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AXIAL BEHAVIOR OF RC COLUMNS RETROFITTED USING BAMBOO REINFORCED CONCRETE JACKET

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ABSTRACT: Weak or damaged reinforced concrete columns need to be retrofitted in order to increase the strength capacity and ductility. Concrete jacketing is one of the most common techniques adopted for such purpose due to its relatively simple and low-cost application. However, the dependency on steel reinforcement in its use is still high and with the sustainability issues that are getting more important nowadays, the idea of bamboo as a replacement for steel as reinforcing bars in the concrete jacketing method has been investigated in this experimental study. A group of short reinforced concrete column specimens with axial load failure state were then retrofitted with a variety of longitudinal and transversal bamboo reinforcement configurations of concrete jacketing and subjected to further compression axial load test. The axial load-displacement behavior, axial strength capacity, and collapse mechanisms were recorded and analyzed. The outcomes showed that bamboo reinforced concrete jacket perform satisfactorily by restoring the axial load capacity and increasing ductility of column specimens providing that the bamboo stirrups spacing was set closer than that of the original column.

Keywords: Concrete jacket, Bamboo rebar, Reinforced concrete column, Retrofitting

1. INTRODUCTION

Frequently, performance and load carrying capacity of structures need to be improved due to damage, bad structural design, or poor construction [1,2]. Several methods commonly applied for strengthening the structure are concrete jacketing, steel jacketing, and fiber reinforced polymer. The comparison of those methods on RC columns has been elaborated by Truong et.al. [3], where the outcomes showed that both steel and concrete jacketing displayed a greater increase of axial load capacity compared to CFRP, however, the effectiveness of both methods on full-scale building was reduced by large weight of the additional jackets. Further investigation is required to obtain general conclusions.

Rehabilitation techniques using reinforced concrete jackets on RC columns have been increasingly investigated in the past decade by observing several parameters such as: flexural strength and ductility of columns [4,5], jacket stiffness and longitudinal reinforcement ratio [6], shrinkage on concrete jacket [7], and interface effect on composite element behaviour [8]. One thing in common, all concrete jacket techniques use steel bars as the main reinforcement; where, as the sustainability issues become paramount nowadays, the need for alternative material is required. Bamboo has increasingly become a substitute to replace steel for reinforcement [9-18], particularly in developing countries. Therefore, bamboo as longitudinal and transverse reinforcement on the concrete jacketing method was investigated in this research project. Short reinforced concrete columns subjected to axial load have been tested where the axial load-displacement behavior, load carrying capacity, ductility and failure mechanism were observed and analyzed

2. EXPERIMENTAL TEST SETUP

The experimental test aimed at the study of concrete jacket effect on damaged short columns subjected to axial load.

2.1 Materials and Specimens

The effect of confinement on axial load-displacement relationship of regular RC columns has been comprehensively understood [19,20] and is influenced by several parameters such as: a) the transverse reinforcement ratio (representing the level of transverse confining pressure), b) the spacing and configuration of stirrups (representing effectiveness of confinement, refer Figure 1), c) the longitudinal reinforcement ratio and configuration (affecting the effective length of stirrups), d) concrete strength (the ductility behavior of concrete), e) yield strength of steel (limiting the peak confining pressure). In this study, three parameters of concrete jacketing were investigated, i.e., the configuration of main bars at the same longitudinal reinforcement ratio, material type and spacing of transverse reinforcement.

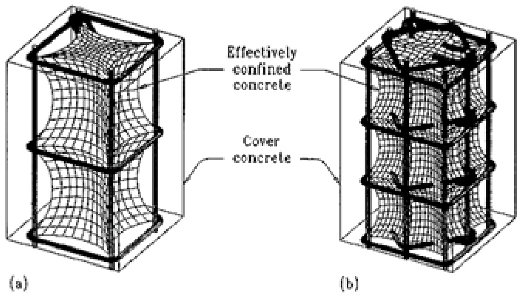


Fig. 1. Confinement effectiveness on RC columns for a) lower confining pressure, b) higher confining pressure (refer [20])

The experimental test has been conducted on groups of specimens with two stages of compressive axial load test (original and retrofitted columns) as shown in Figure 2. The original specimens were 12x12 cm short columns with a height of 30 cm containing four ϕ6 mm (corresponding to a longitudinal reinforcement ratio of 1.4%) as shown in Figure 3. In all cases, stirrups were used at 140mm spacing corresponding to a volumetric transverse reinforcement area ratio of 0.81%. The clear concrete cover was 20mm, whilst the specified concrete compressive strength and steel yield stress for main rebars and stirrups were 20 MPa, 270 MPa and 170 MPa respectively.

