Bamboo building construction is characterised by a structural frame approach similar to that applied in traditional timber frame design and construction. In this case, the floor, wall and roof elements are interconnected and often one dependent on the other for overall stability. A recent study by Arce (1995) has highlighted the need to control lateral deformations inherent in some traditional forms of building.

The adequacy and suitability of the building for occupancy will also depend to a large extent on good detailing, for example to help prevent water and moisture ingress, fungal attack and vermin infestation.

All of the above features are dealt with in the following sections.

Foundations

The types of bamboo foundation identified are:

- Bamboo in direct ground contact
- Bamboo on rock or preformed concrete footings
- Bamboo incorporated into concrete footings
- Composite bamboo/concrete columns
- Bamboo reinforced concrete
- Bamboo piles

Bamboo in direct ground contact

Bamboo, either on the surface or buried, can decay within six months to two years. Preservative treatment is therefore recommended. For strength and stability, large diameter thick walled sections of bamboo with closely spaced nodes should be used. Where these are not available, smaller sections can be tied together.

Bamboo on rock or preformed concrete footings

Ideally, where bamboo is being used for bearings it should be placed out of ground contact on footings of either rock or preformed concrete (see figure 5). As above, the largest and stiffest sections of bamboo should be used.

Bamboo incorporated into concrete footings

The third approach is to incorporate the bamboo directly into the concrete footing. This can take the form of single posts or strip footings (figures 6 and 7).

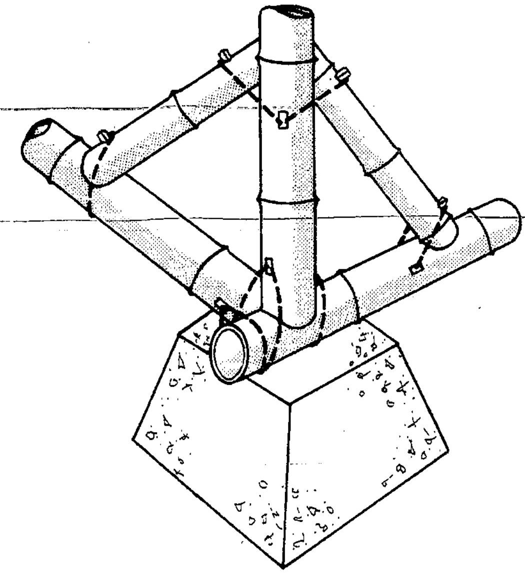


Figure 5: Preformed concrete footings (after Bandara, 1990)

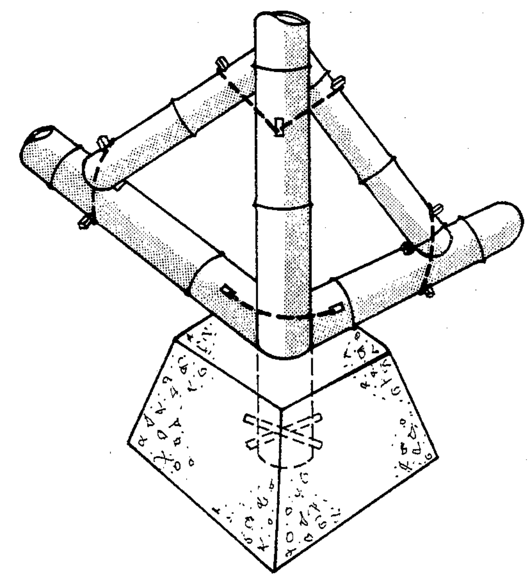


Figure 6: Single post footing (after Bandara, 1990)

Composite bamboo/concrete columns

An innovative development involves the casting of a concrete extension to a bamboo post using a plastic tube of the same diameter (Janssen, 1995). The result is a bamboo post with an integral, durable foundation (figure 8).

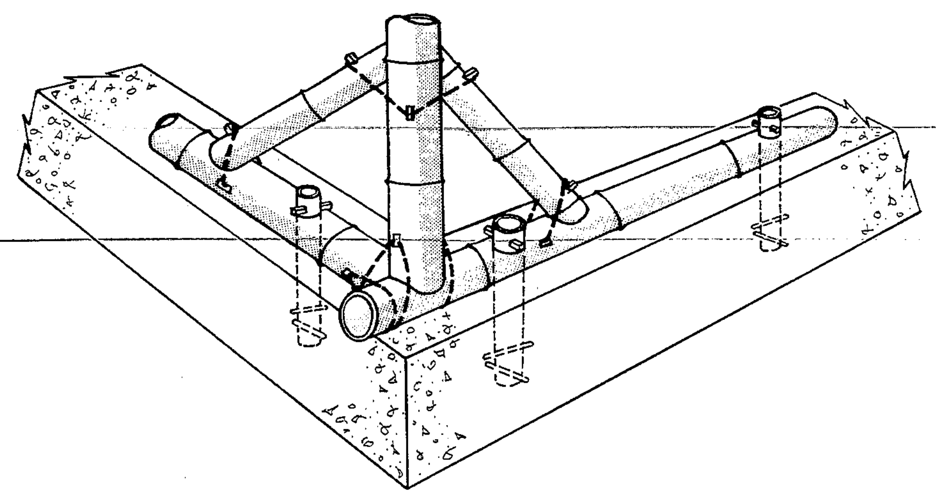


Figure 7: Strip footing

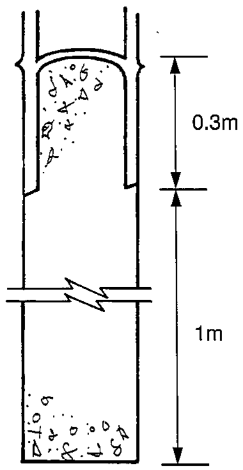


Figure 8: Composite bamboo/concrete column (after Janssen, 1995)

Bamboo reinforced concrete Bamboo reinforced concrete slabs offer another solution, although this type of construction has its own specific problems. These are dealt with in more detail in Chapter 7.

Bamboo piles Bamboo piles have been used successfully to stabilise soft soils and reduce building settlement. In the example cited (Stulz, 1983), treated split bamboo piles 8m long and 80 to 90mm in diameter were filled with coconut coir strands wrapped with jute. The sections were then tied with wire. After installation of the piles at

2m centres by drop hammer, the area was covered with a 2.5m surcharge of sandy material (see figure 9).

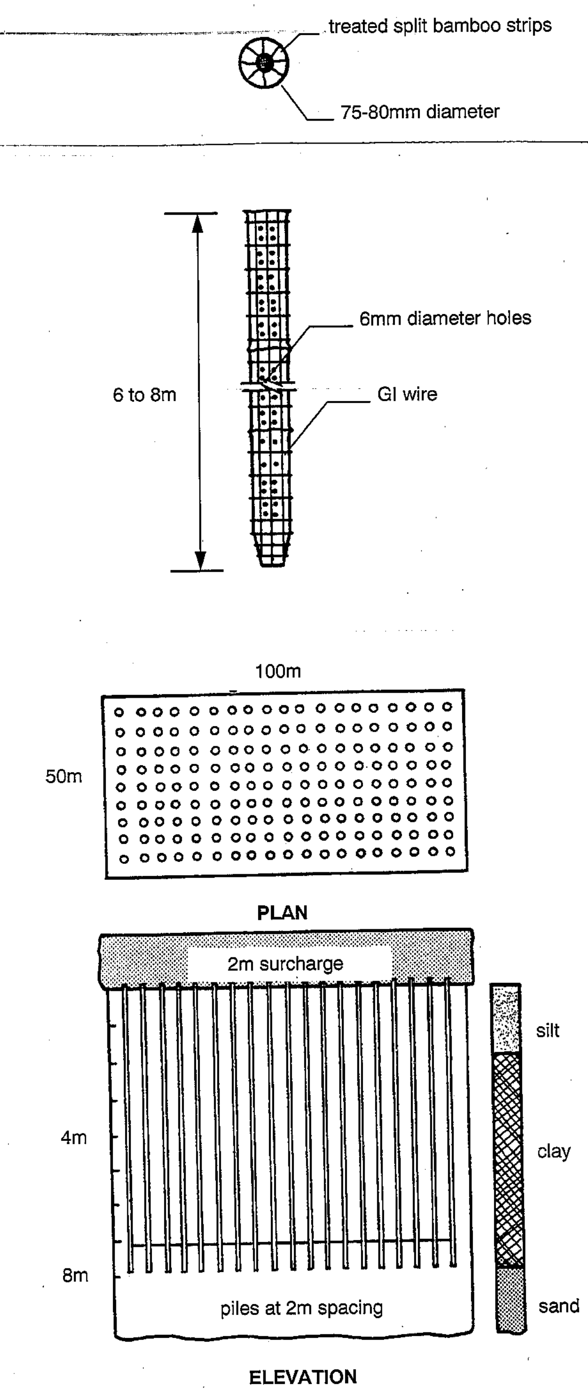


Figure 9: Bamboo piles (after Stulz/ICE, 1983)

Floors The floor of a bamboo building may be at ground level, and therefore consist only of compacted earth, with or without a covering of bamboo matting. However, the preferred solution is to raise the floor above the ground creating a stilt type of construction. This improves comfort and hygiene and can provide a covered storage area below the floor. A minimum ground to floor distance of 500mm is recommended to allow for inspection (Janssen, 1995). When the floor is elevated, it becomes an integral part of the structural framework of the building. The floor will comprise:

- structural bamboo elements
- bamboo decking

Floor structure Floors normally consist of bamboo beams fixed to strip footings or to foundation posts. The beams therefore run around the perimeter of the building. Where the beams are fixed to posts, careful attention to jointing is required (see Chapter 8, *Jointing techniques*). Beams and columns are generally around 100mm in diameter.

Bamboo joists then span in the shortest direction across the perimeter beams. The joists are often laid on the beams without fixing, but some form of mechanical connection is recommended. Depending on the form of floor decking, secondary joists, often taking the form of split culms, may be required. Joist diameters are in the order of 70mm. Joist centres are typically 300 to 400mm, or up to 500mm if secondary joists are used (figures 10 and 11).

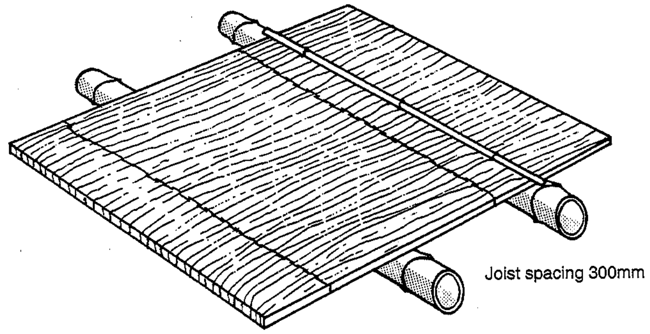


Figure 10: Joist arrangement - primaries only (after Siopongco et al. *1987)*

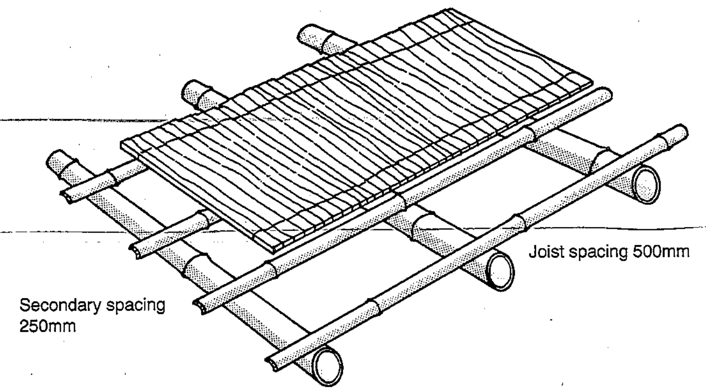


Figure 11: Joist arrangement - primaries and secondaries (after Siopongco et al. *1987)*

Floor decking Bamboo floor decking can take one of the following forms:

- Small bamboo culms
- Split bamboo
- Flattened bamboo (bamboo boards)
- Bamboo mats
- Bamboo panels
- Bamboo parquettes

Small bamboo culms: small diameter culms are tied or nailed directly to the joists (figure 12).

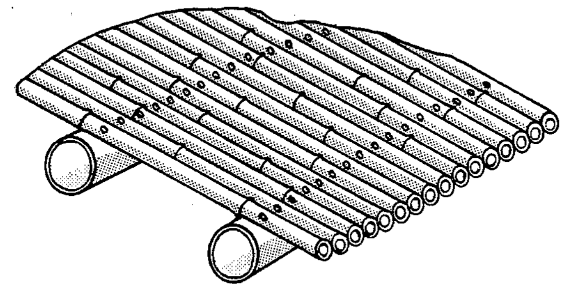


Figure 12: Bamboo cane floor decking (after Janssen, 1995)

Split bamboo: bamboo culms are split along their length into strips several centimetres wide. They can be fixed directly to the joists in the case of tying or nailing, or a timber batten can be fixed to the joist beforehand to facilitate nailing (figure 13).

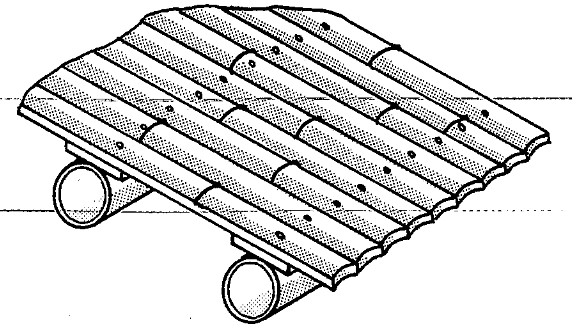


Figure 13: Split bamboo floor decking (after Janssen, 1995)

Flattened bamboo (bamboo boards): these are formed by splitting green bamboo culms, removing the diaphragms then unrolling and flattening them. The resulting board is laid across the joists and fixed by nailing or tying (figure 14).

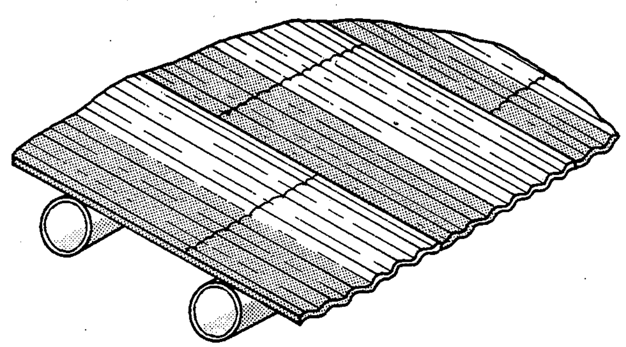


Figure 14: Flattened bamboo floor decking (after Janssen, 1995)

The surface finish of these three types of floor deck is, understandably, uneven and difficult to clean. They can be screeded with cement mortar for reasons of hygiene and comfort.

Bamboo mats: these are formed by weaving thin strips of bamboo. Strips vary in size from 20 x 2mm to 2 x 1mm, depending on the intricacy of the pattern. Some examples are shown in figure 15.

