Bamboo Research in Asia

Organized by the International Development Research Centre and the International Union of Forestry Research Organizations

Editors:
Gilles Lessard and Amy Chouinard
The International Development Research Centre is a public corporation created by the Parliament of Canada in 1970 to support research designed to adapt science and technology to the needs of developing countries. The Centre's activity is concentrated in five sectors: agriculture, food and nutrition sciences; health sciences; information sciences; social sciences; and communications. IDRC is financed solely by the Parliament of Canada; its policies, however, are set by an international Board of Governors. The Centre's headquarters are in Ottawa, Canada. Regional offices are located in Africa, Asia, Latin America, and the Middle East.
Bamboo Research in Asia

Proceedings of a workshop held in Singapore, 28–30 May 1980

Editors: Gilles Lessard and Amy Chouinard

Organized by the International Development Research Centre and the International Union of Forestry Research Organizations
Contents

Foreword 5
Participants 7
Research Needs and Priorities 9
Cooperative Activities 12
Country Reports 13
Bangladesh 15
India 19
Japan 47
China 57
Indonesia 63
Philippines 69
Sri Lanka 81
Thailand 85
Malaysia 91
Discussion Summary 96
Special Papers 97
Bamboos in the Asia-Pacific Region Y.M.L. Sharma 99
Bamboo Taxonomy in the Indo-Malesian Region Soejatmi Dransfield 121
Lessons from Past Studies on the Propagation of Bamboos S.M. Hasan 131
Propagation of Bamboos by Clonal Methods and by Seed Ratan Lal Banik 139
Bamboo Cultivation Etsuzo Uchimura 151
Anatomy of Bamboo W. Liese 161
Preservation of Bamboos W. Liese 165
The Mechanical Properties of Bamboo Used in Construction Jules Janssen 173
Properties and Utilization of Philippine Erect Bamboos Francisco N. Tamolang, Felipe R. Lopez, Jose A. Semana, Ricardo F. Casin, and Zenita B. Espiloy 189
The Angklung and Other West Javanese Bamboo Musical Instruments Elizabeth A. Widjaja 201
The Mechanical Properties of Bamboo Used in Construction

Jules Janssen

This paper highlights a research program on the mechanical properties of bamboo, including tests on compression, bending, shear, etc., in short- and long-term loading. I studied the relationship between these mechanical properties and the moisture content of bamboo, the position along the culm, and the influence of nodes, through statistical analysis. The relationship between mechanical properties and biological composition was also studied. For example, one question I attempted to answer was does the tensile strength on the macroscale agree with the theoretical strength of the cellulose and with the percentage of cellulose. A mathematical model of a sclerenchyma cell is introduced, reflecting the geometry of the cell, the composition, and the properties of cellulose and lignin. This model indicates the capability of the bamboo to withstand strains and stresses. If data on bamboo can be fed into the model and if the model produces strains and stresses similar to those from actual tests, the model represents an understanding of the mechanical behaviour of bamboo. Based on my assessment of the mechanical properties, I designed joints that form part of trusses and tested them. Then, using the best joint, I tested trusses on a full scale. These tests pointed to specific research recommended for the future.

In 1974, I began a comprehensive research program on the mechanical properties of bamboo, particularly for structural uses in joints and trusses. Although the problem of durability of bamboos is also a major one, it fell outside my specific field of interest, as did bamboo as reinforcement in concrete.

My research was prompted by a request made by volunteers in developing countries. They asked for technical advice on how to build bamboo trusses for schools and warehouses. At the University of Technology in Eindhoven there was no one who could help them, but I was able to find some information from the 1880s in the files of the former Royal Dutch Indian Army. With this information some advice could be given, and because the information appeared to be useful to many more volunteers, it was published as a reprint. Since then, several hundred copies of it have been distributed. In addition, a similar English text has been prepared. Both reprints contain information on the use of bamboo in building and should be used as supplements to the well-known UN manual *The Use of Bamboo and Reeds in Building Construction*.

Thus, I became interested in bamboo and developed a research program on the use of bamboo in building structures, especially in trusses for roofs or bridges. My idea was that bamboo could play a bigger role in building than it has. Bamboo trusses need to be streamlined as has been the case with wooden

---

1University of Technology, Eindhoven, Netherlands.
trusses. A century ago every carpenter built a wooden truss like his father did, with too much wood and of unknown safety. Now wooden trusses are designed, calculated, and built on the basis of much research, with less wood and of a known safety. I hope to contribute to the streamlining of bamboo structures.

