Chapter 9
Preservation and Drying of Bamboo

Walter Liese and Thi Kim Hong Tang

Abstract Bamboo culms are a unique building material for various kinds of structures. A wider acceptance of bamboo for structural uses, however, is often hindered by its propensity to biological degradation. The preservation of bamboo structures against biological hazards is an important requirement for utilizing this valuable lignocellulose resource. Compared with the preservation of timber in tropical countries, there are certain similarities, but also considerable differences.

Drying of bamboo before use is necessary since dry bamboo is stronger and less susceptible to biological degradation than moist bamboo. Furthermore, shrinkage and swelling are directly related to the moisture content. Moist bamboo affects the processing, such as machining, gluing and painting. Dimensional changes would ultimately occur if bamboo has not been dried before being used. The bamboo should be dried to the equilibrium moisture content corresponding to the service conditions before the manufacturing process.

Keywords Natural durability • Fungi • Beetles • Termites • Marine borers • Preservation methods • Chemical treatment • Non-chemical treatment • Preservatives • Air drying • Kiln drying

9.1 Natural Durability

Bamboo is one of the strongest bio-based structural materials, but succumbs to physical and mechanical damage by some non-biotic factors and is susceptible to degradation by similar organisms which attack wood. Moreover, bamboo is more likely to biodeteriorate due to its starch content.

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There are quite a number of general and detailed information on causes of bamboo deterioration and methods for protection in Willeitner and Liese (1992), Kumar et al. (1994), Liese and Kumar (2003), Liese (2004a, b), Jiang (2007) and Tang (2009).

The service life of bamboo structures is considerably dependent on the rate of biological degradation. Generally, the natural durability of bamboo is very low and influenced by species, environmental conditions and nature of use. Untreated bamboo has an average life of less than 1 year when exposed to outside conditions and soil contact. Under cover, it may last 4–5 years and longer or even 'forever' under favourable conditions. Split bamboo due to an easier access to the parenchymatic tissue is more rapidly destroyed than culms. The bottom part of a culm has a higher durability than the middle and top portions, and the inner part of the culm is easier attacked than the outer one (Liese and Kumar 2003; Liese 2004a, b, c).

In tropical humid areas, enormous quantities of bamboo culms stored in forest depots and mill yards decay and deteriorate. The severity of decay and biodeterioration depends on the duration of storage, bamboo species and environmental and storage conditions. Degradation of bamboo materials by fungi is a serious problem for bamboo factories during storage, processing and overseas transport of culms and bamboo products (Figs. 9.1 and 9.2) (Tang 2013).

9.1.1 Abiotic Factors

9.1.1.1 Cracks and Splits

Mechanical and physical damage of the culm occurs rarely because of its hard skin. Due to drying stresses mainly in young culms, collapse may arise as a serious defect. Cracks and splits can take place particularly when the culms are stored outdoors, and fungal deterioration may become evident (Fig. 9.1). Cracks can develop if the culm as part of a construction component is exposed to intensive sun. Such cracks may not have much influence on the tensile strength of the culm, but can lead to subsequent deterioration by fungi and insects. Since such cracks often develop on the 'weather side' they are equally exposed to rain so that water collects inside the culm's lacuna. In such a humid chamber, fungi will thrive resulting in rapid deterioration. Splitting cannot be prevented by any chemical treatment because it is a consequence of shrinkage-induced stresses due to too rapid drying.

Bamboo is also subject to mechanical wear caused by rope/wire friction when used for fastening bamboo components. Nailing is a frequently used method for fastening bamboo. Species with thick walls, like *Guadua* spp., appear to tolerate nailing better than thin-walled species.

9.1.1.2 Weathering

Weathering of exposed bamboo structures is a result of an interaction of different atmospheric conditions, such as ultraviolet radiation, surrounding temperature and

Fig. 9.1 Cracks during storage with subsequent fungal decay (Liese and Kumar 2003)

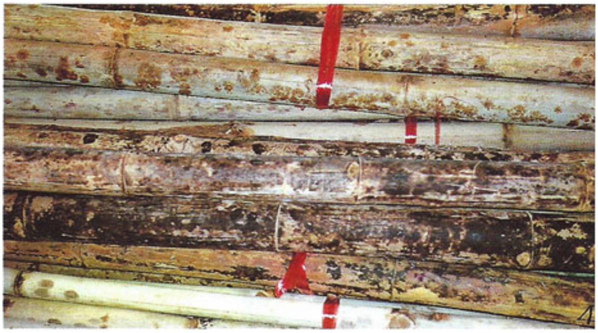

Fig. 9.2 Blue stain on stored culms (Liese and Kumar 2003)

moisture content. Severe temperature and relative humidity changes have an extremely deleterious effect on bamboo because sudden fluctuating atmospheric conditions may produce steep moisture gradients between surface and inner layers, resulting in surface cracks due to repeated swelling and shrinkage. Direct exposure to sun also causes checks in bamboo due to unbalanced shrinkage. Subsequently, water contributes further to cracks and splits.

A major factor in bamboo weathering in outdoor settings is damage by UV and visible light radiation which causes photodegradation. Such radiation breaks down bonds of the lignocellulosic polymer causing the bamboo surface to turn grey and coarse.

9.1.1.3 Fire

Fire is a great danger to bamboo constructions. The material burns easily and the hollow culms explode loudly due to heat expansion, from which the name ‘bamboo’ may have originated. Since bamboo is utilized in modern constructions, corresponding building codes and regulations have to be considered. Approval to use the giant culms of *Guadua angustifolia* as constructional elements besides wooden stems for the impressive ZERI Pavilion at the EXPO 2000 in Hannover, Germany, was granted only after stringent flammability tests were passed.

Whereas the flammability of timber can be reduced with fire retardants applied by pressure treatment, such protection for bamboo is hardly possible because of its refractory nature. Fire-retardant chemicals have to penetrate into the culm tissue and are effective only at a high retention. A surface application on the culm by paint appears questionable, as these decorative coatings are non-fixing. Additionally, economic factors hinder such a fire-protective treatment.

9.1.2 Biotic Factors

9.1.2.1 Fungi

9.1.2.1.1 General

Fungi cause discolouration and decay of bamboo. There are many types that infest and attack bamboo under different environmental conditions. All fungi use the chemical components of the culm cells, either from cell contents (moulds and blue-stain fungi) or from the cell wall (rot fungi), as their energy source. Fungi originate from spores produced asexually from the mycelium (Deuteromycetes) or sexually from fruit bodies (Ascomycetes, Basidiomycetes). As spores can be assumed as omnipresent, they will germinate everywhere under suitable conditions to thin hyphae. The growing hyphae live from the bamboo substances by enzymatic decomposition and develop to mycelium. The effect will often be recognized only at a later stage when substantial decomposition has resulted in discolouration and physical damage (Fig. 9.1). Mould fungi grow on the bamboo surfaces. Blue-stain and decay fungi (soft-rot, brown-rot, white-rot fungi) grow mostly inside the substrate, and some develop mycelium on its surface especially under humid conditions. Later, fruit bodies may be formed on the outside for the release of new spores.

Although fungal spores are present everywhere, they require certain conditions for germination, further growth and for the enzymatic degradation of the substrate.

The required moisture content of the material must be from 40 to 80 % of the oven-dry mass. Dry bamboo with a moisture content below 20 %, which is well below fibre saturation, is not vulnerable to attack.

The temperature range in regions where bamboo is grown and used is well-suited for fungal activities. Direct sun exposure of the mycelium with temperatures above 55 ° C may lead to destruction of the enzyme system by protein denaturation. There are however several decay fungi whose mycelia survive 95 °C for some hours (Schmidt 2006; Wei 2014).

