TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

Bamboo in building structures

Citation for published version (APA):
Janssen, J. J. A. (1981). *Bamboo in building structures*. [Phd Thesis 1 (Research TU/e / Graduation TU/e), Built Environment]. Technische Hogeschool Eindhoven. https://doi.org/10.6100/IR11834

DOI:
10.6100/IR11834

Document status and date:
Published: 01/01/1981

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 09. Jul. 2022

B A M B O O

n building structures.

ules j. a. janssen.

BAMBOO IN BUILDING STRUCTURES

BAMBOO

IN BUILDING STRUCTURES

PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR IN DE TECHNISCHE WETENSCHAPPEN AAN DE TECHNISCHE HOGESCHOOL EINDHOVEN, OP GEZAG VAN DE RECTOR MAGNIFICUS, PROF. IR. J. ERKELENS, VOOR EEN COMMISSIE AANGEWEZEN DOOR HET COLLEGE VAN DEKANEN IN HET OPENBAAR TE VERDEDIGEN OP DINSDAG 19 MEI 1981 TE 16.00 UUR

DOOR

JULIUS JOSEPH ANTONIUS JANSSEN

GEBOREN TE NIJMEGEN

DISSERTATIE DRUKKERIJ
wibro
HELMOND. TELEFOON 04920-23981

Dit proefschrift is goedgekeurd door de promotoren
(this thesis has been approved by the dissertation supervisors)

Prof. ir. W. Huisman
en
Prof. ir. P.C. Kreijger

English translation of the official text on the title-page.

THESIS

to obtain the degree of doctor of Technical Sciences at the Eindhoven University of Technology, by the authority of the Rector Magnificus, professor Ir. J. Erkelens, to be defended in public in the presence of a committee nominated by the Board of Deans, on Tuesday 19th May 1981 at 16.00 hrs, by

Julius Joseph Antonius Janssen

born at Nijmegen (Netherlands)

Susanne

Joost

Marja

Acknowledgements

This thesis, and the research programme on which it is based, could never have been achieved without the help of many colleagues and friends. It is really impossible to mention them all; they are too many.
Just one exception: Wim Overdijk, who gave an enormous push to this research and who was a very kind and sympathetic colleague, whose death we regret very much.

Curriculum Vitae.

1935	Born at Nijmegen
1941-1947	Primary school, Nijmegen
1947-1953	Secundary school, Nijmegen
1953-1956	Technical College, building dept., Heerlen
1956-1963	Delft University of Technology, civil engineering
1963-1967	Consulting Engineer
1967	until now Staffmember (now Senior Lecturer) Eindhoven University of Technology, Faculty of Architecture, Building and Planning.

Private address: 395, de Koppele,
5632 LN Eindhoven, Netherlands.

Contents

Acknowledgements, curriculum vitae, address,			5
Summary			8
Samenvatting			9
Chapter	1,	Introduction	11
	1.1.	General	11
	1.2.	Environmental aspects	12
	1.3.	Cultural aspects	13
	1.4.	Mechanical aspects	14
		References	17
Chapter	2,	The biological composition of bamboo	19
	2.1.	Atoms and Molecules	19
	2.2.	Cellulose, lignin and hemicellulose	21
	2.3.	Cell wall and cell	23
	2.4.	Tissues	23
		References	28
Chapter	3,	Models of Cell and Cell Wall	29
	3.1.	Introduction	30
	3.2.	The Cell Wall	31
	3.3.	The Cell	32
	3.4.	Assumptions	35
	3.5.	A Mathematical Model of the Cell	36
	3.6.	Numerical Values for E and ν	42
	3.7.	The influence of E_T and ν on the resulting w and σ	44
	3.8.	Calculations according to the Model	52
	3.9.	Verification	59
	3.10.	Discussion and comparison with Tests	64
	3.11.	Conclusions	67
	3.12.	What remains to be done	67
	3.13.	Addition	68
	3.14.	Literature	69
	3.15.	Appendix: Calculation of E_T	71

Chapter	4,	Mechanical properties	75
	4.1.	Introduction	76
	4.2.	An example of a statistical model	76
	4.3.	The chosen factors that influence the properties	83
	4.4.	Compression	85
	4.5.	Bending	109
	4.6.	Shear	127
	4.7.	Tension	139
	4.8.	Poisson's ratio	141
	4.9.	Weight by volume; MC versus RH	143
	4.10.	References	145
	4.11.	Appendix	149
Chapter	5,	Joints and Trusses	153
	5.1.	Introduction	154
	5.2.	Bolts in bamboo	154
	5.3.	Bamboo pins	158
	5.4.	Joints, design	165
	5.5.	Joints, tests methods	178
	5.6.	Joints, results	185
	5.7.	Trusses	205
	5.8.	Results of tests on trusses	206
	5.9.	Conclusions	225
		References	226
Chapter	6,	Conclusions and recommendations	227
	6.1.	Retrospective view on chapters 3 and 4	227
	6.2.	Retrospective view on chapter 5	230
	6.3.	Safety	231
	6.4.	Our knowledge about bamboo	233
	6.5.	Recommendations	234
		References	235

SUMMARY

The research programm, described in this thesis, refers to the possibilities of bamboo as a material for building structures in tropical countries.

Chapter 1 describes the origin and the purpose of this research. A general description of bamboo as a building material is given.

Chapter 2, (The Biological Composition of Bamboo) contains a survey of terms used in the following chapters. It is a study on literature only.

Chapter 3, (The Mechanical Behaviour of the Fibres) tries to explain the mechanical behaviour of the fibre, based on its biological composition, with a theoretical model.

Rules of thumb are derived to estimate stresses and deformations in a sclerenchyma-cell under axial deformation. (par. 3.9.7.). Poisson's value, calculated with this model, fits in with test results. (par. 3.10.6.)

Chapter 4, (The Mechanical Properties on Macroscale), reports on the author's tests, compares the results with those by other researchers, and tries to explain the results. (Why are the results as they are?). A statistical analysis is applied. An important conclusion is a ratio between the mass per volume and the ultimate stress in compression, bending and shear, for green and dry bamboo. (par.4.4.5., 4.5.5., and 4.6.6.).

The influence of the position along the culm and (inter)node on some mechanical properties is studied. Finally, bamboo is said to be weak in shear, but in this thesis bamboo is shown to be stronger in shear than wood. (par.4.6.5.); problems in practice relating to shear in bamboo occur due to its hollow shape (par. 6.1.).

