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Selection criteria for a house design method using plybamboo sheets

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Abstract—Plybamboo is a promising structural material for housing. It can be industrially produced and used for prefabricated construction in developing countries, especially if the country possesses bamboo plantations. In this paper, selection criteria are developed and applied for different house design methods which are based on how to make connections between the sheets. Three different designs are then described and the criteria are applied in order to select one of them. A house design method is selected according to the criteria selection. Experimental tests would be the next phase of the research in order to improve the applicability of the method.

Key words: Bamboo; housing; plybamboo; structural design.

1. INTRODUCTION

Bamboo has been used for housing for centuries. However, only recently has it been considered as an engineering material. Although much research has been carried out on bamboo, there is still a long way to go to reach the same level of information as we have on traditional construction materials. Bamboo culms can be transformed into sheets such as plywood by applying an industrial process. The sheets called plybamboo could be suitable for housing. The objective of this research is to develop selection criteria for a house design method using plybamboo sheets. The method is intended to be applied for low-cost housing in developing countries. The design method would be based on how to make connections between the sheets, such as corner connections, T-connections and parallel connections. Bottom (foundation level) and top (roof level) connections have to be considered as well. At the beginning of the paper, a theoretical framework is defined and a list of factors affecting the design method is presented. Afterwards, a selection tool is developed. The following section describes the three design methods that were developed for the final selection. In Section 4, the design methods are compared using selection criteria previously developed and one method is selected. Finally, conclusions regarding the selection are presented. Structural analysis and experimental tests on the selected design method would be carried out in the future in order to obtain accurate structural details.

2. THEORETICAL FRAMEWORK, DEFINITION AND SELECTION OF FACTORS

Every structure is conceived in order to satisfy certain needs with regard to particular specified requirements. For instance, it can be said that 'a house must be able to withstand hurricanes'. This statement is considered as a requirement.

A structure is achieved by combining intention and materiality. The intention is composed by firmness, service, delight and economy whereas materiality is composed by materials, shape, dimension/details and constructive technology [1].

The house represents the structure and it should stay firm after a hurricane has occurred. Hurricane is a factor that interacts with intention and materiality.

If one tries to take into account all the possible factors affecting the performance of the structure the process could be eternal and the list of factors unending. That is why a list of factors was selected as the most representative one considering the structure on study. The list is based on Olie [2] and ISO 3447 [3] and is defined as follows:

1. *Hurricanes*: wind forces caused by hurricanes, storms and the like.
2. *Earthquakes*: seismic forces caused by ground accelerations produced by earthquakes.
3. *Impact*: impact forces caused by people, especially burglars.
4. *Light*: penetration of natural light through the structure and house illumination.
5. *Air*: regular air flow passing through house openings.
6. *Warmth*: transfer of heat from the outside to the inside and vice-versa.
7. *Moisture*: water in general; penetration of water and contact between water and structure. Humidity.
8. *Sound*: transmission of sound from one place to another through a structure.
9. *Fire*: fire propagation caused by flammable materials.
10. *Minerals, plants, animals*: termites, insects, vermin, leaves, fungus, dust, and so on.
11. *Durability*: ability of the structure to withstand the effect of the environment through time while maintaining its properties almost unchangeable.
12. *Execution*: 'the number of parts with their direction of movement and their sequence of assembly, disassembly and reassembly' [2].
13. *Maintenance*: reparation and cleaning of parts of the structure when needed.

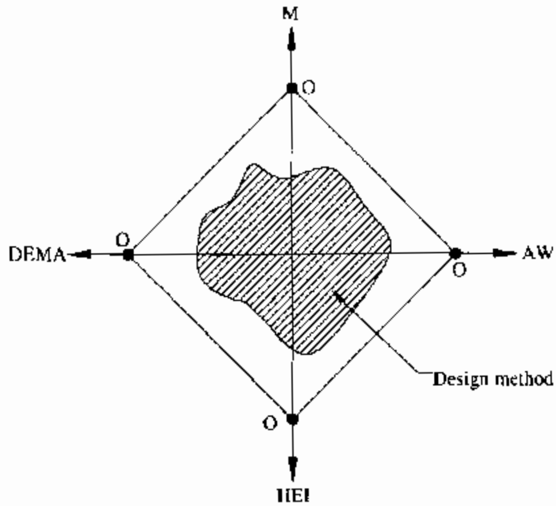


Figure 1. Representation of the design method in relation with the four selected items. O: optimum design. M: moisture. DEMA: durability/execution/maintenance/adaptability. HEI: hurricanes/earthquakes/impact. AW: air/warmth.