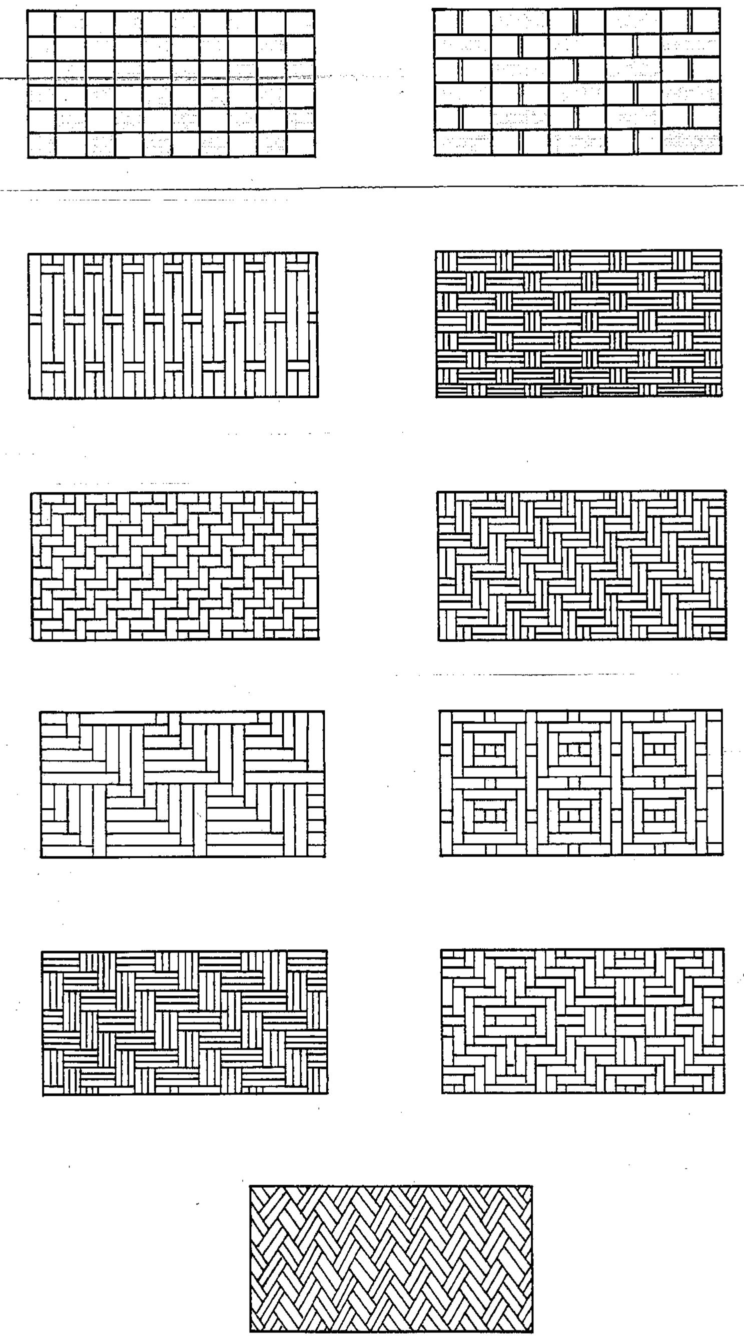


Figure 15: Examples of woven bamboo mats (after Janssen, 1995, Narayanamurty et al. *1972 and Siopongco* et al. *1987)*

Mats should not be fixed by direct nailing, but are held in place by bamboo strips or timber battens tied or nailed over the top (figure 16). This is one of the easiest types of traditional floor to keep clean.

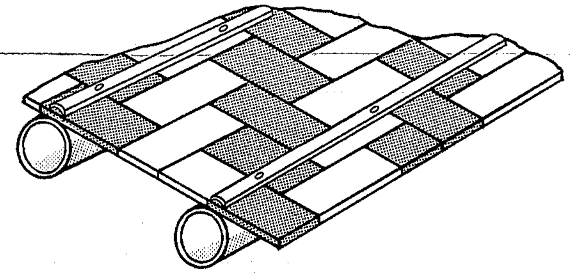


Figure 16: Woven bamboo mat floor decking (after Janssen, 1995)

Bamboo panels: layers of woven mats or strips, laid at right angles, are bonded together into boards (see *Bamboo based panels* in Chapter 7), which are then nailed to the joists.

Bamboo parquette: thin slivers or mats of bamboo are formed into multi-layered tiles and laid on treated bamboo or wooden strips fixed to compacted earth or a concrete sub-floor.

Walls The most extensive use of bamboo in construction is for walls and partitions. The major elements of a bamboo wall (posts and beams) generally constitute part of the structural framework. As such they are required to carry the self-weight of the building and also loadings imposed by the occupants, the weather and, occasionally, earthquakes. To this end, efficient and adequate jointing is of primary importance (see Chapter 8, *Jointing techniques*).

An infill between framing members is required to complete the wall. The purpose of the infill is to protect against rain, wind and animals, to offer privacy and to provide in-plane bracing to ensure the overall stability of the structure when subjected to horizontal forces. The infill should also be designed to allow for light and ventilation. Not least is its architectural and aesthetic function.

This infill can take many forms:

- Whole or halved vertical or horizontal bamboo culms, with or without bamboo mats
- Split or flattened bamboo, with mats and/or plaster
- Bajareque
- Wattle (wattle and daub, lath and plaster, quincha)
- Woven bamboo, with or without plaster
- Bamboo panels

Whole or halved bamboo culms The preferred orientation is vertical as this increases the shear resistance of the wall and is also better for drying after rain. Vertical members can be driven directly into the ground or fixed back to beams by tying with or without facing battens (figure 17). Halved culms can be fixed in the same way, either as a single or double ply construction, or anchored between horizontal halved culms (figure 18). Woven bamboo mats can be attached to one or both faces using tied or nailed bamboo battens.

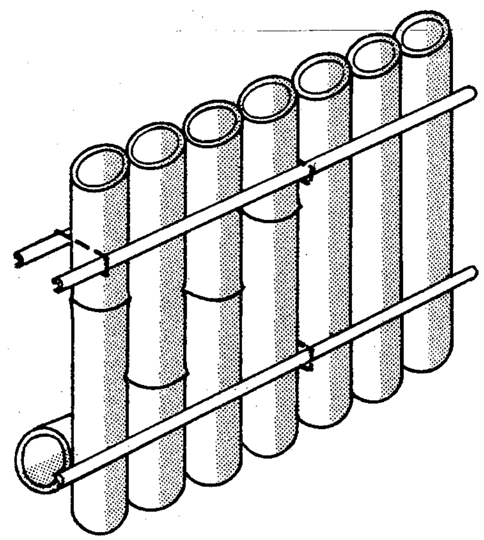


Figure 17: Wall of whole bamboo culms (after Janssen, 1995)

Split or flattened bamboo Split or flattened bamboo (see also *Floors*) can be fixed vertically to intermediate bamboo members tied to or mortised into the posts, or fixed horizontally directly to the posts. Boards can be stretched or covered by wire mesh to provide a suitable surface for plastering. Closely woven matting can also be applied to the board surface, with or without plaster.

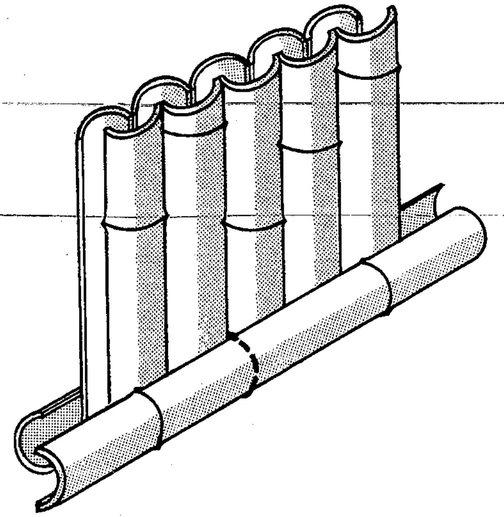


Figure 18: Wall of vertical halved culms (after Bandara, 1990)

Bajareque This is a type of construction commonly employed in Latin America. It consists of horizontal bamboo strips tied or nailed to both sides of the posts. The cavity is then filled with mud or mud and stones, producing a relatively massive form of construction (figure 19).

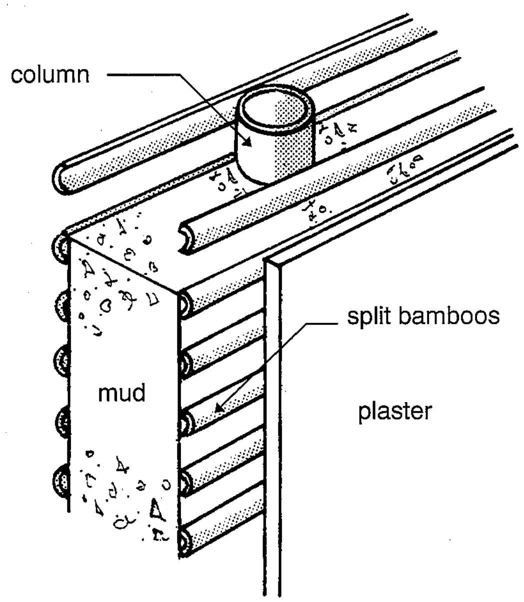


Figure 19: Bajareque wall construction (after Janssen, 1995)

Wattle (wattle and daub, lath and plaster, quincha) Common in parts of India, Peru and Chile, this comprises coarsely woven panels of bamboo strips (vertical weft and horizontal warp), plastered on both sides (figure 20).

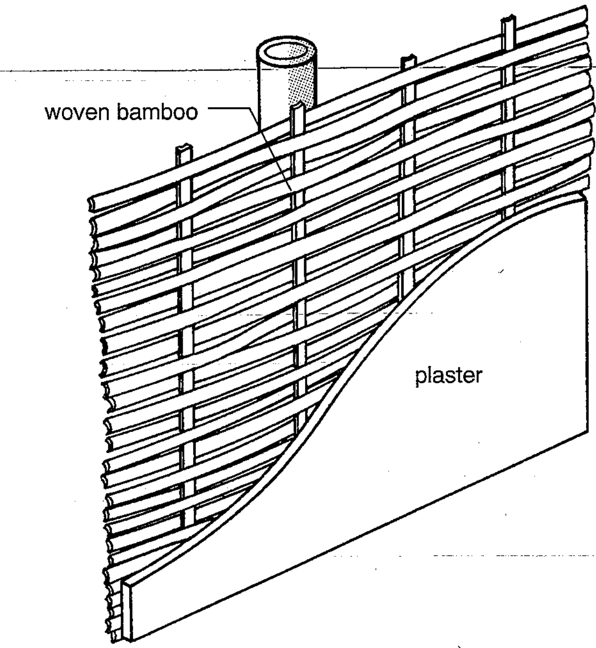


Figure 20: Quincha wall construction (after Siopongco et al. *1987)*

Woven bamboo Coarsely woven panels similar to those for wattle but with closer wefts can be used with or without plaster (figure 21).

The plaster can be made from any combination of mud, clay, and sand, stabilised with lime, cowdung, cement and organic fibres. The surface can be finished with a lime wash to give a typical stucco appearance (Jagadeesh and Ganapathy, 1995).

Preservatives may be added (Satish Kumar *et al.* 1994), but due attention should be paid to health, safety and environmental matters.

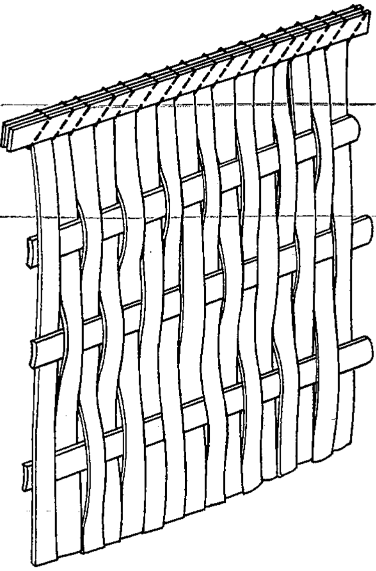


Figure 21: Woven bamboo wall construction (after Siopongco et al. *1987)*

Bamboo panels Panels have been developed specifically for use in walls and partitions and have the advantage of imparting greater structural rigidity to the construction (see *Bamboo based panels* in Chapter 7).

Bamboo has also been used as a reinforcement for stabilised or rammed mud walls (Mishra, 1988). However, difficulties exist in achieving an adequate bond between the mud and bamboo to ensure composite action.

Roofs The roof of a building is arguably its most important component - this is what defines a construction as a shelter. As such, it is required to offer protection against extremes of weather including rain, sun and wind, and to provide clear, usable space beneath its canopy. Above all, it must be strong enough to resist the considerable forces generated by wind and roof coverings. In this respect bamboo is ideal as a roofing material - it is strong, resilient and light-weight.

The bamboo structure of a roof can comprise "cut" components - purlins, rafters and laths or battens, or triangulated (trussed) assemblies. Bamboo, in a variety of forms, is also used as a roof covering and for ceilings.

Roof structure *Traditional roof construction*: The simplest form of roof comprises a bamboo ridge purlin and eaves beams, supported on the perimeter posts. Halved culms are then laid convex side down, edge to edge, spanning from the ridge to the eaves. A second layer, convex side up, is then laid to cover the joints (figure 22). The maximum overall span using this method is about 3 metres.

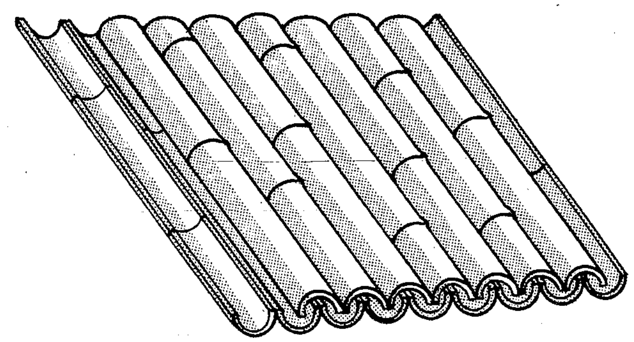


Figure 22: Roof of halved bamboo culms (after Siopongco et al. *1987)*

A variation on this is the use of whole culms, suitably spaced to accept battens for tiles or thatch (see *Roof covering*). To extend the span, a central post can be used. Beyond this, the options are almost infinite. A selection of cross sections is shown in figure 23. Efficient jointing of components is a key consideration (see Chapter 8, *Jointing techniques*).

Trusses: Trusses offer a number of advantages over traditional forms of construction, including more economic and efficient use of materials, the ability to span larger distances, the use of shorter components (counteracting effects of bow, crook and taper) and the use of prefabrication.

Much research and development has been carried out in this area. This work has highlighted the relative weakness of the joints and also of the bamboo in compression perpendicular to its length. In addition, much of the deflection of a loaded truss has been found to be due to deformation at the joints (Janssen, 1995, Punhani *et al.* 1989, Tular *et al.* 1984) (see Chapter 8, *Jointing techniques*).

