Journal of Mechanical, Civil and Industrial Engineering
ISSN: 2709-0809
DOI: 10.32996/jmcie
Journal Homepage: www.al-kindipublisher.com/index.php/jmcie

JMCIE
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| RESEARCH ARTICLE

Study Experimental and Numerical of Cross-Laminated Bamboo with Epoxy Adhesive

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| ABSTRACT

One of the most promising processed wood products today is cross-laminated timber (CLT). Another alternative to cross-laminated timber (CLT) is cross-laminated bamboo (CLB), which can address the challenges of using wood. Cross-laminated bamboo (CLB) is a floor and wall slab made from bamboo slats arranged at 90° angles. Variations in bamboo type and size were analyzed using ANSYS numerical modeling. ANSYS is a FEM software used for the simulation and analysis of engineering products and systems. The purpose of this study was to analyze the flexural strength (MOR), modulus of elasticity (MOE), and ductility of cross-laminated bamboo (CLB) as a floor and wall slab structure. This study investigated whether it could produce satisfactory results using numerical modeling. This study used a two-point method to obtain the modulus of elasticity (MOE), flexural strength (MOR), and ductility. The experimental cross-laminated bamboo (CLB) used Petung bamboo as the test specimen, measuring 1360 mm in length, 660 mm in width, and 44 mm in thickness. Epoxy/Melamine Formaldehyde (MF) glue was used as the adhesive. Numerical modeling of the CLB, with dimensions similar to those used in the experiment, involved modeling two bamboo variations: Petung bamboo and Apus bamboo. Epoxy/Melamine Formaldehyde (MF) glue was used for the numerical modeling. The test results for the cross-laminated bamboo (CLB) showed an average modulus of elasticity (MOE) of 14.56 GPa, an average flexural strength (MOR) of 17.15 MPa, and an average ductility of 5.01. The damage behavior of the CLB was characterized by cracks in the bamboo slats and peeling of the glue. Comparison of the difference between experimental and numerical values of CLB Petung bamboo at the maximum load of 19.96% and the final loading of the deflection difference of 16.29%. In numerical terms, with different types of material variations, namely Petung bamboo and Apus bamboo, the deflection difference at maximum load and final load.

| KEYWORDS

Cross-laminated bamboo, MOE, MOR, Ductility, Ansys Software

| ARTICLE INFORMATION

ACCEPTED: 12 December 2025 **PUBLISHED:** 07 January 2026 **DOI:** 10.32996/jmcie.2026.7.1.2

1. Introduction

The global availability of wood is currently declining due to illegal logging and the dwindling supply of natural wood products. To address this, wood processing is carried out using processed wood from industrial waste, in the form of small pieces of wood from branches, twigs, or low-strength wood. Wood has been widely used in civil engineering, the automotive industry, and the furniture industry, where it meets requirements. One promising processed wood product is cross-laminated timber (CLT).

CLT consists of an odd number of orthogonally oriented layers of wood, with adjacent layers bonded at the surface with structural adhesives under pressure. This specific configuration gives CLT excellent strength, stiffness, and in-plane and out-of-plane stability, making it suitable for load-bearing panels and shear walls (Zhou et al., 2014). However, wood is currently experiencing a decline due to its long growth period, slow regeneration, significant shortages, and low raw material utilization rates in the construction industry (Wei et al., 2015). Therefore, it is necessary to explore more suitable and sustainable materials, and bamboo has attracted the attention of researchers.

Indonesia is the second-largest bamboo producer after China, with 154 species discovered, out of the 1,250 to 1,500 species found worldwide (Abdullah A, 2014). Bamboo is commonly found in Indonesia in lowlands up to 750 meters above sea level and can grow well in areas with wet to dry climates (Esksk, 2016). Raw bamboo is used as a basic component of traditional bamboo buildings. However, due to variability in geometric dimensions and mechanical properties, raw bamboo cannot meet the physical and mechanical requirements specified in modern buildings. Therefore, cross-laminated bamboo, inspired by cross-laminated timber (CLT), was proposed.

The author conducted bamboo research on cross-laminated bamboo (CLB) products, including using glue. This research continues using glue, where the glue chosen is Epoxy/Melamine Formaldehyde (MF) glue with a total of three studies, then continued using the ANSYS program to determine whether there is a difference between the numerical and experimental results, in the numerical test, the manufacture of test objects will also be carried out using Apus bamboo material.

