Civil Engineering and Architecture 10(3): 1056-1070, 2022 http://www.hrpub.org
DOI: 10.13189/cea.2022.100322

Experimental Bond Behaviour of Glued-In Rod Connection for Mengkulang Glulam under Pull-Out Loading

Tengku Anita Raja Hussin[1], Rohana Hassan[2,*], Ali Awaludin[3], Muhd Norhasri Muhd Sidek[2], Nor Hayati Abdul Hamid[2], Mohd Sapuan Salit[4]

[1]Faculty of Engineering and Built Environment, SEGi University Kota Damansara, Malaysia
[2]Institute for Infrastructure Engineering and Sustainable Management (IIESM), Universiti Teknologi MARA, Malaysia
[3]Department of Civil and Environmental Engineering, Gadjah Mada University, Grafika Street # 2, UGM Campus, Indonesia
[4]Laboratory of Biocomposite Technology, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, Malaysia

Received November 29, 2021; Revised March 4, 2022; Accepted March 27, 2022

Cite This Paper in the following Citation Styles

***(a):** [1] Tengku Anita Raja Hussin, Rohana Hassan, Ali Awaludin, Muhd Norhasri Muhd Sidek, Nor Hayati Abdul Hamid, Mohd Sapuan Salit , "Experimental Bond Behaviour of Glued-In Rod Connection for Mengkulang Glulam under Pull-Out Loading," Civil Engineering and Architecture, Vol. 10, No. 3, pp. 1056-1070, 2022. DOI: 10.13189/cea.2022.100322.*

***(b):** Tengku Anita Raja Hussin, Rohana Hassan, Ali Awaludin, Muhd Norhasri Muhd Sidek, Nor Hayati Abdul Hamid, Mohd Sapuan Salit (2022). Experimental Bond Behaviour of Glued-In Rod Connection for Mengkulang Glulam under Pull-Out Loading. Civil Engineering and Architecture, 10(3), 1056-1070. DOI: 10.13189/cea.2022.100322.*

Abstract Mechanical joint and adhesive joint are the two most common types of timber connections. In the case of timber construction, bonded-in rods offer a long-term, aesthetically acceptable alternative to some of the more conventional steel moment connections. Bonded-in rod connections in timber need many desirable attributes inefficiency, manufacture, performance, aesthetics and cost. This paper presents pull-out experimental testing for glued-in rod made of Mengkulang (tarrietia javanica) glulam joints. Hundred and seven (107) specimens were prepared, each with a single glued-in rod parallel and perpendicular to the grain. The steel treaded rod with a diameter of 12 mm, 16 mm and 20 mm with three numbers of adhesive (Sikadur-30) thicknesses of 2 mm, 3 mm and 4 mm were used in this experiment. The pull-out tests observations were on the effects of adhesive thickness, parallel and perpendicular grain directions and modes of failure of the specimens. The result obtained that 4 mm adhesive thickness was the strongest and parallel specimens showed better results than the perpendicular specimens. The pull-out failure modes are affected by the selected factors, i.e. the adhesive thickness, rod diameter and grain directions. Most of the specimens show failures in the timber besides the adhesive to timber interface.

Keywords Adhesive, Glulam, Glued-In Rod, Pull-Out Capacity, Structural Material

1. Introduction

Glued laminated timber (glulam) is a highly engineered product, and the timber is bonded with waterproof adhesives with two or more layers. Glulam is suitable for bridges, commercial buildings, sports complexes and residential houses. Figure 1 shows one of the examples of the curve beam constructed using glulam beams.

Source: [1]

Figure 1. The Disney ICE rink in Anaheim, California Features Glulam Arches Curved to a 75-Foot Radius to Form The Ice Center's Roof System.

Glulam has more than a handful of beneficial characteristics that are crucial in structural behaviour such lighter carbon footprint compared to concrete or steel which needed more energy to produce. Glulam offers the additional advantage of virtually unlimited flexibility in shape and size. Glulam is resistant to most acids, rust and other corrosive agents [2]. According to the American Engineered Wood Association (APA) [3] and Ling et al. [4], glulam is stronger than steel, and it also has greater strength and stiffness compared to the size of dimensional lumber. To fully utilise the benefits of glulam, understanding the behaviours exhibited by different species of timber is essential, because different species of timber can be used together to produce glulam only if the physical and mechanical properties are appropriate [5]. One of the most common tropical species being tested for glulam timber products is Mengkulang (Tarrietia Javanica). Mengkulang glulam was reported on shear block test performance [6]; pull-out strength of steel rods bonded at five different angles to the grain [7]; comparison of bolt withdrawal capacity [8,9], perpendicular dowel-bearing strength properties without glue line [10] and effect of glue line on the parallel withdrawal capacity [11].

Tropical glulam can be manufactured by complying with several Malaysian standards, including; MS 758: 2001: Glued Laminated Timber – Performance Requirements and Minimum Production Requirements (First Revision) [12]; MS 544: Part 3; 2001 Code of Practice for Structural Use of Timber: Permissible Stress Design of Glued Laminated Timber [13]; MS 1714: Visual Strength Grading for Sawn Hardwood Timber [14] and BS 6399-2/BS EN 1991: Wind Loading and Other Loadings [15]. As glulam is still considered new engineered wood product, the information of glulam as the structural member and connections design are also let most importance. Tanaka et al. [2] and Yeboah, Taylor, McPolin, Gilfillan, & Gilbert [16] reported that the design effort could also dictate 70% of the connection if not carefully detailed. Their statement is agreed by Fragiacomo & Batchelar [17]. The selection of the type of connection depends on various factors such as type of load, the direction of load transfer, required strength, ductility, stiffness and finally, the cost. These connections can range from more traditional bolted or nailed connections to more modern but less understood joints, such as glued-in rod connections.

The glued-in rods offer one possible solution to developing more efficient joining methods [16]. Glued-in rod is a new, innovative and highly efficient method to connect timber elements [18]. Glued-in rod is a connection system where rods and adhesive are glued in glulam timber structure and have proven to be an exciting solution for joining timber structural members. Timber joints with glued-in rods have several advantages concerning mechanical connections, higher stiffness, more uniform stress distribution, less bar corrosion problems and better appearance [19,18].

In most cases, it is necessary to obtain the strength properties of the glued-in rod joint from the loading test. The establishment of the comprehensive structural design method of the joint is required [2]. The applications of glued-in connections are still limited in the construction industry. Studies on glued-in connections focus mainly on the design of the connections with variation in rod sizes, glued line thickness and grain directions. Despite many international and national research projects and many practical applications of glued-in rods in timber structures, there is still no universal standard covering the design [18].

According to Ling et al. [4] and Harvey and Ansell [20], the 2 mm adhesive thickness is the strongest for their tested wood product. The thickness up to 2 mm is also defined in the relevant technical approvals by Stepinac et al. [18] and Yeboah et al. [16]. Harvey and Ansell [20] improved timber connections using bonded-in GFRP rods with a rod diameter of 8mm and bonded length of 63 mm shows that for epoxy adhesives, the glue-line thickness of at least 2 mm provides the optimum results. Yeboah et al. [16] observed that the timber-adhesive interface failure was the most significant failure mode based on their test. Therefore, this experimental work aims to determine the strength and optimum glue line made of tropical glulam for thickness between 2 mm, 3 mm and 4 mm for a single rod 12 mm, 16 mm and 20 mm diameter, respectively. The axially loaded tests were followed by comparing the maximum strength of parallel and perpendicular to the grain together with observations on the failure mode behaviour of the pull-out joints.

