6 PHYSICAL - MECHANICAL AND CHEMICAL PROPERTIES

A. PHYSICAL PROPERTIES

For the appropriate use of each specie of bamboo and wood it is very important to study their physical properties (density, moisture content, hardness, etc.) which are related with the characteristics of the material; and also their mechanical properties which are related with the strength of the material (tensile and compresion strength, etc). There is a great relation between the physical and the mechanical characteristics For example the strength properties of bamboo are influenced by the specific gravity and moisture content of bamboo Due to this reasons each bamboo specie can have one or several aplications in one or in severalt fields-(construction, handcrafts etc) depending on their physical and mechanical properties. The main physical properties of the culm are the following:

DENSITY - SPECIFIC GRAVITY

Density is the mass of a material per unit volume.-The specific gravity is the ratio of the density of a material to the density of an equal volume of water. When the metric system is used, the density of the water is 1 gr. per cubic centimeter, and consequently density and specific gravity have the same value.

The specific gravity of culm wood is a measure of its solid wood substance and an index of the mechanical properties of the culm. It depends mainly on the anatomical structure such as the quantity and distribution of fibers around the vascular bundles, as well as fiber diameter, and cell wall thickness. The specific gravity in bamboo varies from about 0.5- 0.9 g/cm3, depending mainly on the species and type of rhizome. According to Du & Zhang et al (1992), the absolute dry density of the clump type (pachymorph) is also higher than that with leptomorph rhizome. In timbers, the specific gravity is in the order of 0.3 -1.04.

The specific gravity or density of bamboo increases from the innermost layers to the peripheral part of the culm and along the culm from the botton to the top with the increase of the fiber percentage (bottom 0.547 - center 0.607 -top 0.675). In the radial direction the variation could be 20-25% in thick-walled bamboos like *Dendrocalamus strictus.*

In thin-walled bamboos, the differences in density are much less. According to Liese (1998) about 50% of the fibres of the culm wall are located in the outer third of the culm wall and this increase its density. These indicates that the strength of the culm wall gradually increases from the inside to the outer part of the wall, and that the strongest part of the culm is the external 1/3 layer of the culm wall.

The specific gravity of the internodes increases from bottom to top (0.75-0.78- 0.78).The specific gravity of the nodes is generally higher than that of the internodes due to less parenchyma, an more fibre wall, whereas bending strength, compression strength and shear strength are lower. (Sharma & Mehra 1970).

A close correlation exists between specific gravity and maximum crushing strength. It seems that resistance to compression parallel to the grain is more or less uniform, hardly being affected by the height of the culm.

The upper part of the culm, with smaller but more vascular bundles and their fiber sheaths, has an increase fiber percentage and hence a higher specific gravity. In most of the species the upper part of the culm is the strongest part to compresion of the whole culm For bending strength and modulus of elasticity, higher values were obtained from the upper part of the culm.

MOISTURE CONTENT

In adition to the anatomical structure of the culm wall, the strength properties of bamboo are influenced by moisture either as vapor in the air or as a moisture content. Moisture content (MC) is the weight of the water contained in the wall and cell lumen of a culm section expresed as a percentage of its oven-dry weight.

For example: If a section of a culm has an initial weight of 10 kg. and the dry weight, once it gets a constant weight in the oven of 7 kg., then the moisture content per cent can be calculated from the following formula

The amount of moisture in a living bamboo varies wide-

$$\text{M.C.\%} = \frac{\text{Initial weight - dry weight} \times 100}{\text{dry weight}}$$

$$\text{Example: M.C.} = \frac{10 - 7 \times 100}{7} = 42.9\,\%$$

ly among species, in individual culms within the same species, in different parts of the same culm, and is influenced by its age and the season of felling. Young inmature culms contain more moisture than mature ones. In the green condition the moisture content in the culm varies from as little as 40% to about 150%.

Young culms have an almost uniform moisture content over their lengt, Young one year-old culms have a moisture content of about 120-130% both at the bottom and top. In culms older than two years the moisture content decreases from bottom to top. e.g. for *Dendrocalamus strictus* about 100% moisture content and 60% respectively.

Generally the internodes have a higher moisture content than the nodes. Across the culm wall the moisture is higher in the inner part than in the outer part. The variation reportrted is 155% for the innermost layer to 70 percent for the peripheral layers. Throughout its life the living culm remains moist or fresh.

Different species show different moisture value even at the same location. This variation is closely related to the amount of parenchyma cells pressent, the site of water storage. The strength properties of bamboo are influenced by the moisture content of the culm as in timber. Generally, in the dry condition the strength of the culm is higher than in the green condition. The differences between the air-dry and green condition are some times relatively small, especially for bending and cleavage. (Liese, 1985).

The moisture content of the bamboo culms varies widely among species, and among individuals culms. In green bamboos the moisture content decreases from bottom to top, but after air drying, the moisture content does not vary greatly from the bottom to the top of the culm. For example, in the studies conducted by Prawirohatmodjo (1988) in several species of Indonesia the moisture content at the basal, middle and top of green *Bambusa arundinacea* was 48.5-38.5-31.6 %. After air-drying it was 15.7-15.6-15.2 %. (Liese, 1985; Sharma & Mehra, 1970; Kumar & Dobriyal, 1988). The moisture content in timber and bamboo is commonly determined using electrical moisture meters.

Equilibrium moisture content

Bamboo and timber are hygroscopic. It means that any dry piece of bamboo or timber in use, placed in a very humid space will take up moisture from the air, but wet bamboo will give up some of its moisture to a drier atmosphere until the amount of moisture in the culm has cometo a balance with that in the atmosphere. The moisture content of the culm at the point of balance is called equilibrium moisture content (E.M.C) and is expressed as a percentage of the oven-dry weight of the culm section. At constant temperature, the equilibrium moisture content depends entirely on the relative humidity of the atmosphere surrounding the culm and the hygroscopicity of the bamboo wood.

Fiber saturation point

Moisture in green bamboo is partly absorbed in the cell walls and partly present in the cell cavities or cell lumen by capillary forces. As the bamboo wood dries and loses moisture, the cell walls do not give off moisture, until the cell cavities are empty. The condition in which the cell walls are fully saturated and the cell lumen are empty is known as the fiber saturation point (F.S.P.). In timbers, the fiber saturation point varies with the species in the range of 28 to 30%. but is commonly taken to be at a moisture content (MC) of about 30%. The fiber saturation point in bamboo is influenced by the composition of the tissue and varies within one culm and between species in the range of about 13% (for *Phyllostachys pubescens*) to about 20% (for *D. strictus*).

SHRINKAGE

Bamboo, like wood, is anisotropic and has as its principal directions the longitudinal or axial, radial and tangencial as referred to the cylindrical shape of the culm In timber, moisture content variations above the fiber saturation point (30%) have no effect upon the volume or strength of wood. As wood dries below the fiber saturation point and begins to loose moisture from the cell walls, shrinkage begins and strength increases.Shrinkage of timber takes place between fiber saturation point and the oven dry condition. It is greatest in the direction of the annual growth rings (tangentially), somewhat less across the rings (radially), and very little along the grain (longitudinally). Unlike timber, bamboo begins to shrink from the very beginning of seasoning. According to Liese (1985) the shrinkage affects both the wall thickness of the culm and the diameter, and it shows a tendency to decrease from the bottom to top. Seasoning of mature culms from green condition to about 20% moisture content leads to a shrinkage of 4 to 14% in the wall thickness, and 3 to 12% in diameter.

Bamboo tissue mainly shrinks in the radial direction, and the minimum deformation occurs in the axial direction. The tangential shrinkage is higher in the outer parts of the wall than in the inner parts. The shrinkage of the whole wall appears to be governed by the shrinkage of the outermost portion which also possess the highest specific gravity. Mature culms shrink less than immature ones.

Shrinkage starts simultaneously with the decrease of moisture content but does not continue regularly. As water content diminishes from 70 to 40%, shrinkage stops; below this range it can again be initiated. Parenchyma tissue shrinks less in bamboo that in timber, while vascular fibers shrink as much as in timber of the same specific gravity. When the moisture content is low, swelling due to absorption of water is almost equal to shrinkage. Moist heating leads to irreversible swelling in all directions.

Variation in moisture content, density and strength along the wall thickness of bamboo is probably responsible for the adverse behavior of bamboo in use. Green bamboo experiences show irreversible and excessive shrinkage well above the fiber saturation point with only partial recovery at the intermediate stages.This behavior is linked to collapse. Below the fiber saturation point the behavior is similar to wood.

Bamboos dries best under air dry conditions. Rapid drying in kiln may lead to surface cracking and splitting due to excessive shrinkage. Values of shrinkage from the freshly felled to the oven-dry state were determined for *Phyllostachys pubescens* as follows: tangential, 8.2% for the outer part of the wall, and 4.1% for the inner. Radial, 6.8 for the outer part and 7.2% for the inner. Longitudinal, 0.17% for the outer part, and 0.43% for the inner. The percentage of swelling decreases with an increase of basic density. (Liese 1985, Sekhar & Rawat 1964. Sattar et all 1992).

Timber increases in strength as it dries. For example, the strength in endwise compresion of small pieces is about twice as great for a moisture content of 12% as for green timber, and drying to about 5% moisture content will some times triple this property (Wood hand book 1955). Unlike timber, the increase in strength in bamboo as it dries, is much lower than that of timber. For this reason there is not any risk in using green bamboos for construction purposes as far as strength is concerned. (See Seasoning or drying of bamboo).

In the study conducted by Prawirohatmodjo (1988) in 6 species from Indonesia related to comparative strengths of green and air-dry bamboo, he found that the moisture contents of green bamboos decrease from bottom to top of the culm e.g., in *Dendrocalamus asper*. 76.-36%; This is due to the amount of parenchyma of the culm wall which also decrease from bottom to top. (Liese,1980).

The average bending strength for the bottom, middle and top part of *Dendro-calamus asper* (green = 6,873 N/cm2; Air-dry =10,336 N/cm2); *Gigantochloa apus* (green =10,203 N/cm2; Air dry = 8,750 N/cm2) . In compression strength the total maximum crushing for the bottom, middle and top portion were respectively for *Dendrocalamus asper,* green =1,462; 2, 453; 2942 N/cm2. Air-dry=2,155; 3,043; 4,261 N/cm2.;*Gigantochloa apus,* green=2,173; 2,372; 2,650 N/cm2; air-dry 2,729; 3654-4,864 N/cm2. In tension parallel the average in *Dendrocalamus asper*; greeen = 28,426 N/cm2.; air-dry 51,916.*Gigantochloa apus,* green = 29,410 N/cm2; air-dry=29,891 N/cm2

SPLITTING

Unlike trees, bamboos has not radial cells which in trees increase their shear strength parallel to the axis. This is the reason why bamboo culms split easily. This could be a disadventage for nailing bamboo but also it could be a great adventage because it makes easy to split bamboo into fine strips for making baskets of various sorts, framework for umbrellas, window screens, fans and so forth.

The splitting quality depends on the number of fibrovascular bundles. The greater the number, the easier the culm splits. The area occupied by the vascular bundles is the sum of those areas seen in cross section. The species belongin to the genus *Phyllostachys*, specially *Ph. niogra henonis* and *Ph. bambusoides* have good spplitting quality so that they are very easily split.

THERMAL CONDUCTIVITY

Thermal conductivity is a measure of the rate of heat flow through materials subjected to a temperature gradient. Bamboo like wood is a cellular substance and in the dry state the cell cavities are filled with air , which is one of thepoorest conductors known. Because of this fibrous structure and the entrapped air , bamboo has an excelent insulation property .Experiments show that the coefficient of thermal conductivity of bamboo is a little higher than that of wood, but the diffference is too small to be taken into account.

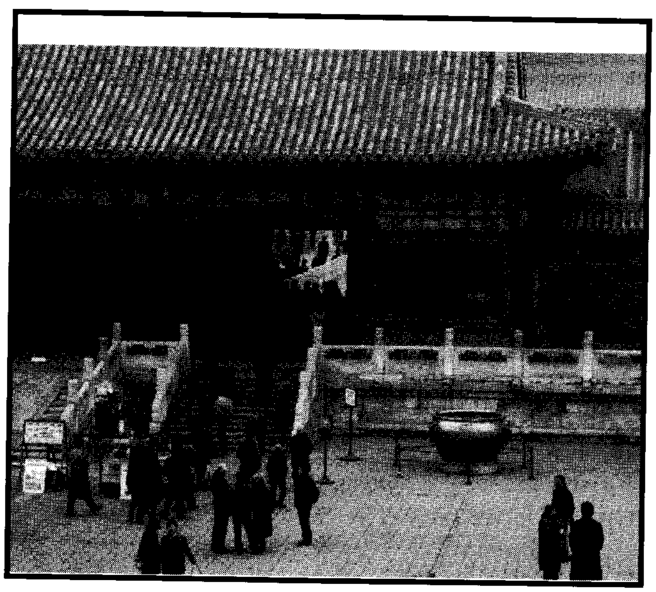
The thermal conductivity of wood is about two to four times that of common insulating materials. For example, structural softwood lumber has a conductivity of about 0.75 British thermal units per inch per hour per square foot per degree Fahrenheit, compared with 1.500 for aluminum, 310 for steell, 6 for concrete, 7 for glass, 5 for plaster, and 0.25 for mineral wool.The thermal conductivity is affected by a number of basic factors such as density, moisture content, temperature. It increases as the density, moisture content, temperature, or extractive content of the wood increases.

HARDNESS

Hardness represents the resistance of bamboo to wear and marring. It is measured in wood by the load required to embed a 0.444 inch ball to one half its diameter in the wood. Values presented are the average of radial and tangential penetrations (Wood Handbook 1987). This method of testing used in bamboo can probably produce the separation of the fibers in the culm and consequently a crack along the internodes, if the ball is located in the center of the internode. For this reason ,it is better to locate the ball near the node where the shortest fibers of the internode are found.

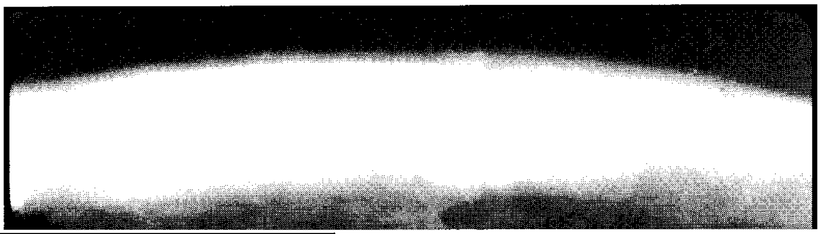
As was explained before, the strongest part of the culm wall is the external third, which includes the largest number of fiber bundles, and the least strong is the internal third of the culm wall where the least number of fiber bundles and the largest amount of parenchyma cells are found.

The cortex or outermost layer of the culm wall consists of two epidermal cells layers with a high silica content which strengthens the epidermal layer. The exterior layer of the cortex is covered by a cutinized layer or glossy surface, which is known as cuticle, and is composed of cellulose and pectin with a wax coating on top. Beneath the epidermis lies the hipodermis, consisting of several layers of thick walled sclerenchymatous cells. These two layers impart an extraordinary hardness to the outer surface of the culm, forming a sort of protective shield against insects, hits, wearing out, and even for improving the acoustical quality of the sound field in a bamboo forest.



Figs 6.1 and 6.2 - *The extraordinary hardness of bamboo cortex is utilized in China in the form of bamboo splints for covering the steps of wooden staircases to protecting them from wearing out, as can be seen in photographs 6.1 and 6.2.taken in the Forbidden City in Beijing, China, which is visited daily by thousands of tourists.*

THE BAMBOO THAT SURVIVED THE RADIATION OF AN ATOMIC BOMB



THE INFLUENCE OF BAMBOO PHYSICAL PROPERTIES ON THE ACOUSTICAL QUALITY OF THE SOUND FIELD IN A BAMBOO FOREST

Sakai, Shibata and Ando (2001), investigated the acoustical quality of the sound field in a bamboo forest of the specie *Phyllostachys pubescens* in Kioto, Japan, in 1997. They concluded in their paper *"Ortogonal acoustical factors of a sound field in a bamboo forest"*, published by the Acoustical Society of America (2001), that the sound field in a bamboo forest have excelent acoustical properties, due to the physical characteristics of their culms such as uniform diameter, hollow tube structure and hardness or rigid surface

Before this investigation, a number of acoustical measurements were carried out in three tree forests in England under different atmospheric conditions of temperature, humidity, and sound speed. The reverberation time and the attenuation of the sound pressure level (SPL) as a function of distance in a tree forest were also investigated. A prediction model that considered excess attenuation by the ground and multiple scattering by trees was used. However, it is quite difficult to estimate sound fields due to the complicated conditions of excess attenuation , multiple scattering effects, temperature, tree leaves, tree distribution, and so on, especially for the higher frequency range.

Recent results related to the acoustical quality of sound fields in a tree forest are briefly introduced by Sakai *et al, (1998)*. In this study the temporal and spacial factors were analyzed and the results were compared with those in a concert hall. First, subsequent reverberation time T_{sub} became larger mainly in the middle frequency range such as 500 Hz and 1 kHZ of 1/1 octave band center frequency and at measurement points far (40 m) from the sound source.

Second, the decay level of reverberation in the forest kept its level after an initial decay as a result of multiple scattering from tree trunks althought it normally decreases linearly in an inclosure. Such a decay curve shape is generally considered to be specific characteristic of a sound field in the tree forest.

Third, IACC, which is defined as a maximum value of interaural cross-correlation functions between signals at the ears withinits time duration t=± 1 ms, decreased at positions farther from the source. Finnally, SPL relative to that at 5 m from the source decreased by about 12 dB for every doubling of distance, although in a free field it decreases in accordance with the low inverse square.

This article o only include part of the investigation carried out by Sakai,Shibata and Ando (2001) about the acoustical characteristics in a bamboo forest obtained by using the same procedure for the previous measurement in the tree forest and in an enclosure. Bamboo is unique for its uniform diameter, hollow tube structure and rigid surface. In the previous forest the wave- length of the frequency band that was efective for T_{sub} and IACC approximatelly matched the diameters of the tree trunks (0.6 m in average). thus a bamboo forest was selected in order to ensure the relationship between the efective frequency band and trunk diameter. In such a sound field, complicated conditions such as multiple scattering from tree trunks, excess attenuation by the ground , trunk distribution , and many atmospherical factors , including temperature, humidity and wind affect the sound field. Considering these factors , the sound field is difficult to simulate and the impulse responses are to complicated to calculate. At the present stage, therefore the only effective approach is to use measure results.

Site description Acoustical measurements were conducted in part of the bamboo forest of the specie *Phyllostachys pubescens* which consists of randomly distrubuted culms of bamboo. The density of bamboo in the area was about 50 culms per 100 m². Althought the tree diameters in the previously studied forest were almost random between 0.3 and 1.0 m, those in the bamboo forest were almost uniform with its diameter about 0.13 m. The height of bamboo around the area was about 8 m. The area had a space about 3 m wide in front of the source without any bamboo. The area in front of the sound source had a gentle slope (10-12°). On the day when the measurements were conducted, there was not wind, and the temperature was between 25-27° C.