2. Literatur Review

Previous studies on hydrological-station rationalization are reviewed as follows. Li et al. (2013) investigated the compressive performance of laminated bamboo. The experimental program consisted of testing 24 laminated bamboo specimens in compression. Three groups of specimens were generated from different growth stages of bamboo culms, such as the upper third, middle third, and lower third. It was observed that the average compressive strength of samples from higher growth stages was higher. Conversely, the highest modulus of elasticity was obtained from bamboo laminates from the middle growth stage. However, the variation of modulus of elasticity with growth stage was smaller. The average compressive strength and standard deviation for the 24 specimens tested were 60.9 MPa and 5.2 MPa, respectively. The average modulus of elasticity was reported to be 9391 MPa with a standard deviation of 719 MPa.

Dong et al. (2021) investigated the flexural properties of CLBT composites. Two types of CLBT specimens were used for this experiment, with bamboo strips as either the transverse layer or the outermost transverse and longitudinal layers. Dynamic and three-point bending tests were conducted to determine the flexural properties. The test results showed that one group of CLBT specimens had a bending modulus and peak load of 23.7% and 60.5% higher than those of spruce-pine-fir specimens, respectively.

Lv et al. (2019) studied the flexural strength of cross-laminated bamboo plates incorporating a carbon fiber-reinforced polymer (CFRP) network. The CFRP-reinforced one-way plates were subjected to four-point bending. They found that the load-bearing capacity of the composite plates increased with the number and thickness of the layers and the application of the CFRP network. Furthermore, a theoretical modulus for calculating the bearing capacity of cross-laminated bamboo plates was proposed, and its accuracy was evaluated.

Xing et al. (2019) studied the bond shear strength of cross-laminated bamboo for overall structural performance, assessing the bond shear capacity of different cross-laminated bamboo configurations. Three parameters were studied, namely, grain direction, adhesive type, and clamping pressure. Five types of adhesives, three clamping pressures, and test specimens bonded with grains in the same direction and cross-laminated configurations were used for the experiments. Based on the test results, the most suitable adhesive for cross-laminated bamboo glue was selected, namely melamine-urea-formaldehyde. Among the different configurations, the final grain specimens showed the same highest bond shear strength.

3. Methodology

3. 1 Floor slab

Floor slabs only account for fixed loads (occupants, furniture, the weight of the tile layer, and the slab's own weight) that operate continuously over a long period. Unforeseen loads such as earthquakes, wind, and vibrations are not considered. This study uses a one-way floor slab system.

One-way slab system if the slab is considered to be supported on both sides and the ratio of the long span is twice or more greater than the short span, Ly ≥ 2 Lx. In Figure 2.1b, the floor slab supports beams B1 and B3, while beams B2 and B4 are only small in carrying the slab load. Thus, the slab can be considered as a one-way slab (x direction).

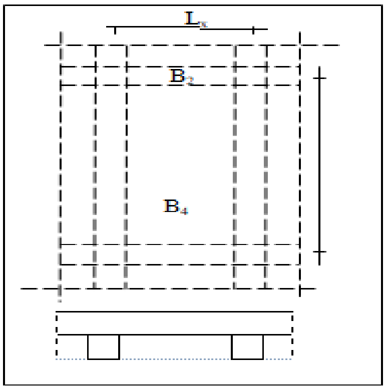


Figure 1 Floor slab

3. 2 Modulus of elasticity, flexural strength of CLB and Ductility

The modulus of elasticity is a value that measures the relationship between stress and strain at the proportional limit and describes the terms flexibility and strength. The higher the modulus of elasticity, the stiffer the test object, and conversely, the lower the modulus of elasticity, the more flexible the test object. To calculate the modulus of elasticity, use Equation (1) below:

$$E = \frac{Py\ L^3}{4\ bh^3 \Delta y} \quad (1)$$

Meanwhile, the flexural strength is calculated using the following Equation (2):

$$f_b = \frac{PL}{bh^2} \quad (2)$$

Ductility is the ability of a structure to experience repeated, large, alternating post-elastic deformations due to earthquake loads above the initial yielding load, while maintaining sufficient strength and stiffness to allow the structure to remain standing, even on the verge of collapse. The ductility value is based on the ratio of the maximum displacement at the point of failure to the displacement at the point of first yielding (SNI 1726:2002).

A graph of the relationship between load and deflection can be seen in Figure 2. The Commonwealth Scientific and Industrial Research Organization (CSIRO) method was used to determine the proportional limit load (Py) and the ultimate limit load (Pu). In this case, the yield deflection point was obtained using the assumption of multiplying the deflection at 40% of the peak load by a factor of 1.25 (Munoz et al, 2010). Equation 3 was used to calculate ductility.