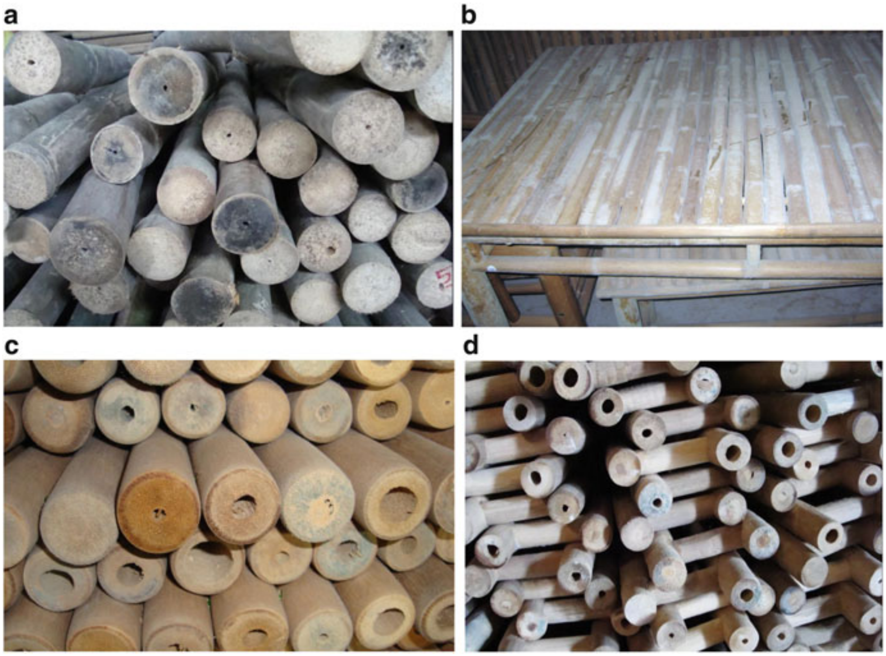

Fig. 9.3 Moulded bamboo materials at a bamboo factory in Vietnam (Tang 2013). (**a**) Moulded fresh culms during storage. (**b**) Surface of a table infected by moulds. (**c, d**) Moulded culm parts after processing

9.1.2.1.2 Moulds and Blue-Stain Fungi

Mould fungi can occur on the surface and at the cross ends of fresh culms in a humid atmosphere as these fungi require high relative humidity, generally above 70 %. Their hyphae do usually not penetrate into the culm but obtain their nourishment from sugars and airborne impurities on its surface. Moulds may easily develop in chip-storage piles where the inner, nutritious, culm part is exposed at the cut surface of the chips, but also on finished products, like furniture during transport in containers, resulting in considerable economic losses (Figs. 9.3, 9.4). Moulds do not influence the culm's physical properties but reduce its aesthetic appearance. Different mould species produce large quantities of spores of various colours: black, blue, green and yellow. The spores of some species cause skin irritations, respiration problems and allergic reactions for human beings, particularly in indoor environments. The mycotoxins produced by some moulds, e.g. aflatoxin from *Aspergillus flavus*, are highly toxic to humans and animals

Blue-stain fungi, on the contrary, easily enter through the cross ends of fresh/moist culms and penetrate the parenchyma. They nourish on the starch and soluble carbohydrates stored in these cells. Their pigmented hyphae cause a blue-greyish-black discolouration of the inner tissue. Such discolouration occurs also on the

Fig. 9.4 Moulded bamboo culm parts at arrival in Hamburg after shipping from Vietnam (Tang 2013)

surface (Fig. 9.2) in various shades, as spots, streaks or in a uniformly scattered pattern. It reduces the aesthetic quality, especially of split bamboo and slivers, but does not affect the strength properties, except impact strength in severe cases. Moulds and blue-stain fungi belong to the so-called lower fungi, Deuteromycetes, and in case of producing sexual fruit bodies, to the Ascomycetes.

9.1.2.1.3 Decay Fungi

True bamboo-destroying fungi belong to the group of the so-called higher fungi, the Basidiomycetes and Ascomycetes. Their hyphae penetrate deeply into the bamboo tissue. The Basidiomycetes grow within the lumen of the cells and produce different enzymes according to the specific fungal type which diffuse into the cell wall. Either the enzymes decompose only the cellulose and hemicelluloses, with the lignin remaining, leading to the brown-rot type or they decompose all wall substances resulting in the white-rot type. Bamboo is mainly destroyed by white-rot fungi. A common white-rot fungus is *Schizophyllum commune* (Fig. 9.5) easily recognized by its white fruit body with a radial lamellate underside (Ashaari and Mamat 2000).

The enzymatic degradation of bamboo leads to a loss of cell wall substance which results in a reduction of strength properties. Even before a slight colour change or weight loss become apparent, the strength properties are much reduced, in particular the impact-bending strength. The relation between mass loss and strength reduction appears more severe in bamboo than in timber as the weight loss concerns mainly the strength-giving fibres. Incipient decay is often overlooked resulting in severe consequences for the safety of constructions and the possible restoration of infested building components. At late stages of deterioration, the culm appears soft to touch, and only a fibrous or powdery mass may remain.

Besides the white- and brown-rot fungi, the soft-rot fungi are a special group, belonging mostly to the Ascomycetes. In contrast to the Basidiomycetes, their hyphae grow mainly inside the cell wall. They use cellulose/hemicellulose wall

Fig. 9.5 Fruit bodies of *Schizophyllum commune*, a white-rot fungi (Liese and Kumar 2003)

substances and produce few changes in the lignin molecule. This fungal type needs less oxygen and can tolerate a higher moisture content, even above 80 %, which is prohibitive for other fungi. Soft-rot fungi also resist the toxic concentration of many chemical preservatives. Culms in ground contact are generally attacked by this fungal type. The colour of the infested culm changes from its natural cream yellow to dark brown black, and normally no surface mycelium can be recognized.

9.1.2.2 Insects

9.1.2.2.1 General

Insects are responsible for the most destructive attack on bamboo. Warm and moist climatic conditions in tropical regions favour their development. About 50 insect pests have been reported to attack felled culms and bamboo products (Wang et al. 1998). Among these insects, two types are notable: borers, such as bostrychid, Lyctid and cerambycids, and termites. The life cycle of borers can be divided into four stages: egg, larva (caterpillar and worm), pupa and adult. The female beetle burrows into the bamboo tissue, particularly into the vessel openings at the cross ends or in wounds, and lays abundant eggs. Minute larvae develop and penetrate further, gnawing through the tissue by mechanical action. The particles are digested in the gut of the larvae to a variable extent, and the faeces or frass is excreted as pellets from the rear end. For wood-destroying insects in general, the pellets and the form and size of exit holes have characteristics that allow for species identification. After a certain time (weeks or months) the larva is transformed into a pupa which soon changes into a beetle. The beetle then chews its way out of the bamboo culm leaving exit holes on the surface. Pellets falling out of the flight holes are often the first sign of an ongoing attack (Fig. 9.6). The adult beetles themselves generally do not destroy the bamboo tissue as their only purpose in life is procreation.

9.1.2.2.2 Beetles

The so-called powder-post beetles cause the most devastation in stored bamboo culms. They can reduce the tissue to a flour-like powder, leaving only a thin outer shell. The beetle attack can commence within 24 h after culm felling. The larvae feed on the starch and the soluble carbohydrates in the parenchyma cells; thus, the attack occurs primarily at the inner part of the culm where most of the parenchyma is situated within the diaphragm. They can tunnel through the entire inner tissue leaving behind only a thin surface of the hard cortex which may give a false impression when evaluating the significance of damage for repair work. The most destructive species are *Dinoderus minutus* and *D. brevis* (Bostrychidae), responsible for over 90 % of damage on harvested culms and bamboo products. The adult beetle is blackish brown and about 2.5–3.5 mm long (Fig. 9.7). The new beetles make their exit through the hard cortex of the culm by circular bore holes of about 1 mm diameter. In bamboo species with a thick culm wall, like *Guadua* spp., the

Fig. 9.6 Powdery mass of pellets due to beetle attack (Liese and Kumar 2003)

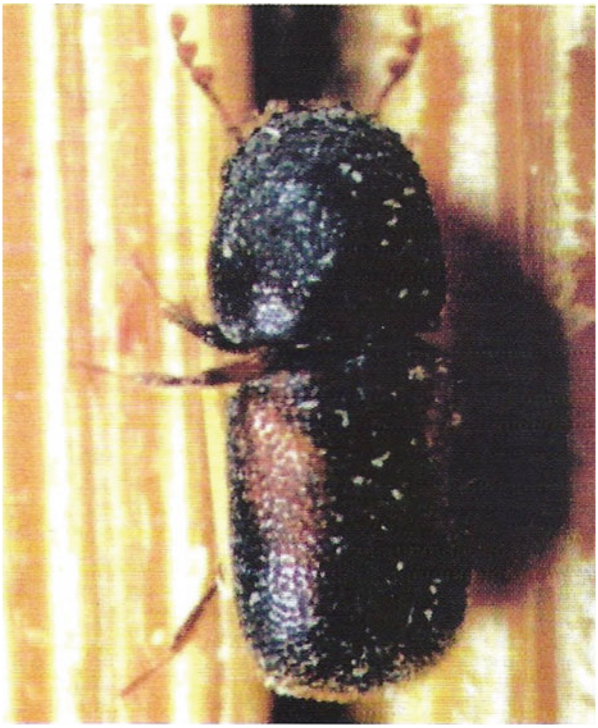

Fig. 9.7 Beetle of *Dinoderus* sp. (Liese and Kumar 2003)

beetles will demolish the inner starchy tissue and then exit without much structural damage because the strength is maintained by the thick outer fibrous tissue.

