a_2 (perpendicular to grain)	$0^\circ \le \alpha \le 360^\circ$	$4\,d$
$a_{3,t}$ (loaded end)	$-90^\circ \le \alpha \le 90^\circ$	max (7 d; 80 mm)
$a_{3,c}$ (unloaded end)	$90^\circ \le \alpha < 150^\circ$ $150^\circ \le \alpha < 210^\circ$ $210^\circ \le \alpha \le 270^\circ$	$\max([1 + 6\sin\alpha)\, d; 4d)$ $4\,d$ $\max([1 + 6\sin\alpha)\, d; 4d)$
$a_{4,t}$ (loaded edge)	$0^\circ \le \alpha \le 180^\circ$	$\max([2 + 2\sin\alpha)\, d; 3d)$
$a_{4,c}$ (unloaded edge)	$180^\circ \le \alpha \le 360^\circ$	$3\,d$

Figure 1 Minimum spacing and distance for dowels [11]

Another requirement that is stated in the code is the minimum bonded length of glued-in steel rods, $L_{b,min,}$ which is the maximum value achieve from Equation 1;

$$L_{b,min} = \max \{0.4 d_r^2 \text{ or } L_{b,min} = \{8 d_r \quad (1)$$

Where d_r is the diameter of rod in mm.

There are only two types of joints failure which is either adhesively or cohesively. Adhesive failure is between the adhesive and the adherent interfacial bond failure, while cohesive failure happens in the adhesive material or the adherent [5].

The common failure modes of glued-in rods in glulam are rod failure, shear failure in the adhesive or cracks of the timber around the bond and failure due to splitting of host timber or tensile failure as shown in Figure 2.

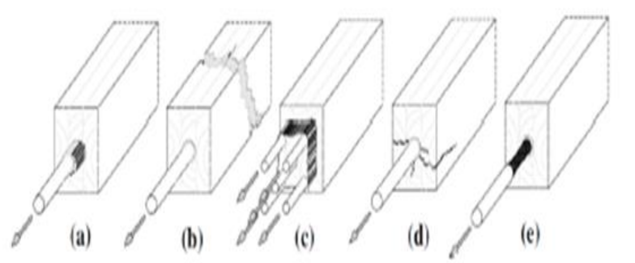


Figure 2 Failure modes for glued-in rods. (a) Shear failure along the rod, (b) tensile failure, (c) group tear out, (d) splitting failure, (e) yielding of the rod [12]

Experiment carried out by Molina *et al*. [13] on pull-out strength of axially loaded steel rods bonded-in glulam at a 45 degree angle to the grain with the aim to estimate the ultimate fatigue strength of the connection system. They obtained six failure modes that were observed in the fatigue test as shown in Figure 3.

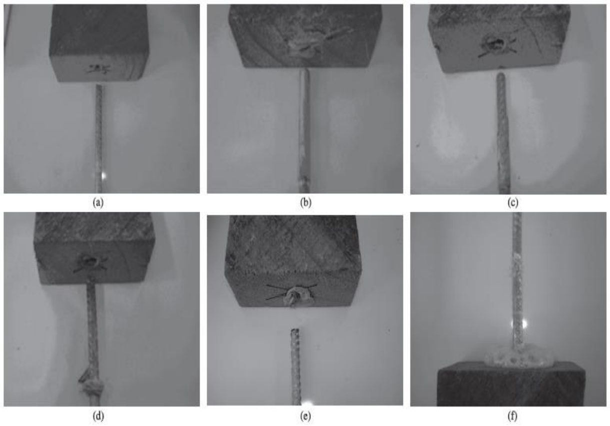


Figure 3 Failure modes for glued-in rods. (a) rod interface failure, (b) timber interface failure, (c) combined timber/rod interface failure, (d) combined rod interface/timber substrate failure, (e) rod failure, (f) cohesive failure of the adhesive [13]

Experiment carried out by Yeboad *et al*. [8] with regard to the behaviour of joints with bonded-in steel bars loaded parallel to the grain in timber shows the results of the pull-out test in the aspect of bonded length, bar diameter and failure load as shown in Figure 4. It is also observed that the most significant failure mode based on his test is at the timber/adhesive interface and pull-out steel bar as shown in Figure 5. This failure is mainly due to the shear failure at the interface of timber.