After the first compressive axial load test, the damaged columns were then retrofitted using a bamboo reinforced concrete jacket as follows (refer to Table 1 and Figure 4). The retrofitting was set by investigating two factors (i.e. effectiveness and an upper limit of confinement) as follows:

- The effectiveness of confinement of concrete jacket was studied by examining the combination of two parameters, i.e. longitudinal reinforcement configuration and stirrups spacing. Two configurations of bamboo longitudinal reinforcement used were 4 bars 10x10 mm (specimens A-B, E-F) and 8 bars 10x5 mm (specimens C-D) corresponding to the same rebar ratio of 1.23% and 2.47% respectively. Petung bamboo (*Dendrocalamus asper)* with the yield stress of 190 MPa was used for the main rebar
- Further, in order to observe the effectiveness of stirrups in terms of the upper limit of the confining pressure, two materials for transverse reinforcement were used, i.e., bamboo (specimens A-D) and steel (configurations E-F). Bamboo bars used for stirrups were apus bamboo (*Gigantochloa apus*) due to the more flexibility to be bent for stirrups fabrication compared to the stiffer petting bamboo. Since the yield stress of apus bamboo (f_y = 120 MPa) was considerably smaller compared to steel (f_y = 240 MPa), hence the dimension of bamboo stirrups was set larger of about 10x5 mm compared to ϕ6mm of steel stirrups for maintaining the force similitude. In all specimens, the spacing of transverse reinforcement was set of 7cm, 10cm and 14 cm.
- The short column is the case of this study, where the column length effect will be investigated in the future study and hence beyond the scope of this paper.

Table 1. Retrofitting set up for column specimens.

Columns	Longitudinal Reinforcement		Transverse Reinforcement		
	Dimension	Ratio (%)	Stirrups Material	Spacing	Ratio (%)
Original	4ϕ8	1.40	Steel	ϕ6 – 150	0.81
A1R	4 bamboo bars 10x10 mm	1.23	Bamboo	10×5 – 100	1.21
A2R				10×5 – 140	0.81
A3R				10×5 – 70	1.61
B1R	8 bamboo bars 10x5 mm	1.23	Bamboo	10×5 – 100	1.21
B2R				10×5 – 140	0.81
B3R				10×5 – 70	1.61
C1R	4 bamboo bars 20x10 mm	2.47	Bamboo	10×5 – 100	1.21
C2R				10×5 – 140	0.81
C3R				10×5 – 70	1.61
D1R	8 bamboo bars 10x10 mm	2.47	Bamboo	10×5 – 100	1.21
D2R				10×5 – 140	0.81
D3R				10×5 – 70	1.61
E1R	4 bamboo bars 10x10 mm	1.23	Steel	ϕ6 – 100	0.68
E2R				ϕ6 – 140	0.46
F1R	8 bamboo bars 10x5 mm	1.23	Steel	ϕ6 – 100	0.68
F2R				ϕ6 – 140	0.46

Fig. 2. Axial loading test setup using the Compression Testing Machine.

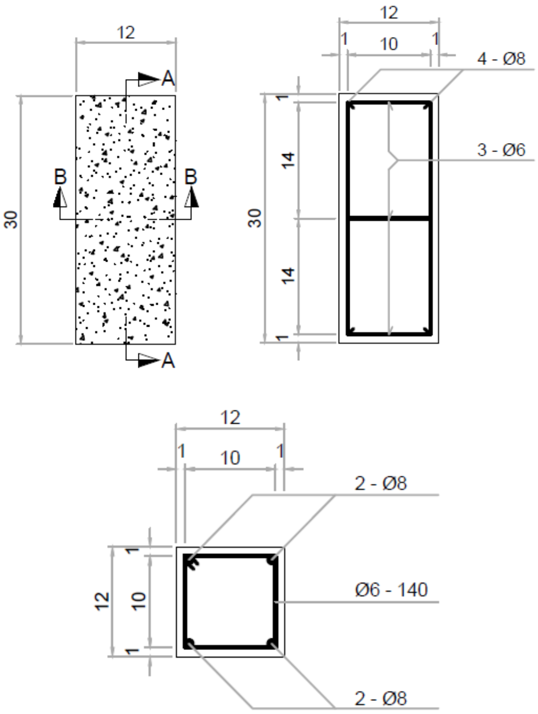
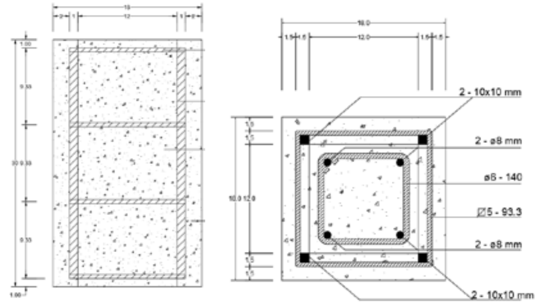


