Effects of Bolt Diameter and Loading Direction on Bearing and Withdrawal Resistance of Half-Threaded Bolts in Glued Laminated Timber

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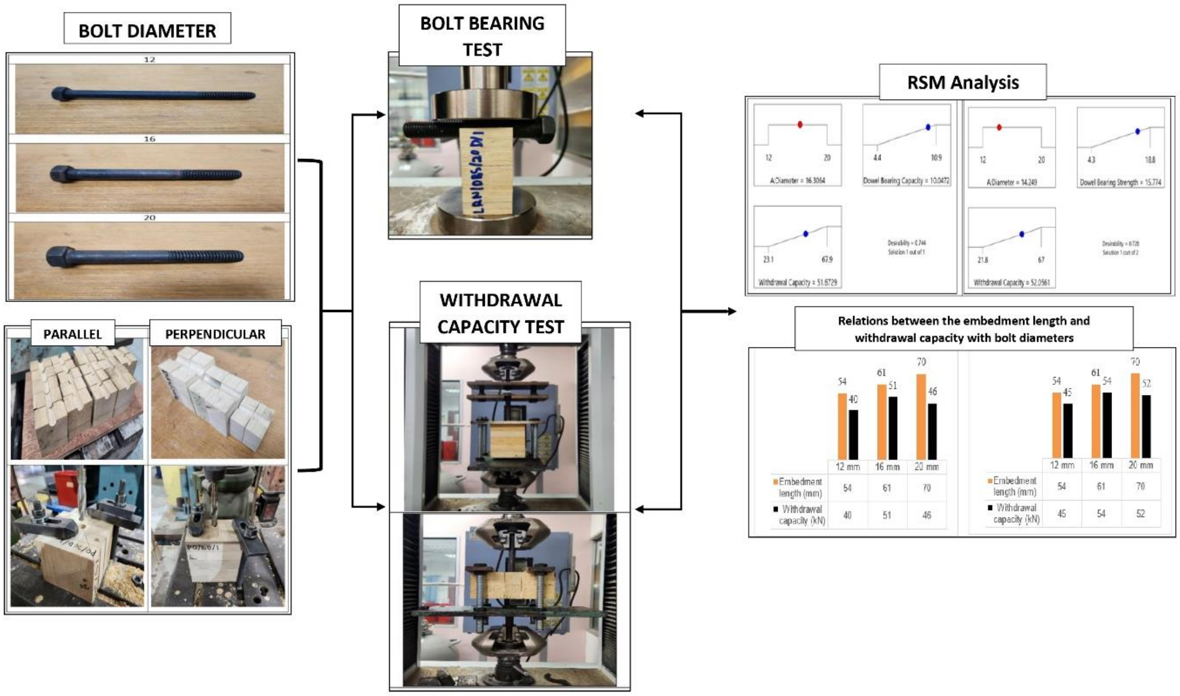
GRAPHICAL ABSTRACT



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Timber connections were prepared using glulam from tropical plantation species, focusing on key properties for dowel-type joints with half threaded bolts without nuts: Bolt bearing strength and bolt withdrawal capacity. Tests were performed according to ASTM standards. Three half-threaded bolt diameters (12 mm, 16 mm, and 20 mm) were tested in two loading directions, parallel and perpendicular to the grain, with 12 replicates for each configuration. Response Surface Methodology (RSM) using Design Expert Software was applied to optimize bolt diameter for both loading directions. Results showed that bolt bearing strength was higher in perpendicular loading, with the 12 mm bolt achieving 16.6 N/mm², compared to 6.01 N/mm² in parallel loading. Withdrawal capacities varied, with the 16 mm bolt showing the highest capacity in perpendicular loading at 54.2 kN. The study demonstrates that the 16 mm bolt exhibited the optimal diameter-to-embedment length ratio compared to 12 mm and 20 mm bolts, resulting in the highest withdrawal capacity. Consequently, the 16 mm bolt represented the best balance for achieving maximum withdrawal capacity. The optimization suggests using a 16 mm bolt for parallel loading to the grain and a 14 mm bolt for perpendicular loading.

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Keywords: Connection; Bolt bearing strength; Glued laminated timber; Tropical plantation species; Withdrawal capacity

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INTRODUCTION

Recently, engineered timber products (ETPs) have gained popularity as structural elements in construction, including beams, columns, wall panels, and more. These ETPs encompass various types such as glued laminated timber (glulam), laminated veneer lumber (LVL), cross laminated timber (CLT), parallel strand lumber (PSL), and laminated strand lumber (LSL). Glulam, in particular, stands out for its reliable strength properties and versatility (Qiu *et al*. 2013). Glulam is made by gluing together dimensioned and strength-graded wood pieces under regulated circumstances (Norshariza *et al*. 2016).

Efficient connection systems are crucial for the effective use of glulam in large-scale construction projects.

Timber connections are a critical area of research in engineering, particularly due to their susceptibility to failures, often occurring at these junctions (Wang *et al*. 2018). Understanding how connections, such as bolts and dowels, respond under varying loads is crucial for ensuring its structural integrity. The widespread adoption of bolted connections in modern building design can be attributed to their remarkable capacity for energy dissipation and ductile performance (Xue *et al*. 2021). Recent research by Stamatopoulos (2016) has shed light on the superior performance of timber structures with threaded rods compared to those employing glued-in rods. Zhang *et al.* (2019) discussed that by using partially threaded bolts for timber connections, the moment resisting capacity of the timber structures can be improved. As bolt diameter increases, the risk of wood splitting also rises. Although larger bolt diameters are expected to improve withdrawal strength, the occurrence of splitting can weaken this connection. When splitting happens, it reduces the bolt's engagement with the wood fibers and lowers the overall withdrawal capacity. This highlights the importance of balancing bolt size with the wood's structural integrity. Bolt reinforcement can help control wood splitting, and its effectiveness is influenced by the bolt's pull-through and withdrawal capacity. Santos *et al*. (2010) highlights that bolt-bearing behavior is crucial in designing laterally loaded joints with bolt-type fasteners, as it greatly impacts the strength and stability of timber structures. Accurately assessing the bolt bearing strength and withdrawal capacity of glulam connections is essential to ensure that these connections can endure the applied forces without risking damage or failure.