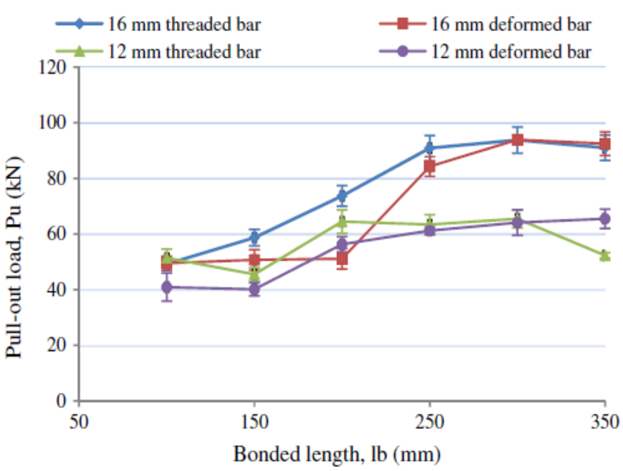


Figure 4 Pull-out capacities of steel bars [8]

Failure mode	Average percentage failure (%)			
	Deformed bar		Threaded bar	
	12 mm	16 mm	12 mm	16 mm
Timber/adhesive interface failure	24	26	43	38
Pull-out of bar	28	24	43	38
Timber splitting	22	28	10	20
Rod/adhesive interface failure	22	22	4	4
Bar tensile failure	4	0	0	0

Figure 5 Failure modes of sample [8].

Besides, experiment carried out by Harvey and Ansell [9] on improved timber connections using bonded-in glass fiber reinforced plastic rods showing the effect of glue-line thickness with average failure load. The experiment appeared to be that when the glue-line thickness increases, the pull-out failure load of the joint will increase as well. This phenomenon can be due to the spreading of stress in the glue-line which the size of the adhesive/timber interface is increased.

Figure 6 shows the effect of glue-line thickness and Figure 7 shows the failures of different glue-line thickness and the increment in glue-line will lead to more wood being pulled out with the rod.

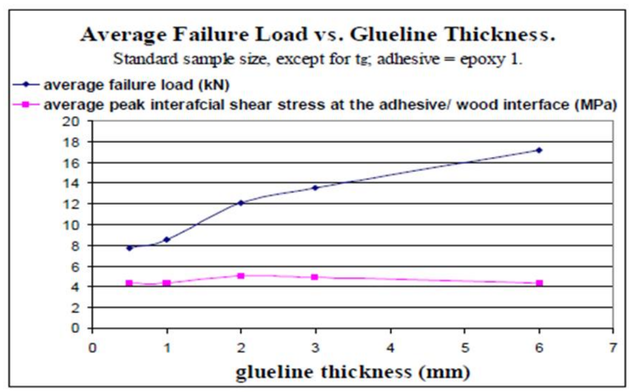


Figure 6 Effect of glue-line thickness [9].

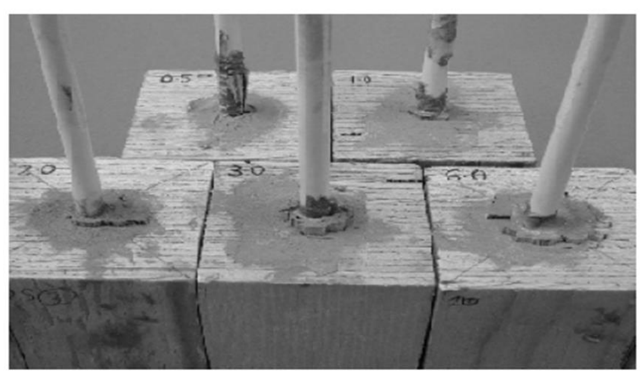


Figure 7 Failure for different thickness of glue-line [9].

