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Strength and behaviour of bamboo reinforced concrete wall panels under two way in-plane action

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Abstract. An experimental investigation has been carried out on the use of an environmentally sustainable material, bamboo, in the construction of precast concrete structural wall panels. The strength and behaviour of three prototype bamboo reinforced concrete wall panel specimens under two-way in-plane action was studied. The specimens with varying aspect ratio and thinness ratio were tested to fail under a uniformly distributed in-plane load applied at an eccentricity of *t*/6. The aspect ratio of the specimens considered includes 1.667, 1.818 and 2 and the thinness ratio includes 12.5, 13.75 and 15. The influence of aspect ratio and thinness ratio of bamboo reinforced concrete wall panels, on its strength and behaviour was discussed. Varnished and sand blasted bamboo splints of 20 mm width and thickness varying from 8 to 15 mm were used as reinforcement in concrete. Based on the study, an empirical equation was developed considering the geometrical parameters of bamboo reinforced concrete wall panels for predicting its ultimate strength under two way in-plane action.

Keywords: bamboo reinforced concrete; two way; in-plane action; wall panels; slenderness ratio; aspect ratio; thinness ratio

1. Introduction

In the present scenario, the whole world is moving towards the use of eco-friendly and sustainable materials in all fields of science and technology by replacing the conventionally used energy intensive materials. While considering the fact that the construction industries are the major consumers of natural resources all over the world, many researches have been carried out on the use of naturally available renewable resources in construction. Bamboo is one such environmentally sustainable material that has quickly changed its name from the poor man's tree to an excellent industrial material (Lobovikov *et al.* 2007).

Bamboos are giant grasses that fall in the family of Poaceae (Agarwal *et al.* 2014). It is the fastest growing plant on earth with high productivity and attains its maximum strength in just three years. Of the 36 million hectares of bamboo area available in the world, India, one of the largest producers of bamboo possess around 11.4 million hectares of bamboo area (Chaowana 2013). This

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indicates the suitability of using bamboo as reinforcement in concrete wall panels in a country which stands second in world population and is estimated to have a housing shortage of 18.78 million at the beginning of the 12th five-year plan (Report of the technical group on urban housing shortage (TG-12) 2012-2017). It was estimated that two tons of CO_2 are released into the atmosphere during the production of one ton of steel, while one ton of CO_2 from the environment is absorbed during the production of one ton of bamboo. As a result, bamboo is considered as a good CO_2 fixator (Kumar and Mandal 2014). This indicates the necessity for the replacement of a material like steel having a high carbon footprint with a sustainable material like bamboo as reinforcement in concrete.

Extensive studies were conducted on the use of bamboo as reinforcement in cement concrete matrices by replacing steel reinforcement, which is one of the high energy intensive materials used in the field of construction. Investigations done on the feasibility of using bamboo as reinforcement in concrete proved that it can be an excellent replacement for steel provided proper treatments for better water resistance and bonding between bamboo and the surrounding concrete are taken care of (Agarwal *et al.* 2014). Studies were reported on bamboo reinforced concrete structural elements like beams, columns and slabs (Ghavami 2004). Investigations were also carried out on prefabricated non-load bearing bamboo reinforced cement mortar walls that could act as partition walls (Puri *et al.* 2017). A study was recently reported on the replacement of steel with bamboo splints in precast concrete wall panels (Himasree *et al.* 2017).

The present study suggests the use of bamboo in the construction of load bearing concrete wall panels that make construction more sustainable and affordable. Wall panels are two-dimensional structural elements with negligible thickness compared to its other dimensions and are subjected to in-plane loads. The panels can be either a one way wall panel that transfer load in one direction or a two way wall panel that transfer load in more than one direction.