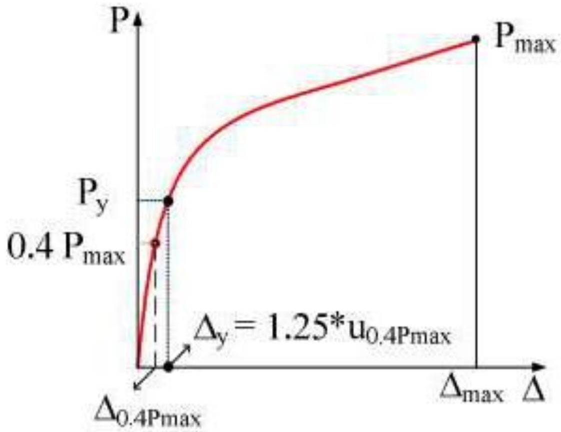


Figure 2. Method for determining the ultimate or proportional limit load and ultimate limit load

$$Daktilitas = \frac{\Delta u}{\Delta y} \quad (3)$$

From the test results with existing load and ductility data, it can be used to calculate the modulus of elasticity, flexural strength and ductility of CLB, where the values used are proportional load, ultimate load, proportional deflection and proportional deflectionwith the CSIRO method.

Notes : E = modulus of elasticity (MPa), Py = load at proportional limit (N), P = span length (mm), b = width of test specimen (mm), h = height of test specimen (mm), Δy = proportional deflection (mm), f_b = flexural strength (MPa), Δu= ultimate deflection (mm).

3.3 Ansys Modeling Of Cross-Laminated Bamboo and Filler Material

Ansys is a FEM software used to simulate and analyze engineering products and systems in various industries, such as aerospace, automotive, energy, construction, and others. This software is designed to help engineers and designers optimize the performance and reliability of their products by enabling them to simulate virtual models before the product is physically manufactured. ANSYS has various modules that can be used to simulate structural mechanics, fluid dynamics, electronics, and more, and has become one of the world's leading simulation software.

Ansys was founded in 1970 by Dr. John Swanson in Canonsburg, Pennsylvania, United States. Dr. Swanson was a mechanical engineer interested in the use of computers for engineering simulations. He started the company with the goal of developing simulation software that could help engineers optimize their engineering products and systems. Since then, Ansys has continued to grow and become one of the world's leading simulation software companies with offices and research and development centers in various countries.

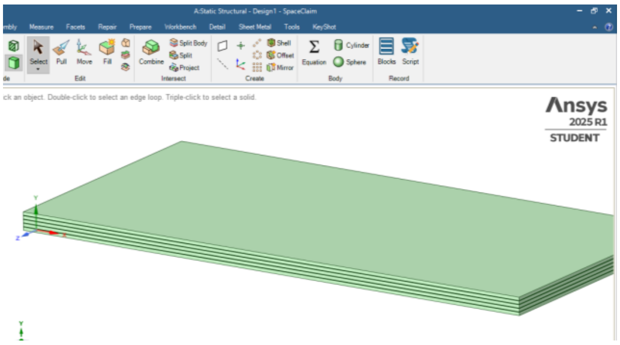


Figure 3 Modeling Of Cross-Laminated Bamboo

Experimental Cross Laminated Bamboo (CLB) test objects with existing dimensions were then simulated in the ANSYS program. In numerical bamboo, only each layer is assumed, not each bamboo blade, where the distance between the bamboo is filled with epoxy glue (Melamine Formaldehyde). The modeling dimensions in ANSYS are 1360 mm long, 660 mm wide, and 44 mm thick, the thickness used is the thickness of the CLB 1 and CLB 2 test objects.

3.3.1 Petung Bamboo
Petung bamboo (Dendrocalamus asper) is a type of bamboo with a large stem circumference and belongs to the grass family. Petung bamboo is large, with internodes measuring 40-50 cm long and 12-18 cm in diameter. The entire bamboo cane reaches a height of 20 m with curved tips; its color varies from green, dark green, purplish green, whitish green, or white spots due to lichen. The nodes are surrounded by aerial roots. The cane wall thickness ranges from 11 to 36 mm.

Petung bamboo has many benefits and is primarily used as a building material and structural timber for the construction of various types of buildings, such as: house posts, boat awnings, tobacco warehouse frames, bridges and footbridges, scaffolding and others. Its thick bamboo is generally considered strong and durable. At 8% moisture content, the wood density is between 0.7-0.8 g/cm³. At 15% moisture content, the fracture toughness of petung bamboo is 103 N/mm²; the compressive strength parallel to the grain is 31 N/mm²; and the shear strength is 7.3 N/mm² Apus bamboo is also known as rope bamboo, awi tali, or pring tali. It belongs to the genus Gigantochloa, which has dense clumps. However, its scientific name is Gigantochloa apus.