Procedure The measuring procedure was exactly the same as for the previous measurements in the tree forest Receiver positions for sites, 5-10-20 and 40 m from the sound source S were selected. An omni directional dodecahedron loud speaker was used as a sound source with its height 1.5 m. As a receiver, a person with a tiny half-inch condenser microphone at each ear was used. The maximum length sequence (MLS) was used as a source signal . The signal was radiated from the dodecahedron loudspeaker with its A-weighted SPL 100 dB at 1 m from the source. In this measurement, sequence length was 2.7 s, the number of average was four and sampling frequency was 48 kHz. Binaural impulse responses (h_l and h_r) at each receiving position were calculated using the Hadamard transformer of signals at both ears, all acoustical factors were calculated from the binaural impulse responses.

The results were compared with previous results for a sound field in a tree forest (Sakai, S.Sato and Y. Ando, 1998). The IACC, which is defined as a maximum value of the normalized interaural cross-correlation function between signals at the ears , was 0.07 (4kHz) and 0.16 (2kHz) at positions 20 and 40 m from the source, respectively. these values are much better than those in the previously investigated forest.

The subsequent reverberation time T_{sub} was up to 1.5 s in the frequency range above 1 kHz at the position 40 m from the source. For certain music sources with higher frequency components, therefore, sound field in the bamboo forest have excellent accoustic properties The results show that the sound field in a bamboo forest is suitable for listening to music. Thus, these measurements provide valuable and useful information for designing outdoor concert spaces using bamboo an other natural forests and concert halls having a number of columns

Like the sound field in the ordinary forest previously investigated. The specific sound field was determined, especially in terms of the factors T_{sub} and IACC. The tendency found was that the effect appears in higher frequency ranges (around 1 kHz). than in the sound field in an ordinary tree forest.

B.- MECHANICAL PROPERTIES OF THE CULM

Wood and bamboo are both ancient organic building materials and their use in this field has been more traditional than technical. Metals are of more recent origin and are produced from a materials technology. To meet the competition from metals, a technology has arisen in the United States and Europe during the past 80 years for the appropriate use of wood in the construction field and for the manufacture of composite materials such as wood laminated beams, plywood boards, etc. For this purpose, in the forties, several universities, research centers and wood associations of the United States, in conjunction with the American Standard forTesting Materials (ASTM), laid down the standard test procedures for the determination of the mechanical properties of timber, which include the dimensions and shapes of the test specimens based on the anatomy and morphology of softwoods and hardwoods.

However, in the case of bamboo, in the Americas and in Asia there are no forest research centers or universities interested in studying the norms or standard test procedures for the evaluation of the mechanical properties of their native bamboo species, because it has been considered unnecessary since in these continents bamboo has been mostly used by the poor people for the construction of their houses, in which they employ traditional construction technologies which do not require architects or engineers.

The first serious study on the mechanical properties of bamboo was carried out in Germany in 1912 by Von R. Bauman. He found that the tensile strength of the outer culm wall was about twice as strong as the interior layer ([illegible] - 1504 Kg/cm2). The strength of the entire thickness of the wall cross section was 2070 Kg/cm2. In a smaller diameter bamboo (Tonkin cane) with an outer diameter of 5.5 cm, the tensile strength of the outer and interior fibers was 3543 and 1353 Kg/cm2 respectively, which is greater than in the 8 cm diameter bamboo.

The most complete research related to the mechanical and chemical properties of several species of bamboo was carried out in Japan by Sioti Uno at the Utsunomiya Agricultural College in 1932. He found that the top part of the culm is stronger in compression than the central and lower part of the culm and that the central part is stronger in tension than the upper and lower parts of the culm; and that there are species such as Bambusa stenostachya in which the exterior layer of the culm wall of the lower part of the culm is 5.5 times stronger than the interior layer, as can be seen in the tables in this chapter.

The most important research about the mechanical properties of bamboo and its application as reinforcement in concrete instead of steel bars, was promoted by the United States Army during the Second World War and carried out by H.E. Glenn in 1944 at Clemson Agricultural College in South Carolina and published in 1950.The purpose of this research was to study the use of both bamboo strips taken from giant bamboos and small diameter culms as reinforcement in concrete. The final results of this research were applied during the Vietnam War in the construction of warehouses and other types of buildings with disappointing results. (See Concrete reinforced with bamboo.)

The reason for this lack of success was that at that time (1944) there was no information about bamboo anatomy, which is different from that of timber, and Glenn, like many other people, erroneously considered that if both bamboo and wood were woody plants, it was possible to evaluate the mechanical properties of bamboo culms using the norms for shapes and dimensions of test specimens recommended by the ASTM for the evaluation of the mechanical properties of wood. This was a big mistake because bamboo anatomy and morphology are quite different from that of wood.

It is very important to point out that the reason the ASTM had for using small specimens for testing the mechanical properties of wood is that the strength properties of any species of wood are truly representative only when obtained from tests on small, clear pieces of wood, because the effect of such things as knots, cross grain, checks and splits, and wood compression is then eliminated (Hoyle Jr. 1973). All of these defects are not present in bamboo wood because it has a different type of anatomy and morphology. On the other hand, the structure of the bamboo culm is composed of a series of internodes separated by nodes which impart great mechanical strength to the culm and permit the culms to be bent by the wind without damage to their structure. Consequently, each internode with the two nodes forms a structural element and this has to be tested instead of using small rings taken from the internode which are 10 cm high or ten times the thickness of the culm wall, as is erroneously recommended by some bamboo researchers.

The problem is that all of the methodology followed by Glenn (1944) in his experiments, and the dimensions of the test specimens used for testing the mechanical properties of bamboo based on the recommendations of the ASTM for testing the mechanical properties of wood have been taken as a guide by most reseachers and students at different engineering colleges in Europe, the United States and South America who have carried out studies or theses related to the mechanical properties of bamboo and its use as reinforcement in concrete since 1950. This means that in all of these studies bamboo has been tested erroneusly, as if it were timber. As a consequence of the inadequate data obtained using different methods of testing, bamboo culms and the use of widely varying dimensions and shapes of test specimens, there are many variations and significant differences in the results obtained in studies of the mechanical properties of bamboos. This is why the studies that have been carried out so far in different parts of the world on the mechanical properties of different bamboo species are not trustworthy.

For the above reasons, and due to the growing interest in planting several bamboo species for the development of new industries for the production of composite materials and for the construction of spatial structures, which require a study of the mechanical properties of the bamboo species; it is very important to develop a new methodology and a new type of specimens for testing the mechanical properties of bamboo culms, based on the anatomical structure, morphology, and physiology of this organic material, in this chapter I am suggesting a new methodology for testing bamboo that I have developed based on the anatomy and structural behavior of bamboo.

DIFFERENCES BETWEEN WOOD AND BAMBOO

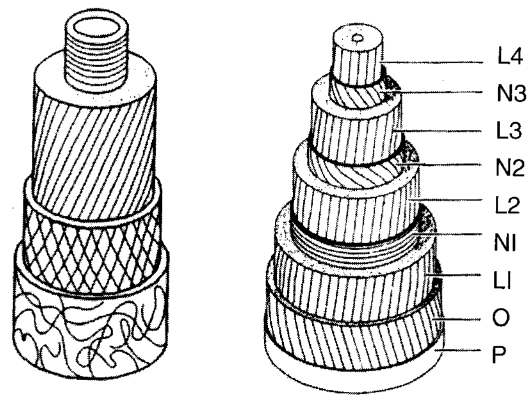
The first thing that wee have to establish is that bamboo is not a tree but an arborescent grass that the only thing that it has in common with trees (*hardwoods* and *softwoods*) is that both are woody plants, with very similar chemical components (See Table 6-2),but both have differences in their anatomy, morphology, in the growing process, and even in their mechanical properties which are superior in bamboo. (See Table 6-1) On the machro scale, wood is a solid cylinder composite of bark, sapwood and heartwood, conformed by alternative spring and summer wood which consists of cells of various sizes, shapes and functions, while bamboo is a hollow cylinder with many internodes separated by nodes. These nodes play an important role of the axial crack arrester, in preventing the cylinder from structural buckling, in strengthening bamboo and in increasing bamboo's rigidity.

In its ultrafine structure the cell wall of wood fiber appears as a multilayered composite cylinder and the helical angle s of the microfibrils in each layer are different, greatly affecting the mechanical properties of the wood. The majority of cells are elongated and pointed at the ends and are called *fibers (*in hardwoods), or *tracheids* (in softwoods); they impart strength to the wood.

Bamboo can be taken as unidirectional ligno-cellulosic composite material, reinforced axially by bast fibres sheaths in vascular bundles surrounded by a matrix of thin-walled cells known as *parenchyma.*

The vascular bundles consist of conducting tissue (metataxylem vessels, sieve tubes with companion cells) and fibers. The total number of vascular bundles decrease from outer to inner part and from bottom to top On an average, a culm consists of about 52% of parenchyma, 40% of fibers and 8% of conducting tissue. These values vary with species (Liese 1998). Regardles of the five type of vascular bundles seen in the first part of this book, all bamboos exhibit striking differences in the distribution of cells within one culm, both horizontally and vertically.

On the micro scale, wood tracheid and bamboo bast fiber are both hollow tubes or cylinders composed of several concentric layers and each layer is reinforced with helically wound michro fibrils (Fig, 6.5). In bamboo cells the lamellation consist of alternating broad and narrow layers with different fibrillar orientation. In the broad lamellae the fibrils are oriented at small angle to the fibre axis, whereas the narrow ones show mostly a transversal orientation. Liese,1985. Li, Zeng, Xiao, Fu, Zhou (1995). Amada *et al* (1996).



(a)
Wood tracheid fiber

(b)
Bamboo fiber

Fig. 6.5 (a)*Schematic diagram of wood tracheid. and* ***(b)*** *polylamellate structure of a thick bamboo fiber.* ***(P)*** *= Primary wall,* ***(O)****= outermost layer of the second wall* **-(L1-L4)** *broad layers.***-(N1-N3)**, *narrow layers (After Wai et al, in Li et al 1995)*

Due to the differences which exist in the anatomy and morphology between wood and bamboo it is necessari to establhish a new methodology or test procedures for the determination of the mechanical properties ot bamboo which include the dimensions and shapes of the test specimens, based in the anatomy and morphology of bamboo, which are going to be discussed in this section .

Table 6-1 Mechanical properties of several woods and bamboo *(Phyllostachys edulis)*

Woods	Strength (MPa)	Mod. Elast (GPa)	Density (g/cm3)
Cedar	29.3-48.5	4.4-9.8	0.29-046
Fir	30.7-33.8	5.9-6.7	0.31-0.34
Pine	34.0-41.6	6.5-8.8	0.36-0.42
Spruce	31.0-40.0	7.3-8.5	0.38
Hickory	62.5-81.0	8.9-11.4	0.56-0.67
Oak	47.7-74.9	7.9-12.4	0.53-0.61
Bamboo (fibre)	610	46	1.16
Bamboo (matrix)	50	2	0.67
Bamboo (composite)	140-230	11-17	0.6-1.1

Source: (Bodig & Jaine, 1993) in Amada *et al* (1996)

Table 6-2 Chemical composition and tensile strength of wood and bamboo *(Ph. edulis)*

Components	Wood	Bamboo
Cellulose (%)	40-50	45.3
Hemi-cellulose (%)	20-35	-
Lignin (%)	15-35	25.5
Polyoses (%)	--	24.3
Extractive (%)	<10	2.6
Tensile strength (MPa)	34-220	150-520

Source: Li, Zeng, Xiao, Fu, Zhou (1995)

THE MAIN FACTORS WHICH WE HAVE TO KEEP IN MIND FOR STUDYING THE MECHANICAL PROPERTIES OF THE CULM

Every bamboo species has its own anatomical, physical and mechanical properties, which varies from one specie to another, even within the species of the same clump.

These variations depend on several factors such as: the environmental conditions under which they grow, which includes the climate, altitud above sea level, soil, the chemical components of the soil, and the topographical conditions.

For the above reasons, one cannot use the strength values, for example, of *Guadua angustifolia*, and apply them to other species of the same genus, even if the other species grows in the same area, for example, *Guadua amplexifolia*."

1.-The Climate

In the study conducted by Gnanaharan (1991) related to the physical and mechanical properties of mature culms of *Dendrocalamus strictus* grown in three different locations in Kerala, India, at different altitudes (1,000 - 200 - 800 meters) respectively, and with different annual rainfall (2,500 to 3,000; 1,000 to 1,500 and 1,000 to 1,500 mm); he found a great variation in the physical and strength properties depending on the location from which the bamboo wascollected. *Dendrocalamus strictus* that grew in a moist area had longer internodes, a larger diameter and poorer strengths in modulus of rupture and modulus of elasticity. *D. strictus* that grew in a dry place was much stronger, even though the culm and internode length and diameter were shorter. This means that the best bamboo of this species is that which grows in a dry location.

2.-The Topography

In Indonesia, the Sundanese who live in West Java, use the bamboo species *Gigantochloa pseudo-arundinacea* for house construction. They believe that the best quality bamboo, in strength, of this species should be harvested from the slope inhabiting groves, rather than from those growing in the valley. In order to determine whether the Sundanese pratice had any scientific justification, Soeprayitno et al (1988) undertook a study of the physical-mechanical properties of this species growing on the hill slopes and in the valleys of Cibitung village near Bogor in West Java.

The results show that the preference of the Sundanese for slope-inhabiting bamboo is scientifically justified, because the specific gravity, static bending and tensile strength of the culms growing on hill slopes are higher than those of culms growing in the valley.

The modulus of rupture (MOR) of bamboo culms from the two habitats did not differ significantly. On the other hand, the modulus of elasticity (MOE) and tensile strength of the slope-inhabiting bamboo culms were markedly higher than the other, maybe due to the higher specific gravity. This information is very important for rural people who have sloping areas on their farms where they cannot use their tractors for preparing the soil. In this case, it is recommended that they use these sloping areas to plant giant bamboos for construction and other uses. Bamboo is also the most appropriate plant for planting in areas where there are problems of erosion or to prevent it. The scientific reason for this belief is clearly explained in the studies carried out by Nogata & Takahashi (1995) in item No. 9 in this section.

3.-The soil

Most bamboo species grow in fertile soils and at certain elevations to develop their best physical and mechanical properties. According to Deogun (1936), *Dendrocalamus strictus* is the only bamboo species which grows in very good soils as well as in coarse grained dry soils such as those derived from sandstone, granite and granitic gneisses. It is is completely absent from the pure quarzite soils. In some places of India it has been successfully planted on sand dunes. This bamboo, as mentioned before, develops its best physical and mechanical characte-ristics when it is cultivated in dry areas. Therefore, I consi-der this species to be one of the best in the world.

4.-The altitude above sea level

Guadua angustifolia, only grows in fertile soils from sea level to 1800 m. These specia develops its best physical and mechanical properties when it grows at about 1400 meters above sea level (in Colombia) and particularly in volcanic soils like those of the area around the city of Armenia in Colombia. At this location, this species has an average diameter of 14-16 cm, while at sea level on the coast of Ecuador, it has an average of 9-10 cm at the base.

From the above, we can conclude that if the species *Guadua angustifolia* which grows in the coastal area is going to be used as a structural element, it is not possible to use the strength values obtained from the study of the mechanical properties of *Guadua angustifolia* which grows at 1,400 meter above sea level because they are different from those of the species which grow at sea level. In this case, it is necessary to study the mechanical properties of the species which grows at sea level. This is why it is necessary to study the mechanical properties of each giant species of each genus located at different elevations.

5.- The influence of the culm's age

For trees, aging has considerable influence on the cellular make-up and thus on the technological properties. In bamboo, aging effects are restricted to the primary tissue and this is an important factor for the development of strength properties in bamboos. It is a general assumption that bamboos mature until they are about three years old and have reached their maximum strength.

According to Liese (1985), investigations with *Dendrocalamus strictus* have shown that when they are green, older bamboo culms have higher strength properties than younger ones (the moisture content of the latter is much higher).

When they are dry, however, higher values were obtained at the age of one and two years than from older culms. Tests on splints from the central portion of the culm wall indicated better strength properties for one year old bamboos than for two year old ones, whereas those of older Comprehensive tests by Zhou (1981) revealed a further increase of strength properties with age, as well as for radial and tangential bending strength up to 8 years. Older culms (10 years) decreased in all strength properties.

In most of the research which has been carried out in different universities in the United States and Europe, where giant bamboos do not grow, this material has been imported from China, Japan Indonesia and India.

During the long trip by ship, they have lost their natural color and consequently it is impossible to determine the age of the culms. Furthermore, because of the lack of experience or ignorance, many researchers do not know how to determine the age of the culms, or they believe that this is not necessary in order to determine their mechanical properties. As a consequence, there are many differences in the results because mature culms and very young culms are tested at the same time. Due to this reason, the results of most of the researches which has been carried out in the United States and in several countries of Europe, which imported the bamboo, are not trustworthy.

The best method for selecting bamboos which are going to be studied is that the researcher visits the plantation and choose the bamboos, with the help of an expert, before exporting them, and also to find out the scientific name of the species which are going to be tested.

6.-Parts of the culm which have the lowest and highest strength

a)-In the whole culm. According to studies carried out by Sioti Uno (1930) and other researchers, the mechanical properties vary from the base to the top of the culm. If we divide the useful part of the culm into three sections of equal length (See Fig. 6.6), in most cases the top section is stronger in compression and bending strength than the central and lower sections. The central section, which has the longest internodes is stronger in tension than the top and lower sections; and the lower section has the lowest values for mechanical properties, in most of the cases.

b)-In the internode. According to studies carried out by Liese, in the internode, the fibers are short in the area near the nodes and the longest are found in the center of the internode (See Fig. 6.6(a). Consequently, the strongest part is located in the center of the internode, and the weakest near the nodes.

For this reason, if we test one internode in tension, with the nodes and another internode without the nodes, according to Zen, Li, Zhou (1992) (See Table 6-3), the tension strength of the cylinder which is tested with the nodes will be 19.2 % lower than that of the cylinder tested without nodes. In compression, the cylinders tested with nodes will be 6.4% lower than the cylinder tested without nodes.

c)-In the culm wall. The specific gravity and the tension and compression strength of the culm wall increase from the internal to the external surface ofthe culm. Consequently, the zone with the lowest strength is the internal 1/3 of the culm wall.

7.-The extraordinary tensile strength of vascular bundles

As mentioned before, the vascular bundles of bamboo internodes consist of two metaxylem vessels, phloem, protoxylem which are partially surrounded by fiber bundles which impart strength to the culm. Each one of these vascular bundles which looks as points in the culm section, once enlarged looks like the ones shown in Fig. 1.21. (Page 23).

The shape and size of vascular bundles change tremendously across the bamboo wall and along the culm. The size of vascular bundle is getting smaller toward the exterior surface of the culm wall. On the other hand, the distribution density of vascular bundles is much higher near the exterior surface as compared to that near the interior surface of the culm wall or endodermis.

M.C.Yeh (1995) conducted an interesting study in Taiwan related to the evaluation of the tensile strength of vascular bundles of the specie *Phyllostachys pubescens.*

The size of vascular bundle is getting smaller toward the exterior surface of the culm wall. On the other hand, the distribution density of vascular bundles is much higher near the exterior surface as compared to that near the interior surface of the culm wall.

The bamboos of the specie *Phyllostachys pubescens.* were selected from a plantation which grows in the central Taiwan at 1200 m above sea level. The ages of the bamboo culms were 4-5 years.The portion used for the experimens were located about 1.80 m above the ground from where were taken sections of 1.20 m long.