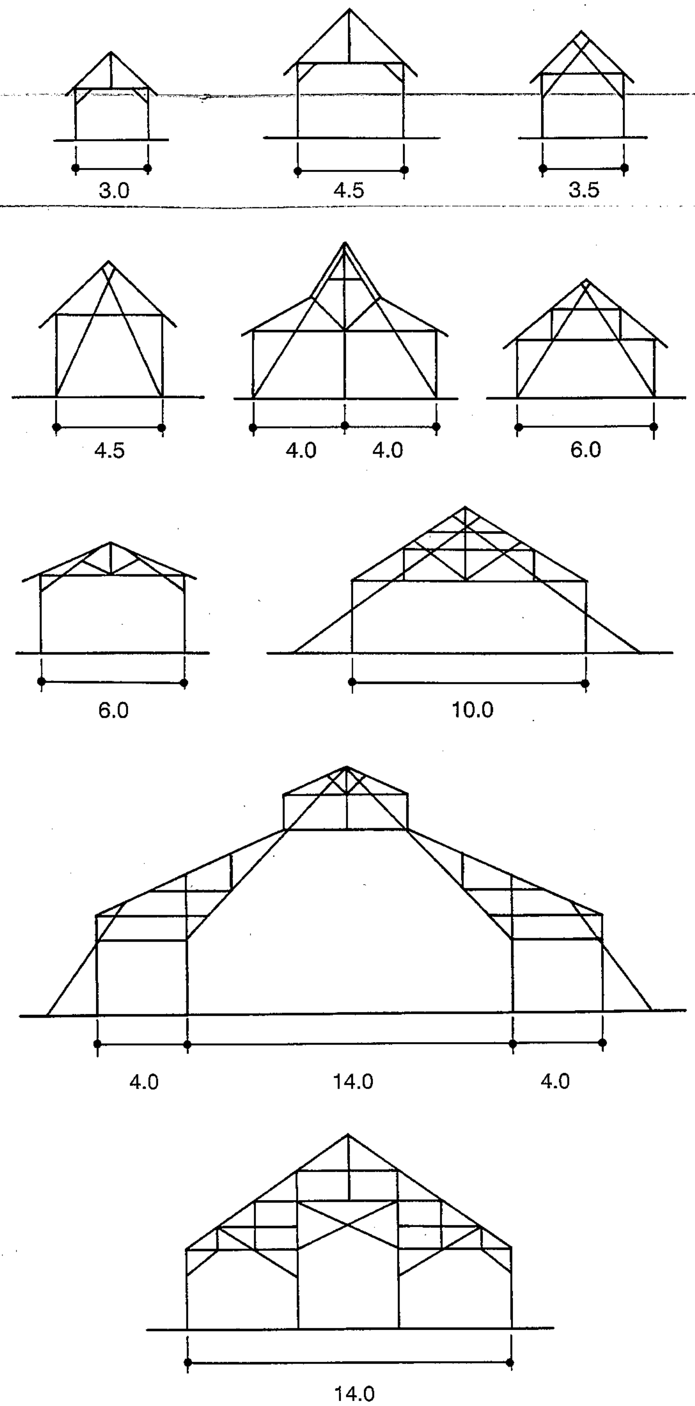


Figure 23: Possible roof framing configurations using traditional forms of construction - dimensions in metres (after Tular et al. *1984 and Janssen, 1995)*

As with cut roofs, truss configurations are many and various. The King-post and Fink are the simplest, readily spanning 4m using traditional jointing (figures 24 and 25). Culm diameters typically range from 40-100mm. Janssen (1995) has achieved an 8m span using improved jointing (figure 26).

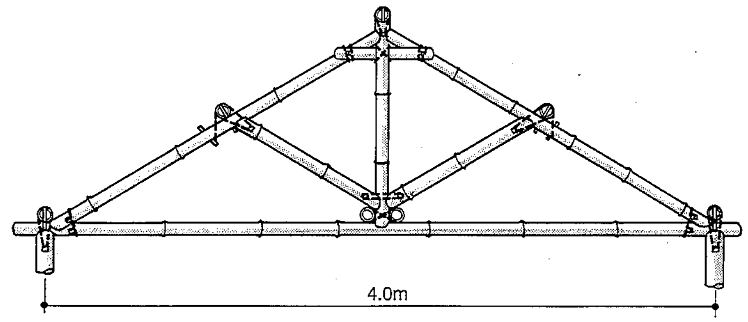


Figure 24: King-post truss (after Siopongco et al. *1987)*

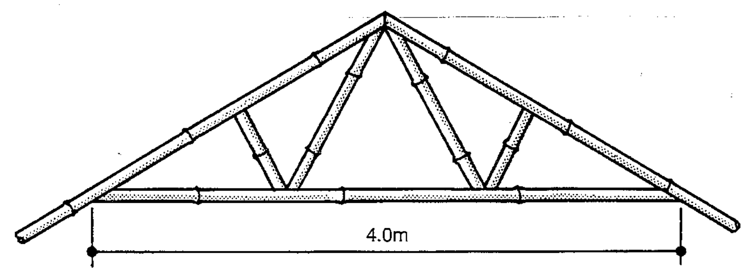


Figure 25: Fink truss (after Punhani et al. 1989)

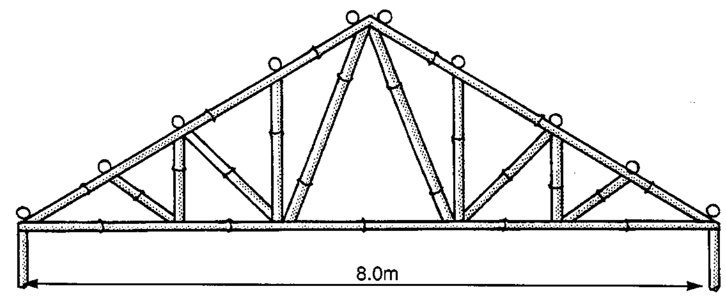


Figure 26: Janssen (1995) truss configuration (joints omitted for clarity)

The pitch of the truss should be at least 30° in areas of high rainfall (Narayanamurty *et al.* 1972). Truss spacings are consistent with the use of bamboo purlins (2-3m).

Needless to say, for both cut and trussed types of roof, the applied loads must be considered and, for trusses in particular, the design justified by test. In-plane stability is another primary consideration; this is usually provided by diagonal bracing members.

Roof covering

Bamboo roof coverings can form an integral part of the structure, as in the case of overlapping halved culms. More often, they are non-structural in function. Examples include:

- Bamboo tiles
- Bamboo shingles
- Bamboo mats
- Corrugated bamboo roofing sheets
- Plastered bamboo

Bamboo tiles: these can take the form of halved, internodal culm sections, fixed to battens and overlapped in a similar manner to the full length halved culms (figure 27). Roofs covered in this manner are susceptible to leakage (Mathur *et al.* 1964).

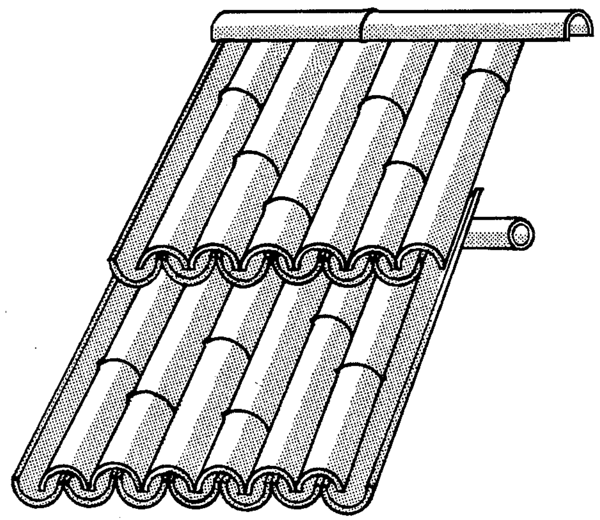


Figure 27: Bamboo tiles (after Mathur et al. *1964)*

Bamboo shingles: shingles, measuring 30-40mm wide x internodal length (400-600mm) are cut from green culms, 70mm or more in diameter and then air dried. The shingles are hooked onto bamboo battens (maximum spacing 150mm - Narayanamurty *et al.* 1972) by means of a tongue cut into the underside (figure 28). Three laps are required to make a roof watertight, requiring some 200 shingles per square metre. Nailing may need to be considered if high winds are likely.

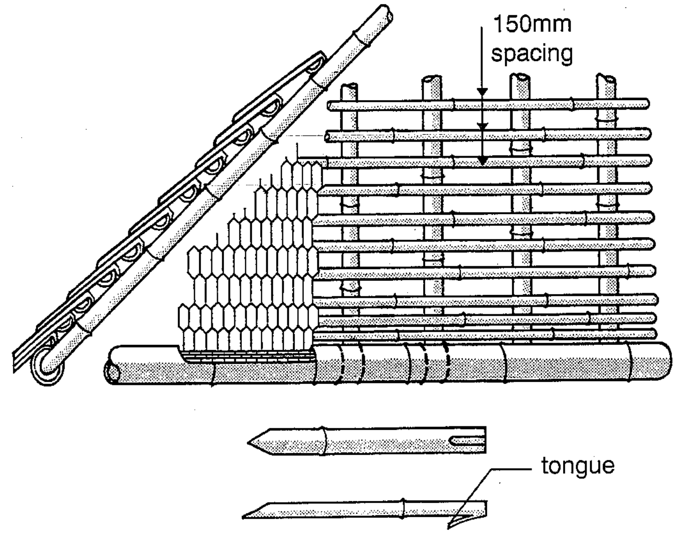


Figure 28: Bamboo shingles
(after Narayanamurty et al. *1972)*

Bamboo mats: a layer of bitumen is sandwiched between two mats forming a semi-rigid panel. The mats can be fixed to rafters at 200-250mm centres (figure 29). A bituminous or rubberised weatherproof coating is then applied to the finished roof (Damodaran *et al.* 1991).

Corrugated bamboo roofing sheets: PF resin is applied to a bamboo mats to form a five layer set which is then hot pressed between corrugated platens. UF resin bonded sheets overlaid with PF resin impregnated paper have also been produced. These products are strong and lightweight with good insulation properties.

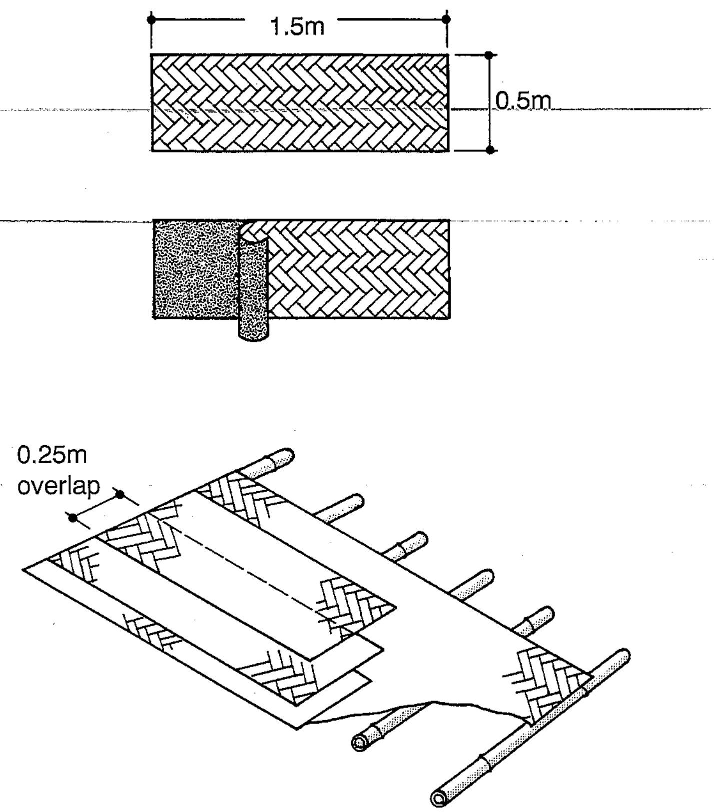


Figure 29: Bituminised bamboo mats
(after Damodaran et al. *1991)*

Plastered bamboo: a cement plaster, with or without the addition of organic fibres, is traditionally applied to bamboo roofs in South America.

Other typical roof coverings include:

- Reed thatch
- Corrugated iron sheeting
- Plain clay tiles
- Clay or concrete pan tiles

The weights of roof coverings vary considerably (20kg/m^2 for bamboo tiles and shingles, 42kg/m^2 for reed thatch, 13kg/m^2 for corrugated iron and 71kg/m^2 for clay tiles - Herbert *et al.* 1979) and this must be reflected in the strength of the roof structure.

Ceilings

The provision of a ceiling can help to reduce heat radiation into the occupied space and also induce a cooling airstream through the roofspace. However, these advantages are often offset by the need to disperse smoke from cooking fires, the reduction in headroom and reduced air circulation within the occupied space. Whether or not a ceiling is installed is therefore dependent upon local needs and customs.

Ceilings can be made from small, closely spaced culms, split or flattened bamboo, bamboo boards or bamboo mats in a manner similar to that for floors (see *Floors*). Woven mat ceilings are sometimes applied as sarking to the topside of the rafters or purlins, separated from the roof covering by battens.

Doors and windows

In traditional types of bamboo building, doors and windows are usually very simple in form and operation. Bamboo doors can be side hinged or sliding, comprising a bamboo frame with an infill of woven bamboo or small diameter culms (figures 30 and 31).

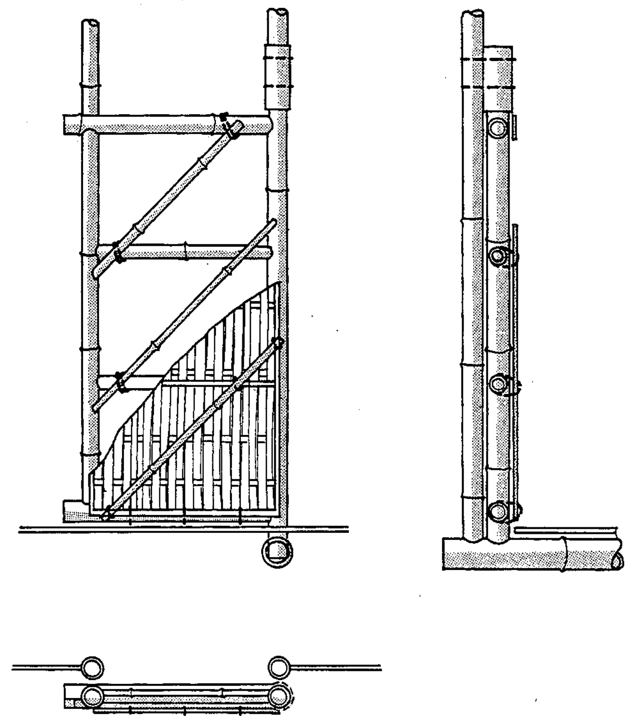


Figure 30: Arrangement of hinged door
(after Siopongco et al. *1987)*

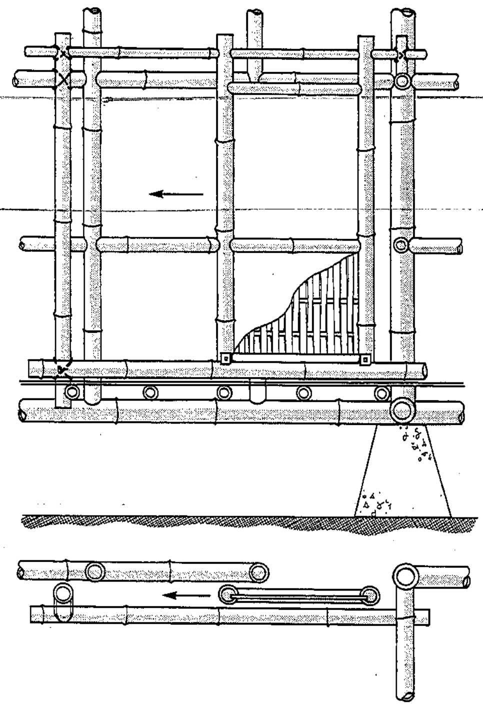


Figure 31: Arrangement of sliding door (after Siopongco et al. *1987)*

In higher grade buildings, wooden doors are common. Doors and shutters comprising bamboo mat board as panelling, or as flush skins for hollow core doors (figure 32) offer another solution (Ganapathy and Zoolagud, 1993).