Several factors determine the intensity of attack. The larval activity depends very much on the availability of starch and is therefore strongly influenced by the season. Beetle infestation is enhanced when culms are harvested just prior to the shooting time. Younger culms with a higher moisture content are more easily attacked than older ones which contain less starch and moisture. Flowering bamboo culms with their low moisture content contain hardly any starch as it has been used for seed production and remain therefore almost immune to attack.

The incidence of borer attacks depends also on the bamboo species. Although no systematic record seems to exist so far, it is well documented that *Bambusa vulgaris* is always heavily infested, whereas *Pleioblastus* species are seldom attacked.

Besides *Dinoderus* spp., other powder-post beetles, like *Lyctus* spp. and *Minthea* spp. (Lyctids), can attack dry bamboo and bamboo products, but they cause less damage in most bamboo countries. The common wood-boring beetles (cerambycids) can cause damage to bamboo. They form larger tunnels inside the tissue (Fig. 9.8). Wasps can also damage bamboo.

Fig. 9.8 Deterioration of imported bamboo furniture parts by a cerambycid beetle (Liese and Kumar 2003)

Carpenter bees are seldom serious pests, but more a source of annoyance. Once a bamboo component, like a rafter or support, is attacked, it will be repeatedly visited and can be seriously affected.

9.1.2.2.3 Termites

Termites are the most aggressive insects to wreak havoc on bamboo and wood. As social organisms, they live in well-organized groups of several hundreds to some millions of individuals. They have a strong caste system with the so-called sterile ‘workers’, a smaller number of blind ‘soldiers’ for defence and only one pair of fertile termites, the king and the queen as the primary producers. The damage to bamboo or wood is done exclusively by the worker caste who construct galleries and tunnels in their search for food and who also care for the feeding of the queen. They are among the few insects capable of using cellulose as a source of food due to

Fig. 9.9 Termites are aggressive insects that wreak havoc on bamboo (Liese and Kumar 2003)

Fig. 9.10 Culm deterioration by termites (Liese and Kumar 2003)

symbiotic bacteria and protozoa in their gut. Their attacks lead to rapid destruction often leaving behind only a thin layer of the bamboo cortex (Figs. 9.9 and 9.10).

Among the various termite genera, a distinction exists between subterranean termites as soil-dwelling species and dry-wood termites which can live without ground contact in wood/bamboo structures.

Subterranean termites need high humidity and access to water and often build their nests as large mounds (Fig. 9.11). They live underground and extend above ground through tube-like runways made of soil and faeces in search of food. The gnawing takes place inside the bamboo culm (Fig. 9.12). Though the erection of

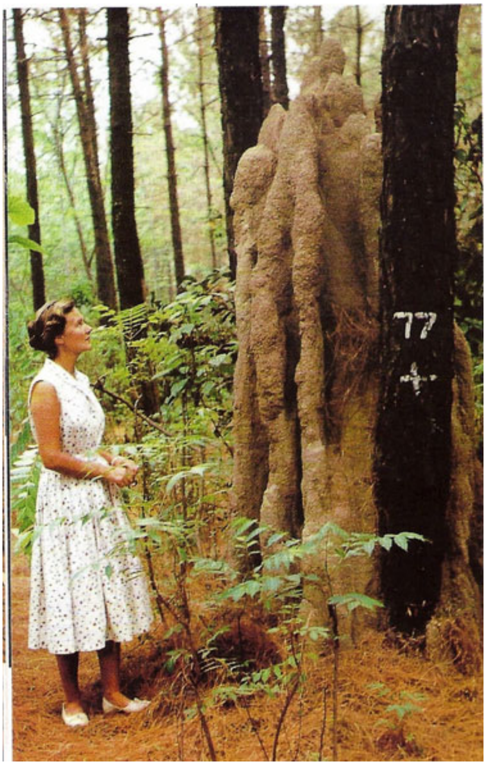

Fig. 9.11 Large mound by subterranean termites, India 1957 (Liese and Kumar 2003)

galleries can be quite fast, an attack can be stopped if all outside galleries leading to their underground home are completely and repeatedly destroyed. Termite shields on a cement foundation prevent gallery construction.

Dry-wood termites may build their nest inside the bamboo culm parts that they are eating. The infestation is done by flying adults who enter the bamboo though cracks or openings at cross ends. Consequently they can attack constructions above ground level. Often their attack is only recognized at a later stage of deterioration. They recycle their own body moisture and can survive on a minimal amount of moisture obtained from the bamboo itself.

9.1.2.2.4 Marine Borers

There is large-scale use of bamboo for waterfront structures, as poles in stake-net fishing, in coastal aquaculture farms and also for bamboo-made rafters/vessels. Bamboo fencing can run to several kilometres in length, and much bamboo is used

Fig. 9.12 Galleries by subterranean termites to maintain ground contact (Liese and Kumar 2003)

in fishing activities (Fig. 9.13). All structures in marine and brackish waters are physically damaged by marine wood borers within a short time, often within a few months. The pattern of destruction varies among the groups of marine wood/bamboo destroyers, but their economic cost is generally high. The principal culprit, Teredinidae *(Banksia* spp., *Teredo* spp.), or shipworms, bores into the culm and tunnels through the tissue leaving only a small hole of the size of a pinhead on the surface. Although more obvious, the damage, however, proceeds more slowly.

No protection of bamboo marine structures appears possible by technical means, and chemical treatment is not viable due to the refractory nature of the culm structure and the great environmental danger through leaching of preservatives.

Fig. 9.13 Bamboo fencing in seawater, Philippines (Liese and Kumar 2003)

9.2 Preservation Methods

Bamboo preservation can be divided into non-chemical and chemical methods. The selection of the appropriate treatment method depends on various factors such as the state of the bamboo, green or dry, and end use, indoor or outside exposure and ground or food contact (Moran 2002; Liese and Kumar 2003).

9.2.1 Non-chemical Methods

Several traditional methods for bamboo protection have been applied in rural areas without the use of chemicals since ages. These methods are easy to follow and can be carried out by untrained villagers, without the need for technical equipment and with little cost. Through experience, harvesting rules, like the proper season and the selection of mature culms, are considered as traditional rules of good practice.

Some traditional or advanced non-chemical methods can considerably increase the resistance against fungal and beetle attack. However, for bamboo structures in long-term use, their efficiency regarding the required safety aspects and the real cost-saving benefits need to be carefully evaluated.

9.2.1.1 Reduction of Starch Content

In bamboo culms, the cellulose (structural carbohydrates) and starch and sugar (nonstructural carbohydrates) are the principal nutrients for fungi and insects. While cellulose content cannot be reduced without negative effects on strength properties, a reduction of sugar and starch makes bamboo unattractive for discolourating fungi and many insects. Methods commonly used for lowering starch/sugar content are as follows.

9.2.1.1.1 Harvesting of Bamboo During the Low-Sugar Content Season

The sugar content in the culms varies with the season. During the growing season, the culm reduces its carbohydrates in the parenchyma to provide building material for the expanding shoot. Thus, the carbohydrates are reduced (Magel et al. 2006). Therefore, the culms are preferably harvested at the end of the rainy season and beginning of the dry season when the culms are fully developed.

9.2.1.1.2 Curing

The bamboo culms are cut at the bottom and left for some time with branches and leaves at the clump (Fig. 9.14). As respiration of the tissue still goes on, the starch and sugar contents in the culm are decreased. Thus, the infection by borers is reduced, but there is no effect on the attack by termites and less by fungi.

9.2.1.1.3 Waterlogging

Waterlogging is commonly applied in many Asian countries. Fresh bamboo culms are soaked in running or stagnant water for 1–3 months. This process is said to partially leach out carbohydrates thus resulting in an enhanced resistance of the culm. In fact, during water storage the starch content is reduced partly by bacterial action. The method might therefore improve the resistance against borers but not against termites and fungi (Sulthoni 1988; Ashaari and Mamat 2000; Nguyen 2002). Submergence in water may lead to staining and bad odour of the culms due to the bacterial action.