Many investigations have been carried out on one way wall panels to determine the effect of slenderness ratio (SR) (Oberlender and Everard 1977, Pillai and Parthasarathy 1977, Kripanarayanan 1977), aspect ratio (AR), percentage of reinforcement (Zielinski *et al.* 1982, Saheb and Desayi 1989) and eccentricity at which load is applied (Fragomeni *et al.* 1994, Doh and Fragomeni 2004) on the performance of reinforced concrete (RC) wall panels. Even though the behaviour of wall panels under two way in-plane loads are more realistic compared to one way wall panels, limited studies are reported on the strength and behaviour of wall panels under two way in-plane action (Doh and Fragomeni 2004, Saheb and Desayi 1990, Fragomeni and Mendis 1996, Sanjayan and Maheswaran 1999, Ganesan *et al.* 2013, Ganesan *et al.* 2013).

In this experimental investigation, treated splints of Bambusa bambos is used as reinforcement in concrete wall panels. The effect of AR and thinness ratio (TR) on the strength and behaviour of Bamboo Reinforced Concrete Wall Panels (BRCWP) under two way in-plane action was studied. A method for predicting the ultimate load of BRCWP under two way in-plane action was proposed.

2. Experimental work

The experimental work consists of the casting and testing of three prototype specimens of BRCWP with varying AR and TR. The wall panels were tested to fail under uniformly distributed load applied at an eccentricity of $t/6$. Table 1 provides the details of the specimens and the variables considered in the study. The SR of all specimens was kept a constant as 25.

Table 1 Details of the specimens and variables

Panel designation	Specimen size ($L \times h \times t$) (mm)	Variables	
		AR (h/L)	TR (L/t)
BRCWPI-TW	1000×2000×80	2	12.5
BRCWPII-TW	1100×2000×80	1.818	13.75
BRCWPIII-TW	1200×2000×80	1.667	15

Note: L - length (span) of the wall panel
h - height of the wall panel
t - thickness of the wall panel

where,

aspect ratio is the ratio of height to length of the wall panel

Aspect ratio (AR) = $\frac{\text{Height of the wall panel}}{\text{Length of the wall panel}}$

thinness ratio is the ratio of length to thickness of the wall panel

Thinness ratio (TR) = $\frac{\text{Length of the wall panel}}{\text{Thickness of the wall panel}}$

slenderness ratio is the ratio of height to thickness of the wall panel

Slenderness ratio (SR) = $\frac{\text{Height of the wall panel}}{\text{Thickness of the wall panel}}$

2.1 Materials used

2.1.1 Concrete

Materials used for the preparation of M20 grade concrete includes Portland Pozzolana Cement, M-sand as fine aggregate, coarse aggregate having a maximum size of 12 mm and potable water. M20 grade concrete mix was designed as per IS: 10262 (2009).

2.1.2 Reinforcement

Bambusa bambos splints of 20 mm width were used as reinforcement in concrete. Bamboo splints were initially coated with varnish to make them water resistant. Then sandblasting was done on varnished splints using *M*-sand grains passing through 4.75 mm IS sieve and retained on 2.36 mm IS sieve, in order to have better bonding between bamboo splints and the surrounding concrete. Then the treated splints were kept in air for drying for 24 hours before using as reinforcement in concrete. The properties of the bamboo splints are given in Table 2.

Splints are distributed at equal spacing in both horizontal and vertical directions as per the NBC-Part 6 (2016). Fig. 1 illustrates the typical arrangement of bamboo splints. The reinforcement cage prepared for using as reinforcement in concrete wall panels is shown in Fig. 2.

Table 2 Properties of bamboo splints

Properties of bamboo	Average value	Standard deviation
Ultimate tensile strength	125MPa	27 MPa
Compressive strength	40MPa	4 MPa
Modulus of elasticity	7.5 x10^4 MPa	0.5 x10^4 MPa