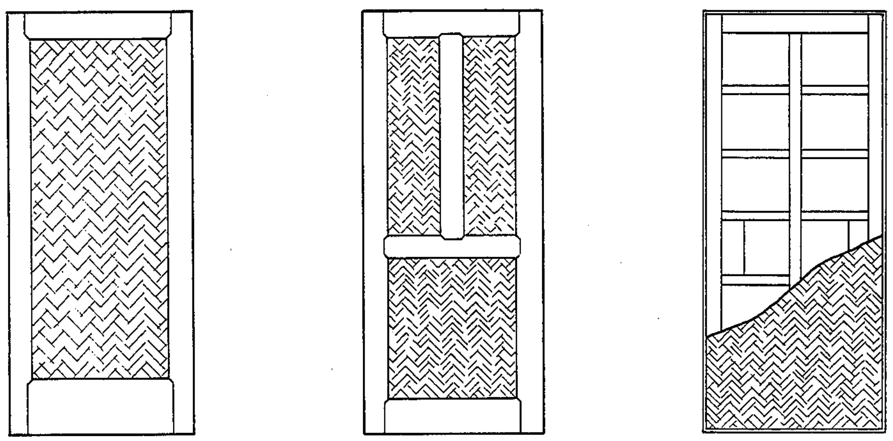


Figure 32: Bamboo mat board panelled and hollow core doors (after Ganapathy et al. *1993)*

Bamboo windows are generally left unglazed and can have bamboo bars, or a sash with woven bamboo infill. The sash can be side hinged or sliding (figure 33), or, more commonly, top hinged to keep out direct sunlight and rain. At night, windows are closed to protect against insects and animals. Hinges are formed from simple bindings, or connecting bamboo elements.

As with doors, in higher grade buildings windows are more commonly made of wood and are often glazed.

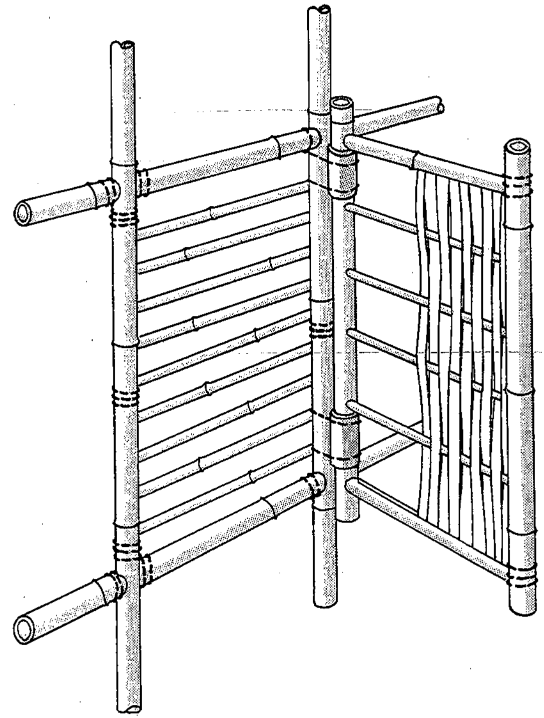


Figure 33: Hinged sash window (after Siopongco et al. *1987)*

Water pipes and gutters

Whole bamboo culms, with the diaphragms removed, can be used as water pipes either below or above ground.

Below ground: the system is usually gravity fed. To ensure watertight connections, the ends of the culms can be reamed and fitted into short sections of metal, pvc or bamboo pipe and suitably caulked (figure 34). To control insect attack, the trench can be treated with insecticide before the pipes are laid.

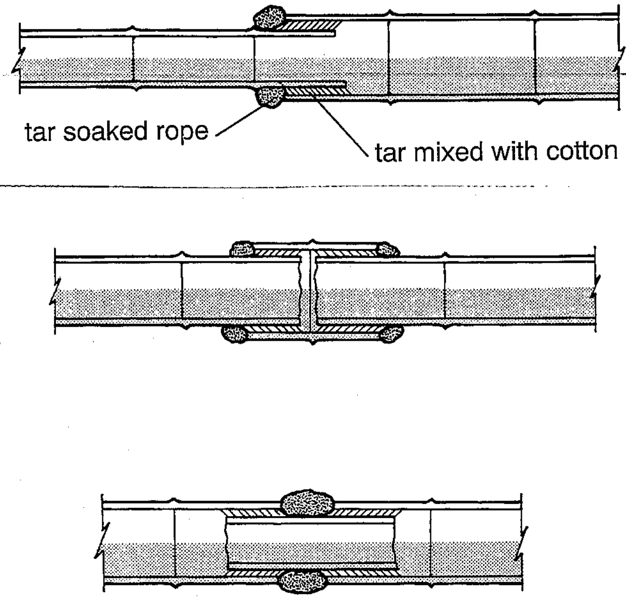


Figure 34: Jointing of bamboo pipes below ground (after Bandara, 1990)

The development of water piping in Tanzania (Lipangile, 1985) presents possibilities for the wider use of bamboo as piping for the supply of drinking water. In this particular process, the bamboo pipes are coated internally and externally with an approved bituminous paint. The exterior of the pipes can also be treated with a hot bituminous coating which gives sound protection against exterior attack. The pipes are then buried in trenches treated with insecticides which fix in the ground. It has been shown that the life of bamboo pipes can be simply extended by ensuring that the bore is full and that the water carried is clean. It is reported that the bamboo pipes treated in the above manner have given good service for ten years.

Above ground: again, the system is usually gravity fed with pipes supported on bamboo trestles. Joints can simply be formed by tapering or scarfing the ends of the culms to enable the sections to be fitted together end to end (figure 35). Watertight connections can be achieved as for pipes below ground.

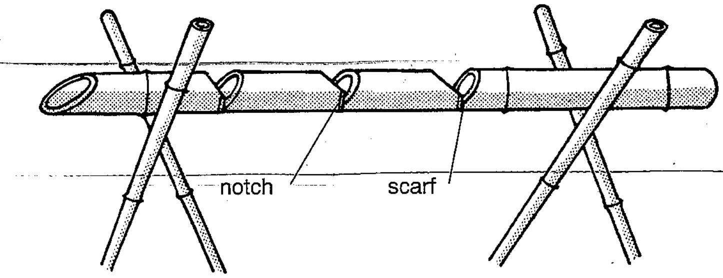


Figure 35: Bamboo piping above ground (after Janssen, 1982)

Halved culms, with the diaphragms removed, can be used as eaves gutters and drainage troughs (see *Detailing for durability*).

Detailing for durability

In addition to structural and functional considerations, the suitability and durability of any construction will depend to a large extent on good detailing. Protection against wetting and vermin infestation are two such factors with particular relevance to bamboo buildings.

Wetting

Inhibiting wetting is the first defence against decay. Wetting is caused by direct rain, flooding and, to a lesser extent, washing and cooking water.

To prevent wetting of the interior, water can be ducted away using bamboo pipes and troughs (see *Water pipes and gutters*). To protect the foundation posts against flooding, local effects caused by roof run-off can be minimised by ensuring good eaves and gable overhangs, and perhaps guttering to discharge the water some distance from the building. The provision of good overhangs will also help to protect the walls from direct rain. The effects of more generalised flooding can be countered by building above the ground on a graded site and using stone or concrete footings.

The life of foundation posts can be further shortened by splashing rainwater. Janssen (1995) proposes interchangeable post ends as a possible solution to this problem (figure 36).

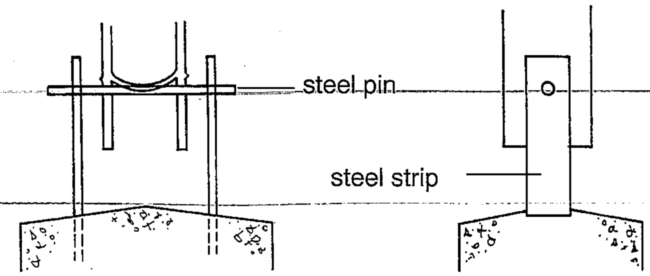


Figure 36: Arrangement for interchangeable post ends (after Janssen, 1995)

Vermin infestation

Bamboo constructions by their nature feature hollow members and overlapping joints, forming cavities which can provide ideal nesting areas for rodents. This problem can be largely overcome by careful detailing. In general, open beam, joist, rafter and purlin ends should be plugged. More specifically, relating to different constructional details, the following points should be observed:

Floors: wall cladding should not extend past the end of the joists - this creates a concealed area between the beams and floor deck (figure 37).

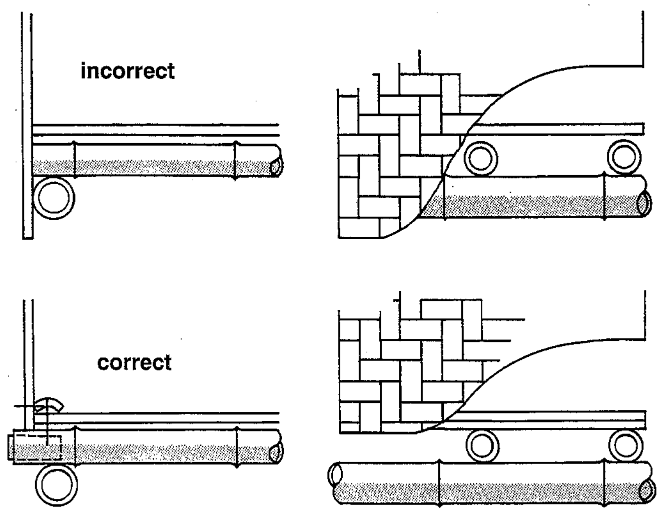


Figure 37: Preferred beam/joist end detail

Walls: walls should preferably not be of cavity construction. If two layers of bamboo are used (halved culms, boards or mats, or any combination of these), they should be fitted closely together.

Roofs: cavities will inevitably result where rafters cross ridge purlins and eaves beams. Here, the solution is to ensure good visibility and regular inspection.

Ceilings: access to the roof space via a closeable hatch should be provided for inspection purposes. Where the ceiling takes the form of sarking, it should extend past the wall (figure 38).

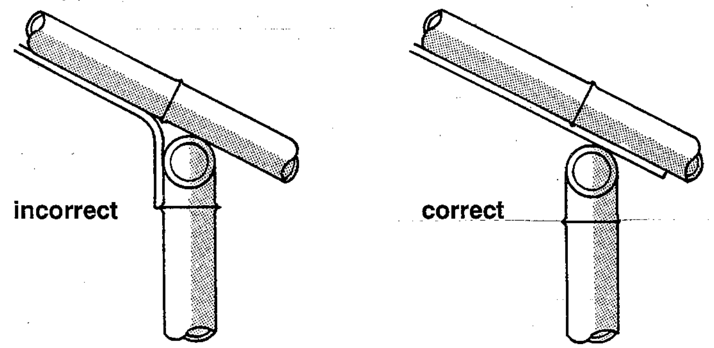


Figure 38: Preferred ceiling (sarking) detail

6. Other types of construction

While domestic housing and small buildings account for the majority of bamboo construction, applications extend to other areas often less constrained by scale and convention. Bridges and scaffolding fall into this category.

Bridges A bridge can be defined as an elevated structure supported at intervals for carrying traffic across obstacles (valleys and rivers, for example). In general terms, therefore, the range of types, spans and capacities is almost infinite. Bamboo bridges, however, are generally of trestle construction and of limited span for carrying only light (usually pedestrian) traffic. Simple trussed constructions have also been built and have been shown capable of supporting substantial loads.

Some examples of bamboo bridges are described below:

Footbridge (figure 39): this bridge consists of simple cross-braced frames with the walkway formed at the crutch. Culms of 50-75mm diameter are bound with bamboo lashings. The bridge is suited to rivers with muddy or sandy bottoms where the height above the bed does not exceed 5m (Royal Engineers Training Memorandum, 1945). A typical crossing might be 20m.

Handcart bridge (figure 40): this is a more elaborate construction with abutments and pilings. The abutments are formed from pairs of culms staked to the ground. The piles, culms of 80-120mm diameter, are cut to a point at the thinner end and driven in with a sledgehammer. A pair of horizontal culms form the pile cap and diagonal braces stabilise the assembly. The projecting pile ends act as handrails. To form the roadway, three longitudinal bamboo beams of 100mm diameter are lashed to the caps and tied together at the centre of each bay with a cross-member.

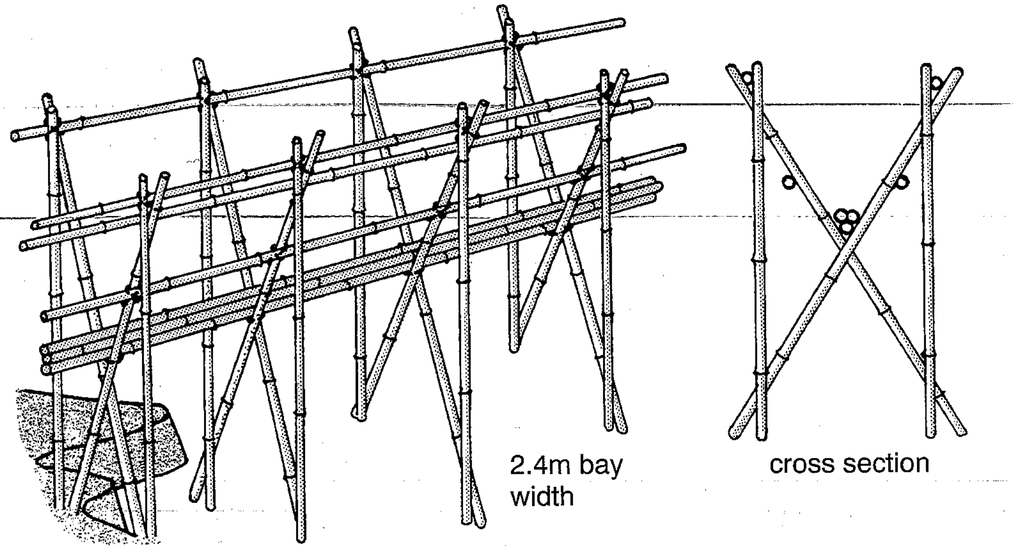


Figure 39: Footbridge (after Janssen, 1982)

Closely spaced culms laid transversely and covered with split bamboo form the deck. A kerb is laid along each edge of the deck and secured to the outer beams by torsion lashing (twisting the lashings with a cane or stick). This ties the deck assembly together.

A bridge of this type can support 200kg per metre length, for example people carrying loads on their backs or propelling small handcarts (Trojani, 1930).