Waterlogging is still used for treating bamboo materials for making handicraft and furniture in many traditional craft villages of bamboo countries as well as generally for housing in rural areas (Fig. 9.15).

Comprehensive studies were recently undertaken with *Dendrocalamus strictus* in India on the traditional waterlogging in a water tank for 4 weeks with weekly changed water. Decay resistance was found better than untreated and partly comparable to chemical-treated samples. However, water leaching alone cannot be considered as long-term preservation and must be integrated with other technologies to provide viable resistance (Kaur et al. 2013).

9.2.1.1.4 Boiling

Green culms or slivers for weaving are boiled in water for about 30–60 min.

Fig. 9.14 Clump curing of *Bambusa blumeana*, Philippines (Liese and Kumar 2003)

Fig. 9.15 Water storage of culms in Thailand (Liese and Kumar 2003)

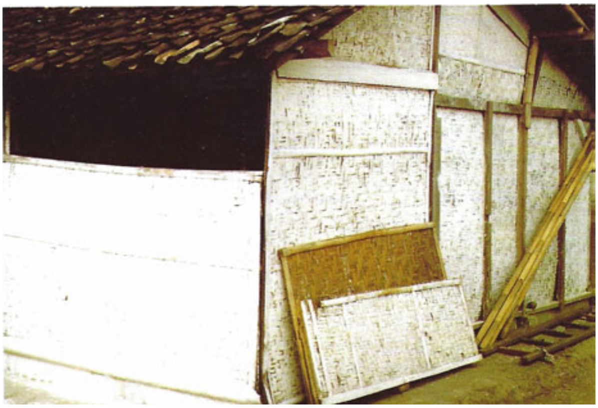

Fig. 9.16 Whitewashing of bamboo mats, Indonesia (Liese and Kumar 2003)

Fig. 9.17 Plastering of bamboo mat walls, India (Liese and Kumar 2003)

As an improved method, boiling in 0.5–1 % solution of caustic soda (up to 30 min) or sodium carbonate (about 60 min) is applied. The culms are wiped to remove the wax coating for better finish. Longer or repeated boiling can dull the colour of the material. Boiling may cause starch to leach out or denature, improving resistance to borers and stain fungi.

9.2.1.2 Limewashing

Lime or whitewashing is a traditional treatment and mainly used for ornamental effects (Figs. 9.16 and 9.17). Bamboo culms and mats for houses are painted with slaked lime ($CaOH_2$), which is transformed into calcium carbonate ($CaCO_3$) and inhibits water absorption. The surface becomes alkaline thus delaying fungal attack which requires an acid environment. Bamboo mats are also tarred and then sprinkled with fine sand. When the sand and tar have dried, it is limewashed up to four times.

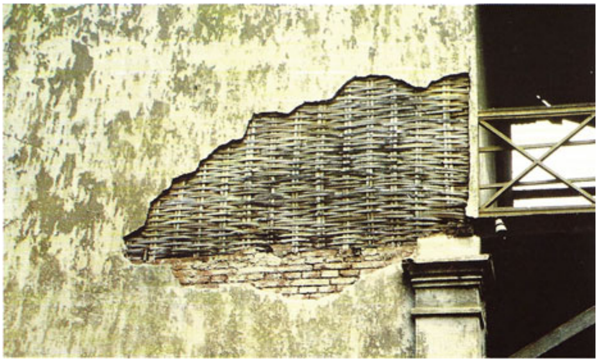

Fig. 9.18 Cement plaster on a city house, India (Liese and Kumar 2003)

Fig. 9.19 Bamboo house with plastered walls in Costa Rica (Liese and Kumar 2003)

9.2.1.3 Plastering

Plastering of bamboo mats is a common method used by villagers using mud, clay or sand mixed with lime, cement or cow dung for stability. Plastering is also a widely applied method for city houses in many countries like India or Colombia where the walls made of split bamboo are covered with mortar on both sides. The tight seal keeps the bamboo culms, splits or mats protected against rain and prevents the entry of beetles (Fig. 9.18).

House constructions with cement-covered bamboo mats on dry foundations have been in service for decades (Fig. 9.19). Social housing programmes in Colombia and other countries as well as houses constructed by FUNBAMBU, a nongovernmental organization in Costa Rica, have applied this system on a larger scale (Liese 1989, 1990; Jayanetti and Folett 1998; Gutiérrez 2000). The common bahareque technique uses coarsely woven bamboo panels whose purpose is to hold the mud or cement. The surface will be finished with a limewash (Fig. 9.20). The

Fig. 9.20 City houses with bamboo construction and plastered walls in Manizales, Colombia (Liese and Kumar 2003)

mats can be protected by boron soaking/diffusion. Plastering can be considered partly as a constructional method.

9.2.1.4 Smoking

Fresh bamboo culms in rural areas are, by tradition, still stored inside the house above a fireplace. The moisture content is thereby considerably reduced and insufficient for biological degradation. The culm darkens in colour due to heat. The build-up of deposits from smoke such as carbon and its derivatives forms a protective layer preventing physical and probably chemical contact of the culm material with fungal spores as well as beetles. Smoke drying also reduces splitting.

Besides this traditional way of conservation, green bamboo is stacked in a furnace of about 4.5 m in length and 2.5 m in height and heated at 120–150 °C. Due to the build-up of soot and other pyrolytic chemical products on its surface, the bamboo is said to be protected against beetles.

The traditional smoking method as applied in Japan has been developed for commercial operations in Colombia. A square chamber or a similar device of about 14 m length with a 4×4 m^2 cross-section, standing upright, is filled with semidry culms with a moisture content below 50 %. The cylinder is heated from below with organic combustibles for 12–20 days, depending on the culm proportions, until the moisture content is reduced to about 12 %. During heating with circulating air, partial pyrolysis of bamboo substances occurs. The pyrolized products drip down, are pumped up to the top and flow down the culm surface again where they eventually dry.

A strong acid odour is produced which will influence the fields of application. These culms are mainly for outdoor use. So far, an improved resistance against beetles is reported which is likely because of chemical changes in the carbohydrates. The durability against fungi and termites as well as in ground contact and for a longer exposure time has still to be proven.

9.2.1.5 Heat Treatment

Wood submitted to thermal treatments well above 150 °C shows a notable decrease of water absorption, a better dimensional stability and an improved resistance against microorganisms due to modification of the organic matter. The efficacy against beetles and termites is still under evaluation, and results so far indicate an improved resistance. Mechanical properties of bamboo, especially the elasticity and strength of the heat-treated material, are evidently reduced (Leithoff and Peek 2001). This effect is also observed in timber.

9.2.1.6 Constructional Methods

Much damage can be avoided by suitable construction methods by which the moisture content of bamboo components is kept well below fibre saturation, so that no fungal attack can occur. A long-standing tradition exists, now hundreds of years old, on the proper construction use of bamboo without chemical treatment. Common methods are to place bamboo posts or walls on either stones, preformed concrete footings or durable or pressure-treated wood blocks instead of putting them directly on the ground. The culm should be cut just below a node for better stability. Good air circulation throughout the structure is also important. Houses made from bamboo mats, as is common in rural areas, should not be placed directly on the ground, but on a cement base (Fig. 9.21). An overhanging roof will protect bamboo mats against rain.

By tradition and experience sound construction methods are often applied. The houses in the Cordillera Central region of Colombia and in the lowland coastal provinces of Ecuador with an extensive use of bamboo are impressive examples (González and Gutiérrez 1996; Gutiérrez 2000). They last for over 90 years without any treatment because the plaster on the ceilings and walls prevents beetle damage.

For roofing, halved culms allow an easy run-off for rain. Due to their water-repellent cortex, they last several years until fruit bodies indicate their internal

Fig. 9.21 Social housing programme with bamboo houses in Manizales, Colombia (Liese and Kumar 2003)

Fig. 9.22 Fruit bodies indicate advanced decay of a bamboo roof (Liese and Kumar 2003)

degradation (Fig. 9.22). Only older culms with a well-developed skin should be used, as chemical protection is not feasible for roofing.

The traditional methods outlined briefly can be effective against fungal and partly against beetle attack but hardly against dry-wood termites. The invasion of subterranean termites can be prevented by removing their earthen tunnels, by placing termite shields on the cement foundation or by using soil poisoning barriers, if permitted (Nguyen 2002).