Fig. 3. Typical original column specimens

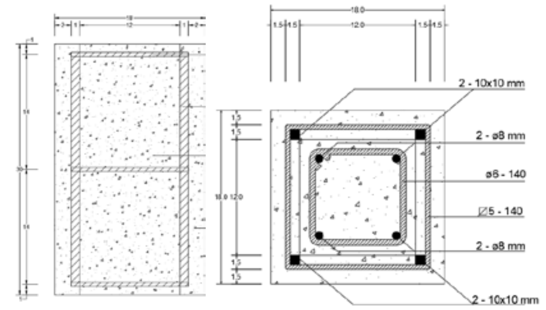
The limitation of bamboo is the absorption of water during the setting time of fresh concrete which will expand the volume of bamboo, but then shrink when losing the water content during hardening time causing a gap between bamboo bars and concrete. Additionally, the lack of bonding strength between bamboo bars and concrete also results in the slip mechanism of bamboo bars. To solve the problem, the layer of fine aggregates were glued to the bamboo surface using varnish.

2.2 Test Setup

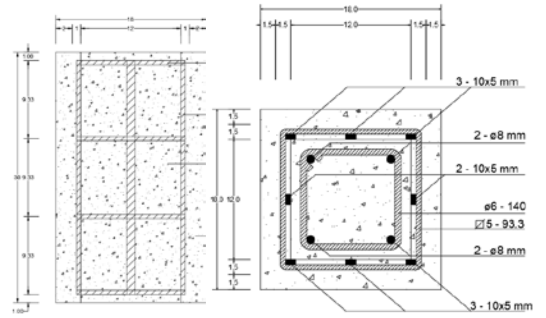
The columns were axially loaded using the Compression Test Machine (CTM) at two stages. The first test stage was conducted on the original columns and stopped when the peak axial load capacity of the specimens reduced by 50%. After being retrofitted, the second loading tests were undertaken with the same procedures of the first tests. In all tests, the axial deformation was measured using dial gauge assembled vertically on the CTM.



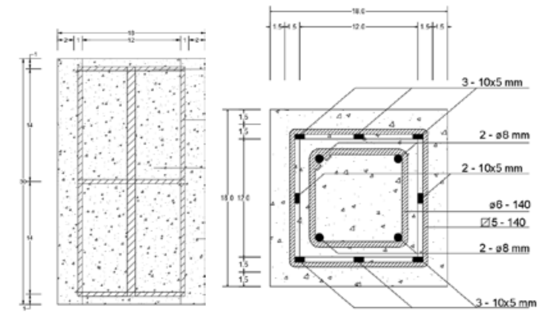
a. Concrete jacket with 4 main bars and stirrups spaced at 100mm.



b. Concrete jacket with 4 main bars and stirrups spaced at 140mm



c. Concrete jacket with 8 main bars and stirrups spaced at 100mm



d. Concrete jacket with 8 main bars and stirrups spaced at 140mm

Fig. 4. Typical retrofitting for columns.

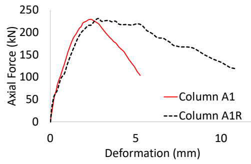
3. TEST RESULTS

The measured axial load and deformation relationships for all retrofitted columns are shown in Figure 5. The ductility ratio was calculated from P-Δ curves based on Reduced Stiffness Equivalent Elasto-Plastic Yield [21] using secant stiffness at 75% of the peak load.