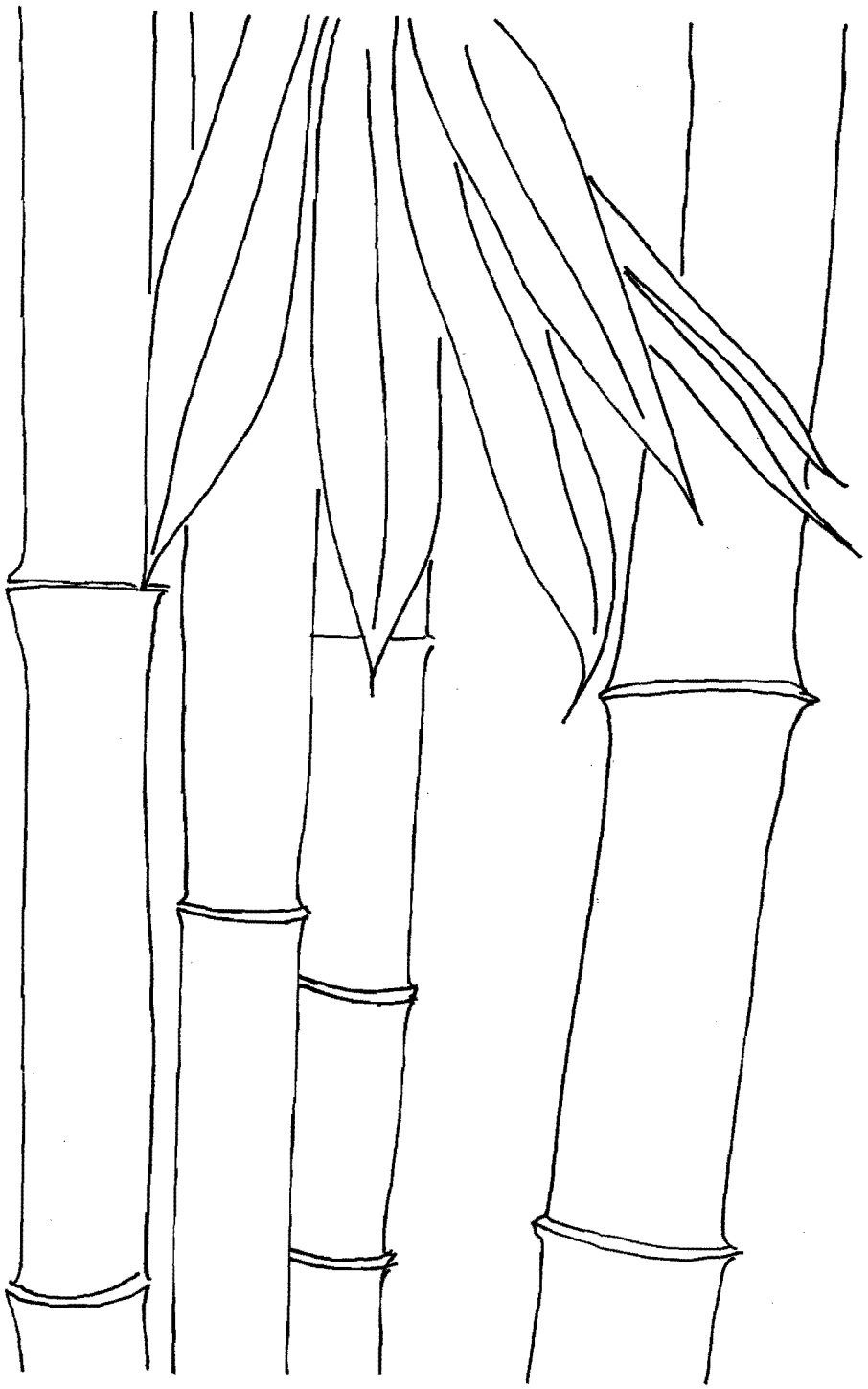
Chapter 5 tries to apply the results of the study on mechanical properties to joints and trusses. Joints and trusses have been designed, built and tested on full scale. Data on strength and stiffness have been determined for four different joints (par.5.6.5.). A truss with an 8 m. free span has been tested on short and long-term (creep and recovery, par. 5.8.). This truss fails due to limits in material strength and not on account of joint strength. The problem of bamboo joints has been solved for this type of truss. (par. 5.9.).

Chapter 6 contains conclusions and recommendations.

References are given at the end of each chapter.

SAMENVATTING

Het hier beschreven onderzoek heeft betrekking op de mogelijkheden van bamboe als materiaal voor bouwkundige konstrukties in tropische landen.
In hoofdstuk 1 wordt beschreven, hoe het onderzoek tot stand is gekomen, wat het doel er van is, waarop een algemene beschouwing van bamboe als bouwmateriaal volgt.
Hoofdstuk 2 geeft een overzicht van de biologische terminologie, die in volgende hoofdstukken wordt gebruikt. Het is een literatuuroverzicht. In hoofdstuk 3 wordt een rekenmodel opgesteld om na te gaan in hoeverre de mechanische eigenschappen verklaard kunnen worden uit de opbouw en samenstelling van de cel. Met dit model worden eenvoudige regels afgeleid om spanningen en vervormingen te schatten in een sclerenchymacel onder axiale vervorming. (par. 3.9.7.). De constante van Poisson, berekend met dit model, klopt met de resultaten van proeven (par. 3.10.6.).
Dan volgt in hoofdstuk 4 een materiaalkundig onderzoek naar botanische en fysische invloeden op mechanische eigenschappen, met statistische analyse. Als resultaat hiervan wordt o.m. een verband afgeleid tussen de volumieke massa en de maximale druk-, buig-en schuifspanning, voor droge en natte bamboe. (par.4.4.5., 4.5.5. en 4.6.6.). Verder wordt het verloop van mechanische eigenschappen als funktie van de plaats in de bamboestam onderzocht, alsmede de invloed van de dwarsschotten. Bamboe heeft de naam zwak te zijn met betrekking tot afschuiving; in dit proefschrift wordt aangetoond dat bamboe een betere afschuifweerstand heeft dan hout, maar dat de problemen in de praktijk ontstaan door de geringe wanddikte van bamboe vergeleken met de massieve doorsnede van hout (par. 4.6.5. and 6.1.).
Tenslotte wordt in hoofdstuk 5 verslag gedaan over onderzoek naar verbindingen van bamboe zoals deze in bouwkundige konstrukties gebruikt kunnen worden, en naar enkele spantkonstrukties op ware grootte. Voor enkele typen van een verbinding, zoals deze voorkomt in spanten, zijn sterkte en stijfheid bepaald. (par. 5.6.5.) Voor een spant met 8 m. overspanning is de lange-duur-sterkte en stijfheid (kruip en relaxatie) onderzocht (par. 5.8.)
Gebaseerd op het onderzoek naar verbindingen is dit spant van 8 m. zodanig ontworpen, dat het niet meer bezwijkt op verbindingen (zoals algemeen wordt aangenomen) maar op materiaalsterkte. (par. 5.9.)
Conclusies en aanbevelingen staan in hoofdstuk 6.
Literatuur-lijsten staan aan het eind van elk hoofdstuk.