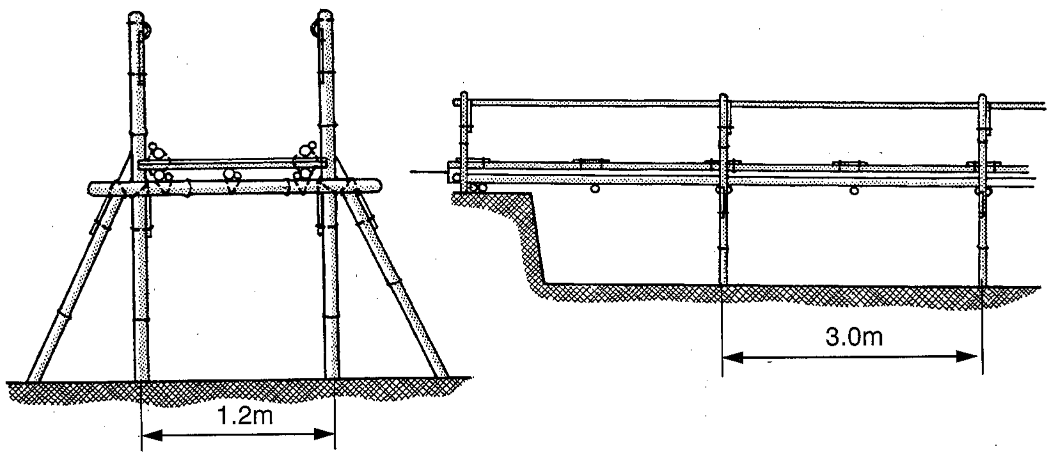


Figure 40: Handcart bridge (after Janssen/Trojani, 1982)

Light traffic bridge (figure 41): this is a heavier duty version of the handcart bridge. It features four piles per bay and double abutments. The bay size remains the same (about 3m) but the piles are at closer centres (nominally 750mm). Bracing is also increased with the addition of two diagonal tie members. The roadway comprises paired beams, rather than singles, decked in a similar manner to the handcart bridge. This bridge can support 500kg per metre length, for example herds of cattle or animal-drawn wagons with four people plus loads (Trojani, 1930).

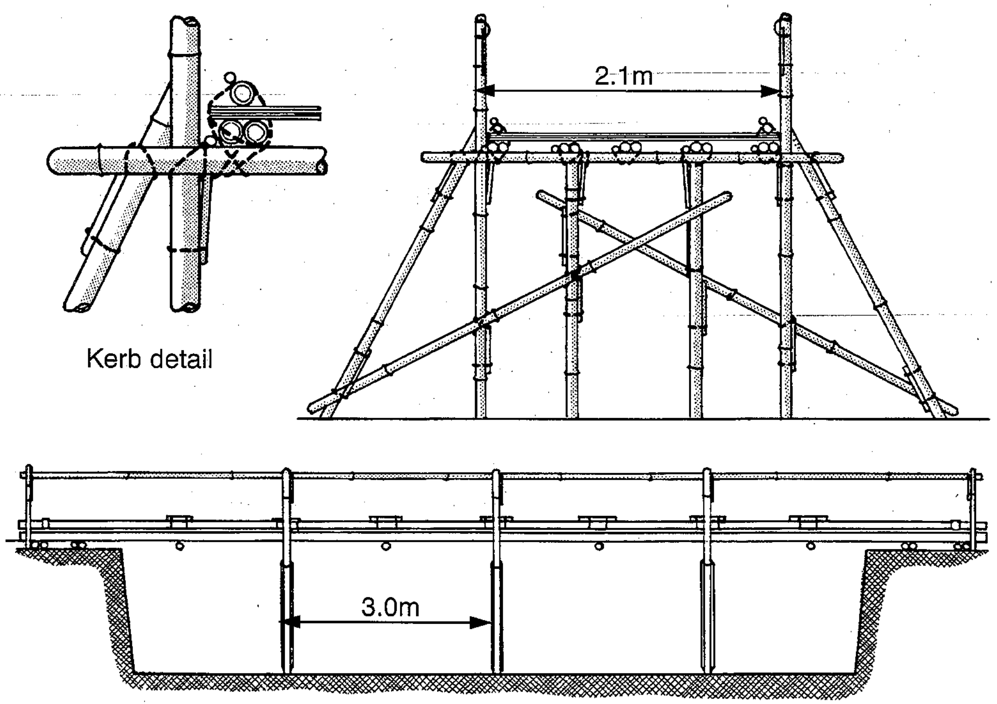


Figure 41: Light traffic bridge (after Janssen/Trojani, 1982)

Simple truss (flying buttressed) bridge (figure 42): this bridge is designed to cross deep, narrow rivers. It will clear-span about 4m and relies on triangulation to carry the loads back to the abutments. The scissors frame is made from culms of 100-120mm diameter, stabilised with diagonal members. The roadway and deck are made in a similar manner to that for the handcart bridge, and the bridge will carry similar loads (Janssen, 1985).

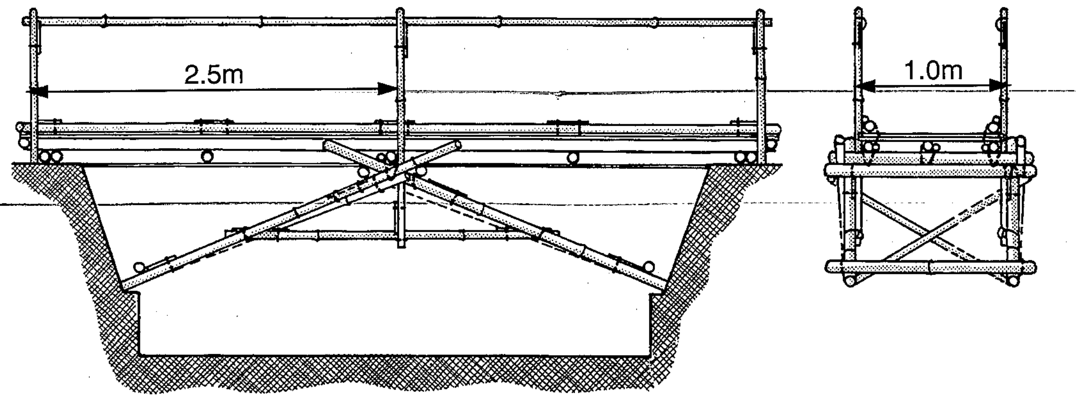


Figure 42: Simple truss (flying buttressed) bridge (after Janssen/Trojani, 1982)

Pylon bridge (figure 43): Prefabricated bamboo pylons, or towers, are set at intervals across the bed of a shallow river using an aerial ropeway. The pylons can then be decked *in situ* or by using prefabricated sections of walkway (Janssen, 1982).

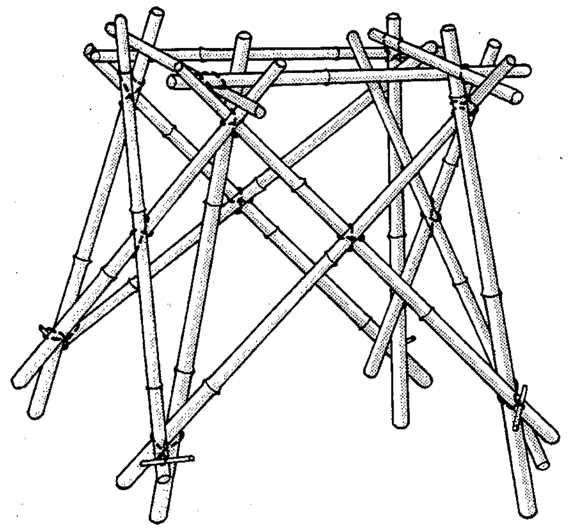
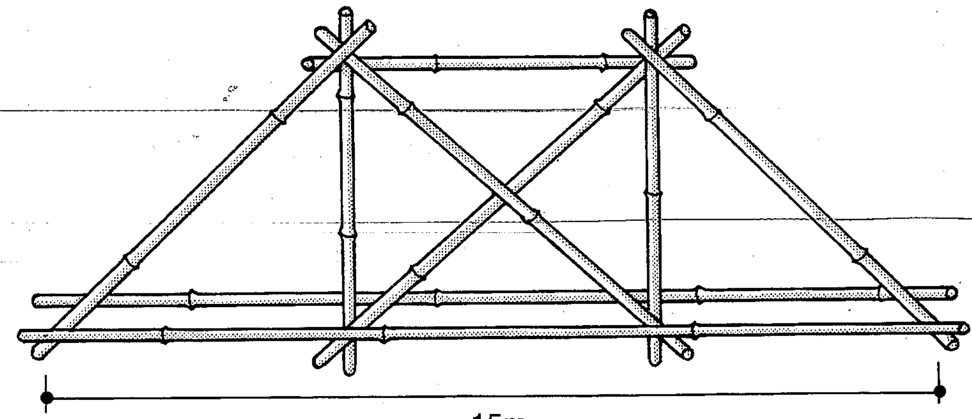


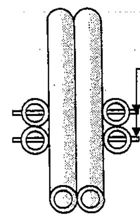
Figure 43: Pylon bridge (after Janssen/Sweet, 1982)

Queen post truss bridge (figure 44): using compound members (four culms per chord) and a combination of wire lashing and steel pins, a 15m span prototype bridge was constructed comprising two modified queen post trusses. The bridge supported a load of 1.6 tonnes with only slight damage to the deck and some of the pinned joints (Kumpe, 1937).



schematic - compound members omitted for clarity

connection details



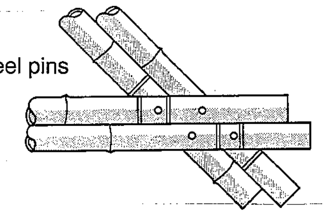


Figure 44: Queen post truss bridge (after Janssen/Kumpe, 1982)

Scaffolding Bamboo scaffolding is widely used throughout South and South East Asia and also South America as a temporary structure for supporting working platforms in building construction and maintenance. There appears to be no height limit - 40 storeys is not uncommon - but for taller constructions wooden posts are often used as the main supports (Fu, 1979).

Usually, two layers of scaffolding are used. The outer layer provides the main strength and stability and is fixed to the building at intervals. The inner layer provides the means of supporting walkways (timber boards or bamboo culms) and accessing the face of the building. The distance between components is dictated by practical considerations such as the effective reach of the scaffolder. The strength and stability of the scaffold is judged to be adequate if individual components and joints can support the weight of the scaffolder. Joints are typically made with bamboo strips.

The main advantages of bamboo scaffolding when compared with steel are its lightness and low cost. It is also readily tailored to suit the shape of a building. A typical arrangement is shown in figure 45.

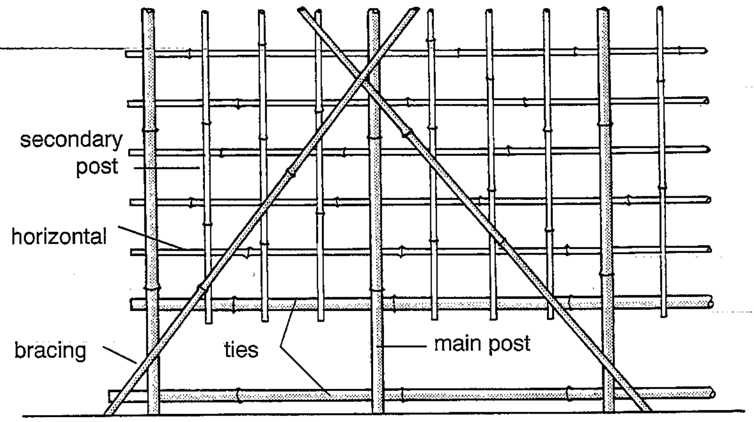


Figure 45: Typical scaffolding arrangement (after Fu, 1979)

7. Other applications relevant to construction

Bamboo reinforced concrete

The use of bamboo as concrete reinforcement is one of the more broadly covered topics relating to bamboo in construction and considerable research effort continues to be directed at this subject.

There are several good reasons why bamboo might be considered as reinforcement for concrete:

- It is of low cost compared with steel
- It is readily available
- Its strength to weight ratio compares favourably with steel

However, bamboo exhibits certain characteristics which limit its effectiveness as concrete reinforcement. The more important considerations are summarised below:

Bond

If seasoned (dry) bamboo is used as reinforcement, when the concrete is poured it will absorb water and swell. Later, as the concrete dries, the bamboo will shrink and the bond will be broken. If unseasoned (green) bamboo is used, it will lose water and shrink as the concrete dries and again the bond will be broken.

The bond can be improved in a number of ways:

- Mature culms (at least 3 years old) should be used.
- Bamboo strips rather than whole culms should be used as the inner surface develops a better bond than the outer surface. Also, culms with prominent and numerous nodes offer improved bonding (figure 46).
- Moisture related movement can be inhibited by the use of a brushed bitumen coating which acts as a moisture barrier. If the coating is too thick, it can create a shear zone which will in itself reduce the bond.

- Sand, nails and thin rope can be used in conjunction with the bitumen coating to improve the bond.
- Thin strips of bamboo with the inner layer removed, plaited into a cable, exhibit improved characteristics (figure 47).

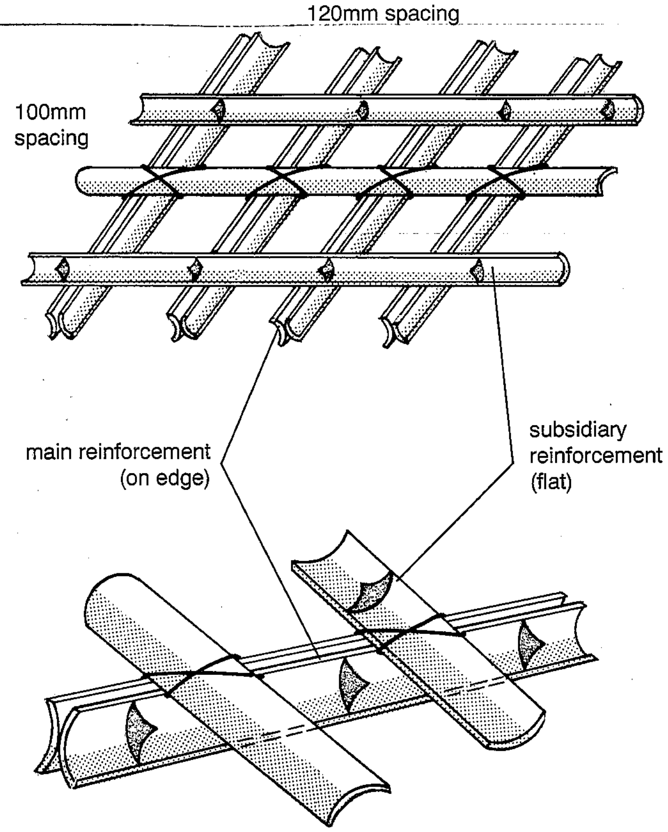


Figure 46: Bamboo strip reinforcement (FRI, India)

Low modulus of elasticity The relatively low modulus of elasticity can cause problems in respect of the following:

Cracking and deflection: a bamboo reinforced element will crack and deflect perhaps 50% more than a steel reinforced element of equivalent section.

Quantity of reinforcement: ten times more bamboo is required than in an equivalent steel reinforced section, i.e. 5% of the cross sectional area compared with 0.5% for steel.