Bolt bearing strength significantly influences the performance of timber connections. Factors such as bolt diameter (Ramirez *et al*. 2012) and loading direction either in parallel or perpendicular, play crucial roles (Sawata and Yasumura 2002; Awaludin *et al*. 2007). In addition, the timber density and moisture content (MC) also impacts this strength (Rammer 1999; Jumaat *et al*. 2006; 2010; Glisovic *et al*. 2012; Zitto *et al*. 2012; Hassan *et al*. 2013). Rammer (1999) found in his experiment that bolt bearing strength appears to decrease as bolt diameters increase. Research done by Jumaat *et al.* (2006) found that there was a lack of correlation between bolt diameter and bolt bearing strength, as larger bolts exhibited lower bolt bearing capacity. However, a study by Sawata *et al.* (2002) revealed a different trend for bolts oriented parallel to the grain. In contrast, for bolts perpendicular to the grain, multiple investigations have observed a decrease in bolt bearing strength with increasing bolt diameter, likely attributed to the development of cracks. However, there is a lack of information regarding the influence of the bolt diameter and loading direction for tropical plantation species. Thus, there is an urgent need to have sufficient data regarding this study especially for tropical plantation species for their implementation in structural engineering use.

The withdrawal strength of a bolt refers to its ability to remain securely inserted in timber, effectively transferring stresses to the engaged timber fibers *via* its threads (Gutknecht *et al*. 2019). This capacity is influenced by several factors, including bolt diameter, the contact area between the bolt and timber, withdrawal speed, timber grain orientation, condition of the pre-drilled hole, insertion depth, and overall timber density (ASTM D1761 2020). Studies by Hassan *et al*. (2021) and Malek *et al*. (2016) have explored withdrawal capacity in glulam, specifically from Mengkulang species, examining how loading direction and bolt diameter affect performance. However, these studies use tropical nature species; thus, the withdrawal capacity in tropical plantation species is still uncertain. In terms of bolt diameters, the withdrawal capacity increases as the bolt diameters increase, based on study by Hassan *et al.* (2019). Experimental study by Shakimon *et al.* (2022) stated that the bolt with larger diameter has the highest withdrawal capacity compared to smaller bolt diameters. The withdrawal capacity has a positive correlation with the brittle failure, which is influenced by the diameter of the bolt. Study by Stamatopoulus *et al*. (2015) found that the withdrawal strength for parallel to grain is significantly smaller than the withdrawal strength for perpendicular to grain. Ringhofer and Schickhofer (2014) also reported that the performance of axially loaded screws inserted parallel to grain is very poor, especially for long-term purpose. These studies conclude that the withdrawal capacity of a bolt will be influenced by the bolt diameters and loading direction. In recent years, studies have been conducted on the withdrawal behavior of various types of fasteners embedded in timber elements. This research has focused on withdrawal capacity of bolts, focused on tropical plantation timber with the effect of bolt diameters and loading direction because there is limited information regarding to this topic.

Thus, this study aimed to evaluate the bolt bearing strength and withdrawal capacity of glulam specifically made from tropical plantation species, namely Laran (*Neolamarckia cadamba* spp.). Three different bolt diameters (12 mm, 16 mm, and 20 mm) loaded in different grain directions (parallel and perpendicular) were conducted in accordance with ASTM D5764-9a (2013) for bolt bearing strength and ASTM D1761-20 (2020). Later, Response Surface Methodology (RSM) was applied to propose the optimal bolt diameter for both parallel and perpendicular loading directions, considering bolt bearing strength and withdrawal capacity. This optimisation can serve as a recommendation for timber beam-to-column and beam-to-beam connections, whether loaded parallel or perpendicular to the grain direction. Understanding these properties is crucial as they directly influence the safety and performance of timber structures, mainly with the growing adoption of engineered timber products.

MATERIALS AND METHODOLOGY

This study was part of a series focused on testing glulam timber connections. The glulam wood samples tested for bolt bearing strength and withdrawal capacity were extracted from the glulam beams used in the connection tests. The timber species selected for both tests was laran, a tropical plantation species with density of 400 kg/m³ and classified as strength group SG5 (MS 544: Part 2 2001). Wood samples for both tests were tested in two loading directions, which are perpendicular to grain and parallel to grain. All wood samples were in dry condition (moisture content range between 10% and 11%).

Half-threaded hexagon-headed bolts (without nuts) of grade 8.8 with diameters of 12, 16, and 20 mm were used in these tests. The bolt yield strength (f_{yb}) and ultimate tensile strength (f_{ub}) were 640 MPa and 800 MPa, respectively. The threads on the bolt enhance bonding between the rod and timber by providing more grip due to their surface features (Stamatopoulos 2016).

