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Experimental study of precast concrete walls using bamboo as alternative reinforcement

Ronny Hasudungan Purba[a], Titis Lukita Sari[a*], Sugito[a] and Muhtar[a]

[a]*Department of Civil Engineering, Bandar Lampung University, Bandar Lampung 35142, Indonesia*

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A B S T R A C T

The public's demand for simple, livable houses means that material studies to support this continue to be carried out today, starting from using natural materials such as bamboo as precast concrete walls. This study aims to conduct an experimental study using bamboo rope from the *Gigantochloa Apus* variety as an alternative reinforcement for precast concrete walls. Research was carried out on 12 precast concrete wall test specimens, and the flexural properties, flexural strength, and crack patterns were formulated when subjected to a quasi-static load concentrated in the middle of the span. The concrete slab measures 600×800 mm with a 50 and 75 mm thickness. The three configurations of bamboo bones used include (1) Gedhek-type woven bamboo slats, (2) bamboo slat type, and (3) Sasak-type woven bamboo slats. The research results show that Sasak-type woven bamboo slat reinforcement is the most effective alternative reinforcement. The behavior of the test specimen shows a ductile failure pattern similar to conventional reinforced concrete. The maximum moment capacity achieved is 1.5 to 2.2 times greater than the theoretical nominal moment capacity. Meanwhile, the behavior of test specimens with conventional plate-type woven bamboo slat reinforcement showed sudden and brittle failure due to slippage at the bond between the bamboo reinforcement and concrete. The average maximum moment from the test results is 60% of the theoretical nominal moment. The results of this research recommend that woven bamboo slats of the conventional plate reinforcement type are less effective as alternative reinforcement if they are not given special treatment to increase their adhesion to concrete. Gedhek-type woven bamboo slats are not effective as alternative reinforcement because they cause separation of the top and bottom parts of the woven concrete, thereby reducing the integrity of the cross-section and causing the cross-sectional capacity to be relatively small.

1. Introduction

Public demand for housing that prioritizes simplicity, livability, quality, and health remains robust, especially in regions like Indonesia. One prevalent architectural style in Indonesia is characterized by wall houses constructed with red brick infill walls reinforced with aloof components, practical columns, and ring beams (Guedes, 2016). These houses typically feature foundations made of Riverstone, providing stability and durability. The roofs are commonly supported by wooden frames and covered with tiles or zinc sheets, offering protection from the elements. While these traditional elements endure, there's a growing interest in incorporating modern technologies and sustainable materials to enhance both these homes' functionality and environmental friendliness (Cascone, 2019; George *et al.*, 2020; Omer, 2008; Sugito *et al.*, 2022). Additionally, there's an increasing emphasis on integrating natural light, ventilation, and green spaces into house designs to promote inhabitants' health and well-being. As urbanization accelerates and population densities rise, the demand for such houses that balance practicality, aesthetics, and sustainability will likely continue to grow, shaping the future housing landscape in Indonesia and beyond.

* Corresponding author.
E-mail addresses: titislukitasari@ubl.ac.id (T. L. Sari)

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A bamboo house is an alternative to a simple house that is widely known to the public. All components forming the structure of a bamboo house, such as beams, columns, infill walls, and roof frames, use bamboo. Compared to wall house construction, bamboo houses are relatively cheaper. Of course, this is a suitable alternative for many Indonesian people with limited economic conditions. Furthermore, if the bamboo house construction is designed and built correctly, the bamboo house can also be earthquake resistant (Correal, 2020; Familiana *et al.*, 2017; Kaminski *et al.*, 2016; Manandhar *et al.*, 2019). However, bamboo houses are still relatively uncomfortable to live in because of the possibility of outside air, especially at night, entering the house, which can affect the health of the occupants. If the components of a bamboo house are not given special protection against termite attacks, the bamboo house will not last relatively long. Bamboo fiber can experience weathering in a relatively short time span (Bulan *et al.*, 2020; Das *et al.*, 2009; Hung *et al.*, 2012; Zhang *et al.*, 2022). Apart from that, there is still a connotation in Indonesian society that bamboo houses are homes for people experiencing poverty, even though the quality has been tried to improve by making bamboo slat walls plastered using sand and cement.

Along with improving the quality of bamboo houses, a new idea for precast concrete houses that use bamboo as reinforcement and an alternative casing will be developed. Furthermore, this form of structure is called a prefabricated bamboo house. This new idea combines the advantages of concrete, bamboo, and precast technology to build a simple house that is structurally strong, relatively cheap, has a relatively short construction period, is healthy, and meets aesthetic values. Like precast concrete structures, the components of prefabricated bamboo houses (beams, columns, and walls) are also prefabricated at the construction site (De Araujo *et al.*, 2023; Raj *et al.*, 2021; Wei *et al.*, 2021). After the concrete reaches a certain age, these components are assembled into a complete house structure. In the precast bamboo house structure, the beam and column components are composite elements of bamboo casing and concrete filling material, while the wall components resemble conventional precast concrete walls; only in this case are bamboo slats used as the main reinforcement. Furthermore, the components of this prefabricated bamboo house are named prefabricated bamboo beams, columns, and walls, respectively. Therefore, this study aims to experimentally examine precast bamboo walls, focusing on the formulation of their mechanical behavior, including flexural properties, wall flexural strength, and wall crack patterns under quasi-static loads.

