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Bamboo reinforced concrete slab with styrofoam lamina filler as solution of lightweight concrete application

Ari Wibowo[1,*], *Indradi* Wijatmiko[1], and *Christin* Remayanti Nainggolan[1]

[1]Department of Civil Engineering, Faculty of Engineering, Brawijaya University, 65149 Malang, Indonesia

Abstract. Energy resilience is becoming more important nowadays especially in the field of building sustainability. Some implementations can be carried out including using recycled materials instead of nonrenewable materials such as steel. Hence, one of the investigation conducted in this paper is replacing steel reinforcement with bamboo bars and using recycled materials such as Styrofoam with the aim of producing a concrete element structure that is lighter and more economical. In this research stage, flexural strength test on bamboo reinforced concrete slab with Styrofoam lamination filler was conducted. The results showed that the flexural strength of specimens decreased by 15% but with the weight advantage of 20% less compared with those of normal reinforced concrete slab with the same dimension. It is considered good performance in practical design context, since the nominal flexural capacity of RC slab when designed with minimum reinforcement are usually much higher than the required moment.

1 Introduction

Bamboo reinforcements become increasingly considered as substitutes for steel reinforcements since being cheaper especially in developing countries where bamboo can be obtained more easily. The production of bamboo also does not endanger environment and hence it is environmentally friendly. However, material properties of bamboo and its application as reinforced concrete materials still need further investigation. Many research studies on bamboo reinforced concrete members have been conducted in the last few years. Ghavami [1] has invesigated the characteristics of bamboo as an engineering material (including mechanical properties, durability, water absorption effect, bonding strength), as replacement of steel bars in concrete members and also flexural strength analysis of concrete elements. The study showed that bamboo can substitute steel reinforcement satisfactorily. However, more research studies need to be undertaken to further determine international norms for bamboo reinforcement design applications. Yamaguchi et al [2] studied on applying bamboo as main rebars and stirrups replacement for reinforced concrete beams. The experimental tests demonstrated that the collapse mechanism of the beams were affected by the rupture strength of bamboo bars, whilst the stiffness of beams was inluenced by bond slip strength between bambo rebars and concrete. Further, Terai and Kinami [3] focused on bamboo bond slip strength capacity as their main study by conducting tests using various bonding agents, application methods and treatments. It was observed that the bond strengths of coated bamboo were found in between those of plain and deformed steel bars. Also the difference shrinkage rate of bamboo and concrete caused the deterioration of the bond stress, and hence, the choice of proper curing treatment can be significant.

To further improve the sustainability of structural elements, styrofoam can be used as panel filler inside the concrete element which is also useful to minimize the self-weight of concrete member. Styrofoam is regarded as environmentally friendly material since it is fully recyclable and reusable made of plastic. Moreover, by providing lightweight concrete member, the total weight of the building can be lowered and in turn reduces the lateral loads imposed by the earthquake excitation as well. However, previous reconnaissance study in damage area due to earthquake disaster observed that many lightweight concrete members did not have adequate strength and deformation capacity to withstand such energy [4]. Therefore, many further investigations are required to address the issue.

In this study, the applications of bamboo as reinforcement and styrofoam as lightweight filler for concrete member are combined and investigated. The members studied in this test were bamboo reinforced slab using styrofoam panel filler as shown in Figure 1.

Fig. 1. Bamboo reinforced concrete with styrofoam panel filler

* Corresponding author: ariwibowo@ub.ac.id

The main aim of this study was to study the ultimate strength capacity and collapse mechanism of such slab system so that it can be applied in concrete design and construction practices.

2 Experimental test program

2.1 Pull-out test on bamboo bars

Bamboo can expand while absorbing water and shrink while losing its water content. The shrinkage volume and speed of bamboo are larger and faster compared to those of concrete, and hence bamboo bars need to be coated for preventing water absorption and also strengthening the bond strength between bamboo and surrounding concrete. Therefore, varnish were brushed on the bamboo bar surface; and while the coating was still viscous, bamboo bars were rolled onto fine aggregates to create rough surface and to improve the friction between concrete and bamboo bars.

Pull-out tests were conducted on 6×6 mm sand coated bamboo bars which embedded in concrete cubes (fc' = 20 MPa) with embedment length of 220mm as shown in Figure 2. The test results showed that the pull-out force was about 1.5kN, which equivalent to pull-out strength of 0.3 MPa.