Tests on Mechanical Properties

My research started with a study of the available literature (not reported here). Next, I ordered bamboo from the Philippines and equipped a laboratory that had 70% relative humidity and was kept at about 25°C. First, I carried out a series of tests on compression, bending, shear, etc. in short- and long-term loading, statistically analyzing the relationship between these mechanical properties and moisture content, position along the culm, and the influences of nodes. One immediate problem with tests of bamboo is that no agreed standards exist; in contrast these are readily available for timber. In the past, researchers postulated their own separate criteria and tests. Thus, comparisons of results are extremely difficult. To give bamboo an equivalent place among other building materials, one should promote both standardization of test methods and intensive investigation into the mechanical properties of bamboo and the physical and biologic influences on these.

A Simplified Explanation of a Statistical Model

This research program started from an analysis of variances. The advantage of this statistical method is the fact that one can test moisture content and other physical or biologic factors together and calculate the influence of every single factor. For example one can test the influence of moisture content (4%, 8%, and 12%), node (N), and internode (I) on the compression strength using six specimens (one each for N and I at the three levels of moisture); the results are a linear model:

\[ y = \beta_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + e \]

in which \( y \) equals the estimated value of compression stress at failure; \( e \) equals the random error; \( \beta_1 \) equals the constant, approximately the mean value; and \( \beta_2 x_2 + \beta_3 x_3 \) is equal to the contribution to the compression stress due to moisture content, the \( x_2 \) (for simple calculation) being 1, 0, -1, and \( x_3 \) being 1, -2, +1 for 4, 8, and 12% respectively; \( \beta_4 x_4 \) is equal to the contribution of (inter)node such that \( x_4 \) equals -l(node) or +1 (internode). Based on these \( x \) values and on the results of the actual tests (i.e., the ultimate stresses), the values of \( \beta \) are (in N/mm²) \( \beta_1 = 81.1; \beta_2 = 3.5; \beta_3 = 0.4; \) and \( \beta_4 = 2.3. \) Their significance can be calculated as well, and then the ultimate stress can be estimated for each combination of influences. For example, the estimated compressive stress for 12% moisture content (MC) and node is:

\[ y = 81.1 + 3.5 (-1) + 0.4 (1) + 2.3 (-1) = 75.7 \text{ N/mm}^2. \]

Influences on Mechanical Properties

When testing the mechanical properties of bamboo, one deals with a series of influences. Some are constant and some variable. In my program the constants were the species (Bambusa blumeana); the age (3 years old); the conditioning (conditioned as opposed to green); and speed of loading/deforming. Considered as variables were moisture content (4%, 8%, or 12%, in equilibrium with 30, 50, or 70% relative humidity); position along the culm (bottom, middle, or top); node or internode; form and size of the specimen;
and short- or long-term loading. It must be emphasized that the purpose of my tests was not to determine the mean strength of the bamboo but to determine which influences determine the strength.

**Compression**

Compression tests were carried out on full cylinders cut from bamboo stems. The variables taken into account were moisture content (MC) (4, 8, and 12%); height of the specimen (50, 100, and 200 mm); node or internode; the stems from which the specimens were cut (a necessary variable for the correctness of the model only); position along the culm (bottom, middle, or top); as well as several interactions.

The results of the tests are listed in Table I. The P-value is the probability that any value could be greater than the critical value in an F-distribution; with 5% level of probability, only the factors with a P-value <0.05 are significant. These are the constant (obviously), the MC, the stems (not of interest to this study), the position along the culm, and three interactions (14, 16, and 18). These results indicated that not all 18 parameters were needed; therefore the model was simplified.

The results also indicated that the compressive stress increases with decreasing MC. The height of the specimens, as defined in these tests, was not significant nor was the node or internode — a finding in the studies by Atrops (24) and Limaye (220). The position along the culm was very significant, that is, the top portion was much stronger due to the greater number of sclerenchyma than was the bottom (220). Failure was due to splitting, i.e., an excess of

