Tests on Compression-Bending Behavior of Moso Bamboo Pipe

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Abstract

Bamboo is a natural and reproducible material with short growth cycle. The compressive tests and bending tests were carried out to explore the compression-bending behavior of both original bamboo pipes and the same size pipes filled with concrete which were used for micro-piles in shallow excavation support, and to compare with the enhanced effects of its compressive bearing capacity and bending rigidity due to concrete filled into it. The tests results indicate that compressive bearing capacity of same bamboo pipes gradually amplify with the increase of its diameter while its corresponding compressive strength gradually decline. The bamboo nodes have little impact on compressive bearing capacity of bamboo pipes. When the compressive strength of filled concrete is lower than 30MPa, it isn't obvious to improve compressive bearing capacity of bamboo pipe micro-piles. Whereas, the bending rigidity of bamboo pipe micro-piles increase significantly due to filled concrete through bending tests. It would be enhanced two to three times on average. Meanwhile, concrete is also helpful for controlling the deformation of bamboo pipes filled with concrete. This research would provide reference basis for engineering design of composite retaining structure with bamboo pipe micro-pile rows and bamboo soil nailing wall shallow during excavation support in soft soil layers.

Keywords

Original bamboo pipe; pipe filled with concrete; compressive bearing capacity; bending rigidity.

1. Introduction

Bamboo structure with light weight and high strength has been widely used in the early buildings. Currently, bamboo is still in favored by the residence of minorities, temporary shelters, scaffolding and support for shallow pits on construction site. The research has been shown that bamboo structure with good performance of earthquake resistance and disaster reduction could buffer and scatter earthquake force (Ke. 2014). Abundant bamboo resources in China provide material basis for the heavy use of bamboo. Meanwhile, bamboo with short growth cycle could be utilized as raw material after 3 to 5 years generally. Test results demonstrate that tensile strength of bamboo could reach to 370MPa, which is equivalent to the design value (360MPa) of tensile strength for steel called HRB400 (Chen. 2014). Compressive strength of moso bamboo and bambusa pervariabilis McClure is about 47MPa to 62.8MPa in the South of China, which is far more than design value (14.3MPa) of compressive strength for C30 concrete recommended by Code for design of concrete structures (GB50010-2010) (Che. 2011; Ghavami. 2005). Special structure for bamboo brings high strength and stiffness-to-weight ratio relative to ordinary steel. At present, Techniques of bamboo processing are maturing gradually. Various bamboo engineering components are more systematic and standardized, such as laminated strand lumber, glue-laminated bamboo and reconsolidated bamboo et al (Wei et al. 2011; Li et al. 2013; Wei et al. 2010). Li (2009) have further researched physical and mechanical properties of bamboo on the basis of previous studies and laid the foundation for determination of test standards of bamboo. Li (1994) pointed out that bamboo nodes could improve the tensile strength and splitting strength of bamboo in transverse. Nevertheless, it declined the tensile, compressive and bending strength of bamboo in longitude. Jiang (2005) indicated that glued-laminated bamboo had great mechanical properties on horizontal shear strength, bending strength and elastic modulus. Bending test of laminated rectangular bamboo beams with large size showed four typical failures of bamboo beams (Wei et al. 2010). Allowable design load was controlled by the section stiffness rather than strength. Zhang (2012)utilized bamboo pipe to test the properties of bamboo relative to that of bamboo piece and indicated that the compressive and shear strength of both were little difference. Although, bending strength has great difference between the two, both of which had the same change rule. Moso bamboo employed as soil nails and piles was used for retaining structure named moso bamboo soil nailed wall. The stability of bamboo reinforced system was verified by the In-situ tests and numerical simulation. The prediction agreed well with the measured settlement (Dai. 2016).

In foreign countries, the effects of diameter and bamboo age on compressive strength of bamboo have been studied (Lo et al. 2004). Through three point bending method, fracture toughness tests have been conducted on bamboo specimens with one or five-year-old to explore the relationship among hardness, flexural strength, impact toughness and fracture toughness (Low et al. 2006). At the same time, Amada (2001) detected the fracture toughness of bamboo in different height and radius direction by tensile tests and observed fracture surface by sweep electron microscope. Then, the results of fracture toughness of bamboo were obtained. Kariuki (2014) pointed out flexural capacity of bamboo laminated beams were better than that of cypress laminated beams with same size. The compression-shear test of soaking bamboo got the corresponding data of strength and elastic modulus. This result indicated that when water content reached 30%, mechanical properties of bamboo were significantly decreased, which showed 30% was a fiber saturation point of bamboo (Harries et al. 2014).

