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RESEARCH ARTICLE

Shear performance evaluation of Laran glulam beam-to-column T-Stub connector at different load positions

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ABSTRACT

Glued laminated timber (glulam) structures are increasingly favoured due to sustainability, lightweight properties, and excellent strength-to-weight ratio. Therefore, understanding the relationship between loading position, shear performance, and bearing strength of this structure is crucial for optimising structural connections and preventing premature failure. This study investigated the shear performance of beam-to-column connections using plantation-grown Laran glulam. Shear tests were conducted at two load application points: 160 mm (near the support) and 600 mm (in the cantilever region) from the column face. The results indicated that a shorter loading position (160 mm) leads to significantly higher shear stress values, ranging from 3.42 N/mm² to 3.91 N/mm², with a mean of 3.62 N/mm². In contrast, a longer loading position (600 mm) resulted in lower shear stress values, ranging between 0.24 N/mm² and 0.37 N/mm², with a mean of 0.33 N/mm². These findings indicated that reducing the load distance intensified stress concentration and affected the structural integrity. Additionally, these findings provided valuable insights into stress distribution and failure mechanisms in glulam structures. Identifying critical load distances can minimise stress concentrations; thus, optimising the connection design as proposed in this study can aid in improving structural stability and durability. Finally, these findings can serve as a reference for engineering guidelines and design standards, aiding in the development of more reliable glulam structures for practical applications in sustainable construction.

1. INTRODUCTION

Glued laminated timber (glulam) structures have become increasingly popular, owing to properties such as sustainability, lightweight, and excellent strength-to-weight ratio (Bhkari et al., 2016). Thus, it is crucial to understand the relationship between loading position, shear performance, and bearing strength to improve structural connections and prevent premature failure. In this study, the shear force (F) and shear strength (τ) of the beam-to-column T-stub connector specifically made from the tropical plant species, Laran (*Neolamarckia cadamba* spp.), at different distances of point load (160 mm and 600 mm).

The materials used for connection details, such as metal plates or bolts, must be compatible with glulam to ensure optimal performance, structural stability, and durability. Incompatibility can lead to issues such as corrosion or unintended movement between components. Historically, connection and structural failures have been proven catastrophic, as observed in the Hartford Civic Centre and the Hyatt Regency Hotel incidents (Moaveni & Chou, 2014). Since then, numerous studies have investigated the load distribution among connectors in mechanical timber joints of glulam structures as a significant factor influencing the overall capacity of the joint and structural stability (Iraola-Sáenz et al., 2016).

Beam-to-column connections are crucial in structural engineering due to the significant impact on the overall structural stability and performance. Specifically, T-stub connectors are widely used in various structural systems, including steel and timber constructions, due to the efficient load transfer, ductility, and strength (Stamatopoulos et al., 2010). Understanding the impact of connection design on structural stability is essential, as this component directly affects the shear performance and overall mechanical behaviour of glulam manufacturing.

The shear performance in glulam structures can be significantly enhanced through the use of proper connections. Zhang et al. (2023) demonstrated that slotted steel plate connectors substantially improved the rotational performance of bolted glulam beam-to-column joints, particularly upon exposure to a combination of bending and shear forces. Furthermore, studies on dowel-type fasteners and slotted-in steel plates indicated that these connections can effectively mitigate bending moments and enhance the stiffness of glulam assemblies, leading to improved shear performance (Rosdi et al., 2015; Malo et al., 2023; Wang et al., 2021). Recent studies by Zhang et al. (2018) also reported that these connections reduced the localised stress concentrations and promoted structural resilience under shear loading conditions.

The distance of the applied load position influences shear performance and subsequently stress distribution within glulam structures. Variations in load position can significantly impact the failure modes, potentially leading to a premature structural failure. When the load is applied closer to the connection, shear forces are more concentrated, increasing the chances of localised failure. A larger distance when applying load may introduce additional bending effects, altering the shear stress distribution and affecting overall joint performance.