Chapter 1

INTRODUCTION

1.1. General

To increase the self-sufficiency of developing countries, indigenous materials must be exploited to the full. Among them bamboo is a familiar material with a long history of usefulness, and in building it has been employed in South-East Asia for housing and for scaffolding; but could it play a bigger part in building, especially in structural applications? To answer this question in 1974 the author began a comprehensive research programme on the mechanical properties of bamboo, and on structural use in joints and trusses.
The present thesis highlights the research done on these subjects. The problem of durability remains a major one, of course, but falls outside the author's specific field of activity. Similarly, bamboo as a reinforcement in concrete is not described here.

The reason for the start of my research was a request made by volunteers in developing countries. They asked technical advice on how to build bamboo trusses for schools and warehouses. I did not know how to help them to solve their problems, but I found old information in the files of our former Royal Dutch East Indies' Army, from the 1890's. With this information I could give them a proper advice. This old information, however, appeared to be useful to many volunteers, and so I published a reprint. (Janssen, 1979) Several hundreds of copies of this Dutch reprint have been distributed among volunteers. In addition to this text, a similar English text has been prepared (Janssen, 1980). Both reprints contain information on the use of bamboo in building, and both should be used as supplements to the well-known U.N.-manual on bamboo: "The Use of Bamboo and Reeds in Building Construction". I thus became interested in bamboo, and I developed a research programme on the use of bamboo in building structures, especially in trusses for roofs and bridges. The idea is that bamboo can play a bigger role in building than before, because the mechanical properties are not used to the full. In bamboo structures a development is required similarly to that in e.g. wooden trusses: a century ago every carpenter built a wooden truss like his father did, with sometimes 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 wish to contribute to such a development with specific regard to bamboo.

The purpose of this thesis is to promote scientific research on bamboo and its justified application. Materials like steel, concrete and timber frequently are the subject of research; bamboo, however, is hardly considered as such. I hope to have shown that bamboo really merits scientific research, and I hope other researchers will follow this example.

It remains a remarkable fact that this research on an Asian material like bamboo has been carried out in Holland. This is only due to my personal initiative, and I agree with any one who is surprised at it. Concerning the trusses in chapter 5, evidently there is a cultural gap between this laboratory work and the client in the developing country. These trusses, however, are not meant as a specific solution for a typical problem, but as an example of how to develop bamboo structures, and how to test them.

There is a frequently heard remark: "What is needed is not more research into techniques, but bright ideas about how to get these techniques out of the laboratory and into actual building programmes". However, in the laboratory there is (was) not enough knowledge on the mechanical properties of bamboo. Research reports on wood could fill a whole library (and even a large one) but the reports on the mechanical properties of bamboo can be stored in one single bookcase. Therefore, I plea not guilty to the above-mentioned charge. However, if in a hopefully nearby future enough technical knowledge will be available, then this knowledge has to be brought into practice. (which perhaps will be even more difficult than all laboratory work).

As to building practice in the third world, a manual for field workers will be composed in 1982.

1.2. Environmental aspects

An immediate advantage of bamboo is that it belongs to the renewable resources. What is more, during growth it has a good influence on the climate in the region, and it helps to control erosion and floods.
The crop takes place in such a way that only ripe culms are cut and the remaining younger culms (i.e. the majority) are left and this is done each year. For the microclimate as well as for the economy of the population this yearly crop is better than that of wood, where sometimes a whole area is cut once in 20 to 40 years.
Once more as to the energy, a quantitative judgement is a comparison of the energy needed for the production of construction materials with their strength.

As construction materials reinforced concrete, steel, wood and bamboo are taken, all as a mean or a representative of their groups. Rough data of the energy needed for production, compared with strength, is given in table 1.1.

material	energy for production MJ/kg	weight per volume kg/m^3	energy for production MJ/m^3	stress when in use N/mm^2	ratio energy per unit stress
(1)	(2)	(3)	(4)	(5)	(4)/(5)
concrete	0.8	2400	1 920	8	240
steel	30	7800	234 000	160	1500
wood	1.	600	600	7.5	80
bamboo	0.5?	600	300	10?	30

Table 1.1. Energy, needed for production, compared with stress when in use.

The figures in table 1.1. are not exact, they give only an order of magnitude. From the last column, however, it can be seen that steel and concrete make a heavy demand on a large part of the energy resources of the "missile" Earth, contrary to wood and bamboo.
In fact, this table should be enlarged with the lifetime of the materials concerned.

1.3. Cultural aspects

Another advantage of bamboo is its important place in the culture of people in those regions where bamboo is a local material. However, in these days feelings are changing rapidly, as described by Gordon (1976):
"In many tropical regions, such as parts of Africa, it is difficult to improve upon the traditional construction of mud and reeds which can be put up cheaply and quickly and which is cool to live in. Most of the drawbacks of these buildings can be got over by making use of various forms of modern technology. I am told however that the inhabitants reject this construction with scorn and insist on building with concrete and corrugated iron which are both hot and expensive. As long as such attitudes prevail it is difficult to see what science can be expected to do".
In my personal conviction it is good to promote the use of a traditional material by scientific research in order to extend the possibilities; this idea has been a stimulus for the research behind this thesis.
Note: it is not the intention of this paragraph to describe all the cultural aspects of bamboo; I refer to books such as Austin or Hommel.

1.4. Mechanical aspects

In this paragraph some typical mechanical aspects of bamboo will be compared with those of concrete, steel and wood in order to give bamboo its proper place.