14. *Adaptability*: possible extension or replacement of parts that could be built onto the already existing structure.

The method is intended to be applied in developing countries. Therefore, climatic, cultural and socio-economic conditions should be defined. For this study, places possessing tropical wet and tropical wet and dry climates (average temperature no lower than 18 Celsius degrees) are considered. Culture involves traditional materials, method of building, tools, equipment, workmanship and other issues that are important for housing. The design method is intended to be flexible and adaptable to the culture. Regarding socio-economic conditions, the design method is directed to the lowest-income people of the country or region.

Even though fourteen factors have been selected, they must be reduced to a simpler analyzing tool. Four items shown in Fig. 1 comprise this tool. Thus, hurricanes/earthquakes/impact form the item HEI which interact with intention and materiality in the same way; air/warmth form the item AW because usually, in tropical countries, a good ventilation system provides thermal comfort; moisture forms the item moisture; durability/execution/maintenance/adaptability form the item DEMA because they are dependent on each other; light, sound, fire and minerals, plants, animals are not considered in the analyzing tool because they are out of the scope of this research.

3. SELECTION AND DESCRIPTION OF DESIGN METHODS

19 different types of designs based on the principles shown in Fig. 2 were analyzed using the selection tool described in the previous section. From these, three were

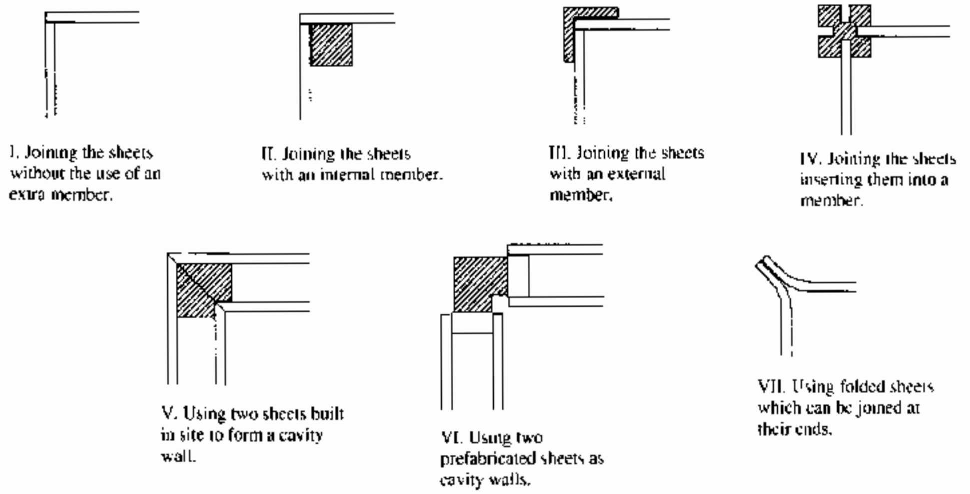


Figure 2. Joiting principles for flat sheets.

selected. For each design, each of the factors in the selection tool were qualified as good, regular or bad. The three selected ones had the best performance.

3.1. Description of design method A

Figure 3 shows several details of design method A. The walls consist of prefabricated panels composed of two horizontal members at the top and the bottom, three vertical members and one plybamboo sheet nailed to the vertical and horizontal members (see Fig. 3a). The horizontal and vertical members are supposed to be wooden elements. However, since the wood is expensive in developing countries, the horizontal and vertical elements could be laminated bamboo elements.

The wall to foundation connection is shown in Fig. 3b. It is based on a foundation system that has been developed and used by FUNBAMBU (Costa Rican Bamboo Foundation) [4]. It consists of a reinforced concrete strip foundation. Two concrete hollow blocks are placed on the concrete foundation. Steel anchors from the foundation are passed through the hollow part of the blocks. This part is then filled with mortar. The lower soleplate is fixed to the concrete blocks by means of the steel anchors from the foundation. A detail is shown in Fig. 3b (2). The wall to wall connections are shown in Fig. 3c and they consist of nailing on-site the vertical members of each of the panels. The T-joints (4, 5 and 6 of Fig. 3c) depend on the modular basis of the house. In general, the connections 4 and 6 are for external walls whereas 5 is for internal walls.