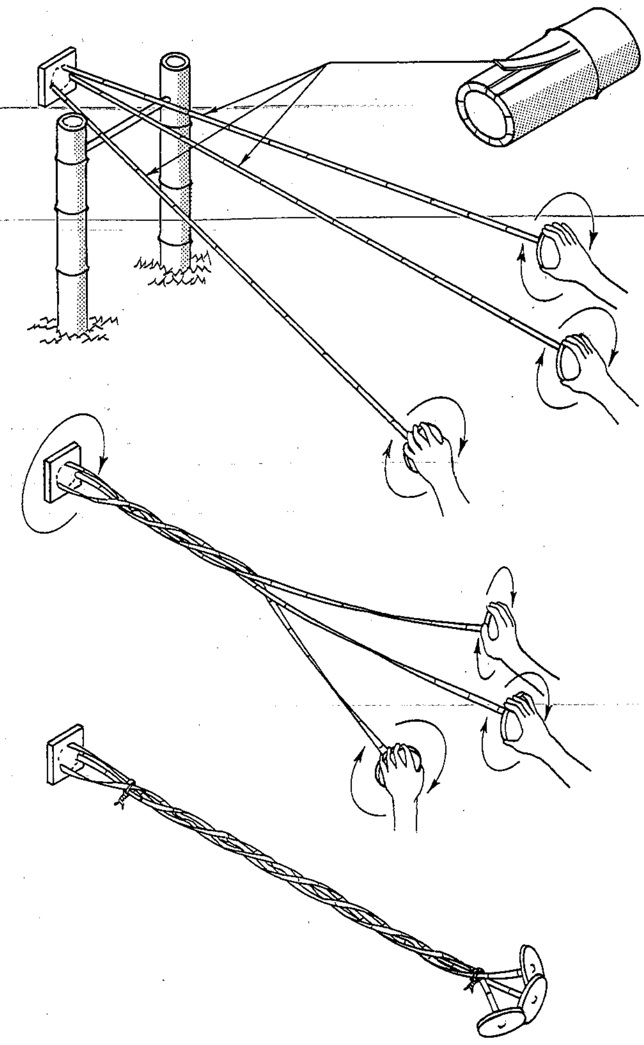


Figure 47: Bamboo cable reinforcement (after Hidalgo, 1992)

Durability Concrete is very alkaline and will attack the bamboo reinforcement. Little is known about its likely long term performance. In addition, cracking can allow water ingress which will cause further deterioration.

In general, while bamboo can be used to reinforce beams and suspended slabs, it is perhaps more suited to use in floor slabs, roads and lightly loaded elements such as partition walls where cracking, or even failure, would not be so critical.

Bamboo based panels

The earliest bamboo panel was made in China during the First World War. To date, some 28 different panel types have been developed, mostly in Asia, but investigations into construction applications have only recently been carried out (Ganapathy *et al.* 1995). Bamboo based panels have proved suitable for structural as well as non-structural applications, in both low and high grade building work. Specific end uses include floors, walls, partitions, doors, ceilings and roofs, and by virtue of their inherent rigidity and enhanced durability (through preservative treatment), such panels can offer significant advantages over the use of bamboo in its natural state. The various types of panel product can be broadly classified as follows:

- Processed strips, laths or slivers
- Processed, peeled veneers
- Strands, particles or fibres reconstituted into panels
- Combinations of one or more of the above
- Combinations of one or more of the above with wood, other lignocellulosic materials and inorganic substances

The two most common panel types, for which product standards have been formulated in countries where they are commercially produced, are:

- Bamboo mat board (bamboo mat plywood)
- Bamboo strip board (bamboo strip plywood)

Bamboo mat board (bamboo mat plywood): as the name suggests, these boards are formed from bonded layers of mats (see figure 15), woven from mechanically or manually cut slivers of uniform size (8-16mm wide x 0.8-1.2mm thick). After drying to a moisture content of 8-16%, adhesive is applied to the mats by spreader or by dipping. Several layers are then either cold pressed (urea-formaldehydes) or hot pressed (phenol-formaldehydes) to produce the board. The boards are finished by sanding and then trimmed to size.

To increase durability, preservative chemicals are generally incorporated in the adhesive, but better results can be achieved by treating the mats themselves (Padmanabhan *et al.* 1994). To improve the

appearance of the board, slivers can be sanded, bleached and dyed prior to weaving.

The number of layers and board thickness will vary according to end use. 2 to 7 layers are common, varying in thickness from 1 to 10mm, with the thinner boards used for panelling and the thicker boards for concrete formwork. Products of this type have also been used for roof cladding, barrel vaulting, grain silos and as webs in I- or box-beams spanning up to 9m (Damodaran *et al.* 1991).

Using a similar process, researchers in China have developed a bamboo curtain plywood laminated with resin impregnated paper, or BCPLRIP, panel with properties equivalent to those for plywood and also suitable for use as concrete formwork (Zhao *et al.* 1992).

Bamboo strip board (bamboo strip plywood): in its simplest form, common to South America where bamboos do not split so easily, this is made by gluing together cross-banded flattened bamboo or bamboo strips (Janssen, 1995).

The process, however, lends itself well to improved methods of processing and production. With the outer surface and nodal projections removed, culms are split then softened by soaking and heating at 130-145°C. The pieces are flattened, the inner surface is scraped and they are then dried by heat and pressure to 8% moisture content. The subsequent manufacturing process is much the same as for conventional plywoods (Guisheng, 1987). The strips are planed and edged, spread with PF adhesive, assembled into cross-banded panels and then hot pressed. The resulting boards are finished by sanding and trimming. Typical applications include floor decking and walling. The product has good strength and stiffness properties and a high degree of resistance to abrasion and weathering. (Ganapathy *et al.* 1995)

It is now possible to obtain automated processing and production machinery for the manufacture of high quality laminated bamboo flooring following the principles outlined above. The material compares favourably with other panel products in terms of mechanical performance and is also highly decorative (Chin Yung Machine Works, 1995).

Bamboo mat board, coated with a PF film or overlaid with suitable materials, offers a stable and durable alternative to plywood for concrete shuttering and formwork.

8. Jointing techniques

Effective jointing is fundamental to the structural integrity of a framed construction. Furthermore, the suitability of a material for use in framing is largely dependent upon the ease with which joints can be formed.

Because of its round, tubular form, jointing of two or more bamboo members requires a different approach to that adopted for, say, solid timber. Despite its relatively high strength, bamboo is susceptible to crushing, particularly of open ends. It is also characterised by a tendency to split; the use of nails, pegs, notches or mortises can therefore result in considerable reductions in strength. Connections must also cope with variations in diameter, wall thickness and straightness.

Clearly, these limitations have not presented an obstacle to the use of bamboo in traditional forms of construction. However, the building of structurally efficient, more durable and possibly larger and more economical bamboo structures will depend to a large extent on improvements and developments in jointing technology.

Traditional joints

Traditional jointing methods rely principally on lashing or tying, with or without pegs or dowels. The basic joint types are:

- Spliced joints
- Orthogonal joints
- Angled joints
- Through joints

Spliced joints

Two (or more) culms are joined in line to form longer members. Splicing is usually carried out in one of four ways:

Full-lapping: Full section culms are overlapped by at least one internode and tied together in two or three places. For greater strength, bamboo or hardwood dowels can also be used. One disadvantage of this joint is that it quite bulky (figure 48).

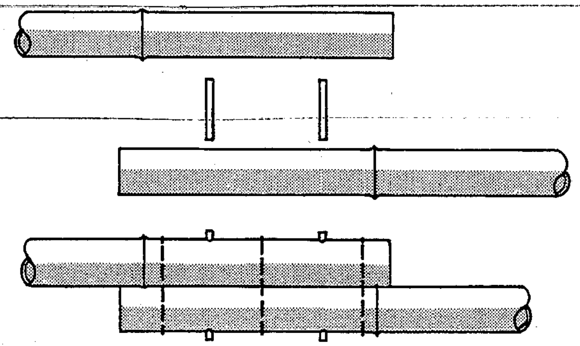


Figure 48: Full lapped splice joint

Half-lapping: Culms to be joined should be of similar diameter and cut longitudinally to half depth over at least one internode length. The components are fixed as for the full lap joint (figure 49).

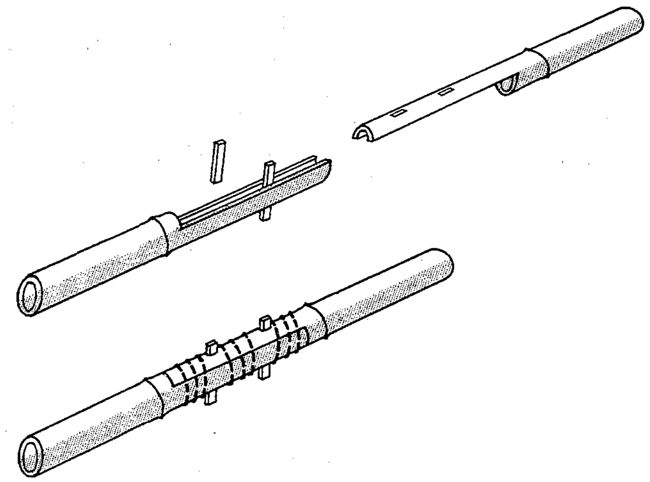


Figure 49: Half-lapped splice joint (after Siopongco et al. *1987)*

Butt joint with side plates: Culms of similar diameter are laid end to end. Side plates, made from quarter-round culms of slightly larger diameter and two or more internodes long, are fixed over the joint by tying and, usually, dowelling (figure 50).

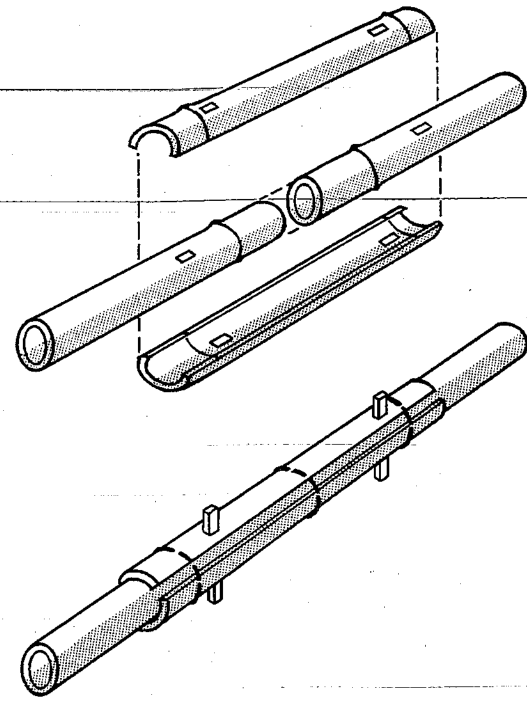


Figure 50: Butt joint with side plates

Sleeves and inserts: short lengths of bamboo of appropriate diameter are used either externally or internally to join two culms together (figure 51).

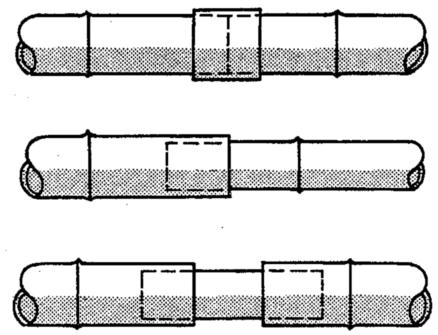


Figure 51: Sleeves and inserts (after Stulz/Hidalgo, 1981)

Variations on the basic splice joints described above are shown in figure 52.

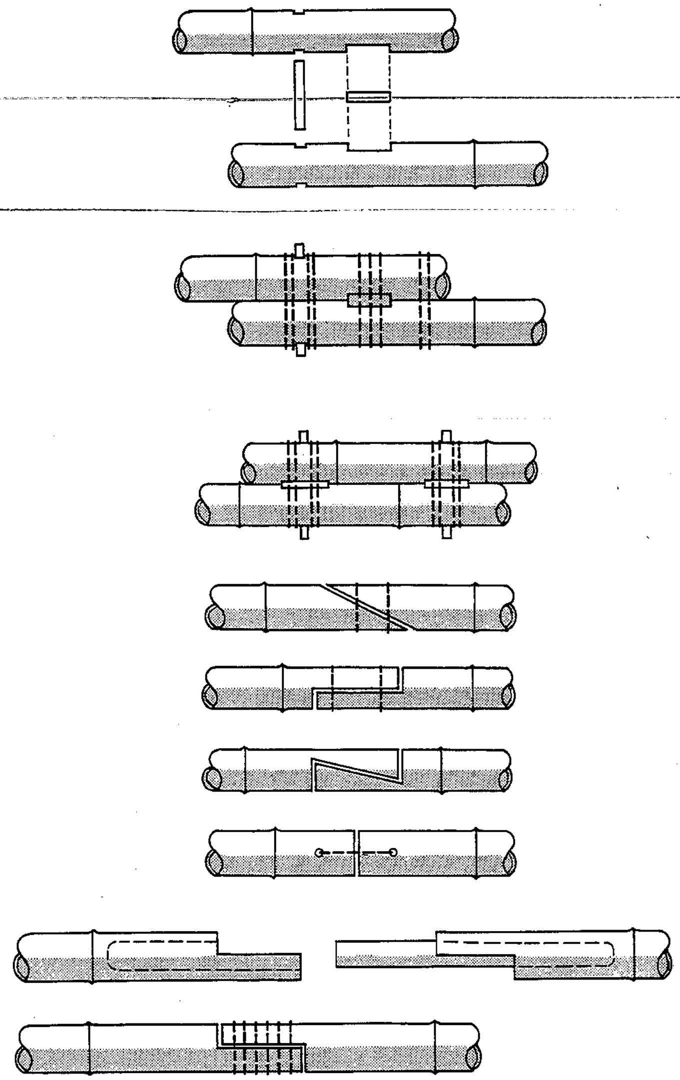


Figure 52: Variations on splice joints
(after Nienhuys, 1976, Stulz/Hidalgo, 1981 and Narayanamurty et al. *1972)*

Orthogonal joints These are the commonest types of joint, where two or more members meet or cross at right angles. The basic configurations are:

- Butt joint
- Crossover joint

Butt joint: The simplest form of butt joint comprises a horizontal member supported directly on top of a

vertical member. Typical examples would be roof eaves beams on posts or floor beams on intermediate posts. The top of the post can be cut to form a saddle to ensure secure seating of the beam and good load transfer (figure 53). The saddle should be close to a node to reduce the risk of splitting. A variation on the saddle involves the cutting of a long, integral tongue which is bent right over the transverse member and tied back (figure 54). Other details include square notched ends, side plates and tenons (figure 55).

