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Kajian Eksperimental Kegagalan Sambungan Balok-Kolom Bambu Laminasi *Hollow Section* Menggunakan *Glue in Rod-Bracket*

(*Experimental Study on the Failure of Bamboo Laminated Hollow Section Beam-Column Joints using Glue-in-Rod Bracket*)

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ABSTRACT

Building materials that emit pollutants, are non-renewable, and generate environmental waste require attention. Wood, a popular and natural material, is facing increasing scarcity, necessitating a substitute. Laminated bamboo emerges as the most akin and natural alternative to wood. Research into laminated bamboo encompasses diverse cross-sections, joint types, and field applications, demanding further investigation. This study aimed to ascertain failure types and damage patterns in laminated bamboo hollow section beam-column joints modified with glue-in rod-bracket connections, using petung bamboo (dendrocalamus asper). The research employed an experimental approach with descriptive analysis. Joint failures were evaluated based on moment-rotation relationships within prescribed rotational limits per standards, while joint damage was assessed through visual inspection of joint components.The study's dependent variables included thread rod diameters of 6 mm, 8 mm, & 10 mm, and 4 & 6 embedded thread rods, while the independent variables were failure types and joint collapses. Results revealed serviceability failures in samples 8.6, 10.4, and 10.6. Joint damage across all test specimens primarily manifested as broken thread rods. The highest joint strength observed was 6.28 kNm in sample 10.6, with the lowest at 2.25 kNm in sample 6.4.Based on the findings, increasing thread rod diameters to achieve ductile joints resulted in longer rotations but did not meet the planned strength due to bracket-induced prying effects causing bolt head failure. Despite this, the collapse type aligned with the research plan. Addressing the bracket's fulcrum effect during field applications requires solutions, potentially involving enlarging the bracket's base and increasing the number of thread rod points. The tests did not damage the laminated bamboo components, emphasizing the need to consider laminated bamboo cross-sectional dimensions and thread rod fulcrum effects in subsequent tests to ensure uniform component performance.

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1. INTRODUCTON

Building materials today face issues such as emitting emissions when applied, being environmentally unfriendly, and non-renewable. Natural materials that have been used for a long time and are still popular include wood, but the current limitations of wood [1] call for renewable and eco-friendly material solutions. Alternatives range from aluminum, and wood-plastic composites (WPC), to laminated bamboo. Laminated bamboo is chosen due to its rapid harvest in 3 to 5 years [2], easy growth, especially in Asia [3], and mechanical properties identical to wood, such as wood's orthotropic nature [4].

Laminated bamboo is made from a collection of bamboo that is arranged and bonded together into various desired profiles. Laminated bamboo exhibits physical properties similar to wood. Bambu petung (Dendrocalamus asper), for example, has a density of 0.55 g/cm³ and a moisture content of 11% [5], which, when compared to the teak wood with a density of 0.54 g/cm³ and a moisture content of 16.5%[6]. Highlights its favorable characteristics. The choice of laminated bambu petung offers superior mechanical properties compared to regular bamboo [7].

Research on the forms of laminated bamboo is rapidly advancing. Laminated bamboo can take on various shapes, including solid forms capable of supporting an average maximum load of 55.59 kN [8]. It can also be shaped into I-profiles, boards, and hollow sections with a modulus of elasticity (MOE) of approximately 11.537 GPa [9] , and Studies have shown that edge thickening in 1/3 of the span enhances the strength of hollow-section laminated bamboo [10]. Among the various forms of hollow section laminated bamboo studied, a ratio of b:h around 1.5 has been found to be the most efficient, resulting in a MOE of 14.504 GPa and a modulus of rupture (MOR) of approximately 106.5 MPa [11]. The calculation formula for laminated bamboo forms is as follows.

$$M = S_x \; x \; \sigma_b \quad \text{(1)}$$

$$S_x = \frac{I_x}{y} \quad \text{(2)}$$

$$I_x = \frac{1}{12}\;(bd^3 - ah^3) \quad \text{(3)}$$

M = Bending Strength (N), Sx = Elastic Modulus of Section (mm^3), Ix = Sectional Moment of Inertia, y = Midpoint (mm), b = Width of Section (mm), d = Height of Section (mm), a = Width of Hollow (mm), h = Height of Hollow (mm).