1) The strain energy.

material	working stress σ N/mm^2	E N/mm^2	working strain ε in 10^{-6}	strain energy stored Joules/m^3	Joules/kg
concrete	8	25 000	300	1 200	0.5
steel	160	210 000	800	64 000	8.2
wood	7.5	11 000	700	2 600	4.3
bamboo	10?	20 000	500	2 500	4.2

Table 1.2. Strain energy stored

The strain energy stored is the surface of the stress-strain-diagram, i.e. $0.5\sigma\varepsilon$. In bamboo as much strain-energy can be stored as in wood, and both are between steel and concrete. The more strain-energy is stored into a material, the greater its toughness and consequently its safety.

2) The efficiency of materials for strength (i.e. working stress/weight by volume) or for stiffness (i.e. E/weight by volume).

material	$\frac{\text{working stress}}{\text{weight by volume}}$	$\frac{E}{\text{weight by volume}}$
Concrete	$\frac{8}{2400} = 0.003$	$\frac{25000}{2400} = 10$
Steel	$\frac{160}{7800} = 0.020$	$\frac{210\,000}{7\,800} = 27$
Wood	$\frac{7.5}{600} = 0.013$	$\frac{11\,000}{600} = 18$
Bamboo	$\frac{10}{600} = 0.017$	$\frac{20\,000}{600} = 33$

Table 1.3. Efficiency of materials for strength and for stiffness.

From this table it is clear that bamboo is as efficient as steel, because in both columns the efficiency for bamboo and steel are rather equal, and better than those for concrete and wood.

3) The efficiency of materials to act as a column in Eulerian buckling, as developed by Gordon (1978).

material	$\frac{\sqrt{E}}{\text{weight by volume}}$
Concrete	0.07
Steel	0.06
Wood	0.17
Bamboo	0.24 (if straight!)

Table 1.4. Efficiency of materials acting as a column.

Bamboo and wood seem to act very well in buckling. However, we should bear in mind the low stresses in these materials compared with that of steel, and the fact that bamboo is not straight, and consequently it behaves worse in buckling than might be concluded from this table.

4) The same concerning bending, for which case a simple bridge is calculated:

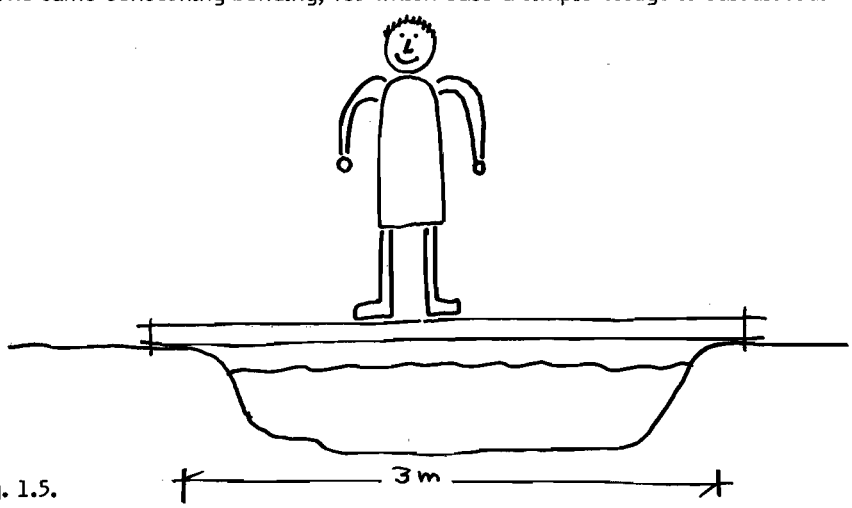


Fig. 1.5.
The bridge has been calculated on 750 N plus dead weight.

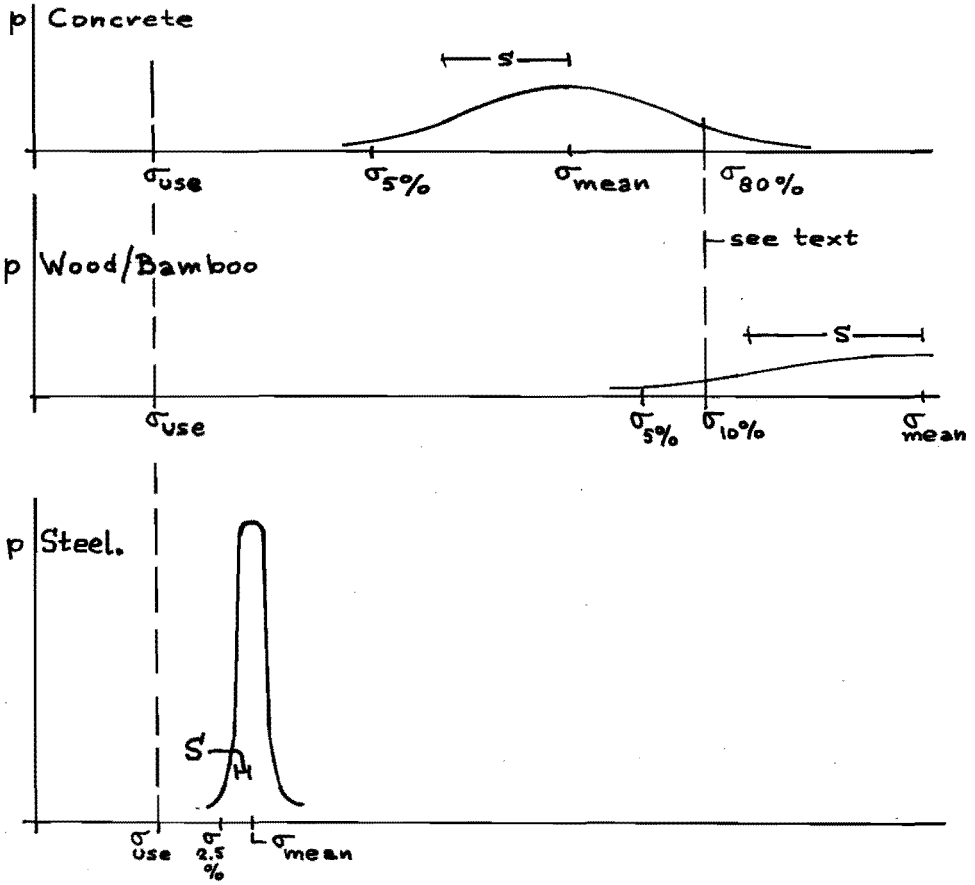
material	stress N/mm^2	cross-section mm	deflection mm	mass of bridge kg
Concrete (reinforced)	10	40x100	9	32
Steel	160	30x30	31	13
Wood	10	35x100	15	6
Bamboo	10	100/80	7.5	5

Table 1.6. Efficiency of materials in the bridge of fig. 1.5.