<table>
<thead>
<tr>
<th>Factor and levels</th>
<th>Value of x</th>
<th>Estimated parameter $\beta$ (N/mm$^2$)</th>
<th>P-value $a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>$x_1 = 1$</td>
<td>81.1</td>
<td>0.00</td>
</tr>
<tr>
<td>RH (30, 50, 70%)</td>
<td>$x_2 = \frac{50-RH}{20} + 1,0,-1$ (respectively)</td>
<td>3.5</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>$x_3 = 3x_2 - 2 = 1,-2,1$ (respectively)</td>
<td>0.4</td>
<td>0.55</td>
</tr>
<tr>
<td>Height (50,100,200 mm)</td>
<td>$x_4 = \frac{H}{50} - 2 = -1,0,2$ (respectively)</td>
<td>-0.2</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>$x_5 = x_2^2 = 1,0,4$</td>
<td>-0.4</td>
<td>0.67</td>
</tr>
<tr>
<td>Node or internode</td>
<td>$x_6 = -1$ or +1 (respectively)</td>
<td>2.3</td>
<td>0.11</td>
</tr>
<tr>
<td>Stems</td>
<td>$x_7 = -1,0,1$</td>
<td>3.5</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>$x_8 = 1,-2,1$</td>
<td>0.2</td>
<td>0.69</td>
</tr>
<tr>
<td>Position along culm (bottom, middle, top)</td>
<td>$x_9 = -1,0,1$</td>
<td>6.8</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>$x_{10} = 1,-2,1$</td>
<td>-0.6</td>
<td>0.32</td>
</tr>
<tr>
<td>Interaction: RH and (inter) node</td>
<td>$x_{11} = x_2x_6$</td>
<td>1.1</td>
<td>0.29</td>
</tr>
<tr>
<td>Interaction: RH and position</td>
<td>$x_{12} = x_2x_6$</td>
<td>0.6</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>$x_{13} = x_2x_9$</td>
<td>0.9</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>$x_{14} = x_2x_{10}$</td>
<td>-2.3</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>$x_{15} = x_2x_9$</td>
<td>0.6</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>$x_{16} = x_2x_{10}$</td>
<td>-1.1</td>
<td>0.01</td>
</tr>
<tr>
<td>Interaction: height and (inter) node</td>
<td>$x_{17} = x_4x_6$</td>
<td>-2.4</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>$x_{18} = x_5x_6$</td>
<td>2.3</td>
<td>0.02</td>
</tr>
</tbody>
</table>

$a$ Significant P-values are italicized.
the tensile strain on the pectin holding the fibres together. If one finds this tensile strain, it might be possible to explain the compressive strength of the bamboo.

Bending

Bending is an important factor in building construction; therefore many reports on bending of bamboo are available, e.g., Limaye (220), Karamchandani (185), and Sekhar (358). I also carried out short-term bending tests on 25 full stems, free span 4.50 m, four-point bending test, at 12% MC. My results varied markedly, with the mean for stress at failure being 84 N/mm², a standard deviation of 26 and an E-value of 20 000, SD of 3000. Failure occurred not in the tensile strength of the fibres but in the shear strength of the pectin in the neutral axis of the stem and in the tensile stress of the pectin, transversal to the fibre, in the area with longitudinal compression. The mean shear strength was as low as 2.25 N/mm² in short-term loading and 1.01 in long-term (6 months to 1 year) loading. Preliminary results with long-term bending tests are similar, and although the data are as yet insufficient to describe the creep and the recovery, the long-term strength seems to be about 55% of short-term strength; i.e., 0.55 × 84, or 46 N/mm². This value fits fairly well with the results to date.

My plans are to go on with these tests in 1981 but to be more systematic, e.g., 30 days creep and 30 days recovery repeated, perhaps, five times at stresses of 40 and 50 N/mm².

For bamboo tests, a Burgers-model, as for wood, seems appropriate. The highly crystalline regions have the properties of a spring, whereas the amorphous lignin has the properties of a dashpot (202). Creep occurs because in the amorphous parts of the cellulose, the relatively weak hydroxyls move away from their positions.

Although it would be interesting to study the relationships between creep and crystallinity in wood and bamboo, the differences in crystallinity between wood and bamboo are smaller than the differences due to the method of investigation (325).

Shear

Shear is important in bamboo because it is the weakest point. Hardwood has rays, which make the fibres form a union, but bamboo does not. The fibres of bamboo are merely glued together by pectin. As early as 1922, Meyer and Ekelund gave an overview of the tension-, deflection-, and shearing-strength of beech, oak, pine, fir, and bamboo to demonstrate that bamboo is as strong as wood in tension and deflection but much weaker in shear. In their opinion, the shear strength of the woods is 20–30% of the respective compressive strength, but bamboo's shear strength is only 8% of its compressive strength. One may assume that the wood gains 8% shear strength from the pectin and the remainder (up to 20–30%) from the transversal strength of the rays.