2. Materials and methods

2.1 Preparation of bamboo specimens

This type of bamboo rope from the *Gigantochloa Apus* bamboo variety is used as an alternative reinforcement for precast bamboo walls (Darwis *et al.*, 2023; Manik *et al.*, 2020; Nugroho and Bahtiar, 2017). This selection is based on the nature of bamboo rope, which has a high level of flexibility, strength, and durability, making it very suitable for construction. Apart from that, rope bamboo is also commonly found in Indonesia, specifically in Lampung Province. To determine the tensile strength of the bamboo rope material, ten specimens (5 specimens each with a bamboo node in the middle of the specimen (B1) and without a bamboo node in the middle of the specimen (B2)) were tested following the ISO/TR 22157-2:2004 procedure (Janssen, 2004). Bamboo specimens that do not have nodes are more ductile than specimens with nodes. The average yield stress for B2 bamboo specimens reached 134.6 MPa, or 45% higher than the value for B1 bamboo specimens, which only reached 92.8 MPa. The average tensile strength of B2 and B1 bamboo specimens is 247.7 and 176.6 MPa, respectively. With these results, the bamboo characteristics of specimen B1 were used in the cross-sectional strength analysis.

2.2 Preparation of test concrete specimens

Apart from the bamboo rope material, other basic materials such as cement, which meet the criteria of SNI 15-7064-2004 (Indonesia and Nasional, 2004), fine aggregate, and coarse aggregate were obtained from local building shops in Bandar Lampung, Indonesia. The test results for fine and coarse aggregates are summarized in **Table 1**. The weight ratio of the concrete constituent materials (mix design) follows a ratio of 1: 2.3: 3.4 for cement: fine aggregate : coarse aggregate with a water-cement ratio of 0.68 (Bint Ashraf, 2012; Kurda *et al.*, 2022; Quiroga, 2003). The average compressive strength of the concrete cube obtained was 194.75 kg/cm^2, or 13% lower than the planned compressive strength of 225 kg/cm^2.

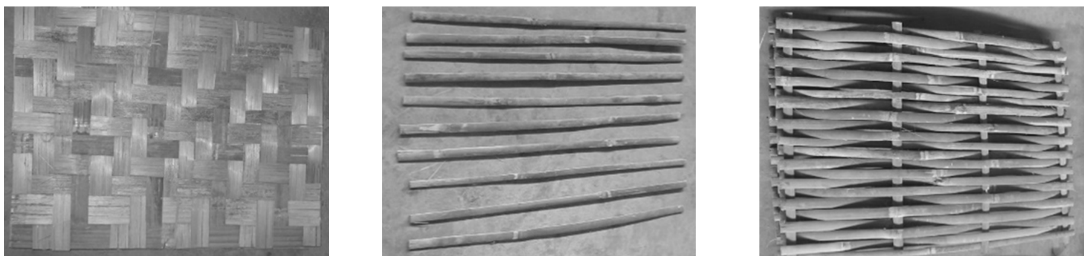
Table 1. Fine and coarse aggregate test data

Parameters	Unit	Fine aggregate	Coarse aggregate
Moisture content	%	4.74	2.35
Specific gravity	-	2.54	2.39
Fineness modulus	-	3.27	8.13
Solid volume weight	kg/m^3	1528.88	1542.18
Sludge levels	%	0.88	

A total of 12 precast bamboo wall test objects measuring 600×800 mm with two thicknesses, namely 50 and 75 mm, were prepared in this research. The test objects were grouped into three groups based on the configuration of the bamboo reinforcement used, namely woven bamboo slats of the gedhek type (D1), woven bamboo slats (D2), and (3) woven bamboo slats of the sasak kind (D3). Woven gedhek-type bamboo slats (D1), as shown in Fig. 1a, have a thickness of 1.5 – 3.0 mm.

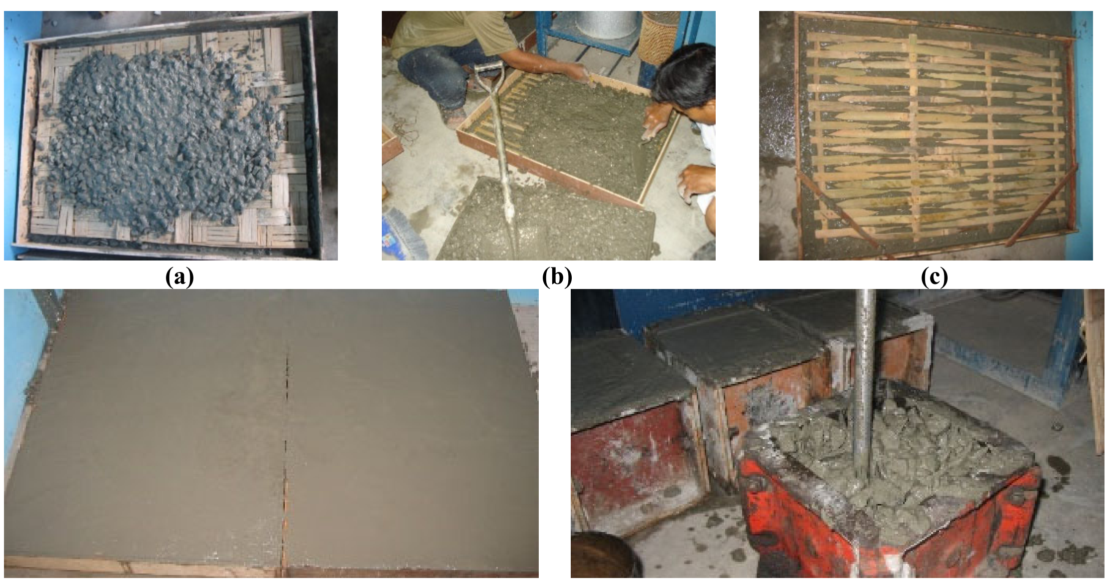
The bamboo slat type (D2), as indicated in Fig. 1b , with a cross-sectional size of 25×8 mm, is arranged like conventional reinforcement with a distance between slats of 20 mm, and there are 14 bamboo slats along the width of the test object. The woven sasak-type bamboo slats (D3), as shown in Fig. 1c, measure 25×8 mm and are woven with a sasak pattern, and there are 24 bamboo slats along the width of the test object.

