

Bamboo trusses with low cost and high ductility joints

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Abstract

Innovative solutions of joints for bamboo trusses are presented. Experimental tests show the performances and the high level of ductility of the proposed technique, joined with simplicity in the concept of the joints, low level of technology and low cost of all used materials. It can permit a proper dissemination and a sustainable maintenance in developing countries.

Keywords: Bamboo constructions; Trusses; Structural optimization; Low-cost technology

1. Introduction

The theme of the structural behaviour on traditional constructions is wide and complex. The necessity to get houses, schools and social or other public constructions with low-cost, simple to build and to maintain involves primary attention to communities. About 30% of the world population lives in earth housing and about 50% of the earth houses are located in developing countries. In turn, the areas affected by the earthquake risk involve the majority of areas with low socio-economic development: large parts of Asia, Latin America and the Rift Valley in Africa are areas susceptible to earthquake or other extreme loads (i.e. tornados, heavy rains) [1] [2] [3].

It is well-known that low-cost new buildings should integrate with the habits of communities for availability of materials technical maintenance. Past experiences have shown that a strict import of modern construction techniques leads to rapid deteriorations due to problems of sustainability of the work and maintenance techniques and management. The implementation of indigenous building materials and structural forms should be socially harmonized to perform a real improvements in the construction types [4] [5] [6] [7] [8].

Bamboo is a low-cost building material available in wide parts of the world: it is lightweight, durable, flexible, and easily cultivated and processed [9] [10] [11] [12] [13].

An interesting use of bamboo for low-cost buildings is the erection of light roofs well-connected to the walls, and the arrangement of frames entirely made by bamboo or with the help of other materials. The mechanical properties of bamboo are relevant in seismic areas: lower inertia involves minor seismic actions and a good

connection to the top of the walls reduces the slenderness for the benefit of stability [14] [15] [16].

A priority in structural behavior under earthquake is the ductility: unfortunately bamboo shows a short plastic phase after elastic limits – mainly in case of traction – and the collapse is often associated to fragile longitudinal fractures. An other inconvenient in traditional building techniques is the reduced strength due to the joints between bamboo rods, in respect to the resistance of the element. Traditional techniques typically require the use of ropes or ties with buckles, or the mortgage by simple snap: it can obtain simple knots but not efficient from structural point of view. However, improving technology permits high resistance joints even in the mentioned kind of areas but the technological transfer into the economic flow of developing countries [15] [16] [17] [18] is quite hard. Proposal to optimize those aspects are presented.

2. Optimization of bamboo connections

A set of experimental studies and technical solutions for joints have been conducted to combine economy and ease with static and seismic saving. It have been proposed three different solutions of connections: each type of joint has been tested with traction experiments, applying quasi static loads, monotonic or cyclic, to reach the collapse of the element.

2.1. Joint with screw nails and steel plate

A first pilot proposal has been conducted in the laboratory of University of Pisa [19] [20], with a single joint in a bamboo rod (diameter of 60 mm, thickness of 5 mm) reinforced with a massive wood cylinder, glued

and/or screwed with a metal plate. The pilot trials showed the axial force displacement diagram in **Figure 1**, with three different stages of the mechanical behaviour:

Stage 1 (elastic): the connection highlights no cracking and the metal bolts and the glue layer are perfectly embedded in the wood mass.

Stage 2 (inelastic): the bamboo rod end reinforced by screw nails (joint B) reveals longitudinal splitting along the line of the hole centres; no movements are between the reinforcing wood cylinders and bamboo rod.

Stage 3 (collapse): the reinforced extremity (joint B) featured an increase of the longitudinal crack, without significant displacements between the wood core and the bamboo. Instead, the collapse was reached at the joint A, due to the slip between glued wood and internal vegetal skin, without significant plastic phase.

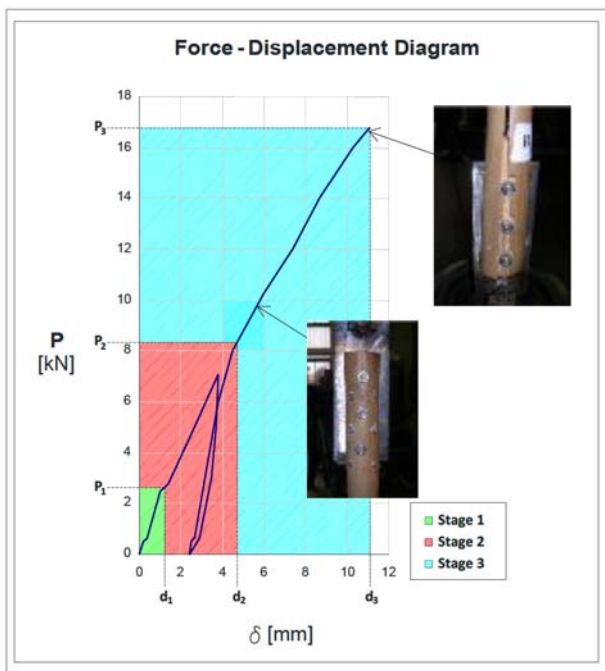


Figure 1. Traction test on 1st type joint.