Using laminated bamboo as a structural element requires connectors or joints. The most relevant joint for laminated bamboo is the glue-in rod joint. Research on glue-in rod joints, including the diameter and adhesive thickness, has an impact on strength [12]. Studies on the edge-to-edge distance for the installation of glue-in rods have shown a consistent increase when placed at a distance of 3d [13]. According to ASTM D1761-88 [14] the formula for installing glue-in rods is as follows.

$$F = f_v \; x \; s \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (4)$$

$$untuk, S = L_a \; x \; \pi \; x \; d_a \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (5)$$

F = Force Value (N), Fv = Shear Strength (N/mm^2), S = Bonded Area Value, L_a = Bonding Length (mm), d_a = Hole Diameter (mm).

Furthermore, brackets are needed to facilitate easy disassembly and assembly (knock-down) of the joint. The modified brackets in the study are bowl-shaped, as shown in Figure 1. The formula for the bracket refers to the lever effect, also known as prying [15] [16] with the formula as follows.

$$t_{min} = \sqrt{\frac{4.44Tb'}{pFu}} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (6)$$

tmin = Minimum Wing Plate Thickness (mm), T = Tensile Force Acting (N), b' = Distance (mm), p = Width of the Examined Bolt's Tributary (mm), *Fu*= Ultimate Plate Stress (Mpa).

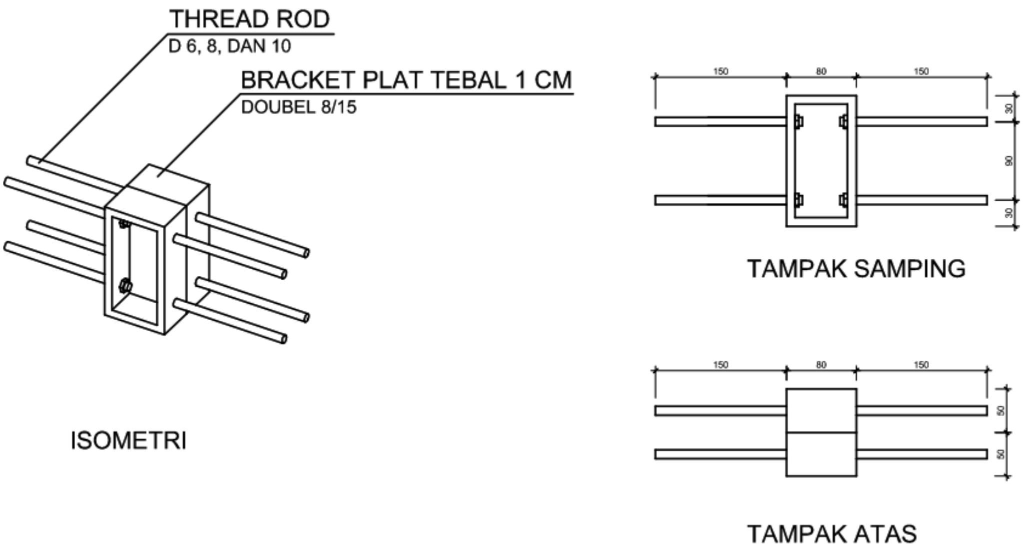


Figure 1. Bracket and Thread Rod

The purpose of this research is to investigate the behavior of the joint, particularly the types of failure and the failure modes of the joint. The joint consists of three components: laminated bamboo, glue-in rods, and brackets. This study focuses on the glue-in rod and bracket components, with an approach based on the strength calculation of "laminated bamboo > glue-in rod < bracket."

The types of failure that occur in laminated bamboo refer to ASTM D-143-94 [17]. These failure modes include (a) simple tension failure, (b) cross-grain tension failure, (c) uniform failure resulting in fracture, (d) beam shear failure, (e) compressive failure, and (f) horizontal shear failure. Since the dominant loading will be flexural, the potential failure is simple tension, as illustrated in Figure 2.