Although the lack of shear strength is considered a disadvantage for the structural use of bamboo, it is a big advantage for the use of bamboo by farmers and other people in basketry, matting, and handicrafts in which split bamboo is used. In the use of bamboo in structures, shear strength is needed in bends and joints. When failure occurs during bending, it is not because of a shortage of tensile strength in the fibres but because of incohesiveness between the fibres, in which shear plays a role. In the construction of joints, holes are needed, and these introduce shear in the bamboo.

To measure the influence of moisture content (4, 8, or 12%); position along the culm (bottom, middle, or top); node or internode; and size of specimen
80, or 120 mm), I needed 54 specimens, which were made from three stems. The differences between stems were taken as a parameter, thus freeing the study from the influence of this factor.

The series of tests on the chosen design (Fig. 1) were an orthogonal scheme so that an analysis of variances was very easy (Table 2). At a 5% probability level, only the interaction between moisture content and position can be ignored. In other words, all the factors (moisture content, height of the specimen, inter node, and position along the culm) are significant; their influence on the shear stress is shown in Fig. 2. The significance of the moisture content fits with studies by Ota (302). It is commonsense: the strength of a material decreases with increasing moisture content. The best shear strength was at 80 mm height. Less strength at a shorter length may have been due to local irregularities, whereas less strength at a longer length is logical because the central part does not act as effectively as do the ends.

An internode appears to be better in shear than a node. In an internode all fibres run precisely along each other, but in a node they are interrupted by many vessels that cross them to reach the diaphragm inside the node.
The last relationship, between shear stress and position along the culm, is one in which the shear strength decreases from bottom to top. In contrast to this finding, Atrops (24) found that the shear strength increases with decreasing wall thickness, i.e., from bottom to top. He argued that the percentage of sclerenchyma increases with decreasing wall thickness. Grosser and Liese (113) had similar findings. One reason for the sharp contrast with my results may be that Atrops, Grosser, and I studied different species.

**Conclusions:** The moisture content, height and form of the specimen, node or internode, and position along the culm all have a significant influence on the shear strength of bamboos. They should be defined in every researcher's series of tests and standardized, if possible, so that comparisons of results can be made.

My findings show that a shear area in a joint should be made from an internode because the ability to withstand shear stress in a node is less. It is true that the wall thickness in a node is greater than that in an internode, but this difference is not enough to make the shear strength per length of the culm better.

**What remains to be done?:** A study of designs for shear testing needs to be done, including those with only one shear area. Also a theoretical calculation of the
shear strength of pectin and a comparison of this value with the shear strength found on the macroscale are needed as are long-term tests on shear and standardization of methods.

**Tension**

Tensile strength and elasticity under tension are important qualities for bamboo used in suspension bridges (84) and as reinforcement in concrete. Several authors have described methods to test the tensile strength of bamboo, but I met with many problems when trying to follow their prescriptions. The tensile strength of bamboo is rather high, e.g., 200–300 N/mm², but the E-modulus in compression transversal to the fibres is very low — a fact that causes considerable problems in grip. Also, bamboo has such a low shear strength that, in many cases, failure in tensile tests occurs by longitudinal shear or by transversal compression in the grip. My tests on tensile strength were similar to a method described by Atrops (24) but were few and are not reported here because the tensile strength is not important in trusses, my specific interest. Even in bamboos used for reinforcement in concrete, the tensile strength is not as critical as the durability and the bond. However, the relationship between tensile strength and the E-modulus is one key to the relationship between strength and structure. It is well known that the tensile strength and the E-modulus in tension are mainly determined by the percentage of sclerenchyma fibres, i.e., by the percentage of cellulose (Fig. 3).

![Diagram](image-url)