The INBAR Technical Reports No. 15 by Jayanetti and Folett (1998), No. 19 by Gutiérrez (2000) and No. 20 by Janssen (2000), as well others (Cusack 1999; Heinsdorff 2010), illustrate the manifold of possibilities for bamboo protection by design and construction.

Traditional construction techniques as well as the new designs by architects like Simon Velez in Colombia, Jorge Arcila and Jorge Moran in Ecuador and a generation of very dedicated bamboo architects and promoters, like Oscar Hidalgo in Colombia, have now turned bamboo into a ‘high-tech’ material. The bamboo bridge constructed by Jörg Stamm in Pereira, Colombia, with a 52 m span and a 2.8 m width, is an impressive example (Fig. 9.23). It should be noted that the culms were given a boron treatment against beetles by a 4–5-day soak with punctured internodal walls for complete internal penetration.

9.2.2 Chemical Methods

In most cases, chemical treatment of bamboo is required. A key factor for the protection is the sufficient preservation of the culm. Unlike timber, the bamboo tissue is rather resistant towards penetration of liquids due to its anatomical structure (Liese and Kumar 2003).

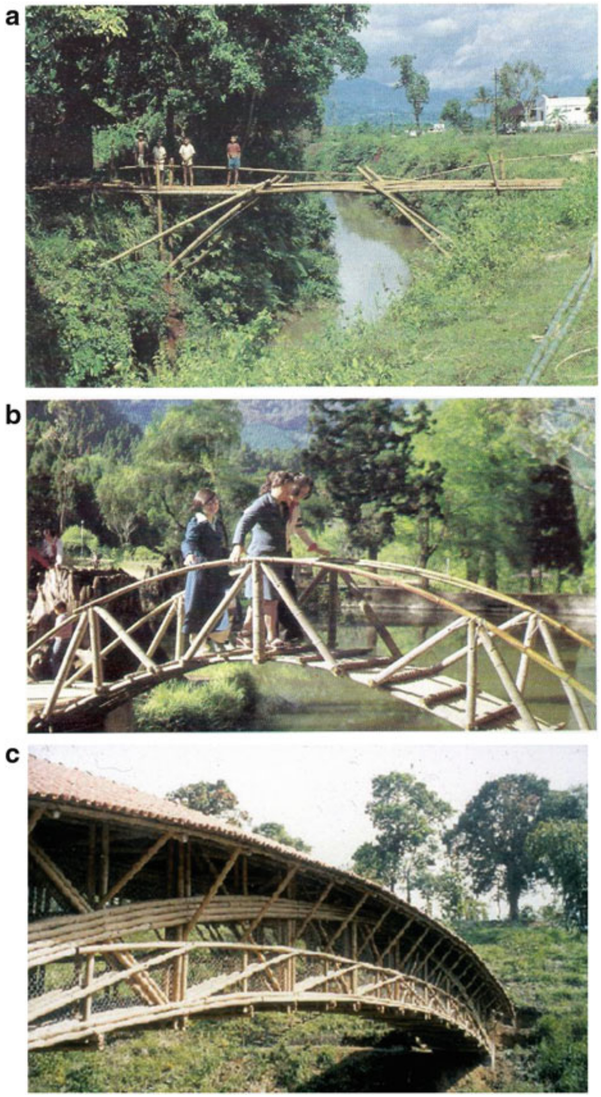

Fig. 9.23 Bamboo bridges in (**a**) Indonesia, (**b**) Malaysia and (**c**) Colombia (Liese 1985)

9.2.2.1 Treatability

The uptake of a preservation solution is restricted mainly to the metaxylem vessels, which run through the culm like long 'water pipes'. At the nodes, they become partly structurally modified by branching, so that the passage through a node may be hindered. Their total volume amounts to only 6–8 %, so that the remaining tissue of fibres and parenchyma has to be protected by diffusion. Ray cells, like in wood, do not exist in bamboo. As a typical wound reaction, slime extrudes from the parenchyma cells into the vessels causing a blockage of the lumina. Monopodial bamboos, like Moso (*Phyllostachys edulis*), also produce tyloses as balloon-like protrusions into the metaxylem vessels.

The culm is covered on its outer side by a special layer, the cuticula, which hinders any penetration by simple treatments, such as soaking. At the inner culm wall, suberin layers lying on sclerotic parenchyma cells also hinder any penetration, although to a much lesser extent than from the outside (Liese and Schmitt 2006).

This special anatomical make-up of the bamboo culm as well as its moisture content must be taken into consideration when choosing a suitable preservative and treatment method to be applied.

9.2.2.2 Preservatives

Most preservative formulations for wood have also been found suitable for bamboo. The preservatives are either waterborne or oil-based types; for specific purposes, some special formulations already exist.

9.2.2.2.1 Waterborne Types

Water-soluble inorganic or organic salts are dissolved in water and introduced into the bamboo. The water evaporates leaving the salts inside. They are either non-fixing or fixing to the bamboo tissue.

The application of non-fixing preservatives is restricted to bamboo used in dry conditions and under cover only, as in wet conditions or exposed to rain they are of no use as the chemicals are washed out.

Fixing-type preservatives are chemically bound in the woody tissue and can be applied both inside and outside. The type of product, expected durability and use dictate the type of preservative to be used.

Preservatives are sold as solids or as a paste. Salts, more recently, are often provided as pre-solutions for health and safety reasons and to minimize pollution by chemical dust.

Waterborne preservatives are clean and odourless and offer widely recognized advantages coupled with effectiveness and permanency. Such preservatives are more cost-effective as solvent costs are eliminated. Waterborne preservatives are divided into non-fixing types and fixing types.

9.2.2.2.2 Non-fixing Types

Non-fixing or leachable salts penetrate essentially by diffusion and can thus reach the entire tissue of a culm. They provide the best way to obtain full treatment which is important for the bamboo with its small volume fraction of vessel pathways. The salts remain mobile after treatment and continue to diffuse into the bamboo tissue after penetrating through the vessel walls. Bamboo culms or products treated with such preservatives should not be exposed to rain or ground contact.

Many single or mixed salts are in use. The important ones are as follows:

Boron-containing compounds are the most widely used preservatives for protecting bamboo, usually as a mixture of boric acid and borax. Disodium octaborate, formed by mixing boric acid and borax in specific proportion (1:1.4), which has a very high solubility in water, comes as a ready-made formulation. Boron salts are effective against a variety of fungi, insect borers and termites but not against soft rot. They are applied in 5–10 % concentration, depending on the moisture content and the treatment method. Boron salts in a high concentration also have fire-retardant properties.

Zinc chloride/copper sulphate may be used as single salts for protection of bamboo. Solutions of both these salts are highly acidic and can corrode metal fittings. It can retard fire to a certain extent due to the release of water vapour contained in the salt's crystal structure.

NaPCP (sodium pentachlorophenate) is the water-soluble sodium salt of the much-used preservative, pentachlorophenol. It has been extensively used in the past, but is now banned or restricted in several countries. It is basically a fungicide to protect freshly felled lignocellulosic materials against fungi that cause stain and decay.

TCMTB (thio-cyanomethyl-thio-benzothiazole). TCMTB + MBT (methylene-bis-thiocyanate) is a substitute for NaPCP and promoted for protection of green wood/bamboo against sap stain and fungi.

Non-fixed-type formulations may be used for both non-pressure methods and pressure treatment and hence can be applied to bamboo at any moisture content level. The borax/boric acid formulation is the most common preservative for the sap-replacement treatment in several countries and widely used in diffusion treatments.

Non-fixing salts can only be used for bamboo under cover. In contrast to timber, the cortex of the culm better protects the treated tissue against leaching as loss of salts only occurs through the open ends and the nodal parts. These salts have no toxicity to humans.

9.2.2.2.3 Fixing Types

Such formulations no longer remain soluble in water after fixation, due to their chemical reaction with bamboo substances, and are therefore more weather-resistant.

The preservatives are mixtures of different salts in appropriate proportions which interact with each other in the presence of wood/bamboo and become chemically fixed. Chromium is responsible for fixation, copper is effective against soft-rot fungi and a third compound, which varies according to brand, acts against white- and brown-rot fungi and insects. Preservative solutions containing chromium, such as CCB, should not be heated before or during treatment as it precipitates chromium, making them ineffective due to the infiltration of sludge through the fine pit pores of the cells.