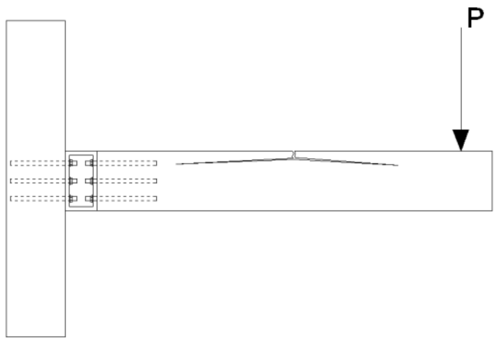


Figure 2. The Potential Failure of Test Specimen

As for the types of failure that occur in glue-in rods, they are based on previous research [17]. There are several types of failure, including (a) bolt failure, (b) ultimate longitudinal wood failure, (c) wood splitting, and (d) tensile rupture of wood over the cross-section. You can refer to Figure 3 by Gattesco et al. for illustrations.[17]

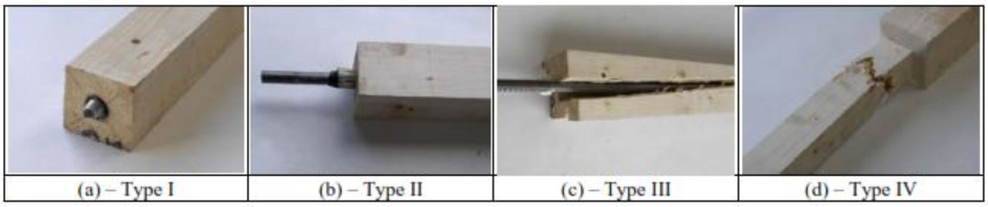


Figure 3. Test Specimen Failure Potential

As for the types of failure that occur in brackets, referring to the Steel Structures and Behavior literature [16], there are seven types of failure: bolt shear failure, plate shear failure, bolt bearing failure, plate bearing failure, bolt tensile failure, bolt flexural failure, and plate tensile failure. Based on this, the potential failures that occur around the bracket are (a) tensile rupture failure at the bolt and (b) hole-pulling failure at the plate. The failure modes between the bracket and the bolt can be seen in Figure 4.

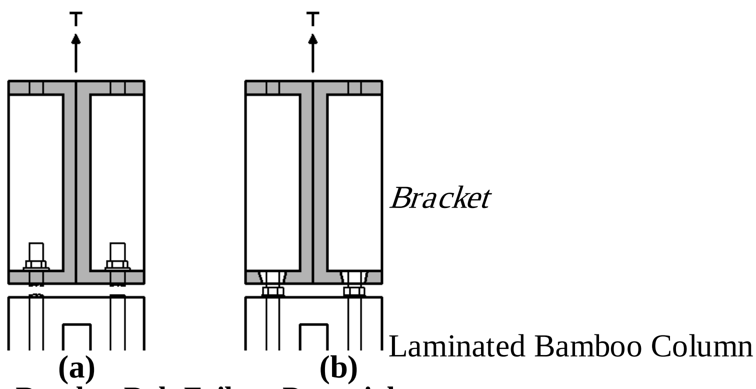


Figure 4. Bracket-Bolt Failure Potential

The types of failure that occur in the joint are when the joint is unable to fulfill its role (serviceability failure). Failure occurs when the joint exceeds the standard rotation or can no longer support the applied load. The failure referred to here is when the joint has exceeded the standard rotation limit of 0.03 radians according to AISC [18].

2. RESEARCH METHODS

The research conducted is an experimental study on the failure of laminated bamboo hollow section beam-column joints using glue-in rods and brackets. A descriptive analysis method is employed to understand the joints' failures concerning existing standards. The independent variables in the research are the number of embedded thread rods and the diameter of the thread rods, while the dependent variables are the types of joint failure and failure modes. The flowchart of the research can be seen in Figure 5.