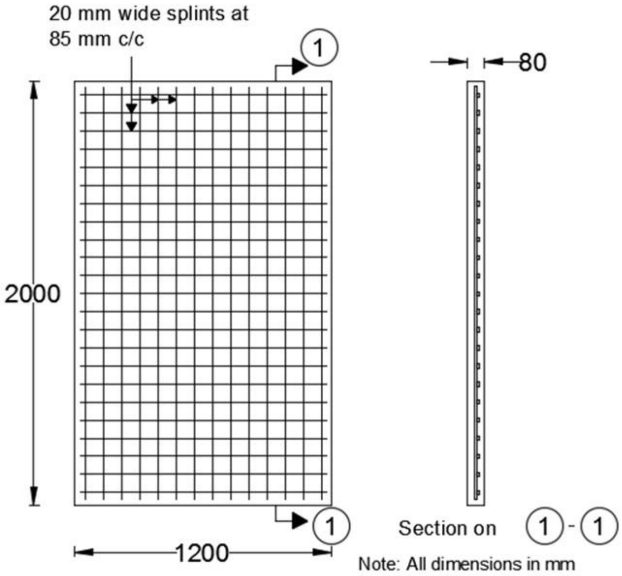

Fig. 1 Typical arrangement of bamboo splints

Fig. 2 Reinforcement cage ready for casting

2.2 Casting of specimens

Casting of wall panels was done by keeping bamboo reinforcement cage at the mid-thickness of the plywood mould. Compaction of concrete was done using needle vibrator. Curingof specimens was done by covering it with wet gunny bags for 28 days. Fig. 3 shows casting of BRCWP specimen.

2.3 Test set-up for two way action

In order to simulate two way in-plane action, the wall panels were supported along its four edges. A uniformly distributed load was applied at an eccentricity of t/6 on top of the wall panel to reflect the possible eccentric load in practice as done by other researchers (Oberlender and Everard 1977, Pillai and Parthasarathy 1977, Kripanarayanan 1977, Fragomeni *et al*. 1994, Doh and

Fig. 3 Casting of specimen under progress

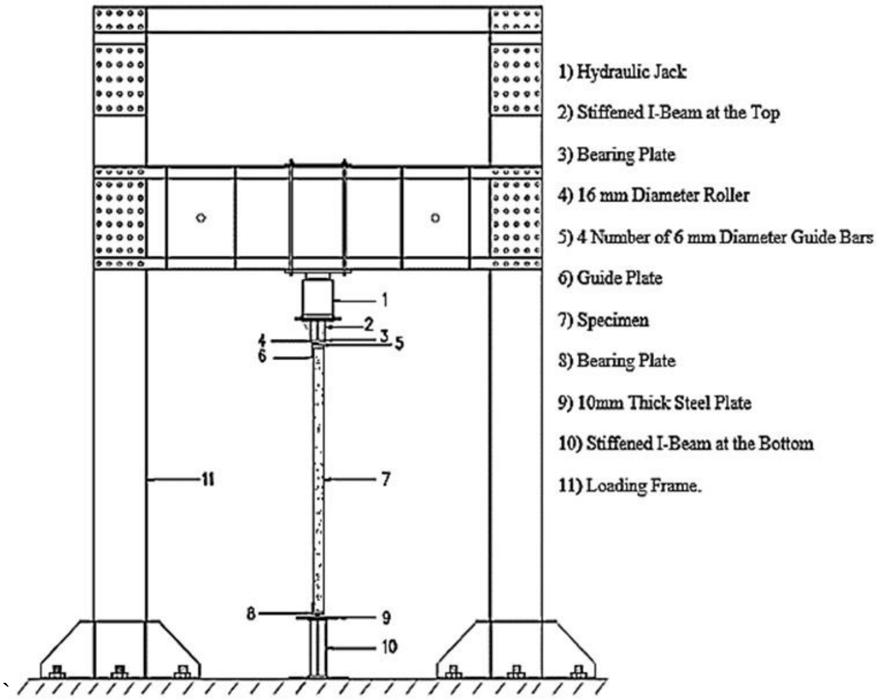

Fig. 4 Schematic loading diagram

Fragomeni 2004, Doh and Fragomeni 2004, Saheb and Desayi 1990, Fragomeni and Mendis 1996, Sanjayan and Maheswaran 1999, Ganesan *et al*. 2013, Ganesan *et al*. 2013). The testing of the specimens was carried out in the loading frame of 981 kN (100 tons) capacity. The load was applied by using a hydraulic jack of 1000 kN (101.93 tons) capacity. The schematic loading diagram is shown in Fig. 4.