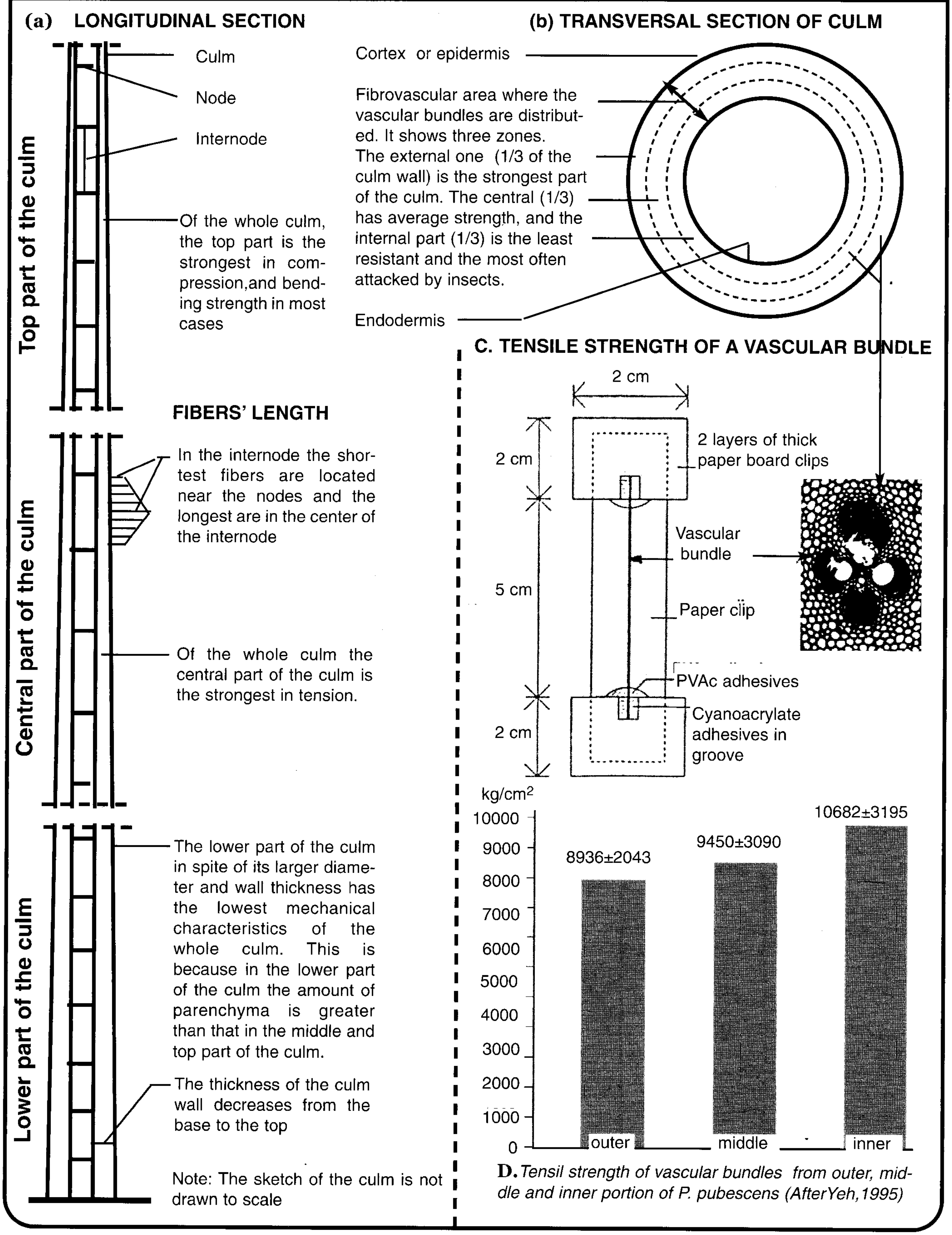
All the split bamboo culm were wrapped with plastic bags to prevent the evaporation of moisture so the fiber remain flexible. The separation of vascular bundles were done mechanically with some skill instead of using chemical process.

Twenty samples of vascular bundles 7 to 9 cms in length were prepared and divided into three portions across the wall thickness by knife, i.e. inner, middle and outer portion, in order to evaluate the strength of vascular bundles from different portions of bamboo wall and all conditioned under 65% RH and 23° C for moisture equilibrium.

The tensile tests were performed in a Shimadzu AG-10 T universal testing machine with a load cell of 50 kgf capacity, and a testing speed of 1 mm/min. was used. The vascular bundle is mounted between two pairs of 1.5 mm thick paper board on both ends and the clear length of vascular bundle between paper board clips is 5 cms (Fig. 6.6 C). The paper board is carved a small groove about 1.5 cm long to accommodate one of the ends of vascular bundle to prevent crash during the test and then glued together with cyanocrylate adhesives.

The plastic PVAc glue was then applied at the junture of bundle and paper board to release the possibility of stress concentration at that particular location.The resulted tensile strength of vascular bundle from different portions of bamboo wall are shown in Fig 6.6 D. (Tensile strenght of the vascular bundle).

Fig.6.6 AXIAL AND TRANSVERSAL BAMBOO STRUCTURE



D. *Tensil strength of vascular bundles from outer, middle and inner portion of P. pubescens (AfterYeh,1995)*

As can be seen in table 6-6 D, there are not significant difference in the tensil strength values for vascuar bundles among inner, middle and outer portions of bamboo wall.

Outer portion = 8936 ± 2043 kgf/cm² ; Middle portion=9450 ±3090 kgf/cm² ; Inner portion =10682±3195 kgf/cm². The average tensile strength value = 9689 kgf/cm²

The average number of vascular bundles is estimated across the bamboo wall from microscopic photos.There seems to be no variation in the number of vascular bundles in bamboos up to a height of 12 feet. However, significant differences in the amount of vascular bundles can be found across the bamboo wall, i. e., about 5.41/mm² for the outer portion, 2.69/ mm² for the middle portion, and 1.97 mm² for the inner portion.

The number of vascular bundles in the outer layer of the culm is twice that in the middle layer, also 2.75 times that of the inner layer. The difference of the tensile strength among the inner, middle and outer layer of strip specimen can be explained by the difference in the amount or distribution of vascular bundles across the bamboo wall mentioned above by.M.C.Yeh (1995).

8.-The mechanical properties of each of the internodes vary along the culm

Table 6-4 show the results of the study carried out by Sjafii (1984),on the mechanical properties of the internodes 1-3-5-7 (including the nodes) which correspond to the lower part of the culms of 4 different species of bamboo.

Table 6-3 AVERAGE MECHANICAL PROPERTIES OF BAMBOO INTERNODES WITHOUT AND WITH NODES (*Phyllostachys pubescens*)

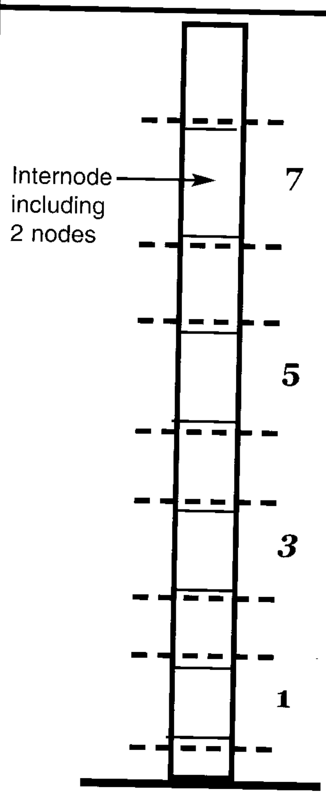
Property	Without node (MPa)	With node (MPa)	Change due to node
Tensile (Longitudinal)	263.4	212.8	-19.2%
Flexural (L)	136.6	131.3	-3.9%
Compressive (L)	62.6	58.6	-6,4%
Shear (L)	13.1	12.2	-6.9%
Tensile (Transversal)	3.0	3.6	+20.%
Cleavage (T)	0.6	0.8	+33.3
Toughness (L) (in kJ/m²	89.6	77.7	-13.5%

Source: Zen, Li, Zhou (1992) in Zhou (1994)

This study concludes that each of the internodes of the whole culm has different mechanical properties, which in some species do not increase progressively from bottom to top. For example, in *Dendrocalamus asper* the compression strength of the 1st inter-node is 639 kg/cm², and in the 7th is 566 Kg/cm².

However, they increase in the center and top parts of the culm, where the compression and tension strength are higher than in the lower part. On the other hand, according to Table 6-3, in most cases, when the internode is tested in compression with the nodes, strength is reduced by 6.9% and tension by about 19.29% compared to internodes tested without nodes, but the transversal tension and cleavage increase by 33.3%.

Table 6-4 Mechanical properties of various bamboos at various internodes of the lower part of the culm.



Species	IInternodes of basal part	Modulus of elasticity Kg/cm²	Modulus of rupture Kg/cm²	Compres. strength Kg/cm²	Tensile strength Kg/cm²
Dendrocalamus giganteous	1	172,097	1828	602	1836
	3	122,463	1758	619	1946
	5	147,912	1827	640	1880
	7	130,352	2880	646	1966
	Average	143,206	1823	627	1907
Dendrocalamus asper	1	122,073	1637	639	2145
	3	149,587	1741	592	2040
	5	129,542	1595	622	2220
	7	123,966	1578	566	2104
	Average	131,292	1638	605	2127
Gigantochloa robusta	1	94,208	1384	533	1970
	3	92,367	1294	510	1767
	5	109,217	1398	511	1854
	7	97,381	1345	530	2066
	Average	98,293	1355	521	1914
Bambusa vulgaris var. *striata*	1	60,652	1075	484	1392
	3	71,931	1123	443	1196
	5	88,297	1105	475	1352
	7	83,939	1286	417	1346
	Average	76,205	1147	455	1322

Source: (After Sjafii, 1984) in Widjaja & Risyad (1985)

9 -The ability of bamboo cells to generate electrical signals when stressed and the influence of their electrical properties in the modeling and remodeling of their hard tissue

Nogata & Takahashi (1995) studied the ingenious construction and strength of bamboo (*Phyllostachys pubescens*), in order to gain an understanding of the principles of design and processes found in biological materials and to apply these findings for the development of new and superior material/structure concepts, such as composites in multiphased and funcionally graded materials, by using and/ or modifying those models which are found in living organisms. (See Biomimetics). This study was published by their authors with the title: "*Intelligent functionally graded material: bamboo*" which is focused on the microstructure, strength and mechano sensing system of bamboo.

According to this study, the authors examined first some biological load carriers such as plant and tree stems, animal bones and other biological hard tissue, and observed that their geometry changes under loading to match mainly stress-or strain-dependent requirements. For example, the interior structure or architecture of a bone exhibits and optimized shape with respect to the principal stress directions and the shear stress magnitude in the body. This indicates that the bone is managed by a self-optimizing system with sensing mechanism (e.g. piezoelectric effect of bone) that detect external mechanical stimuli to control the modelling /remodelling of the skeletal system. Thus it can be inferrred that the shape and ingenious construction of biological hard tissues are the result of a continuous process of intelligent optimization. The basic characteristics of biological hard tissues such as microstructures, functions, and modeling systems are a source of both fascination and inspiration to the designers of engineering structures.

On the other hand, the basic difference between biological and artificial structures is that the former have living organisms which can be characterized by multyfunctionality, hierarchical organization, and adaptability (Srinivasan et al, 1991). As result biological structures are complicated and non uniform, which suggests that judicious combination of elements, materials and components of differing strength in the same structure can lead to acceptable and adequate hybrid systems whose properties are managed for specific purposes.

Mechano sensing system and adaptive modelling of bamboo

The Fig. 6.7 (1), shows the enlarged photograph of a vascular bundle located at the center and outside of cross-section of the culm wall. It shows a flower shape and a figure eight shape, respectively. There are two big holes (metaxylem vessels) and two in the center (phloem with sieve tubes and protoxylem). If we replace these holes by one big hole , the meaning of the flower shape will be realized by comparing the stress distributions around a hole in an infinite plate subjected to a uniaxial tension. (2)

Figures 6. 7 (3) and (4) show the photoelastic stress pattern around three holes in a plate model, with similar dimensions to those in a bamboo, which is subjected to two different loading directions, respectively. The best way to reinforce these holes is to set in fibre bundles accorting to the stress distribution. Therefore, it seems that the placement of the fibre bundle indicates a stress situation around the vessels in the xylem and phloem.

Mattheck (1990) and Mattheck and Burkhardts (1990), showed that the contour shape of biological structures such as tree stems, red deer antlers, human tibia , and tiger claws are highly optimized in terms of mechanical strength and minimum weight. This implies that biological structures may have mechanical sensing devices.

Therefore, in order to gather information and examine the sensing ability of bamboo cells, when stress is induced by external mechanical stimuli, the authors tryed to detect a biological signal which may be induced. For this purpose they used an electrocardiograph machine for the human body for a measurement system. A half size diagnostic ECG (electrocardiogram) electrode with adhesive paste was used.

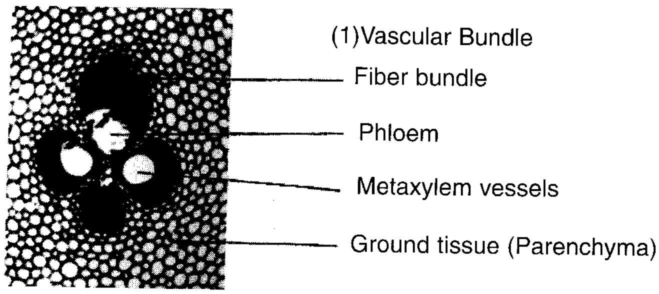
Fig. 6.8 shows an example of the voltage signal curves which were obtained from a bamboo culm subjected to an external bending moment. The curves show the presence of a spike upon loading and upon unloading. The higher voltage signal was recorded on the compression side rather than the tension side of the bamboo culm. These signals may be used as a trigger to organize adaptive growth related to the stress direction. The authors' data, obtained from other plants (ruber and palm tree), showed that the characteristic features of the signals depended on the kinds of plants, and there was no voltage signal induced from specimen boiled in a hot water bath for one hour or from a dried specimen with a weight loss of one half. Because boiling or drying of specimens means the death of the plant cells , it is clear that the voltage signals recorded were produced from live cells in stressed materials This indicates that the lieve bamboo cells have the ability to sense some information induced by external mechanical stimuli.

On the other hand, Fukuda and Yasuda (1957) found piezoelectrical properties in bone which was stressed. There are several reports quoted by the authors which are based on evidence that bone demostrates a piezoelectric effect. This is used to explain the concept of stress or strain -induced bone remodelling which is often referred to as Wolff's law (1870). Thus, bone converts mechanical stress to an electrical potential that influences the activity of osteoclasts and osteoblasts (Hayes *et al*, 1982). It is also known that the interior structure of bone (trabecular architecture) is arrenged in compressive and tensile systems corresponding to the principal stress direction. (Koch , 1917).

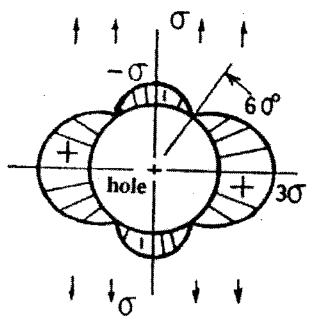
The properties of the voltage signals induced in bamboo may also be similar to the piezoelectric effect in bone. Therefore, it may be shown that the electrical properties of bone and bamboo play an important role in the remodelling/modelling of the skeletal system in biological hard tissues.

Fig. 6.9 shows the enlarged vascular bundle of bamboo which was grown on steep ground. It is clear that the deformed contour shape of the bamboo culm and the asymetric shape of the fibre bundles are a reflection of biased

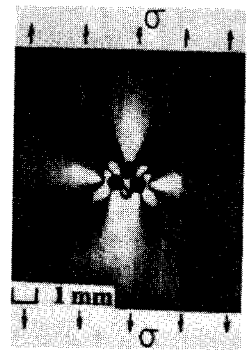
THE ABILITY OF BAMBOO CELLS TO GENERATE ELECTRICAL SIGNALS WHEN STRESSED



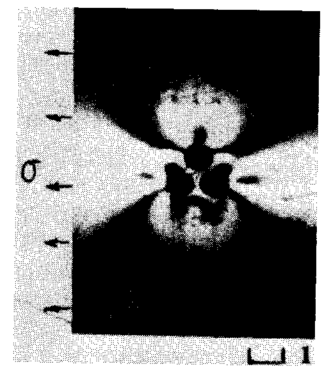
(1)Enlarged photograph of vascular bundle



(2) Stress distribution around a hole in an infinite plate



(3) Photoelastic stress pattern around three holes



(4) Photoelastic stress pattern around three holes. Note the diffrence of load direction between (3) and (4)

Fig.6.7 *Transverse section showing the vascular bundle and photoelastic stress pattern around the 3 holes . Note the difference of vases. (Nogata & Takahashi 1995)*

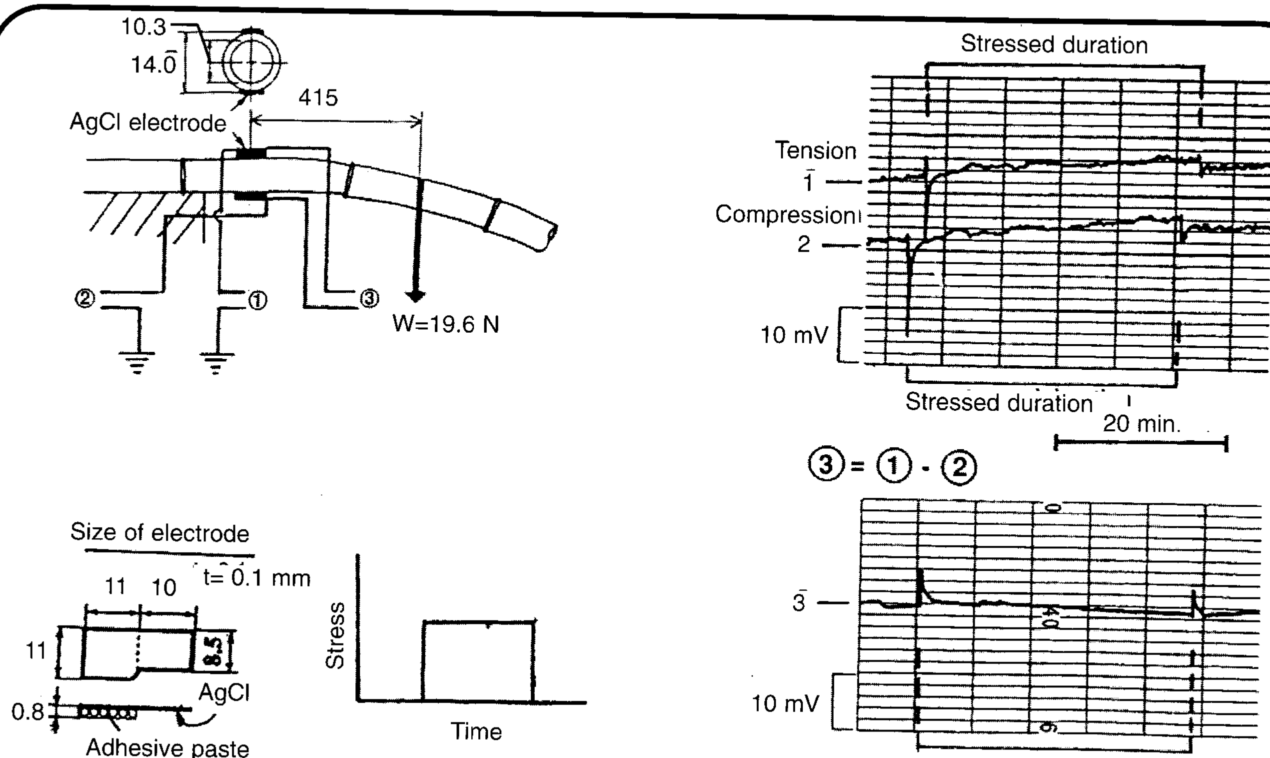
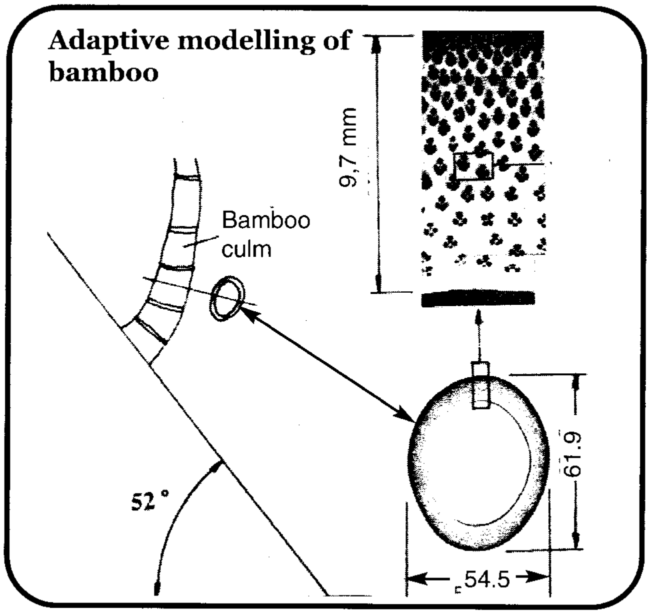


Fig.6.8 *An example of the voltage signals induced by bending moment for a bamboo culm. Nogata & Takahashi (1995)*



loading conditions by their environment. Therefore, the electric signals recorded and the location of the fiber bundle are evidence suggesting that bamboo has a stress/strain-induced adaptive modeling system. This system uses cell-based mechanosensors which may be utilized toaffect or change their shapes (e.g. placement and volume density of fibre, thicknes of stem which can compensate for applied extrnal loads in order to avoid any loclized stress peaks. Thus the characteristic stress/ strain states lead to the modeling of hard tissue and ingeniously customized microstrutures in bamboo.