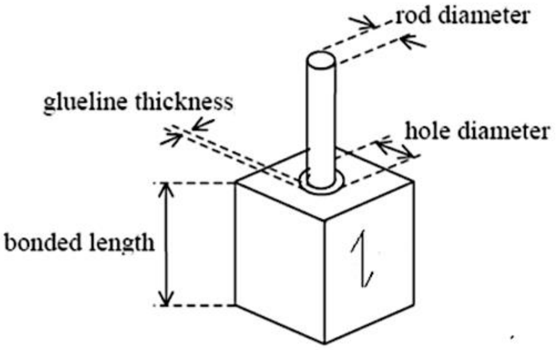
2. Materials and Methods

2.1. Glued-In Rod Preparations

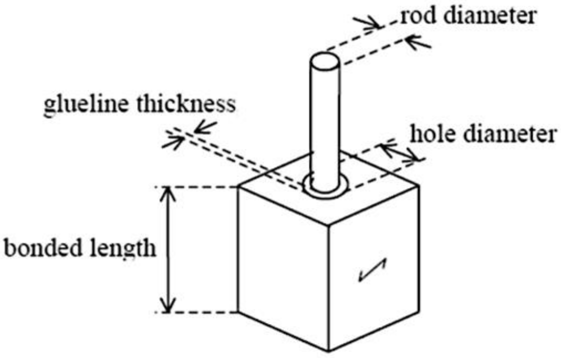
The glued-in rod of glulam timber test and preparation of samples were conducted in Heavy Structure and

Concrete Laboratory at the School of Civil Engineering, Universiti Teknologi Mara (UiTM) Shah Alam, Malaysia. The pull-out test was carried out using Universal Testing Machine (UTM) with load cell of 1000kN. The test and procedures were set up according to ASTM 5764: 1995 standard. The samples supplied by a local factory in the actual size of Mengkulang glulam beams were thoroughly checked for defects and fungi attack.

These specimen timber blocks were then drilled and followed by the insertion of a steel dowel in an axial direction (Figure 2). Specimens were kept in the storage area away from sunlight and moisture exposure and left in a temperature-controlled room at 28 ℃ to avoid shrinkage before inserting the adhesives and rods. Adhesive used in this study was Sikadur-30. To guarantee that the glue was strong enough to attach the rod and the wood, it was required to wait ten days to cure. The blocks for 12 mm, 16 mm and 20 mm rod diameters were prepared parallel (PR0°) and perpendicular (PP90°) to the grain directions (Figure 2).



a) Parallel (PR0°)



b) Perpendicular (PP90°)

Figure 2. Specification of Glulam Specimen Block for Pull-Out Strength Test

The blocks were cut in the form of cuboid structure with the length and width of the timber was at least 52 mm, and the depth or the thickness of the timber cuboid should be at least 60mm [19]. Pull-out strength tests were tested with a single rod where only one hole was drilled in each specimen. For edge and end distance, Stepinac et al. [18] stated values of more than 2.5d were presented in most design equations. EN 1995:2001: Eurocode 5 [22] had recommended an edge distance of 2.5d. Hundred and seven (107) specimens of pull-out test were divided into PR0° and PP90° as shown in Table 1.

Table 1. The Specimens Preparation

Rod Size mm	Glue Line Thickness mm	No of samples		Sample Block Size mm
		PR0°	PP90°	
12	2	18	18	100 x100 x 100
16	3	17	18	115 x115 x 115
20	4	18	18	170 x170 x 170
Total samples		53	54	

2.2. Adhesive

In this research, Sikadur-30, i.e. a product from a local manufacturer, was used. Sikadur-30 is a bonding agent for structural bonding of Sika CarboDur laminates to concrete, steel and timber. The similar bonding agent was also used by Chahrour and Soudki [23]. This bonding agent is a solvent-free adhesive based on a combination of epoxy resins and special filler. It is a strong bonding agent used to bond between bars and plates to the timber beams.

2.3. Holes Drilling on Timber Block

Three different glue-lines with the thickness of 2 mm, 3 mm and 4 mm were prepared. Holes thicknesses for rods size 12 mm, 16 mm, and 20 mm with embedded length were 90 mm, 105 mm and 160 mm respectively. Figure 3 shows the cross-section of the specimens. The holes were drilled in the middle of the specimen using a vertical drill, with a sharp auger bit, perpendicular or parallel to the grain through the entire length of each specimen block.

The minimum embedded length, L_b, min for rod is recommended by EN 1995-2: 2004 – Eurocode 5 [22]. The minimum embedded length was calculated using (1).

$$L_b minmax = \}\begin{matrix}0{,}4dr^2\\ 8dr\end{matrix} \qquad (1)$$

where dr is the rod diameter and L_b is the minimum embedded length.

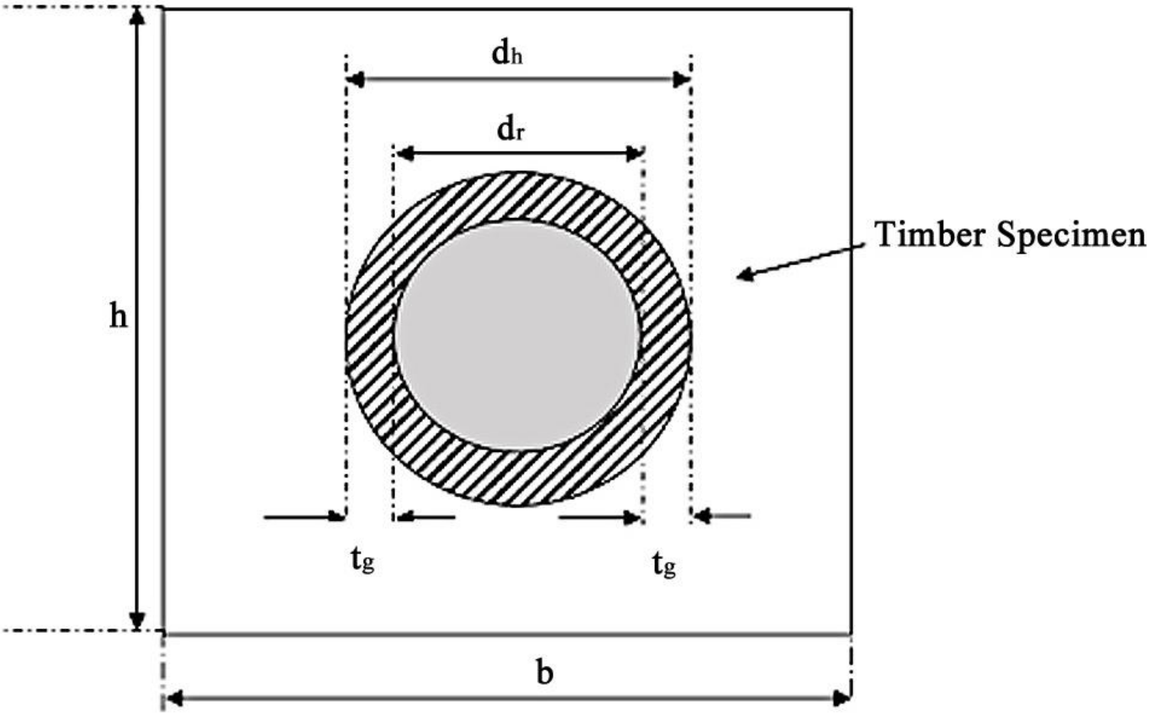


Figure 3. Cross-Section of the Specimen (Dh – Hole Diameter; Dr – Rod Diameter; Tg – Glue Thickness, B-Block Width and H – Block Thickness)

2.4. Installation of Steel Rod and Adhesive

Part A and B of Sikadur-30 adhesive were mixed thoroughly, and a gun was used to inject the adhesive into the hole, filling one-third length of the hole. The rod was slowly pushed in and gently rotated to squeeze the excess adhesive without causing any air voids. The steel rod was then inserted into the hole filled with the adhesive and twisted until the edge of the rod reached the bottom of the hole to prevent a trapped air bubble that could affect the joint's strength and ensure good wetting. An O-ring was inserted into the hole to centre the position of the rod, as shown in Figures 4-6.