CCB (copper-chrome-boron) has excellent fungicidal and insecticidal properties. It is a good alternative to CCA but slightly less effective with a lower degree of fixation, particularly the boron component. A typical formulation contains copper sulphate 3 parts, sodium or potassium dichromate 4 parts, and boric acid 1.5 parts; required levels of retention are 4–16 kg/m^3.

9.2.2.2.4 Oily Preservatives: Creosotes

Tar products of both coal and wood have been used as wood preservatives since biblical times. There are two types of creosotes available, normal creosote from coal tar produced at high temperature and low-temperature creosote produced from tar produced at low temperature. Both creosotes have similar physical, fungicidal and insecticidal properties.

Coal tar creosote is a blend of several fractions of distillation containing more than 200 major and several thousand minor constituents. Creosote is a dark brown or black viscous liquid.

Creosote should be used exclusively for pressure impregnation or hot and cold processes. Being oily in nature it is insoluble in water and in fact imparts water repellency to the treated material. This, in itself, has an important protective effect as moisture is an essential requirement for fungal attack. Its dark brown colour and bad odour prevent its application for indoor use. Creosote is very effective against a wide variety of wood rotting fungi and insects and long-lasting at very heavy doses ranging from 50 to 200 kg/m^3 depending on the use of the treated bamboo. Loss of creosote from treated poles resulting from downward movement within the poles in combination with gravity is well known, which helps protection at ground contact level but leads to a contamination of the surrounding soil. Due to its carcinogenic character, creosote use is regulated in many countries, and its application and use is limited to licensed pesticide applicators.

9.2.2.2.5 Organic Acids

For short-term protection against moulding of the freshly harvested culms with their high moisture content during oversea transport, dipping the culms in harmless solutions of 10 % acetic acid or propionic acid can prevent mould growth totally during the first two sensitive months (Tang et al. 2012).

9.2.2.3 Methods of the Preservative Treatment

For preservative treatments of bamboo, two main treatment methods can be considered, non-pressure and pressure processes.

9.2.2.3.1 Non-pressure Methods

Steeping or Butt-End Treatment

Freshly cut culms with the branches, soon after harvesting, are placed upright in a suitable container (usually plastic buckets) containing a treatment solution. The butt end of the culm is kept immersed in the solution up to about 25 cm. The time of treatment may take 8–14 days, depending on the freshness and the length of the culms as well as on the type of preservative (Fig. 9.24).

The steeping or butt-end treatment is often applied to culms used to support fruit trees or banana plants. Here replacements are needed in great quantities due to

Fig. 9.24 Butt-end treatment of *Thyrsostachys siamensis* in a trough in Thailand (Liese and Kumar 2003)

decay at the butt end. It is a simple process applied without special skills and equipment which can result in great savings due to enhanced life span of the support materials.

Soaking/Diffusion

This method provides good protection and is simple and economical. Freshly felled bamboo or almost fresh culms are stripped of branches and foliage, prepared to size and submerged in a water-based preservative solution for diffusion. Since bamboo has a specific gravity below 1.0 g/cm^3, the material has to be placed in the container and weighed down before the solution is added (Fig. 9.25). Diffusion occurs mainly in axial direction, less in transversal whereby radial is slightly better than tangential.

For larger bamboo culms boring holes on opposite sides in each internode aids penetration but causes difficulties when drawing the solution out again. More effective is the puncturing of the diaphragm with a long stick making holes of about 2 cm; puncturing the solid nodal wall opens up the vessel system and allows access to the internodes. Scratching of the outer skin (Fig. 9.26) is sometimes applied and may help penetration, especially for slow-diffusing preservatives.

Fig. 9.25 Soaking method (Liese and Kumar 2003)

Fig. 9.26 Skin removal by sanding, Co. Bamboo Nature, South Vietnam (Tang and Liese 2011)

Half-split or quarter-split material may be treated in 7–10 days, whereas round bamboo behaves less satisfactorily due to its impervious and refractory skin and requires at least double the time. After soaking, the material has to be placed on a support to let the solution drip off.

If the treated bamboo is to be used only indoors, boron-based preservatives 8 % should be preferred because of their low mammalian toxicity and excellent diffusion behaviour. The soaking process requires larger tanks for efficient production. After soaking, the culm parts should be stored horizontally and closely together for about 1 week to facilitate further diffusion of the preservative before drying.

Vietnam Method

The 'Vietnam method' is a speciality of bamboo treatment, applied for fresh culms. Its principle is the use of the upper internode as a reservoir for the treatment solution. Its inner wall is either scraped at a depth of 1–2 mm or by a round incision with a sharp tool to disrupt the inner terminal layer. The cavity is filled up daily with the preservative solution, which diffuses into the parenchyma tissue, fibres and especially the vessels located in the inner part of the culm wall, where it flows down by gravity. Therefore, this method is also called in Vietnam the 'gravity method'. The treatment is completed, when the liquid at the culm foot has the same colour as the initial solution (Tang 2009) (Fig. 9.27).

Vertical Soak and Diffusion Method

The same principle as of the 'Vietnam method' has been used for the Vertical Soak and Diffusion method developed by the Environmental Bamboo Foundation (EBF),

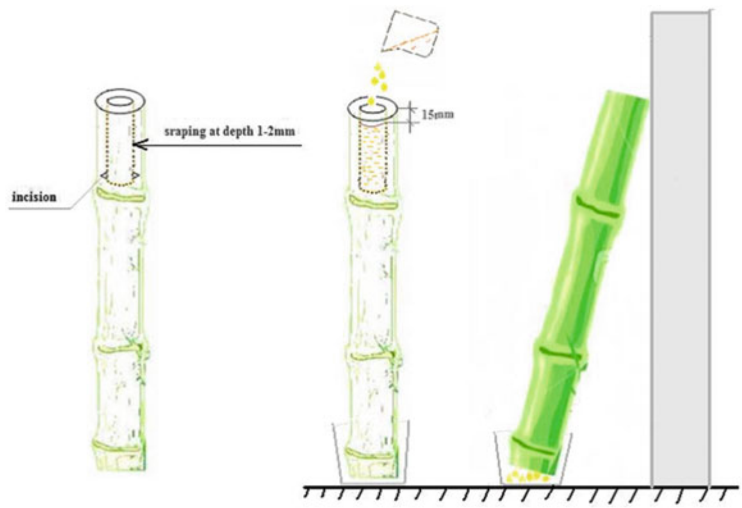

Fig. 9.27 Steps of the Vietnam method for bamboo treatment (Tang 2009)

Fig. 9.28 The Vertical Soak and Diffusion method for treating bamboo culms at the Environmental Bamboo Foundation in Ubud, Bali (Liese and Kumar 2003)

Bali, Indonesia (Fig. 9.28). The standardized treatment process is called 'Vertical Soak and Diffusion (VSD)' system (EBF 2003). This method does not use only the lacuna of the upper internode, but the whole culm serves as a reservoir for the solution as all diaphragms are fractured with a sharpened stick, except the lowest. The lacuna of the internodes is filled up with a borax/boric acid solution and refilled daily. After about 2 weeks the lowest diaphragm is punctured and the solution collected for further use with the required concentration (Tang 2009).

Hot and Cold Treatment

The hot and cold process is one of the most efficient production methods for large quantities of treated wood/bamboos. It can be applied without the need for any sophisticated equipment. Its principle is based on a heating of the bamboo by which the air in the cells will expand and escape. During the following cooling period, a slight vacuum effect occurs which causes the preservative to soak into the cells. Round bamboos are usually treated with two holes on opposite walls of each internode near the node or with ruptured diaphragms to allow access to the inner surface. The submerged bamboo is heated to raise the temperature to about 90 °C and maintained at this level for 2–3 h. The preservative is then allowed to cool down completely, e.g. overnight, and the oil is drained out. After treatment, the culms have to be stored to allow drainage of excess preservatives from the lacuna. This treatment is most suited for bamboo to be used as reinforcements for mud in adobe-type construction in rural and tribal areas.

9.2.2.3.2 Sap-Replacement Treatment

The sap-replacement treatment, also called Boucherie process, named after its French inventor Auguste Boucherie in 1839, has been applied since long for the treatment of wooden poles (Willeitner and Liese 1992). Its use for bamboo was first tried in India by Narayanamurti et al. (1947) and further developed to the 'modified

Boucherie treatment' by Purushotham et al. (1954), Liese (1959) and Liese and Kumar (2003).

The principle of the process is based on a pressure pump that pushes a preservative solution through the entire length of the culm, so that the sap in the vessels is replaced by the preservative. Sap replacement is a safe and environmentally friendly treatment for bamboo culms as the preservative remains entirely inside the culm. Several parameters have to be considered for a successful treatment (Fig. 9.29a, b).