Sample Preparation

For bolt bearing strength testing, each sample was sized at 4 *d* (width) × 4 *d* (length) × 2 *d* (thickness), where "*d*" represents the diameter of the bolt. The wood samples featured a half-hole on the surface, parallel to grain and perpendicular to grain which the bolt was placed during the test. All wood samples were prepared in accordance with ASTM D5764-97a (2013). Meanwhile for withdrawal capacity, 36 wood sample replicates were prepared for every loading direction, measuring 135 mm × 100 mm × 175 mm for perpendicular and 175 mm × 100 mm × 135 mm for parallel (width × length × thickness). All wood samples were drilled using a drilling machine at the marked location on the sample. The holes were made slightly smaller in diameter than the bolt's thread pitch, and the drill lengths matched the bolt's thread length. Then, the bolts were inserted into the pre-drilled holes using wrench slowly to avoid applying excessive force that could damage the bolt threads and allowing the bolts engage with the wood fibers properly. No nuts were utilised in this test. Only the threaded section in the bolt was embedded in the wood sample for the parallel and perpendicular to grain orientations. All wood samples were prepared in accordance with Eurocode 5 (EC5) (2008). Table 1 shows the wood sample specifications for bolt bearing strength test as well as for withdrawal capacity test.

Table 1. Sample Specifications for Bolt Bearing Strength Test and Withdrawal Capacity Test

Grain Direction	Bolt Diameter (mm)	Thread length (mm)	Bolt Bearing Strength		Withdrawal Capacity	
			Dimension (mm)	No. of Sample	Dimension (mm)	No. of Sample
Parallel	12	54	50 × 50 × 25	12	100 × 175 × 135	12
	16	61	70 × 70 × 40	12		12
	20	70	80 × 80 × 40	12		12
Perpendicular	12	54	50 × 50 × 25	12	175 × 100 × 135	12
	16	61	70 × 70 × 40	12		12
	20	70	80 × 80 × 40	12		12

Testing Procedures

Bolt bearing test

The bolt bearing strength was tested using a universal testing machine with load capacity of 50 kN at a constant rate of 1 mm/min for every sample. Figure 1 shows the bolt bearing strength test set-up on the universal testing machine at the laboratory. The test was stopped after the maximum load has been reached or when the moveable crosshead contacted with the sample's surface. Initial weight of the sample was recorded and oven-dried for 24 h and weighted to determine the moisture content and density. Failure modes and other important details were observed and recorded.

Fig. 1. Test set-up for bolt bearing strength test

The bearing yield for bolt bearing strength was then determined based on the offset line of deformation that equals to 5% of the bolt diameter according to the procedure stated in ASTM D5764-97a (2013), as presented in Fig. 2. Later, the bolt bearing strength was calculated using the Eq. 1.

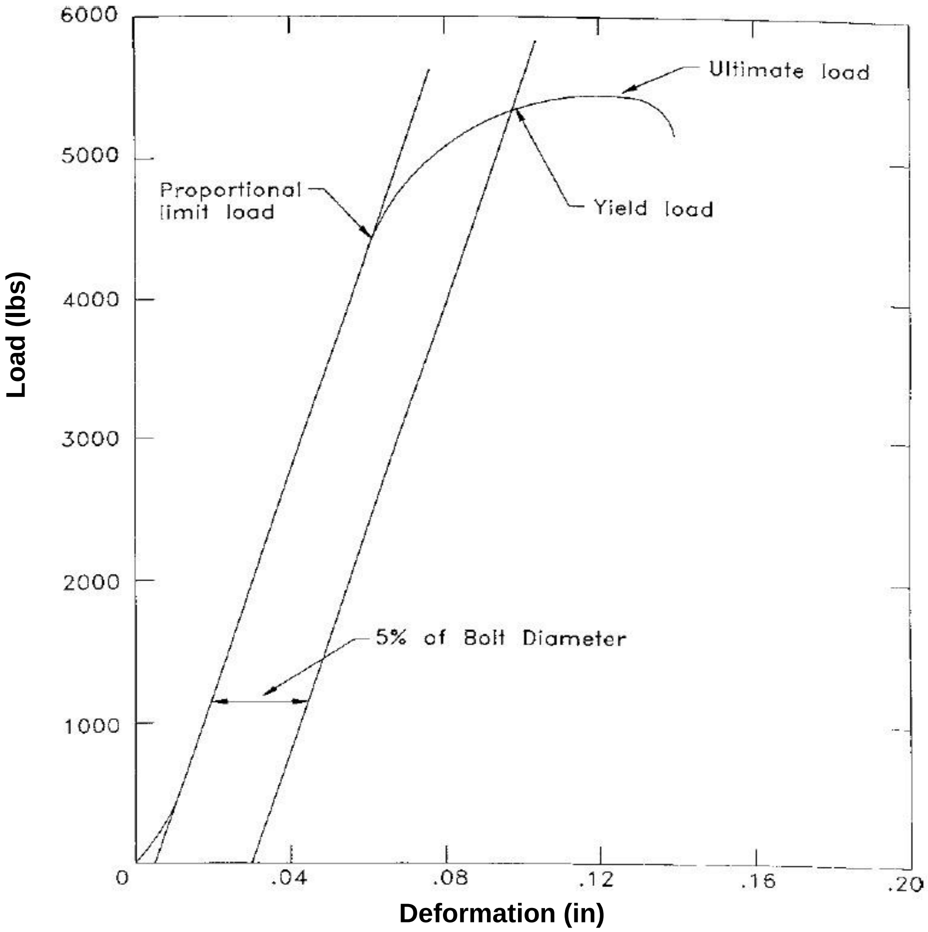


Fig. 2. Definition of load obtained from load-deformation curve (ASTM 5764-97, 2013)

$$F_y = F_{5\%}/dt \tag{1}$$

where F_y is bolt bearing strength (N/mm^2), $F_{5\%}$ is 5% offset load, d is diameter of the bolt (mm), and t is thickness of the sample (mm).