In this study, shear tests were conducted using Laran glulam beam-to-column T-stub connectors at two load positions (160 mm and 600 mm) from the column face. Analysing the shear force and strength at these distances can aid in understanding the influence of different loads on the mechanical response of the connection. Subsequently, the effect of dowel bearing on the shear strength of the samples was observed. Understanding these properties is crucial to ensuring the safety and performance of timber structures due to the growing adoption of engineered timber products.

2. MATERIALS AND METHODS

This study assessed the shear strength in beam-to-column T-stub connector under different load positions from the column face. The beam-to-column connection samples were manufactured using Laran, a tropical timber species with a density of 400 kg/m³ and classified under strength group SG5 (MS 544: Part 2, 2001). The samples were subjected to unidirectional loading, perpendicular to the grain under dry conditions, with moisture content maintained between 10% and 11%.

Nine samples of beam-to-column T-stub connectors were manufactured and evaluated under different load positions (160 mm and 600 mm). Each sample was fitted with an S275-grade steel plate, with a flange thickness of 20 mm and a web thickness of 10 mm. Additionally, half-threaded hexagon bolts (with nuts and washers) of grade 8.8, with diameters of 16 mm, were utilised, as recommended by Amrudin et. al. (2024). The study reported that a 16 mm bolt diameter is optimal based on the response surface methodology (RSM) analysis, compared to 12 mm and 20 mm bolt diameters. The yield strengths of the steel plate and bolts ($f_{y,p}$ and $f_{y,b}$) were 275 MPa and 640 MPa, respectively. Meanwhile, the ultimate tensile strengths ($f_{u,p}$ and $f_{u,b}$) were 430 MPa and 800 MPa, respectively. The arrangement of bolts at the beam and column was designed based on the BS EN 1995-1-1 (2004).

2.1. Sample preparation

2.1.1 Glulam preparation

The Laran timber (n = 5) used in this study originated from Sapulut, Sabah, and was manufactured by Konsortium PEKA, Karak, Pahang, in accordance with MS 758 (2020). Phenol resorcinol formaldehyde (PRF) acted as the adhesive for glulam manufacturing. The dimensions of the glulam samples were 135 mm (width) × 175 mm (depth) × 600 mm (length), with a thickness of 35 mm. Figure 1 illustrates the flowchart of glulam beams manufacturing following the national standards (Rosli et al., 2023).

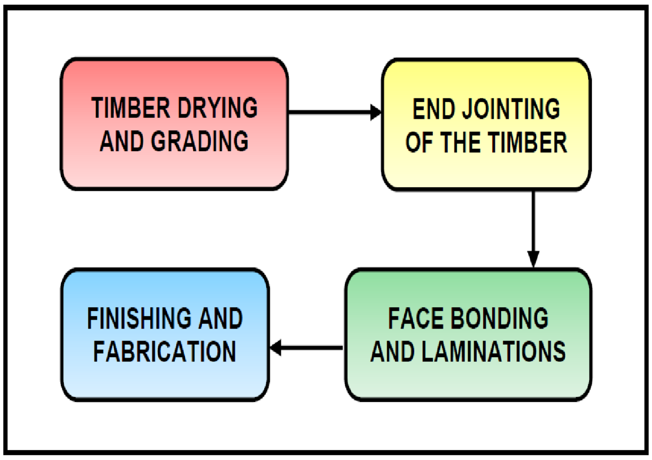


Figure 1: Glulam manufacturing (Rosli et al., 2023)

2.1.2 Welded t-stub

The dimensions for the T-stub manufactured for this study were as follows: flange member, 135 mm (width) × 295 mm (length) × 20 mm (thickness), and web member, 175 mm (width) × 210 mm (length) × 10 mm (thickness). Eight holes were drilled through the flange member and four holes on the web member using a factory drill and following the bolt diameter (16 mm). The steel plate was welded into a T-shaped stub with a weld thickness of 10 mm (see Figure 1). Figure 2 demonstrates the welded T-stub with holes. The welded thickness was designed based on BS EN 1993-1-8 (2005).