Bamboo and wood are also efficient in bending, because only 5 or 6 kg are required compared with 13 or even 32 kg for steel or concrete.

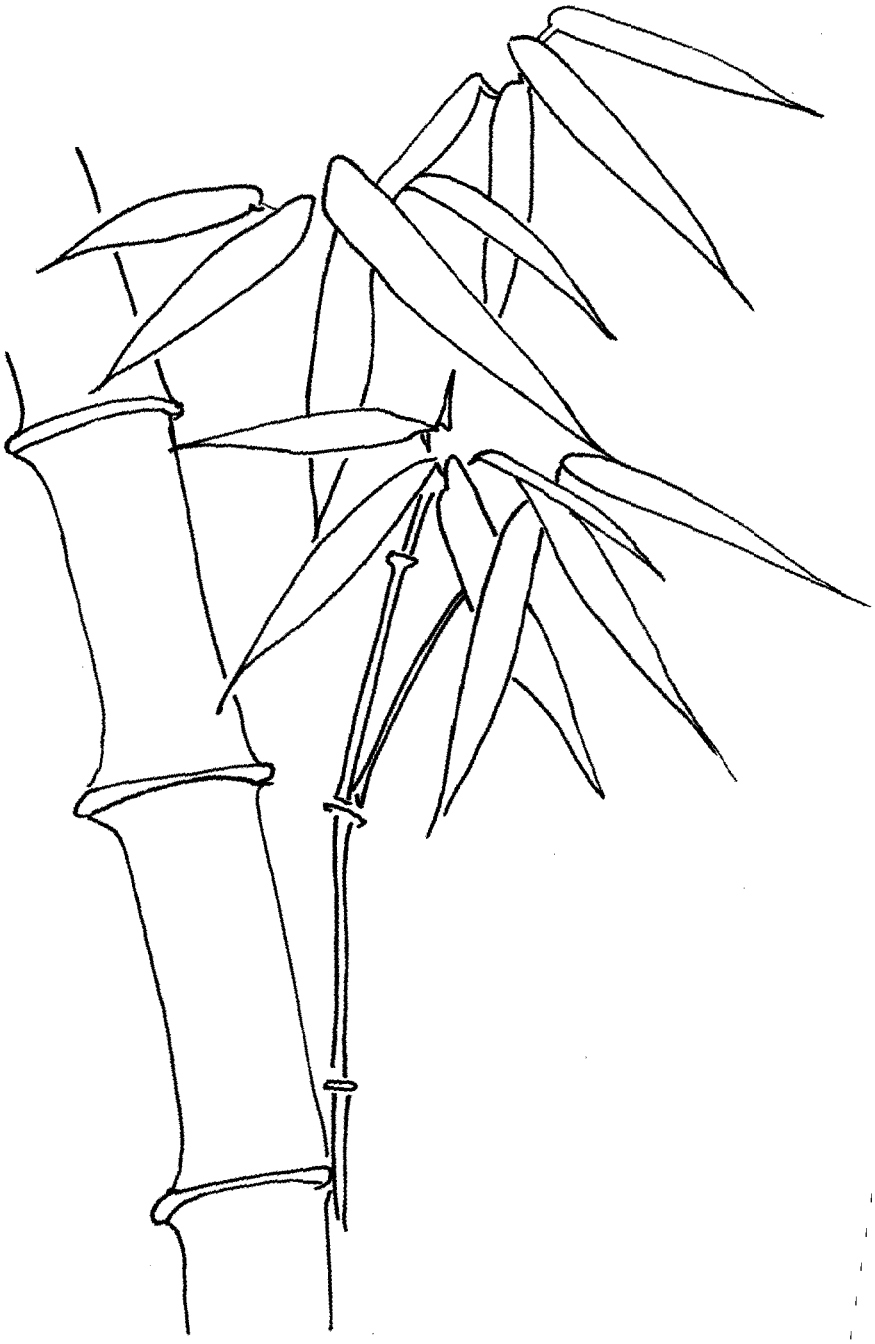
5) The behaviour of bamboo in an earthquake or a cyclone, which in fact is a dynamic overloading. Its behaviour in overloading can be seen in fig. 1.7., where Gaussian curves are plotted for stresses in concrete, steel, and wood plus bamboo, in such a way that the "stress when in use" is the same value in each plot. In case of an earthquake or cyclone, the stress increases, and from this figure it can be seen that steel will fail before concrete does. Fig. 1.7. is statical only; in fact it should be enlarged with the dynamic aspects, i.e. the surface under the stress-strain-diagram.
When all steel has failed, and 80 percent of the concrete, only 10 per cent of the wood and bamboo has failed, and the remaining 90% is still present.
However, sometimes earthquakes and cyclones are followed by fire, due to stoves falling on the floor, and this destroys wood and bamboo as well.
An advantage of bamboo, not taken into account in the previous text, is the absorption of energy in the joints. In the static loading on the trusses (in par.5.8.1.) it will be found that 85% of the deformation is due to the joints and only 15% to the elasticity of the material.

Fig. 1.7. Gaussian curves of stresses.



References

Austin, Robert, and Dana Levi and Koichiro Ueda,	Bamboo. Weatherhill (1978).
Gordon, J.E.(1976)	The New Science of Strong Materials. Cited is from chapter 11.
Gordon, J.E.(1978)	Structures. Cited is chapter 14 and appendix 4.
Hommel, Rudolf P.	China at Work. MIT Press 1969.
Janssen,J.J.A. (editor)(1979[3])	Bamboe, 164 pp., in dutch Amsterdam, Foundation TOOL.
Janssen,J.J.A. (editor)(1980)	Bamboo, a series of articles on the use of bamboos in building construction. 124 pp. I.T. Publications, 9 King Street, London WC2E 8HN.