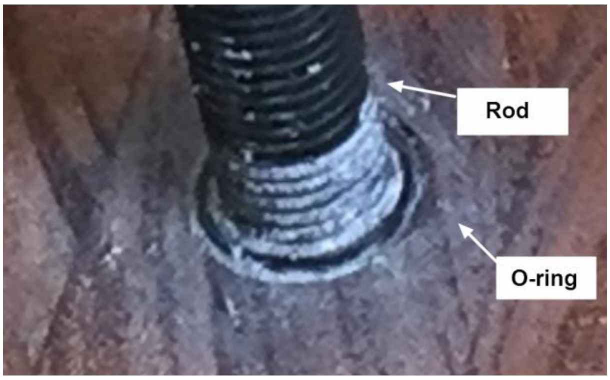


Figure 5. O-Ring at the Position

Figure 4. O-ring with 12 mm Internal Diameter

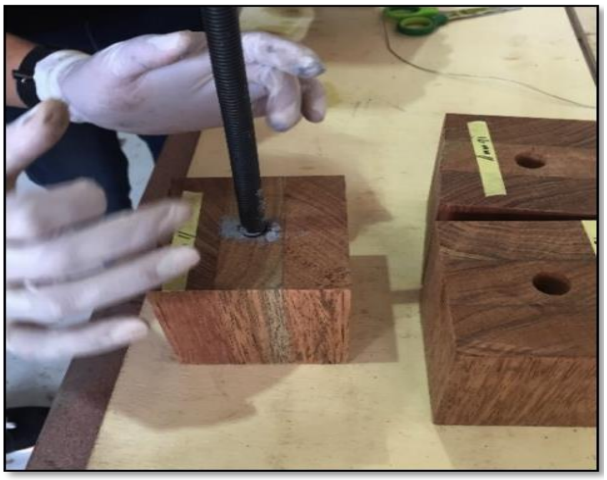


Figure 6. The Rod in The Position Aligned using O-Ring

2.5. Pull-Out Test Method

The Universal Testing Machine (UTM) with load cell of 1000kN was used to apply an axial load to the rods. The loading at a crosshead rate of 2mm/min up to failure, so that test duration was approximately six minutes. A rig was used to support and align the specimens in the pull-out tests. The rig plate consists of a top plate, a bottom plate with a steel rod attached at the middle, a threaded rod, bolts made out of aluminium.

The rig plate was then placed on the UTM machine and clamped from the bottom steel rod. The sample was inserted into the rig plate and tied from the top jaw at the steel rod. The sample was placed in a way that it could not move in any direction. The base plate geometry is presented in Figure 7, and the test rig is shown in Figure 8, respectively.

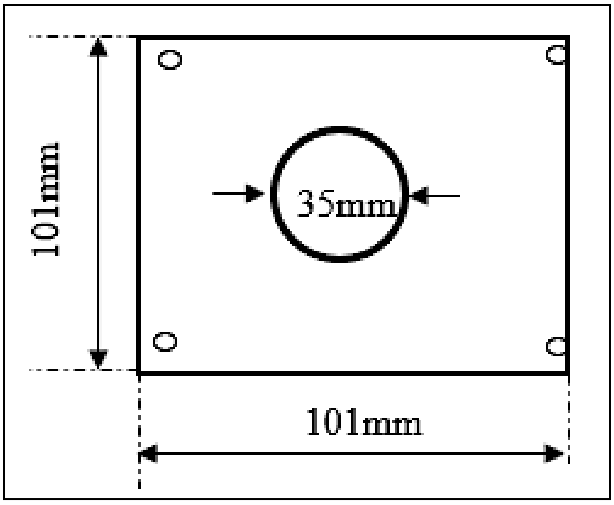


Figure 7. Stainless Steel Base Plate Geometry

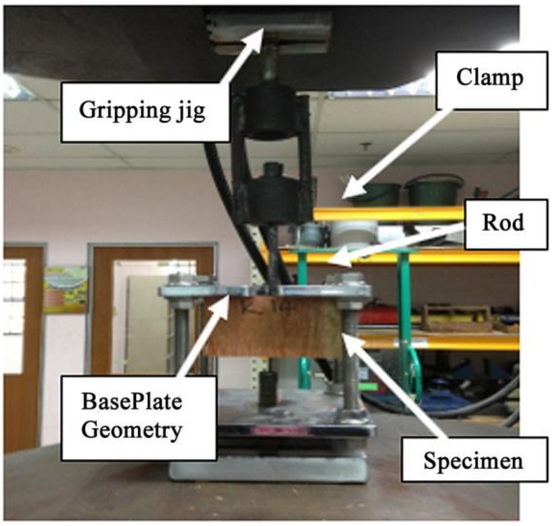


Figure 8. Pull-out Test Set Up

2.6. Observation on Bonding and Failure Mode Behaviour

The average pull-out shear stresses at the adhesive, timber and rod interfaces were calculated based on the type of failure by dividing the failure by bond area. This test closely simulates a bonded-in connection under load. The mode of failure was observed after the pull-out test was completed. The observations on shear-stress behaviour and bond ability were made on the failure modes of each specimen. The behaviour includes timber layers, rod and adhesive, intersection layer and slope of grain. The average shear strength, τ, at the adhesive, timber and rod interfaces was calculated by dividing the failure load by the bond area and the schematic diagram illustrated in Figure 9.

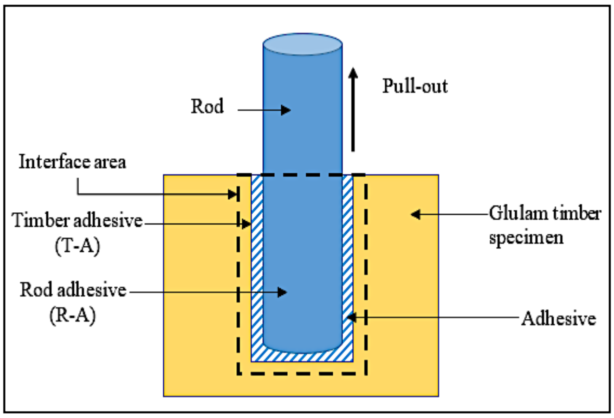


Figure 9. Schematic Diagram of Interface Area

The basic formula of pull-out strength is as (2);

$$P_u = \frac{P}{A} = \frac{P}{(T-A)+(R-A)} \tag{2}$$

where;

P_u = is the pull-out strength
P = is the maximum load
A= is the adhesive

The average pull-out shear stresses at the adhesive to timber and rod to adhesive interfaces denoted as τ_{ta} and τ_{ra} respectively were calculated using (3) and (4). The relationship between the strength of the bonding and the variables was examined. Finally, the modes of failure were observed for each test and a summary of these modes was compiled.

Road-Adhesive interface

$$\tau_{ta} = \mathrm{Pmax}/(\pi d_h l_b) \tag{3}$$

Road-Adhesive interface

$$\tau_{ra} = \mathrm{Pmax}/(\pi d_r l_b) \tag{4}$$

where P_{max} is the maximum pull-out load of the specimens, l_b gives the bonded/embedded length, d_h the hole diameter and d_r is the rod diameter.

3. Results and Discussion

With the aim to characterise the mechanical behaviour of the bonded-in rod connection, a series of pull-out tests with various parameters was carried out. The pull-out static tests investigated the influence of the glue line thickness, different rod diameters and grain directions behaviour of the joints. The observations were also reported for the failure mode behaviour of the pull-out tests.

3.1. Pull-Out Test Performance for Parallel Grain Direction (PR0°) and Perpendicular Grain Direction (PP90°)

Tables 2 and 3 show the summary of pull-out strength test results for the 12 mm, 16 mm and 20 mm for pull-out in the PR0° and PP90°, respectively. For PR0°, results between the 2 mm, 3 mm and 4 mm glue thickness, in the parallel grain direction, for the 12 mm and 16 mm rod diameters the optimum results were using 2 mm while for the 20 mm rod diameters, 4 mm is the optimum strength. These results are agreeing the statement made by Stepinac et al. [18], Yeboah et al. [16] and Harvey et al. [20]. Comparison of percentage difference between the glue thicknesses for 20 mm rod diameter is shown in Figure 10. The bars show that the average load for 4 mm glue-line thickness is 10.84% higher compared to 3 mm glue-line thickness and 23.05% higher compared with 2 mm glue-line thickness. It can be concluded that the results for 4 mm give the best glue-line thickness for rod 20 mm diameter parallel direction.