3.3.2 Apus Bamboo
Apus bamboo also has benefits and is primarily used as a material for rope, handicrafts, bridges and walkways, scaffolding, and other purposes. Test values for apus bamboo include physical and mechanical properties, respectively: an average moisture content of 10.72%, an average density of 0.68 g/cm³, a compressive strength parallel to the grain of 34.46 MPa, a compressive strength perpendicular to the grain of 21.56 MPa, a tensile strength parallel to the grain of 187.67 MPa, a shear strength parallel to the grain of 9.22 MPa, an average flexural strength (MoR) of 162.50 MPa, and a modulus of elasticity of 19,047.65 MPa (Prasetyo, 2013).

4. Result
4.1 *Flexural Strength Test Results of Cross-Laminated Bamboo*
The cross-laminated bamboo (CLB) test object with epoxy glue adhesive is a cross-laminated bamboo consisting of five layers of bamboo with epoxy glue adhesive. The number of test objects used in this test is 3 pieces with the code for each test object being CLB1, CLB2, CLB3. The results of the flexural strength test can be seen in Table1.

Table 1. Results of flexural strength of cross-laminated bamboo

Kode CLB	40%		proprrsional		Maksimum	
	P (N)	δ (mm)	P (N)	δ (mm)	P (N)	δ (mm)
CLB 1	2844,35	3,13	3261,78	3,91	7110,88	23,63
CLB 2	3096,35	5,09	3616,44	6,36	7740,88	21,97
CLB 3	6948,35	5,85	9031,73	7,31	17370,88	26,63
rata-rata	4296,35	4,69	5303,32	5,86	10740,88	24,08

From the calculation results, the load and deflection at the elastic and maximum times are obtained as shown in the table above, the average load at the elastic time is 5303,32 N and the deflection is 5,86 mm. at the maximum load and deflection the average values are 10740.88 and 24,08 mm, respectively. The graph of the relationship between load and deflection that occurs in cross-laminated bamboo (CLB) with epoxy glue can be seen in Figure 4.

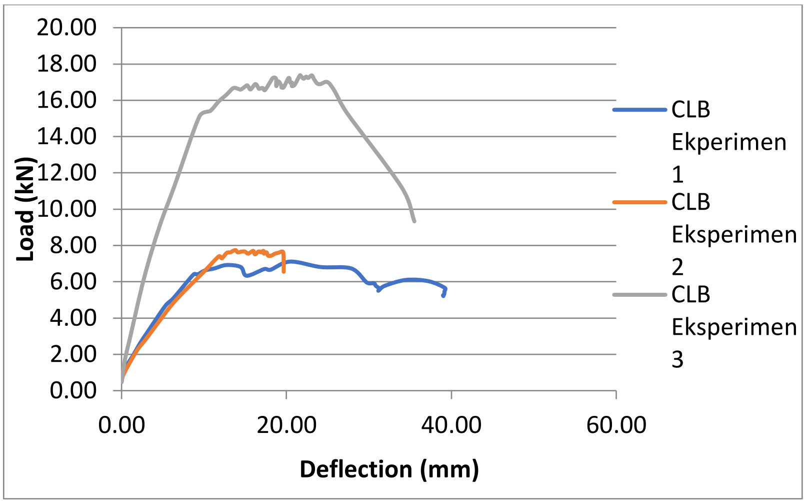


Figure 4. CLB load and deflection graph

In the image above, there is a significant value between the CLB 3 test object and the CLB 1 and CLB 2 test objects. The value in the CLB 3 test object is caused when the test object is made, where the test object is thicker and the shape of the bamboo blade is not neat when made among the other test objects. The load that will be used in ansys is the average between the CLB 1 and CLB 2 loads with the same thickness of the test object.