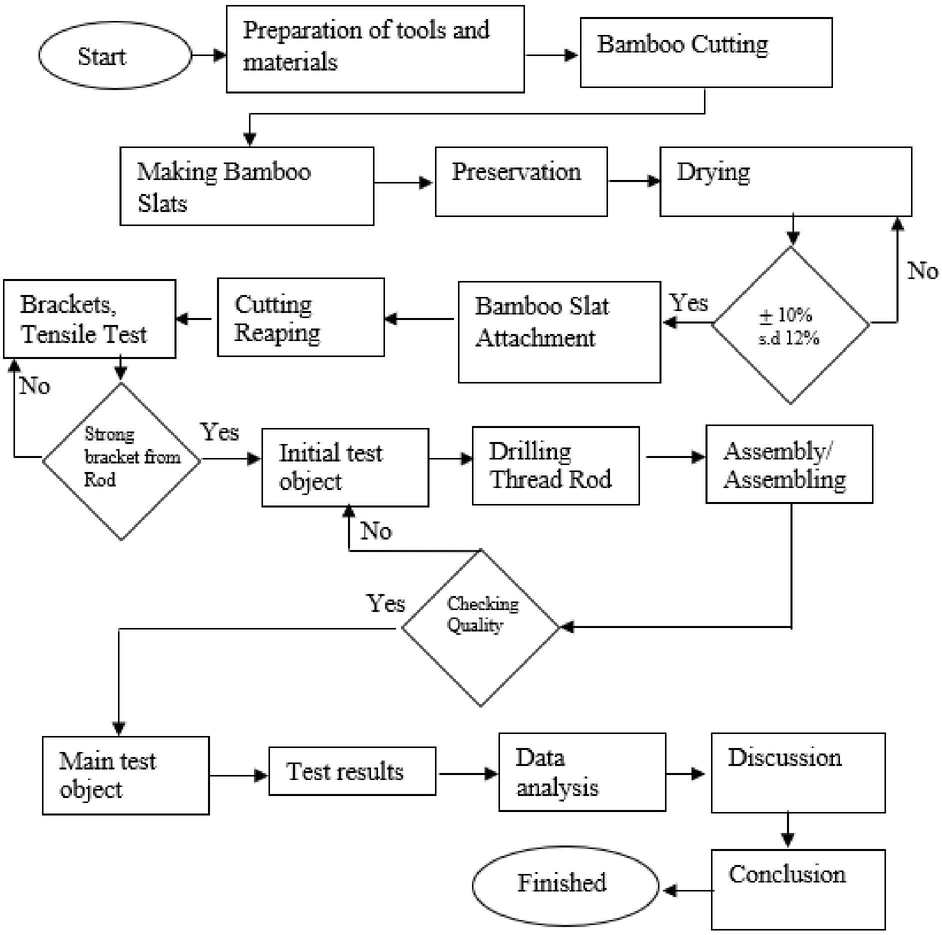


Figure 5. Research Flowchart

2.1. The research subject

The research subject is the connection of laminated bamboo hollow section beams and columns using glue-in rods and brackets. The laminated bamboo is in the form of a hollow section with dimensions of 10 cm x 15 cm x 100 cm as the beam-column element, as depicted in Figure 6. The embedded thread rods are in quantities of 4 and 6, with diameters of 6 mm, 8 mm, and 10 mm, as illustrated in Figure 7. Modifications to the connection brackets can be seen in Figure 1. Details of the research object samples that have been conducted are provided in Table 1.

Table 1. List of Research Object Samples

No	Diameter *Thread rod* (mm)	Beam-Column Dimensions (cm)	Number of Thread Rods	Specimen Code
1	6	10x15x100	4	6.4.1
2	6			6.4.2
3	6			6.4.3
4	6		6	6.6.1
5	6			6.6.2
6	6			6.6.3
7	8	10x15x100	4	8.4.1
8	8			8.4.2
9	8			8.4.3
10	8		6	8.6.1
11	8			8.6.2
12	8			8.6.3
13	10	10x15x100	4	10.4.1
14	10			10.4.2
15	10			10.4.3
16	10		6	10.6.1
17	10			10.6.2
18	10			10.6.3