Figure 2: Welding process

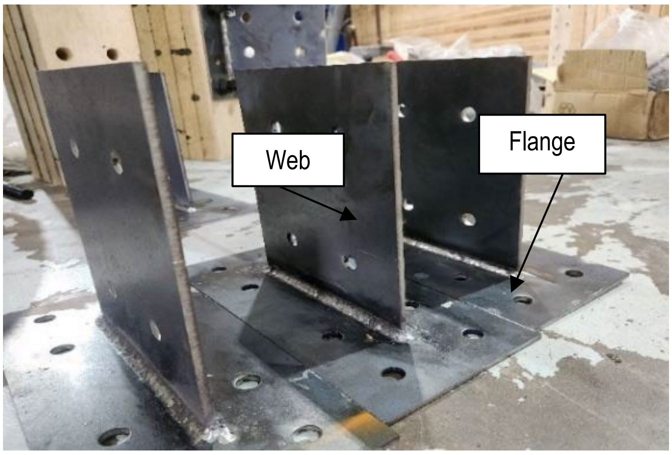


Figure 3: Welded T-stub

2.1.3 Beam-to-column connection

The dimensions for the beam-to-column connection sample were 175 mm × 135 mm × 600 mm, while the column measurements were 135 mm × 175 mm × 600 mm. The beam and column samples were prepared based on the resources available. A pre-drilled groove was made on each beam sample for T-stub web installation. The completed beam-to-column T-stub connector samples are presented in Figure 3. Eight and four pre-drilled holes were made at the column and beam surface, respectively, following the diameter of the bolt. Table 1 details the sample specifications for the beam-to-column T-stub connector.

Figure 4: Beam-to-Column Stub Connector

Table 1: Sample Specifications for Beam-to-Column T-stub Connector

Sample	Dimension (mm)	Bolt Diameter (mm)	Load Location (mm)	No. of Sample	
				160 mm	600 mm
Beam	175 × 135 × 600	16	160 & 600	3	3
Column	135 × 175 × 600			3	3
Steel Web	175 × 210 × 10			3	3
Steel Flange	135 × 195 × 20			3	3

2.2. Testing procedure

2.2.1 Shear test

The beam-to-column stub connector was tested under shear load at the closest and furthest distances without affecting the load head of the machine: 1) Free end of the beam (600 mm from the column face) and 2) Near the beam-column joint (160 mm). The column part was held to the strong wall using a steel plate (thickness: 20 mm) to avoid any movement during testing. In the first three setups, the load head was positioned 160 mm away from the column face, and a support was placed under the free end of the beam. Meanwhile, the second setup was 600 mm away from the column face, at the free end of the beam. Five linear variable displacement transducers (LVDTs) were attached to the column and beam and pointed at the selected distances. Firstly, LVDTs 1 and 2 were attached to the column face under the beam and pointed to the beam to measure any movement from the beam. Secondly, LVDTs 3 and 4 were attached to both sides of the column and pointed to the beam to measure the opening distance between the beam and the column. Finally, LVDT 5 was placed parallel to the load head under the beam to measure the load displacement.

The universal testing machine (UTM) with 1000 kN load was utilised to load the sample at a constant rate of 1.6 mm/min at both distances. Figure 4 illustrates the shear test set-up at both positions on the laboratory UTM. The shear test configurations were set up following Hassan (2011). Failure modes and maximum load achieved for all samples were observed and recorded. Each test was ended after the maximum load was achieved.

Results were evaluated based on the load-displacement curve obtained from the test. The plotted displacement curve was based on the outcomes of LVDT 5, which was located parallel to the load head. The shear force of the sample was obtained based on the maximum load of each sample before failure. The shear force value was then used to calculate the shear stress of the sample using equation 1:

$$Tau\tau = \frac{V}{A} \quad (1)$$

Where τ is shear stress (N/mm^2), V is shear force or maximum load, and A is area of beam cross section (mm).

The values obtained at each distance were compared at the end of the experiment.