Fig. 2. Bamboo bar pull-out test setup

2.2 Slab specimens

The specimens consisted of two types of bamboo reinforced concrete slabs i.e.: Spesimen S series (with Styrofoam panel filler) and specimen TS series (without Styrofoam panel filler). All slab specimens had the same dimension (width × length × thickness) of 40×80×5 cm as shown in Figure 3. Main reinforcements were manufactured by splitting Petung bamboo (botanical name: *Dendrocalamus Casper,* giant bamboo) bars with dimension of 6 × 6mm and placed on both longitudinal and transversal directions of slab. The presence of Styrofoam panel alters the load-displacement mechanism from regular flexural member to composite system. And hence, galvanized wire shear connectors were placed via 3cm diameter holes connecting top and bottom longitudinal-transversal bar joints. The clear concrete cover was 8mm, whilst the specified concrete compressive strength and bamboo yield stress were 20MPa and 190 MPa respectively.

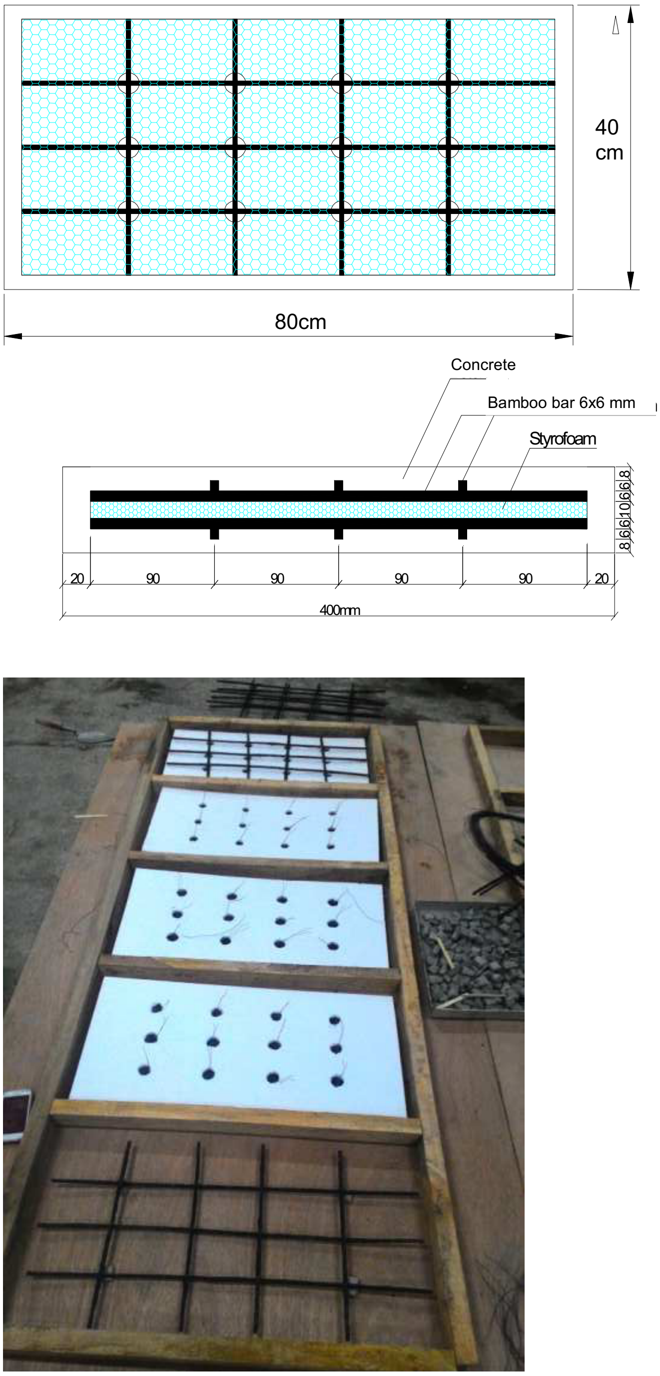


Fig. 3. Detail of slab specimens

The slab specimens were tested as one-way slab system spanning 75cm between two pin supports (refer to Figure 4). Concentrated line loading was applied at mid span of slab under load control mechanism at increment of 20 kg until peak load and then followed by displacement-controlled load until failure.