The process of casting test specimens starts by measuring the slump of fresh concrete, which in this study is 100 mm. This is greater than the design slump of 80 mm. This is thought to be because the proportion of water used does not consider the water content of the fine aggregate. Next, fresh concrete is poured into the mold until it reaches half the design thickness. Manual vibration is applied to the mold and concrete mixture to ensure that segregation of the concrete mix does not occur. All types of bamboo reinforcement are then placed on top of the poured concrete mixture (**Fig. 2**). To ensure that the bamboo reinforcement blends into the mortar, the bamboo reinforcement is pressed until the cement paste comes out from between the woven bamboo reinforcement. The final step is to pour the remaining fresh concrete until it reaches the desired thickness. Manual vibration was carried out again to ensure that segregation of the concrete mix did not occur. Next, the test object's surface is leveled using a cement spoon. From each casting, one concrete cube measuring 15×15×15 cm was cast, and 12 test objects were obtained.



(a) **(b)** **(c)**

Fig. 1. Woven bamboo slats for alternative reinforcement. (a) Gedhek-type woven bamboo slats (D1), (b) bamboo slat type (D2), and (c) Sasak-type woven bamboo slats (D3).

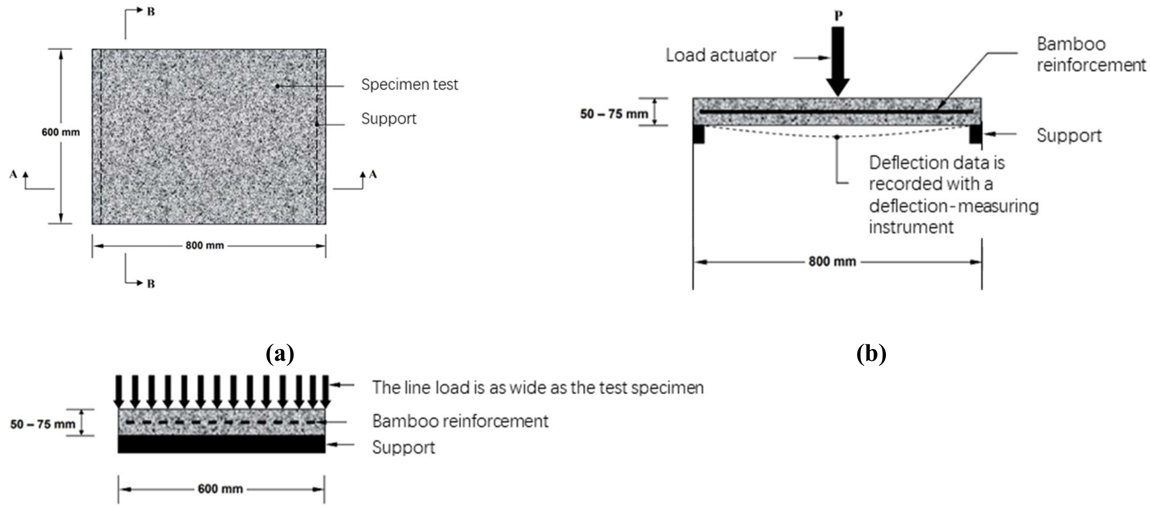


(a) **(b)** **(c)** **(d)** **(e)**

Fig. 2. Test concrete specimen preparation process. (a) Gedhek-type woven bamboo blade test object (D1), (b) bamboo blade type test object (D2), (c) Sasak-type woven bamboo blade test object, (d) finished molding test object, (e) and manufactured concrete cube.

2.3 Testing of precast bamboo wall specimens

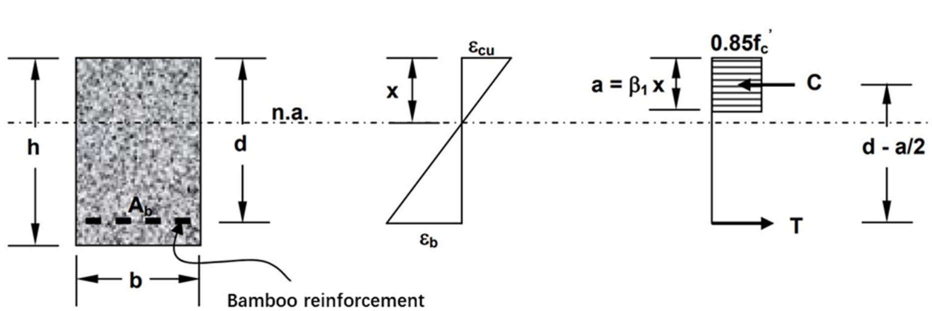
The test scheme for a precast bamboo wall is illustrated in **Fig. 3**. The test object is placed on two supports following a length of 800 mm. Next, an incremental load is given via a load actuator placed in the middle of the test object (**Fig. 3b**). Employing rigid iron, this load will be received by the test object as a line load (**Fig. 3c**). As the load increases, the specimen deflection is measured, and each specimen's crack pattern is recorded. Even though the bamboo reinforcement is placed in the middle of the thickness of the test object, the test object cannot be placed upside down. The test object must be placed where the outer bamboo fiber is on the bottom side. This condition will maximize the tensile strength of the bamboo reinforcement because the tensile strength of the outer bamboo skin is greater than the inner fiber.