Table 2. Glue thickness, Load-Carrying Capacity and Strength and For Rod 12 mm, 16 mm and 20 mm Dia in PR0^0

Rod diameter (mm)		**12**			**16**			**20**		
Glue thickness (mm)	**Remarks**	**Max. Load**	**Strength**		**Max. Load**	**Strength**		**Max. Load**	**Strength**	
		Load (kN)	**Stress (MPa)**	**Strain %**	**Load (kN)**	**Stress (MPa)**	**Strain %**	**Load (kN)**	**Stress (MPa)**	**Strain %**
	Mean (kN)	**51.82**			**91.15**			121.86		
2	StD	1.04	5.65	0.11	27.51	6.11	0.08	11.19	4.96	0.05
	CoV	0.02			0.09			0.09		
	Mean (kN)	51.52			83.93			120.49		
3	StD	9.03	6.22	0.08	73.9	7.65	0.08	106.99	5.75	0.05
	CoV	0.18			0.88			0.82		
	Mean (kN)	47.25			86.39			**152.52**		
4	SD	7.31	5.57	0.07	69.91	7.26	0.07	64.04	5.82	0.05
	CoV	0.15			0.81			0.42		

Table 3. Glue Thickness, Load Carrying Capacity and Strength and For Rod 12 mm, 16 mm and 20 mm Dia in PP90^0

Rod diameter (mm)		**12**			**16**			**20**		
Glue thickness (mm)	**Remarks**	**Max. Load**	**Strength**		**Max. Load**	**Strength**		**Max. Load**	**Strength**	
		Load (kN)	**Stress (MPa)**	**Strain, %**	**Load (kN)**	**Stress (MPa)**	**Strain %**	**Load (kN)**	**Stress (MPa)**	**Strain %**
	Mean (kN)	42.93			73.27			120.04		
2	StD	15.29	4.68	0.06	19.59	2.98	0.04	27.72	4.89	0.05
	CoV	0.36			0.27			0.23		
	Mean (kN)	47.06			65.77			134.7		
3	StD	10.48	5.13	0.06	61.13	2.67	0.04	36.4	5.48	0.05
	CoV	0.22			0.93			0.27		
	Mean (kN)	**50.25**			**75.13**			**140.57**		
4	StD	18.72	5.47	0.07	70.66	3.06	0.04	60.07	5.72	0.05
	CoV	0.37			0.94			0.43		

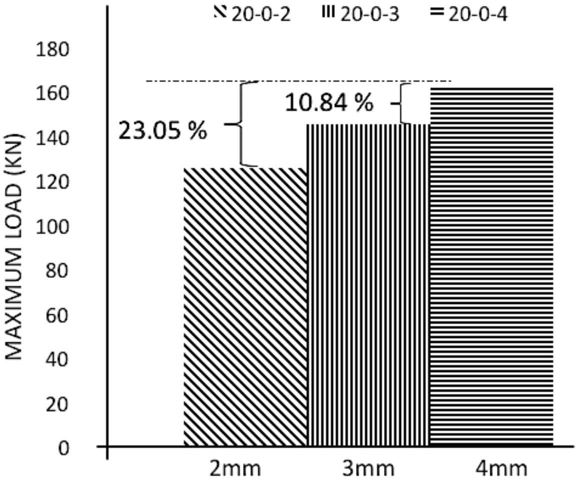


Figure 10. Percentage Different For 20 mm Rod Diameter for Different Glue Line Thicknesses in PR0^0

Load-deflection curves for all rod diameters are shown in Figure 11. This plot shows that for parallel to the grain, regardless of diameters', all joints have a sudden drop at the point of failure. The load-deformation response of the glued-in rod in the timber under axial tension loading is linear until failure. The same phenomenon was also revealed by Zhu et al. [24]. Seemingly, it indicates an interaction between the rod diameter and the pull-out strength of the joints [19]. The most significant displacement until failure is 10.48 mm, and the smallest is 5.85 mm.

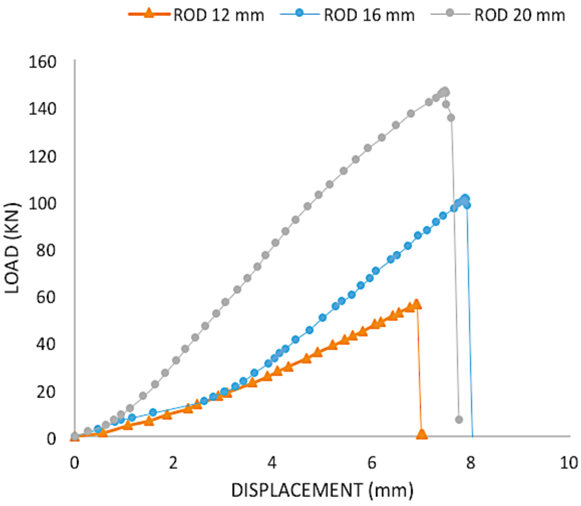


Figure 11. Typical Load Versus Displacement for PR0°

The initial curve is relatively linear up to a load roughly between 15 kN to 80 kN. For the bigger diameter (20 mm), after this point, the behaviour of the joint is no longer linear as it approaches the failure of the joint. This behaviour agrees with the typical load-deflection behaviour curve for timber basic behaviour; up to the limit of proportionality, the behaviour is linearly elastic. After this point, the behaviour is no longer linear and could be either elastic or plastic.

Nevertheless, the smaller 12 mm and 16mm diameter joints show a constant linear behaviour until the point of failure. However, the increases in the rod diameter size will increase the linear strength of the connection. This difference in behaviour is likely to be due to the mode of failure of the specimens. It's expressed that the bigger size of rods created an excellent effect on the strength of pull-out test. The brittle behaviour of failures is similar to the studies reported by Yeboah, Taylor, Mcpolin, & Gilfillan [25]. Concisely, the higher diameter will reflect the higher pull-out joints capacity.

For the PP90°, Table 4 shows that the optimum of 12 mm, 16 mm and 20 mm are for 4 mm glue thickness. Figure 12 shows the percentage difference between 2 mm, 3 mm, and 4 mm glue line thickness for 20 mm rod diameter. It was discovered that the strength of joints with a 4 mm glue-line is 14.44% greater strength than that of a 2 mm glue-line and 1.28% greater than that of a 3 mm glue-line. It is concluded that perpendicular to the grain, the results for 4 mm give the optimum glue-line thickness.

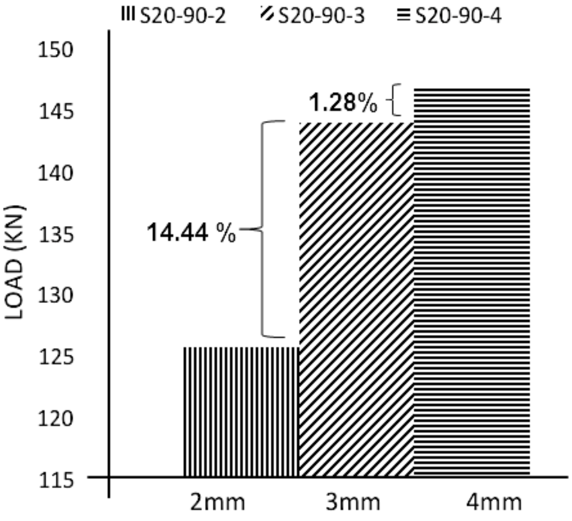


Figure 12. Percentage Different for 20 mm Rod Diameter for Different Glue Line Thicknesses in PP90°

The load versus displacement plotted for PP90°of glued-in rod in joints was not much alleviated from the joints in parallel behaviour. In similar, the increase of rod diameter will increase the load capacity of the joints. The same phenomenon was revealed by Faghani et al. [18] and Hussin et al. [26].

Figure 13 shows the typical load versus displacement for perpendicular to the grain direction. The most significant displacement until failure is 8.15 mm, and the smallest is 6.28 mm. The graph patterns showed brittle behaviour of failures and were found consistent with findings obtained by Mohamad et al. [7], Steiger et al. [27] and Ling et al. [4]. Plot patterns for 12 mm and 16 mm rod diameter demonstrated the same behaviour compared to the pattern for 20 mm rod diameter, rapidly increasing to the highest load. It was shown that a higher load was required to pull the bigger size of the rod. The statement was in line with previous researchers such as Hussin et al. [26]; Mindrasari [28] and Zhu et al. [24].

