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Comparative Study of Mechanical Performance of Bamboo Joints

*Yu-Guang Fu[1)], Ben-Shun Shao[2)] and Shen-Chao Fu[2)]

[1), 2)] *College of Civil Engineering, Tongji University, Shanghai 200092, China*
[1)] *yuguangworld@126.com*

ABSTRACT

Bamboo has been nowadays recognized as one of the most potential sustainable structural materials. Major forms of bamboo joints mainly rely on bolts and shear strength of bamboo, and the strength of the connection is normally governed by brittle failure mode of shearing-split. A sleeve-cement connection has been proposed. The novel type of the bamboo joints behaves ductile under tension and possesses high strength under compression but leaves much to be optimized in its design. In this paper, a new configuration of sleeve-gypsum bamboo joint is designed by replacing cement with gypsum and improving surface treatment of inner walls of bamboo tube. In addition, three other connections including the sleeve-bolt, the sleeve-bolt-cement and the sleeve- cement are introduced and studied. Comparative loading tests were carried out to study the static tensile, compressive and bending performances of the four types of bamboo joints. The test results are analyzed and the performances of the four joints are evaluated. It is found that the joint with sleeve-gypsum connection has the best ductile performance. Meanwhile, this novel joint has highest capacity under tensile load and bending respectively. but under compression load, its loading capacity is lower than the joint with sleeve-bolt-cement. With the expansibility of gypsum, the sleeve-gypsum connection has excellent ductility and ensures effective transition of axial load and bending moment in the bamboo joint.

1. INTRODUCTION

On a global scale, building material resource has been over-utilized, for instance, forests have been over logged and destroyed. Also, production and construction with traditional materials has high energy consumption and severe pollution. The above facts have raised concerns for green building materials, such as bamboo material. Having a maturity cycle of 3-4 years, bamboo is one of the fastest renewable structural materials (Austin and Ueda 1972). Meanwhile, it has been recognized as one of the most sustainable potential structural materials, based on several factors which include low cost, light weight, high strength, excellent seismic performance and less harm to environment during construction and service (Sudhakar et al 2010). In summary, bamboo structure has a lot of merits and fits well sustainably the future demands.

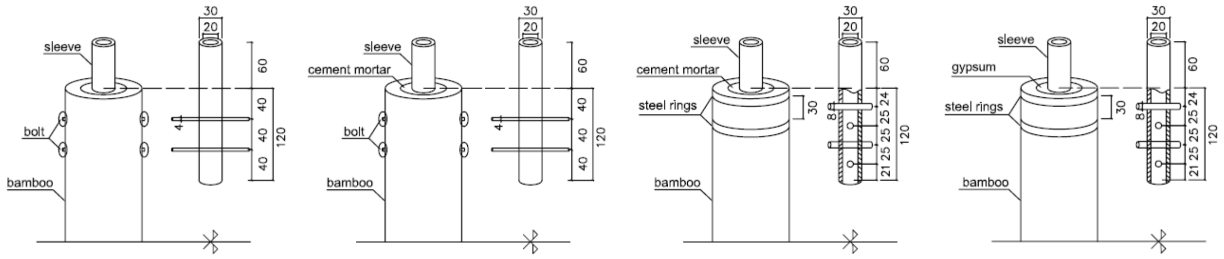
[1)] Postgraduate Student
[2)] Undergraduate Student

However, bamboo is mainly used in small houses or temporary structures. And one of the most important reasons for this situation is lack of efficient bamboo connections. For years, the sleeve-bolt and the groove-plate are the two major types of joints under axial load (Chen and Zhao 2009). The sleeve-bolt type is a joint where a steel sleeve is embedded into the bamboo ports, being fixed to the bamboo using a bolt, which is put through the predrilled holes in the sleeve and in the bamboo panel. The groove-plate is a joint in which the end of bamboo tube is slotted and embedded with a steel plate, connected by bolts. The strength of the connection is normally governed by brittle failure mode of shearing-split, and the strength of the material in these two connections cannot be fully used. A bamboo joint with cement to fasten bolts connection invented by Simon Velez, a Columbian architect, was found possessing a much higher bearing capacity (Velez 2000); however, the failure pattern of the joint is still controlled by the brittle shearing-split collapse. Recently, a sleeve-cement bamboo joint was introduced (Fu et al 2012). It is a joint in which the prefabrication steel connections are embedded in the bamboo tube where the bamboo's inner wall is notched and roughened. Then cement is filled into cavity, with two steel ring strapped outside the wall. Comparing to the traditional ones, the ductility of this kind of connection is much better and it possesses high strength especially under compression load. However, due to the shrink property of cement, the connection between cement and inner wall of the bamboo is not reliable, especially under tension load. Accordingly, the anchorage of chemical cementation is not fully realized in the sleeve-cement bamboo joint.