The above considerations also indicate that the volume density of fibres and their distriution give us important information from the mechanical and morphological points of view.

Fig. 6.9 *Transverse sections showing the placement of fiber bundles on the culm of bamboo grown on steep ground (After Nogata & Takahashi (1995).*

EVALUATION OF THE TENSILE STRENGTH OF THE CULM WALL

As was explained before,the first research about the mechanical properties of bamboo and its application as reinforcement in concrete instead of steel bars, was carried out by H.E. Glenn in 1944 at Clemson Agricultural College in South Carolina during the Second World War.

Due to the lack of technical and scientific information about bamboo which there were at that time , Glenn, like many other researchers, erroneously considered that bamboo was a tree, and he evaluate the mechanical properties of various bamboo species following the norms and shapes of testing samples recommended for the evaluation of the mechanical properties of timber. This was a big mistake because bamboo is a giant grass;and their anatomy, morphology physiology and growing process are quite different from .that of trees. By by the other hand the mechanical properties of the culm varies from the lower to the top part of the culm and transversally from the interior to the exterior part of the culm wall. Consequently bamboo has a different structural behavior of that of timber

Based on the similarity which exists between a metal chain and a bamboo culm (when tested in tension) since the internodes with their nodes serve a similar function to that of a link in the chain; we can apply on bamboo the principle that the maximum tensile strength of a chain corresponds to that of its weakest link, this means that the first thing that we have to fine out (and evaluate) is the location of the weakest and strongest zones in tension ,compression and bending of the transversal section of the culm wall (SeeFig.. 6.10), and vertically from the lower, central and top part of the culm. (See Fig.6.15A)

In the evaluation of the lower , central and top parts of the culm we will find that the top section of the culm is the strongest in compression, and bending strength of the whole culm.The central section, which have the longest internodes is the strongest in tension; and that the lower section of the culm, in spite of its larger diameter and wall thickness, have the lowest mechanical properties of the whole culm.Transversally,the fiber density and tensile strength increases from the inside to the outside of the wall.

At the present time,the most complete and accurately study related to the distribution of the fiber density, tensile and modulus of elasticity along the transverse section of the culm wall, was carried out in Japan by Nogata & Takahashi (1995).(See Fig 6.10) The material tested,was a culm of the specie *Phyllostachys pubescens (P. Edulis).* Two internodes (without nodes) were taken from the culm, the "A" internode was cut at 1 m above the ground and the internode "B" at 5 meters above the ground (See Fig.6.10). They divided the culm thickness in 9 plies and in each one they studied the fiber density and the tensile strength (See Fig.6.10 C-D-E). Two types of specimens as shown in the same figure, were shaped, using a knife, from a single culm of bamboo which was 13 meters long. Tension tests were performed within 48 hours after it was taken from the field, to prevent any change in the mechanical properties due to moisture loss.

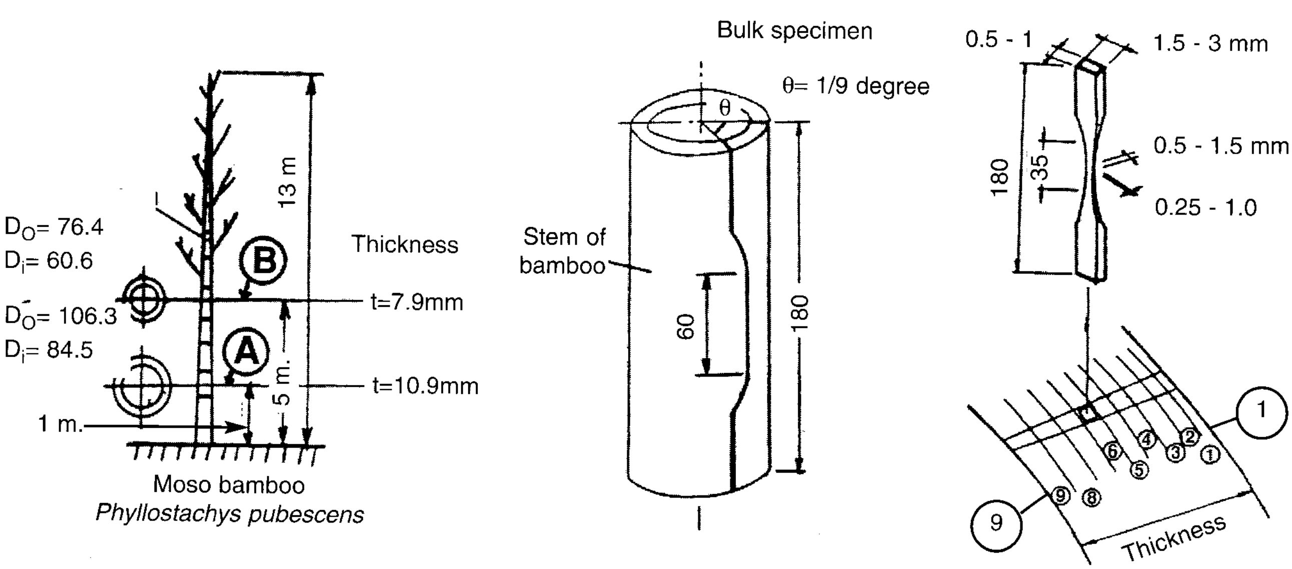
The Fig:6.10 D shows that the fiber density gradually increases from the inside to the outside surface, as well as from the lower part to the upper part of the culm. According to the authors, this graded structure will produce a uniform internal stress distribution in both radial and axial direction. .Tension tests were performed using very small specimens with cross- sectional areas of about 0.25 mm^2. The specimens were taken from the nine areas arranged as shown in Fig. 6.10 C. The Fig. 6.10 E shows the tensile strength and Young's modulus for A and B specimens along the transverse section of a bamboo culm, which indicates that the strength gradually increases from the inside to the outside, and also that specimen B has higher strength than specimen A. This variation is the same as the variation of volume density of fibres that was mentioned in Fig. 6.10 E. Since the extreme inside, the specimen No. 9 was made of pure ground tissue, its strength was correspondingly about 25 MPa.

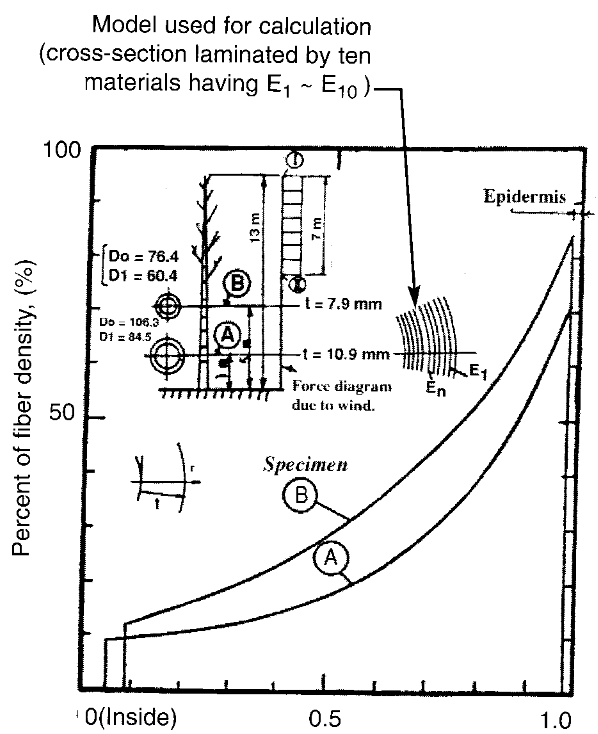
Thus, the strength of pure fiber was estimated to be about 810 MPa (using rule of mixtures), which is equivalent to that of steel (600-1000 MPa). Furthermore, Young's modulus of pure fibre was 55 GPa. This value is about one quarter of the value of steel which is 200 GPa. This data shows that the bamboo has high strengh but low rigidity.

RADIAL DISTRIBUTION OF TENSILE STRENGTH IN THE WALL

Fig.6.10 **SPECIMENS' GEOMETRY FOR TENSION TESTS** *(After Nogata & Takahashi (1995)*

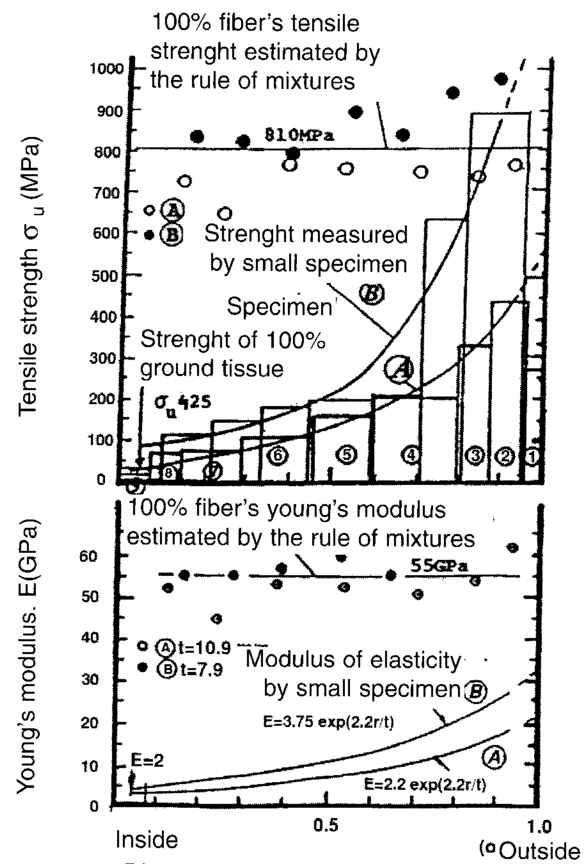
A.-Location of the samples in the culm **B.-Internode (without nodes)** **C.-Tensile specimen and location in the culm wall**





Distance from inner surface

D. *Distribution of fiber density along the transverse section of the culm.Nogata & Takahashi (1995)*



Distance from the inner surface

E. *Distribution of tensile strength and Young's modulus along the transverse section of the culm wall.*

TENSION TEST OF CULMS

Tension tests with round specimens (full cross section of culm) are difficult to carry out because it is not easy to find a method for fastening a round piece in the testing apparatus so that it can be severed by tension. It is therefore preferable to test strips from the culm wall similar to the one shown in Fig. 6.10 C, but including the nodes, and without nodes.

Bauman (1912) was the first researcher to determine the difference in tension between the outer layer of the culm wall and the interior one. He found that the strength in tension for the outer layer of "black bamboo" (*Phyllostachys nigra*) was 3.068 kg/cm²; for the interior layer it was 1594 kg/cm²; and for the entire thickness of the wall it was 2070 kg/cm². In specimens taken from "tonking bamboo" (*Arundinaria amabilis*), he found that the tensile strength for the outer layer was 3,843 kg/cm², and for the inner layer it was 1353 kg/cm².

In Japan, in 1930, Sioti Uno carried out the most complete study that I have seen on the mechanical and chemical properties of several native species of bamboo in which he studied the strength properties only of the outer and inner layer of the culm wall, in the lower, middle, and top part of the culm. In this chapter, I have shown all of the results of his research as a model for future researchers. Nevertheless, I consider that the strength should be studied in 3 layers (minimum) instead of two.

Many authors consider that the tensile strength in bamboo increases with the age of the culm and that the maximum values for tensile strength occur in specimens three to five years old. This could be true for compression and bending strength, but it can not be taken as a rule for tension strength. In the experiments I carried out using the species *Guadua angustifolia* (Hidalgo 1978) to find the strength to tension of bamboo cables used as reinforcements in concrete, about 162 strips taken fromthe outer part of the culm were tested. The maximum tensile strength was 3,213 kg/cm² in a strip taken from the upper part of a three and a half year old culm. The lowest tensile strength was 1,017 kg/cm² in a strip taken from a 5 year old culm. However, I found values as high as 3,018 and 3,206 kg/cm² in strips taken from one year old bamboos.

On the other hand, according to the *Chu pu* book, written by Tai Kaichih in the year 420 A. D., "The Chinese bamboo 'Chin chu' which grows twenty or more feet high and has a circumference of several Chinese inches, is suitable for making bow strings before the shoots become a culm" (less than one year old). This means that very young bamboos of this species are stronger to tension than the older ones.

With the information I got from my research, I realized why the Chinese used strips taken from young green bamboos for the manufacture of bamboo cables (up to 30 cm in diameter) used in the construction of suspension bridges with a span of more than 100 meters. (See supension bridges.) They also manufactured the small diameter cables used by the junk-hauliers in the largest rivers of China.

According to Needhan (1965), on a journey up the Yangtze river in 1908, Esterer made some measurements on the bamboo cables used by the trackers or junk-hauliers and found a tension of 518 kg/cm²., which was of the same order as that normally found in steel wires. Meyer (1937) found that the tensile strength of the bamboo cables used in the construction of suspension bridges in China was about 1,828 kg/cm². Moreover, while hemp ropes lose some 25% of their strength when wet, the tensile strength of plaited bamboo cables increases about 20% when they are fully saturated with water (Needham 1965).

Table 6-5 TENSILE STRENGTH OF BAMBOO AND MODULUS OF ELASTICITY

A. Tensile strengh (kg/cm²)						B. Modulus of elasticity (kg/cm²)				
Species	Layer	Lower section	Middle section	Upper section	Average	Layer	Lower section	Middle section	Upper section	Average
Ph.bambusoides	Inner	1.876,2	1.295,5	2,259.3	1,810.3	inner	219,375	170,461	262,413	224,083
	Outer	4.207,6	3.868,5	3.494.0	3,856.7	Outer	618,765	508,897	443,056	523,573
Ph. nigra var. Henonis	Inner	608,4	2.237,6	940.7	1.262,2	Inner	126,750	329,067	167,982	207,933
	Outer	2.383,2	3.128,3	1,632.4	2,381.3	Outer	590,600	605,442	453,444	549,895
Ph. pubescens	Inner	730,0	1.060,5	887.4	892.6	Inner	24,013	115,272	116,675	85,320
	Outer	3.254,0	3.166,4	2,532.5	2,964.3	Outer	135,583	494,750	381,250	337,194
Ph. lithophila	Inner	639,8	1.885,9	1.891.0	1,472..2	Inner	26,325	235,738	429,772	230,612
	Outer	2.094,9	4.269,4	2.946.0	3,103.4	Outer	84,452	533,675	669,544	429,224
Dendrocalamus latiflorus	Inner	506,5	1.007,3	1,057.9	857..2	Inner	55,054	185,145	154,397	130,865
	Outer	2.336,0	3.633,7	3,163.7	3,045.1	Outer	116,800	807,933	608,404	511,046
Bambusa oldhamii	Inner	1.621,8	2.046,5	2,614.6	2,094.3	Inner	224,694	292,357	344,026	287,026
	Outer	4.221,9	4.846,6	4,757.8	4,608.7	Outer	753,911	683,139	594,700	677,250
B. stenostachya	Inner	697,6	2.649,6	2,377.7	1,908.3	Inner	91,789	378,514	349,662	273,322
	Outer	3.836,0	2.957,5	2,407.3	3,066.9	Outer	532,778	434,926	316,663	428,122
B. vulgaris var . vittata	Inner	1.569,5	1.993,8	2,465.0	2,009.4	Inner	186,846	207,563	----------	197,204
	Outer	4.303,2	4.554,6	3.460.9	4,106..2	Outer	672,375	669,794	----------	671,085

Source: Sioti Uno (1930) Note: The original scientific names were corrected in the translation made by McClure

COMPRESSION STRENGTH PARALLEL TO THE GRAIN

Compression strength parallel to the grain is the capacity of the bamboo fibers to resist longitudinal compression, as is the case of a bamboo used as a column. The harder the fiber and larger the area of fibers, the greater the compression resistance.

The relationship between compression strength parallel to the grain and the moisture content of a bamboo splint is similar to that of wood; this means that there is an increase in maximum crushing stress from the green to the air-dry condition. By assuming that the fiber saturation point of bamboo is 20%, the increase in crushing strength from green to air-dry condition is 4.9 percent per one percent decrease in moisture content. In the testing to compresion of 76 specimens of the species *Guadua angustifolia* (Hidalgo 1978), we found that the compression strength of the culm increases with the age of the culm and with its height. A maximum compression strength of 705 kg/sq. cm. was found in the top portion of a 5 year old culm, and the minimum compression strength of 261 kg./sq. cm. was found in a one year old culm. The tensile strength, compression and bending increase with the height of the culm. Bending and compression strengths also increase with age until they are 7 or 8 years old, depending on the species. As mentioned earlier, fiber length has a correlation with the modulus of elasticity and compression strength. A close correlation also exists between specific gravity and maximum crushing strength. The compression strength, as well as the percentage of sclerenchyma fibers, increases vertically from the bottom to the top of the culm, and horizontally from the innermost layers to the peripheral part of the culm. There are cases in which the compression strength of the top is almost twice that of the lower part. In experiments conducted by Uno (1930), he found that the compression strength in the lower, middle and top part of the culm of *Phyllostachys bambusoides* were respectively: 442 - 342 - 835 kg/cm^2 and in *Ph. Lithophila* 644 - 667 - 1,284 kg/cm^2.