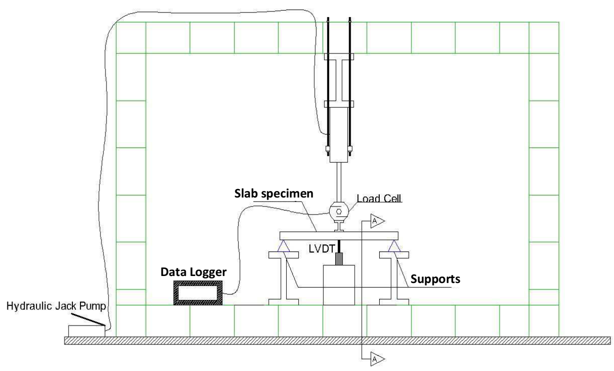


Fig. 4. Experimental test setup

3 Experimental test results

All specimens were set as one-way slab member, where the LVDTs were initialized for subsequent readings. The subsequent load-controlled were then applied. The peak loads obtained for specimens without Styrofoam TS1 and TS2 were 6.7 KN, 6.3 KN, whilst the line loads of specimens S1, S2 and S3 (with Styrofoam) peaked at 5.5 KN, 5.7 KN and 5.2 KN respectively; which correlated with 15% reduction of ultimate strength capacity. Correspondingly, the ultimate deflections at mid span for specimens TS1 and TS2 were about 23 mm and 21 mm respectively, whereas the deflections for specimens S1, S2 and S3 reached 31 mm, 21 mm and 22 mm; which generally showed no significant decrease in deflection at failure point. All test results are shown in Table 1.

Table 1. Peak load and displacement test results for specimens TS and S (without and with Styrofoam respectively)

Specimen	P_{cr} (KN)	P_u (kN)	Δ_{cr} (mm)	Δ_u (mm)
TS1	4.0	6.7	1.45	23
TS2	4.0	6.3	1.35	21
S1	4.3	5.5	5.2	31
S2	4.6	5.7	1.2	21
S3	4.0	5.2	4.7	22

Note Pcr = Cracking Load, Pu = Peak Load, Δ_{cr} = cracking displacement Δu = Displacement at Failure

The load-deflection behavior for all specimens are shown in Figure 5. Interestingly, two different type of initial stiffness were observed on the specimens. Specimens TS1, TS2 and S2 had a very similar initial stiffness which are steeper than those of specimens S1 and S3 (refer Figure 6). It shows that the Styrofoam panel did not directly contribute to the initial stiffness of the slabs. The reason for this behavior might be attributed to the different bond slip strength between bamboo bars and concrete, since the sand as coating for bamboo could not be applied homogeneously over the bamboo length. The use of Styrofoam also reduced the thickness of concrete layer surrounding the bamboo bars, and hence reduced the bond slip resistance; which in turn, increased the possibility of slippage of bamboo bars. From the tests, it was obvious that specimens with Styrofoam tended to have lower initial stiffness up to the first crack compared to those of slabs without Styrofoam.

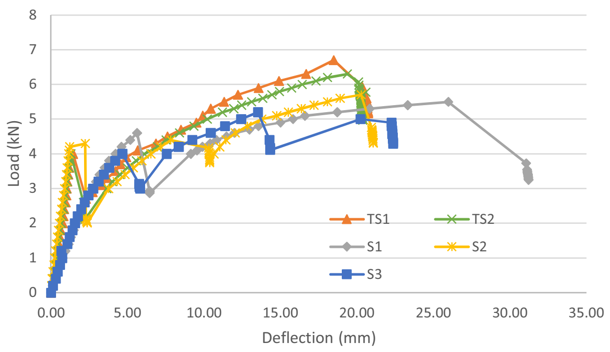
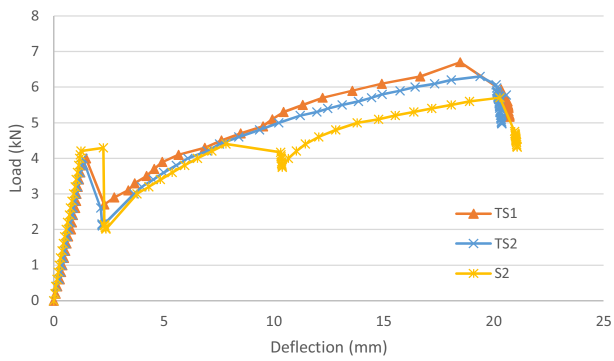
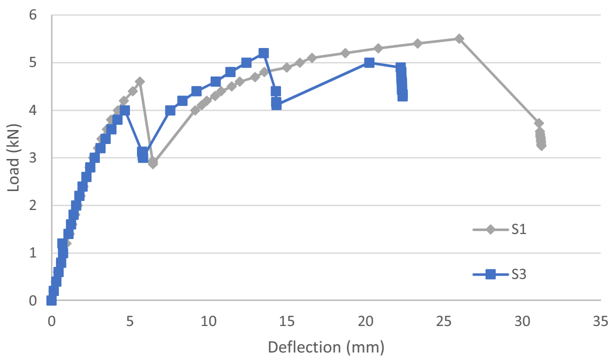