In this paper, a new bamboo connection named as sleeve-gypsum joint is proposed and designed. It is a joint improved from sleeve-cement joint. In this joint, steel connection and rings are similar to those in the sleeve-cement type, but the surface treatment is more reasonable and the cement adhesive is replaced by gypsum with additives. The shear bond force is provided by the friction shear and the mechanical interlock force between gypsum and bamboo's inner wall. Due to the expansibility of gypsum, the anchorage is enhanced. Static tests are carried out to compare the mechanical properties and the performance of four types of bamboo joints including the traditional sleeve-bolt, the sleeve-bolt-cement, the sleeve-cement, and the newly proposed sleeve-gypsum. Specifically, axial load and bending tests are carried out respectively to get a fully comparing of the characteristics among these four joints.

2. SPECIMENS

Fig.1 shows the shapes and notation for dimensions of the bamboo joints with sleeve-bolt, sleeve-cement, sleeve-bolt-cement and sleeve-gypsum connections respectively. Four groups of specimens are designed, each consisting of three specimens, one for tensile test, one for compression test and the other for bending test. Numbering of specimens and corresponding dimensions for each type of joints are given in Table1. Moso original bamboos with appearance of green, bought in the Anji Bamboo Wholesale Market in Shanghai, China were used for structural components. Two ends of each Bamboos member are open, 160mm in depth, 80mm in outside diameter and 60mm in inner diameter (Fig.2). Connection sleeves and accessories were all made of steel Q235. For specimens under axial load, each bamboo member consists of an entire internode and two intact nodes. And for specimens under bending, each side of bamboo member has one intact node. The schematic view of specimens for axial load and bending are shown in Fig. 3 and Fig. 4, respectively.



a) sleeve-bolt b) sleeve-bolt-cement c) sleeve-cement d) sleeve-gypsum

Fig.1 Bamboo joints and connection dimensions

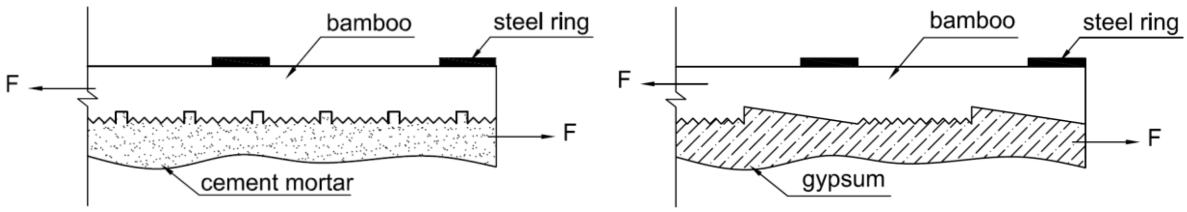
Table1. Member groups and connection details

Number	Types of joints	Test	Sleeve		Pin/bolt		Ring
			D [mm]	L [mm]	D [mm]	L [mm]	W [mm]
At	sleeve-bolt	tension	30×5	180	4	100	-
Ac	sleeve-bolt	compression	30×5	180	4	100	-
Ab	sleeve-bolt	bending	30×5	180	4	100	-
Bt	sleeve-bolt-cement	tension	30×5	180	4	100	-
Bc	sleeve-bolt-cement	compression	30×5	180	4	100	-
Bb	sleeve-bolt-cement	bending	30×5	180	4	100	-
Ct	sleeve-cement	tension	30×5	180	8	60	10
Cc	sleeve-cement	compression	30×5	180	8	60	10
Cb	sleeve-cement	bending	30×5	180	8	60	10
Dt	sleeve-gypsum	tension	30×5	180	8	60	10
Dc	sleeve-gypsum	compression	30×5	180	8	60	10
Db	sleeve-gypsum	bending	30×5	180	8	60	10

Notes: D stands for section dimension; L stands for length. W stands for width of ring. The rings' diameters are flexible.