Moreover, in the same experiment performed by Harvey and Ansell [9] as stated before, when the bonded length of the rod has an increment, the pull-out failure load of joint also increases, due to the increment of contacted surface area of timber and rod with the adhesive. In Figure 8, there is only insignificant change in pull-out failure load; therefore, longer bond length will lead to only slight changes in failure mode. Concluding that, more samples will fail in the interface of rod or adhesive compared to samples that fail in the wood.

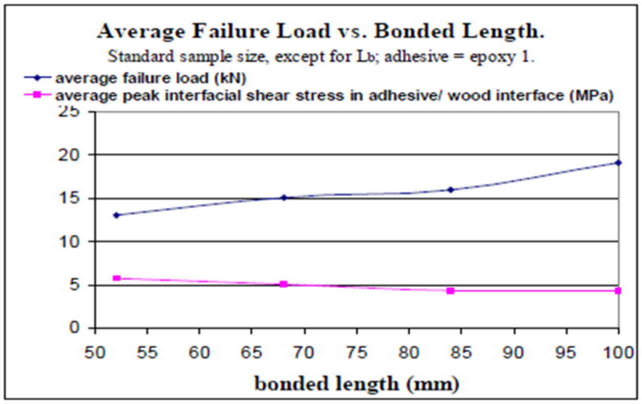


Figure 8 Effect of bonded length [9].

The main aim of this study is to investigate the effects of material and geometrical properties on the pull-out strength and bond behaviour of glued-in rod joint and also to analyze the failure modes of glulam through pull-out strength test of glulam for Mengkulang species.

2.0 EXPERIMENTAL

This research requires laboratory work and the data required to obtain by experimenting the materials and samples based on pull-out strength test on glued-in steel rod embedded perpendicular to the grain in glulam. The varying parameter is the glue-line thickness and determining the bond behaviour of glued-in steel rod in glulam with PRF adhesive. This test is carried out by using Universal Testing Machine (UTM) with load cell of 1000kN for glued-in rod in glulam at a rate of 2mm/min [6].

This test is carried out until failure in the specimen by using the Universal Testing Machine. Data such as load and displacement is recorded using LVDT (Linear Variable Differential Transformers) and the failure mode in the specimen is observed. Figure 9 and 10 shows the set-up of pull-out strength test

The timber species used in this research is mengkulang with grade of SG5. The preparation of glulam is done initially for this research and the whole glulam is segmented out according to the dimension required to conduct this experiment. 9 samples with cross sectional area of 130mm x 130mm and 130mm in depth are required for pull-out strength test as shown in Table 1. In this experiment, steel bars are used as glued-in rod or also known as dowels for the pull-out strength tests. Steel rods of grade S235 was used with diameter of 10mm and embedding 80mm of bonded in length into the glulam.

Figure 9 Pull-out strength test set-up (real picture)

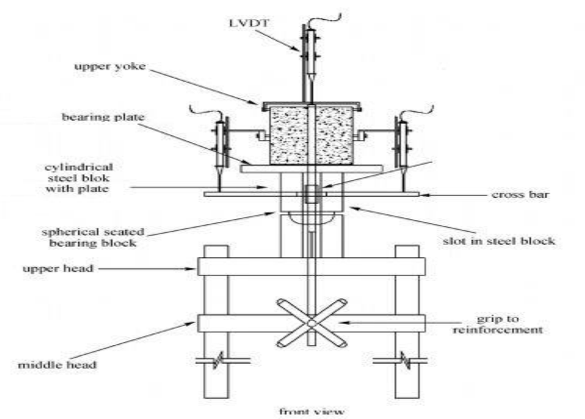


Figure 10 Pull-out strength test set-up (sketch)

Phenol-resorcinol-formaldehyde (PRF) was used as an adhesive in this experiment with three different glue-line thicknesses of 2mm, 3mm and 4mm were tested on pull-out test. The ratio of PRF hardener and resin of 1:5 was used in this experiment.