Fig. 5. Load-deflection behavior for all specimens



a. Load-deflection behavior for specimens with higher initial stiffness



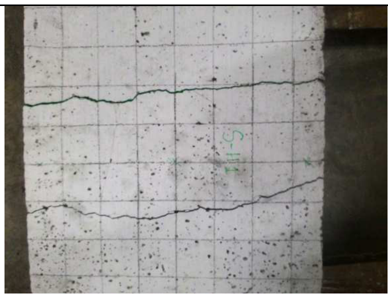
b. Load-deflection behavior for specimens with lower initial stiffness

Fig. 6. Detail of load-deflection behavior of specimens

The load-displacement behavior for specimens S2 and S3 showed two peak loads which correlated with the occurrence of two subsequent main flexural cracks, whereas the flexural cracks of specimen TS1, TS2 and S1 occurred simultaneously. Interestingly, instead of only one crack at maximum moment location as commonly found at one-way slab, those two cracks were observed propagated from tension extreme fiber below the lateral bamboo bars close to mid span. The thin concrete cover underneath lateral bamboo bars reduced the cracking moment capacity compared to that at mid span (the area in-between two lateral bamboo bars) and hence shifted the cracks further from mid span. This showed that concrete cover provided significant effect on cracking moment compared to the gross area of concrete especially on thin element structures such as slabs.

The collapse of concrete slabs occurred with two different behaviors for each type of element as shown in Table 1. Concrete slabs with Styrofoam failed due to bond slip mechanism between Styrofoam and compression concrete since the bond slip strength between concrete and Styrofoam was relatively small. In contrast, classical flexural failures were observed at concrete slabs without Styrofoam. However, the ultimate moment capacity between those two failure mechanisms were quite similar due to the short level-arm moment of concrete slab on both types of slabs

Table 1. Crack patterns for specimens S1, S2 and TS1

Crack pattern	**S1**	**S2**	**TS1**
under side of slab			
Outer edge of slab			

4 Analytical results

Flexural displacement prediction of a slab has been developed in this study based on the fiber section method by Park and Paulay [5] to obtain a moment-curvature relationship. Further, from the obtained moment and curvature, the load and deflection of slab can be calculated.

The moment-curvature analysis used the assumption that plane section remains plane as shown in Figure 7. Hence, the strain of concrete is equal to the strain of reinforcement bamboo at the same depth level and consequently, stresses of concrete and bamboo can be calculated from the stress-strain relationship of each material. The moment (M) and curvature (φ) relationship is defined as follows:

$$EI = \frac{M}{\varphi} \tag{1}$$

$$\varphi = \frac{\varepsilon_c}{c} = \frac{\varepsilon_c + \varepsilon_b}{d} \tag{2}$$

where c is neutral axis depth, d is slab effective depth, and ε_c and ε_b are concrete and bamboo strain respectively.

The stress-strain curve for the concrete cover is assumed to have the same strain-stress relationship as unconfined concrete for strains up to fracture, whilst for larger strains, the concrete cover is assumed to have spalled and is ignored.

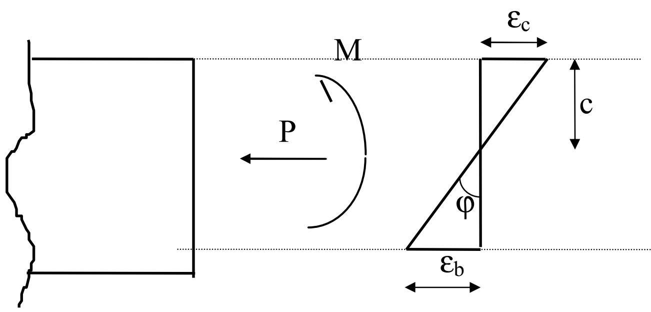


Fig. 7. Moment-curvature relationship

For simplicity, buckling is assumed not to occur on the compressive longitudinal reinforcement. Consequently, in the analysis the longitudinal reinforcement will not lose the compressive strength when the surrounding concrete cover spalls.