Withdrawal capacity test

The sample for withdrawal capacity testing was installed on a universal testing machine with a load capacity of 50 kN. The bolt's head was clamped at the mould, and two steel plates were placed above the glulam block to hold the sample. The sample was secured to avoid any movement during the testing. The bolt was pulled upwards at an adjusted rate based on the failure time between 5 to 7 min according to ASTM D1761-20 (2020). The load was applied until the sample failed. Failure pattern and maximum load was observed and recorded for each sample. Figure 3 shows the withdrawal capacity test set-up on the universal testing machine at the laboratory.

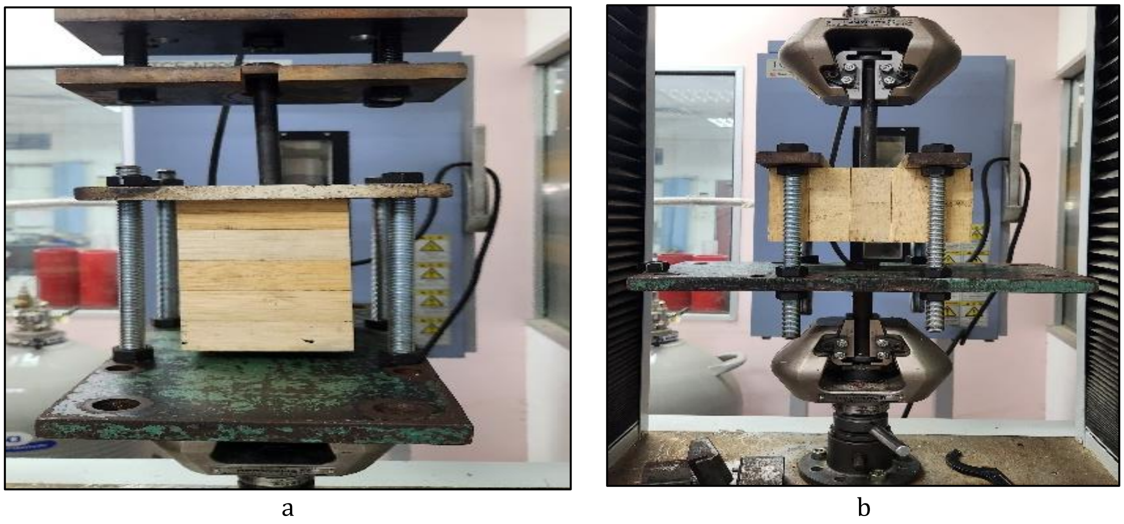


Fig. 3. Test set-up for withdrawal capacity test: a) perpendicular to grain; and b) parallel to grain

Withdrawal strength and withdrawal capacity of the samples were obtained using Eqs. 2 and 3 below,

$$F_{ax,k} = F_{max}/A \tag{2}$$

where $F_{ax,k}$ is withdrawal strength (kN/mm^2), F_{max} is max load (kN), and A is friction area between bolt and timber surface.

$$f_{ax,Rk} = f_{ax}.d.t_{pen} \tag{3}$$

In Eq. 3, $f_{ax,Rk}$ is withdrawal capacity (kN), f_{ax} is withdrawal strength (kN/mm^2), d is diameter of the bolt (mm), and t_{pen} is threaded length of bolt (mm).

Experimental design plotting and analysis

In the optimisation of bolt diameter between 12, 16, and 20 mm for both directions, the response surface methodology (RSM) analysis was utilised. The analysis involved creating mathematical models that illustrate the relationship between input variable (bolt diameter) and key outcomes, such as bolt bearing strength and withdrawal capacity, for each direction.

RESULTS AND DISCUSSION

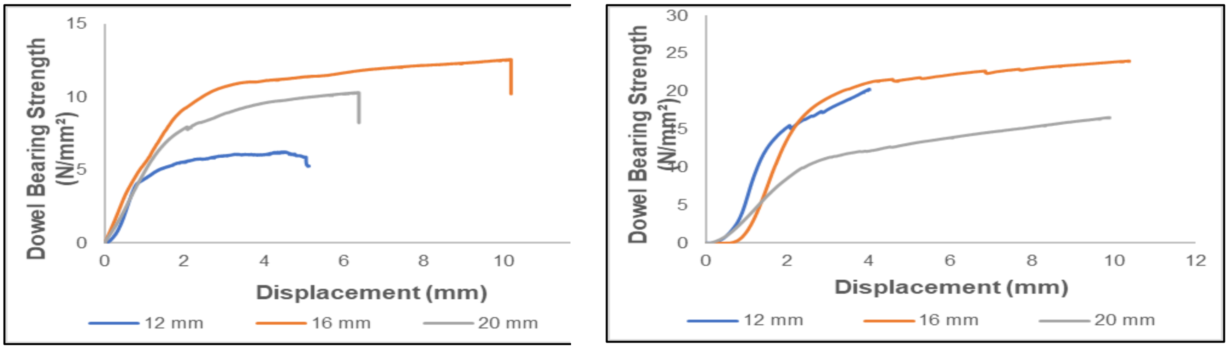
Bolt Bearing Strength

Table 2 shows the mean bolt bearing strength and the respective coefficients of variance (COV) of bearing strength for each bolt diameter and direction of load to grain. The value of mean bolt bearing strength, F_y was calculated according to Eq. 1. Based on the results, the bolt bearing strength in load perpendicular to grain direction exhibits higher value compared to that in load parallel to grain direction. Figure 4 shows the typical load deformation curves of Laran glulam for 12-, 16-, and 20-mm bolt diameter in both directions.