Equation 2 was used to calculate the total shear capacity to determine the safety of the connection. Subsequently, equation 3 was used to calculate the bearing resistance of the dowel, as proposed by Amrudin et al. (2024).

$$V_{Rd} = n \times F_{h,Rd} \quad (2)$$

$$F_{h,Rd} = \frac{d.t.f_h}{\gamma_m} \quad (3)$$

Where n is the number of bolts at the shear plane, γ_M is the partial safety factor for timber in BS EN 1993-1-8 (2005), d is the bolt diameter (16 mm), t is the beam thickness, and f_h is the dowel bearing strength perpendicular to the grain of the bolt (16 mm).

(a)

(b)

Figure 5: Test set-up for shear test in two different locations of point load: a) 160 mm, b) 600 mm

3. RESULTS AND DISCUSSION

3.1 Shear Force

The shear test results for the beam-to-column T-stub connector samples demonstrated that shear forces were associated with loading position. Table 2 highlights a significant difference in shear force values between samples loaded at 160 mm and 600 mm from the column face.

Table 2: Summary for Sample Beam-to-Column T-stub Connector Shear Test

Location (mm)	160			600		
Sample	ST/1a	ST/1b	ST/1c	ST/2a	ST/2b	ST/2c
Shear force, V (kN)	80.8	83.39	92.39	8.73	8.73	5.71
Mean	85.51 (6.06) 7.08*			7.72 (1.74) 22.58*		

Note: Values in brackets show standard deviation, while values with an asterisk (*) represent a coefficient of variance

Shear force can be defined as the internal force parallel to a surface that slides or deforms one part of a surface relative to another (Ernst & Ernst 2025). Based on the findings, the average shear force at 160 mm was significantly higher (85.51 kN) than at 600 mm (7.72 kN). These outcomes indicated that the samples loaded closer to the column face (160 mm) exhibited significantly higher shear resistance than those at 600 mm. This finding aligns with well-established structural mechanics principles, as shear forces in beams are greatest near the supports and decrease progressively toward the free end. Furthermore, the reports by Furlong (2007) stated that shear forces were highest at the beam support and decreased in proportion to the load distribution along the beam length. Szotkowski (2021) also stated that loads applied closer to the beam-column joint result in higher shear forces and stresses concentrated at the joint region. Consequently, the intensity of forces transferred through the shear connectors increased, including bolts at the connection.

Another notable aspect of the dataset is the variation in shear force values within each loading condition. For instance, individual shear forces range from 80.8 kN to 92.39 kN at 160 mm, with a standard deviation of 6.06 and a coefficient of variance (CoV) of 7.08 %. Conversely, the shear forces were substantially lower at 600 mm, with values ranging from 5.71 kN to 8.73 kN, with a standard deviation (SD) of 1.74 and a coefficient of variance (CoV) of 22.58 %. The CoV for this set recorded a much higher level of dispersion, indicating greater inconsistency in shear performance at this loading distance (600 mm). The SD values indicated the extent of data variation. A small SD suggests that the data values are consistently close to the average, indicating uniformity in the dataset. In this study, the SD of the 160 mm loading position is higher (6.06) than the SD of the 600 mm (1.74). These outcomes indicated greater variability in shear performance at a shorter loading distance, potentially attributed to localised stress concentration near the connection that led to unpredictable failure mechanisms. Furthermore, material inconsistencies in the glulam structure significantly impacted the load distribution at shorter distances.

The load-displacement curves presented in Figure 5 provide valuable insights into the shear behaviour of beam-to-column T-stub connectors at different loading distances.

These curves reflected the structural response under shear forces, highlighting the effects of loading position on shear resistance and deformation characteristics.