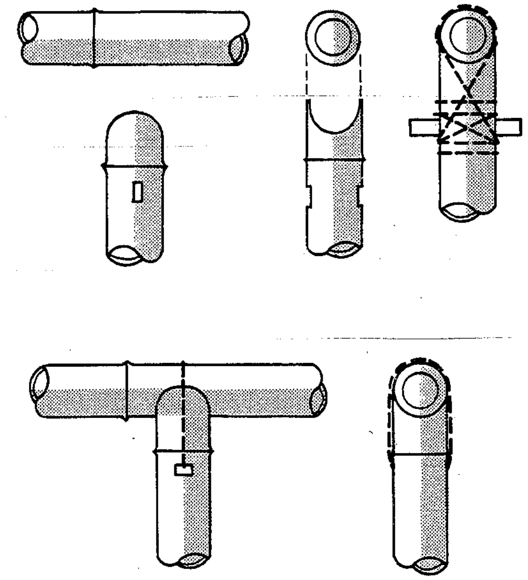


Figure 53: Saddle (butt) joint
(after Nienhuys, 1976 and Narayanamurty et al. *1972)*

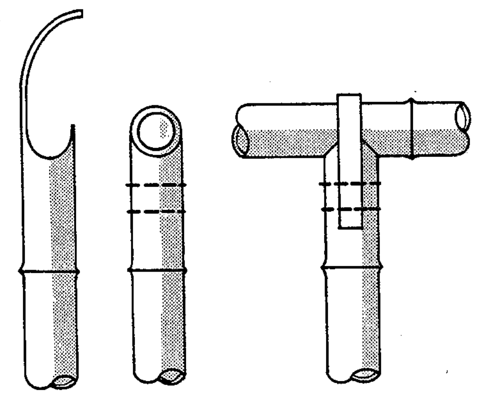


Figure 54: Saddle joint with tongue
(after Stulz/Hidalgo, 1981)

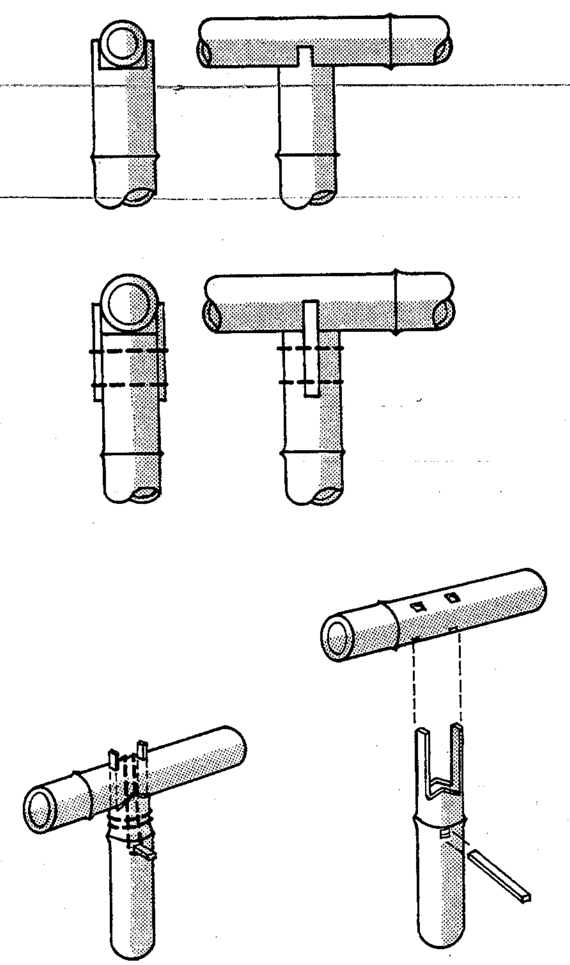


Figure 55: Variations on the saddle joint (after Siopongco et al. *1987 and Stulz/Hidalgo, 1981)*

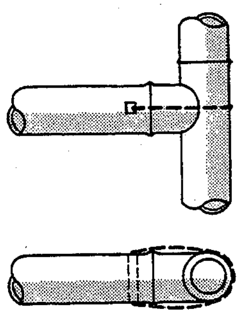


Figure 56: Saddle detail applied to horizontal framing (after McClure, 1953)

The saddle detail can also be applied to horizontal framing (figure 56). Variations include the double joint (figure 57) and the double bent joint (figure 58).

For the single butt joint, improved stiffness can be achieved by the use of a hardwood tenon and key (figure 59). The ends of the horizontal members can be cut to form horns or integral tenons to be located in corresponding mortises in the post (figure 60). However, for both these methods, splitting is a risk. Bamboo inserts also offer a solution, but this requires the cutting of an even larger hole in the vertical member (figure 61).

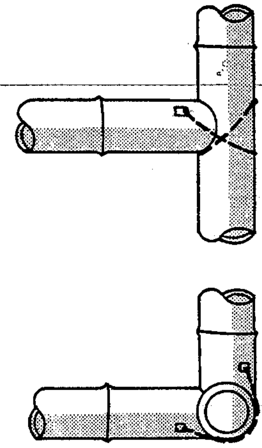


Figure 57: Double butt joint (after McClure, 1953)

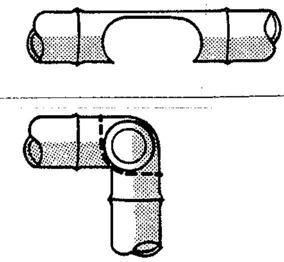


Figure 58: Double bent joint (after Stulz/Hidalgo, 1981)

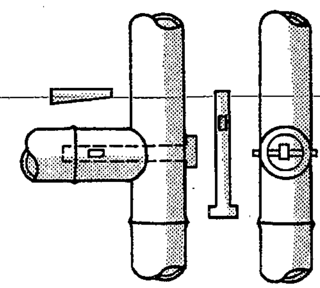


Figure 59: Tenon and key joint (after Stulz/Hidalgo, 1981)

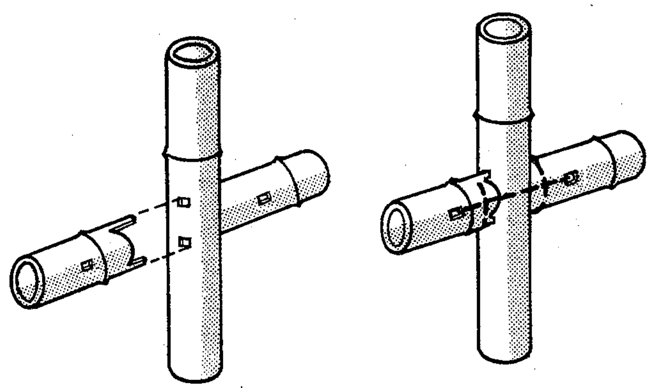


Figure 60: Integral tenon (horned) joint (after Siopongco et al. *1987)*

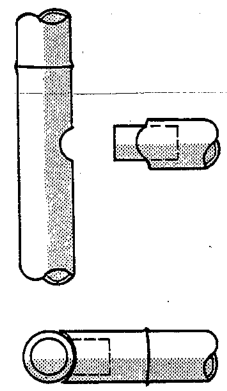


Figure 61: Insert joint (after Stulz/Hidalgo, 1981)

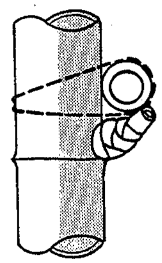
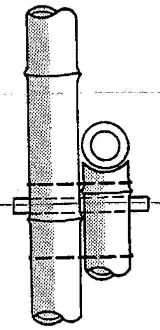


Figure 62: Beam supported on stump of branch

Crossover joint: these are formed when two or more members cross at right angles. In the horizontal plane, the function of the joint is mainly to locate the members and to provide a degree of lateral stability. Examples would include joist to beam connections which can be effected simply by tying. Where the crossover is in the vertical plane, the joint could be loadbearing, as in the connection of floor beams to posts. Simple tying is an option, although improved stability can be achieved by supporting the beam either on the stump of a branch at a node (figure 62) or on a short length of culm tied independently to the post. The tendency to slip can be



reduced by insetting the supporting piece into the post, or by dowelling (figure 63).

Most crossover joints are also suitable for connecting inclined members, for example purlin to rafter connections. Variations on these types of joint are shown in figure 64.

Figure 63: Beam supported on independent bracket (after Janssen, 1995)

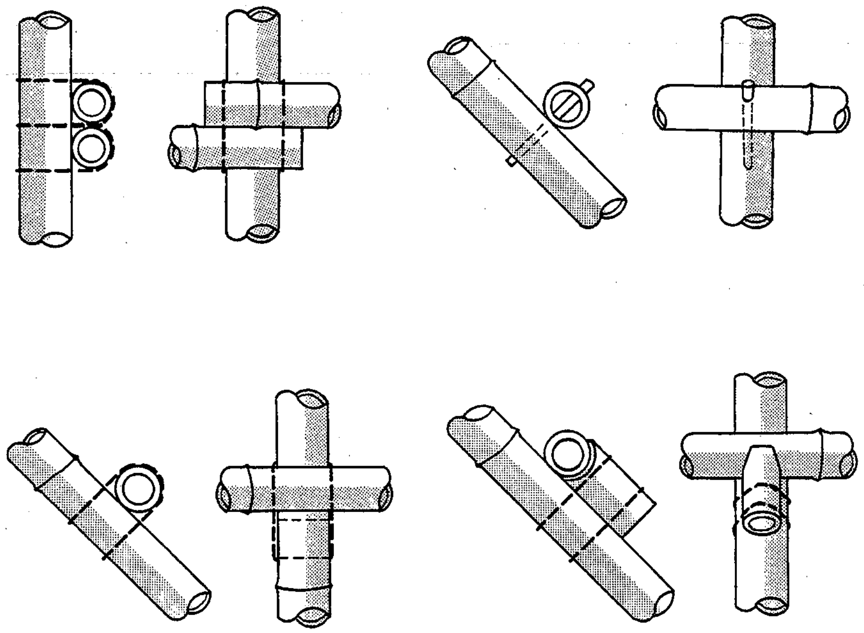


Figure 64: Variations on crossover joints (after Stulz/Hidalgo, 1981)

Fixing methods: Most types of joint rely mainly on tying or lashing, with or without the use of pegs or dowels. Ties can be made from split bamboo, coir rope, palm fibre rope, iron wire (preferably galvanised) or tape. In the case of butt joints, the ties can be passed through a predrilled hole (figure 56) or around hardwood or bamboo pegs or dowels inserted into preformed holes. Pegs are driven from one side, usually at an angle to increase strength (figure 65); dowels pass right through the member, usually at right angles (figure 66). Crossover joints can similarly be dowelled and tied.

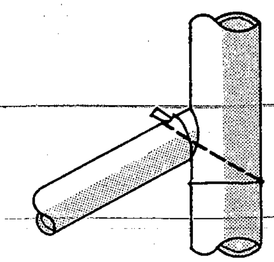


Figure 65: Example of pegged and tied joint

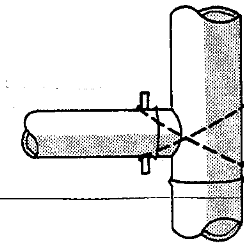


Figure 66: Example of dowelled and tied joint

Angled joints

Angled joints are formed where two or more members meet or cross other than at right angles. For butt joints, the ends of the member can be shaped to fit in much the same way as an orthogonal saddle joint. Horns (integral tenons) might also be used but fabrication is time consuming. Examples would include web members in trusses (figure 67). Angled crossovers can be dealt with in much the same way as orthogonal crossovers, for example the diagonal bracing in the plane of a roof.

Through joints

Members of differing diameters can be joined by passing the smaller through a hole drilled in the larger. The joint is secured by a dowel passing through both members (figure 68). Applications for this type of joint might include partitions, doors and window framing.

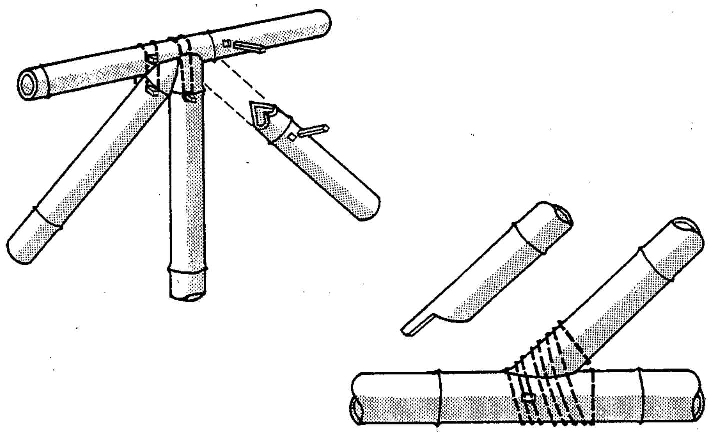


Figure 67: Angled joints with integral tenons (after Siopongco et al. *1987 and Nienhuys, 1976)*

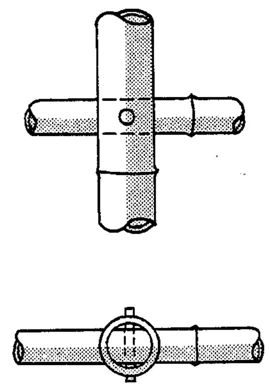


Figure 68: Through joint (after Stulz/Hidalgo, 1981)

Improved traditional joints

The mechanical performance of traditional bamboo joints can be improved by the adoption of the following procedures:

Form joints at or near nodes: nodes are more resistant to splitting than internodes. It is therefore good practice to make joints as close to nodes as possible. For example, in the simple saddle joint, the saddle should be formed directly above a node.

Minimise on holes: it is generally accepted that holes, cuts and notches will reduce the ultimate strength of a bamboo culm. If a hole is made in a culm (for a peg, dowel, mortise, inset support or insert) this should be as close as possible to the node, paying particular attention to the direction of the applied force. Furthermore, whenever possible holes should be round or radiused rather than square cut as these are less likely to propagate splits.

Use seasoned culms: seasoned rather than green bamboo should be used for two reasons. Firstly, bamboo shrinks on drying and this will generally cause joints to loosen. Secondly, drying splits can form which could further weaken the assembly (Narayanamurty *et al.* 1972).

Reinforce against splitting and crushing: tight binding, especially with wire, can in itself offer good resistance to splitting. In trusses, the use of quarter-round bamboo bearing plates reduces the risk of crushing of the chords by the compression webs (Janssen, 1995).

Improve durability: preservative treatment of the bamboo and protection from wetting by good detailing will increase the life of the joint. The use of wire is in many cases preferable to bamboo lashings or rope as it is not subject to insect attack.

Recent developments

By building on traditional methods and exploiting the strengths and advantages of bamboo, a number of jointing techniques have been developed which offer more structurally efficient solutions to jointing problems. However, their adoption and suitability will depend to a large extent on the cost and availability of materials, equipment and skilled labour.

Gusset plates: plywood or solid timber side plates, applied to joint assemblies in trusses for example, and fixed with either bolts or bamboo pegs, show improved stiffness and strength when compared with traditional jointing methods (Janssen, 1995, Punhani *et al.* 1989) (figure 69).

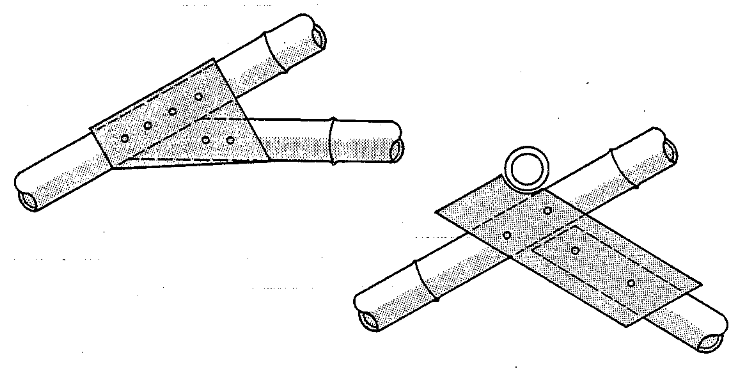


Figure 69: Gusset plated joints (after Mishra et al. *1991 and Janssen, 1995)*

ITCR joint: this is a simple joint developed by the Instituto Tecnologico in Costa Rica and a variation on the gusset principle. It comprises a plywood insert glued into slots sawn into the ends of the bamboo elements to be joined (figure 70). During curing, the assembly can be readily clamped together using Jubilee clips. A disadvantage of this jointing method is that the ends of the culms remain open. It is also difficult to achieve good and consistent quality glued joints in the field.