Table 2. Summary for Sample Bolt Bearing Strength Test

Bolt Diameter (mm)	Grain Direction	Mean Bolt Bearing Strength, *F*y (N/mm^2)
12	Parallel to Grain	6.01 (0.51) 8.41*
16		10.05 (1.15) 11.46*
20		6.78 (2.02) 29.79*
12	Perpendicular to Grain	16.65 (1.47) 8.80*
16		14.03 (2.37) 16.91*
20		7.21 (1.91) 26.50*

Note: Value in bracket shows standard deviation, meanwhile value with asterisk (*) is a coefficient of variance



a b

Fig. 4. Load deformation curves for 12 mm, 16 mm, and 20 mm bolt diameter samples: a) parallel to grain, b) perpendicular to grain

The COV for bolt bearing strength was generally lowest with a 12 mm diameter bolt (8.41%) and highest with a 20 mm diameter bolt (29.8%). In the load parallel to grain direction (Table 2), bolt bearing strength initially increased from a 12 mm (6.01 N/mm^2) to a 16 mm (10.05 N/mm^2) bolt diameter, but the strength decreased when the bolt diameter was 20 mm (6.78 N/mm^2). The decreases of bolt bearing strength in 20 mm bolt diameter was attributed to the larger surface area of the timber hole with larger bolt diameters, weakening the timber's strength limit. The pattern of findings is consistent with the study conducted by Herawati *et al*. (2022) on Terap, Durian, Midi, and Rubberwood species. In Fig. 4(a), the load increased linearly with displacement up to the bolt bearing yield load within a displacement of 2 mm. Beyond this point, the specimens failed abruptly and in a brittle manner.

Conversely, in perpendicular to grain direction, bolt diameter directly influenced bolt bearing strength. The 12 mm bolt diameter exhibited the highest bolt bearing strength (16.65 N/mm^2), followed by 16 mm (14.03 N/mm^2) and 20 mm (7.21 N/mm^2) bolt diameters, indicating a decrease in average bearing strength (F_y) as bolt diameter increases. This trend aligns with findings from Chew *et al*. (2016), where increasing bolt diameter led to reduced bolt bearing strength. These results highlight the critical interaction between bolt diameter and grain direction in determining bolt bearing strength within timber materials. Figure 4(b) shows the load-deformation curves behaviour that contrasts with samples loaded parallel to the grain, where the graph exhibited a decline after reaching its peak load. The load-displacement curves exhibited a continuous increase in loading following the yielding phase. For bolt diameters ranging from 12 mm to 20 mm, the plastic displacement of the curves initially increased and then flattened afterwards.

Withdrawal Capacity

Table 3 presents the mean values for withdrawal strength and capacity obtained from calculations for 12, 16, and 20 mm bolts in parallel and perpendicular to the grain. Withdrawal tests are essential for assessing the performance of various bolt diameters for direct withdrawal timber-based materials. Withdrawal capacity refers to the resistance to withdrawal force in a plane normal to the surface panel (Malek *et al*. 2020). Withdrawal capacity also affects the load carrying capacity of timber's connection, alongside with bolt bearing strength and bolt yield moment. The withdrawal strength, $F_{\mathrm{ax,k}}$ was determined using Eq. 2, and withdrawal capacity, $F_{\mathrm{ax,Rk}}$ was obtained by multiplying the withdrawal strength, $F_{\mathrm{ax,k}}$, with the diameter of bolts, d, and the penetration of the threaded part, t_{pen}, as shown in Eq. 3.

Table 3. Summary for Withdrawal Strength and Withdrawal Capacity

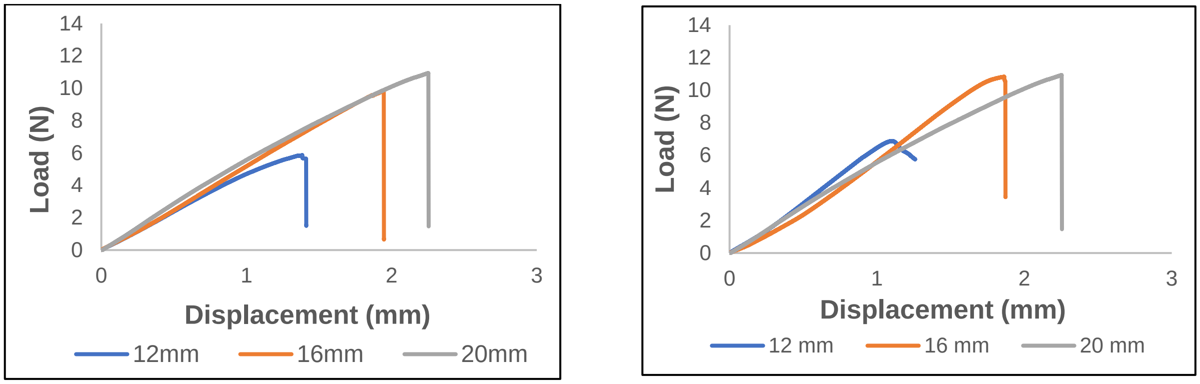
Bolt Diameter (mm)	Grain Direction	Max Load (kN)	Mean Withdrawal Strength ($F_{\mathrm{ax,k}}$) (MPa)	Mean Withdrawal Capacity ($F_{\mathrm{ax,Rk}}$) (kN)
12	Parallel to Grain	5.19 *26.72	62.25 *26.72	40.34 *26.72
16		8.16 *26.6	53.04 *26.6	51.76 *26.6
20		7.92 *26.47	32.94 *26.47	46.12 *26.47
12	Perpendicular to Grain	5.82 *15.4	69.89 *15.4	45.29 *15.4
16		9.15 *22.74	55.56 *22.74	54.23 *22.74
20		8.94 *23.22	37.18 *23.22	52.05 *23.22

Note: Value with asterisk (*) is a coefficient of variance

In Table 3, the withdrawal strength for parallel to grain was shown to be dependent to the bolt size diameter. As the bolt diameter increased from 12 to 20 mm, the withdrawal strength decreased from 62.2 MPa (12 mm) to 32.9 MPa (20 mm). Meanwhile for withdrawal capacity, the value initially increased from a 12 mm (40.3 kN) to a 16 mm (51.8 kN) bolt diameter but decreased when the bolt diameter was 20 mm (46.1 kN). This result suggests that bolt diameter did not have a remarkable impact on withdrawal capacity.