In the sleeve-gypsum joint, high strength gypsum powder is applied and special additives are added to improve the performance of gypsum, illustrated as follows (Zhang 2008). 1) Boric acid is added to slow the solidification of gypsum, so as to improve the compaction of adhesive. 2) Waste paper fibers are added to reduce the liquid adhesion of gypsum so as to stir the adhesive easily. 3) Fly ash is added to improve water resistance of gypsum. These additives are all low-cost and easy to get, in accordance with green and low-carbon concept.

Fig. 2 shows the surface treatment of inner wall in bamboo joints with sleeve-cement and sleeve-gypsum connections. It is found that the former is so complicated that the surface treatment cannot be fully accomplished during construction. On contrary, the latter is more convenient for fabrication, expected to behave more efficiently than the former.



a) sleeve-cement b) sleeve-gypsum

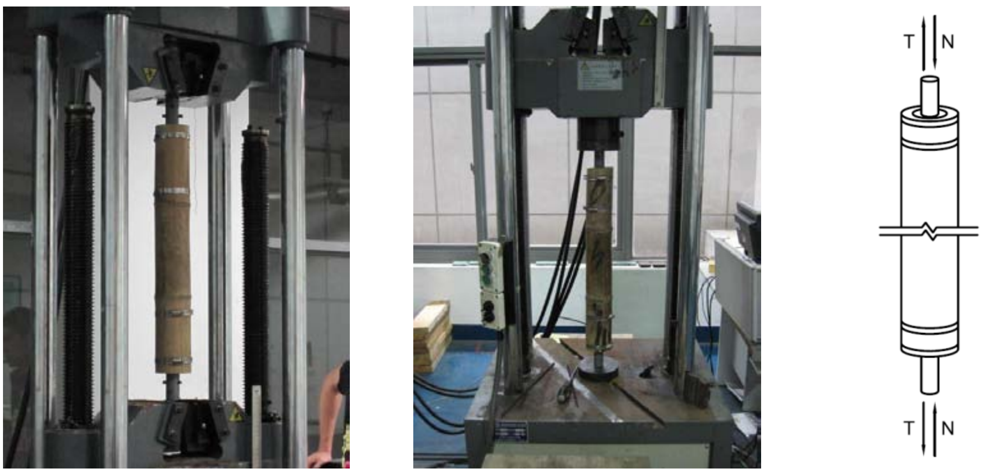
Fig.2 Surface treatment at the interface (schematic view)

3. TEST PROGRAM

Tensile, compression and bending tests were carried out on each type of the bamboo joints, respectively. Prior to each test, preloading and calibration were conducted. Loading rate was controlled according to the increasing speed of the force, and all electric digital data were collected using a data logger, controlled by a PC computer. Full range of test loading was recorded for each specimen.

3.1 Axial loading test

Tensile and compression loading tests were carried out on bamboo joints, respectively. All specimens were tested in a computer control electro-hydraulic servo universal testing machine (WAW-200). The exerted axial load and the deformation of each joint were recorded during the whole process of test. The failure patterns were captured using a digital camera for different bamboo joints. Fig. 3 shows the test setup and schematic view of loading.

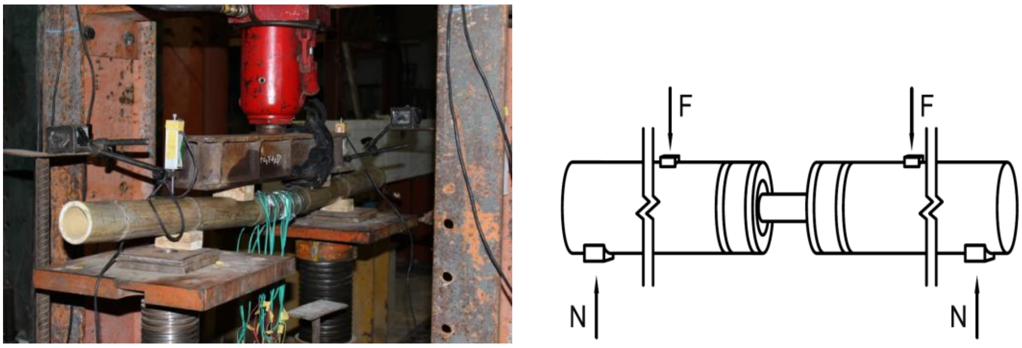


(a) under tension (b) under compression (c) schematic view

Fig. 3 Test setup for axial load

3.2 Bending test

Bending test is carried out using the Hydraulic loading machine. Fig. 4 shows the test setup and loading form. The loading points on the bamboo were on the two 1/3 points of the whole length of the bamboo joint as the figure shows. Distributive girder was adopted and the region of connection was within the pure bending section. The Load was from 0 to the point that the member breaks down. Displacement meters were placed on the two supports and the middle of the span of the specimen. Several strain gages were applied in the test. The strain gauges arrangement is shown in Fig.5. During the test, Load, the displacement and strain of were recorded, and the failure patterns were captured for different types of bamboo joints.