(c)

Fig. 3. Precast bamboo wall testing scheme. (a) layout, (b) section A-A, and (c) section B-B.

With this test scheme, conventional reinforced concrete analysis can be used to analyze precast bamboo walls by replacing the parameters of iron reinforcement (A_s) with bamboo reinforcement (A_b). Therefore, the strain and stress distributions often used in conventional reinforced concrete analysis are assumed to apply to precast bamboo walls—**Fig. 4.** The magnitude of the forces experienced by concrete (C) and bamboo reinforcement (T) is in Eq. (1) and Eq. (2), respectively.



(a) (b) (c)

Fig. 4. Distribution of strains and stresses in the cross-section of the beam. (a) cross-section of the beam, (b) strain distribution, and (c) Whitney stress distribution of the block.

$$C = 0.85 f_c' b a \tag{1}$$

$$T = A_b f_{yb} \tag{2}$$

where, f_c' is the compressive strength of the concrete, b is the cross-sectional width of the concrete, a is the thickness of the concrete section under compression, A_b is the area of available bamboo reinforcement and f_{yb} is the yield stress of the bamboo. Based on the Whitney stress block approach (Hakeem, 2022; Karthik and Mander, 2011; Liu *et al.*, 2012), the value $a = \beta_1 x$, where β_1 is 0.85 for $f_c' \leq 30$ MPa, and x is the neutral line's height calculated from the concrete cross-section's top fiber. Using the balance equation $\Sigma F_H = 0$, parameter a can be calculated using Eq. (3), and the nominal moment M_n precast concrete walls can be estimated using Eq. (4).

$$a = \frac{A_b f_{yb}}{0.85 f_c' b} \tag{3}$$

$$M_n = A_b f_{yb}\left(d - \frac{a}{2}\right) \tag{4}$$

where, d is the height of the center point of the bamboo reinforcement calculated from the top fiber of the concrete cross-section, other parameters have been previously defined. Eq. (4) is derived based on the assumption that the outer fibers of the concrete experience an ultimate strain $\varepsilon_{cu} = 0.003$, and all bamboo reinforcement reaches a yield condition. This condition is known as under-reinforced. This condition will be achieved as long as the ratio of the area of bamboo reinforcement to the effective cross-sectional area of concrete ($\rho = A_b/bd$) fulfills the relationship in Eq. (5).

$$\rho_{max} \leq 0.75\rho_b = 0.75\frac{0.85 f_c^{'}}{f_{yb}}\beta_1\left(\frac{600}{600+f_{yb}}\right) \tag{5}$$

On the other hand, if Eq. (5) is not fulfilled, then the bamboo reinforcement will not reach the yield condition. This condition is known as over-reinforced. The bamboo reinforcement configuration used in this research may be in the over-reinforced condition. For this condition, the analysis of precast bamboo walls begins by calculating the actual stress experienced by the bamboo reinforcement using the strain balance equation (Eq. (6)) and stress (Eq. (7)).

$$Strain \rightarrow \frac{x}{d} = \frac{\varepsilon_{cu}}{\varepsilon_{cu}+\varepsilon_b}; \quad \varepsilon_b = \frac{f_b}{E_b} \tag{6}$$

$$Stress \rightarrow \sum F_H = 0; \quad C = T \tag{7}$$

$$C = 0.85 f_c^{'} b \beta_1 x \tag{8}$$

$$T = A_b f_b \tag{9}$$

where, ε_b, f_b and E_b are the strain, stress, and elastic modulus of bamboo reinforcement, respectively, other parameters have been previously defined. To calculate the nominal moment M_n, Eq. (3) and Eq. (4) can be used again by replacing the quantity f_{yb} with f_b. Next, the cracking moment (M_{cr}), elastic deflection (δ_e), and shear capacity (Vc) of precast concrete walls can each be calculated using Eq. (10) to Eq. (12).

$$Mcr = \frac{0.62\sqrt{f_c^{'} I_g}}{Y_t} \tag{10}$$

$$\delta e = \frac{1}{48}\frac{PL^3}{E_c I_g}; \quad Ec = 4700\sqrt{f_c^{'}} \tag{11}$$

$$Vc = \frac{1}{6}\sqrt{f_c^{'} bd} \tag{12}$$

where, I_g is the moment of inertia of the intact precast bamboo wall section, Y_t is the distance from the center of gravity of the precast bamboo wall section to the outer fiber, P is the quasi-static load applied to the test specimen, L is the span length, and E_c is the elastic modulus of the concrete.

3. Results and Discussions

3.1 Results of testing the mechanical behavior of precast bamboo walls

Testing of precast bamboo walls is carried out when the concrete is more than 28 days old. The front view of the precast concrete walls test instrument series is presented in **Fig. 5**.

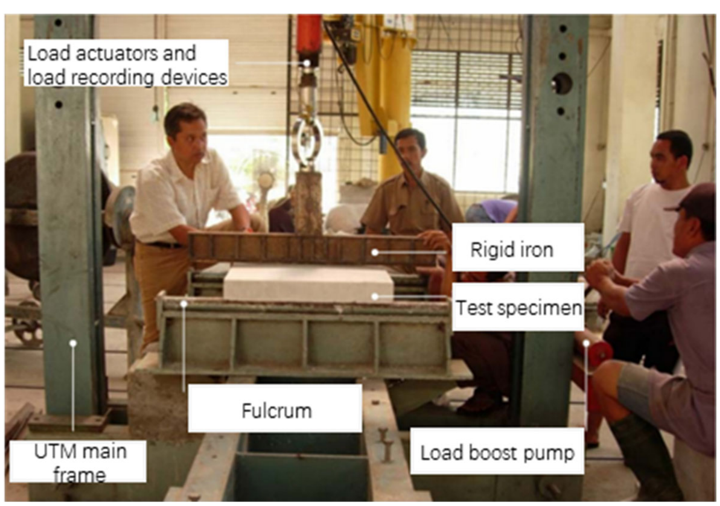


Fig. 5. Precast bamboo wall test settings.