Withdrawal strength for the sample loaded perpendicular to grain showed the same pattern as sample loaded in parallel to grain. The withdrawal strength decreased from 69.9 to 37.2 MPa as the bolt diameter increased from 12 to 20 mm. As for withdrawal capacity, larger bolt diameter not necessarily will produce a higher value. The 20 mm (52.0 kN) bolt diameter showed slightly lower values than the 16 mm (54.2 kN) but still higher capacity than the 12 mm (45.3 kN) bolt diameter. These values agreed with a previous study by Shakimon *et al*. (2022), where the 16 mm bolt achieved the highest withdrawal capacity compared to 12 mm and 20 mm bolt diameters.

Figure 5 compares load-deformation curves for three bolt diameters across two loading directions—parallel and perpendicular to the grain. The line graph for samples loaded both parallel and perpendicular to the grain shows a proportional increase in load up to the maximum load, followed by a sudden drop. This abrupt decrease may be due to sample failure such as splitting or cracking. The bolt maintains strong integrity at the bottom of the timber hole, requiring a higher withdrawal strength to initially pull out the bolt, which leads to reaching the maximum load. The sample loaded parallel to the grain failed with less deformation compared to the sample loaded perpendicular because bolt withdrawal resistance was greater and forces were distributed along the grain direction, providing better resistance and smaller deformation. Previous studies have shown that bolts inserted perpendicular to the grain are stronger than those inserted parallel to the grain. This occurs because the uniaxial force transfer in the bolt inhibits force development in the weaker perpendicular grain direction, thereby reducing the likelihood of brittle failure modes (Sofi *et al.* 2021).

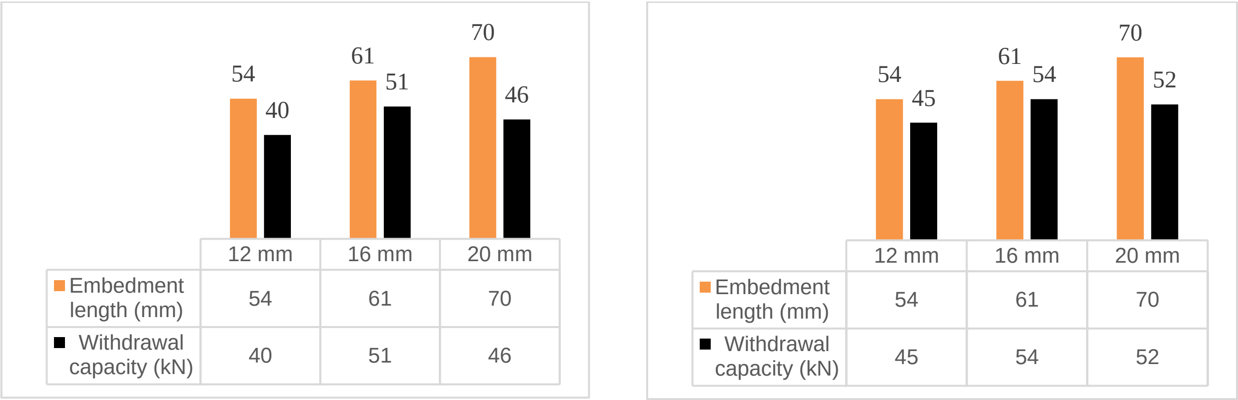


a b

Fig. 5. Load deformation curves for 12 mm, 16 mm, and 20 mm bolt diameters: a) parallel to grain, b) perpendicular to grain directions

Ratio of Bolt Diameter to Embedment Length

The ratio of bolt diameter to embedment length is a crucial factor influencing the withdrawal capacity. This ratio directly affects the shear stresses developed within the wood sample as the bolt is pulled out. Deeper embedment length typically increases withdrawal capacity, but this must be balanced with the timber capacity to hold the bolt without splitting. A larger bolt may need to be embedded more deeply to develop full strength, but the wood must be thick enough to accommodate this. However, a larger bolt in thinner wood increases the risk of fracturing or splitting, which reduces withdrawal capacity. Table 1 shows that 12 mm bolt diameter has shorter embedment length which is 54 mm embedment length compared to 16 mm and 20 mm that has longer embedment lengths which is 61 mm and 70 mm, respectively. Figure 6 illustrates relation between the embedment length for each diameter with the withdrawal capacity, for both loading directions.