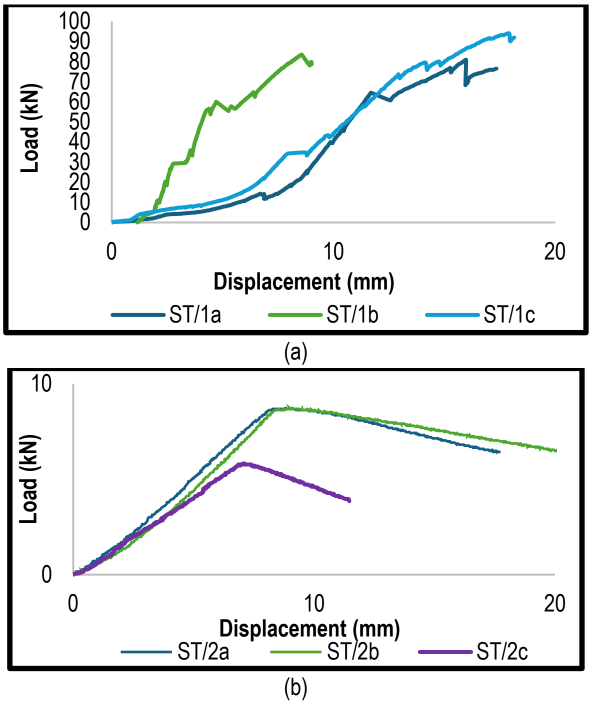


Figure 6: Load deformation curves for individual shear forces at different locations: a) 160 mm, b) 600 mm

The load-displacement curve for the 160 mm loading position demonstrated significant variability in shear performance across three samples (ST/1a, ST/1b, and ST/1c), with peak loads recorded at 80.8 kN, 83.39 kN, and 92.39 kN, respectively. Following peak load, the curves exhibited a gradual reduction in load capacity, suggesting that the structure retains some residual strength after primary failure. The presence of multiple load drops (drop cracks) along the curves suggested unstable failure mechanisms, likely attributed to progressive fibre racking and localised stress concentrations in the glulam samples. Continuous fibre cracking was observed during testing, leading to successive drops in load capacity. This behaviour is indicative of a brittle failure mode, where crack initiation and propagation occurred in a stepwise manner instead of a single failure.

The load-displacement curve at the 600 mm loading position exhibited a more stable and consistent response compared to the 160 mm loading position. Two samples (ST/2a and ST/2b) recorded an identical peak load of 8.73 kN, while ST/2c reached a lower peak load of 5.71 kN. Unlike the multiple sudden load drops observed at 160 mm, this graph demonstrated a smoother progression of load application with minimal fluctuations**.** The linear elastic region of all three curves followed a similar trend, indicating uniform stiffness in the initial loading phase. As the applied load increased, the curves reached the respective peak load values, after which a gradual decline in load capacity was observed. The smoother post-peak behaviour suggested a superior controlled failure mechanism, potentially dominated by material yielding rather than sudden fibre cracking. In contrast to the lack of significant drop cracks at 160 mm loading position, the shear stress is more evenly distributed at longer loading distances, thus reducing the likelihood of sudden failure events.

3.2 Shear Strength

Shear strength is the maximum load required for the sample to completely shear, divided by the shearing cross section (Murphy, 2001). Shear strength of structural elements is a fundamental parameter in the design of beam members, particularly timber structures, to ensure that beams can resist loads without failing. The shear stress, τ, and the mean values of shear stress, τ_{mean}, of each sample at different locations are detailed in Table 3, as calculated using Equation 1.

Table 3: Summary of Shear Stress, τ, at different loading distances

Sample	Load Location (mm)	Shear Stress (N/mm²)	Mean Shear Stress, τ_{mean}
ST/1a	160	3.42	3.62 (0.21) 0.06*
ST/1b		3.53	
ST/1c		3.91	
ST/2a	600	0.37	0.33 (0.06) 0.004*
ST/2b		0.37	
ST/2c		0.24	

Note: Values in brackets show standard deviation, while values with an asterisk (*) represent a coefficient of variance

The 160 mm loading position exhibited significantly higher shear stress values, ranging from 3.42 N/mm² to 3.91 N/mm², with a mean of 3.62 N/mm². In contrast, the shear stress values are significantly lower at the 600 mm loading position, ranging from 0.24 to 0.37 N/mm²**,** with a mean shear stress of 0.33 N/mm², a standard deviation of 0.06, and a coefficient of variation (COV) of 0.004. These outcomes indicated that a shorter load distance intensified stress concentration within the material. Main and Sadek (2013) supported these findings, reporting that shorter spans or loads close to the joint often improved load capacity of shear connections, while longer spans or farther loads showed reduced capacity due to increased deformations imposed on the connection. As the load position moves farther from the column, shear strength decreases due to reduced force concentration near the joint and changes in stress distribution (Crocetti et al., 2010; Yang et al., 2020a).