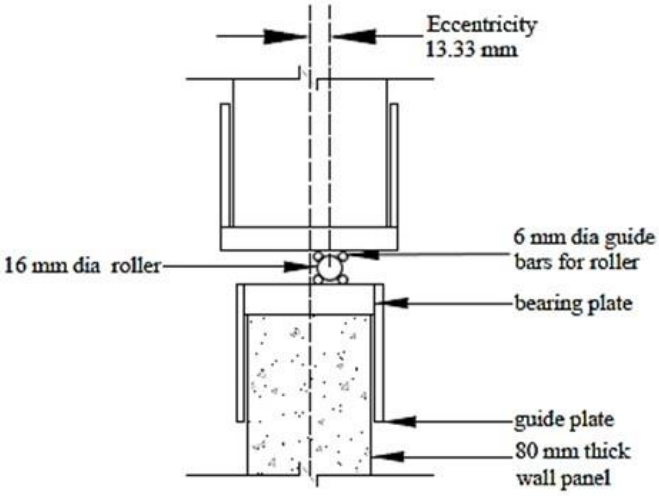

Fig. 5 Details of top hinged edge

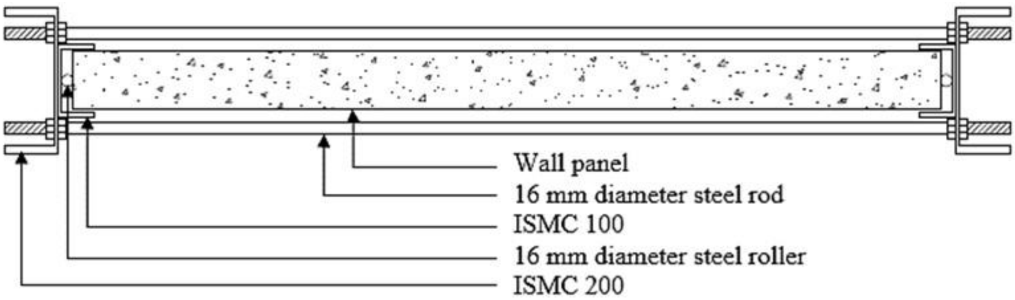

Fig. 6 Details of the hinged support on either side of the wall panel

The pinned end conditions at its top and bottom were achieved by placing a 16 mm diameter polished rod in between four 6 mm diameter rods welded to the bearing plates. The details of the top hinged edge are shown in Fig. 5. In order to provide hinged support along the sides of the wall panel, ISMC 100 and ISMC 200 were welded back to back with a 16 mm diameter smooth steel rod welded along the web of ISMC 100. Two such elements provided on either side of the panel were tightly held in position by bolted connections. The details of the side supports are depicted in Fig 6.

3. Test result

BRCWP were tested under a uniformly distributed load applied gradually at an eccentricity of $t/6$. The experimental test set-up for testing BRCWP under two way in-plane action is shown in Fig. 7. At each load increment, lateral deflection at midspan and quarter points was recorded using Linear Variable Differential Transducer (LVDT). The ultimate experimental load carried by the wall panels was also noted. Table 3 provides the values of experimental ultimate loads obtained for the wall panels.