2.2. Joint with screw nails and plywood plate

An evolution of the joint to reach simpler solution and major ductility has been performed by way of plywood plates – instead of steel - and filling in the internal part of bamboo with a set of wooden sticks. In the Laboratory of the Polytechnic of Malawi [18] [21] a series of nodes with single or twin connection, reinforced with slivers of bamboo and wooden plates screwed to the plywood has been tested. Two kinds of tests have been carried on. The first consists of a single rod traction test performed with two plywood plates bolt at the bottom, linked to the

testing machine through two steel supports. The second type of joint connects a couple of bamboo rods through plywood plate and steel nails with a relative angle of about 60°. Both joints are fixed to the traction machine through appropriate steel supports as shown in **Figure 2**. The bamboo rods and plywood plate were linked by three steel bolts of Ø8 mm; moreover a pine timber cylinder was inserted in the bottom of each of the rods to reinforce the link. This element is different in each pole. With the purpose to fix it to the bamboo and to improve the resistance of the joint, six screw nails of Ø4 mm and length of 40mm were inserted to the bamboo joints.



Figure 2. Tests on single and double 2nd type joints.

The assembly of the specimen, simple and easy to disseminate, was carried out as follows:

- the internal reinforcements were modeled and inserted inside the bamboo rod,
- the bottom of the pole was cut in a longitudinal way to allow inserting the plywood plate,
- the bamboo rods were drilled and bolts with screw nails through the plate.

A steel support (a couple of 2 mm steel plates) hanged the plywood plate to transmit the forces from the pole to the machine through the bolts and the friction between the two elements. The test machine is an Avery-Denison, with resolution of 50 daN and a maximum load of 1000 kN. The tests were performed in displacement control. The length of the rod were 470 mm in the single joint tests and 600 mm in the double joint tests; the average transverse section had a diameter of 50 mm and a thickness of 6mm. **Table 1** summarize the experimental results of the collapse forces. The average ductility for single joint tests was 4.5 and for double joint tests 3.8: both remarkable values were due to the role of plywood strongly deformed around the bolts.

Table 1. Collapse force of traction tests.

| N. | Force [daN] |
|----|-------------|
| 1 | 1380 |
| 2 | 1380 |
| 3 | 1300 |
| 4 | 1300 |
| 5 | 1400 |
| 6 | 1400 |
| 7 | 750 |
| 8 | 750 |
| 9 | 970 |
| 10 | 970 |
| 11 | 1100 |
| 12 | 1100 |

| N. | Force [daN] |
|----|-------------|
| 1 | 450 |
| 2 | 400 |
| 3 | 550 |
| 4 | 800 |
| 5 | 840 |
| 6 | 850 |

Single rod (up)

Coupled rod (left)



Figure 3. Truss with 2nd type joint.

- The main results of the tests have been the following:
- the use of plywood to connect bamboo elements through steel bolts permit ductility during collapse, due to the deformation of the holes around bolts;
 - the joint reinforcement offered by timber cylinders inside the bamboo extremity avoids the fragility resulting from the longitudinal fracture of the bamboo fibers;
 - in all tests the joint configuration permitted applying relevant normal stress on bamboo elements, giving the

maximum high span of rods, useful for trusses especially for roofs, as in **Figure 3**;

- to avoid fragile collapse, nails or glue are applied for connecting the bamboo extremity to the internal wooden cylinder, or to execute external wraps for acting transverse containment

2.3. Joint with wooden pins and plywood plates

The third proposed solution is the simplest from constructive and economic point of view: it consists of a couple of bamboo rods connected by wooden pins, instead of steel nails, without the insertion of the wooden core and transversally reinforced by canapé ropes. The entire constructive process can be conducted by a portable drill to execute the holes on the bamboo and on the plywood plates, a hammer and a saw to fix and cut the wooden nails, using only low-technology structural materials (**Figure 4**).



Figure 4. The 3rd type joint with drill and materials used.