The standard deviation at 160 mm (0.21) is notably higher than at 600 mm (0.06), suggesting greater variability in stress distribution for the shorter load position. Furthermore, the COV for 160 mm (0.06) was considerably larger than for 600 mm (0.004), reflecting a more inconsistent stress response at the shorter distance. This finding aligns with the frequent load drops in the load displacement curve, indicating material cracking and localised failures. Conversely, the lower SD and COV at 600 mm suggested a more uniform shear stress distribution, consistent with smoother failure behaviour in the load-displacement curve.

The bearing resistance per dowel can be calculated using equation (3):

$$F_{h,Rd} = \frac{d.t.f_h}{\gamma_m}$$
$$F_{h,Rd} = \frac{16.175.14.8}{1.3}$$
$$F_{h,Rd} = 31.88\ kN\ /\ dowel$$

This value is used to obtain the total shear capacity of the connection can be obtained by using equation (2):

$$V_{Rd} = n \times F_{h,Rd}$$
$$V_{Rd} = 8 \times 31.88$$
$$V_{Rd} = 255.02\ kN$$

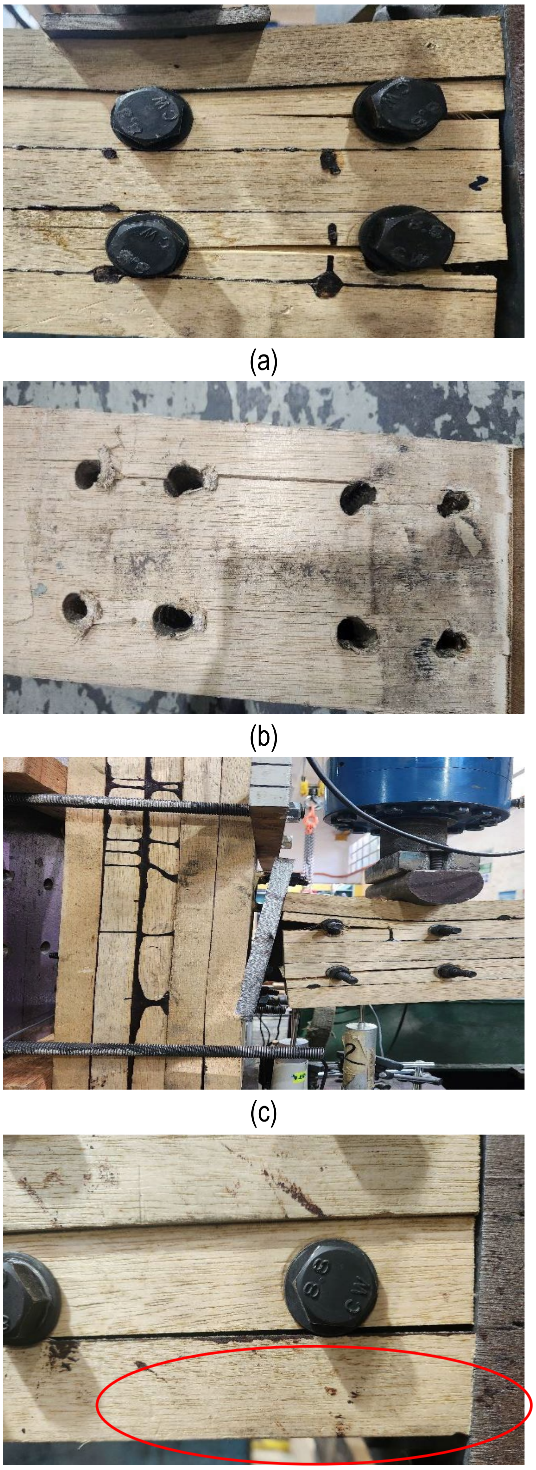
These findings highlighted the critical interaction between shear performance and bearing strength, as the intensified stress concentration at the 160 mm loading position potentially contributed to localised crushing and material failure near the contact area. The maximum value of shear force between the six samples was 92.39 kN (see Table 2). As V = 92.39 kN and V_{Rd} = 255.02 kN, the design was considered safe under the given loading conditions.