Finally, the wall to roof connection will depend on the type of roof structure that is going to be used. Basically, this structure could be easily joined to the upper soleplate as shown in Fig. 3d. The upper soleplate could be nailed to the horizontal member of the prefabricated panel.

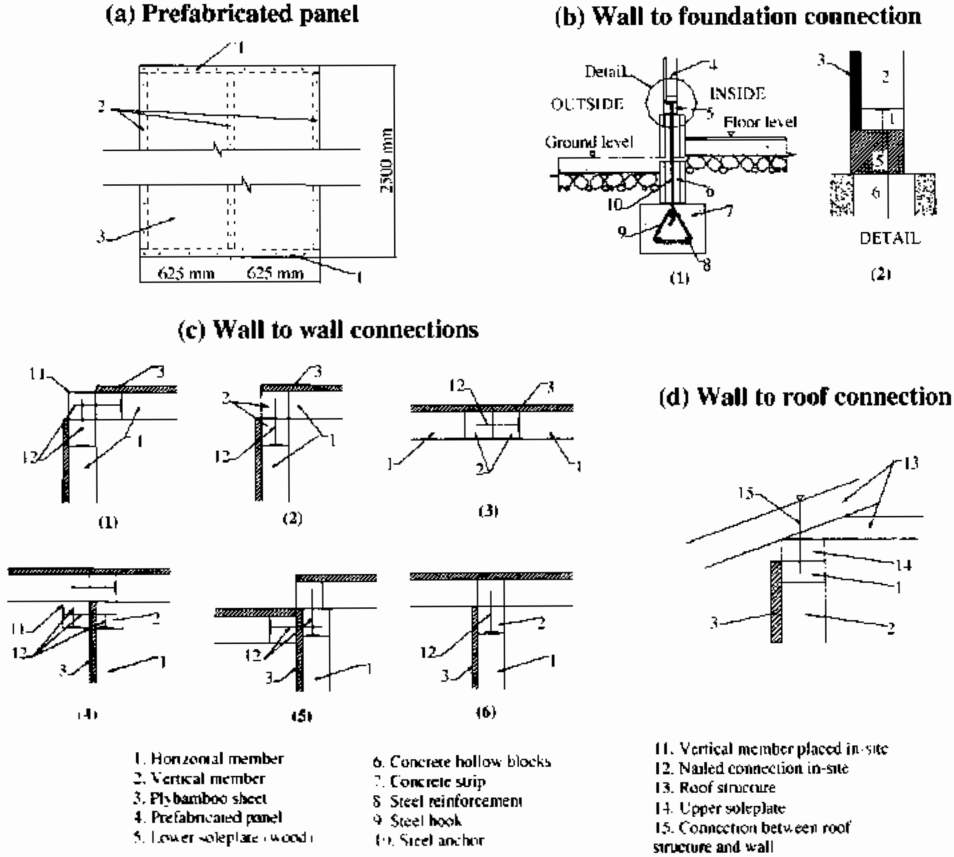


Figure 3. Design method A. Wall and connection details. Dimensions in mm.

3.2. Description of design method B

The idea of design B is to build a prefabricated cavity wall with two plybamboo sheets thinner (6 mm thick) than the ones used for design A (12 mm thick). More vertical members are needed in order to avoid local buckling of the sheets (see Fig. 4a).

The wall to foundation connection could be as the one shown in Fig. 4b. In this case, the lower soleplate is an element made in factory that consists of a wooden member with a channel section (7 in Fig. 4b) in which a wooden or plybamboo strip is glued in factory (6 in Fig. 4b). The prefabricated panel is placed over the lower soleplate. This is possible because the horizontal member (4 in Fig. 4b) of the prefabricated panel also has a channel section that fits in the wooden strip. Afterwards, the panel could be joined to the lower soleplate as shown in the figure.

The wall to wall connections (Fig. 4c) follow the same principles as for design A with the exception of the parallel connection (when two panels meet at their ends), which follow the wall to foundation connection principle.