Pull-out strength test was tested with single rod where only 1 hole is needed to be drilled in each specimen prepared. Three different glue-line thicknesses of 2mm, 3mm and 4mm were tested, thus holes thicknesses of 14mm, 16mm and 18mm were drilled on 9 specimens with 3 specimens of each thickness. The hole were drilled in the middle of the specimen using a vertical drill, with a sharp auger bit, perpendicular to the grain through the entire length of each specimen block.

Table 1 Dimension and specification of glulam specimens

Test	Species	Glueline Thickness (mm)	Number of Samples	Dimension (mm)		
				Width	Length	Depth
Pull-out strength	Mengkulang Grade SG5	2	3	130	130	130
		3	3	130	130	130
		4	3	130	130	130

3.0 RESULTS AND DISCUSSION

3.1 Glue line Thicknesses

Figure 11 indicates for 2mm, Figure 12 indicates for 3mm and Figure 13 indicates for 4mm thickness. The graphs show the pattern of slow increment and decrement throughout the whole test until the steel rod is freed from the glulam. The constant increment of loading until the maximum loading is achieved indicates that the glue has a good elastic behavior with 2mm of glue line thickness compared to 3mm and 4mm.

Furthermore, where the graph faces slow decrement shows the plastic behavior of the adhesive and steel rod. All the 3 figures of graph with difference of 1mm glue line thickness exhibit different of graphical patterns. This indicates that the role of glue and glue line thickness as an adhesive for the connection between the steel rod and glulam is very important in term of strength, plastic behavior and elastic behavior. Samples of 2mm glue line thickness show the highest average maximum strength obtained and followed by 3mm of glue line thickness.

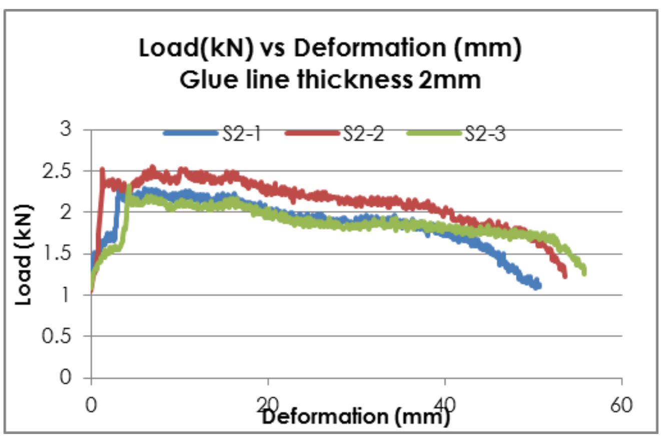


Figure 11 Load vs Deformation of glue line thickness of 2mm

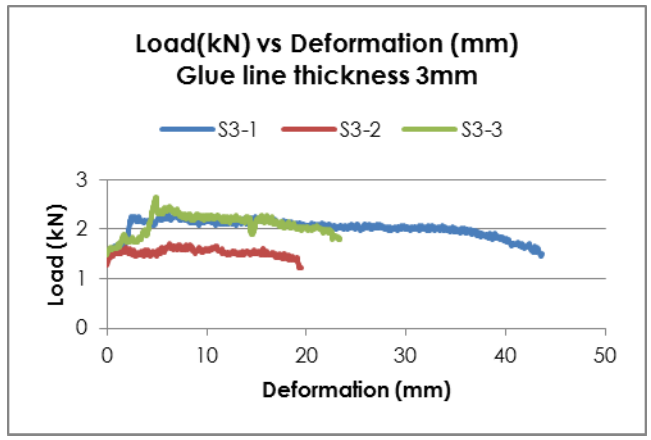


Figure 12 Load vs Deformation of glue line thickness of 3mm.