Testing of bamboo to compression

In most research carried out up to the present time, the specimens used for the evaluation of compression parallel to the fiber, consist of bamboo cylinders 10 centimeters high (or 10 times the thickness of the wall) taken from the center or from the lower part of the internode. However, most researchers ignores the fact that in the internodes, the fibers near the nodes are short and longest fibers are in the center of the internode. This means that if the specimen is taken from the lower part or top part of the node, where the fibers are short, the value of its compression strength will be lower than that of a specimen taken from the center of the internode where the fibers are the longest. The reason for this is that fiber length has a correlation with compression strength.

Table 6-6 COMPRESSION PARALLEL TO THE GRAIN OF INTERNODES OF *G. angustifolia*

Age of culm sections	Position on the culm	Crushing strength Kg/cm^2	Fiber stress at proport. lim .Kg/cm^2	Modulus of elasticity Kg/cm^2	Moisture content %	Specific gravity
1 to 3 years	Lower section	maximum **381.20**	265.00	85.714	26.58	-------
		average 318.34				
		minimum **255.48**	185.00	42.500	63.75	------
	Midle section	maximum **482.40**	395.00	89.286	16.16	0.686
		average 389.15				
		minimum **295.91**	230.00	84.000	28.88	0.651
3 to 5 years	Lower section	maximum **502.42**	385.00	62.216	42.56	0.666
		average 445.80				
		minimum **389.19**	290.00	55.555	41.50	0.634
	midle section	maximum **629.73**	550.00	124.038	16.06	0.797
		average 491.30				
		minimum **352.88**	270.00	65.909	27.72	0.583
More than 5 years	Lower section	maximum **505.45**	432.50	77.344	37.16	0.612
		average 408.61				
		minimum **311.78**	275.00	58.871	42.57	0.578
	middle section	maximum **549.31**	465.00	130.555	14.13	0.787
		average 438.15				
		minimum **327.00**	255.00	78.333	18.87	0.666

Source: Martin, Mateus-Hidalgo (1981) -Number of tests 90- The top section of the culm was not sended from the farm

From the above we can conclude that in order to study the compression strength of bamboos, it is necessary to test the whole internode including the two nodes) taken from the central part of the lower, middle and top portions of the culm. As mentioned earlier. In order to establish a methodology for testing the mechanical properties of bamboos under compression, I suggest dividing the whole length of the useful height of the culm (after removing the top most-branch) into three sections of equal lengths and taking 2 internodes from the central part of each section, one with the two nodes, for testing the minimum compression strength, and the other without nodes, for testing the maximum compression strength.

Testing in compression sections of 1- 2 and 3 meters long.

From the studies carried out by Sjafii (1984) on the mechanical properties of various bamboos at various internodes of the lower part of the culm (See Table 6-4), we concluded that each of the internodes of the culm has different mechanical properties, which generally do not follow a progressive value from the bottom to the top of the culm. Consequently, the best solution for testing bamboos under copression is to test sections of culms which are one, two and three meters long (these are the dimensions most used in construction, indicating for each one the number of internodes and the wall's thickness and diameters (internal and external). In this way we can get the most exact and safer results from the compression tests.

In 1981, I was the adviser of the thesis of two students from the College of Agricultural Engineering of the National University of Colombia in Bogota (Martin & Mateus). We studied the compression strength of sections 1, 2 and 3 meters long taken from the lower, and middle part of culms of *Guadua angustifolia* with different ages. (The top section was not sent from the plantation). The results are summarized in the Table 6-7.

The purpose of this study was to provide information to the bamboo builders in Colombia on the appropriate use of different length bamboos, as columns and supports for buildings built on sloping grounds and in secondary structures, such as those used for the construction of concrete slabs, in order to use a minimum of bamboo supports and larger spans between supports. At the present time, distances of supports in both directions are 80 cm.The tests were carried out in the materials laboratory of the Engineering Faculty at the National University of Colombia in Bogota.

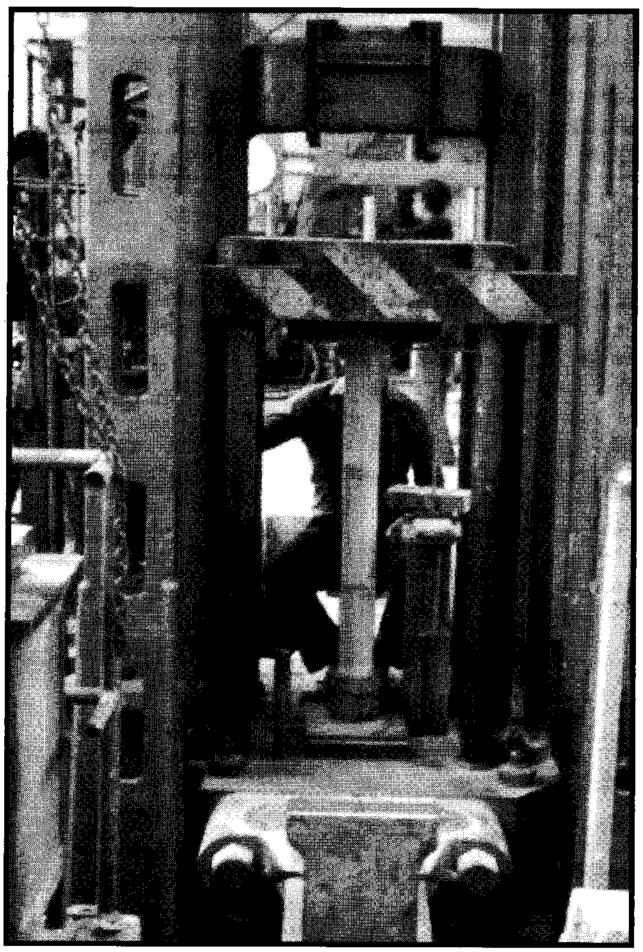


Fig. 6.11 *Compression evaluation of sections 1 and 2 meters long of Guadua angustifolia at the college of Engineering of the National University in Bogota.*

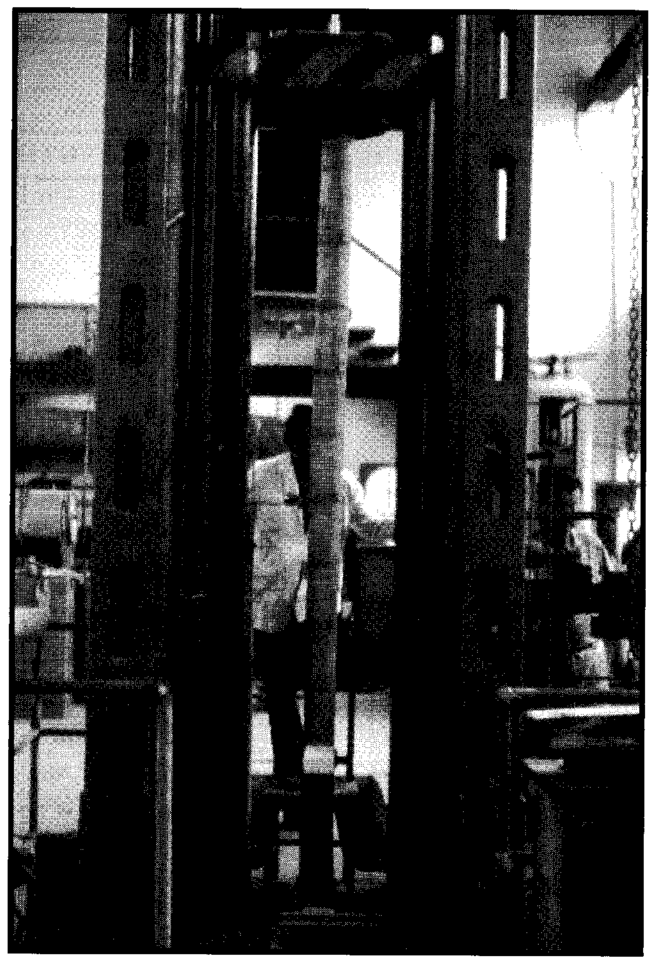
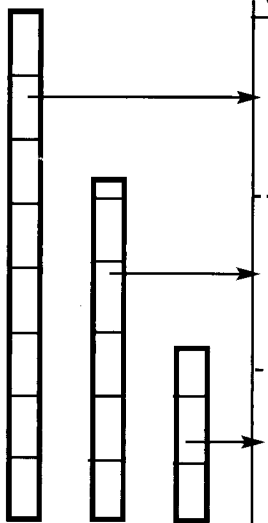


Fig. 6.12 *Compression evaluation of sections 3 m long of Guadua angustifolia.*

Table 6-7 COMPRESSION STRENGTH OF SECTIONS OF 1- 2 AND 3 METERS LONG OF *Guadua angustifolia*



Lenght of culm sect.	Culm age (years)	Crushing strength Kg/cm²		Base Diam Cm	Wall thick. Cm	Number of nodes
3 meters	1 to 3 years	Maximum	4,930	9.08	0.79	8
		minimum	2,740	9,44	0.97	10
	3 to 5 years	Maximum	8,350	10.76	1.58	13
		minimum	2,775	9.04	0.96	9
	more than 5 years	Maximum	16,600	13.09	1.92	13
		minimum	3,200	9.89	0.87	9
2 meters	1 to 3 years	Maximum	10,125	11.33	1.15	7
		minimum	3,830	7.86	0.71	6
	3 to 5 years	Maximum	12,830	11.73	1.52	7
		minimum	5,100	9.53	1.26	7
	more than 5 years	Maximum	22,500	14.33	1.62	7
		minmum	6,600	9.09	0.88	6
1 meter	1 to 3 years	Maximum	14,050	9.27	1.50	5
		minimum	7,350	8.39	0.73	3
	3 to 5 years	Maximum	19,000	11.57	1.72	4
		minimum	8,000	8.28	0.98	4
	more than 5 years	Maximum	23,650	13.50	1.55	4
		minimum	9,910	10.23	1.20	5

Source: Martin, Mateus, Hidalgo (1981) - Total number of tested samples 129

Table 6-8 COMPRESSION STRENGTH AND MODULUS OF ELASTICITY

Species	Section of the culm	Compression strength Kg/cm²	Average com-presion stren. Kg/cm²	Average modulus of elasticity Kg/cm²	Area in cross section of wal /Area in cross sect. of culm	Average thereof
Ph.bambusoides (Ma bambus)	lower	442.96	540.55	2,242.95	47.6 cm²	38.40
	middle	342.75			37.5	
	upper	835.95			30.1	
Ph. nigra var. Henonis (Ha bambus)	lower	411.58	411.28	2,433.61	55.5	51.87
	middle	458.85			34.1	
	upper	363.43			65.4	
Ph. pubescen (Moso bambus)	lower	588.67	610.90	2,395.69	40.4	42.07
	middle	648.84			38.4	
	upper	597.19			47.4	
Ph. lithophila (Seki-bambus)	lower	644.94	862.29	3,527.50	49.8	41.43
	middle	667.09			37.4	
	upper	1,274.85			37.1	
Dendrocalamus latiflorus (Mor- bambus)	lower	272.02	356.86	1,612.86	36.3	45.67
	middle	532.21			29.5	
	upper	266.35			71.2	
Bambusa oldhamii (Tiosi-bambus)	lower	532.48	311.64	2,398.59	67.4	47.10
	middle	542.18			31.2	
	upper	760.25			42.7	
B. stenostachya (Si-bambus)	lower	361.26	341.54	1,187.05	32.7	71.83
	middle	221.60			68.8	
	upper	441.75			64.0	
B. vulgaris var. vittata (Daisan -bambus)	lower	506.24	534.03	1.545,43	45.0	43.20
	middle	515.54			39.7	
	upper	580.31			44.9	

Source: Sioti Uno (1930) Note: The original scientific names were corrected in the translation made by McClure
The Amsler Co.'s apparatus of 30 tons capacity was used.

BENDING STRENGTH

The cortex or mechanical tissue that is arranged around the outer part of the cylindrical culm, performs the function of protecting the culm so it can resist bending forces. When the culm in the clump is bent by the wind or by the weight of the snow in winter time, it becomes elliptic in cross section.

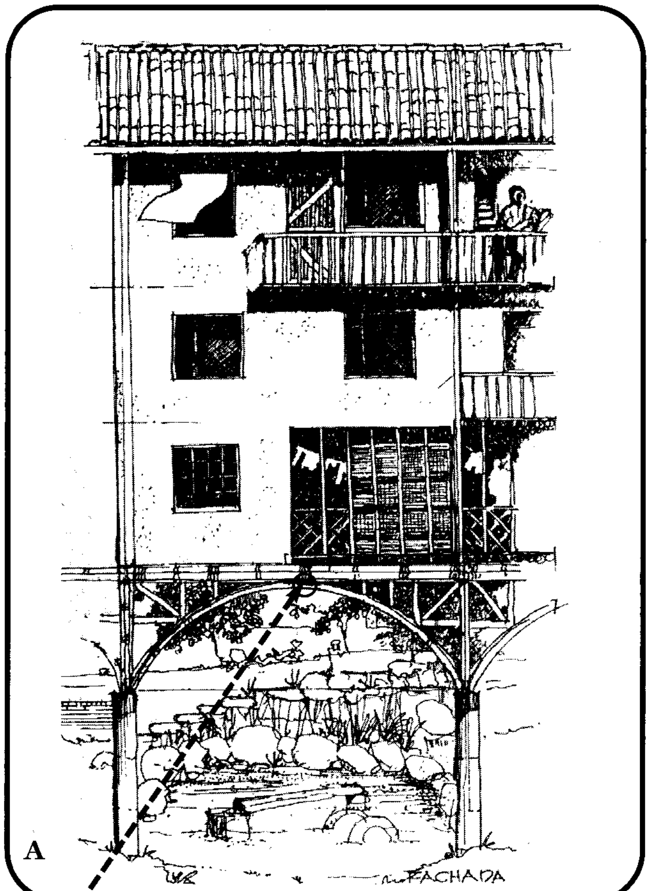
The bending culm is thus compressed along the lower part, and expanded along the upper part. If this force of compression and tension becomes greater than the bamboo wood can support, the culm will break along the center of the cylinder or neutral axis. When the culm, once cut, is used in beams, it has the same structural behavior.

According toTakenouchi (1932), if the thickness of the wall of the culm internode is 1/8 or 1/5 of the diameter of the cylinder, this culm cylinder is, as a rule, much more resistant to bending forces than a solid culm of the same diameter. The culms of *Phyllostachys bambusoides* (Madake) and *P. nigra henonis* (Hachiku) and some others which have a wall thickness of about 1/9 the diameter of the cylinder, can withstand the weight of snow without breaking. But the culm of *Ph. edulis* (*Ph. pubescens*) (Mosochiku) whose thickness is 1/11 the diameter of the cylinder, is comparatively easy to break.

Assuming that the fiber saturation point of bamboo is 20%, the increase in bending strength from green to air-dry condition is 0.05 percent per one percent decrease in moisture content. This value is lower than that of wood, which is approximately 4 percent per one percent decrease in moisture content. According to Bauman (1912), the bending strength of the inner layers is 950 kg/cm², and of the outer layers is 2535 kg cm².

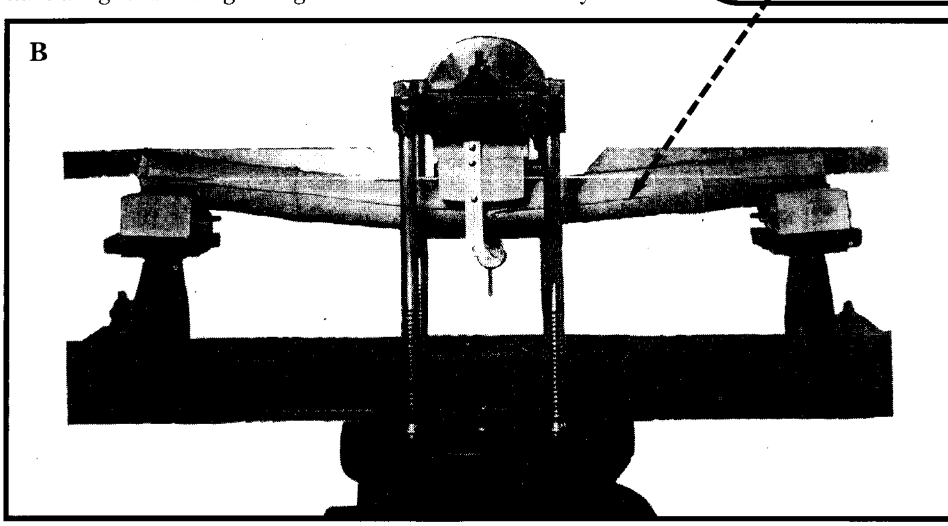
Bamboo possesses excellent mechanical properties which depend mainly on the fiber content and, therefore, vary considerably within the culm and between species. At the base, for example, the bending strength of the outer part is 2 - 3 times that of the inner part. Such differences become smaller with increasing height of the culm. With the decreasing thickness of the culm wall, there is an increase in specific gravity and mechanical strength of the inner parts, which contain less parenchyma and more fibers, whereas in the outer parts these properties change only slightly. For bending strength and modulus of elasticity, higher values were obtained from the upper part. Bamboo splints with the epidermis downwards have a higher bending strength and modulus of elasticity than those with the epidermis upwards.

Bending tests. Bauman (1912).- The specimens were placed on two supports whose distance apart, as a rule was, in round numbers, 25 times as great as the largest diameter of the bamboo to be tested and a load was placed at the middle between the supports. The failure occurred when there was splitting parallel to the axis of the specimen, as a result of shearing forces. The bending strength of bamboo cylinders varied between 722 and 2760 kg/cm². The thicker cylinders (outer diameter about 8 cm), were weaker than the thinner ones (outer diameter approximately 2 - 3 cm).



A

B



Figs. 6.13 (A) (B)
(A).This is a very interesting architectural design that was the winner of a giant bamboo housing project competition in Colombia. The problem is that the architect and the judges ignored the fact that a bamboo culm can not be bent like a metal bar, because it cracks along the neutral axis with the smallest deflection as is shown in the testing machine. (B) The solution is to build a three articulate arch. (See bamboo deformed structures.)

SHEAR STRENGTH

Although trees (hardwoods and softwoods) and bamboos are woody plants, as mentioned earlier, their anatomy, morphology and growing processes are different, as is their structural behavior. Most researchers do not realize that bamboo does not have radial cells like those in timber which increase its shear strength parallel to the axis. This is why bamboo has very low shear strength parallel to the axis and the presence of nodes has only a slight significant effect on shear strength.

This low shear strength of bamboo is an advantage for some purposes, for example, in the manufacturing of bamboo strips for weaving baskets or for making cables, but it can also be a disadvantage in construction, particularly when researchers try to make the same type of bamboo specimens that are used for testing timber. Bamboo specimens generally break very easily in the direction parallel to the axis.

In the experiments we did on the shear strength of *Guadua angustifolia* (Hidalgo 1978), we tested 27 specimens of different ages using stair shaped specimens and dimensions recommended by Motoi Otta (1955). The maximum shear strength was 144 kg/cm^2, the minimum was 45 kg/cm^2, and the average was 93 kg/cm^2. Today, I consider that this very common method of evaluation is impractical and the results are useless; the best method of testing bamboo shear strength is using the whole inter-nodes with the nodes and also without them. The specimens have to be taken from the lower, center and top sections of the culm, and they will have different diameters and wall thicknesses.