Therefore, study on the basic mechanical properties of bamboo at home and abroad are mainly concentrated on the bamboo piece test unit with small dimension, to which bamboo pipe are split and fabricated, and glued laminated bamboo from split bamboo strips. The research on bamboo pipe filled with concrete are extremely lacking, relative to less research on total mechanical properties of original bamboo pipe in compressive test, bending test and shear test. In addition, Test standard for physical and mechanical properties of entire or part bamboo pipe is non-existent currently in China. Taking those into account above, through compressive tests and bending tests of bamboo pipes and bamboo pipes filled with concrete, the preliminary exploration on calculation model in force and calculation method of bamboo pipe filled with concrete are received. It also provides some theoretical basis and design reference for practical engineering application.

2. Compression Tests

The compressive properties of bamboo pipe must be clarified before chosen as pile or column of building. Thus, bamboo with different varieties and ages should be categorized and determined its design value by necessary test, according to measured value and relevant design code. Meanwhile, comparative tests were conducted on part bamboo specimens filled with concrete to enhance its compressive stiffness (Fig. 1).

Fig.1 Compressive specimens

2.1 Materials

Specimens were originated from 2-year-old bamboo in Xianning, Hubei province. Considering the actual requirements of tests, bamboo with smooth surface, no crack and mildew was processed to specimens, the size of which are 150mm(height), d1(diameter) and t1(thickness). Specimens, whose diameter deviation is less than 10%, were selected as one group and numbered with 1-1 for bamboo pipe, 1-2 for bamboo pipe filled with concrete. Same as follows, number to 34-1, 34-2. To show experimental regular pattern obviously, test data were taken from different groups whose diameters differed considerably. The basic parameters of the test are shown in Table 1.

Table 1 Parameters of specimens

Number	*External diameter*(mm)	*thickness* (mm)	*Length*(mm)	*Area*(mm^2)	F_{max}(kN)	σ_{max}(MPa)
1-1	37.88	10.57	150	540.83	35.84	66.26
1-2	39.42	10.21	150	518.75	37.62	—
5-1	45.98	13.69	150	841.14	51.46	61.18
5-2	43.21	11.24	150	663.09	49.45	—
18-1	53.88	11.87	150	893.41	52.86	59.16
19-1	53.05	11.60	150	860.19	52.24	60.73
26-1	60.17	12.06	150	1024.63	50.91	49.68
29-1	62.01	12.73	150	1112.13	60.99	54.84
29-2	62.55	12.86	150	1132.97	62.3	—
31-1	61.18	12.18	150	1053.08	49.29	46.81
31-2	62.45	13.47	150	1042.08	53.12	—

The change rule of compressive strength was analyzed by comparison of corresponding data between bamboo pipe and bamboo pipe filled with concrete. Given limited diameter of bamboo pipe, mixing proportion of concrete was identified as 0.8(cement):2(sand):1(stone):0.63(water) by a lot of trial for concrete flow and compaction. Actual cubic compressive strength was mensurated by tests.

Portland blast-furnace cement graded 32.5 was chosen in tests. The size of concrete cube specimens numbered 1 to 3 were 100×100×100mm due to aggregate size less than 31.5mm (China Standard. 2002). Concrete testing models, staying in same circumstance with bamboo pipe filled with concrete, were cured under natural conditions and experimented at 28th age

2.2 Loading

Specimens with flat surface were exactly put on loading plate in press (Fig.2 (a)). The speed stayed at a constant rate throughout whole test. Force-displacement curve of specimen descended abruptly after a stable straight line. At that time, we could hear crack sound and see crack clearly, which meant that specimen was destroyed under compression. But bamboo pipes weren't completely split because of fiber (Fig.2 (b)).