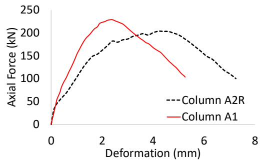
a. The original column specimens had an average peak axial load capacity of 212 kN and the average deformation ductility ratio of 3.3.
b. All retrofitting methods on damaged columns showed improvement in ductility ratios compared to those of the original columns as shown in Figures 6-11 and Table 2. For the same stirrups spacing range of 100 and 140mm, the steel stirrups generated ductility ratios of column ranging from 5.05-6.21, whilst the bamboo stirrups had relatively similar ductility ratios of about 3.62-6.77. Whereas by increasing the bamboo stirrups to 70mm, the ductility also increases up to 9.0. Hence, it can be deducted that bamboo stirrups can be considered as effective as steel stirrups on increasing the ductility ratio of columns providing that the force similitude can be maintained.
c. In terms of axial load-carrying capacity shown in Table 2, the use of steel stirrups resulted in an increase of peak axial load of about 24-97% (refer Figures 10-11) compared to the peak load of original columns prior to failure. On the other hand, the use of bamboo stirrups considerably failed to reach the same peak load level on original columns if the bamboo stirrups spacings were the same or larger than those of original columns. It can be attributed to the higher yield strength of steel and therefore the higher upper limit of confinement. The higher peak strength could be achieved for column retrofit with bamboo stirrups spacing smaller than that of original columns.
d. Generally, the use of 8 smaller bar configuration of 10x5mm generally exhibited a ductility ratio of 30% higher than those of columns with 4 larger bars 10x10 mm (refer Table 2 and Figures 12-14). It indicated that for the same longitudinal reinforcement ratio, the distribution of bars uniformly over the column perimeter relatively be more preferable due to the larger confinement area. However, the slenderness ratio of the bamboo bar to the unsupported length of bars between stirrups needs to be checked when using a smaller bar diameter in order to maintain the effective length of stirrups.
e. The use of 8 small bars and 4 larger bars did not seem to affect the peak axial load-carrying capacity of columns.
f. The wider the stirrups spacing from 10 cm to 15 cm generally reduced the ductility ratios of about 10% and decreased the axial load capacity of about 20% as shown in Table 2. On the other hand, by reducing the stirrups spacing from 10cm to 7.3 cm, the ductility ratio and axial load capacity increase to 15% and 10% respectively.
g. The increase of longitudinal reinforcement ratio from 1.23% to 2.47% increase the overall peak strength of about 10% but reduce the ductility ratio of 20%. However, the increase of peak strength reasonably depends on the degree of damaged original concrete and the quality of the concrete jacket. The concrete-to-concrete bond strength between original and retrofit also affect the failure mechanism which influenced by interface roughness and the use of various concrete bonding adhesive. More studies are required to investigate these parameters.

For original columns, the average peak axial load of experimental test on original columns of 212 kN was in a good agreement with the estimate peak axial load of 228 kN. Whereas, the measured peak axial loads of retrofitted columns ranged relatively wide between 160 – 370 kN showing that several considerations need to be set in order to increase the effectiveness of this technique as follows:

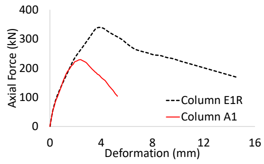
a. The bamboo elastic modulus of about 70 GPa is less than that of steel of about 200GPa, and hence the confinement effect of bamboo stirrups might not be very effective as it needs large strain to develop the stress in stirrups. It can be solved by setting the closer stirrups spacing of bamboo compared with that of steel stirrups.
b. The use of bamboo for stirrups needs a bending process which tends to crack the bamboo stirrups at corners. Different methods have been applied using heating, cutting-gluing, and filling the cracks with epoxy with no significant improvement indicated by rupture failure of bamboo stirrups as shown in Figure 15. On contrary, steel stirrups showed reasonably more ductile behavior as seen in Figure 16. The best results for bamboo stirrups were obtained using a laminated bamboo periphery (outer) layer. Each bar layer was bent individually and then be assembled and glued together to make laminated bamboo stirrups as shown in Figure 17.