Chapter 2

THE BIOLOGICAL COMPOSITION OF BAMBOO

Note: The content of this chapter does not form part of the author's scientific research. This chapter only introduces some ideas and definitions to be used later on; it is meant for structural engineers to get a rough idea about biological definitions.

2.1. Atoms and molecules

The interest is in bamboo, but attention will also be paid to wood and glassfibre-reinforced plastics in as much as these materials can help to understand bamboo. To start from the beginning, these materials can be studied on different levels:

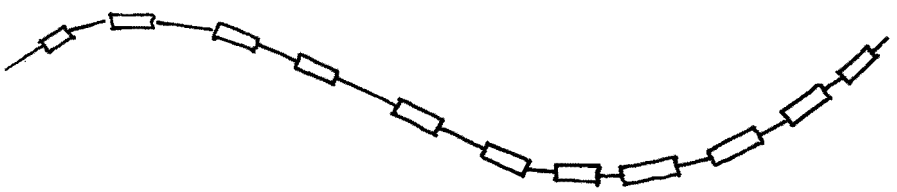
- atomar (10^{-9} - 10^{-10} m), at which level atoms are kept together by covalent bonds, which means: they share a pair of electrons. This bond is very hard, strong and rigid. The covalent bond results in a force with a direction, which in its turn results in a spatial molecular structure.

- molecular (10^{-8} - 10^{-9} m), e.g. large chains of molecules like cellulose etc., kept together by hydrogen bonds (OH-groups attracting each other).

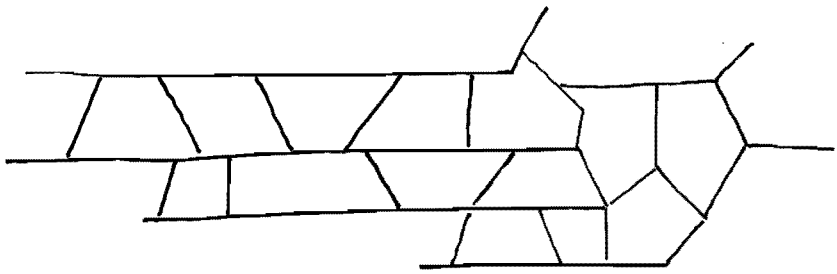
- microscopic ($>10^{-7}$ m), e.g. the cell with its wall and content.

- macroscopic ($>10^{-4}$ m), e.g. the fibres and vessels in bamboo, the grain and the rays in wood.

Bamboo, wood and plastic are polymers, high molecular weight substances of large molecules. They are called macromolecules, and are built up from small molecules, called monomers, by polymerization reaction. The molecule of the monomer must be bi- or polyfunctional, which means that the molecule that is to undergo polymerization, must contain two or more reactive or functional groups. Depending on the functionality of the monomers, two main structural types are formed: linear polymers or chain-polymers, like cellulose:



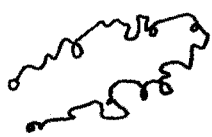
in which —▭— is a bifunctional molecule, and 3-dimensional network of cross-linked polymers, like lignin, in plane view:



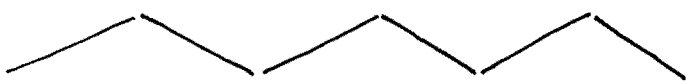
Most of these polymers are anisotropic, (with different physical properties in different directions) and inhomogeneous (not having the same composition, structure or character throughout).

For the mechanical behaviour it is important to consider the forces that hold the molecules together (intramolecular forces), and the forces that attract the molecules to each other (intermolecular forces).

The intramolecular forces are large if deformation of a polymer molecule occurs by stretching, compressing or bending the covalent bonds, as in cellulose. In a cellulose chain there is a continuous rotation and vibration of the atoms or groups of atoms about the main chain. The freely rotating polymer chain tends to assume a curl or a spherical shape:



the ends of which are at a distance of $0.03\ 10^{-6}$ m in the case of polyethylene. If such a polymer is fully extruded, the C-atoms of the main chain will assume a zig-zag planar arrangement:



the length of which is much greater than in the non-extruded case; in the given example 80-fold the distance of the ends.

This deformation requires large forces, which explains both the stiffness of cellulose, as well as the fracture energy. The configuration of the extruded chain can only be altered by breaking or reforming covalent bonds.

The intramolecular forces are small if deformation can be accomplished simply by small rotations about various C-C and C-O bonds. These rotations require less energy than a deformation of atomic bonds. This difference explains why lignin is weaker than cellulose. One might compare the quick deformation of lignin with that of a helical coil under axial tension with freely rotating ends. An example on macro-scale is rubber.

The intermolecular forces attract the molecules to each other.They consist of weak Van der Waals polarization forces, arising from small local variations of charge over the surface of the molecule, and/or stronger hydrogen bonds, caused by attraction of -OH groups.
Mechanical properties like E-values are determined mainly by the intramolecular forces.
After this introduction on mulecular structure follows a description of the components of bamboo and wood: cellulose, lignin and hemicellulose.

References: Jayne (1972), Kollmann (1968), Gordon (1968).

2.2. Cellulose, lignin and hemicellulose (ref. see par. 2.5.)
Cellulose is a carbohydrate, forming the fundamental material of all plants. The name is derived from "cell", obviously, and "-ose", being the chemical termination for all sugars.
A cellulose polymer is built up from monomer molecules ($C_6 H_{10} O_5$), molecular weight 162, length 0.5 10^{-9} m. The degree of polymerization is very different in the various plants; for wood and bamboo a mean value of 10 000 can be taken, and so the molecular weight of the polymer is 1.6 10^{6} and the length 5 10^{-6} m. The width is 0.8 10^{-9} m.
Cellulose is the main source of the mechanical properties of bamboo and wood. In the structure of a cellulose molecule three planes are defined; they are mutually perpendicular. The cellulose molecules are kept together in the first plane by numerous and strong hydrogen bonds, in the second plane by much weaker Van der Waals forces, and in the third plane by covalent bonds. So cellulose is simultaneously a chain lattice and a layer lattice, which results in an anisotropic behaviour, see table 2.1.

Table 2.1. Mechanical properties of cellulose I in N/mm^2.

E_{11} = 25 000	G_{12} = 240
E_{22} = 280 000	G_{23} = 170 à 390
E_{33} = 16 000 à 37 000	G_{31} = 3000

These values are calculated and are the highest possible values. (Jayne, p. 74-77). The indices 1, 2 and 3 refer to the three principal axes of the unit cell of cellulose I; axis no. 2 is the chain-axis. G = shear modulus.