Fig.2 (a) Test equipment

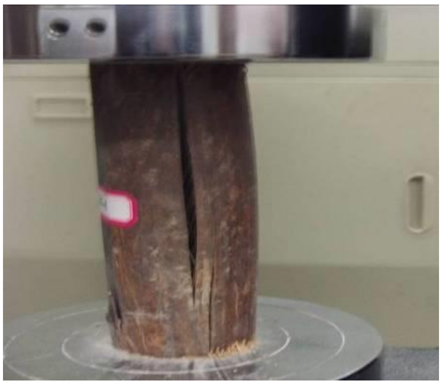

Fig.2 (b) Failure of specimen

2.3 The calculation and analysis on axial compression of bamboo pipe

According to the stabilization of compressive rod, it is known that compressive bearing capacity of straight rod is not only dependent on the axial compressive strength of material, but also relevant to bending deformation of straight rod under compression (Sun et al. 2009).

Axial compression straight rod under the action of critical force stayed in a stable status with micro curvature. An approximate differential equation of the deflection curve could be written as Eq.(1) via bending moment equation of compression bar in y section as M(y)= Fcrw (Fig.3).

$$EIw``=-M(y) =-F_{cr}w \quad (1)$$

where Fcr is critical value of axial pressure.

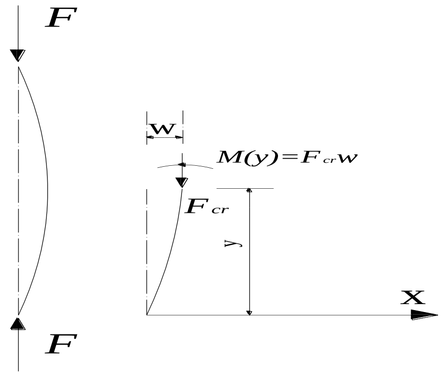

Fig.3 Diagram for compression bar calculation

Suppose Fcr/EI=k2. Thereby, second order linear differential equation (2) with constant coefficients was given as follows:

$$w``+k2w=0 \quad (2)$$

General solution of derived from Eq. (2) could be expressed as

$$w =Asinky+Bcosky \quad (3)$$

where A, B and K are determined by boundary condition of deflection curve

Eq. (3) was put into Eq. (1). Fcr was achieved the minimum value

The critical value of axial pressure, Fcr, was determined using the following equation:

$$Fcr=\pi 2EI/ (\mu l)\ 2 \quad (4)$$

where μ is length factor of compressive rod and relevant to end restrain.

From Li (2009), we could conclude that the compressive strength and elastic modulus of bamboo piece test unit with biennial and small dimension were approximately about 145MPa to 170MPa and 8.5GPa to 9.2GPa respectively. Critical slenderness ratio (λp) was calculated for 24 via the formula Eq. (5), which outweighed the slenderness ratio 15 calculated by Eq. (6). It couldn't satisfy the requirement of slender compressive rod. Therefore, the compressive bearing capacity of bamboo specimens was controlled by the axial compressive strength of bamboo.

$$\lambda_p = \pi\sqrt{E/\sigma_P} \quad (5)$$

$$\lambda=\mu l/i \quad (6)$$

where E= elastic modulus; λ and λp are the slenderness ratio and critical slenderness ratio; I is radius of inertia; and σp is proportional limit of material.

2.4 Results and Discussion

The compressive tests were carried out on 34 groups' specimens and 3 concrete testing models. Through induction and classification of some experimental data, basic parameters of concrete testing models (Table 2), pressure-strain and stress-strain curves of bamboo pipe were got naturally as follows (Fig.4~ Fig.6):

Table 2 Parameters of concrete specimen

Number	*Length* (mm)	*Area* (mm^2)	F_{max}(kN)	σ_{max}(MPa)
1	100.00	10000.00	70.00	7.00
2	100.00	10000.00	71.45	7.15
3	100.00	10000.00	72.30	7.23