The failure that occurred in each test object can be seen in Figure 5, namely cracks in the bamboo blades and the opening of the epoxy glue adhesive on each test object

a) Opening of the adhesive on the CLB

b) Breakage of CLB bamboo blades

Figure 5. Failure on CLB

4.2 Results of Modulus of Elasticity (MOR), Flexural Strength (MOR) and Ductility

From the test results with existing load and ductility data, it can be used to calculate the modulus of elasticity, flexural strength and ductility of CLB, where the values used are proportional load, ultimate load, proportional deflection and proportional deflection. with the CSIRO method, and the results of the load can be seen in Table 4.8. The results of the calculation of MOE, MOR and ductility can be seen in Table 2

Table 2. MOE, MOR and Ductility Result

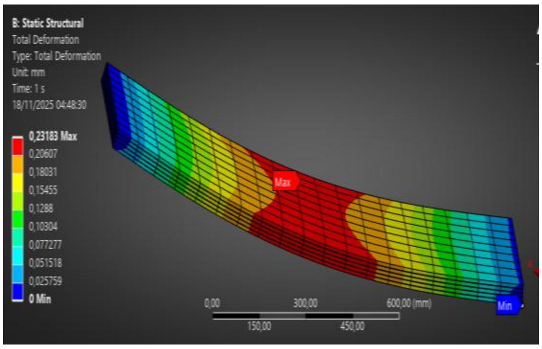
Benda Uji	P	δ	P_y	Δy	E	E rata-rata	f_b	f_b *rata-rata*	Daktilitas	Daktilitas rata-rata
	(kN)	(mm)	(kN)	(mm)	(GPa)	(GPa)	(MPa)	(MPa)	(mm)	(mm)
CLB1	7,11	23,63	5,68	9,19	6,922		11,35		2,57	
CLB2	7,74	21,97	6,19	12,91	5,36	8,98	12,36	17,15	1,70	2,26
CLB3	17,37	26,63	13,89	10,59	14,67		27,73		2,51	

From the analysis results, the average values of MOE, MOR, and ductility of CLB with epoxy adhesive (MF) were obtained, respectively, at 8,98 GPa, 17,15 MPa and 2,26.

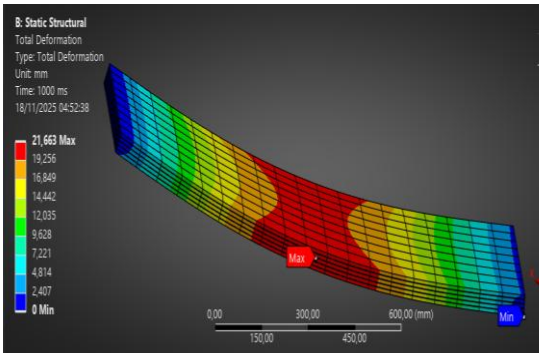
4.3 Modeling analysis using the ANSYS program

4.3.1 Ansys CLB modeling results for petung bamboo

The pressure data load is assumed to be 1/2P with an elastic modulus of 16269 MPa and a Poisson ratio of 0.3. At the initial load of 470 N, the deflection in Ansys is 0.23 mm and at the maximum load of 7385.88, the deflection that occurs is 21.66 mm. After the maximum load occurs, the deflection in the CLB continues to run up to a deflection of 32 mm at a load of 6345.88 N. The image of the petung bamboo deflection in the Ansys program can be seen in Figure 6.



a) Deflection at a load of 470.88 N



b) Deflection at a load of 7385,88 N

Figure 6. Visualization of deformation in ANSYS Petung bamboo

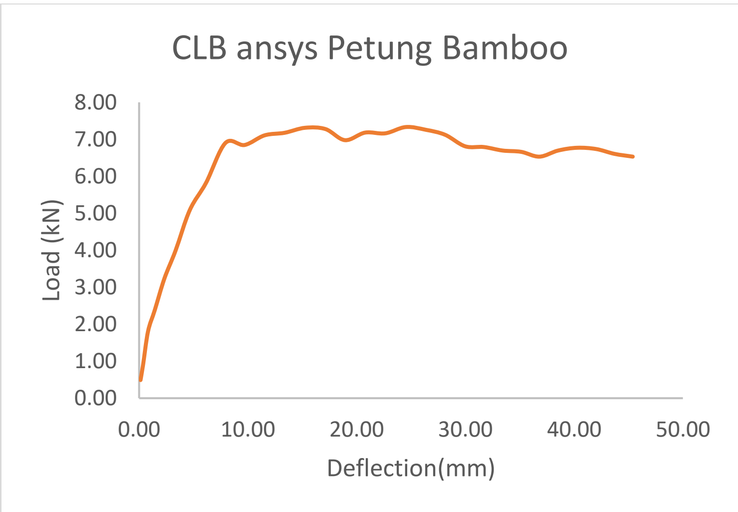
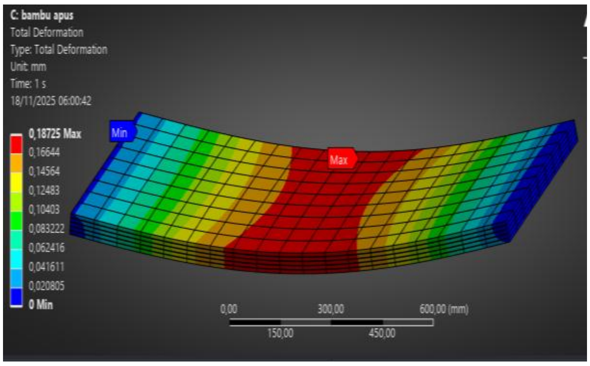