The test object is placed on two permanent supports resembling a simple stand with a distance between the supports of 700 mm. A rigid iron is placed above the test object in the mid-span position, stretching the test object's width. The load actuator from the hydraulic jack connected to the load-increasing pump is placed in the middle of the rigid iron. The load actuator equipped with a load recording device is integrated with the main frame of the testing instrument. Under the test object, a deflection recording device is placed as a dial gauge with an accuracy of 0.01 mm. Data was collected every time the load recording device increased by ±72 kg. Recording of the amount of load applied and the deflection that occurs is done manually. The relationship curve between the moment carried by the test object and the deflection that occurs is shown in **Fig. 6**. In each figure, there are four curves from the test object groups: D1 (woven Gedhek-type bamboo slats), D2 (woven bamboo slats type), and D3 (woven bamboo slats). The crack patterns of the twelve precast bamboo walls on the bottom side are depicted in **Fig. 7** when the maximum load is reached. The mechanical behavior of precast bamboo walls for each group of test objects is described in Section 3.2 to Section 3.4.

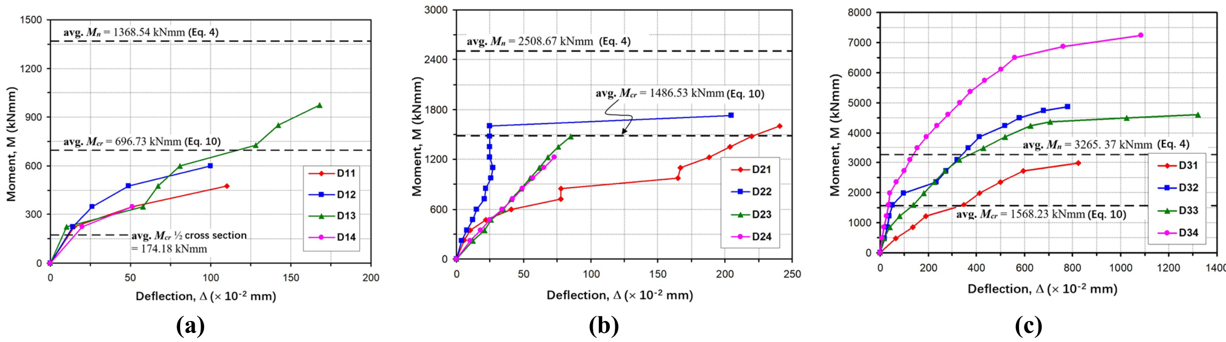


Fig. 6. Test results for test objects: (a) woven bamboo slats of the Gedhek-type, (b) woven bamboo slats of the Sasak type, and (c) woven bamboo slats of the Sasak type.

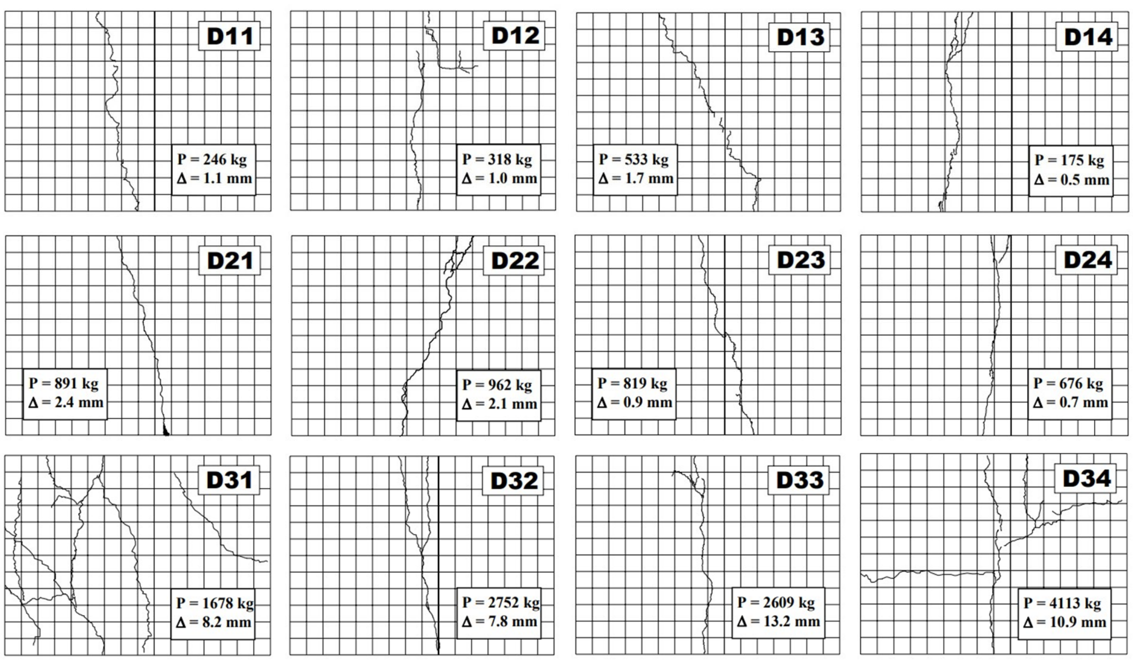


Fig. 7. Crack patterns of 12 precast bamboo wall specimens under maximum loading conditions