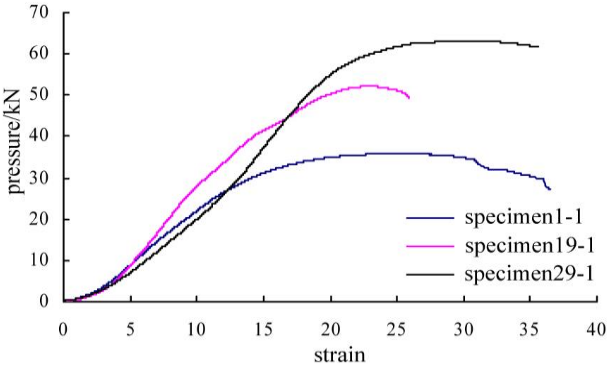

Fig.4(a) Pressure-strain curves of bamboo pipe

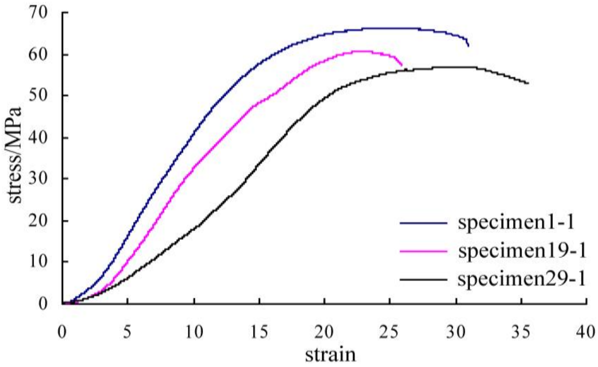

Fig.4 (b) Stress-strain curves of bamboo pipe

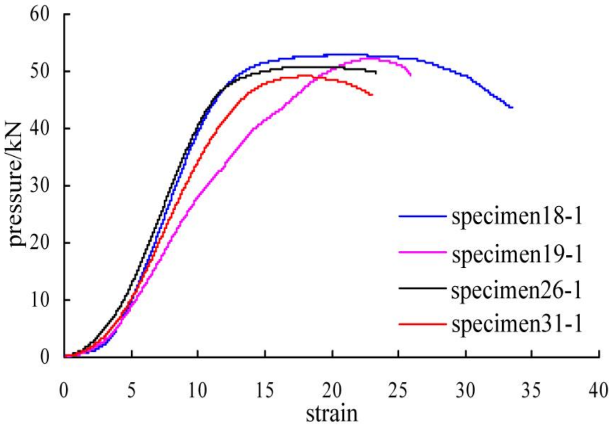

Fig.5 Pressure-strain curves of bamboo pipe under the effect of bamboo nodes

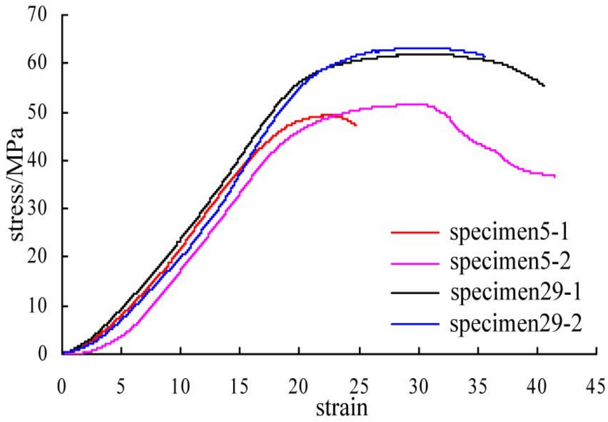

Fig.6 Pressure-strain curves of bamboo pipes and bamboo pipes filled concrete

In Figure 4, Bamboo pipe specimen named 1-1 where external and inside diameter is 37.88mm, 27.31mm respectively, could be born the minimum pressure about 35.84kN, while the maximum stress about 66.26MPa. Similarly, bamboo pipe specimen named 29-1 where external and inside diameter is 62.01mm, 49.28mm could be withstood the maximum pressure about 60.99kN, while the minimum stress about 54.84MPa. The pressure and stress which bamboo pipe specimen named 19-1 was supported, was at moderate level. That's to say, the more net cross section bamboo pipe specimens had, the more pressure and less stress it need bear.