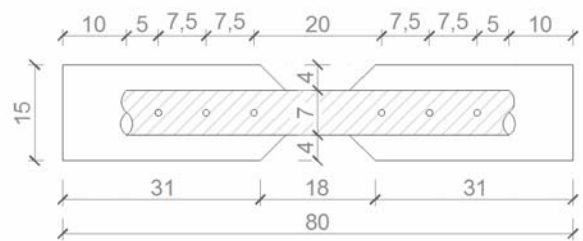


Figure 5. The specimen for traction tests on 3rd type joint.

Traction tests have been performed using specimen in **Figure 5** and **Figure 6** (bamboo rod diameter of 50 mm and thickness of 5 mm, plywood thickness of 8 mm, canapé wire diameter of 3mm) with a couple of connecting steel element designed to avoid premature collapses on the hanging area. The canapé wires have been manually pre-stressed around the bamboo elements through holes in the plywood.



Figure 6. The assembled 3rd type joint.

The tests, regarding three couples of joints, have been executed on INSTRON Mod. 1186 with full scale of 1000 daN, controlling relative displacement of upper and lower joint with n.4 LVDT transducers (precision 1/100 mm) as in **Figure 7**. The main results are summarized in **Table 2**, while in **Figure 8** is the typical diagram of traction force F and relative displacement d of each joint: the collapse traction tests have been conducted applying cycles with increasing loads. It is possible to individuate following four stages in the mechanical behavior of the connections:

1. the joint shows elastic characteristics, without relative displacements between plywood and bamboo;
2. relative displacements between plywood and bamboo are due to the bending of wooden pins;
3. inelastic large deformations in wooden pins perform wide relative displacements up to collapse.
4. softening behavior are due to the progressive rupture of the wooden pins (starting from the extremity pins) partially constrained by the canapé.



Figure 7. The traction tests on 3rd type joint.

The collapses of wooden pins (diameter of 10 mm) protect plywood and bamboo elements from damages: the joint has been then repaired replacing the wooden bars and the canapé rods; the further tests provided similar results.

Table 2. Force P [kN] – displacement d [mm] of the tests.

| Spec. | Joint | P_1 | d_1 | P_2 | d_2 | P_u | d_u |
|-------|-------|-------|-------|-------|-------|-------|-------|
| 1 | Top | 4.60 | 1.25 | 6.09 | 2.10 | - | - |
| 1 | Down | 4.85 | 1.80 | 6.67 | 5.04 | 7.65 | 7.72 |
| 2 | Top | 2.80 | 1.79 | 4.66 | 3.38 | 5.67 | 5.72 |
| 2 | Down | 2.92 | 0.78 | 4.93 | 1.73 | - | - |
| 3 | Top | 3.26 | 2.26 | 7.92 | 7.99 | 9.19 | 10.46 |
| 3 | Down | 2.46 | 0.83 | 5.69 | 2.65 | - | - |

It is noted in **Table 2** that the collapse load could be reached only in one of the two ends of the sample: nevertheless it has been possible to obtain, on both joints of each sample, the elastic limit value P_1 and the start of inelastic deformations in the wooden pins P_2 .

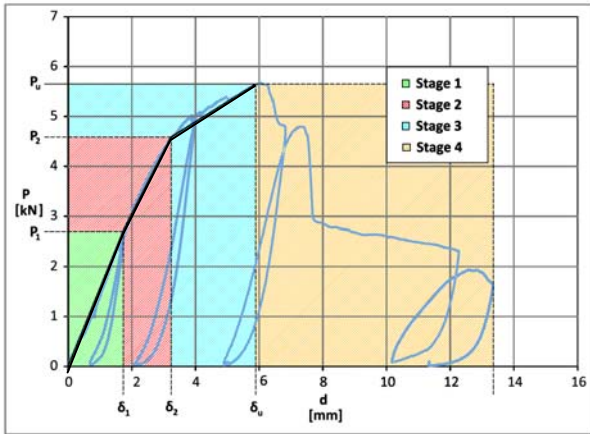


Figure 8. Typical Force [kN] - Displacement [mm] diagram

It is noted in Table 2 that the ultimate value of the load could be reached in one of the two ends of the sample: nevertheless it has been possible to obtain, on both joints of each sample, the elastic limit value P_1 and the value of start of inelastic deformations in the wooden pins P_2 . The main collapse mechanisms are:

1. shear-bending rupture of wooden pins;
2. upsetting of the holes in plywood plate;
3. traction tearing of the bamboo cane;
4. longitudinal crack on bamboo cane between the holes.

The design of joints has been addressed to conduct the mechanism n.1 (“weak pins”) as in Figure 9.



Figure 9. View of a collapsed joint.