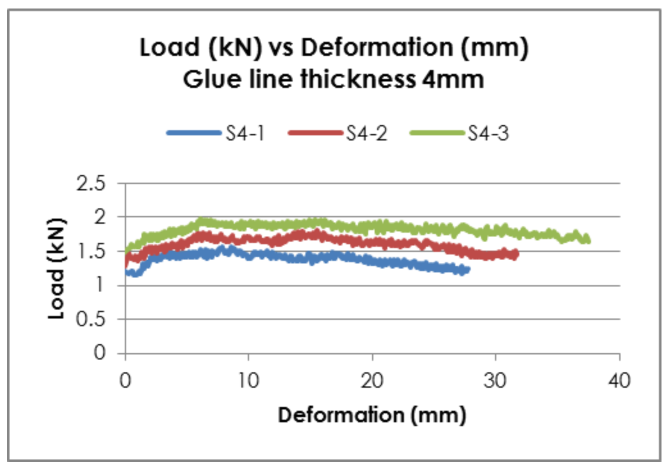


Figure 13 Load vs Deformation of glue line thickness of 4mm

It is also observed shown in Figure 14 below that when the glue faces failure, the glue cracks and produces friction force grazing with the steel rod that also contributed on the slow decrement before the steel rod is completely free from the glulam.

Figure 14 Cracking of adhesive

Table 2 Maximum load and breaking load of all samples obtained from UTM

Sample	Glueline thickness (mm)	Max Load (kN)	Average Maximum Load (kN)	Breaking Load (kN)	Average Breaking Load (kN)
S2-1		2.314		1.137	
S2-2	2	2.554	2.394	1.894	1.631
S2-3		2.314		1.863	
S3-1		2.308		1.514	
S3-2	3	1.711	2.223	1.825	1.714
S3-3		2.651		1.804	
S4-1		1.574		1.247	
S4-2	4	1.818	1.789	1.474	1.454
S4-3		1.974		1.642	

The above Table 2 shown the results obtained from UTM coded, UTS010 1.06 Materials Strength Test which was carried out at UiTM, Shah Alam. The data shows that glueline thickness of 2mm does generate the highest maximum load compared to 3mm and 4mm of glueline thickness with the value of 2.394kN compared to 2.223kN and 1.789kN respectively. However, glueline thickness of 3mm shows highest breaking load of 1.714kN compared to 1.631kN of 2mm glueline thickness and 1.454kN of 4mm glueline thickness.

Table 3 Average Maximum Shear of Timber-Adhesion and Rod-Adhesion

Sample marking	Maximum Shear of Timber-Adhesive (MPa)	Average Maximum Shear of Timber-Adhesive (MPa)	Maximum Shear of Rod-Adhesive (MPa)	Average Maximum Shear of Rod-Adhesive (MPa)
S2-1	0.658		0.921	
S2-2	0.726	0.681	1.016	0.952
S2-3	0.658		0.921	
S3-1	0.574		0.918	
S3-2	0.425	0.553	0.681	0.885
S3-3	0.659		1.055	
S4-1	0.348		0.626	
S4-2	0.402	0.395	0.723	0.711
S4-3	0.436		0.785	

Table 3 above shows the average maximum shear of timber-adhesion and rod-adhesion. Maximum Shear of both timber-adhesion and rod-adhesion for 2mm glue line thickness is the highest among the 3 different glue line thicknesses. Furthermore, comparing both shear values, the shear at rod-adhesive has the higher stress compared to shear at timber-adhesive. Thus, comparison of rod-adhesive shear with glue line thickness is more sensible. Experiment on pull-out strength test was definitely end in shear stress failure which is because of the act of pulling the rod out from the glulam in Figure 15.

In this experimental study, all the failures of 9 specimens despite the size of glue line thickness have the rod interface failure mode. The factor of such failure is caused by improper cleaning of rod before gluing process and smooth surface of the rod. It is concluded that the factor of such failure is due to the smooth surface of the steel rod which has low friction or gripping strength with the adhesive.

Figure 13 Failure mode of rod interface

4.0 CONCLUSION

In conclusion, the glue line thickness for this pull-out strength test was 2mm which give the best strength of 2.394kN in average of 3 samples compared to 2.223kN and 1.789kN of 3mm and 4mm glue line thickness respectively. There were four types reported from previous study [7] but only two types of failure were observed in this study. The specimens failed in the mode of adhesive-dowel, yet one sample failed in timber-adhesive mode.

Therefore, the result shows that the 2 mm glue line thickness is the optimum glue line thickness.

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