The wall to roof connection would be the same as for design A.

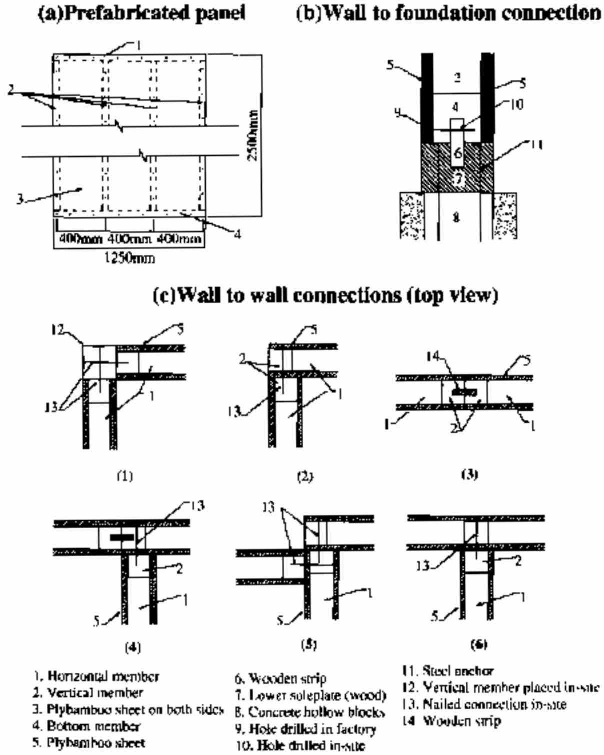


Figure 4. Design method B. Wall and connection details. Dimensions in mm.

3.3. Description of design C

The idea of design C is inspired by another building system developed by FUNBAMBU. It consists of prefabricated bamboo columns with 6 inserted wooden plates along the length of the bamboo culm (see Fig. 5a). The process carried out in the factory would consist of preparing and treating the bamboo culms of specific diameter, thickness and length as well as the wooden plates. Afterwards, holes would be drilled (by hand or machine) and finally, the wooden plates would be inserted into the culms. The connection is achieved because the wooden plates are tightened by friction into the hole.

A possible wall to foundation connection for design C is shown in Fig. 5b [5]. Each bamboo culm would have a single concrete footing. This footing would be a prefabricated concrete cylinder (10 in Fig. 5b) with a longitudinal steel bar (11 in Fig. 5b) and holes at ground level in order to insert longitudinal bars (8 in Fig. 5b) that would brace the columns. The concrete cylinder is buried in the soil over a 10 cm concrete footer cast on-site. The cylinders would be connected by a mortar or concrete strip (7 in Fig. 5b) and a steel bar as shown in the figure. A row of concrete hollow blocks would be placed over the mortar strip. Steel anchors coming from the mortar strip would join the lower soleplate. The bamboo culms are then placed over the concrete cylinders. The culm is inserted into the reduced area of the