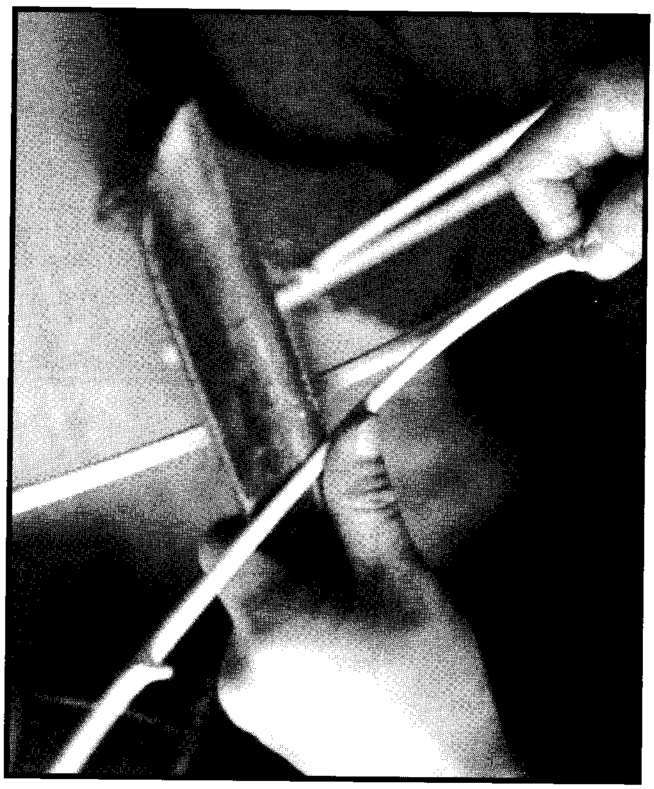


Fig.6.14 *The low shear strength of bamboo is an adventage for some purposes, for example in the manufacturing of bamboo strips for weaving baskets and many other articles.*

IMPACT TESTS

Baumann (1912) carried out some impact tests on round bamboos. The work to failure was from 2.2 to 3.3 m kg/cm2; the distance between supports was 25 cms. A pronounced difference due to the place where the impact was applied could not be observed. In contrast, the mode of fracture was entirely different. Whereas in impact on the nodes, the specimen was severed in strips parallel to the axis, in impact on the shaft, the specimen consistently broke through. In this case, the tensile strength of the fibers was exceeded.

In the pendulum impact tests carried out by Jain, Kumar and Jindal (1992) in bamboo strips, the test specimens were 75 mm long and the cross-section was 10 mm x 10 mm taken from the culm wall. Tests were performed on notched and unnotched bamboo fiber, and bamboo mat reinforced plastic composites. Notched specimens had a 2 mm deep 450 notch angle at a distance of 28 mm from the top end. The samples were fractured in a Hounsfield plastic impact testing machine. Impact toughness was calculated from the energy absorbed at the cross-sectional area without notch and at the cross-sectional area at the notch.

Results and analysis. The percentage of cellulose (fibers) and lignin (binding material) in bamboos fibers is higher than in other natural fibers. The microfibril angle of the cellulose fibers is very small and bamboo has a polylamellate wall structure. These are the factors responsible for the higher tensile, flexural and impact strength of bamboo in the direction of the fiber. Perpendicular to the fiber direction, bamboo has minimum strength.

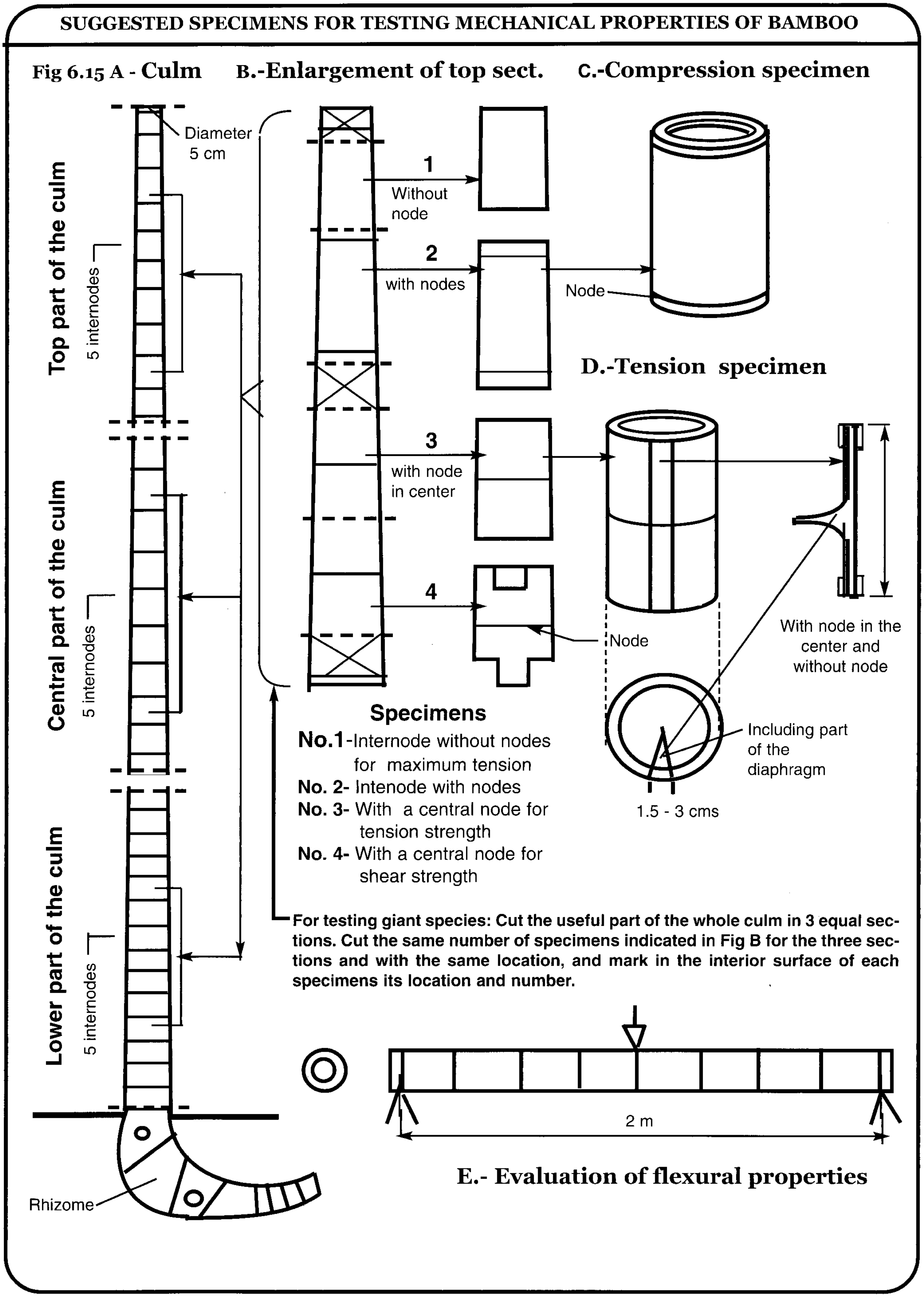
Table 6-9 Impact Tests	Impact strength (CoV[2]) (kJm $^{-2}$)
Bamboo (across the fiber)	3.02 (±1.08)
Bamboo (along the fiber)	63.54 (± 4.63)

The results of pendulum impact carried out by the same authors on bamboo orthogonal mats are shown in Table 6-9A. Fiber composites have a higher impact strength than mat composites. This can be explained because 50% of the fibers in the mat are in the direction of impact, and the other 50% are perpendicular to the impact. Only perpendicular fibers are capable of arresting and diverting the propagation of the notch by delamination .

Another important fact which has emerged is that the notch has no affect on the strength of the mat (bamboo-fiber reinforced plastic composite-BFRP) (See bamboo composite) The high impact strength of BFRP composite puts it in the category of tough engineering materials .

Table 6-9A. Impact strength of BFRP composite

	V_f (%)	Impact strength specimen (CoV[2]) (kJm $^{-2}$)	
		notched	unnoched
Fibre composite	35%	43.71(± 2.92)	45.62(± 3.01)
Mat composite	65%	33.87 (± 2.20)	34.03(± 1.26)


SUGGESTED SPECIMENS FOR TESTING MECHANICAL PROPERTIES OF BAMBOO
Fig 6.15 A - Culm
B.-Enlargement of top sect.
C.-Compression specimen
Diameter 5 cm
Top part of the culm
5 internodes
Central part of the culm
5 internodes
Lower part of the culm
5 internodes
Rhizome
1
Without node
2
with nodes
Node
D.-Tension specimen
3
with node in center
4
Node
With node in the center and without node
Including part of the diaphragm
1.5 - 3 cms
Specimens
No.1-Internode without nodes for maximum tension
No. 2- Intenode with nodes
No. 3- With a central node for tension strength
No. 4- With a central node for shear strength
For testing giant species: Cut the useful part of the whole culm in 3 equal sections. Cut the same number of specimens indicated in Fig B for the three sections and with the same location, and mark in the interior surface of each specimens its location and number.
2 m
E.- Evaluation of flexural properties

HOW TO UPGRADE THE BAMBOO MECHANICAL PROPERTIES (REFORMED BAMBOO)

Reformed Bamboo

The density or specific gravity of wood timber and bamboo culm wood is a measure of its solid wood substance per unit volume and an index of their physical and me-chanical properties. Wood of hight density is stronger and stiffer than wood of low density. Nevertheless, it is possible to increase the strength and the stiffness of wood of low density if the volume of a wood timber piece is compressed or compacted perpendicularly to the axis of the piece with the purpose of reducing its volume, increasing in this way its density per unit volume. This technology was developed in wood timber by Ruyter,& Arnoldy in 1994 when they patented a *Process for upgrading low quality wood* (Eur. Pat. Appl. EP 623, 433-Cl.B27K5/06-09 Nov.1994).

This process comprises: (1) A softening stage, in which low-quality wood is heated to 160-240^0 in the presence of an aqueous medium and an aqueous pH buffer (pH 3.5-8.0) and at a pressure which is at least the equilibrium vapor pressure of the aqueous medium at the operating temperature, to at least partially hydrolyze the hemicellulose and disproportionate the lignin. (2) A dewatering stage, and (3) A curing stage. Thus air-dry sawn poplar wood was soaked overnight in an aqueous solution containing 6 g/L Na acetate at 95^0, heated by steam at 200^0 condensing on the surface until the temperature in the center of the wood was 185^0, cooled to 10^0 and compressed for 5 minutes, with gradually increasing pressure from 1 to 3 bar to remove the aqueous face. The sections were pressed in a platen press at 195^0 and 5 bar for 1.5 hours to give wood having Shore D hardness 70 and bending strength 125 MPa compared with 30 and 60 respectively for a sample without the Na acetate

A similar technique called "*reformed bamboo*" has been developed in China at the Academic Sinica by Li, Fu, Zhou, Zeng and Bao (1994) This new technique which aims at changing the form of bamboo from its natural circular cross section into a plate for convenient structural use.

The manufacturing technique covers three major processes after the bamboo culm is separated into several splints longitudinally which were then compressed after a treatment of softening.

The microstructure of reformed bamboo was studied, their mechanical properties were tested and the results show a remarkable increase compared with normal bamboo. According to the different uses, the mechanical properties and comprensive ratio (which is defined as r=(Ho - H1)/Ho, where Ho is the original thickness and H1 the thickness after compression) of reformed bamboo can be designed beforehand and adjusted in the manufacturing process. As a new attempt reformed bamboo was used to reinforce aluminum alloy for the purpose of protecting reformed bamboo itself and substituting some aluminium alloy .(See composite materials) .

General structure and properties of bamboo

As mentioned earlier, all bamboos share some common features: they are natural ligno-cellulosic composite and are composed of fibres (bast fibres in vascular bundles) and matrix (parenchyma thin-walled cells around vascular bundles, vessels and sieve tubes in vascular bundles). Natural bamboo can be taken as unidirectional fibre-reinforced composite and its fibre volume fraction has an intimate relation with its mechanical property. The distribution of bast fibres of bamboo along the radial direction shows a gradient trend, and this undoubtedly influences its mechanical properties, as do synthetic fibre-reinforced composites. However in previous works, when the mechanical properties of bamboo were concerned, average values across the thicknes were more often used rather than those of a specific part of the bamboo culm. In fact, the heterogeneity, porosity and anisotropy are important features of bambo.

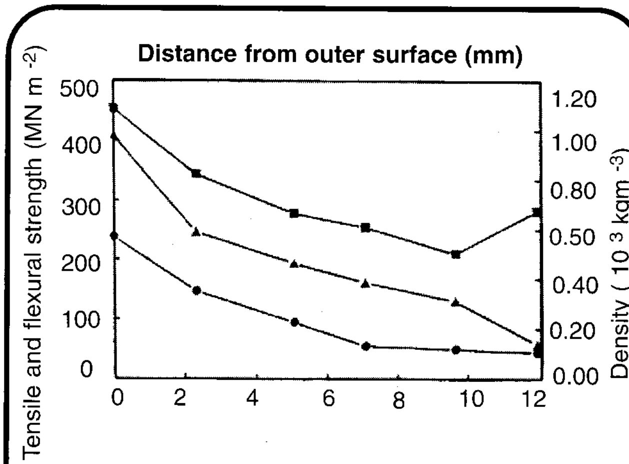


Fig. 6.16 *The radial changing trends of (▲) tensile and (●) flexural strength and (■)density of Ph. pubescens.*

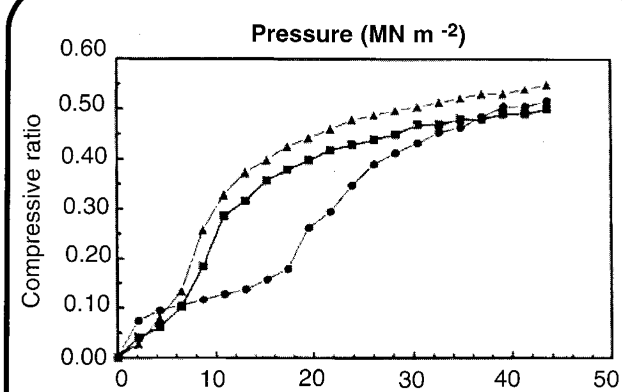


Fig. 6.17 *Relationships between moisture content, compresive ratio and pressure of bamboo. Moisture content (●) 8.5% (■) 22.6%. (▲) 28.9%*
(●) 8,5%, (-) 22.6%, (s) 28.9%

Because the fraction of bamboo fibres is not constant along the radial direction (fibers are denser in the outer part than in the inner part), to make the measurement of mechanical properties more accurate, one bamboo was cut longitudinally into several beams, with the width of each beam being about 15 mm; then each beam was separated into several strips of increasing thickness from the outer surface to the inner surface, and the tensile strength and effective modulus of each layer were measured experimentally. Owing to the gradient of fiber volume fraction in the radial directions, strictly speaking, there will be a coupling between stretching and bending under tension. To weaken the unexpected effect of coupling, each strip was made very thin; therfore, within the thickness of each strip, the modulus can be assumed to be a constant, which is the factual tested data of the effective modulus. End-taped specimens were made for testing tensil strength and effective modulus, of size 120 mm x 12 mm x *h* mm (*h* is the thickness of the specimens. The flexural strength was measured in three-point bending with a span of 40 mm for bamboo strip specimens. Fig. 6.16 shows the changing trends of the major mechanical properties of bamboo (*Phyllostachys pubescens*) along the radial direction.

It is obvious that there are many voids inside and outside the vascular bundles, and the number of voids in the inner part of the bamboo is greater than that in the outer greeen bamboo. The gradient structure of bamboo is optimum to adapt to the living environment, because this structure (a thick-walled circular cylinder with one end fixed) can provide optimum strength distribution and maximum structural stability with minimum material weight.

However, while bamboo is used as structural material, i.e. bamboo fibre-reinforced polymer (BFRP), the inhomogeneity of bamboo is usually an unexpected feature. To make the use of natural bamboo more convenient and more abundant, the microstructure of bamboo is redesigned and reformed to enhance the homogeneity of structure and property distribution.

Manufacture of reformed bamboo

Bambusa pervariabilis from China was chosen for this experiment. The manufacturing procedure consists of three steps: softening, compression and fixture. First , natural bamboo was separated longitudinally into several parts (usually two to four parts) and the diaphragms in the nodes were cut off roughly. Then the bamboo strips were heated in a container to adjust the moisture content to certain value. The strips were then compressed with a compressor to obtain the required compressive ratio. Finally under certain pressure, strips were pressed for 3 hours for the purpose of fixture. During the process, the moisture content of the bamboo is very important. The technological conditions can be determined according to Fig.6.17 which shows the relationships between moisture content, compressive ratio and pressure.

If the moisture content of bamboo is too low (such as 8.5%), as illustrated in Fig. 6.17, the bamboo is too rigid and brittle to be compressed rapidly; the other two curves show similar trends. It should be noticed that when the moisture content reaches 30%, the saturation conten,the water in bamboo will damage cell tissues during the compression process, and this will deteriorate the mechanical performance of reformed bamboo.

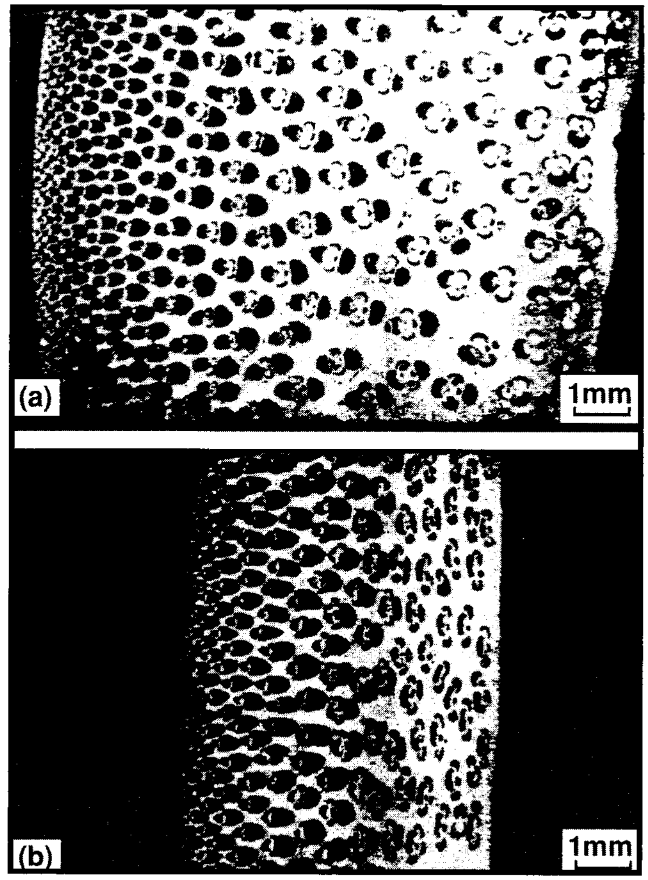


Fig.6.18 *Optical photographs of cross sections of **(a)** Normal bamboo, and **(b)** reformed bamboo. (After Li , Fu, Zhou, Zeng and Bao (1994)*

The structure of reformed bamboo

The structural changes of reformed bamboo derive from the distribution of vascular bundles and the vascular-bundles themselves. Fig.6.18 shows optical photographs of cross-section of normal bamboo (a), and reformed bamboo (b). From the comparison of these two photographs, it can

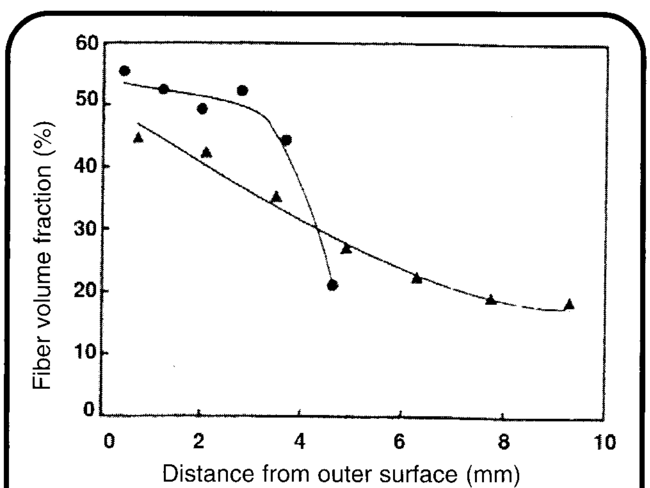


Fig. 6.19 *Fiber volume fraction of bamboo (▲) before and (●) after compresion (Compresive ratio is 0.49)*

be seen than the vascular bundles, or exactly speaking, the bast fibers in the inner part near the pith ring of the culm, became denser, and many voids in the vascular bundles (vessels and sieve tubes) disappeared after compression; the shape of the vascular bundle also changed from circular to elliptical.