Fig. 7 Test set-up

Table 3 Experimental ultimate loads obtained for BRCWP

Panel designation	P_{ue} (kN)
BRCWPI-TW	533.98
BRCWPII-TW	582.52
BRCWPIII-TW	631.07

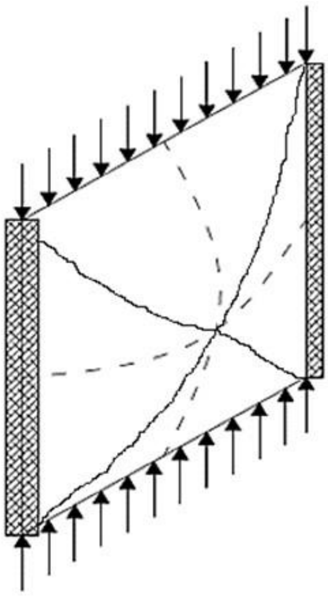

Fig. 8 Behaviour of wall panel under two way in-plane action

AR=2

Fig. 9 Failure of BRCWPI-TW

AR=1.818

Fig. 10 Failure of BRCWPII-TW

AR=1.667

Fig. 11 Failure of BRCWPIII-TW

The hypothetical deflection and cracking behaviour of wall panels subjected to two way in-plane action is depicted in Fig. 8. The figure indicates that due to two way action, biaxial bending of wall panels takes place in the planes parallel and perpendicular to the axis of loading, leading to the development of diagonal cracks originating from the corners of the wall towards the centre of the wall panel.

In this experimental study, a realistic value of thickness of 80mm was considered for the prototype BRCWP, whereas most of the investigations on RC wall panels used scaled down models of wall panels with smaller values of thickness ranging from 35 to 50 mm. In their cases because of the lesser values of thickness, diagonal cracks originating from the corners and extending towards the midpoint of the wall panel was observed. However in the present study, due to the 80mm thickness of the wall panel specimens, crushing failure was noticed in almost all specimens at their top and bottom edges. Figs. 9-11 show the crushing failure obtained for BRCWP specimens with AR 1.667, 1.818 and 2.

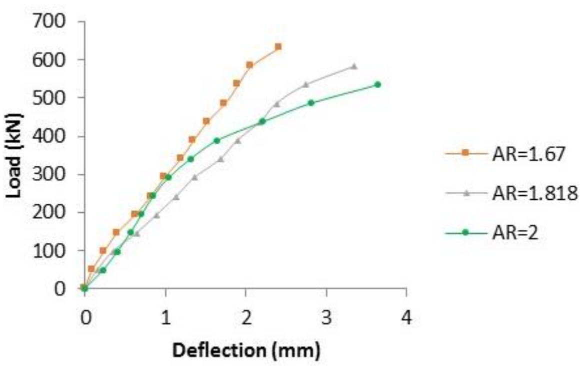

Fig. 12 Load-deflection behaviour at the midpoint of two-way BRCWP with varying AR

3.1 Load deflection behaviour

Lateral deflections at the mid and quarter points of wall panels were determined using LVDTs placed perpendicular to the wall panel. The load-deflection behaviour of wall panels for varying AR is illustrated in Fig. 12. It is perceived from the Fig. 12 that the deflection of wall panels increases with an increase in its AR.

The variation of load with different values of TR of specimens is presented in Fig. 13, and it is

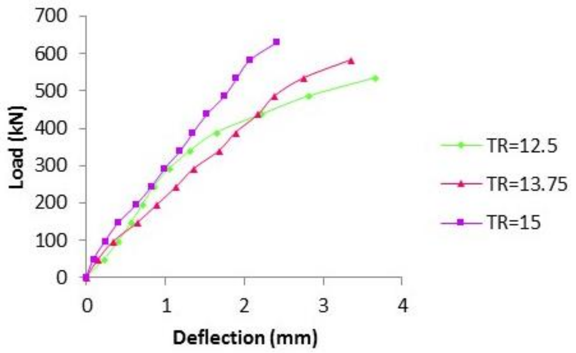

Fig. 13 Load-deflection behaviour at the midpoint of two-way BRCWP with varying TR