**Fig. 2.** Estimated values of ultimate shear stress as a function of moisture content, with 90% areas, and influences of other factors.
I tried to collect data from the literature on tensile strength together with data on the sclerenchyma or cellulose content for several species, but the results were not sufficiently comparable because the different authors used many test methods. A theoretical calculation of tensile strength for cellulose of 1500 N/mm² is possible (202). A sclerenchyma cell in bamboo contains 40% lumen, 50% cell-wall layer with cellulose fibrils parallel to the cell axis, and 10% cell-wall layer with cellulose fibrils in a spiral. In calculating the tensile strength, one neglects the lumen and the spiral layer; the remaining 50% consists of 50% cellulose and 50% lignin. Again, in calculating the tensile strength, one neglects the lignin. Then, the tensile strength of a sclerenchyma fibre is \(0.5 \times 0.5 \times 1500 \text{ N/mm}^2 = 375 \text{ N/mm}^2\). Thus, a rule of thumb for the ultimate tensile strength in N/mm² is \(3.75 \times 0.5\) the percentage of sclerenchyma fibres, which fits well with Fig. 3. Using the E-value of 70 000 N/mm² for the layers in the cell wall in which the microfibrils are parallel to the cell axis and assuming they constitute 50% of the layers, I calculated an overall E-value for the sclerenchyma cells of 35 000 N/mm² \((0.50 \times 70000)\). With this value, I derived a rule of thumb for the overall E-value of a bamboo culm: E-value (N/mm²) = 350 \times\% sclerenchyma. Applied to data from the literature, this rule of thumb provides an E-value for *Bambusa tulda* (45% sclerenchyma) of 15 750 N/mm² and for *Dendrocalamus strictus* (43% sclerenchyma) of 15 000 N/mm². The actual E-values are 19 300 (113) and 17 400 N/mm² (148) respectively. Although these figures are reasonably consistent, further study is needed.

![Graph](https://example.com/graph.png)

**Fig. 3.** A cross section of the culm wall: (a) ultimate tensile stress and E-value for *Phyllostachys pubescens* from Duff (84) and (b) percentage of fibres for *Phyllostachys makinoi* from Grosser and Liese (113).

![Graph](https://example.com/graph2.png)

**Fig. 4.** Relationship between MC and RH for wood and bamboo; the saturation points are at 100% RH.
Coefficient of Poisson

I determined Poisson's coefficients for the outer skin, the cross section of the wall of the culm, and the inner side of the culm, in a pure tensile test, with strain gauges. My results were: outer skin 0.46; cross section 0.32; and inner side 0.34; these fitted well with Cox and Geymayer's findings (75) that Poisson's coefficient for bamboo is 0.317.

For timber, a value of 0.5 is common, approximating that for the outer skin of bamboo, which has a high silica content and a high percentage of cellulose. In contrast, the cross section and the inner side of bamboo, with its increasing portion of lignin, gives a value of 0.3, similar to that for steel and concrete. These facts present questions that need to be answered through further study and testing.

Weight by Volume; MC versus RH

It is rather simple to determine the weight by volume; it is more interesting to explain the determined weight. The specific gravity of cellulose is 1.58, and lignin 1.4. Assuming 50% of each and 44% materials (the remaining 56% being lumens and vessels), one can estimate weight by volume as 0.44 × ([1.58 + 1.4]/2) = 0.66.

The relationship between the moisture content in bamboo and the relative humidity of the air can be explained similarly (Fig. 4). If bamboo contains 55% cellulose, which, in turn, is crystalline (58%) or amorphous (42%) (325), the composition is 32% crystalline cellulose, 23% amorphous cellulose, and 45% lignin. The crystalline cellulose does not absorb any water. The amorphous cellulose does, and its absorption ratio is 1.85, which means that it absorbs 1.85 times as much water as native cotton (Table 3). This theoretical value fits well with actual figures (Fig. 4). In my opinion such explanations help in an understanding of mechanical properties and are a means to build bridges between biologic and mechanical researchers.

Defects

Bamboo seems to have more consistent properties than does wood because knots and slope of grain do not occur, but decay by rot and insects and splitting have a much greater influence in bamboo.

A Model in Cell Mechanics

It is interesting to build a mathematical model of a cell. Based on the results of botanic and biologic researchers, such a model could explain the mechanical behaviour of bamboo (and wood as well). Such model studies have been published by Mark (232) and Schniewind and Barrett (352), but they simplify the cell wall to a flat layer, although a three-dimensional model is more attractive. My work on a mathematical model is not complete, but a brief look at it is necessary for fruitful discussions with botanists and biologists. As a basis for it, I collected data on the geometry and size of the cell and the cell wall.

The Cell Wall

The cell wall is a composite of fibres of cellulose in a matrix of lignin and hemicellulose. The composition is different for bamboo and wood, and a comparison of the two casts some light on their respective mechanical performance (Table 4 and 5).
Table 3. Theoretical calculation of the moisture content (MC) of bamboo.