A computer program [6] was developed to establish the moment-curvature relationship by dividing the cross section area into '*n*' layers as follows (refer Figure 8):

1. Fix increment of compressive concrete strain ε_{cm},
2. Guess an initial value of neutral axis, $c = kd$.
3. Calculate concrete and bamboo forces:
    a. Divide the cross section area into n horizontal layers. This program uses 2000 layers.

b. For each depth y_i, calculate the strain that directly proportional to the strain ε_{cm} at the extreme fiber
c. Calculate concrete stress f_{ci} for segment-*i* based on modified-Kent & Park stress-strain relationship diagram.
d. Calculate force at each layer, $P_i = b(h/n)f_{ci}$
e. Calculate moment about the extreme fiber,

$$M_i = P_i\, d_i$$

f. Total concrete force: $P_{tot} = \sum_{i=1}^{n} P_i \quad (i=1,n)$

g. Total moment: $M_{tot} = \sum_{i=1}^{n} M_i \quad (i=1,n)$

4. Check equilibrium equation:

$$P = 0.85\ f_c'\ b\ kd + \sum_{i=1}^{n} f_{bi} A_{bi}$$

where:

b = the column width
d = the effective depth of a column
kd = the neutral axis depth
f_{bi} = bamboo stress of each main rebars
A_{bi} = cross section area of each main rebars

Iterate steps 2-4 with new value of neutral axis (*kd*), until equilibrium equation is satisfied and then calculate the moment capacity and the related curvature.

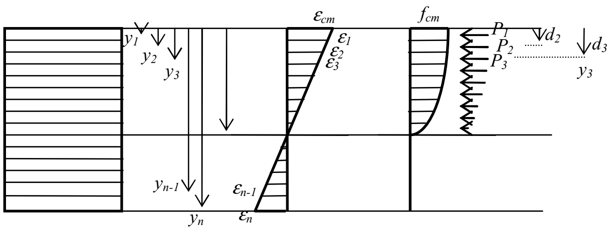


Fig. 8. Fiber section analysis

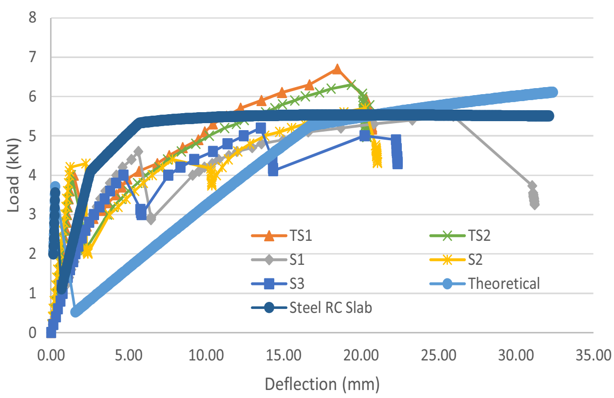


Fig. 9. Comparison of load-deflection relationship between experimental and theoretical results

For simplicity, the bilinear behavior of stress-strain relationship for bamboo derived from experimental data was used. Whereas, the Modified-Kent & Park model as stress-strain relationship of concrete was applied into the model.

The theoretical model using moment-curvature analysis describe above showed good agreement with the experimental results as shown in Figure 9. The cracking load, ultimate load and the corresponding deflections of theoretical model were also in good agreement with experimental data (refer Table 2).

Table 2. Comparison of average load and deflection of experimental data and theoretical model for specimens TS and S (without and with styrofoam respectively)

Specimen	P_{cr} (KN)	P_u (kN)	Δ_{cr} (mm)	Δ_u (mm)
TS	4.0	6.5	1.40	22
S	4.3	5.5	1.2-4.7	21-31
Theoretical	3.8	6.1	0.9	32

As comparison, the load-deflection of steel reinforced concrete slab with identical dimension and concrete properties as bamboo reinforced concrete slab has also been obtained. The steel reinforced concrete used the three steel bars with dimension of 6mm (corresponding to ϕ6-100) and yield stress of 240 MPa. Interestingly, as shown in Figure 10, the performance of bamboo reinforced concrete slab was relatively similar but with less stiff and less ductile to those of steel reinforced concrete slab.

5 Conclusions

Five similar bamboo reinforced slabs have been tested with three slabs were designed with Styrofoam panel as filler and the other two without the Styrofoam panel. The theoretical modeling based on moment-curvature relationship has also been conducted which showed good agreement with experimental test data. Several outcomes can be observed as follows:

1. The ultimate load of slabs without Styrofoam panel were 15% higher but 20% heavier compared with those of Styrofoam panel slabs with the same dimension It is considered good performance in practice design context, since the nominal flexural capacity of RC slabs when designed with minimum reinforcement are usually much higher than the required moment.
2. However there was no significant difference in ultimate deflection capacity, since the deflections at failure point for all specimens were roughly similar.
3. Bamboo reinforced concrete slabs with Styrofoam panel were adequate as a substitute for normal reinforced concrete slabs.

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* Corresponding author: ariwibowo@ub.ac.id