Figure 5 showed that when bearing area was approximately equal, the maximum pressure, which specimen called 18-1 with no node and specimen named 19-1 with one node were bore, were 52.86kN and 52.24kN respectively. Similarly, the maximum pressure, which specimen called 26-1 with no node and specimen named 31-1 with one node were supported, were respectively50.91kN and 49.3kN. Thus, bamboo node had little effect on compressive bearing capacity of bamboo pipes.

In Figure 6, the bearing capacity of specimen called 5-1, 29-1 were 51.46kN and 60.99kN, relative to that of bamboo pipe filled with concrete named 5-2(49.45kN), 29-2(62.3kN). Thus, it wasn't obvious to improve compressive bearing capacity of bamboo pipe due to concrete in tests. Considering mobility of concrete, little coarse aggregate was used in the production of bamboo pipe filled with concrete. The compressive strength of cubic specimens , fc , were approximately 7.51 to 7.84MPa, which was far less than the compressive strength of bamboo pipe. Thereby, concrete with low strength had a little influence on compressive bearing capacity of bamboo pipe.

3. Bending tests

3.1 Outline

First of all, combined with mechanics calculation method, bending stiffness of bamboo pipe had been calculated through the bending test of original bamboo pipes. Then, the concrete with same ratio above was poured into bamboo pipes and bending test of bamboo pipes filled with concrete would be done again. Finally, its flexural rigidity would be estimated roughly through deflection measured. Compared the bending stiffness in two conditions, contribution of concrete in bamboo pipes had been determined, which provided some theoretical support for the practical application of bamboo pipe filled with concrete in the future.

3.2 Experimental principle

Referred to the reinforced concrete structure, following assumptions on bamboo pipe filled with concrete had been made to facilitate the analysis:

(1) bamboo pipes and bamboo pipes filled with concrete remained linear-elastic in process of loading.

(2) The concrete bonded well with inside wall of bamboo pipes didn't slip under stage of elasticity. The position of neutral axis was constant and plane-section assumption was reasonable throughout tests.

When shear deformations was neglected, based on two-point loading tests for simply supported beam, the deflection , f , at 1/3 beam length was determined as follows:

$$f = \frac{5Fl^2}{162EI} \tag{7}$$

where E and I are modulus of elasticity and moment of inertia. F is the force at 1/3 beam length.

Similarly, based on uniformly distributed loads tests for simply supported beam, the deflection formula at 1/3 beam length was expressed as:

$$f = \frac{0.01132ql^4}{EI} \tag{8}$$

where q = uniformly distributed load of piles.

3.3 Experimental Program

3.3.1 Fabrication of specimens

Bamboo with smooth surface, no crack and mildew was processed to specimens with 1.4m in length. Both sides were set aside 10cm for the convenience of support. the bamboo piles were numbered by 1~10 and recorded as first group.

After completion of first group, bamboo piles were removed load and left under natural conditions. A period of time later, concrete, poured into the bamboo piles with one side sealed, should be vibrated mechanically. Bamboo piles filled with concrete ought to be cured under natural conditions and experimented at 28th age. Record them as second group.

3.3.2 Loading and Measurement

When specimen was in exact location, pressure sensor would be dropped to fix it until touching (Fig.7). Two point bending method was used to minimize the effect of shear stress on deflection. The purpose of these experiments was to compare change of bending stiffness between two groups, so bamboo piles need stay in elastic stage.

Fig.7 bamboo pipe in bending tests

As shown in Fig.8, vertical deflection at 1/3 pile length was measured by dial indicators. After the load of all levels is stable, data was recorded.