The tensile strength of cellulose has been determined as 8000 N/mm^2, based on the work required for splitting the primary valence bonds. In practice, however, breaking does occur through slipping, which decreases the tensile strength to 1500 N/mm^2.

The specific gravity of wood cellulose is 1.58.

The cellulose chains are grouped with about 40 together to the "elementary fibril", $\varnothing$ 3.5 10^{-9} m.

Bundles of these elementary fibrils form "microfibrils" with about $\varnothing$ 10 à 30 10^{-9} m. The microfibrils in turn are aggregated into larger "macrofibrils" which constitute "lamellae", the various layers of the cell wall.

Lignin

Lignin is a polymer of phenylpropane units, in its most simple form: $(C_6 H_5 CH_3 CH_2 CH_3)_n$.

The structure and the properties of lignin are hardly known, because the structural chemistry is extremely difficult. The types of lignin differ for bamboo, hardwood and softwood.

Lignin provides rigidity to the tree, it makes upright growth possible. It improves the durability against certain micro-organisms.

Technical data:

E $\approx$ 1800 N/mm^2

Poisson ratio $\approx$ 0.3

G $\approx$ 700 N/mm^2 (G = shear modulus)

No data on strength available; weak.

Specific gravity 1.4.

Hemicellulose

Hemicellulose are polisaccharides consisting of only 150 to 200 sugar molecules, also much less than the 10 000 of cellulose. No technical data available. It is weak.

2.3. Cell wall and cell

A cell is the fundamental structural unit of plant and animal life, consisting of cytoplasma and usually enclosing a central nucleus and being surrounded by a membrane (animal) or a rigid cell wall (plant).

Joining cells form a tough boundary layer, the "middle lamella". The different layers of the cell wall are deposited on the inner side of this lamella; i.e. the primary wall during the growth of the cell, followed by the secundary. In a living cell the middle lamella is mainly pectin, the cell wall mainly contains cellulose.

Data on the sizes and composition of typical cells of bamboo and wood are given in chapter 3, in tables and figures 3.1. to 3.9.

2.4. Tissues

2.4.0. Tissue, general

The tissue of each higher plant consists of the following parts:

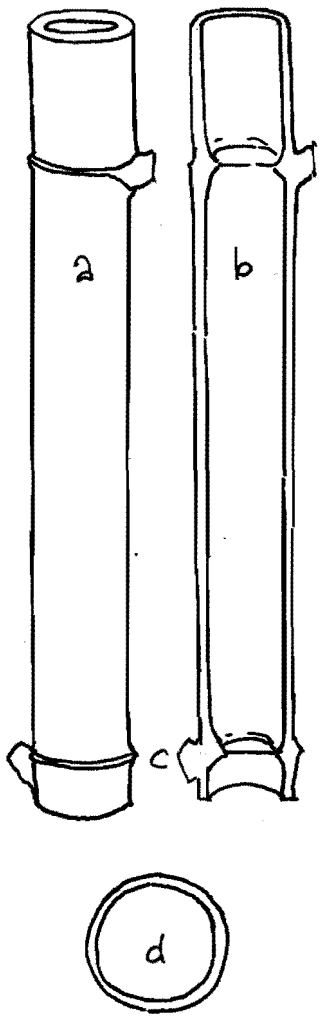
1. Parenchyma is the soft cell tissue of higher plants as found in stem pith or fruit pulp. The cell walls are built up mainly with cellulose. The function of the parenchyma-tissue is to store and to transport the food in the plant.
2. Epidermis, the outmost layer of cells covering the surface of a plant when there are several layers of tissue.
   (Greek: epi = upon, derma = skin).
3. The structural or mechanical tissue, to protect and support plants, divided into:
   - Collenchyma, the structural tissue in living and growing parts of the plants; long, living, thickwalled cells, with much cellulose.
   - Sclerenchyma, a tough thickwalled tissue (Greek: skleros = hard, enchyma = infusion) of adult cells without living content.
4. The transport, or the conducting tissue, consisting of:
   - Xylem, the portion of a vascular bundle in higher plants that is made up of lignified tissue, parenchyma, and associated cells, etc. (Greek: xylon = wood)
   - Phloem, the complex tissue for the conduction of the sap in plants (Greek: Phloos = bark). The Greek origins indicate the position of these tissues in the stem: the xylem on the inside, the phloem on the outside.
5. Several tissues producing gum, oil, latex, etc.; not important for our purpose.
6. Meristema-tissue, the dividing tissue.
   In this tissue the cells divide continuously into two new cells, and so the growth takes place.
   In a tree both length and thickness increase, and so meristema-tissues are found in the end of each branch and as cambium between bark and wood. In a bamboo the thickness does not increase, and consequently meristema is only found in each internode, to increase the length.

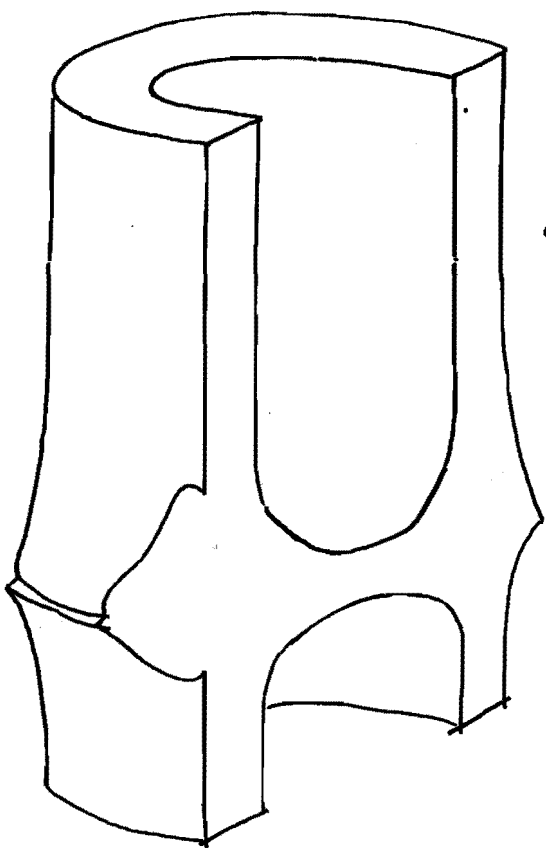
2.4.1. Tissue, bamboo, general.