This allowed ductility factor of node $\mu = d_u/d_1$ between 3.2 and 4.6, typical values of a ductile behavior, in spite of the fragility of the material bamboo without losing significantly in strength. Indeed, the classic formula of the design traction load of bamboo cane (ISO / DIS 22156) with net area A and strength f_k is:

$$P_d = A f_k G D / \gamma_m$$

where G is a load factor (1.0 – 1.5), D reliability factor in execution (mainly 0.5), γ_m safety factor of bamboo (2.25). In the present case from the current values of A equal to 13.7 cm² and f_k of 18 MPa, it can be obtain

$$P_d = 5.50 - 8.25 \text{ kN}$$

comparable to P_1 in Table 2. This last type of joint allows a remarkable combination of static performance and ease technological and design, favoring the composition of the nodes of a truss. Using, for example, a Polanceau scheme is possible to reproduce the various nodes assembling only the tested joint on plywood plates of different geometry as in Figure 10.

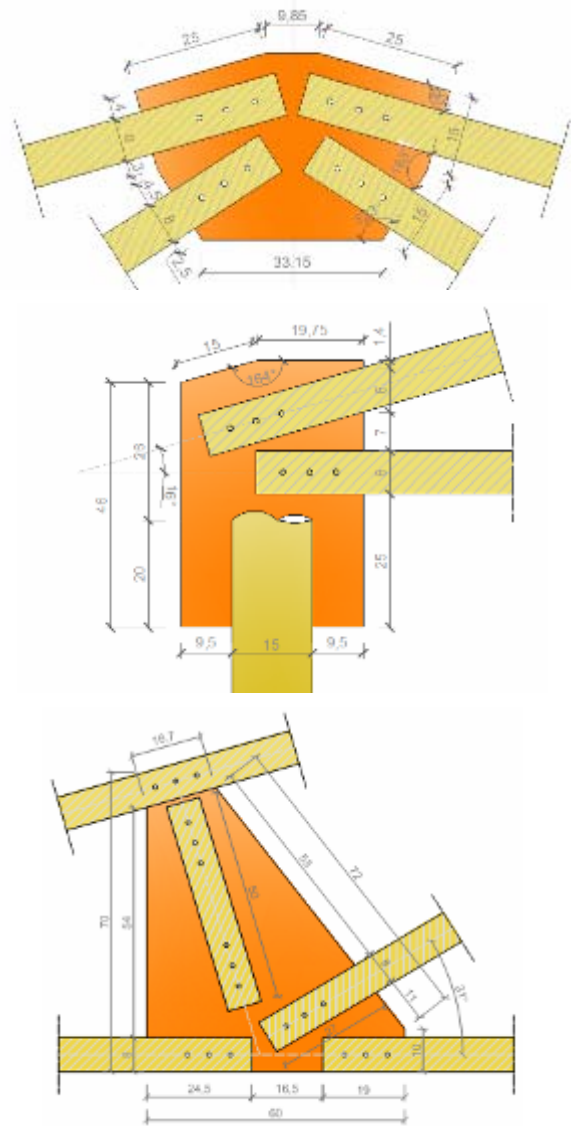


Figure 10. Nodes of Polanceau truss with 3rd type joint.

An example of truss frame as shown in **Figure 11**, can be adopted for a series of one-floor constructions as housings, schools, social or medical centers.

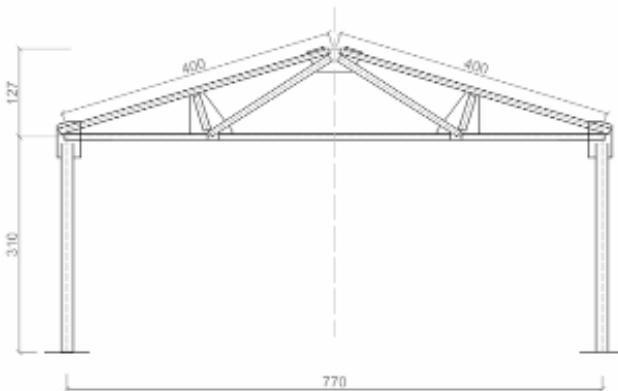


Figure 11. Truss frame for one-floor construction.

3. Conclusions

The three proposed types of joints, furnishing different solutions in terms of technology: it can be seen an increasing ductility from the first to third joint, together with an improvement of simplicity executive and a lowering of the level of technology.

Moreover the strategy of “weak pins” allows quick and easy to repair of the nodes, avoiding collapses in the bamboo canes or in the plywood plates.

Finally the application of the joints to roof trusses permits the use of the same nodes for different size of the frame ensuring it a certain homotheticity: same nodes are useful for a range of trusses, giving an interesting degree of prefabrication to the structural system.

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