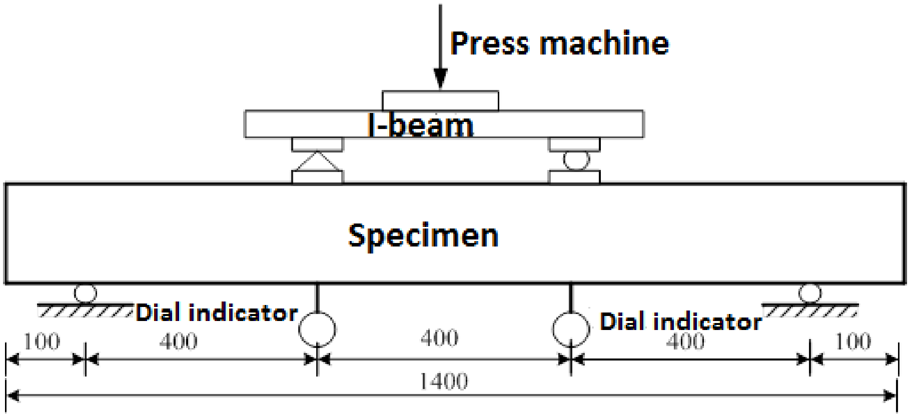

Fig.8 loading of bamboo pipe

3.4 Results and Discussion

The bending tests were carried out on 20 bamboo pile specimens in two groups. The deflection-stiffness relationship of bamboo pile specimen was got in Table 3 through inductive arrangement

As for bamboo piles filled with concrete, the uniform load couldn't be ignored that concrete gravity generated. Conversely, the influence of gravity could be ignored relative to bamboo piles.

In Table 3, the bigger bamboo beams were, the larger its stiffness would be generally, which coincided with stiffness formula. The elastic modulus , E , of bamboo piles for same conditions were little difference. B was mainly controlled by the moment of inertia I , and the diameter D was the decisive factor of moment of inertia I.

Through the comparison of data between two groups, flexural rigidity of bamboo piles was greatly enhanced than before at least 1.2 times, 2 to 3 times on average, 3.5 times in extreme cases.

Table 3 showed that bending stiffness calculated under second stage loading was less than first stage loading no matter what bamboo piles were or bamboo piles filled with concrete. The main reason for this lied in: when second stage loading was doing, deflection of first stage loading wasn't completely finished, so deflection of first stage loading was small, which led to larger stiffness.

Table 3. The relation between deflection and stiffness of bamboo pipe and bamboo pipe filled with concrete

	Bamboo pipe			*Bamboo pipe filled with concrete*			
Number	*Force* (N)	*f* (mm)	*EA*(N·m^2)	*q*(N/m)	*Force* (N)	*f* (mm)	*EI*(N·m^2)
1	200	1.205	8675.96	1344.62	200	2.03	22506.20
	300	2.160	7259.26		300	2.74	15215.31
2	200	2.325	4496.10	1143.29	200	2.23	16349.78
	300	3.230	4854.50		300	3.125	13340.80
3	200	2.045	5111.70	1166.57	200	1.96	18602.04
	300	3.195	4907.67		300	3.205	13007.80
4	200	2.290	4564.83	1084.19	200	1.74	20954.96
	300	3.850	4072.73		300	2.575	16190.87
5	200	3.190	3276.91	968.57	200	2.285	15956.24
	300	4.925	3183.76		300	2.825	14757.52
6	200	2.260	4625.38	1065.72	200	2.58	14131.78
	300	3.460	4531.79		300	3.81	10942.26
7	200	1.575	6637.02	1244.32	200	1.51	24146.16
	300	2.430	6452.67		300	2.205	18907.03
8	200	1.385	7547.51	1334.27	200	1.62	22506.21
	300	2.265	6922.74		300	2.005	20793.02
9	200	2.535	4123.60	1088.25	200	1.855	19654.99
	300	3.660	4284.15		300	2.82	14783.69
10	200	1.230	8498.60	1345.91	200	1.415	25766.78
	300	1.870	8385.03		300	2.085	19995.20

Note: *f* = average deflection; *EA*=compressive stiffness; *q*= uniformly distributed self-weight *EI*=bending stiffness.

4. Comparison of elastic modulus in two conditions

According to the experimental data from compression and bending tests, we could successfully conclude compressive stiffness EA and bending stiffness EI. Bamboo was anisotropic materials, which had significantly different physical properties in longitude and transverse. The modulus of elasticity E1 in compressive test and E2 in bending test was all in same direction of normal stress. On the basis of Hooke's law (ε=σ/E) and formula(B=EI) for bending stiffness, compressive modulus E1 and bending modulus E2 could be got as follow to explore the mutual relationship of elastic modulus in two conditions(Table 4, Table 5).