3.2 Test object group D1 (Gedhek-type woven bamboo slats)

Although it was initially feared that the D1 test specimen group might crack when supporting its weight, this did not happen when observed at 21 days of concrete. However, the additional load (P) that the test object can bear is relatively very small. **Table 2** reports that the maximum load (P_{max}) the test object can carry is 532.63 kg. In fact, one of the test objects could only carry a maximum load (P_{max}) of 174.62 kg. In other words, the test object reaches a maximum moment Mmax of 975.66 kNmm and 348.59 kNmm, respectively. These two values are far below the theoretical nominal moment value calculated using Eq. (4), namely M_n equal to 1105.31 kNmm and 1583.06 kNmm, respectively, or only reaching 88% and 22% of the theoretical value.

Table 2. Analysis of test data for precast bamboo walls using woven Gedhek-type bamboo slats

Code	f_c' (kg/cm²)	A_b (mm²)	ρ_{actual}	ρ_{max}	O/U (l)	M_{cr} (kNmm)	f_b (Mpa)	a (mm)	M_n (kNmm)	P_n (kg)	M_{max} (kNmm)	P_{max} (kg)
D11	213.33	810	0.0540	0.1078	U	715.91	92.84	6.91	1620.19	925.82	474.99	246.22
D12	213.33	1620	0.1080	0.1078	O	715.91	31.79	4.73	1165.62	666.07	600.29	317.82
D13	195.56	1620	0.1080	0.0988	O	685.44	30.27	4.92	1105.31	631.60	975.66	532.63
D14	186.67	810	0.0540	0.0943	U	669.68	92.84	7.90	1583.06	904.60	348.59	174.62

O = Over-reinforced, U = Under- reinforced, f_{yb} = 92.84 Mpa, E_b = 3036.92 Mpa, b = 600 mm, d = 25 mm, Y_t = 25 mm, I_g = 6250000 mm^4.

The curve in **Fig. 6a** illustrates the magnitude of this difference, where the thick dashed line (top position) is the average value of the theoretical nominal moment, and the colored lines are test data. In theory, the crack occurs if the moment carried by the test object exceeds the cracking moment (M_{cr}). However, test data does not support this. Based on the information in **Fig. 6a**, only specimen D13 should crack because the achieved M_{max} = 975.66 kNmm exceeds M_{cr} = 685.44 kNmm. Meanwhile, other test objects should not experience cracks because they only reach 52% - 84% of Mcr. Based on these facts, this is thought to have occurred because the crack occurred at the beginning of loading on the D1 group test specimen. Another thing is due to the moment-deflection relationship (**Fig. 6a**). The elastic condition only occurs until the moment reaches around 200 kNmm with a deflection of 10 - 20 mm. Next, the test object enters the inelastic stage, where the increase in load is not followed proportionally by deflection. This moment is only 0.28 of the average cracking moment of the test specimen calculated using Eq. (10). In other words, this value is possessed by a section with a moment of inertia of around 1/8 of the moment of inertia of the D1 group test specimen section or a thickness of only 50% of the thickness of the test object section. group D1.

These results indicate that only half of the cross-section of the test specimen in group D1 is working to carry the load. This means the gedhek woven configuration separates the top and bottom concrete, so there is no unified cross-section. The thick dotted line (bottom position) in Fig. 6a is the fracture moment value calculated using 50% of the section thickness of the D1 group test specimen, which is around 174 kNmm. This value is equivalent to providing a load of $P \cong 100$ kg. This clarifies why all the test specimens cracked when they reached the maximum load, even though the value was relatively small and the cracks occurred at the beginning of the load.

After the cross-section of the test object experiences a crack, the additional load will cause the crack to become wider and propagate up to the compression area (to the top of the concrete) and stop just below the woven gedhek-type bamboo slats. Cracks cannot propagate to the top of the concrete because the dense gedhek weave blocks them. In this way, the position of the neutral line cannot propagate upward, which means that the load absorption mechanism stops and the test object reaches its maximum condition. The maximum condition is achieved not because the concrete reaches maximum strain (ε_{cu} = 0.003) or the bamboo reinforcement reaches a yielding condition but because the load and deflection recording device always rebounds due to the flexibility of the bamboo weave. Based on these facts, this study recommends that woven gedhek-type bamboo slats are not effective as an alternative reinforcement for precast bamboo walls. Gedhek-type woven bamboo slats separate the top and bottom concrete, thereby reducing the integrity of the cross-section. Apart from that, the additional load that the test object can carry is relatively small, and calculating the nominal cross-sectional capacity for design purposes is difficult to formulate.

3.3 Test object group D2 (bamboo blade type)

Referring to the configuration of the blade reinforcement in the D2 test specimen group, which resembles the configuration of conventional reinforced concrete reinforcement, the bending behavior of this group of test specimens is predicted to follow the bending behavior of conventional reinforced concrete. However, the test data reported in **Table 3** and **Fig. 6b** do not support this. The average maximum moment achieved by this group was 1507.67 kNmm or only 60% of the average theoretical nominal moment calculated using Eq. (4), namely 2508.67 kNmm. Furthermore, the maximum moment achieved by the test specimen was very close to the theoretical cracking moment M_{cr}, which was calculated using Eq. (10), and the maximum moment of the furthest test specimen only deviated 15% from the theoretical cracking moment. Apart from specimen D21, three other specimens showed elastic behavior before reaching the theoretical cracking moment and reached the maximum condition not long after passing through the cracking phase. In particular, this is very clearly visible in test objects D23 and D24.