<table>
<thead>
<tr>
<th></th>
<th>RH air</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC native cotton</td>
<td>3</td>
<td>5</td>
<td>7.3</td>
<td>10.5</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Amorphous cellulose in bamboo MC(0.23 × 1.85 × MC native cotton)</td>
<td>1.3</td>
<td>2.1</td>
<td>3.1</td>
<td>4.5</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>MC lignin (0.45 × MC lignin)</td>
<td>5</td>
<td>8</td>
<td>10.5</td>
<td>12</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>MC bamboo ((0.23 × 1.85 × MC native cotton) + [0.45 × MC lignin])</td>
<td>2.3</td>
<td>3.6</td>
<td>4.7</td>
<td>5.4</td>
<td>6.3</td>
<td></td>
</tr>
</tbody>
</table>

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.6</td>
<td>5.7</td>
<td>7.8</td>
<td>9.9</td>
<td>12.7</td>
</tr>
</tbody>
</table>

**The Cell**

Any examination of the cells in bamboo is hindered by the substantial differences between botanic species, between fibres and other tissues, and between earlywood and latewood. Working with mean diameters and lengths introduces a big standard deviation, but it provides useful guidelines. The diameter of cells of common bamboos in $10^{-6}$ m is 10–30; the length is 1000–3000 (217). Similar values for wood are diameter 33 and length 3500. Mark (232) suggested a model on how to calculate the overall E-value for a fibre, using the percentage of cell-wall constituents and establishing elastic constants.

The sclerenchyma cells are mainly responsible for mechanical properties, and so my model is limited to these. They can be characterized as thick-walled tubes, e.g., with an outside diameter of 0.03 mm, a thickness of 0.006 mm, and a length of 3 mm. The cell wall is a composite structure, built up with strong and stiff cellulose–microfibrils in a matrix of relatively weak and soft lignin. Each cell wall contains a number of layers, with the cellulose–microfibrils alternately nearly parallel to the cell axis and nearly perpendicular to the cell axis. I have

Table 4. Cross section of wall of bamboo cell, moving from the middle lamella to the lumen or from the primary wall through five secondary layers.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Orientation of fibrils</th>
<th>Thickness ($10^{-5}$ m)</th>
<th>Angle of fibrils</th>
<th>Angle of fibrils</th>
<th>Lignin content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary wall</td>
<td>-</td>
<td>0.06</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Transitional lamella (1)</td>
<td>-</td>
<td>0.12</td>
<td>50°</td>
<td>35°</td>
<td>-</td>
</tr>
<tr>
<td>Transitional lamella (2)</td>
<td>-</td>
<td>0.08</td>
<td>35°</td>
<td>20°</td>
<td>-</td>
</tr>
<tr>
<td>Secondary wall (1)</td>
<td>Longitudinal</td>
<td>0.60</td>
<td>2–5°</td>
<td>5–6°</td>
<td>Low</td>
</tr>
<tr>
<td>Secondary wall (2)</td>
<td>Transversal</td>
<td>0.11</td>
<td>85–90°</td>
<td>–</td>
<td>High</td>
</tr>
<tr>
<td>Secondary wall (3)</td>
<td>Longitudinal</td>
<td>1.86</td>
<td>10–12°</td>
<td>5–6°</td>
<td>Low</td>
</tr>
<tr>
<td>Secondary wall (4)</td>
<td>Transversal</td>
<td>0.30</td>
<td>85–90°</td>
<td>–</td>
<td>High</td>
</tr>
<tr>
<td>Secondary wall (5)</td>
<td>Longitudinal</td>
<td>2.70</td>
<td>10–20°</td>
<td>10°</td>
<td>Low</td>
</tr>
</tbody>
</table>

*a* There may be more than five secondary wall layers.

*b* According to Parameswaran and Liese (310).

*c* According to Preston and Singh (326).
I termed the layer with cellulose–microfibrils nearly parallel to the cell axis as "vertical" and the other layer, nearly perpendicular to the cell axis, as "spiral" (Fig. 5).

Assumptions for a Mathematical Model
To build a mathematical model of a cell, I made certain assumptions based on the characteristics of a thick-walled tube under an axial stress. My assumptions were that no external forces are applied in the radial or tangential direction; the load along the x-axis is constant; stresses are rotationally symmetric with respect to the x-axis (no shear); the length of the cylinder is greater than the diameter and wall thickness; the plane cross sections remain plane; and the behaviour is elastic (no buckling). The equations for each layer of the cell wall are three constitutive equations and three equations concerning the equilibrium of forces. Using this model, one can calculate the radial displacement and the axial, tangential, and radial stresses.