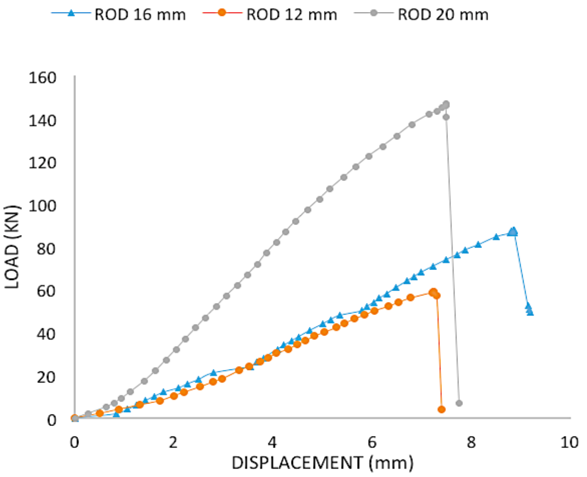


Figure 13. Typical Average Load versus Displacement for PP90°

The comparison between the two-grain directions is shown in Figure 14. Apparently, it demonstrated that the load carrying capacity in PR0°, shows an average of 7.09% higher load capacity than the PP90°. Conversely, similar plot patterns were shown in both grain directions. They were found to support the previous statement that the increase of the rod diameter will increase the load of the shear strength as mentioned by Ling et al. [4]; Yeboah et al. [25]; Hussin et al. [26]; and Serrano [29].

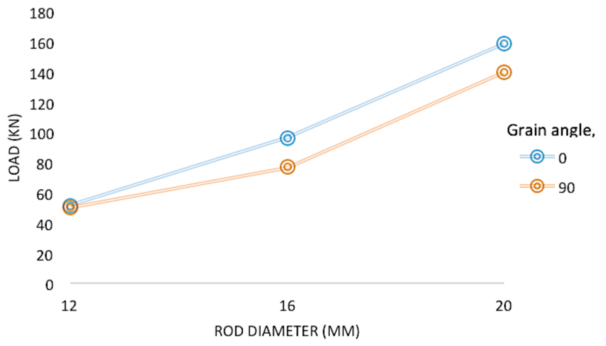


Figure 14. Pull-Out Capacity of Different Grain Directions

3.2. Comparison of Rod Diameter

To observe the effect of different rod diameters on grain direction, the correlation between different rod diameters sizes with varying angles to the pull-out capacity is demonstrated in this section. Figure 15 shows the percentage difference between PR0°and perpendicular PP90° grain direction for 12 mm, 16 mm and 20 mm rod diameter, respectively.

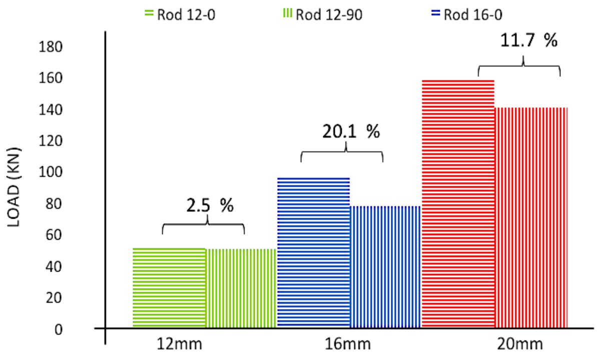


Figure 15. Percentage Difference for Rod 12 mm, 16 mm and 20 mm of PR0° and PP90°

From the bar comparison, the 20 mm rod diameter shows the optimum load compared to the 12 mm and 16 mm rod diameter. It can be seen that the load for the smallest rod diameter (12 mm) against the largest (20 mm) diameters is as wide as 80% difference.

This study also shows similar findings to Feldt et al. [21] that the ultimate load increased with increasing drill hole diameter. However, as no clear correlation between this diameter and nominal shear strength could be confirmed, the influence of drill hole diameter could not be properly evaluated. Figures 16 to 18 show similar pattern of stress versus strain for different rod diameters. It is clearly shown that the parallel to the grain produced higher stress compared to the perpendicular depicted the earlier discussed load versus displacement behaviour.

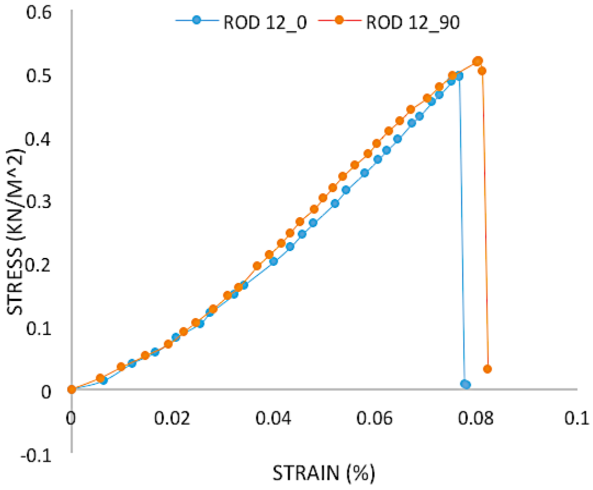


Figure 16. Typical Stress versus Strain (%) for Rod 12 mm Diameter

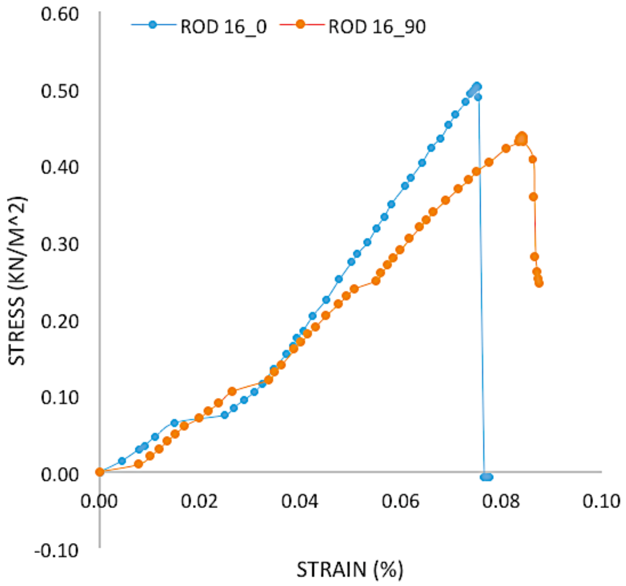


Figure 17. Typical Stress versus Strain (%) For Rod 16 Mm Diameter

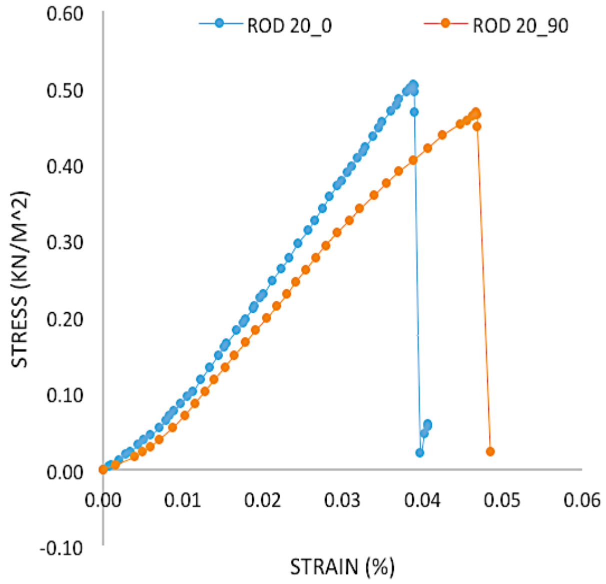


Figure 18. Typical Stress versus Strain (%) for Rod 20 mm Diameter

3.3. Failure Modes Behaviour based on Shear Stress and Bond Ability

According to the experimental data, the force perpendicular to the grain had the lowest shear strength when subjected to a pull-out test (Figures 19). The stiffness at the connection loosens as the bonding area is subjected to many layers and crossing points due to perpendicular glued laminating sections (Figure 20). It indicates that the shear-bond stress of the connection is the highest when the load acts parallel to the grain. This finding is in the agreement with Mohamad [7].