Table 3. Analysis of test data for precast bamboo walls using bamboo slat types

Code	f_c' (kg/cm²)	A_b (mm²)	ρ_{actual}	ρ_{max}	O/U (l)	M_{cr} (kNmm)	f_b (Mpa)	a (mm)	M_n (kNmm)	P_n (kg)	M_{max} (kNmm)	P_{max} (kg)
D21	186.67	2800	0.1244	0.0943	O	1506.77	27.20	8.00	2551.00	1457.72	1602.19	890.65
D22	186.67	2800	0.1244	0.0943	O	1506.77	27.20	8.00	2551.00	1457.72	1726.95	962.25
D23	204.44	2800	0.1244	0.0943	O	1576.89	28.64	7.69	2699.11	1542.35	1465.80	819.05
D24	151.11	2800	0.1244	0.0943	O	1355.70	24.08	8.75	2233.56	1276.32	1225.73	675.84

O = Over-reinforced, U = Under- reinforced, f_{yb} = 92.84 Mpa, E_b = 3036.92 Mpa, b = 600 mm, d = 37.5 mm, Y_t = 37.5 mm, I_g = 21093750 mm^4.

This sudden failure behavior occurred in all groups of test specimens D2. In specimen D22, after reaching the cracking moment, it experienced a sudden jump in deflection with the addition of a load of 72 kg. The deflection increased sharply from 0.25 mm to 2.05 mm. Likewise, in test specimen D21, when the new test object carries a moment of around 850 kNmm ($P \cong 460$ kg), the deflection is around 0.80 mm. After adding a load of 72 kg, the deflection increased sharply to 1.65 mm. This phenomenon generally occurs in conventional reinforced concrete if the steel reinforcement and concrete bond are poor, resulting in slippage. This study suspects the same thing happened to precast concrete wall specimens reinforced with bamboo slats. Although the phenomenon of a sharp jump in deflection was only recorded on specimens D21 and D22. However, when the bamboo reinforcement slips, concrete cracking occurs more quickly. Visual observation when the test specimen reached the maximum load also noted that the crack had propagated upwards to reach the top fiber of the concrete. This phenomenon is very clearly visible in test objects D21, D22, and D24. In conventional reinforced concrete, this only occurs when the concrete cross-section approaches its ultimate condition. This differs from the test specimens in group D2, which experienced around the cross-sectional cracking capacity. This phenomenon explains why the maximum moment capacity of the test object is only around the cracking moment and cannot reach the theoretical nominal moment.

On the other hand, the phenomenon of slippage in bamboo reinforcement cannot explain the brittle behavior of test specimens D22 and D23. The moment-deflection curves of test specimens D22 and D23 indicate that the bamboo reinforcement is not working at all or that there is no bond between the bamboo and the concrete. This shows the need for special treatment of bamboo blades to increase their adhesion to concrete.

3.4 Test object group D3 (Sasak-type woven bamboo slats)

Compared to the two previous groups of test specimens, the behavior of test specimens in group D3 is considered the closest to the behavior of conventional reinforced concrete, specifically test specimens D33 and D34, as shown in **Table 4** and **Fig. 6c**. At the beginning of loading, the increase in load is followed linearly by an increase in deflection. Next, the test object enters the inelastic stage, marked by a curved curve, until finally, it reaches the maximum condition, marked by a flat curve where deflection increases. At the same time, there is no significant increase in load. The D3 group of specimens also showed a ductile pattern, as expected in reinforced concrete structures. When reaching the maximum load, the deflection of the test object ranges from 8 - 13 mm, much greater than the other groups of test objects, which only reach the most considerable deflection of 2.4 mm.

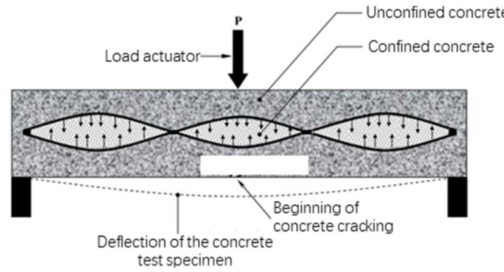
Table 4. Analysis of test data for precast bamboo walls using woven sasak-type bamboo slats

Code	f_c' (kg/cm^2)	A_b (mm^2)	ρ_{actual}	ρ_{max}	O/U (I)	M_{cr} (kNmm)	f_b (Mpa)	a (mm)	M_n (kNmm)	P_n (kg)	M_{max} (kNmm)	P_{max} (kg)
D31	204.44	4800	0.2133	0.1033	O	1576.89	20.97	9.65	3288.83	1879.33	2979.46	1678.28
D32	204.44	4800	0.2133	0.1033	O	1576.89	20.97	9.65	3288.83	1879.33	4859.04	2752.33
D33	195.56	4800	0.2133	0.1033	O	1542.23	20.43	9.83	3194.97	1825.70	4607.34	2609.12
D34	204.44	4800	0.2133	0.1033	O	1576.89	20.97	9.65	3288.83	1879.33	7240.38	4112.78

O = Over-reinforced, U = Under- reinforced, f_{yb} = 92.84 Mpa, E_b = 3036.92 Mpa, b = 600 mm, d = 37.5 mm, Y_t = 37.5 mm, I_g = 21093750 mm^4.