To analyze the fiber volume fraction precisely, an Automatic Image Analyzer (Kontron IPS 500) was used to measure the area fraction of bast fibres over the total area. The specimen was divided into six or seven parts along the circumferential direction. The voids in the vascular bundle were taken to be matrix thus the fibre area fraction of each small divided part can be measured and the fibre area fraction along the radial direction was available. Because bamboo is strict unidirectional fibre-reinforced composite material, the fiber volume fraction VF was also calculated , and is shown in Fig. 6.19. The fibre volume fraction V_f of normal bamboo decreases gradiently along the radial direction; after compression (cf.fig.5), the V_f of most parts of bamboo is in the vicinity of 50%, but the fibre fractions near the pith-ring (the inner surface of bamboo culm) remains the same . The mean value of fiber volume fraction of both kinds of bamboo are listed in Table 6-10.

Mechanical properties of reformed bamboo

To obtain a compressive evaluation of reformed bamboo, tests were made of its density , static properties such as tensile modulus and strength, flexural modulus and strength, and shear strength along the fibre direction. The sizes of the bamboo specimens were determined by referring to the testing standards of wood and fibre-reinforced composites, or according to previous work. Experimental material was purchased from Guangdong province in South China. All tests were performed on a Shimadzu-DCS testing machine at room temperature. The geometric configuration and sizes of specimens are shown in Fig 6.20.

For tensile experiments, because the longitudinal shear strength is much lower than the tensile strength, the side-curved specimens were often found to be damage by shear fracture at the specimen end rather than tensile fracture in the working length, so in our experiments, end-taped specimens were used instead of side-curved ones. Owing to the gradient of bamboo structure, the strength and modulus are very different in the radial direction, so measurements should be thought of as "effective" or "apparent" properties or , in other words, they are the average values across the thickness of the specimens.

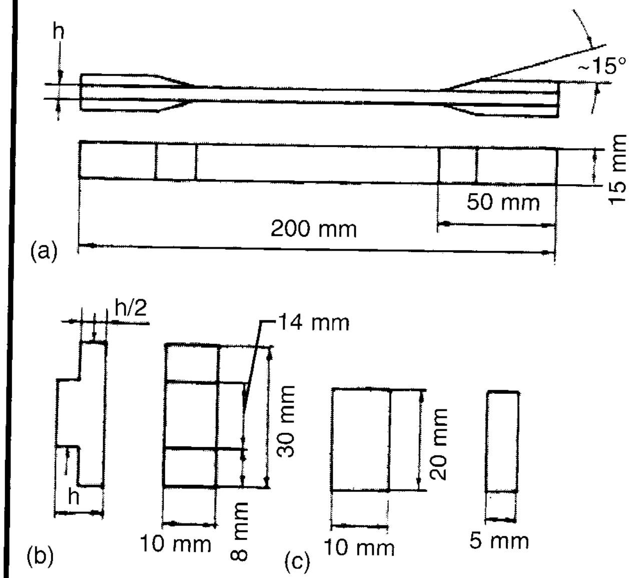


Fig. 6.20 *The shape and size of the bamboo specimens (h is the thickness of the bamboo culm wall (a) Tensile, (b) shear, (c) compressive specimens. (After Li , Fu, Zhou, Zeng and Bao (1994)*

In all the bending tests, the side with the higher strength was loaded in tension. For shear tests, the direction of the loads is shown in Fig. 6.20; the shear test was performed on the basis of the test standard, using the method for wood. The tests result are summarized in Table 6-10.

Table 6-10 Comparison of the mechanical properties of reformed and normal bamboo

		Reformed bamboo		Normal bamboo	
		Mean	Dev.	Mean	Dev.
Fiber volume fraction	(%)	43.6	13.4	29.2	12.8
Shrinkage coefficient	radial	0.252	0.005	0.299	0.02
	tangencial	0.184	0.0570.	0.319	0.076
	bulk	0.446	0.83	0.663	0.132
Density (10^3 kgm^{-3})		0.87	0.17	0.66	0.07
Tensile strength (MN m^{-2})		271.5	60.6	206.2	24.7
Tensile modulus (GN m^{-2})		29.0	5.6	20.1	3.2
Flexural strength (MN m^{-2})		276.6	22.7	210.3	25.3
Flexural modulus (GN m^{-2})		23.2	4.7	13.1	3.0
Compressive strength (MN m^{-2})		104.7	28.4	78.7	7.6
Shear strength (MN m^{-2})		14.5	2.2	15.1	4.6

Source: Li et al (1994).

Table 6-11. Specific properties of normal and reformed bamboo

	Reformed bamboo	Normal Bamboo
Specific tensile strength (km)	31.84	31.88
Specific tensile modulus (Mm)	3.40	3.11
Specific flexural strength (Km)	32.44	32.51
Specific flexural modulus (Mm)	2.72	2.3
Specific shear strength (km)	1.70	2.33

Source Li et al (1994)

The data in Table 6-10 reveal that many mechanical properties of reformed bamboo are obviously increased, for example, the tensile strength is increased by 31.7%, tensile modulus 44%, and flexural strength 31.5%, at the expense of 32.2% increase of density.

The increase in the static mechanical property of reformed bamboo compared with the normal one can be explained by the following four aspects:

(a) Density. It is well known that the mechanical properties of a biomaterial have a close relationship with density of the material. For wood, usually the wood possesses a higher density, and has higher strength; such a correlation also exists in bamboo.between the flexural strength and density of bamboo.

(b) Compressive ratio. For the same bamboo, the higher the compressive ratio, the denser will be the reformed bamboo. The total number of bast fibres in bamboo, which bear most of the load to which the bamboo is subjected, remains the same, so the strength and modulus per unit area will be increased as shown in Fig.6.21.

(c) Fiber volume fraction. According to the mixture principle $\sigma_c = \sigma_f V_f + \sigma m V_m$ for bamboo, σ_f is much higher than σ_m. thus the relationship between σ_c and V_f approaches a linear form; the increase of V_f of reformed bamboo will undoubtedly increase its strength.

(d) Microfibril angle. The microfibril angle of the plant can dominate substantially its mechanical property. During compression the length and width of a specimen must be increased to some extent, and thus so do the lengths of bast fibers.

For a spirally coiled structure, like the cell wall of a plant, the increase in length must result in the decrease of the microfibril angle with the respect to the fiber axis, and this contributes to the increase of tensile property. The specific property, which is the ratio of the property to density, is of particular importance in composites.

Table 6-11 gives a comparison of the specific properties of reformed an normal bamboo. From Table 6-11, it is clear that some major specific properties of both materials are very close or even the same. This is easy to understand, because the effect of compression is to assemble the fibers more densely and the increase in the properties was accompanied by an increase in density.

Disadvantages of bamboo

Although reformed bamboo has many advantages over normal bamboo, it does not overcome the defects of other

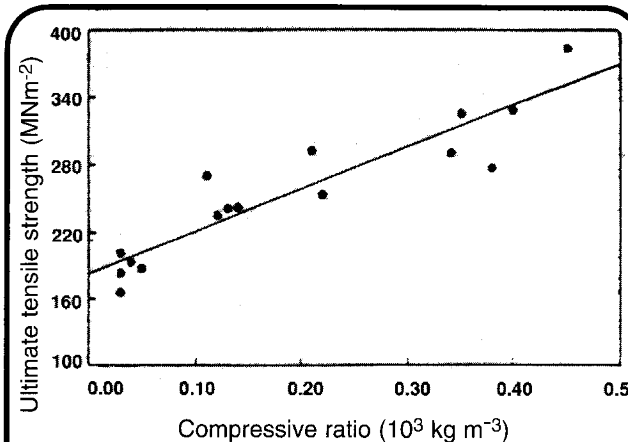


Fig. 6.21 *The tensile strength curve of reformed bamboo versus compressive ratio.*

biomaterials. Because bamboo is a unidirectional fibre-reinforced composite, the mechanical properties in directions other than the fibre direction are less than those in the fibre direction, especially those across the fibre. For example, the tensile strength in the fibre direction is usually more than 50 times higher than that across the fibre, and the case in reformed bamboo is the same.

Another serious disadvantage of bamboo, also suffered by other biomaterials, is hygroscopicity. The shrinkage coefficient of a material represents its ability to absorb water in air and the shrinkage coefficient of reformed bamboo was found to be less than that of normal bamboo (cf Table 6-10); thus the reformed bamboo is superior to the normal one in respect to retaining geometrical stability, in other words under the same conditions, reformed bamboo absorb less water from air than normal bamboo.

After all the moisture content of ligno-cellulosic bamboo will increase due to water in the air and will result in rot during service. The other parameter which describes hygroscopicity is the hygroscopic volume coefficient H, which is defined as H=W/V where W is the moisture content in the specimen, and V is the volume of the dry specimen.

The hygroscopicities of normal bamboo and reformed bamboo composites were measured experimentally for one month. Specimens were placed in a container of 100% relative moisture and a temperature of 20 degree C ± 2°C The moisture content of the specimens were measured regularly (See Reformed bamboo/aluminium alloy composite)

Of the three start points those for reformed bamboo and reformed bamboo/aluminium are lower than that for normal bamboo; this is because the moisture content of reformed bamboo is lowered during the process of heating and compression.

Up to 20 days, the hygroscopic volume coefficient (HVC) of reformed bamboo aluminium remained the lowest. In the other two specimens, without aluminium sheets outside , the HVC of reformed bamboo increased more rapidly than that of normal bamboo; this is also because of the low moisture content in reformed bamboo after treatment. The situation after 20 days is seldom encountered in service, when the relative humidity of 100% in their experiment is taken into account.

C. CHEMICAL PROPERTIES

CHEMISTRY OF BAMBOO SHOOTS AND CULMS

The results of the chemical composition of bamboo shoots carried out by Higuchi (1987) is given in Table 7-1. The sheath of bamboo shoots was peeled off and was cut into the upper, middle and basal portions, respectively. The sample of each portion was homogenized by a Waring blender and the homoginate was pressed to remove the juice. The homoginate was extracted several times with cold and hot water successively to remove the water soluble substances. Bamboos were cut into small pieces which were then pulverized by a Wiley mill.

The samples thus obtained were analyzed by conventional methods based on Schorger's procedure, and the content of lignin was corrected for protein. The contents of ash and the extracts of hot water, 1% NaOH, and ethanol - benzene decreased with maturation of the bamboo shoots, altough they were somewhat larger in bamboos than in shoots.

This may be attributed to the effect of water extractions in preparing the samples of bamboo shoots. The content of cellulose, pentosan, lignin, total methoxyl, and the methoxyl of lignin increased with the maturation of the bamboo shoot; the pentosan content decreased again in bamboos. The proximal chemical compositions of bamboo culms are generally similar to those of hardwoods, except that alkaline extract, ash and silica contents are higher than in hardwoods. High silica content causes scaling during evaporation of the spent liquor for recovery of the chemicals in pulping.

A. Hemicelluloses

Hemicellulose of bamboos have been investigated by several researchers. Maewaka and Kitao isolated a xylan from Madake (P. reticulata) culm by extraction with aqueous alkali of the chlorite holocellulose followed by precipitation of the alkaline extract as a copper complex with Fehling solution.

The xylan thus obtained comprised more than 90%of the bamboo hemicellulose. The structural studies by means of methylation analysis and periodate oxidation (Smith degradation) of the xylan gave evidence supporting a B-1, 4-linked linier polymer with attachments of single unit side chains such as the residues of L-arabinose and D-xylose in a molar ratio of 1.0:1.0-1.3:24-25, respectively.

It seems different from arabino- (4-O-methyl-D-glucurono) xylan found in the wood of gymnosperms, with respect to the degree of branching and the molecular properties.

Some properties of the bamboo xylan are similar to those hardwoods, but the most of the properties are in common with that the *Gramineae*.

It was further found that bamboo xylan isolated by extraction of bamboo holocellulose with DMSO contain 6-7% acetyl group. These results indicate that the bamboo xylan has unique feature of *Gramineae* different from gymnosperm and angiosperm xylans.

In addition, from the water soluble fraction of bamboo shoot-hemicellulose extracted with DMSO, a xylan which

Table 7-1 Chemical composition of bamboo shoots and mature bamboos (Percent of the water-free material)

Species		Ash	Hot-water extract	1% NaOH extract	Alc.-benzene extract	Cellu lose*	Pento-san	Lignin	Metho-xyl	Metho-xyl in lignin
Phyllostachys pubescens	h. p	1.61%	16.16%	45.44%	4.72%	31.69%	25.40%	2.25%	1.21%	5.17
	m. p	0.70	15.78	34.17	3.60	35.44	31.62	6.21	1.34	7.76
	l. p	0.88	14.72	32.86	2.33	38.48	36.20	7.80	1.91	8.27
	m. b	1.31	19.96	32.19	4.63	49.12	27.70	26.06	6.69	14.48
Phyllostachys nigra MUNRO var. *Henonis*	h. p	2.15	19.26	58.14	6.32	43.89	25.56	2.14	1.39	4.26
	m. p	0.88	12.02	46.02	3.35	41.53	27.18	6.93	1.20	5.86
	l. p	0.68	14.14	39.28	2.38	45.41	42.97	7.08	1.62	7.47
	m. b	2.00	21.47	34.03	3.35	42.31	24.13	23.82	6.45	17.06
Phyllostachys reticulata	h. p	1.39	10.84	57.49	6.64	34.36	24.94	3.84	1.47	3.36
	m. p	0.85	8.58	46.18	3.66	37.30	29.58	4.85	1.99	4.78
	l. p	0.78	8.31	34.87	1.21	38.39	49.74	9.17	2.38	6.46
	m. b	1.94	23.24	36.17	3.37	40.97	26.54	25.33	7.02	14.68

h. p: higher portion of bamboo-shoot m. p: middle portion of bamboo-shoot
l. p: lower portion of bamboo-shoot m. p: mature bamboo
*Cellulose content was determinated by modification of JENKINS' $NaClO_2$ method by S. HONDA and was calculated for the pentosan free basis.
Source: Takayoshi Higuchi 1987.

gives no copper complex with Fehling solution, an arabinogalactan, and a-glucan were isolated. The yield of the arabinogalactan was 0.3- 0.4% and was found to be different from conventional plant cell wall arabinogalactan which usually contains D- galacturonic acid.

The structural analysis by methlation and Smith degradation indicated that the arabinogalactan is composed of 1, 3- linked D- galactopyranosyl residues similar to the arabinogalactan from plant seeds and the sap of sugar maple. The molecular weight of a-glucan was 8000.

Kato et al recently found that ferulic acid is esterified to arabinofuranosyl residue of arabinoglucuronoxylan in sugar cane cell wall. Ferulic acid occurring as an ester component of bamboo cell wall may be linked to the hemicellulose as well, altough p-coumaric acid is confirmed to be linked to the side chain of bamboo lignin.

B. Lignin

Lignins are generally classified into three major groups based on their structural monomer units. Gymnosperm lignin is a dehydrogenation polymer of coniferyl alcohol. Angiosperm lignin is a mixed dehydrogenation polymer of conifery - and sinaply alcohols, and grass lignin is composed of mixed dehydrogenation polymer of coniferyl-, sinaply- and p- coumaryl alcohols. In grass lignin p- coumaric acid is esterified to the side chains of the lignin polymer.

1) p- coumeric acid

Grass lignin including bamboo lignin gives absorption bands at 315 nm and 280nm in the UV spectrum . However, when grass lignin is treated with aqueous NaOH and then lignin is precipitated with acid the precipitated lignin gives an absorption bans at 280 nm and p-coumaric acid is isolated from the filtrate. An absortion band at 1730 cm^{-1} in the IR spectrum, which is attributed to the p-coumaric acid ster , also disappeared after saponification of the grass lignin.

On the basis of spectral analyses before and after alcaline hydrolysis and acidolysis of bamboo lignin and model compounds such as veratryl p-coumarate and 3-(3,4 - dimetoxy phenyl) propyl p-coumarate we found that about 80% of the p-coumaric acid in bamboo lignin is sterified to γ–hydroxyl group of lignin side chains, specially of α, β–saturated ones in lignin molecules; α– linked ester of the acid was estimated to be less than 20%

2) Alkaline Nitrobenzen

By alkaline nitrobenzene oxidation gymnosperm lignin gives about 25% vanillin with a small amount of phydrobenzaldehyde ; angiosperm lignin 40-50% of a mixture of vanillin and syringgaldehyde with molecular ratio of 1:1-3 and grass lignin 20-30% of a mixture of vanillin ,syringaldehyde and p- hydrxybenzaldehyde with molecular ratio 1:1-2:1.

About two third of the hydroxybenzaldehyde yielded by alkaline nitrobenzene oxidation of grass lignin is derived from the esterified p-coumaric acid of the lignin. the products and the ratios of the aldehydes reflect aproximate composition in the monomeric components of these types of lignins. These aldehydes are derived from uncondensed aromatic units of lignin and determined by gas liquid chromatography .(Higuchi , 1987)

The main chemical elements entering into the composition of bamboo culms

The main chemical elements entering into the composition of bamboo culms, forming the cell walls are cellulose, hemicellulose and lignin. Minor constituents, enclosed in the cell cavities, are tannins, resins, waxes and inorganic salts.

In the study conducted by Ma & Han (1993) in 26 bamboo species, they pointed out that the cellulose content is 35.86%- 45.76%, averaging41.80%.According to Karlsen *et al* (1967), in trees it can be assumed that softwoods are composed, on the average, of 48-56% cellulose, 20-30% lignin and 23-26% hemicellulose ardwoods contain slightly less cellulose and more hemicellulose. The experimental results indicated that the chemical composition of bamboo culms was similar to that of hardwoods in general, except that alkaline extract, ash and silica contents are higher than in hardwoods. The xylan obtained from culm extraction and precipitation comprised more than 90% bamboo hemicellulose (Higuchi T. 1987).

Liese (1992) points out that bamboo consists of about 50-70% holocellulose, 30% pentosans and 20-25% lignin. This chemical composition varies according to the species, the conditions of growth,the age of the bamboo culm and the part of the culm. Since bamboo completes the maturation of culm tissue within 2-3 years, when the soft and fragile culm becomes hard and strong, the proportion of lignin and carbohydrates changes during this period. However, after full maturation of the culm, the chemical composition tends to remain rather constant.