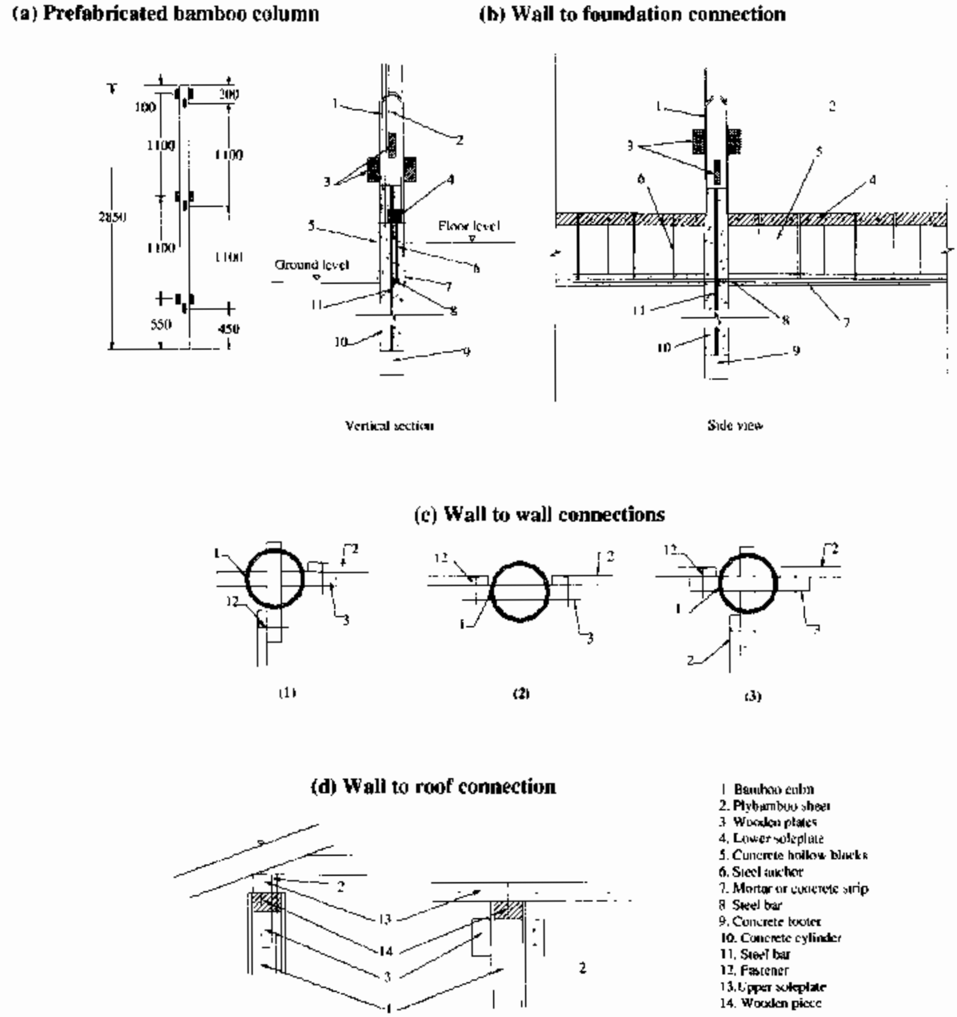


Figure 5. Design method C. Wall and connection details. Dimensions in mm.

cylinder, which is smaller than the hollow part of the culm, and the gap is filled by casting mortar through a hole previously made in the culm. The panels would then be fastened to the lower soleplate and to the wooden plates.

The wall to wall connections consist of fastening the plybamboo sheets to the wooden plates (see Fig. 5c).

Figure 5d shows a possible wall to roof connection for design method C. The top soleplate would be fastened to a piece of wood inserted at the end of the culm (14 in Fig. 5d). This wood insert would be made in the factory. Afterwards, the plybamboo sheet would be fastened to the top soleplate and the wooden plates as shown in the figure. The roof structure would then be fastened to the top soleplate.

4. FINAL SELECTION

The next step is the selection of one of the three presented design methods. This can be achieved by using the criteria selection shown in Fig. 1. Moisture and Air/Warmth can be neglected because they can be regulated in each of the three designs. Hence, DEMA and HEI are the items to be considered in the final selection.

4.1. Analysis of DEMA

1. Durability. In design A and B, only the plybamboo sheets are exposed to the environment whereas in design C, the bamboo culms are also exposed to the environment. The problem with design B against durability is the air space between the two sheets of the panels where termites can penetrate and start eating the sheets from the inside without anybody noticing it. From the reasons cited above, the three methods can be selected according to durability in the following order: A, C and B. All the plybamboo and wooden elements must be preserved and treated against insects and water. As shown in the wall to foundation connections, all the plybamboo and wooden elements are not in direct contact with the soil. Roof overhangs of at least 1 m should be provided in order to avoid contact of the rainwater and the walls as much as possible.
2. Execution. Three different factors regarding execution should be carefully compared. These factors are prefabrication, building site and transportation. Regarding prefabrication, B would be the most difficult to produce because it would require special equipment and glue to produce the special pieces. Besides, three different types of panels are needed in order to be able to make all the possible vertical connections. A would be rather simple to fabricate and C would require the production of the bamboo culms with the inserted wooden plates and the concrete cylinders for the foundation. Comparing building sites, all the design methods would be very simple, especially C, which has a prefabricated foundation system. However, the plybamboo sheets must also be joined in-site. The transportation would be simple for all methods. The foundation in C would require the transportation of the prefabricated concrete cylinders. For the walls in C, the sheets are transported separately from the prefabricated columns. After these statements, it could be concluded that the best method regarding execution is between A and C. B is eliminated because of the first statement. Finally, method A is preferably chosen because of the following disadvantages of method C: irregularity in bamboo culms, gaps between sheets and culms could be rather large and limited to make T-connections just in parallel connections.
3. Maintenance. For design A it would be easy to replace the sheets without replacing vertical or horizontal members, which are not exposed to the outside. If a vertical or horizontal member were decayed it would be more difficult to replace it. Cleaning of all parts of the house would be simple and the presence of termites or insects would be easily noticed and, hence, treatment can be