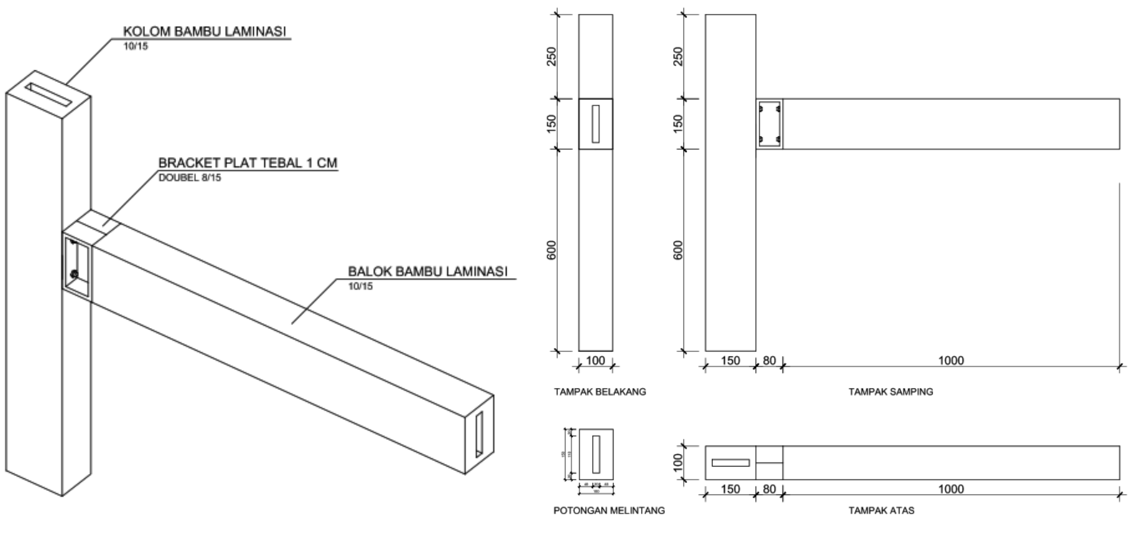
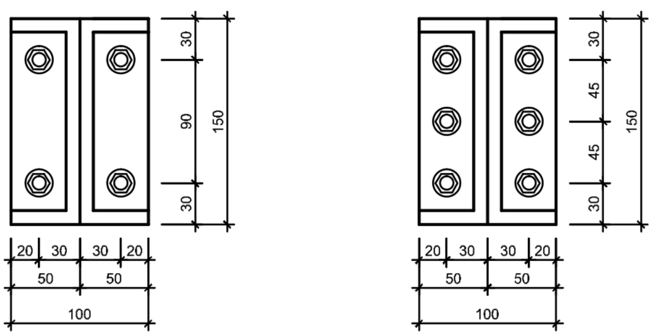


Figure 6. Laminated Bamboo and Connections



(a) 4 *Thread Rods* **(b)** 6 *Thread Rods*

Figure 7. Laminated Bamboo and Connections

2.2. Data Collection Method and Instruments Used

Data collection was conducted through observation. Manually, displacement data and angular rotation were read from the dial gauge and installed inclinometer. Automatically, load and displacement were recorded on the data logger. The data collection instrument is an observation table that includes the sample name, load, displacement, and degree of joint rotation. The setup of the instrument and specimen placement can be seen in Figure 8.