Numerical Example of the Model
I applied the mathematical model to two cells, one wood cell and one bamboo cell. Table 5. Cross section of wall of wood cell, moving from the middle lamella to the lumen, or from the primary wall through three secondary wall layers.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Orientation of the fibrils</th>
<th>Thickness (10⁻⁶ m)ᵃ</th>
<th>Thickness (10⁻⁶ m)ᵇ</th>
<th>Angle of fibrilsᵇ</th>
<th>Lignin contentᵇ</th>
<th>Cellulose contentᵇ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary wall (1)</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
<td>-</td>
<td>High</td>
<td>Low (25%)</td>
</tr>
<tr>
<td>Primary wall (2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Secondary wall (1)</td>
<td>Tangential</td>
<td>0.12–0.35</td>
<td>1.0</td>
<td>50–70°</td>
<td>Low</td>
<td>-</td>
</tr>
<tr>
<td>Secondary wall (1-2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Secondary wall (2)</td>
<td>Longitudinal</td>
<td>5</td>
<td>1–10</td>
<td>10–30°</td>
<td>Low</td>
<td>50%</td>
</tr>
<tr>
<td>Secondary wall (2-3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Secondary wall (3)</td>
<td>Tangential</td>
<td>0.08</td>
<td>1.0</td>
<td>60–90°</td>
<td>10%</td>
<td>-</td>
</tr>
</tbody>
</table>

ᵃAccording to Kollmann and Coté (202).
ᵇAccording to Siau (377).
bamboo cell. I assumed a constant interior radius of 0.010 mm and a constant exterior radius of 0.016 mm. So the wall thickness is always 0.006 mm, and the subdivision of this wall for wood is spiral layer 0.001 mm; vertical layer 0.004; and spiral layer 0.001. For bamboo it is spiral layer 0.0002 mm; vertical layer 0.0003; vertical layer 0.0019; spiral layer 0.0001; vertical layer 0.0006; and spiral layer 0.0002. Next, I calculated values for E-modulus and coefficient of Poisson, each in three directions.

First I looked at the influence of these calculated values on the resulting stresses and displacements. The results comprised the radial displacement, the axial stress, the tangential stress, the radial stress, all as a function of the radius and all as a function of E and Poisson. The results indicate which values influence the deformations and stresses. Some values of E and Poisson have an enormous influence on deformations and stresses; therefore determining them is essential. In contrast, others have no influence at all, and one need not pay much attention to the estimation of them. In fact, however, these calculations are still just an introduction for calculations of the deformations and stresses in cells of bamboo and wood, assuming an external axial force. The calculated stresses have to be converted to the microfibrils with their respective angles with the cell axis, and then they have to be compared with the results of tests.

**Structures**

My interest in the properties of bamboo was primarily in their application to bamboo structures such as pins (instead of steel bolts), joints, and trusses. A summary of my tests and results on such structures follows.

**Bamboo Pins**

The strength of pins is determined by an interaction between the bamboo pin and the bamboo culms connected by the pins. To make things simple I tested the pins with steel "culms," assuming that this method selects the best pins in a similar way as would a method using bamboo culms. I studied the influences of three details; the position along the culm: pins from bottom, middle, or top; the circumference of the culm; pins from each quarter; and the positions of the pins, in relation to the force at 0°, 45°, 90°, and 180° (Fig. 6). Only the details were
significant (F critical, α = 0.05) (Fig. 7). I chose estimated stresses with 90% areas for the figure because a pin is stronger as the distance between the shear areas is smaller, due to the decreasing bending moment. The position of the pins had a slight positive influence at 0° and 45°, due to the hard outer skin of the bamboo culm in the tension area of the bended pin. Also the bottom portion along the culm may be better than the middle or top portion for placement of a pin, and a thin bottom portion is best. There seems to be no relationship with the percentages of parenchyma, sclerenchyma, and vessels. The influence of the quarters is rather small. A relationship between these differences and wall thickness cannot be found.

The results indicate that a bamboo pin can function as a connector, and a bamboo pin can be calculated at a 5% shear stress of 0.55 × 23 N/mm² = 12 N/mm². (This is a rough calculation, and the specimens, which were taken mainly from one culm, do not form a sample. Although the relationship 0.55 between short- and long-term results is valid for wood, it is still unknown for bamboo. The purpose of this rough calculation was to see whether bamboo pins were promising.) To maximize the strength of a pin, one must keep the shear

![Diagram of bamboo pin tests](image)

**Fig. 7.** Results of the tests on pins plotted as estimated mean shear stress.
areas as close together as possible. However, this procedure is not practical in the case of a support of a purlin (third detail). The distance between shear areas is half the diameter of the purlin, and this is a given. The deformations were great in my test with purlins, especially of $0^\circ$ and $180^\circ$; $90^\circ$ was best. As for the other two details, it is easy to place a bamboo pin in the position of $0^\circ$ in a joint, and this is the best solution for practice.