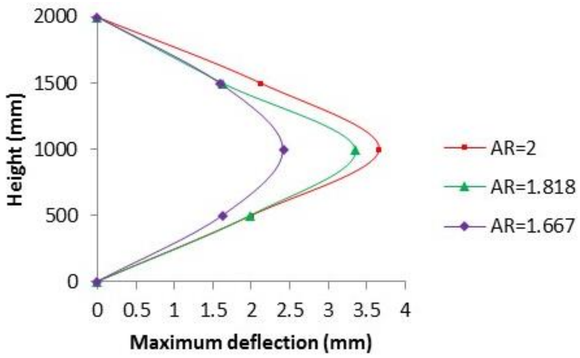

Fig. 14 Maximum deflections obtained at various heights of BRCWP

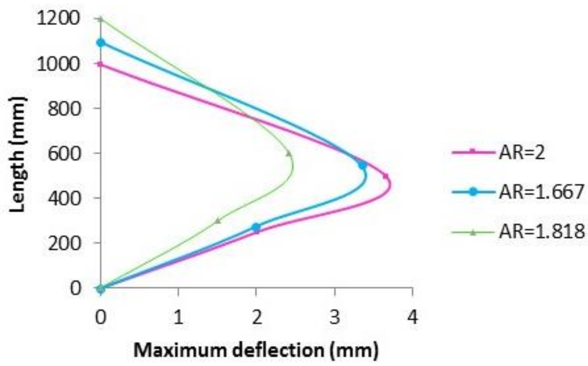

Fig. 15 Maximum deflections obtained along the length of BRCWP

noticed that the increase in TR leads to a reduction in the deflection of wall panels.

Fig. 14 depicts the maximum deflections obtained at the mid and quarter points along the height of the wall panels. It was observed from the figure that the deflections at $H/4$ and $3H/4$ were approximately half that obtained at the $H/2$.

The maximum deflection obtained along the length of the wall panel is shown in Fig. 15. It was found from Fig. 15 that the maximum deflection obtained at $L/4$ was about half that obtained at $L/2$. It is evident from Figs. 14 and 15 that the wall panels deflect under double curvature due to two way in-plane action.

4.Prediction of ultimate load of BRCWP under two way in-plane action

A method for predicting the ultimate load of BRCWP under two way in-plane action was proposed based on the experimental results. To start with, an equation was developed to determine the ultimate load of BRCWP by treating it as a short wall (Ganesan *et al.* 2014). The equation was then modified to account for the effect of properties of bamboo, TR and SR. The assumptions made for the development of the empirical equations are as follows.

i. The load on the wall panel is reasonably eccentric; thus $e \leq t/6$.

ii. The panel consists of the required amount of vertical and horizontal reinforcements as recommended by the NBC-Part 6 for the design of structures using bamboo and timber.

iii. Slenderness ratio (h/t) is kept constant as 25 whereas the aspect ratio (h/L) is limited to 2 and thinness ratio is limited to 15.

The force acting per horizontal length of the wall according to MacGregor and Wight (2009) is

$$P_{ut} = 0.85 f_c'(2/3)Lt = 0.567\, f_c'Lt = 0.567\, f_c'A \tag{1}$$

The term $(f_{ub} - f_c')A_{bc}$ was introduced into the Eq. (1) to account for the contribution of vertical reinforcement in the ultimate load of the wall panel, and the Eq. (1) is modified as follows.

$$P_{ut} = 0.567(f_c'Lt + (f_{ub} - f_c')A_{bc}) \tag{2}$$

In order to determine the contribution of SR and TR on the ultimate load of BRCWP subjected to two way in-plane action, after a series of trials, a parameter β is introduced where,

$$\beta = \sqrt{\frac{h}{t} * \frac{L}{t}} \tag{3}$$

The values of P_{ue}/P_{ut} are plotted against β as shown in Fig. 16.