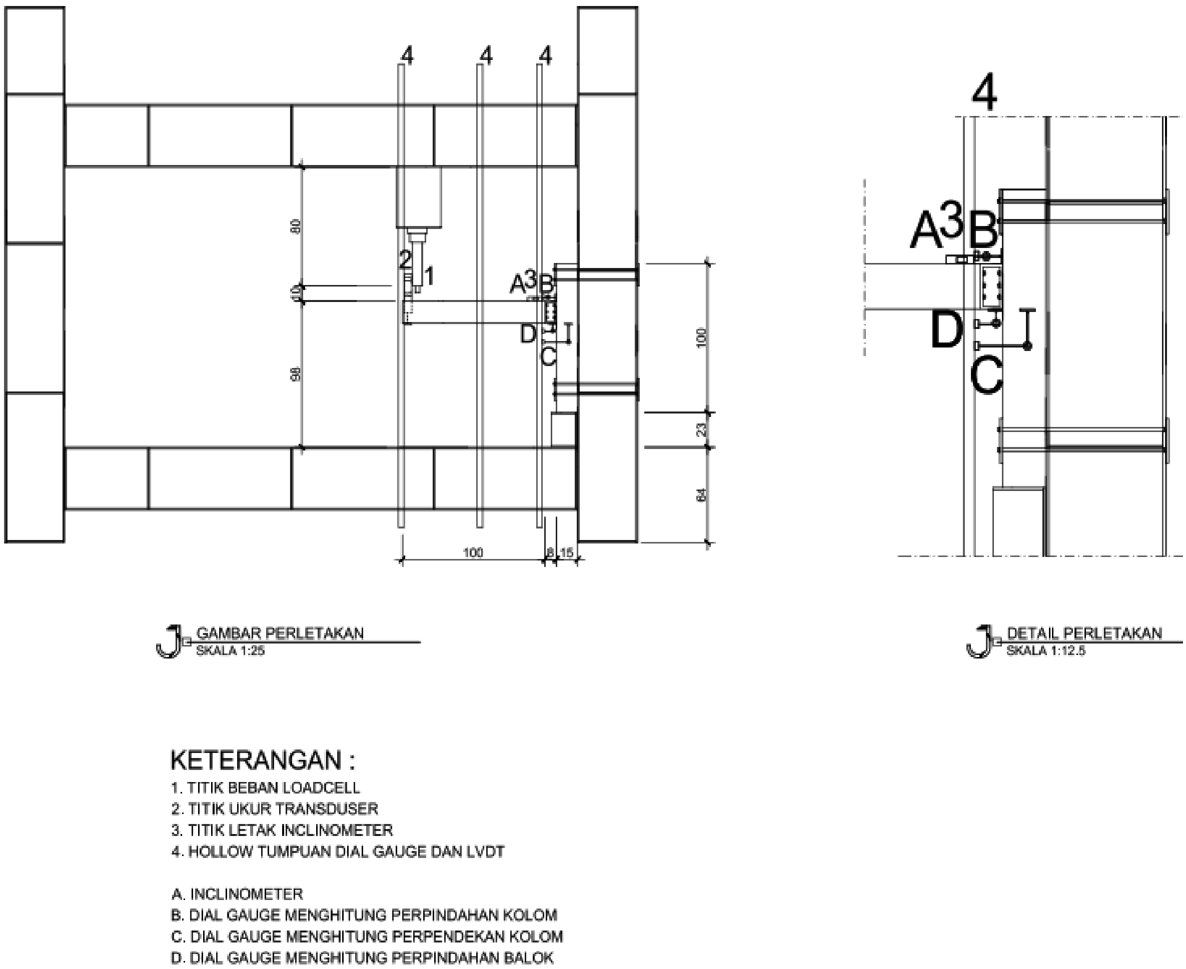


Figure 8. Arrangement of Data Retrieval Tool and Test Objects

2.3. Data Sources and Data Analysis

Primary data sources were obtained directly from the testing of specimens, and data analysis was performed descriptively in accordance with the standards used. The analysis of failure types was done visually by examining the damaged joint components. The analysis of failure types was based on the moment-rotation relationship graph with a limit of 0.03 radians, as per AISC standards. If the rotation exceeds this limit, non-structural components are considered damaged, indicating serviceability failure.

3. RESULTS AND DISCUSSION

The results of the joint failure and damage testing can be seen in Table 2.

Table 2. Joint Failures and Damage from Test Results

No	Specimen	Joint Strength (kNm)	Joint Failures and Damage	
			Graphical	Visual
1	6.4.1	2,18	-	Thread Rod Breakage
	6.4.2	2,28	-	Thread Rod Breakage
	6.4.3	2,28	-	Thread Rod Breakage
	Average	**2,24**	**-**	**Thread Rod Breakage**
2	6.6.1	2,70	-	Thread Rod Breakage
	6.6.2	2,99	-	Thread Rod Breakage
	6.6.3	2,96	-	Thread Rod Breakage
	Average	**2,89**	**-**	**Thread Rod Breakage**
3	8.4.1	4,82	Serviceability Failure	Thread Rod Breakage
	8.4.2	4,95	-	Thread Rod Breakage
	8.4.3	4,49	-	Thread Rod Breakage
	Average	**4,62**	**-**	**Thread Rod Breakage**
4	8.6.1	4,52	-	Thread Rod Breakage
	8.6.2	4,95	Serviceability Failure	Thread Rod Breakage
	8.6.3	4,85	Serviceability Failure	Thread Rod Breakage
	Average	**4,77**	**Serviceability Failure**	**Thread Rod Breakage**
5	10.4.1	5,53	Serviceability Failure	Thread Rod Breakage
	10.4.2	5,70	Serviceability Failure	Thread Rod Breakage
	10.4.3	5,50	Serviceability Failure	Thread Rod Breakage
	Average	**5,58**	**Serviceability Failure**	**Thread Rod Breakage**
6	10.6.1	6,35	Serviceability Failure	Thread Rod Breakage
	10.6.2	5,92	Serviceability Failure	Thread Rod Breakage
	10.6.3	6,58	Serviceability Failure	Thread Rod Breakage
	Average	**6,28**	**Serviceability Failure**	**Thread Rod Breakage**