The findings suggest that a bamboo pin is a promising connector in a joint instead of steel bolts; it is important to keep the shear areas as close together as possible; and in details with short-shear distances (e.g., a few millimetres), bamboo pins should be placed with their outer skin facing the force, but in support of a purlin, their outer skin should be parallel with the force.

*What remains to be done?* Tests are needed on bamboo pins in bamboo culms, as are long-term tests; tests on pins with cross section; tests on the relationship
between the strength of pins and the structure of the bamboo; and descriptions of a method to calculate bamboo pins on shear and bending.

**Bamboo Joints**

After the tests on mechanical properties, I directed my attention to joints that form part of a truss. I found descriptions of joints in the tradition of Southeast Asia, and in the literature. I also designed a few joints. In total I collected about 25 possible solutions for the same joint in a truss. From these, I selected four. The criteria for selection were: Does the joint look strong and stiff enough? Can it be made by people in a village with local materials and skills? And is it a simple joint? The four joints have been built and tested on a full scale, as if they were part of a complete truss. The distribution of forces in the joint was simulated with hydraulic jacks. The first tests failed, but several improvements were introduced and met with success. For each of the four joints, about 12 specimens have been made and tested, about 50 in all. During each test the forces were increased step by step until the joint failed; strains and deformations were measured as well, as a first step toward a better understanding of the mechanical behaviour of the joint. All the joints were made solely with bamboo and sisal rope. No steel bolts or other foreign products were used. The testing, however, was done with high-level Western technology of strain gauges, electronic equipment, and computers.

**Bamboo Trusses**

The joint that proved best was used in the construction of a truss, king-post type, 8-m free span. The diameter of the bamboo was 85–100 mm, the wall thickness 7–10 mm. As it was too difficult to test the truss in a vertical position, the truss was laid on the floor, with teflon on the supports to reduce friction losses. The load was brought on to the purlins by hydraulic jacks and a steel balance system. The load was applied in steps of 3.2 kN uniformly distributed (i.e., 0.4 kN/m'). The immediate deformation of the truss was 50 mm; 15 mm was permanent deformation.

Creep was observed for 5 hours under a load of 18 kN (2.25 kN/m'), which gives an extra deformation of 10 mm. After a few days of testing, the load was increased until failure of the truss, e.g., at 25 or 30 kN. Failure occurred not in the joint but in the bamboo itself, due to a compressive stress of, e.g., 70 N/mm². This result of short-term loading, observed three or four times, is not sufficient basis for technical advice.

Strains were measured at 50 points, and deformations at about 15 points. From these data, the behaviour of the bamboo truss was analyzed. With ICES-Strudl computer language, a model of the truss was built to predict the behaviour of the truss. The model was improved (e.g., with better data on the stiffness of the joints) until the calculated internal forces and external deformations agreed with those measured. The improved model was then used to find a better truss. Better means stronger, stiffer, less laborious to construct.

On the basis of this study a second truss has been built and tested, with the expected result. This procedure will be repeated not only with short-term tests but also with long-term tests as a means to study creep in a complete bamboo truss.

**Recommendations**

Because bamboo should be exploited fully, one needs much more
knowledge toward that end. Some areas where more studies need to be undertaken include:

• Durability. What is the natural durability of the various species? How can this be improved, preferably with local facilities? A classification of the species of bamboo, according to their natural or improved durability and to the use in building structures, is needed and could be similar to such classifications for timber.

• Mechanical properties. Tables listing allowable stresses are widespread for timber and are needed for bamboo. They should be based on a thorough knowledge of the botanic and physical factors with a significant influence on the mechanical properties; standardized tests based on this knowledge; and data on stresses to be used in building engineering practice.

• Relationships. Why are the mechanical properties as they are, based on the relationship with the biologic and chemical composition of bamboo? An understanding would be based on cell size, geometry, chemical composition; the distribution of sclerenchyma fibres along the culm, in node and internode, and in the thickness of the wall of the culm.

• Mathematical models. Models of cells and cell walls, based on the geometry of cells and cell walls, and the mechanical properties of cellulose, lignin, and pectin are needed. With such models, the mechanical properties on the macroscale can be explained or predicted.