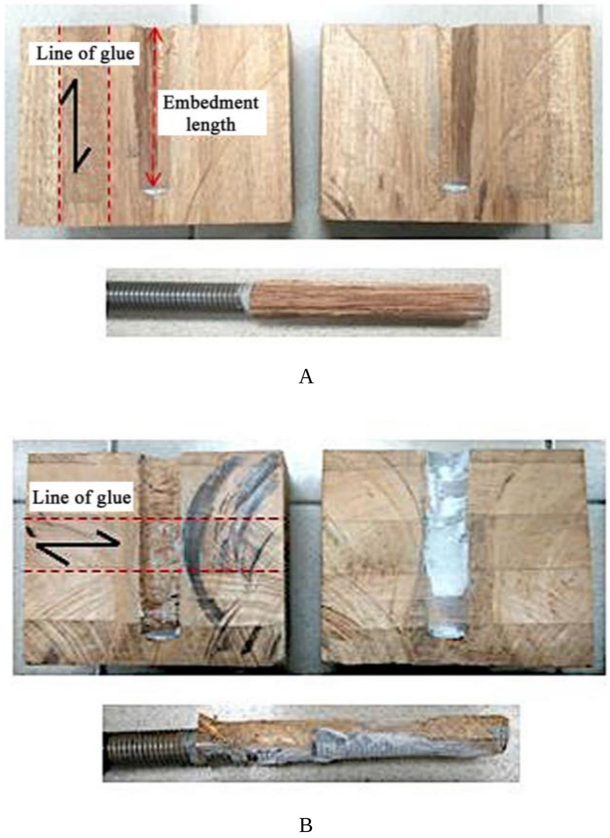


Figure 19. Sample of the Test Specimens of Glued-In Rod Tested According to Grain Directions; (A) Parallel and (B) Perpendicular

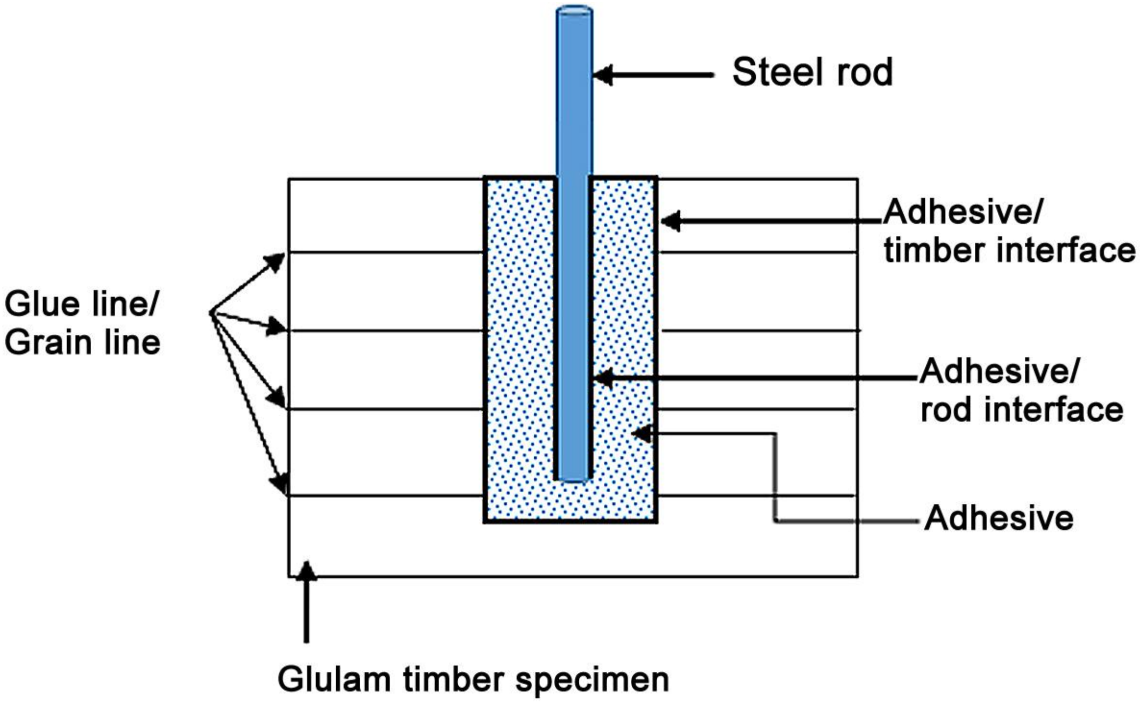
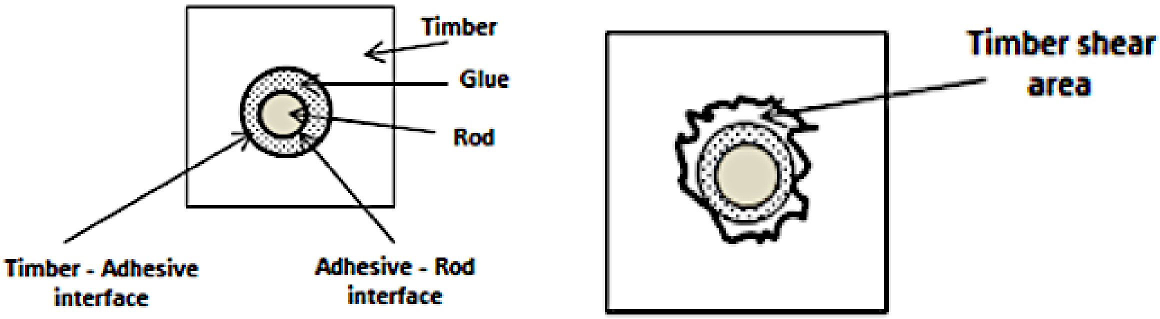


Figure 20. Schematic Diagram of Shear-Stress of Glued-in Rod Bonding Area Subjected to Pull-Out Perpendicular to the Grain Direction.



A B

Figure 21. Cross-Section Specimen Sketches; (A) Before Test (B) Timber Shear Failure after Test

Figure 22. Pull-out Timber Failure after Test

Timber failure, yielding or rod failure, adhesive failure, timber to adhesive interface failure, and adhesive to rod interface failure were the five (5) types of failure for the specimens after tests. Zhu et al. [23], Tlustochowicz et al. [30], and Yusof [31] used to discuss these failures in their studies. Figures 21 and 22 show the cross-section for the specimen before failure and the possible pull-out after test failure.

The highest point from the load-displacement plot was considered as the maximum pull-out strength of the timber joint. After obtaining the maximum pull-out strength, the maximum shear stress at the rod-adhesive and the maximum shear stress at the timber-adhesive was calculated using (3) and (4), respectively (Table 4). Figures 23 to 26 show the specimens that failed in timber-adhesive and rod-adhesive, in the form of sketches and the actual laboratory test, accordingly.

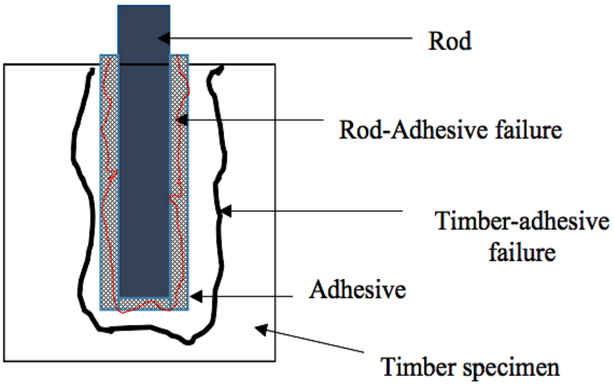


Figure 23. Specimens Failed in Timber-Adhesive and Rod-Adhesive.