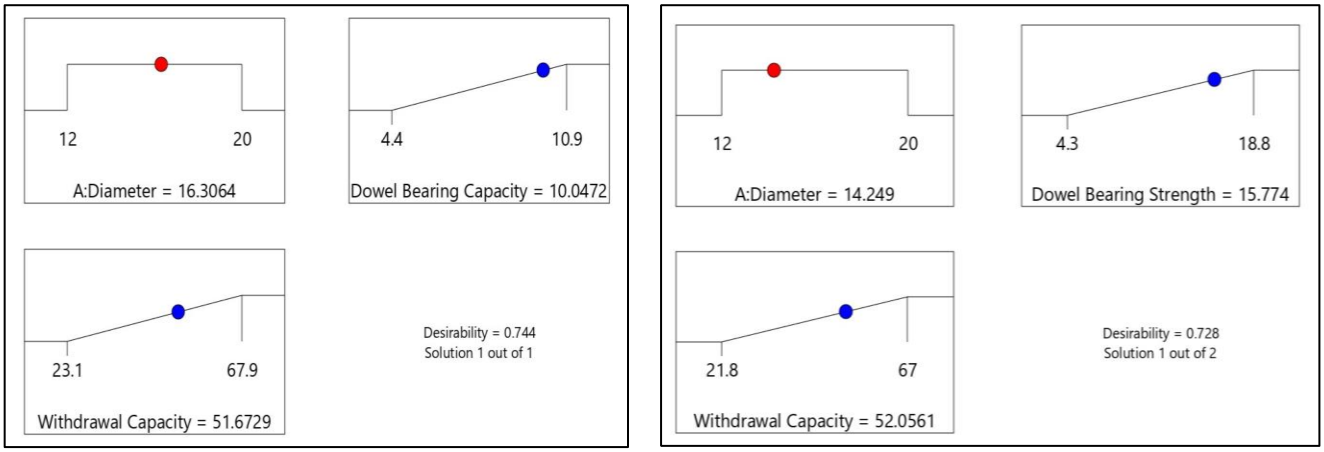


a) **b)**

Fig. 6. Relations between the embedment length and withdrawal capacity with bolt diameters in, a) parallel to grain b) perpendicular to grain

Embedment length is same as the thread length. The bigger size of bolt diameter gave rise to longer embedment depth, as shown in Fig. 6, but it was not guaranteed that it would produce a greater value of withdrawal capacity. In fact, a mid-sized bolt diameter (16 mm) produced highest value of withdrawal capacity (51 kN), even though the embedment length was shorter (61 mm) than max-sized diameter (20 mm) embedment length (70 mm). These statements can be supported by referring to previous research by Shakimon *et al.* (2022) where similar bolt diameters of 12, 16, and 20 mm, but different embedment length, were used. The embedment for 12, 16, and 20 mm were 39, 40, and 41 mm, respectively. Based on the study, an intermediate sized bolt diameter (16 mm) with embedment length of 40 mm conveyed the highest withdrawal capacity (667 N/mm) in comparison to max-sized diameter (20 mm) with embedment length of 41 mm in both direction, parallel and perpendicular. This means that the 16 mm bolt diameter provided a balanced diameter-to-embedment length ratio. In other words, it was a properly sized bolt with an adequate embedment length. A balanced combination of bolt diameter and embedment length maximizes withdrawal capacity. A properly sized bolt with a corresponding embedment length ensures that the withdrawal resistance is optimized without over-stressing either the wood or the bolt.

The RSM method was used to optimise responses, focusing on experimental design to accurately model relationships between inputs and outputs (Rosli *et al.* 2023). Based on Fig. 7 and data from Tables 2 and 3, the optimal bolt diameter for bolt bearing strength and withdrawal capacity were determined, in both directions. According to RSM, optimization was performed to determine the ideal bolt diameter by targeting a range from 12 to 20 mm by maximizing both bolt bearing strength and withdrawal capacity, then comparing the outcomes from actual studies with those from statistical experiments. Figure 7(a) shows the bolt bearing strength (10.05 N/mm^2) and withdrawal capacity (51.67 kN) when the bolt diameter targeted to 16.31 mm (≈16 mm) for parallel to grain. Meanwhile, the maximum bolt bearing strength and withdrawal capacity value for perpendicular to grain were found to be 15.8 N/mm^2 and 52.1 kN, respectively, as shown in Fig. 7(b) when the bolt diameter targeted to 14.2 mm (≈14 mm).



a **b**

Fig. 7. RSM analysis for two directions: a) parallel to grain; and b) perpendicular to grain

FAILURE MODES

Bolt Bearing Strength

Failure mode in bolt bearing strength tests revealed distinct patterns depending on the loading direction relative to the grain in glulam samples. Samples loaded perpendicular to the grain often exhibited cracking on the side, whereas those loaded parallel to the grain tended to split into two parts. This behaviour is attributed to the compression beneath the bolt exceeding tolerable limits, causing deformation and subsequent failure. Herawati *et al*. (2017) highlight these findings, underscoring the structural implications of loading direction on glulam performance. Figure 8 shows the typical failure of the sample for both directions.

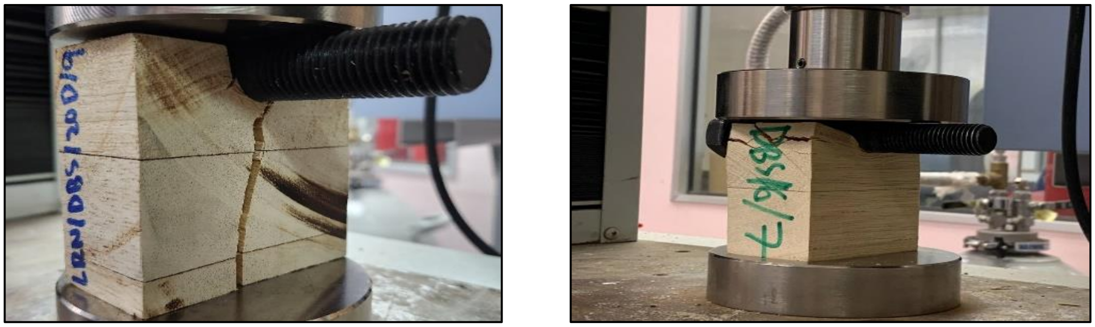

a b

Fig. 8. Typical failure of the sample: a) parallel to grain; and b) perpendicular to grain

Withdrawal Capacity

The bolts inserted into the glulam timber samples were tested until failure. It was noted that the 16 mm bolt diameter showed the highest resistance to withdrawal. It is worth mentioning that despite variations in bolt diameter sizes, load values, and displacements, nearly all samples exhibited a consistent failure pattern. Upon reaching maximum load capacity, the samples tended to crack and split in half. Figure 9 shows the observed failure patterns for both parallel and perpendicular loading directions relative to the grain.