Table 4 The calculation of elastic modulus in compression test

Number	*External diameter* (mm)	*Thickness* (mm)	*Area*(mm^2)	F_{max}(kN)	σ_{max}(MPa)	ε(10^{-3})	*E*(GPa)
1-1	37.88	10.57	540.83	35.84	66.26	24.03	2.757
5-1	45.98	13.69	841.14	51.46	61.18	26.70	2.291
9-1	49.23	9.93	689.79	43.75	63.43	23.10	2.746
19-1	53.05	11.60	860.19	52.24	60.73	23.00	2.640
24-1	58.42	11.64	960.89	56.40	58.70	26.70	2.199
25-1	60.45	12.55	1067.06	61.04	57.20	30.90	1.851
29-1	62.01	12.73	1112.13	60.99	54.84	31.30	1.752
32-1	71.13	16.08	1592.74	80.91	50.80	37.20	1.366

With shorter length in compressive tests, the specimens could be approximated as regular cylindrical rings. In contrast, the specimens with longer length in bending tests led to the existence of 15mm difference at each end in diameter, so we chose cylindrical rings with thin top and thick bottom as calculating model.

Table 5 The calculation of elastic modulus in bending test

Number	*External diameter*（mm）	*Thickness* (mm)	*Area*(mm^2)	*I*(mm^4)	*EI*/($N\cdot m^2$)	*E*(GPa)
1	72.80	19.36	1919.10	978277.68	7967.61	8.145
2	61.91	13.83	1194.34	458698.74	4675.30	10.19
3	63.16	13.63	1206.35	485731.03	5009.69	10.31
4	58.70	13.36	1091.22	375160.56	4318.78	11.51
5	53.44	12.22	908.35	258599.33	3230.34	12.49
6	57.70	13.66	1112.98	380795.11	4578.59	12.02
7	67.37	15.85	1479.69	665248.54	6544.85	9.832
8	72.24	17.07	1708.13	882066.10	7235.13	8.202
9	58.92	13.01	1071.42	373583.37	4203.88	11.25
10	72.87	18.21	1823.95	945908.82	8441.80	8.925

For the difference of elastic modulus above, there are several reasons as follow:

There are more than 5 nodes on one bamboo pile in bending tests, conversely, no node on bamboo pipe specimen in compressive tests, which means that bamboo nodes have effect on elastic modulus of moso bamboo.

Although two groups` specimens were taken from moso bamboo in same region, there are differentia in their modulus of elasticity owing to different site conditions, diameter, growing part and dimension of the specimens, correspondingly 150×d1×t1 and 1400×d1×t1.

The final state in compressive test is failure of specimens, but specimens in bending tests stay in elastic stage, which is also a reason for the difference of elastic modulus.

5. Conclusion and Suggestion

Through the analysis of experimental data in compressive and bending tests, the following conclusions could be drawn:

(1) In compressive tests, pressure of bamboo pipes was in direct proportion to net section area with no node, but its stress was inversely proportional to net section area with no node, which indicated that the more net section area bamboo specimens had, the greater compressive bearing capacity and less compressive strength it had.

(2) Bamboo nodes had little impact on the compressive bearing capacity of bamboo pipes in tests. The reasons for this were that test specimen with 15cm length and bamboo nodes, far away from loading surface, induced that pressure wasn't effectively transferred to bamboo nodes. Thereby, bamboo nodes had little effect on local enhancement.

(3) Due to strength of bamboo pipe in tests reaching 30 to 65MPa, concrete with low strength contributed little to improvement of compressive bearing capacity of bamboo pipe.

(4) Because concrete in bamboo pipe increasing the whole stiffness, bending rigidity of bamboo pipes filled with concrete had been greatly enhanced, relative to original bamboo pipe, which had significant effect on controlling the deflection of bamboo piles. Meanwhile, bamboo pipe was like a hoop to restrain deformation of inner concrete in cross-section.

(5) Early strength of bamboo was gradually decreasing with time, which was extremely similar to characteristic of temporary supporting structure in practical foundation pit engineering. Thus, bamboo pipe filled with concrete could be used as soil nailing or anti-slide pile to replace steel or steel tube during excavation support for shallow pits in soft soil layers. Not only could engineering cost be reduced, but also the schedule was greatly shortened in dismantling temporary supporting structure and recycling useful material. But we should pay more attention to prevention of bamboo rot in its engineering application.

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