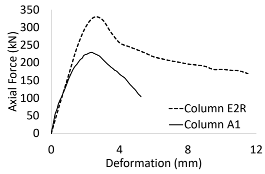
a. Specimen A1R



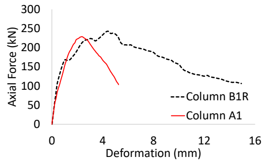
b. Specimen A2R



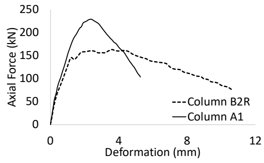
c. Specimen E1R



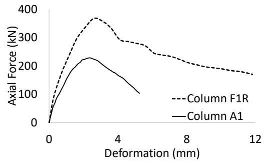
d. Specimen E2R



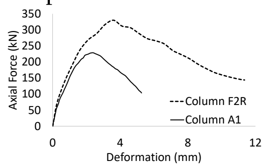
e. Specimen B1R



f. Specimen B2R



g. Specimen F1R



h. Specimen F2R

Fig. 5. The axial load-deformation relationship for column specimens

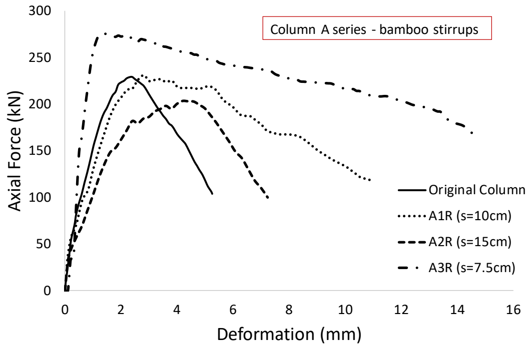


Fig. 6. Bamboo stirrups spacing effect for column A series.

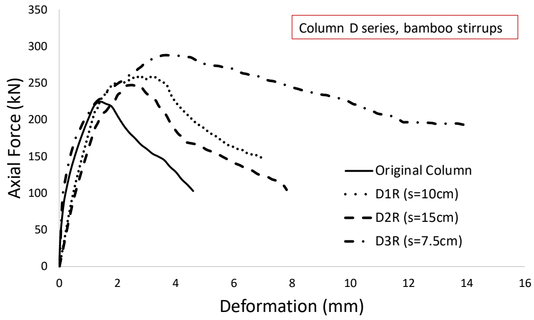


Fig. 9. Bamboo stirrups spacing effect for column D series

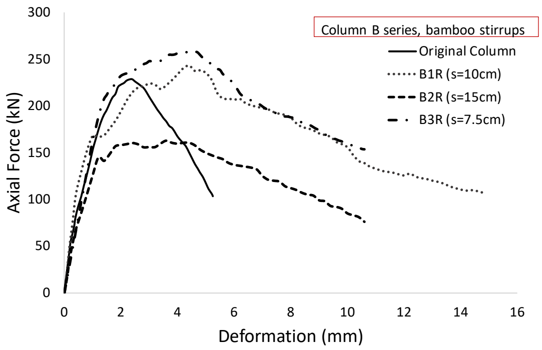


Fig. 7. Bamboo stirrups spacing effect for column B series

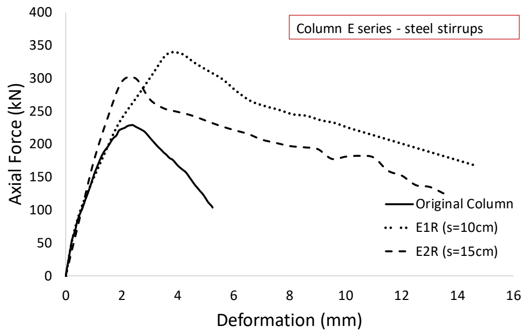


Fig. 10. Steel stirrups spacing effect for column E series

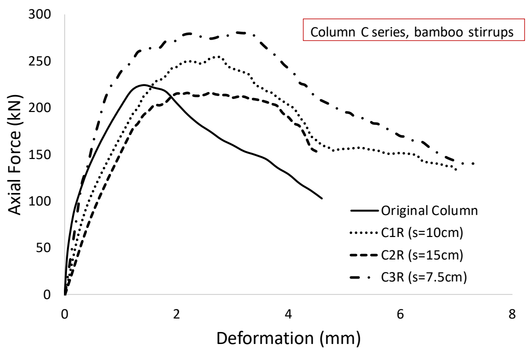


Fig. 8. Bamboo stirrups spacing effect for column C series

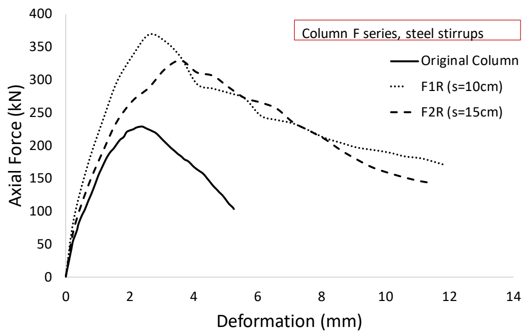


Fig. 11 Steel stirrups spacing effect for column F series.