Figure 7. Results of analysis of CLB petung bamboo with epoxy glue using the Ansys program

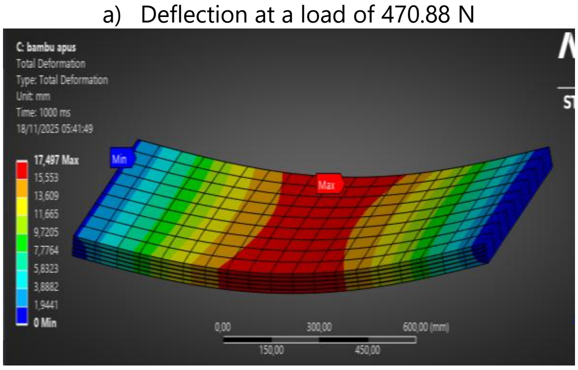
The results of Figure 7 show a constant load increase pattern up to the maximum load, but deflection continues until the load that can be supported decreases.

4.3.2 Ansys Results of Apus Bamboo

The modeling of the CLB of apus bamboo in the ANSYS program is exactly the same size and shape as the test object, but what is changed in this modeling is the material. The modulus of elasticity used in apus bamboo is 19048 MPa, with a Posson ratio of 0.28. The results of the ANSYS modeling for apus bamboo with a load of 470.88 N, obtained a deflection of 0.19 mm, and at a maximum load of 7385.88 N the deflection that occurs is 17.59 mm. The deflection image in ANSYS can be seen in Figure 8.



a) Deflection at a load of 470.88 N



b) Deflection at a load of 7485,88 N

Figure 8. Visualization of deformation in ANSYS Bambu Apus

In the case of the CLB bamboo apus, the deflection that occurs constantly increases, but after the maximum load occurs, the deflection increases while the load decreases. This can be seen in Figure 9.

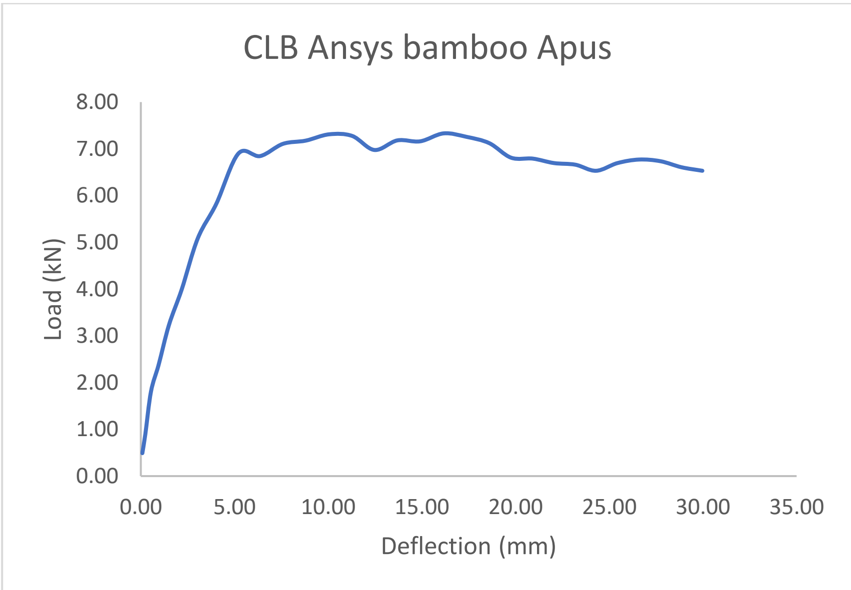


Figure 9. Results of analysis of CLB bamboo apus with epoxy glue using the Ansys program

4.3.3 Comparison Results Between Experimental and Numerical Tests (Ansys)

The results of the differences between the load and deflection from the experimental and numerical on cross-laminated bamboo (CLB) with epoxy glue, where the numerical materials used were petung bamboo and apus bamboo. The results of these similarities and differences can be seen in Figure 10.