Treatment time depends on the bamboo species, age and moisture content, culm length and wall thickness, the preservative and the pressure applied. In general, culms of 150 mm in diameter and 6 m in length are treated in 30–50 min and those of 9 m in length in 60–70 min with a pressure of 1.0–1.3 bar. The main advantages of the modified sap-replacement treatment are the limited need and cost of the technical equipment, the rapid treatment procedure and the complete penetration of the culm with a clean surface, thus avoiding any risks. As the sap-replacement process has been applied in several countries, some modifications have been developed for simplification and efficiency such as the system applied by Cusack (1999) with a standing treatment tank made from heavy plastic. A detailed description of the process and its modifications has been given by the EBF (1994), González and Gutiérrez (1996), Cusack (1999), INBAR TOTEM (Rao 2001) and Liese et al. (2002).

9.2.2.3.3 Pressure Treatment

Pressure treatment is the most effective method to protect bamboo against adverse conditions. Through pressure treatment, deeper and more uniform penetration of preservative can be obtained, and the retention of preservative can be more closely controlled. In addition, the time required to thoroughly impregnate the bamboo can be reduced. A sufficient demand for this value-added product is needed.

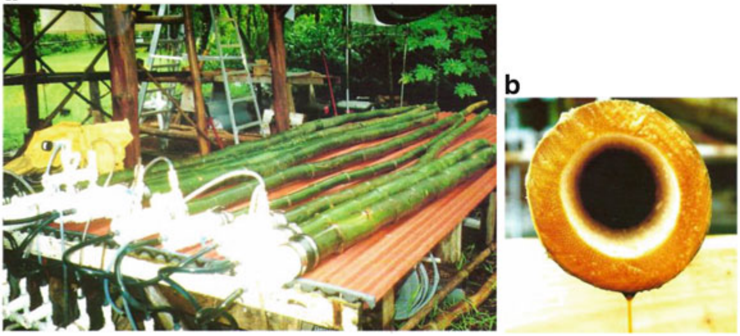

Fig. 9.29 (**a**) Sap replacement with roof sheath beneath by EBF, Bali. (**b**) Preservative solution dripping from the apex (Liese and Kumar 2003)

Fig. 9.30 Culms loaded for pressure treatment, Taiwan (Liese and Kumar 2003)

Fig. 9.31 Ruptured nodal walls by a long iron stick to ease penetration in Thailand (Liese and Kumar 2003)

The pressure method is mainly used for the treatment of dried bamboo. The principle of the process is to force the preservative solution into the bamboo tissue. This can be done by a vacuum and/or by increasing the pressure upon the preservative in the treatment cylinder. It is horizontally orientated for easy handling of the material (Fig. 9.30).

Bamboo culms are difficult to treat due to the refractory nature of their skin which hinders radial uptake. Cracks and collapse can occur, particularly with thin-walled species. To ease penetration, holes are made on opposite sides of the lower and upper part of each internode or the septa are punctured through the entire culm (Fig. 9.31). Split bamboo shows a better absorption as the preservative is pushed

Table 9.1 Vacuum/pressure impregnation schedules for bamboo culm parts (Tang et al. 2013)

Stage	Vacuum/pressure (bar)	Time (min)
Initial vacuum	−0.84	20–40
Pressure	4–10	60–120
Final vacuum	−0.6 to −0.8	15

sidewise into the tissue as well. The basal portion is less treatable than the top; the inner culm portion obtains a higher uptake than the outer one (Tang and Liese 2011). The moisture content of the culms is of more importance than impregnation pressure, vacuum and their duration.

The normal vacuum/pressure impregnation schedule in the treatment of bamboo is given in Table 9.1. The retention obtained depends on the amount of pressure applied, the duration of the pressure period, the bamboo properties and the concentration of the treating solution. For creosote it ranges between 50 and 100 kg/m^3 and for water-based preservatives (CCA or CCB type) between 5 and 15 kg/m^3 expressed as dry salt retention.

Pressure treatment of bamboo can cause environmental pollution, albeit less than for other methods. Preservative residues can remain on the smooth surface of the culm which may drip onto the soil and also dry upon the skin.

9.3 Drying of Bamboo

Drying is an important stage of the manufacturing process of bamboo products. Well-dried culms have the desired appearance, finish and structural properties to meet the requirements for a successful export into demanding markets.

9.3.1 Drying Rate of Bamboo

The drying of bamboo occurs mainly as culm parts. They are round, separated by nodes and inside mostly hollow, called lacuna. At their ends, the metaxylem vessels are the main pathways for releasing moisture. In bamboo the radial passage of moisture is slower than for wood because no ray cells exist. Generally, the anatomical structure of the bamboo culm makes drying more difficult than for wood (Kumar et al. 1994; Liese and Kumar 2003). Comparing with wood of the same density, bamboo takes a longer time to dry (Sekhar and Rawat 1964; Laxamana 1985).

The drying rate of bamboo is notably influenced by its structural features. The studies on bamboo seasoning by Glenn et al. (1954), Laxamana (1985) and Tang et al. (2013) showed a faster drying rate for species with a lower specific gravity and shorter internodes. The culm wall thickness is an important factor influencing controlling the rate of drying. The bottom part of the culm due to its thicker culm walls, therefore, takes much longer to dry than the top portion of the culm. The rate of drying of immature culms is generally faster than that of mature ones, but since the former have a higher moisture content, their rate of drying is longer. In the initial stages, drying occurs quite rapidly, but slows down gradually as drying progresses. Bamboos, from which water-soluble extractives have been removed by soaking, dry faster and take up moisture slower than untreated ones.

9.3.2 Methods of Bamboo Drying

Most drying methods applied for timber drying are also suitable for bamboo. Two major methods can be considered: air drying and kiln drying.

9.3.2.1 Air-Drying of Bamboo Culms

Air-drying is the process of removing moisture from bamboo by exposing it to atmospheric conditions. By proper stacking for air circulation, culms can be dried with no need to add energy above the capacity of the ambient air. There are two types: the horizontal and the oblique stacking (Figs. 9.32 and 9.33). In the same condition of the air-drying, culms which are stacked horizontally dry longer. They need almost double the drying time than those which are standing upright (Glenn et al. 1954; Sharma 1988).

Up to now air-drying is traditionally being used in rural areas and in bamboo factories with small capacities; however, it has some disadvantages. Drying time is long, ranging from several weeks to several months to reach the required moisture content. During air-drying, splits can occur and culms can be infected by fungi, especially moulds. The air-drying depends largely on the climatic conditions. Since the weather cannot be regulated, there is little control over the drying process. The

Fig. 9.32 Horizontal stacking bamboo culms for air-drying under cover (Montoya-Arango 2006)

Fig. 9.33 Oblique stacking bamboo culms for open air-drying, Colombia

air-drying conditions are difficult for reaching a moisture content below about 12 %, as required for later processing (Gandhi 1998; Montoya-Arango 2006).

9.3.2.2 Kiln-Drying of Bamboo Culms

Kiln-drying is more efficient than air-drying. By this method, bamboo can be dried to the required moisture content in shorter time. With great demand for production to export, kiln-drying is a better alternative for air-drying and could ensure high-level bamboo quality.

Kiln-drying is basically a process of stacking bamboo culms or bamboo splits in a chamber (Fig. 9.34) where air circulation and the temperature and relative humidity are maintained and controlled so that the moisture content of bamboo can be reduced to a target level.