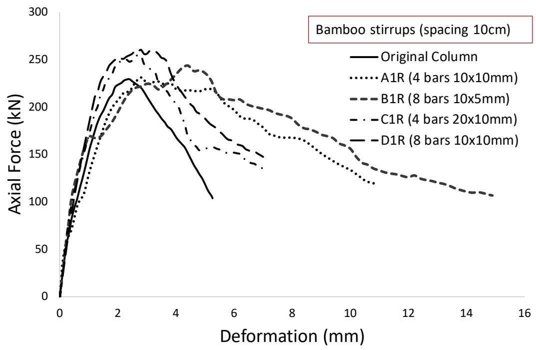


Fig. 12 Comparison of main bar ratio and configuration for columns with stirrups spacing of 100mm

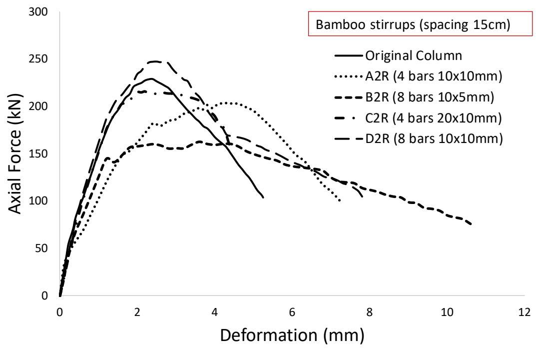


Fig 13. Comparison of main bar ratio and configuration for columns with stirrups spacing of 150mm

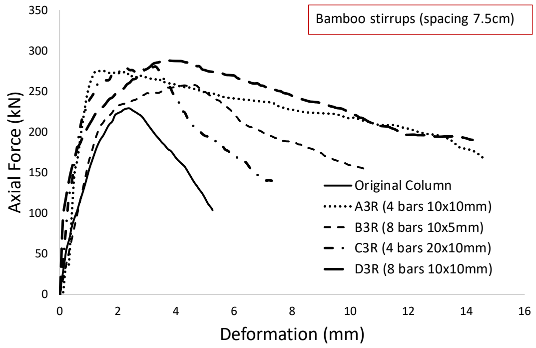


Fig. 14 Comparison of the main bar ratio and configuration for columns with stirrups spacing of 70mm.

Fig. 15 Failure mechanism of columns retrofitted with bamboo transverse reinforcement

Table 2. Axial loads and deformations of all specimens

Col.	P_{peak} (kN)	P_{50} (kN)	Δy (mm)	Δpeak (mm)	Δ50 (mm)	μ
Original	212	104	1.6	2.4	5.2	3.3
A1R	231	118	2.0	2.8	10.9	5.4
A2R	204	100	2.0	4.2	7.2	3.6
A3R	278	173	1.6	1.3	14.4	9.0
B1R	243	106	2.2	4.4	14.9	6.8
B2R	163	76	1.8	3.6	10.6	5.9
B3R	257	156	1.8	4.4	14.2	7.9
C1R	253	133	1.6	3.0	7.0	4.4
C2R	216	120	1.5	2.2	4.8	3.2
C3R	280	140	1.0	2.3	7.3	7.3
D1R	265	151	1.7	2.0	7.0	4.1
D2R	250	124	1.6	2.6	6.9	4.3
D3R	288	190	1.7	3.8	14.2	8.3
E1R	337	197	2.8	3.6	14.6	5.2
E2R	321	145	2.2	2.6	11.1	5.0
F1R	368	171	1.9	2.6	11.8	6.2
F2R	293	144	2.2	3.1	11.4	5.2

Fig. 16 Failure mechanism of columns retrofitted with steel transverse reinforcement

Fig. 17 Laminated bamboo stirrups.

4. CONCLUSION

The experimental test on reinforced concrete columns strengthened with bamboo reinforced concrete jacket has been undertaken. The various parameters investigated were the main bar configuration at the same longitudinal reinforcement ratio, material and spacing of stirrups. The outcomes showed that bamboo reinforced concrete jacket can be used effectively as rehabilitation techniques on damaged RC columns with some findings as follows:

a. Using more distributed bars over the column core circumference (despite smaller bar diameter) is preferable rather than using larger diameter bar placed only at stirrups corners.
b. Retrofitting using steel stirrups provide greater confining pressure compared with bamboo stirrups for the same amount of transverse reinforcement ratios due to the higher yield strength and a hence higher increase of axial load carrying capacity. By using smaller bamboo stirrups spacing than that of the original column, the effectiveness of confinement can be improved. Another alternative is by using bamboo with higher yield and ultimate strengths.
c. In terms of ductility, both bamboo and steel stirrups resulted in similar ductility performance.

5. ACKNOWLEDGMENTS

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