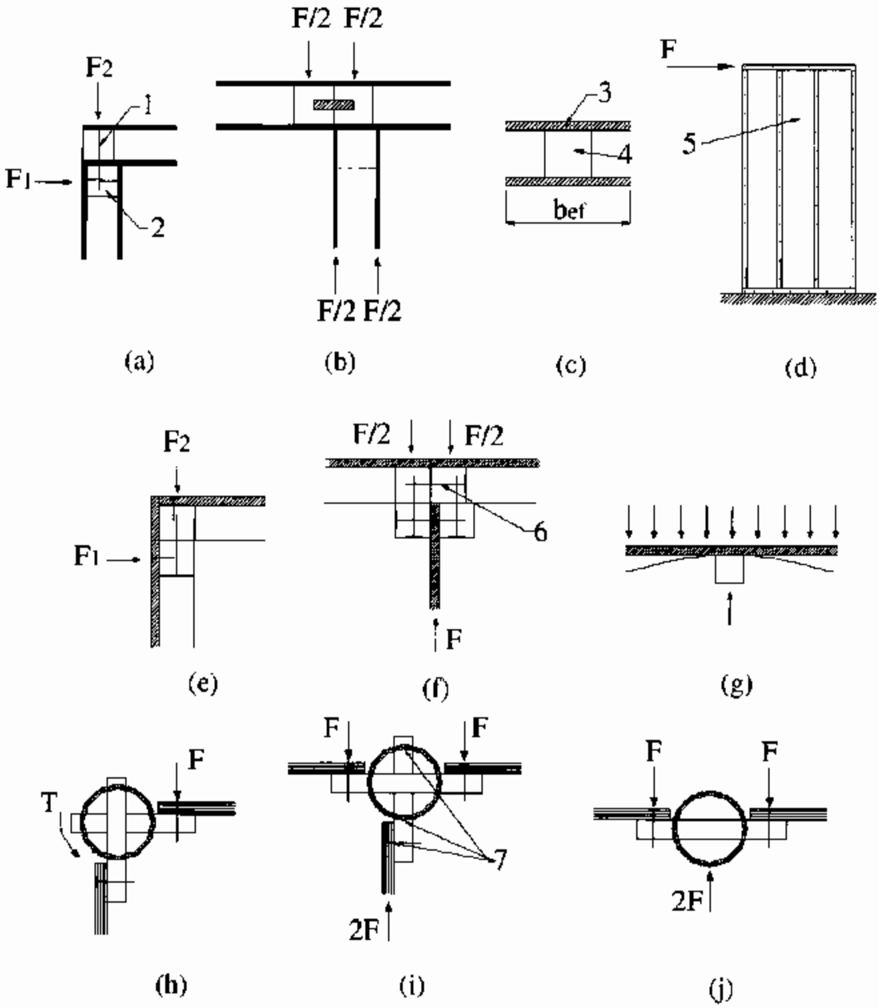
applied before the termites can cause permanent damage to the members. For design B, the replacement of the sheets or the wooden members is not possible. The key problem here is to maintain the exposed sheets. Regarding design C, it can be said that it would be the easiest to maintain because the sheets and the prefabricated culms would be easily replaced. All the parts that can be damaged are visible and hence they could be treated before permanent damage is caused. From this discussion, the methods are selected according to maintenance in the following order: C, A and B.

4. Adaptability. Design A would be very adaptable to new structures. A corner connection could be turned into a T-connection and even a four-wall connection. Regarding design C, one can say that it would be the easiest method considering adaptability. A corner connection could become a T or a four-wall connection. Finally, design B would also be adaptable to new structures. However, more effort would be needed since for every adaptation, a vertical piece besides the prefabricated panel would be needed. Furthermore, the modular basis would be affected by the extra piece. After making this adaptability analysis, the design methods are selected in order of adaptability as follows: C, A and B.