(a) test setup (b) schematic view

Fig. 4 Test setup for bending

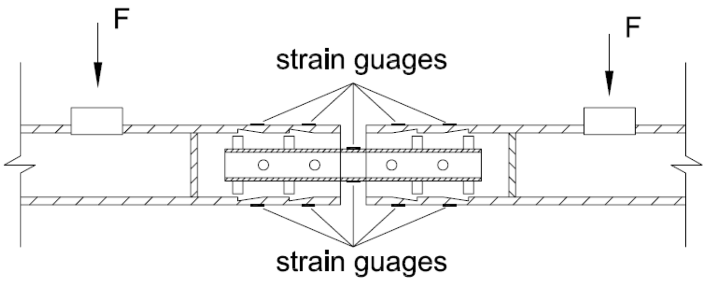


Fig. 5 Strain gauges arrangement

4. TEST RESULT ANALYSIS

Qualitative comparisons have been made on load and deformation data. Test results are presented in Fig. 6, Fig. 8 and Fig. 10, showing the load-displacement curves of four types of bamboo joints. And Table 2 shows the overview of test result. In the table, P_u stands for the ultimate load, and its corresponding displacement is Δ_u, and P_d stands for the load at failure point, and its corresponding displacement is Δ_d. The result of Ab is not acquired during test. Under bending, load recorded in the table stands for the force F applied on the loading point. And the ultimate load and failure load are similar in both the sleeve-cement and the gypsum, respectively.

Table2. Test results

Number	Load	Failure mode	Result			
			P_u [kN]	Δ_u [mm]	P_d [kN]	Δ_d [mm]
At	tension	brittle	7.13	5.16	5.48	5.187
Bt	tension	brittle	7.84	6.55	5.40	6.85
Ct	tension	ductile	0.78	4.05	0.57	28.85
Dt	tension	ductile	8.39	10.48	5.24	25.27
Ac	compression	brittle	11.71	4.38	8.00	4.38
Bc	compression	brittle	18.58	6.16	12.06	6.68
Cc	compression	ductile	10.00	15.59	9.75	20.17
Dc	compression	ductile	14.00	4.76	12.32	7.88
Bb	bending	brittle	3.85	9.36	3.62	12.24
Cb	bending	ductile	7.70	45.00	7.70	45.00
Db	bending	ductile	12.28	41.12	12.28	41.12

4.1 Tensile test

Fig. 6 shows the load-displacement curve of specimens under axial tensile load. As shown in the figure, the bearing capacity of the sleeve-cement is aberrant, merely 1/8 of the others, due to poor fabrication. In order to fulfil the comparison with other joints, the data in the literature can be used, in which the ultimate load is 3.78kN (Fu et al 2012). However, it is still much lower than the bearing capacity of other joints. It is found that the ultimate load of the sleeve-gypsum is the largest, and the sleeve-bolt-cement comes second. Meanwhile, the deformation capacity of the sleeve-gypsum is also the largest, more than twice as compared to the other three types of joints, indicating that the sleeve-gypsum has the best ductility.

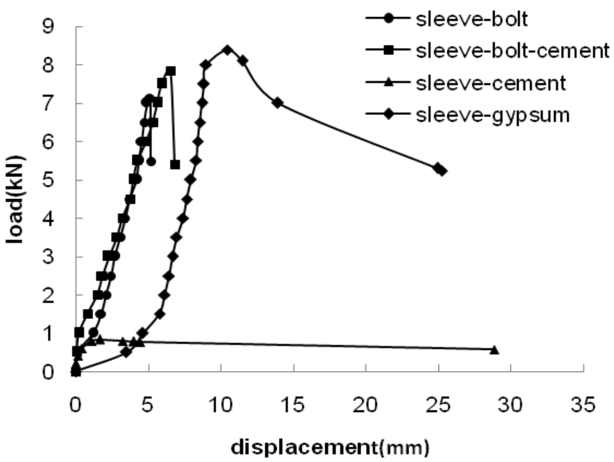


Fig. 6 Load-displacement curves under tension

Under tensile load, the failure modes of sleeve-bolt and sleeve-cement-bolt are both brittle failure characterizing by splitting of bamboo. And the failure mode of sleeve-cement and the sleeve-gypsum are the relative slip between adhesives and bamboo, accompanying by rattle sound. Fig 7 shows the failure modes of the sleeve-bolt and the sleeve-cement under tension.