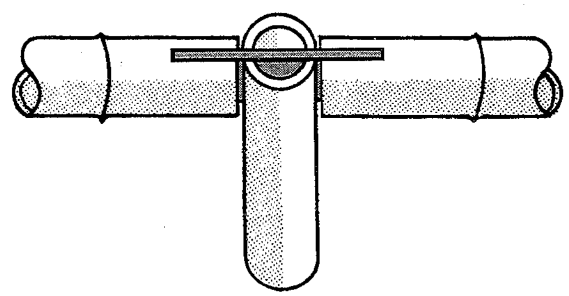


Figure 70: ITCR joint

Arce joint: this technique, developed by Dr Arce of ITCR, relies on the use of wooden inserts to reinforce the end of the bamboo and to form the joint. Rectangular blocks, possibly cut from plantation thinnings, are turned down at one end to fit inside the culm, which can be reamed to a uniform diameter. Slots are sawn into the culm in order to accommodate slight variations in size. The blocks, when glued in place, can be connected using conventional wood fixings (e.g. nails and screws), perhaps in combination with steel plates (figure 71).

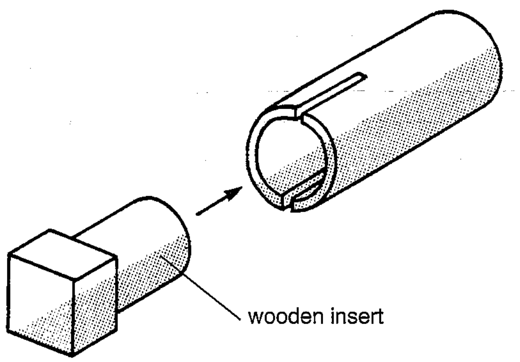


Figure 71: Arce joint

Filled joint: this is a modification of the Arce joint, developed by Morisco and Mardjono (1995). The inner surfaces of the culms to be joined are cleaned with a wire brush. A gap filling resin is used to bond a wooden plug inside the culms. Holes can then be drilled and the assembly bolted together. Cement mortar can be used in place of a timber plug, in which case the bolts are placed before the mortar is poured. Either system can be used in conjunction with steel or plywood gusset plates (figure 72).

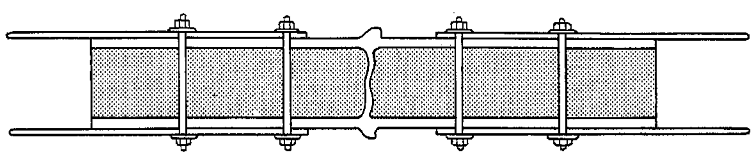


Figure 72: Filled joint (after Morisco et al. *1995)*

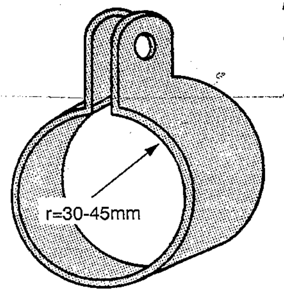


Figure 73: Das clamp

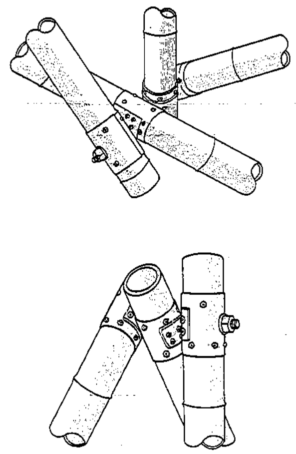


Figure 74: Herbert shear pin connector joint

Das clamp: steel bands with integral bolt eyes are fitted around bamboo sections. The action of bolting two or more elements together tightens the clamps around the culms (figure 73). Additional steel straps can be used if required. This method, designed by the Bhagalpur College of Engineering in India, would be best suited to connections in one plane, e.g. trusses.

Herbert shear pin connector: In this method, developed at the UK Building Research Establishment, bamboo elements are bolted together at sections reinforced with thin gauge steel sleeves. The sleeves are fixed using a series of small diameter pins (pop rivets were found to be more effective than screws and nails) which act to transfer the load to the bamboo (figure 74). Although strong, the joint is bulky and laterally unstable as in-plane connections are not possible. Other methods of fixing suggested include binding, rather than pinning, and the use of sleeves with integral teeth.

Gutierrez joint: this technique is interesting because it exploits the compressive and bending strength of bamboo but does not require it to transmit shear or tensile forces. This is achieved by passing a steel bar through the centre of the element and welding a steel plate at both ends (figure 75). The protruding ends of the steel bars can then be welded together to make a joint.

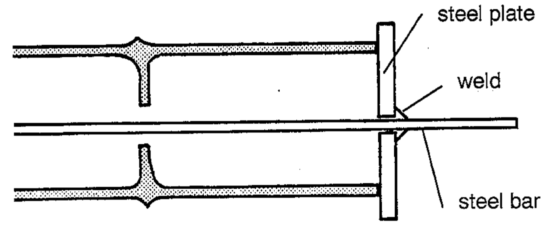


Figure 75: Gutierrez joint

Steel or plastic insert connectors: angled joints can be formed by tightening bamboo elements with slotted ends around prefabricated tubular steel connectors using Jubilee clips (figure 76). Expanding plastic inserts have been used for straight connections (figure 77).

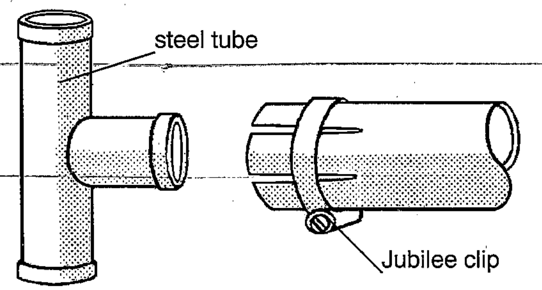


Figure 76: Jubilee clip joint
(after Nienhuys, 1976)

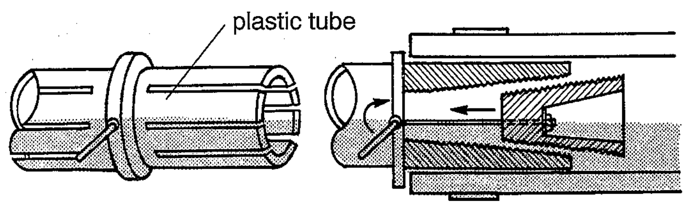


Figure 77: Expanding insert joint
(after Nienhuys, 1976)

The following jointing methods would not truly constitute new developments but should nevertheless be noted:

Nails and screws: the fixing of small elements to larger elements (e.g. floor decking to joists) or the assembly of joint components using splice plates can be effected by the use of nails and screws but, with few exceptions (some *Guadua* and *Chusquea* species - McClure, 1953), this requires pre-drilling due to the tendency of the bamboo to split. Nailed joints also have a tendency to loosen, making for inefficient load transfer and high deformations (Arce, 1991).

Steel straps: to help resist wind uplift forces, steel straps can be used in conjunction with nails to anchor major components, for example trusses to posts. The straps, if tightly applied, will help to counteract the effects of splitting.

9. Design considerations

The use of bamboo as an engineering material is limited from the point of view of design by two major considerations:

- The formulation of structural design guidance is governed to a large extent by practical, engineering experience. In the case of bamboo, information from this source is somewhat limited.

- Basic mechanical properties have been dealt with by many authors, but, unlike timber, bamboo properties do not relate well to species because of the dependency on other factors, such as geographical location and age (Arce, 1993).

Considerable effort continues to be directed at the derivation of mechanical properties, but perhaps with insufficient regard to applications in the field. Janssen (1995), however, has conducted his research with the field practitioner in mind and, as such, his design approach is very simple. Accordingly, it is possibly best suited to simple constructions.

Janssen has shown that a relationship exists between density and permissible stress which forms the basis of the following table:

	Allowable long-term stress (N/mm^2) per unit volume (kg/m^3)		
	Axial compression (no buckling)	*Bending*	*Shear*
Air dry	0.013	0.020	0.003
Green	0.011	0.015	-

For example, if green bamboo has a density of $600kg/m^3$, the allowable stress in bending would be $0.015 \times 600 = 9N/mm^2$. As these are long-term stresses, Janssen suggests they may be increased by 25% for live, or medium-term loading, and by 50% for short-term loading.

Other studies relate to specific species, or groups of species. Rajput *et al.* (1994) considered sixteen species and derived minimum long-term safe working stresses for the green condition as summarised in the tables below:

Group A	*Bambusa glaucescenes* (syn. *B. nana), Dendrocalamus strictus, Oxytenanthera abyssinica*
Group B	*Bambusa balcooa, B. pallida, B. nutans, B. tulds, B auriculata, B. burmanica, Cephalostachyum pergracile, Melocanna baccifera, Thyrosostachys oliveri*
Group C	*Bambusa ventricosa, B. vulgaris, B. bambos* (syn. *B. arundinaceae), Dendrocalamus longispathus*

	Safe long-term stress (N/mm^2)		
	Bending	*Stiffness*	*Compression*
Group A	17.2	1,960	9.8
Group B	12.3	1,370	8.3
Group C	7.4	680	6.9

Although densities are not detailed, assuming $600kg/m^3$, the values for group C compare quite well with those from Janssen (9 and 6.6 N/mm^2 for bending and compression respectively).

Another study conducted by Chandrakeerthy (1995) in relation to temporary bamboo structures deals exclusively with *Bambusa vulgaris*. The recommended design values of $16.7N/mm^2$ in bending and $15.2N/mm^2$ in compression (in the green condition) are considerably higher than those for either Rajput (Group C, within which *B. vulgaris* falls) or Janssen.

Codification, along similar lines to timber, can be seen as the next important step towards the promotion and wider acceptance of bamboo as a valid building material. This will provide an objective and coherent approach to bamboo design, taking into account not only its more favourable qualities but also its limitations.

10. Tools

A major advantage of bamboo is its ability to be worked by hand using very simple tools. If, however, the commercial potential of bamboo as an engineering material is to be realised, then there will be a need to develop efficient handling, machining and production methods.

Hand tools It is possible to build in bamboo with nothing more than a machete, but a few basic tools will greatly increase the scope and effectiveness of the construction process. The tools listed below will enable the preparation and assembly of most bamboo elements used in building. While this subject has been addressed recently in an INBAR initiative (Gnanaharan, 1995), the list draws almost exclusively on McClure (1953), a reference which has lost little of its relevance or value over the last 40 years.

Tool	*Use*	*Recommended specifications*
Machete	Miscellaneous: felling, trimming and cutting culms to length; removing fragments of diaphragms from boards etc.	Preference of the user decides type of blade but long, fairly heavy blade recommended
Hacksaw	Felling culms, removing branches, cutting culms to length	Large size; 18 and 24 teeth per inch alloy steel blades
Tripods or trestles	Elevating culms and holding them firm for sawing to length or cracking nodes	May be made locally following preferred pattern
Axe	Cracking the nodes of large culms for making boards	Light-weight with a thick wedge-shaped but narrow blade
Hatchet or small axe	Cracking the nodes of smaller culms for making boards	Similar but smaller to the axe with a short handle

Whetstone	Sharpening edged tools	Carborundum; coarse grained on one side, fine on the other
Spud	Removing diaphragm fragments and excess soft wood at basal end of bamboo boards	Long handle with broad blade set at an angle to operate parallel to board surface
Adze	Similar use to spud; less convenient but more generally available	Standard design, best quality steel
Gouge	Removing diaphragms to make troughs and drain pipes from split or opened culms	Bent gouge, 25 and 38mm
Chisel	Making holes in culms to accommodate lashings for end ties	Best steel (alloy steel if available), 20mm
Drill	Making holes to accommodate pins or dowels	Hand- or power-drill with best steel twist drills (for metal cutting)
Wood rasps	Levelling prominent culm nodes	Large, half round; coarse, medium and fine
Splitting jig	Facilitating the splitting of whole culms or sections into several strips at once	see figure 78
Splitting knives	For splitting small culms	Short handle, broad blade (figure 79)
	For making bamboo lashings	Long handle, blade bevelled on one side only (figure 80)
Steel rod	Breaking out the diaphragms of unsplit culms	3m x 20mm and 3m x 13mm as a minimum. Hardwood or bamboo may also be used
Pliers	For handling wire used for lashings	Long-nose with wire cutting facility

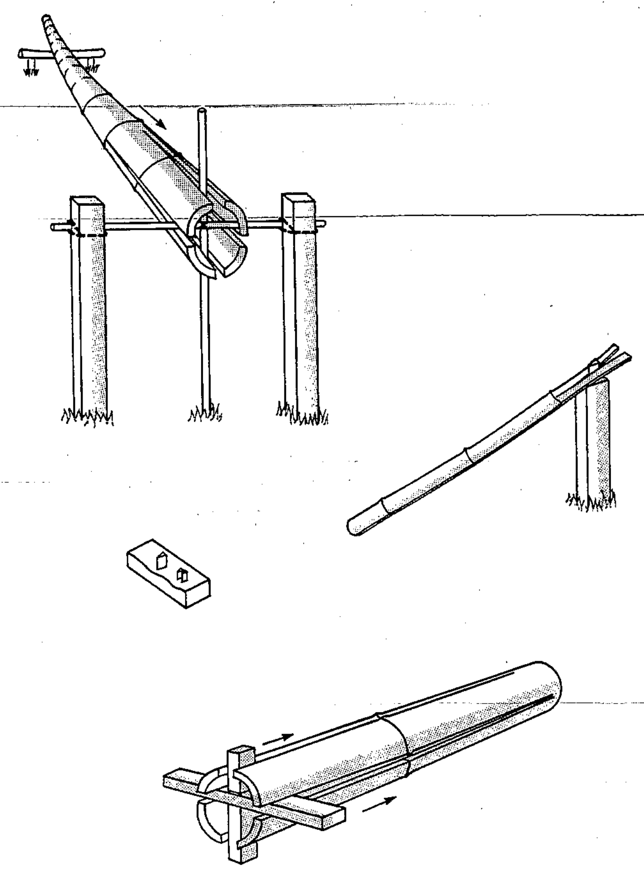


Figure 78: Splitting jigs (after McClure, 1953)

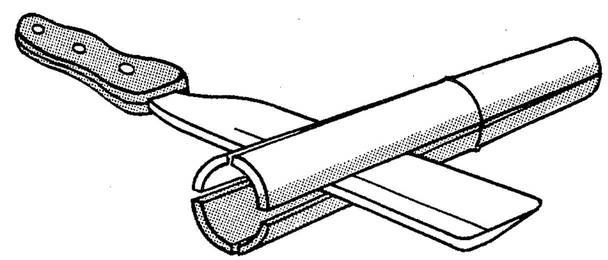


Figure 79: Splitting knife for small culms (after McClure, 1953)

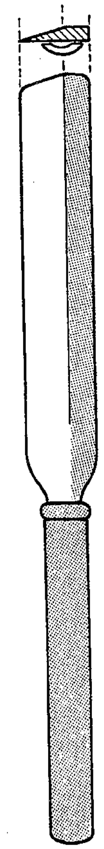


Figure 80: Splitting knife for making lashings (after McClure, 1953)