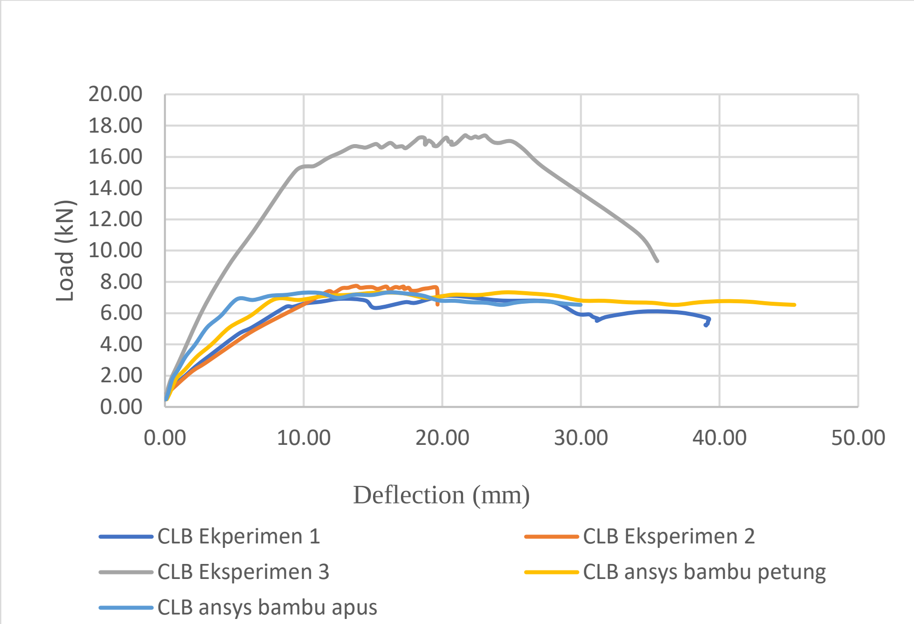
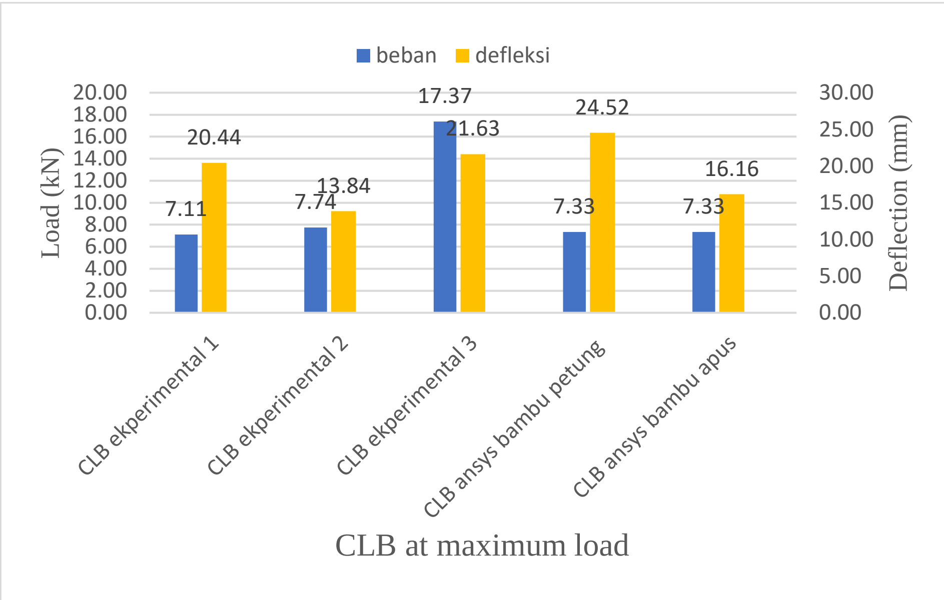
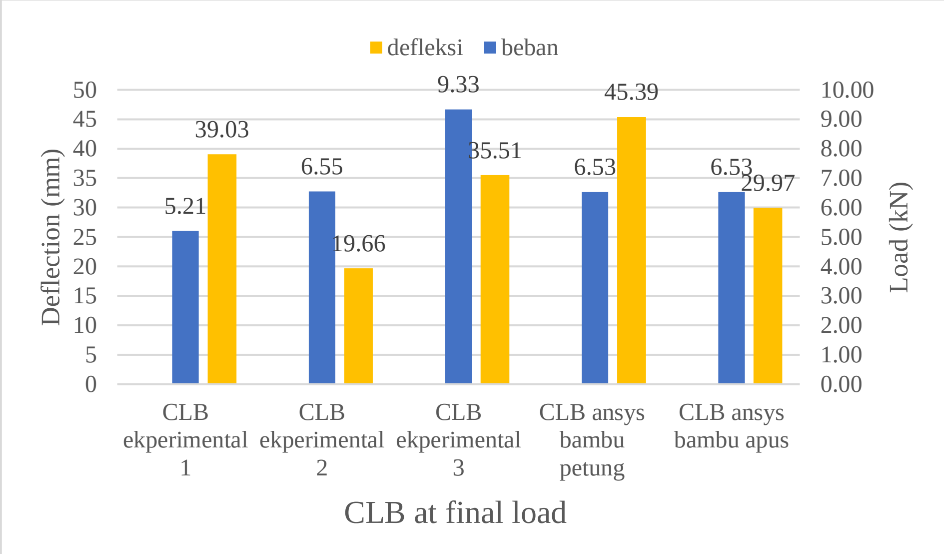