a) sleeve-bolt

b) sleeve-cement

Fig. 7 Failure modes of bamboo joints under tension

4.2 Compression test

Fig. 8 shows the load-displacement curve of specimens under compression load. On can find that the magnitude of the ultimate load of the sleeve-bolt-cement is the largest, and the sleeve-gypsum comes second. Moreover, the bearing capacity of the sleeve-cement and the sleeve-bolt come the last, and the former is little lower than t the latter. Meanwhile, the deformation capacity of the sleeve-cement is the largest, and the sleeve-gypsum comes second, better than the sleeve-bolt-cement. And the ductility of the bolt joint is the worst. Specifically, though the bearing capacity is lower than the sleeve-bolt-cement, bamboo joint with the sleeve-gypsum is much more ductile and performs better than other joints.

Under compression load, though all accompanied with bamboo split, the failure modes of the four joints appear differently. In detail, the crack of bamboo wall takes place in both the sleeve-bolt and sleeve-bolt-cement. And the split of bamboo node occurred in the sleeve-bolt-cement, the sleeve-cement and the sleeve-gypsum. The former failure mode is actually brittle, with a sudden brittle split between the bolt and the bamboo, the bamboo wall splits apart in a second and the connection loses its capacity immediately. While the sleeve-cement and the sleeve-gypsum both have great ductility. Their capacity can remain for a while when they reach their extreme load point especially for the cement one. The cement in the bamboo tube can be compressed and deformed a lot before failure. Fig 9 shows the failure modes of the sleeve-bolt and the sleeve-cement under compression.

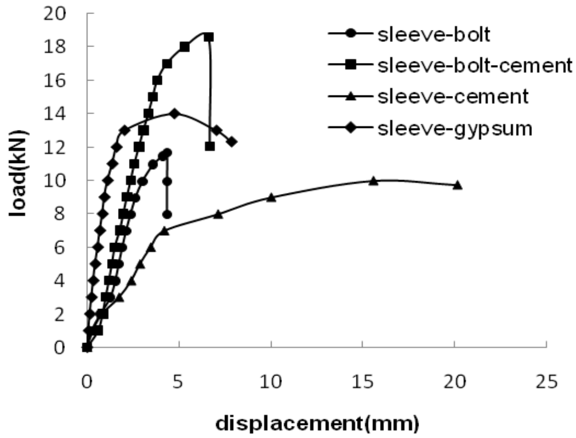


Fig. 8 Load-displacement curves under compression

a) sleeve-bolt

b) sleeve-cement

Fig. 9 Failure modes of bamboo joints under compression

4.3 Bending test

Fig. 10 shows the Moment-deflection curve of specimens under bending. As the figure shows, the sleeve-cement and the sleeve-gypsum have excellent bearing performance. However, the sleeve-bolt-cement has poor bearing capacity because of the shearing spilt between the bolt and the bamboo. Moreover, the sleeve-gypsum performs the best, with great capacity and ductility.

Under bending load, the failure modes of bamboo joints are quite different. The sleeve-bolt-cement failed brittlely, accompanied with the broken of the bamboo tube. However, the other two joints do not suddenly lose the bearing capacity. Actually, when it reaches the ultimate load, the adhesive, cement or gypsum, is pulled out gradually and finally crushed. Fig.11 shows the failure modes of the sleeve-bolt-cement, sleeve-cement and the sleeve-gypsum.