Furthermore, the D3 test object group carried a load of more than 2752 kg before collapsing, except for test object D31, which only reached 1678 kg. The low maximum load that test specimen D31 can bear compared to other test objects in the D3 group is caused by the low quality of work when the test object was printed. During casting, there is a shortage of fresh concrete volume, which is overcome by adding cement and mortar to the test object's surface, which, of course, can reduce the quality of the test object. During testing, the test object is then turned over so that the top side, when casting, becomes the bottom side during testing to maximize the strength of the bamboo reinforcement. This study suspects that this causes the D31 crack pattern (**Fig. 7**) to spread almost throughout the test object's surface. Furthermore, the main crack marked with a thick line in **Fig. 7** for sample group D3 does not occur at the mid-span position. Therefore, the analysis of the behavior of the D3 test object group based on theoretical calculations is more directed at the other three test objects.

One interesting thing was said: the maximum moment that the test object could achieve was far beyond the theoretical nominal moment. The average theoretical nominal moment is only 3265.37 kNmm. Meanwhile, the average maximum test moment reached 4921.56 kNmm, 1.5 times greater than the theoretical value. The D34 test object reached 7240.38 kNmm, 2.2 times greater than the theoretical value. The data in **Table 4** shows that the theoretical stress experienced by bamboo reinforcement when it reaches its nominal moment is only around 21 MPa or only 23% of the bamboo yield stress f_{yb} = 92.84 MPa. Of course, this is caused by the over-reinforced condition of the test object. Based on these conditions, the opportunity to increase the theoretical M_n value can only be achieved if the stress experienced by the bamboo reinforcement is greater than 21 MPa. However, this is not possible other than because it violates the balance principle of Eq. (6). At the same time, theoretically, the stressed outer fiber of the concrete has experienced a maximum strain of ε_{cu} = 0.003, and the entire thickness of the concrete cross-section will crack (as experienced by the group D2 specimen) if the additional load continues. However, on the other hand, visual observations during testing did not support this assumption. **Fig. 8a** shows that when approaching the maximum load, not the entire thickness of the cross-section experiences cracks; there are still intact parts of the concrete to withstand the compressive force to maintain balance.



(a) **(b)**

Fig. 8. Test specimen D33: (a) visualization of cracks when approaching maximum load; (b) confined concrete mechanism.

In other words, the assumption that bamboo reinforcement experiences more than 21 MPa stresses is very possible. This study suspects that the confined concrete mechanism occurs in specimen D3. An illustration is presented in **Fig. 8b** to understand this mechanism better. The configuration of the woven shank reinforcement creates a confined concrete section in the test specimen (in **Fig. 8b**, marked with dotted shading). Even though it only has a thickness of approximately 20 mm, this part is enough to influence the overall behavior of the test object, which only has a thickness of 75 mm. The confined part of the concrete becomes a strong 'belt' to restrain or slow down the rate at which cracks propagate upwards. The cracking rate can be slowed down because confined concrete can have a maximum strain greater than ε_{cu} = 0.003, and the compressive strength of the concrete increases. An approach to calculate the maximum strain value and compressive strength of confined concrete was proposed by Karthik and Mander (2011) in the formulations Eq. (13) and Eq. (14).

$$\varepsilon cc = 0.002\left[1+5\left(\frac{f_{cc}^{'}}{f_c^{'}}-1\right)\right] \tag{13}$$

$$f_{cc}^{'} = f_c^{'}\left(2.254\sqrt{1+\frac{7.94f_l^{'}}{f_c^{'}}}-\frac{2f_l^{'}}{f_c^{'}}-1.254\right) \tag{14}$$

where ε_{cc} and f_{cc}' are the maximum strain and compressive strength of confined concrete, f_c' is the compressive strength of unconfined concrete, and f_l' is the restraint factor, which depends on the reinforcement configuration.

All stress parameters are in units of kip/in^2. As an illustration, in general, the value of $\varepsilon_{cu} \approx 0.0087 - 0.010$ and $f_{cc}' \approx 1.2 - 2.0 f_c'$, if this value is used to calculate the theoretical nominal strength following the previous procedure, then the theoretical nominal moment can reach a value of 4950 kNmm where the stress experienced by the bamboo reinforcement about 35 MPa. So far, this study has found that woven sasak-type bamboo slats are very effective as an alternative reinforcement in precast concrete walls, and for planning purposes, the theoretical nominal moment capacity can be calculated using Eq. (4).

4. Conclusions

Experimental studies using bamboo as an alternative reinforcement for precast concrete walls have been investigated and reported in depth in this study. Woven bamboo slats of the gedhek type (test object group D1) were deemed ineffective as alternative reinforcement. The woven bamboo slats of the gedhek type cause the separation of the top and bottom parts of the concrete, thereby reducing the integrity of the cross-section and causing the cross-sectional capacity to be relatively very small. The flexural behavior of bamboo blade-type specimens (test specimen group D2) is very different from the flexural behavior of conventional reinforced concrete; sudden failure and brittle occur in the specimens, which causes the most significant difference between the maximum moment capacity and the theoretical cracking moment of only around 15%. The average maximum moment from the test results is only 60% of the theoretical nominal moment. The test results indicated a slip in the bond between the bamboo and concrete reinforcement. Bamboo slats are less effective as alternative reinforcement if the bamboo slats are not given special treatment to increase their adhesion to concrete. Sasak-type woven bamboo slats (test object group D3) are the most effective alternative reinforcement. The characteristics of precast concrete walls with woven sasak-type bamboo slats are considered to be closest to the behavior of conventional reinforced concrete and show a ductile pattern. The maximum moment capacity achieved is 1.5 - 2.2 times greater than the theoretical nominal moment capacity. Furthermore, this study suggests using a relatively large area of bamboo reinforcement so that the concrete section falls into the over-reinforced category.

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