Cellulose and hemicellulose, also called holocellulose, are the solid residues of the polysaccharide fraction that remains after extraction of minor components and lignin by mild oxidation. The hemicellulose is extracted from holocellulose with a 17.5 NaOH solution, the residue being cellulose, which is difficult to isolate in a pure form because it is closely associated with the hemicellulose and the lignin. Cellulose is sometimes referred to as alpha-cellulose, which is the principal component in the manufacture of useful products such as paper, explosives, plastics, synthetic textiles, etc., which can be manufactured using bamboo as a raw material, as will be explained in another chapter of this book.

Pentosans are the main constituents (80-90%) of bamboo hemicellulose. In cold water, some dyes and tannins can be dissolved, while hot water extracts more substances from bamboo culms, such as starch and some others.

Alcohol-benzene 1:2 (1/3 ethanol and 2/3 benzene) is used to extract almost all substances not belonging to the cellulose group or lignin. Ether is used to extract alkaloids which do not dissolve in water (PROSEA (1995).

The nodes contain less water-soluble extracts, such as pentosans, ash, and lignin, but more cellulose than the internodes. The season influences the amount of water-soluble material, which is higher in the dry season than in the rainy season. The starch content reaches its maximum in the driest months just before the rainy season and sprouting.

The ash content (1-5%) is higher in the inner than in the outer part. On an average, the silica content varies from 0.5 to 5%, and it increases from bottom to top. Most silica is deposited in the epidermis, "the skin zone", whereas the nodes contain little silica and the tissues of the internodes almost none. The silica content affects the processing and pulping properties of bamboo.

Lignin: After cellulose, lignin is the second most abundant constituent in bamboo and great interest has been placed on its chemical nature and structure. Liese (1985) points out that bamboo lignin is a typical grass lignin, which is built up from three phenyl-propane units, p-coumary, coniferyl, and sinapyl alcohols, which are interconnected through biosynthetic pathways.

Bamboo grows very rapidly, reaching its full size within a few months. The lignification within every internode proceeds downward from top to bottom, whereas transversally it proceeds from the inside to the outside. During the height growth, lignification of epidermal cells and fiber precedes that of ground tissue parenchyma. The full lignification of the bamboo culm is completed within one growing season, showing no further aging effects.

Bamboo has been chosen as one of the suitable plants to study the biosythesis of lignin. Initially, these investigations were almost exclusively based on feeding experiments with radioactive precursors and it was found that lignin is synthesized from glucose formed by photosynthesis via the "Shikimic acid pathway" (Higuchy 1969 in Liese 1985).

Probably, the first and most complete research related to The study of the mechanical properties and chemical composition of bamboos was carried out by Sioti Uno at the Utsunomiya Agricultural College in Japan and published in 1932. I think that these studies are very important because they can be used as the basis for future research.

For his research, Mr. Uno used eight bamboo species and the following procedures for the preparation of the materials or components of the culm. I include this old information even though today there is better equipment and faster methods for obtaining the components.

Preparation of materials.

The material for chemical analysis was taken from the inner and outer layers of the culm wall of the lower, middle and upper sections of the culm. The materials for the quantitative cellulose analysis were prepared in the form of very thin, hand-planed shavings, and those for the other analyses were prepared in the form of sawdust, sifted through a 1 millimeter sieve.

a) Cellulose. The determination of crude cellulose was made by the Cross and Bevan method, and that of the Alpha, Beta and Gamma cellulose by the following method: 5 gr. of dry material were cooked one half hour with one percent caustic soda, washed and set aside in a wet condition for 30 to 60 minutes in a slow stream of chlorine wash. After washing with water, it was irrigated with 2 percent sodium sulphite solution, and slowly heated to boiling. Then 0.2 percent caustic soda was added, and it was boiled for another 5 minutes. It was washed with hot water and finally bleached with a one percent solution of potassium permanganate in order to remove the last traces of colored impurities.

The remaining manganese dioxide was removed with diluted ammonia (1:50); then the residue was well washed, dried and weighed . This substance is crude cellulose.

For the preparation of Alpha-cellulose, the crude cellulose was treated for 30 minutes with 18 percent caustic soda, 50 cubic centimeters of water was added. Then it was filtered through a Buchner funnel and the alkali removed by washing with cold water, after which the residue was dried and weighed. This substance is Alpha-cellulose.

For the determination of the Beta-cellulose in crude cellulose, the foregoing filtrate was used. Acetic acid was added to the solution and was heated to 100°. Then the precipitate was filtered off, dried and weighed. Next, the sum of the Alpha and Beta cellulose is substracted from the total crude cellulose; the difference is the Gamma cellulose.

According to the results of the research, as shown in table 7-2, in many cases the crude cellulose increases in the culm from the lower to the upper portion. In the comparison between the inner and outer layer, the outer has a greater amount, the difference amounts to 15% on the average.

Of the Alpha, Beta and Gamma cellulose as shown in Tables 7-2 and 7-3, the Alpha cellulose content is the greatest, i.e. from 66.86% to 77.62% . Moreover, more Beta cellulose than Gamma cellulose is detectable and this relationship is the same as in softwoods.

b) Pentosans.-The analysis for pentosans was carried out according to the following method whereby 2 grams of dry material were used each time. One hundred cubic centimeters of hydrochloric acid (specific gravity 1.06) were added to the material and the mixture was destilled until the destillate amounted to 30 cubic centimeters. After the addition of another 30 cubic centimeters of hydrochloric acid, the mixture was again distilled until another 30 cubic centimeters of distillate were obtained. The same operation was repeated until the total distillate amounted to 360 cubic centimeters. To this solution a solution of phlorglucin was added in order to precipitate the furfural-phlorglucide. This precipitate was filtered out, washed, dried and weighed.

The pentosans were calculated from total furfural-phlorglucide. According to the results of these investigations, there is a little difference between the upper, middle and lower sections. But between the inner and the outer layers, the former show a greater total pentosan content, as is evident in Table 7-4.

c) Alcohol extract.-For the extraction with alcohol, 2 grams of dry material were taken and extracted in a Soxhlet apparatus for 16 hours. Then the alcohol was evaporated from the extract by heating over a water bath, and the residue was dried and weighed. It was found that the total alcohol extract is relatively larg in old bamboo culms, especially in the upper section.

d).-Lignin. It was determined using the following method: 2 grams of the dry material were treated for 48 hours with 72 percent sulphuric acid, then 50 cubic centimeters of water were added and the solution was heated to 100°. Upon cooling, it was filtered through a Goech crucible with an sbestos mat. The residue was washed with hot water in order to remove the acid, dried, and weighed. According to the investigations, as shown in Table 7-5, there is more lignin contained in the outer than in the inner layer.

Table 7-2 CRUDE CELLULOSE AND ALPHA CELLULOSE CONTENT IN SOME BAMBOOS

Species	A.-Crude cellulose content of bamboo culm (%)					B.-Alpha cellulose content in crude cellulose (%)				
	Layer	Lower Section	Middle Section	Upper Section	Average	Layer	Lower Section	Middle Section	Upper Section	Average
Ph.bambusoides	Inner	33.10	34.48	43.28	36.95	Inner	68.73	66.50	64.97	63.73
	Outer	46.70	46.00	49.62	47.44	Outer	81.46	64.96	85.57	77.33
Ph. nigra var *Henonis*	Inner	44.15	40.86	39.73	41.59	Inner	64.78	76.22	63.64	66.21
	Outer	45.40	47.95	43.03	45.45	Outer	68.67	68.13	80.08	72.29
Ph. pubescens	Inner	32.00	29.70	36.14	32.61	Inner	72.90	80.36	58.56	70.60
	Outer	37.78	37.18	38.75	37.90	Outer	44.14	74.53	70.69	63.12
Ph. lithophila	Inner	39.22	47.65	47.30	44.72	Inner	73.85	72.56	83.30	76.40
	Outer	46.95	54.88	47.60	49.78	Outer	68.81	79.41	80.31	76.18
Dendrocalamus latiflorus	Inner	23.18	28.28	39.80	30.42	Inner	46.28	61.10	65.51	57.63
	Outer	37.72	36.70	40.48	38.30	Outer	82.97	72.65	72.88	76.16
Bambusa Oldhamii	Inner	47.25	48.48	50.08	48.60	Inner	73.02	57.19	73.89	68.03
	Outer	51.93	50.20	51.18	51.10	Outer	62.25	72.90	71.71	68.95
B. stenostachya	Inner	43.17	46.45	37.88	42.50	Inner	79.76	78.79	77.49	78.69
	Outer	50.05	47.03	44.50	47.19	Outer	81.37	79.21	86.85	75.81
B. vulgaris var. *vittata*	Inner	46.58	43.37	39.20	43.05	Inner	72.87	75.97	71.68	73.31
	Outer	51.26	52.48	50.35	51.36	Outer	84.39	85.21	76.20	81.93

Source: Sioti Uno (1932)

Table 7-3 BETACELLULOSE AND GAMMA CELLULOSE CONTENT IN SOME BAMBOOS

Species	A. -Betacellulose content in crude cellulose (%)					B.- Gama cellulose content in crude cellulose (%)				
	Layer	Lower Section	Middle Section	Upper Section	Average	Layer	Lower Section	Middle Section	Upper Section	Average
Ph.bambusoides	Inner	23.18	28.21	33.60	28.33	Inner	8.09	5.29	1.43	4.94
	Outer	17.43	19.19	7.62	14.75	Outer	1.11	15.85	6.81	7.92
Ph. nigra var *Henonis*	Inner	34.94	22.70	27.27	28.50	Inner	0.28	1.09	8.09	3.15
	Outer	18.12	16.85	13.34	16.10	Outer	13.21	15.02	6.58	11.60
Ph. pubescens	Inner	16.54	17.77	22.67	19.03	Inner	10.46	2.64	18.78	10.63
	Outer	20.78	11.15	20.14	17.36	Outer	35.08	14.32	9.17	19.52
Ph. lithophila	Inner	17.61	24.08	14.96	18.88	Inner	9.04	3.36	1.74	4.71
	Outer	22.90	18.36	10.64	17.30	Outer	8.29	2.25	9.05	6.52
Dendrocalamus latiflorus	Inner	24.92	32.75	23.49	27.05	Inner	28.20	6,17	11.00	15.12
	Outer	14.24	25.71	18.10	19.35	Outer	2.79	1.66	9.02	4.49
Bambusa Oldhamii	Inner	14.13	14.49	22.32	16.98	Inner	12.86	28.82	3.79	15.16
	Outer	17.09	20.87	10.55	16.17	Outer	20.66	6.25	17.74	14.87
B. stenostachya	Inner	17.10	13.29	16.44	15.61	Inner	3.12	7.92	6.07	5.70
	Outer	14.01	15.15	23.20	17.45	Outer	4.62	5.64	9.95	6.74
B. vulgaris var. *vittata*	Inner	23.62	15.28	17.01	15.64	Inner	4.11	8.75	11.31	8.06
	Outer	11.48	12.24	15.50	13.07	Outer	4.13	2.55	8.50	4.99

Source: Sioti Uno (1932)

Table 7-4 PENTOSANS CONTENT AND YIELD OF ALCOHOL

A. -Pentosans content (%)

Species	Layer	Lower Section	Middle Section	Upper Section	Average
Ph.bambusoides	Inner	20.75	23.40	25.20	23.12
	Outer	19.60	20.25	24.40	21.42
Ph. nigra var *Henonis*	Inner	26.55	27.55	29.10	27.73
	Outer	26.00	25.35	26.30	25.88
Ph. pubescens	Inner	27.25	29.60	26.00	27.62
	Outer	24.30	25.35	26.50	25.38
Ph. lithophila	Inner	22.65	23.00	23.65	23.10
	Outer	21.45	17.55	23.05	20.68
Dendrocalamus latiflorus	Inner	29.70	28.75	23.14	27.20
	Outer	25.90	24.06	20.30	23.42
Bambusa Oldhamii	Inner	19.95	21.65	19.85	20.40
	Outer	17.05	19.75	15.50	17.43
B. stenostachya	Inner	21.20	20.30	21.60	21.00
	Outer	17.55	18.10	17.65	17.83
B. vulgaris var. *vittata*	Inner	21.40	21.40	21.85	21.55
	Outer	20.0	18.70	18.60	19.12

B.-Yield of alcohol extract (%)

Species	Layer	Lower Section	Middle Section	Upper Section	Average
Ph.bambusoides	Inner	3.80	8.76	4.10	5.47
	Outer	4.45	4.50	7.20	
Ph. nigra var *Henonis*	Inner	6.63	8.15	6.95	6.85
	Outer	6.95	7.74	4.65	
Ph. pubescens	Inner	3.70	5.63	3.40	4.27
	Outer	3.80	5.26	3.80	
Ph. lithophila	Inner	1.45	2.70	3.80	3.42
	Outer	4.55	2.75	5.28	
Dendrocalamus latiflorus	Inner	6.38	6.25	3.35	5.40
	Outer	5.43	6.40	4.58	
Bambusa Oldhamii	Inner	8.30	6.85	4.10	5.33
	Outer	3.60	5.16	3.95	
B. stenostachya	Inner	7.88	5.68	2.52	4.81
	Outer	5.30	4.88	2.60	
B. vulgaris var. *vittata*	Inner	6.13	3.28	4.65	4.98
	Outer	4.70	5.27		

Source: Sioti Uno (1932)

Table 7-5 LIGNIN AND ASH CONTENT

A - Lignin (%)

Species	Layer	Lower Section	Middle Section	Upper Section	Average
Ph.bambusoides	Inner	23.48	28.39	29.04	26.97
	Outer	27.84	30.05	31.00	29.62
Ph. nigra var *Henonis*	Inner	32.57	19.56	29.85	27.33
	Outer	31.07	29.90	30.58	30.52
Ph. pubescens	Inner	29.58	24.33	21.28	25.06
	Outer	36.61	39.26	29.73	35.20
Ph. lithophila	Inner	24.30	26.86	29.61	26.92
	Outer	30.10	32.34	32.10	31.51
Dendrocalamus latiflorus	Inner	18.61	34.85	39.12	30.86
	Outer	27.24	37.26	41.95	35.48
Bambusa Oldhamii	Inner	17.72	28.07	20.02	21.94
	Outer	23.71	29.48	27.16	26.78
B. stenostachya	Inner	25.85	26.52	25.31	25.89
	Outer	29.35	35.91	28.51	31.26
B. vulgaris var. *vittata*	Inner	22.05	25.44	26.00	24.50
	Outer	30.93	25.93	28.93	28.51

B - Ash (%)

Species	Layer	Average of lower, mid. upper sec.	Average thereof	Color
Ph.bambusoides	Inner	1.09	1.07	Ash-white
	Outer	1.06		
Ph. nigra var *Henonis*	Inner	1.22	2.03	Do
	Outer	1.83		
Ph. pubescens	Inner	1.57		Do
	Outer	1.48	1.53	
Ph. lithophila	Inner	2.31	2.10	Ash-dark
	Outer	1.89		
Dendrocalamus latiflorus	Inner	1.74	1.70	Ash-green
	Outer	1.66		
Bambusa Oldhamii	Inner	2.52	2.09	Greenish-White
	Outer	1.66		
B. stenostachya	Inner	2.14	1.74	Do
	Outer	1.33		
B. vulgaris var. *vittata*	Inner	1.44	1.87	Green
	Outer	1.29		

Source: Sioti Uno (1932)

Table 7-6 CULM CHEMICAL COMPOSITION WITH REFERENCE TO THE CULM'S AGE

Species	Age (years old)	Moistu-re (%)	Ash (%)	Cold water sol.(%)	Hot wate sol.(%)	Caust. soda (1%)-%	Alcoh. benz. sol. %	Lignin (%)	Pento-sa (%	Holoce-llulose %	Alpha-cellul. (%
Phyllostachys pubescens	1/2	9.00	1.77	5.41	3.26	27.34	1.60	26.36	22.19	76.62	61.97
	1	9.79	1.13	8.13	6.34	29.34	3.67	24.77	22.97	75.07	59.82
	3	8.55	0.69	7.10	5.41	26.91	3.88	26.20	22.11	75.09	60.55
	7	8.51	0.52	7.14	5.47	26.83	4.78	26.75	22.04	74.98	59.09
Ph. heteroclada	1	8.38	1.24	13.57	9.60	30.89	5.38	22.42	20.43	71.98	58.15
	3	10.87	1.27	9.68	15.94	34.84	9.11	22.72	21.83	59.95	38.96
Ph. nigra	1/2	10.31	1.98	6.72	8.30	31.83	4.12	28.49	22.24	70.77	45.38
	1	7.79	1.84	10.69	8.53	33.24	5.29	23.99	22.08	73.61	58.85
	3	11.61	1.71	6.50	8.36	33.65	5.58	25.00	22.39	68.64	43.79
Ph. bambusoides	1/2	10.69	2.22	4.62	5.93	27.60	1.81	24.51	22.69	76.41	48.92
	1	9.14	1.25	10.49	8.97	29.93	7.34	22.39	22.46	72.65	56.74
	3	9.90	0.98	6.11	7.32	31.33	5.86	25.15	22.65	65.39	42.92
Ph. meyeri	1/2	10.70	1.68	3.69	5.15	27.27	1.81	23.58	21.95	78.47	49.97
	1	8.29	1.29	10.79	8.91	38.28	7.04	23.62	22.35	72.84	57.88
	3	9.33	1.85	8.81	12.71	35.32	7.52	23.35	22.19	62.40	39.05
Ph. praecox	1/2	10.64	3.24	6.72	8.57	33.36	2.25	26.74	21.98	72.83	42.23
	1	8.19	1.96	11.21	7.68	32.84	3.80	24.68	22.24	73.31	56.13
	3	11.29	2.28	7.18	9.09	33.26	5.64	25.65	22.39	65.77	40.81
Bambusa textilis	1/2	9.09	2.39	6.64	8.03	32.27	4.59	18.67	22.22	77.71	51.96
	1	10.58	2.08	6.30	7.55	30.57	3.72	19.39	20.83	79.39	50.40
	3	10.33	1.58	6.84	8.75	28.01	5.43	23.81	18.87	73.37	45.50
B. pervariabilis	1/2	8.38	2.16	4.93	6.35	27.71	2.14	20.92	21.47	79.41	52.63
	1	11.66	2.29	7.64	7.71	29.99	2.15	21.43	20.26	73.34	
	3	11.04	2.65	9.51	9.25	30.63	6.42	22.07	19.22	69.14	48.15 / 45.33
B. sinospinosa	1/2	9.17	2.69	7.29	8.23	29.98	4.23	19.90	21.84	78.29	52.58
	1	11.49	1.92	8.98	9.91	30.25	5.49	20.54	20.72	74.46	49.15
	3	11.13	1.84	9.07	9.29	26.92	5.88	24.17	19.27	72.77	47.10
L. chungii	1/2	9.21	2.73	8.10	9.70	35.17	4.16	17.58	23.91	79.00	47.63
	1	10.33	2.10	8.07	9.46	29.97	4.35	21.41	18.72	73.72	47.76
	3	10.2		6.34 -	9.24	30.57	3.98	22.70	18.88	71.70	
Source: Youdi et al (1985)											
Bambusa vulgaris	----	-----	2.40	-----	5.10	27.90	4.10	26.90	21.10	66.05	43.6
			4.10		3.80	22.30	5.40	25.50	19.60	61.30	------
			5.30		4.40	28.30	3.20	24.20	18.80	62.9	