Based on the experimental results of the moment-rotation relationship graph, it is not only the test specimens that failed at the Thread Rod to obtain the connection feasibility. Serviceability failure leads to damage to non-structural components even though the structural elements can still withstand additional loads and have not yet collapsed. Samples exceeding a rotation of 0.03 radians are categorized as serviceability failures, namely 8.6, 10.4, and 10.6.

Serviceability failure occurs at a diameter of 8.6 and above, indicating that the thread rod-bracket connection with variations $\geq$ 8.6 is more resistant to collapse because it can withstand rotations greater than the standard (0.03 radians). The reason for the extended rotation of the connection is due to the large diameter of the thread rod and the number of embedded thread rods. Based on the research conducted, if one intends to create a glue-in rod connection with specific characteristics, it is necessary to increase the diameter and the number of embedded thread rods.

Based on visual observations of the test objects loaded until they collapsed, all test objects experienced failure at the thread rod, in accordance with the planned connection strength, which is "laminate bamboo strength > thread rod < bracket." Although the failure pattern aligns with the planned design, as the sample size increases, the planned strength values are less likely to be achieved. The analysis of the reasons for the unmet planned strength in the research is the lever effect from the bracket, which causes an abrupt increase in load on the bolt head, leading to breakage.

Compared with other research, the influence of the bolt/Thread Rod connection model on the flexural strength of laminated bamboo produces varying connection model lengths and bolt diameters, which in turn reduce the load-bearing capacity of laminated bamboo [19]. In a study conducted by Darwis Z and his colleagues, direct testing of laminated bamboo connections resulted in damage at the ends of the laminated bamboo, while when connections were introduced, the dominant load was supported by the connections [20]. This aligns with the design principle that the dominant load will occur on the Thread Rod. The research also demonstrates that larger Thread Rod diameters exhibit greater rotations, leading to serviceability failures. The planning process focused excessively on strength, and therefore, further consideration of lever effects in calculations is needed.

The next research recommendation is that visual observations need validation by providing each measurement tool component to enable performance comparisons between components. The chosen rotation angle standard is 0.03 radians because each structure in a building has its own considerations. The failure standards in ACI 318M-14 [21], ASCE/SEI 7-16 [22], dan FEMA P-58-1 [23] provide a rotation standard of 0.01 radians, whereas AISC sets a rotation limit of 0.03 radians, and the Handbook of Structural Steel Connection Design and Details allows for a larger limit of 0.04 radians. Furthermore, when creating and calculating test objects for each connection component, it is recommended to reference small differences in strength, aiming to produce balanced and efficient connections.

4. CONCLUSIONS

In terms of the results of connection failure testing based on the moment-rotation graphs exceeding the angular rotation limits, they were 8.6, 10.4, and 10.6. The type of failure that occurred in all connections was a breakage at the thread rod. The research findings indicated that the damage to the connections in all test specimens was due to thread rod breakage, with the highest connection strength in sample 10.6 measuring 6.28 kNm, and the lowest in sample 6.4 measuring 2.25 kNm. Based on the research results, if detailed connections are desired, modifications involving an increase in the thread rod diameter result in longer rotations. However, the strength did not meet the planned values because the lever effect of the bracket caused the bolt heads to break prematurely, even though the type of failure aligned with the research plan. Addressing the lever effect of the bracket during field application requires a solution, and possible alternative methods may involve enlarging the bracket base and increasing the number of thread rod points. The testing conducted had no effect on the laminated bamboo component; thus, considerations should be made regarding the dimensions of the laminated bamboo cross-section and the lever effect of the thread rod in future tests to ensure that each component plays an equal role.

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