The dowel bearing strength is a critical factor in determining the shear performance of beam-to-column stub connectors in timber structures. Dowel action facilitates load transfer within the connection, and the bearing resistance directly influences the overall shear capacity. For instance, a study by Seri et al. (2016) demonstrated that dowel-bearing strength was essential for evaluating the performance of wood connections, particularly the effects of different bolt diameters on shear capacities. In this study, the dowel bearing strength was referenced from the study conducted by Amrudin et. al. (2024), which reported that a 16 mm bolt diameter provided optimal performance in glulam connections. Specifically, the reported mean dowel bearing strength for 16 mm bolt diameter loaded perpendicular to the grain was 14.03 kN/m^2.

Understanding the interaction between load position, shear force, shear stress and dowel performance provides essential guidelines for designing efficient and safe timber joints in real construction settings. These outcomes are directly applicable in structural engineering practices, particularly for prefabricated timber elements, where accurate connection detailing is crucial to ensure long-term performance and compliance with structural codes

4. FAILURE MODE

All test samples experienced fractures when tested under shear load at 160 mm and 600 mm, where the failure modes were relatively similar (see Figure 6). Samples at the 160 mm load location underwent severe damage at the joint area, characterised by splitting, bearing, shear, and glue line failure. Samples at the 600 mm load location also demonstrated the same failure mode as the other samples.



(a) (b) (c) (d)

Figure 7: Failure modes: a) Splitting, b) Bearing failure, c) Shear failure, and d) Glue line failure

When a glulam beam was subjected to shear force and bending moment, failure occurred due to the development of cracks and splitting (see Figure 6a) caused by high tensile stress perpendicular to the grain and shear stresses (Okamoto et al., 2022). The cracks continued to propagate, seeking the weakest point within the material until ultimate failure. Bearing failure (see Figure 6b) occurred when the timber in contact with the bolt was crushed when the material reached the bearing strength limit (Yang et al., 2020b). Bearing failure was initiated near the hole edge, caused by the formation of high stress concentration zones at the affected locations. A study by Lam et al. (2008) reported relatively similar failure modes when the load was applied at the free end of the beam. Finally, most samples experienced glue line failure (see Figure 6d), which was also observed along the glue line as the samples were made of glulam.

5. CONCLUSION AND RECOMMENDATIONS

Several conclusions can be drawn regarding the effects of loading placement on the shear force and shear strength towards the beam-to-column T-stub connector of Laran glulam under shear load:

1. At a loading distance of 160 mm, the mean shear force of the beam-to-column T-stub connector made from Laran glulam was 85.51 kN.
2. The mean shear force of the beam-to-column T-stub connector of Laran glulam at a loading distance of 600 mm was 7.72 kN.
3. These results indicated that the shear force nearer to the support was higher when a point load was applied closer to the support, compared to the load application at a longer distance. These outcomes were potentially attributed to the direct relationship between the load position and the shear force distribution under such loading conditions.
4. The shear strength of the beam-to-column T-stub connector made from Laran glulam at 160 mm loading distance was the highest (3619.47 kN/m^2) in this study, surpassing the shear strength value at 600 mm (326.91 kN/m^2).

Based on the current findings, future research can explore other load positions along the beam span to provide a comprehensive understanding of shear distribution. The findings can aid in refining the design parameters for varying real-world load scenarios involving the beam-to-column T-stub connector of Laran glulam.

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