Figure 10. Graph of experimental and numerical results

Figure 10 shows the similarity of the curve shape between experimental CLB 1, experimental CLB 2, numerical CLB of Petung bamboo, and numerical CLB of Apus bamboo, in deflection, which shows a very different result between experimental and numerical. The results of similar research with experimental CLT test objects with Abaqus numerical have the same graphic results. The graph of the CLT test can be seen in Figure 10 below (Wahyudin, 2016).



a) Deflection and load diagram at maximum load



b) Deflection and load diagram at the final test load

Figure 11. relationship between load and deflection at maximum load and final test load

Figure 11 shows the results of the comparison between the experimental and numerical CLB at the time of maximum load and at the end of the test. The deflection at the time of maximum load for each experimental and numerical test object has the following results: experimental CLB deflection 1 of 20.44 mm, experimental CLB deflection 2 of 13.84, experimental CLB deflection 3 of 21.63 mm, numerical CLB deflection of Petung bamboo of 24.52 mm and numerical CLB deflection of Apus bamboo of 16.16 mm. The value at the end of the CLB test load has a consecutive deflection, namely experimental CLB 1 of 39.03 mm, experimental CLB 2 of 19.66 mm, experimental CLB 3 of 35.51, numerical CLB Petung bamboo of 45.39 mm and numerical CLB Apus bamboo of 29.97 mm. The difference in deflection at the time of maximum load between the experimental CLB Petung bamboo and the numerical CLB Petung bamboo is 19.96%, the deflection at the end of the test load has a difference of 16.29%. [9] conducted a similar test, namely experimental CLT and numerical CLT with the Abaqus program, which had results at a maximum load of 4448.22 N, an experimental deflection of 27.67 mm was obtained, and a numerical deflection of 67.30 mm was obtained. Comparison of the difference in deflection values with the same load between the numerical CLB of Petung bamboo and the numerical CLB of Apus bamboo at a maximum load of 8.36 mm, and the difference at the final test load of 15.42 mm.

5. Conclusion

- Experimental results of cross-laminated bamboo using epoxy adhesive conducted in the laboratory yielded an MOE of 8293.56 MPa. The MOR value for the experimental cross-laminated bamboo (CLB) was 8.24 MPa. The experimental ductility of the cross-laminated bamboo (CLB) with epoxy adhesive was 6.80 mm.
- The similarity between the experimental cross-laminated bamboo (CLB) and the numerical cross-laminated bamboo (CLB) with Petung bamboo showed a difference in deflection at maximum load of 19.96%. At the final test load, the difference in deflection was 16.29%.
- The difference in deflection between the numerical Petung bamboo and Apus bamboo at maximum load and final test load was 8.36 mm and 15.42 mm, respectively.

Funding: his research did not receive any financial support from other organizations or institutions. All expenses and required resources were provided by the author. No entity was involved in any stage of the research, and it is confirmed that there was no support that could influence the results. This reflects the author’s independence.
Conflicts of Interest: Conflict of Interest: The author declares that there are no conflicts of interest in this study. There are no financial or personal relationships that could affect the research. All opinions and conclusions are based on scientific evidence, and this statement contributes to the transparency and ethics of the research.
Acknowledgment: I would like to express my sincere gratitude to Prof. Ir. Buan Anshari, S.T., M.Sc(Eng)., Ph.D., IPM and Prof. Dr. Ir. Ngudiyono, S.T., MT. for their guidance and supervision throughout all stages of the research and writing process, which enabled this manuscript to comply with the standards of academic research and journal publication.
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