The regression equation obtained for Fig. 16 is

$$P_{ue}/P_{ut} = 0.0068\beta^2 - 0.2433\beta + 2.72 \tag{4}$$

The above equation is rewritten as

$$P_{ue}/P_{ut} = \left(1 - \frac{4\beta}{45} + \left(\frac{\beta}{20}\right)^2\right) 2.72 \tag{5}$$

Finally, Eq. (6) is modified by replacing P_{ue} by P_u since the experimental values resembles true ultimate values (P_u)

$$P_u = 1.54\,(f_c'Lt + (f_{ub} - f_c')A_{bc})\left(1 - \frac{4\beta}{45} + \left(\frac{\beta}{20}\right)^2\right) \tag{7}$$

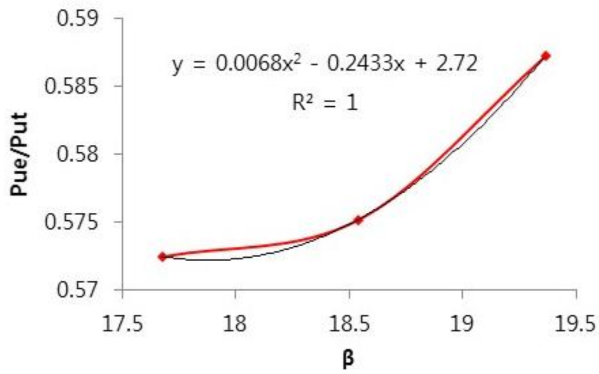

Fig. 16 BRCWP Effect of β on ultimate load

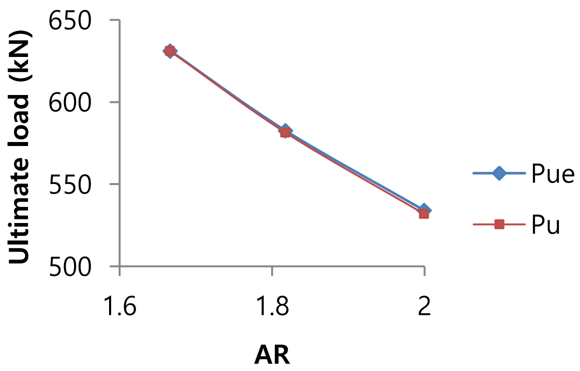

Fig. 17 Comparison of empirical and experimental ultimate load values for varying AR

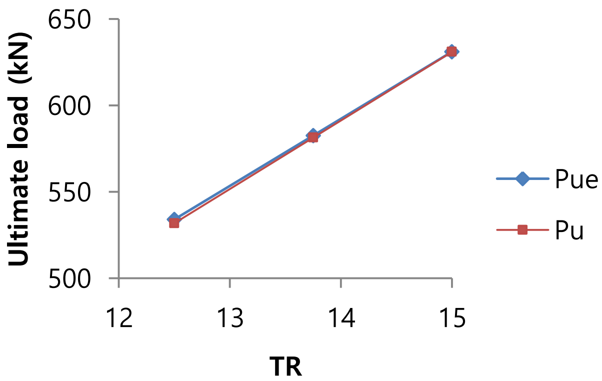

Fig. 18 Comparison of empirical and experimental ultimate load values for varying TR

The values of ultimate loads obtained experimentally as well as computed by using the above proposed equation are plotted against AR of wall panels as shown in Fig. 17. The figure indicates that the ultimate load of wall panel decreases with increase in values of AR.

Similarly, the computed values of P_u were plotted against TR of wall panels in Fig. 18. It was found that ultimate load of wall panel increases with increase in TR.

5. Conclusions

1. The study indicates that bamboo reinforced concrete wall panels of aspect ratio varying from 1.667 to 2 and thinness ratio varying from 12.5 to 15 could sustain loads as high as 530 to 630 kN.
2. The ultimate load of wall panels was found to decrease with an increase in aspect ratio whereas it increases with increase in thinness ratio.
3. A method is proposed for predicting the ultimate load of bamboo reinforced concrete wall panel under two way in-plane action and it compares satisfactorily with the test results.

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Nomenclature

A	Cross-sectional area of the wall panel
A_{bc}	Area of bamboo under compression
f_c'	Compressive strength of concrete cylinder
f_{ub}	Compressive strength of the bamboo splints
h	Height of the wall panel
L	Length of the wall panel
P_u	Ultimate load
P_{ue}	Experimental ultimate load
P_{ut}	Theoretical ultimate load
t	Thickness of the wall panel