4.2. Analysis of HEI

After making the structural analysis of the three design methods, it can be concluded that the best one is B followed by A and C. The reasons are as follows:

1. Design B. The corner connection is very strong since the force F_1 is taken by three shear planes in nails 1 and F_2 is taken by two single shear planes in nails 2 (Fig. 6a). In the T-connection, the force is taken by the two-plybamboo sheets and transmitted to the foundation (Fig. 6b). In parallel connections, there is going to be a composite action between the vertical elements and the sheets, which would act as an I-beam bending in its longitudinal direction and transmitting the reactions to the soleplates (Fig. 6c). Finally, for lateral loads, the panel would be very strong because it has double sheathing and four vertical members (Fig. 6d).
2. Design A. The corner connection is also a strong connection in which the spacing of the nails could be adjusted to the required strength. However, it is not as strong as the one in design B because the force is taken only by one shear plane (Fig. 6e). The T-connection is basically achieved by the double-shear connection shown in Fig. 6f. It is a very strong connection although not as strong as the one in design B. The parallel connection is achieved by bending of the sheets in their short direction. The reactions will be transmitted by bending of the vertical members in their longitudinal direction to the soleplates (Fig. 6g). There is basically no composite action between the sheets and the vertical members as for design B. Lateral loads are taken by one sheet, which is basically half as strong as design B.



1. Nails with three shear planes
2. Nails in single shear
3. Flange
4. Web
5. Double sheathing
6. Nails in double shear
7. Critical connections

Figure 6. Analysis of HEI for each of the design methods.

3. Design C. The corner connection in design C is probably the weakest one because it depends on the torsion capacity of the bamboo culm (Fig. 6h). Even though this property is still unknown, it would not be expected to be high. The T-connection could be critical considering that stresses would concentrate in the connection between the wooden plates and the sheets parallel to the loads. Besides, the connection between the culm and the wooden plates is based on friction forces, which could be also critical in this kind of connection (Fig. 6i). The parallel connection would be very strong since the wooden plates would

Table 1.
Comparison between design methods

Factor/place	1	2	3	Weight	A	C	B
D	A	C	B	10%	0.3	0.2	0.1
E	A	C	B	25%	0.75	0.5	0.25
M	C	A	B	7.5%	0.15	0.225	0.075
A	C	A	B	7.5%	0.15	0.225	0.075
Total DEMA				50%	1.35	1.15	0.5
HEI	B	A	C	50%	1	0.5	1.5
Total				100%	**2.35**	**1.65**	**2**

transmit the forces to the bamboo culm, which will transmit some of them to the foundation, and the rest to the upper soleplate (Fig. 6j). Finally, for lateral loads, the approach is basically the same as for the T-connection.

4.3. Discussion of results

All the designs have been selected according to each of the considered factors in the criteria selection. In order to make a numerical selection, a certain percentage of importance has been given to each of the items. This is shown in the column of Table 1 named 'Weight': 50% has been given to DEMA and 50% to HEI. Moreover, each of the factors or sub items of DEMA has a weight as well. The columns 1, 2 and 3 are the places in which each design has been selected according to the factors. In this case 1 is the best. The last three columns represent the points that each of the design methods has gained for each of the factors. For instance, since A was number 1 in Durability (D) it gets 0.3 points (3*0.1). Hence, place multiplied by weight gives the number of points for each factor. Finally, the total row shows the final point score of each of the designs. With 3 being the maximum, A has obtained 2.35, B — 2 and C — 1.65 which means that the best design method for the purpose of this research is design method A.

5. CONCLUSIONS

1. For the design of corner, parallel and T-connections of a plybamboo house, the most important factors to be considered are hurricanes, earthquakes, impact, durability, execution, maintenance and adaptability.
2. Selection criteria for different design methods can be applied by analyzing each of the factors previously mentioned.
3. A house design method using prefabricated panels composed by a wooden (or laminated bamboo) frame with a plybamboo sheet joined to it could be a suitable solution for low-cost housing in developing countries, certainly for those countries with bamboo plantations.

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