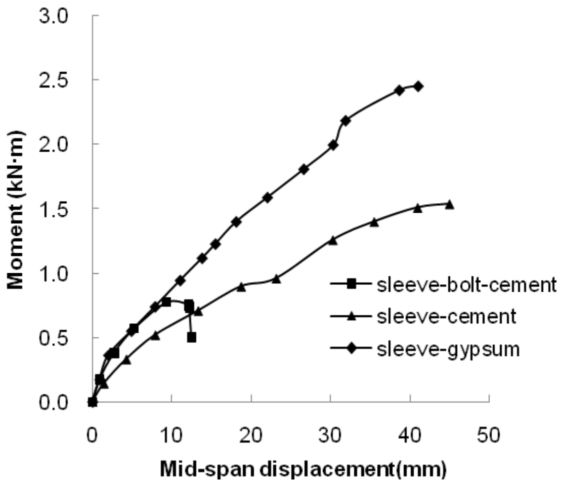


Fig. 10 Moment-deflection curves under bending

a) sleeve-bolt-cement b) sleeve-cement b) sleeve-gypsum

Fig. 11 Failure modes of bamboo joints under bending

The stress of the steel sleeve recorded in the bending test is shown in Figure 12. It is found that the stress of steel sleeves in the sleeve-gypsum and sleeve-cement connections were both over 250Mpa, which was larger than yield strength. In other words, the strength of the steel member in the joint was fully used. However, when it comes to the sleeve-bolt connection, the stress of the steel sleeve was just around 140Mpa, indicating that the steel is not be fully used even the connection is broken.

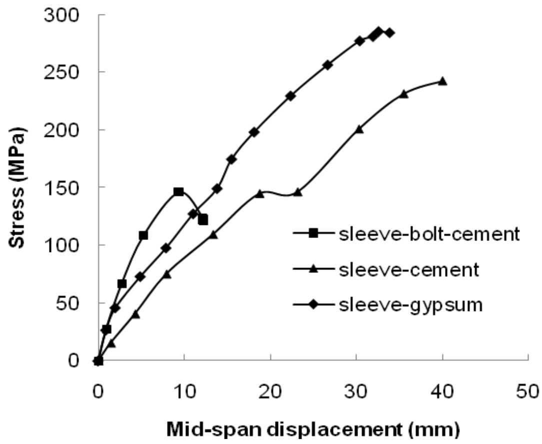


Fig. 12 Failure modes of bamboo joints under bending

Based on the test result, it is concluded that the joint with sleeve-gypsum connection performs much better than the joint with sleeve-cement connection. Under the axial tensile load, the sleeve-gypsum connection not only has the same ductility as the sleeve-cement type, but also has much larger bearing capacity which is even higher than that of the traditional bamboo joints. Under the axial compression load, the bearing capacity of joints with the sleeve-gypsum connection is much better, though its deformation capacity is smaller than that of the sleeve-cement type. The jont with sleeve-gypsum connection has larger bearing capacity and ductility than those of the sleeve-cement type under bending load. In conclusions, the anchorage force of cement is much lower than that of gypsum. In fact, due to the shrink of cement mortar and relative difficult curing conditions for cement, the pressure between cement and inner wall of bamboo is not strong enough to ensure efficient friction and anchorage force. Accordingly, when the tensile load increases, the cement is pulled out easily. On the contrary, the expansion of gypsum ensures a reliable connection between the gypsum and bamboo tube. Therefore, the sleeve-gypsum has higher bearing capacity and better ductility.

5. CONCLUSIONS

Bamboo is nowadays recognized as one of the most sustainable building materials. The efficient joint of individual structural bamboo elements is important and crucial. A novel bamboo joint, the sleeve-gypsum, is designed in this paper. Comparative loading tests were carried out to study the static performances of the bamboo joints namely the sleeve-bolt, the sleeve-bolt-cement, the sleeve-cement and the sleeve-gypsum. The following conclusions can be drawn:

1) The sleeve-gypsum is an efficient bamboo joint. It has the best ductility among the four types of bamboo joints studied, such as the sleeve-bolt, the sleeve-bolt-cement and the sleeve-cement. Its bearing capacity is the largest under axial tensile load and bending respectively, while under axial compression, its bearing capacity is slightly smaller than that of the sleeve-bolt-cement.

2) The failure mode of the sleeve-cement and the sleeve-gypsum is relative slip between bamboo and adhesives, which ensures a good ductility. However, the failure mode of the sleeve-bolt and the sleeve-bolt-cement is mainly governed by brittle shearing split of bamboo, which should be avoided in design of structures.
3) The sleeve-gypsum type is improved from the sleeve-cement type, by means of replacing cement with gypsum and changing the surface treatment of inner wall of bamboo. The expansion of gypsum ensures the strong bond force, leading to better ductility and bearing capacity. And it has much room to be improved in the future.

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