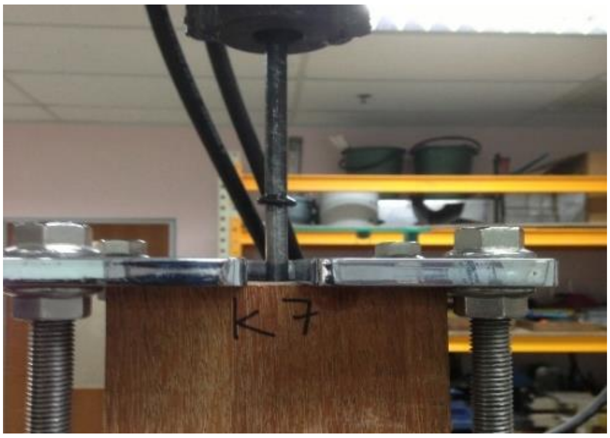


Figure 24. Specimen Failure in Rod-Adhesive

Table 4. The maximum pull-out Strength, maximum shear at T-A and shear at R-A

Nos	**Descriptions**	**PR0°**	**PP90°**	**Percentage of failure (%)**
1	Timber	16	9	23.15
2	Rod	7	8	13.89
3	Adhesive	6	11	15.74
4	Timber-Adhesive interface failure	17	12	27.14
5	Adhesive-Rod interface failure	9	13	20.08

A B

Figure 25. Timber-adhesive Type of Failure (A) Sample 1 (B) Sample 2


A B

Figure 26. Rod-Adhesive of Failure (A) Sample 1 (B) Sample 2

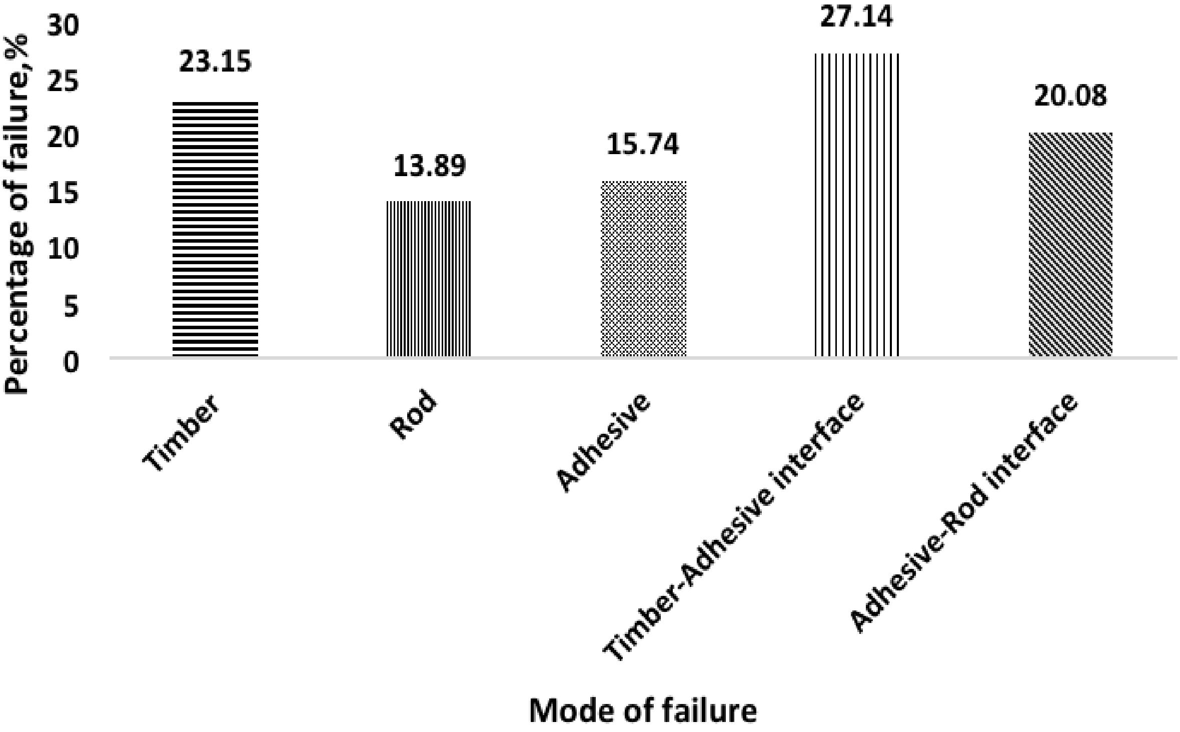


Figure 27. Percentage of common failure modes according to the type of failure

In this study, the average shear stress at the rod-adhesive interface was found to be identical in both directions, the shear stress increasing as the rod diameter reduced. Figure 27 displays the percentage of common failure mechanisms based on the type of failure. This finding agrees with Broughton and Hutchinson's [32] that a larger rod diameter (as a separate variable) resulted in lower shear stress at the rod-adhesive contact due to a greater bonding surface. The failure of the timber to adhesive interaction is shown in Table 5. Both the bonding stress at the rod to adhesive interface and the bonding stress at the timber to adhesive interface were considered to be linear. Despite using different parametric studies, the results obtained from this study were similar to those obtained by other researchers such as Mohamad [7]; Hussin et al. [27] and Ling et al. [4].

Table 5. Maximum shear at T-A and R-A for three diameters

Rod Diameter	Grain Direction	Glue Thickness	Maximum Shear at T-A, (MPa)	Maximum Shear at R-A, (MPa)
12	PR0°	2	9.452	7.089
		3	13.664	10.248
		4	12.532	9.399
	PP90°	2	11.386	8.540
		3	12.482	9.361
		4	13.327	9.996
16	PR0°	2	24.175	18.131
		3	22.260	16.695
		4	19.093	14.320
	PP90°	2	19.432	14.574
		3	17.444	13.083
		4	19.925	14.944
20	PR0°	2	32.320	24.240
		3	34.608	25.956
		4	40.451	30.339
	PP90°	2	31.838	23.878
		3	35.724	26.793
		4	37.283	27.962

Figures 28 and 29 show the correlation effect for parallel and perpendicular grain direction parameter studies. The failure modes and bond stress were found to be perpendicular to the grain resulted in a reduction of average bond stress at both rod-adhesive and timber-adhesive interfaces according to the effect of grain direction on the average bond stress significantly influenced by both grain direction and rod diameter.

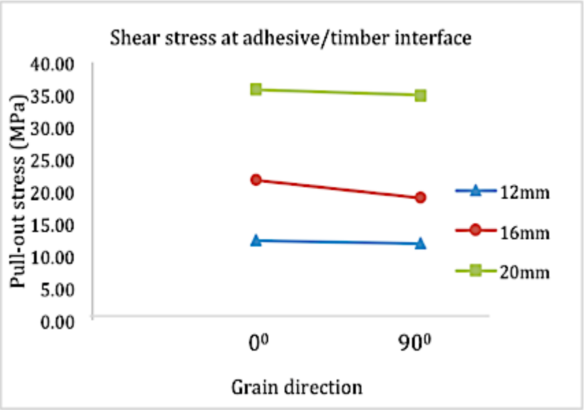


Figure 28. Pull-out Stress of Adhesive to Timber Interface

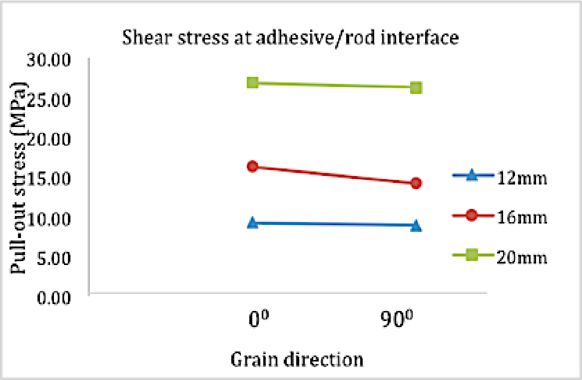


Figure 29. Pull-Out Stress of Adhesive to Rod Interface

4. Conclusions

The optimum glue line thickness for this pull-out strength test was 4mm, which give the best strength on average compared to the samples of 2 mm and 3 mm glue line thickness, respectively. It can be concluded that the parallel to the grain shown a 7.09% higher strength compared to the perpendicular to the grain. All joints show load versus displacement relations resulted in brittle failure with linear relations. Most of the specimens display failure modes in the timber, away from the adhesive to timber interface.