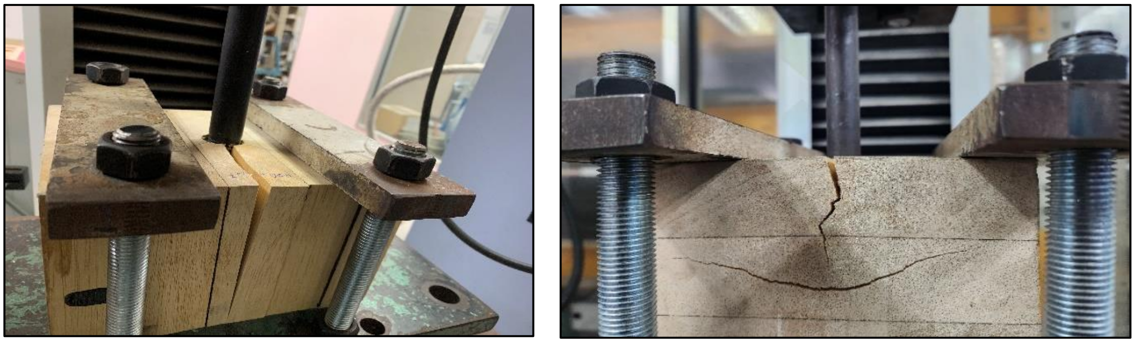

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Fig. 9. Typical failure of the sample: a) parallel to grain; and b) perpendicular to grain

A study from Malek *et al.* (2016) showed the same failure mode for withdrawal capacity test using Mengkulang glulam. The bolt detached from the glulam block along the predrilled holes before splitting in half. Failure was also observed along the glue lines, as the sample was made of glulam. In the present study, it was found that there was a sample crack on the timber first, before failure continued at the glue line. Figure 10 shows the sample that failed at the timber and glue line.

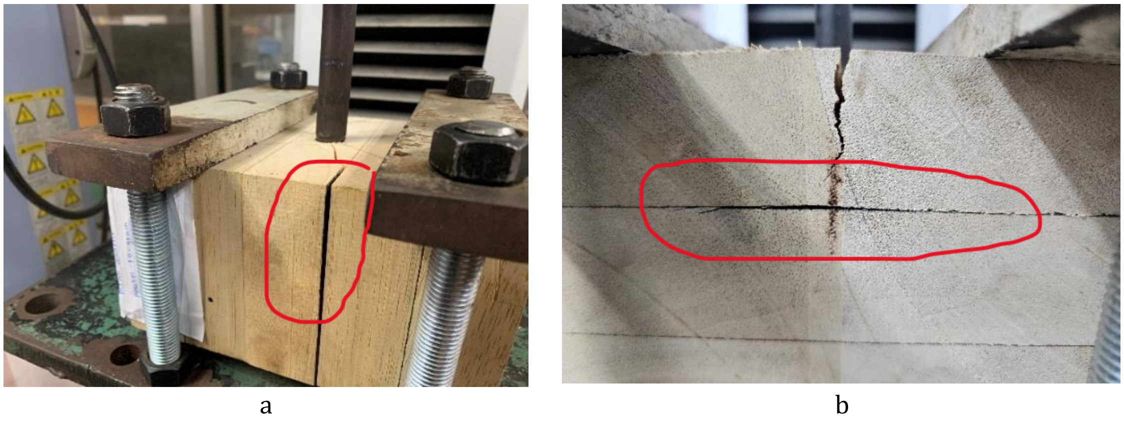
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Fig. 10. Sample that failed at the glue line: a) parallel to grain; and b) perpendicular to grain

CONCLUSIONS AND RECOMMENDATIONS

Based on the observations from the bolt bearing strength and withdrawal capacity tests, several conclusions can be drawn regarding the effect of bolt diameters and loading directions on laran glulam samples:

1. In parallel to grain direction, the mean bolt bearing strength of laran glulam was 6.01 N/mm² for 12 mm, 10.05 N/mm² for 16 mm, and 6.78 N/mm² for 20 mm bolt diameter.
2. Meanwhile for perpendicular to grain, the mean bolt bearing strength was 16.6 N/mm² for 12 mm, 14.0 N/mm² for 16 mm, and 7.21 N/mm² for 20 mm bolt diameter.
3. The 16 mm bolt diameter exhibited the highest withdrawal capacity in parallel to grain (51.8 kN), surpassing the withdrawal capacities of 12 mm (40.3 kN) and 20 mm (46.1 kN) bolt diameters.
4. Withdrawal capacity in perpendicular to grain demonstrated the same pattern as parallel to grain, where 16 mm bolt diameter showed the greater value (54.2 kN), exceeding the 12 mm (45.3 kN) and 20 mm (52.0 kN) bolt diameters
5. The results show that the 16 mm bolt had the best diameter-to-embedment length ratio compared to the 12 mm and 20 mm bolts. It achieved the highest withdrawal capacity, with the 12 mm bolt being too small and the 20 mm bolt being too large, making it the most effective for withdrawal capacity
6. The outcome from RSM showed that the optimised size of bolt diameter in parallel direction was 16 mm, whereas in perpendicular direction it was 14 mm, both for bolt bearing strength and withdrawal test.

The current specimen size is acknowledged as the limitation of the study, with a suggestion for future research to explore using wood specimens that are at least twice or four times as long to determine if the trends observed are same for larger sizes. Additionally, a brief speculation on how longer specimens might impact the outcomes should be included, while emphasizing the need for further investigation to confirm these effects.

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