9.3.2.2.1 Dry Kilns

Dry kilns are classified in some different ways and often described and named according to its operational technique, type of heating or energy source. The kilns

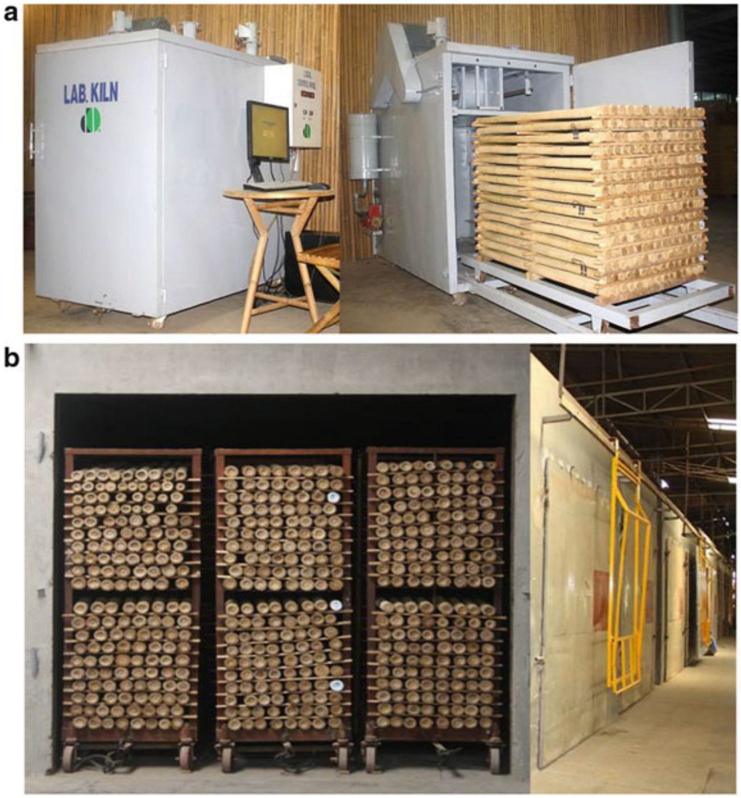

Fig. 9.34 (**a**) Pilot kiln-drying and (**b**) industrial kiln-drying at Bamboo Nature Co., South Vietnam (Tang et al. 2013)

commonly used for timber drying are conventional heat and vent kilns, dehumidification kilns, vacuum kilns and solar kilns. For bamboo drying, the conventional heat and vent kilns, either equipped with heat exchangers (hot water or steam) or directly heated with flue gas from waste incineration, and solar kilns should be considered.

9.3.2.2.2 Kiln-Drying Schedule

Kiln schedules are used to define the temperature and relative humidity needed in the kiln to dry bamboo with a minimum occurrence of degrades and in the shortest time possible. A typical kiln schedule is a series of drying conditions, expressed as temperature and relative humidity, which is used as a directive on how to operate a kiln throughout a period of time comprising the whole drying process. A drying schedule may be designed for manual, semi-automatic or fully automatic control

Table 9.2 Three drying schedules, applying for bamboo culm parts of the three main species of Vietnam (Tang et al. 2013)

Step	Moisture content (%)	Schedule No. 1 Mild		No. 2 Severe		No. 3 Highly severe	
		T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)
1	Over 90	50	80	55	80	65	80
2	90–70	50	70	55	75	65	60
3	70–50	60	60	60	65	70	45
4	50–40	60	50	65	50	70	35
5	40–30	60	30	65	35	70	30
6	30–20	65	30	70	25	75	25
7	20–10	65	20	70	20	75	15

Schedule No. 1 applying for *Dendrocalamus asper,* No. 2 for *Bambusa stenostachya,* No. 3 for *Thyrsostachys siamensis*

Table 9.3 Drying schedule for bamboo splits of *Bambusa blumeana* (Yosias 2002)

Step	Drying time (hours)	T (°C)	RH (%)
1	24	38	30
2	48	38	30
3	56	49	25

systems. It is usually formulated in a table-type format showing the drying conditions at different stages or periods of a drying process.

In kiln-drying, two general types of kiln-drying schedules (Tables 9.2 and 9.3), i.e. moisture content schedules and time-based schedules, are commonly employed. When bamboo is dried by moisture content schedules, the temperature and relative humidity conditions are changed according to the loss of moisture content, which has to be determined either by electrical moisture content measurements or by means of process control samples which are weighed at regular intervals to be able to calculate actual moisture content. When bamboo is dried by time-based schedules, drying conditions are kept constant for certain periods of time and changed to new set point values after this time has elapsed. Sometimes, also combinations of these two types of schedules are applied.

For developing a kiln schedule, culms of one bamboo species, with different diameter and wall thicknesses, initial moisture content and other factors, are dried according to several different drying schedules. The result of the kiln runs has to be evaluated and expressed in the form of using specific drying quality indicators. The schedule leading to the best results is selected and applied. Successful kiln-drying of bamboo requires an appropriate (optimized) drying schedule and good control of drying condition.

Kiln-drying of bamboo culms normally takes 6–15 days, depending on the bamboo species, the kiln and the schedule being used (Laxamana 1985; Montoya-Arango 2006; Tang et al. 2013). Kiln-drying enables to dry bamboo to any moisture content. For large-scale operations with high-level bamboo quality, kiln-drying is more efficient than air-drying. With the growing demand of large quantities of high-quality products for export, many big bamboo manufacturers have expanded their kiln-drying facilities and run batteries of kilns parallel to each other.

9.3.2.3 Drying of Bamboo Splits, Strands and Splinters

Bamboo is not only used and dried in the form of culms but also in the form of splits, strand or splinters, depending on the type of processes for further processing into a wide range of different bamboo-based products. These industrial drying processes can be differentiated into batch-type and continuous drying processes.

9.3.2.3.1 Batch-Type Bamboo Particle Driers

Bamboo splits are normally dried either in bundles or placed on special racks in batch-type drier which are similar to conventional kilns. Due to the smaller dimensions of the bamboo particles to be dried, drying time is much shorter. As for culm drying specific drying schedules will be used. Air circulation can be along the longitudinal orientation of the splits or transversal. With the aim of changing the colour of the bamboo splits, the chambers might also be used for steaming or heat treatment. When temperatures close to or even well above 100 °C are used, the colour of the bamboo split will change from light yellow to light or even dark brown.

Normally drying will be completed within several hours and certainly will not last longer than 1 or 2 days.

9.3.2.3.2 Continuous-Type Bamboo Particle Driers

There are quite a number of different drying systems in the wood sector which can also be used for drying bamboo particles. In belt dryers the material to be dried is spread in the form of thin layers on a moving belt. Hot air is circulated in the dryer and forced through the thin layers. While moving through the kiln, the bamboo particles will lose their moisture and leave the kiln in dry form. To adjust the drying conditions, the temperature, relative humidity, thickness of the material layers and speed of the belt can be changed.

9.3.3 Drying Defects

Defects may develop during and after drying of the bamboo. Some common defects are ruptures of culm tissue such as surface checks, end checks, node checks and splits (Fig. 9.35). Uneven moisture content within individual culms or moisture

Fig. 9.35 Drying defects: end checks and splits (Tang et al. 2013)

differences between the culms of a kiln load as well as discolouration, i.e. mould, blue staining and water staining at the nodes, also negatively affect the drying quality.

Cell collapse is a serious seasoning defect. It occurs during artificial as well as during natural air-drying processes and leads to cavities on the outer surface and to wide cracks in the inner part of the culm. Green bamboo is susceptible to collapse due to capillary tension during drying. Cells while still filled with liquid water collapse which leads to unusual high shrinkage. Collapsed tissue regions exhibit a higher density than non-collapsed regions. In the vicinity of collapsed tissue regions, small internal checks can frequently be observed. This abnormal shrinkage takes place in the early stages of seasoning while the average moisture content is still well above fibre saturation. Immature bamboo is more likely to develop collapse than mature bamboo. Collapse occurs more often during the dry season than during the rainy season, because of more severe drying conditions and the associated faster drying during the dry season. The lower portion with thicker walls is more susceptible to collapse than the upper portion. Slowly drying bamboo species are apparently more prone to collapse than others.

Changes in colour can occur during seasoning. Fresh bamboo normally looks green or rather yellowish according to the stage of maturity; it changes during seasoning to a light green shade. Immature bamboos turn emerald green and mature ones pale yellow. Culms which are slowly air-dried develop a darker yellow colour than those which are dried rapidly in a kiln. Discolourating fungi can grow during kiln-drying when bamboo moisture content is still high and kilns are operating at low temperature and high humidity.

Under very mild drying conditions, the bamboo will not collapse and will shrink almost equally in radial and tangential direction. The bamboo which has been dried carefully will exhibit volumetric shrinkage and swelling behaviour very similar to most wood species but with less anisotropy.

Different bamboo species require drying at different temperatures and different speeds to produce the best results. Each species has a different drying behaviour and, therefore, requires a specific and well-adapted drying schedule. If a correct kiln-drying schedule is used, good results in terms of drying time and drying quality can be achieved leading to a low percentage of rejects and good economic results. Laboratory and industrial investigations on kiln-drying of bamboo have led to suitable schedules for the three main bamboos of Vietnam (Tang et al. 2013), which are now applied by industry to reach high quality of dried culms and derived products for export.

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