Acknowledgments

The authors gratefully acknowledge the monetary supports from Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia through the internal fund (600 IRMI/PERDANA 5/3/MITRA (001/2018)-2), and cooperation from the technical staff and students (Muhammad Faiz Kamaruddin, Abdul Rauf Mohd Radzi, Razeen Azry Abdul Razak) of Infrastructure University Kuala Lumpur (IUKL), Kajang, Selangor and SEGi University, Kota Damansara that contributed to this research.

REFERENCES

[1] APA- Wood Engineered Association (2008). Glulam .Product Guide. Online available from wood.X440.pdf .https://law.resource.org/pub/us/code/bsc.ca.gov/sibr/org.apa

[2] Tanaka, K., Kawano, K., Noguchi, Y., Mori, T., & Inoue, M. (2012). Proposal of Calculation Method for Pull-Out Strength of Glued-in Rod Connector Embedded in Perpendicular To the Grain in Glulam. *World Conference on Timber Engineering*, 6.

[3] Wood Engineered Association (APA), America. Retrieved: https://www.apawood.org

[4] Ling, Z., Yang, H., Liu, W., Lu, W., Zhou, D., Wang, L. (2014a). Pull-out strength and bond behaviour of axially loaded rebar glued-in glulam. *Construction and Building Materials*, *65* (August 2015), 440–449.

[5] Wan Mohamad, W., Razlan, M. A., & Ahmad, Z. (2011b). Bending strength properties og glued laminated timber from selected Malaysian hardwood timber. *International Journal of Civil & Environmental Engineering*, *11*(4), 7–12.

[6] Abd. Malek, N.J.A, Al-Afif, A. A., Hassan, R. (2019). Shear Block Test Performance of Melunak and Mengkulang Parallel to Glueline. IOP Conference Series: Materials Science and Engineering 2019, 507(1), 012015

[7] Mohamad WNN, Suliman NH, Kamarudin MK, Mohd Amin N, Hassan R (2018). Pull-out Strength of Steel Rods Bonded into Mengkulang (Tarrietia Javanica) Glulam At Five Different Angles to the Grain. Journal of Tropical Forest Science 30(1):67-74. DOI:10.26525/jtfs2018.30.1.6774

[8] Abd. Malek N.J.A., Hassan R., Kamari S.N.S.M., Shakimon M.N., Long C.Y. (2016). Performance comparison of bolt withdrawal capacity for mengkulang glulam. Journal of Mechanical Engineering 2016, 13(2), pp. 113–124

[9] Abd. Malek, N.J.A., Hui, L. S. and Hassan, R. (2020). Performance of Withdrawal Capacity for Mengkulang Glulam Perpendicular to the Glue Line for 14mm and 20mm Bolt Diameter. International Journal of Innovative Technology and Exploring Engineering (IJITEE) ISSN: 2278-3075, Volume-9 Issue-3, January 2020

[10] Abd. Malek, N.J., Hassan, R., Hussin, T.A.R., Tern, N.D., Adam, C. (2016b). Perpendicular dowel-bearing strength properties without glue line for Mengkulang species. Journal of Mechanical Engineering 2016, 13(1), pp. 45–56

[11] Hassan, R, Abd Malek, N.J., Shakimon, M.N. and Sapuan M.S (2021). Parallel Glueline of Withdrawal Capacity for Mengkulang Glulam, Environment-Behaviour Proceedings Journal: Vol. 6 No. SI4 (2021): Jul. Special Issue No. 4. CSSR2019 Pulau Pinang, 04-05 Dec 2019.

[12] MS 758: 2001: Glued Laminated Timber – Performance Requirements and Minimum Production Requirements (First Revision). SIRIM, Malaysia.

[13] MS 544: Part 3; 2001 Code of Practice for Structural Use of Timber: Permissible Stress Design of Glued Laminated Timber. SIRIM, Malaysia.

[14] MS 1714: Visual Strength Grading for Sawn Hardwood Timber. SIRIM, Malaysia.

[15] BS 6399-2/BS EN 1991: Wind Loading and Other Loadings

[16] Yeboah, D., Taylor, S., McPolin, D., Gilfillan, R., & Gilbert, S. (2011). Behaviour of joints with bonded-in steel bars loaded parallel to the grain of timber elements. *Construction and Building Materials*, *25*(5), 2312–2317.

[17] Fragiacomo, M., & Batchelar, M. (2012). Timber Frame Moment Joints with Glued-In Steel Rods. II: Experimental Investigation of Long-Term Performance. *Journal of Structural Engineering*, *138*(6), 802–811.

[18] Stepinac, M., Rajcic, V., Tomasi, R., Hunger, F., Van de Kuilen, J.-W. G., & Serrano, E. (2013). Comparison of design rules for glued-in rods and design rule proposal for implementation in European standards. *Working Commission W18 - Timber Structures*, (August 2013). Retrieved from http://costfp1004.holz.wzw.tum.de/fileadmin/tu/wz/costfp1004/CIB_Paper_Stepinac_et_al_-_46-07-10_copy.pdf

[19] Faghani, P. (2013). Investigations on Pull-out strength of timber joints with glued-in rods. Master's Thesis. Vancouver: University of British Columbia.

[20] Harvey, K., & Ansell, M. P. (2003). Improved Timber Connections Using Bonded-In GFRP Rods. *Proceedings of 6th World Conference on Timber Engineering-Paper P04*, (Johansson).

[21] Feldt, P., & Thelin, A. (2018). Glued-in Rods in Timber Structures Finite Element Analyses of Adhesive Failure. Master Thesis, Department of Architecture and Civil Engineering Division of Structural Engineering Lightweight Structures Chalmers University of Technology. Sweden.

[22] EN 1995-1-1 (2004) (English): Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings [Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC].

[23] Chahrour and Soudki (2005). Flexural Response of Reinforced Concrete Beams Strengthened with

End-Anchored Partially Bonded Carbon Fiber-Reinforced Polymer Strips. Journal of Composites for Construction 9(2). DOI: 10.1061/(ASCE)1090-0268(2005)9:2(170).

[24] Zhu, H., Faghani, P., & Tannert, T. (2017). Experimental investigations on timber joints with single glued-in FRP rods. *Construction and Building Materials*, *140*, 167–172.

[25] Yeboah D, Taylor S, McPolin D, Gilfillan J (2013). Pull-out behaviour of axially loaded Basalt Fibre Reinforced Polymer (BFRP) rods bonded parallel to the grain of glulam elements. Construction and Building Materials, Volume 38, Pages 962–969.

[26] Hussin, T.A.R., Iswandi, M. & Hassan, R. (2016). Pull-out Strength for different size of dowel. *Jurnal Teknologi.*, *4*, 63–69.

[27] Steiger, René, Serrano, E., Stepinac, M., Rajčić, V., O'Neill, C., McPolin, D., & Widmann, R. (2015). Strengthening of timber structures with glued-in rods. *Construction and Building Materials*, *97*, 90–105.

[28] Mindrasari, P., Awaluddin, A, Muslikh (2018). The Effect of Diameter and Anchorage Length of Keruing Wooden Dowels, Deformed Steel Dowels and GFRP Dowels on Pull-out Strength of Keruing Timber Block with Epoxy Resin Adhesive. Civil Engineering and Environmental Symposium 2018, Yogyakarta, 2 Mei 2018.

[29] Serrano, E. (2018). Experimental investigation of the axial strength of glued-in rods in cross laminated timber, (October). https://doi.org/10.1617/s11527-018-1268-y

[30] Tlustochowicz, G., Serrano, E., & Steiger, R. (2011). State-of-the-art review on timber connections with glued-in steel rods. *Materials and Structures*, *44*(5), 997–1020. https://doi.org/10.1617/s11527-010-9682-9

[31] Yusof, A. (2010). Bending Behavior of Timber Beams Strengthened using Fiber Reinforced Polymer Bars and Plates, 251.

[32] Broughton, J. G., & Hutchinson, A. R. (2001). Effect of timber moisture content on bonded-in rods. *Construction and Building Materials*, *15*(1), 17–25. https://doi.org/10.1016/S0950-0618(00)00066-0