A bamboo stem is hollow, and contains nodes:

Fig. 2.4.1. →

a. the culm
b. vertical section
c. the node
d. cross section





← fig. 2.4.2.
Node in bamboo.

A detailed (enlarged) cross section of the wall of a bamboo culm is shown in fig. 2.4.3.

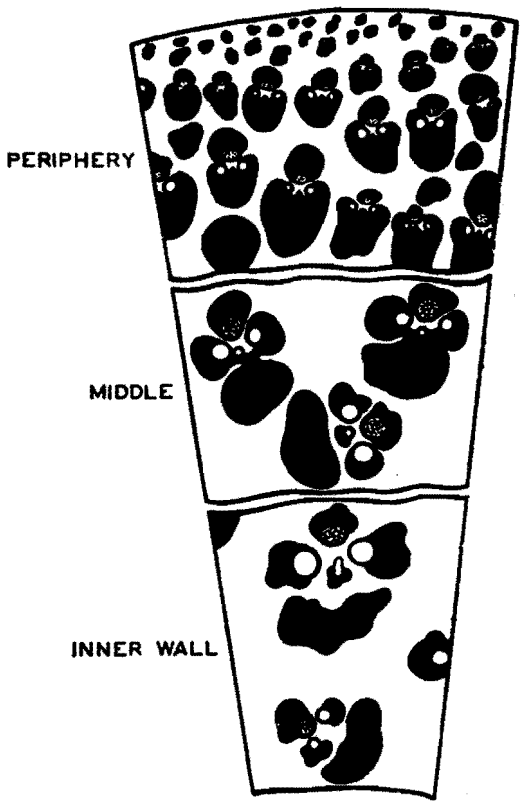


Fig. 2.4.3.
Cross section of the wall of a culm (15 à 20x), showing the regular pattern (in black) of vessels and fibres in groups together.
On the outside many and small vascular bundles, near the inside fewer and bigger.
For further details see next figure.

Source:The Use of Bamboo and Reeds in Building Construction (United Nations 1972).

More details on the systematic pattern of vessels, fibres, and other parts of the tissue are given in figure 2.4.4.

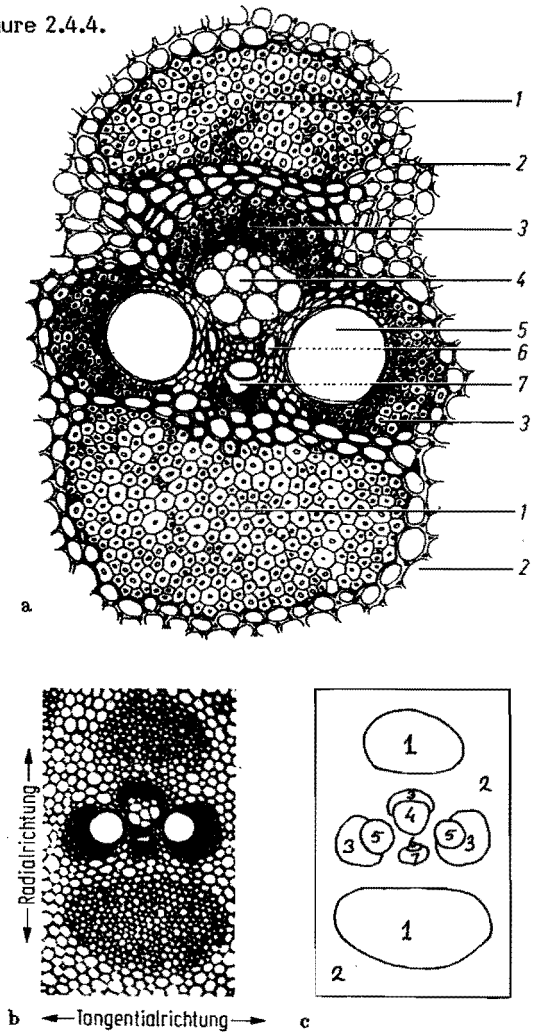


Fig. 4. a: Bamboo vascular bundle; (1) fibre strand; (2) parenchyma cells, (3) sclerenchyma sheath, (4) phloem, (5) metaxylem vessel, (6) small metaxylem elements, (7) intercellular space derived from protoxylem. b: Vascular bundle embedded in parenchymatous tissue and consisting of three parts (central vascular strand and two fibre strands); radial direction = radial diameter, respectively length of the vascular bundle, tangential direction = tangential diameter, respectively width of the vascular bundle. c: Simplified illustration of a vascular bundle as employed in the Plates I–IV

Figure 2.4.4. The tissue in bamboo (fig. a about 150x).

Source: Grosser and Liese (1971).

2.4.2. Tissue, bamboo, types

1. Sclerenchyma cells are long, dead, thick-walled cells and serve as strengthening material. They surround the vascular bundles, separated by parenchyma. Just inside of the outer skin of the stem a couple of layers of heavy sclerenchyma cells are found.
   The length of the fibres depends on the species, and varies in the culm.
2. The parenchyma tissue forms a ground tissue in which the vessels and fibres are embedded. The parenchyma cells are mostly thin-walled and connected to each other by numerous pits.
   The shape of the cells is either long or cube-like.
   The parenchyma tissue is the weakest of all tissues in bamboo.
3. The vascular system in bamboo is divided into two parts:
   - the phloem, that part of the vascular bundle towards the epidermis, made up of sieve tubes, for the conduction of food materials principally downwards; large and thin-walled cells.
   - the xylem, inside of the phloem, composed of vessels, principally for the transport of water and minerals upwards; thicker walled cells.

   The pattern of the vascular system in the cross-section of a culm, the longitudinal variation within the whole culm (decreasing from base to top), etc. is described in detail by Grosser and Liese (1971) and (1974).
   When bamboo is dried, the sap in the vessels dries up, the vessels fill with air, but the pits are closed and so form an important bearing for the preservation.
4. The parenchymatous ground tissue is lined on the outer and the inner sides by special terminal layers. The layers are heavily cutinized, i.e. overlaid with a waxy covering or cutin (1), to prevent loss of water from the culms (and to make the preservation difficult). The outside has a heavy deposit of silica, sometimes enough to use bamboo as a whetstone. This silica makes the bamboo impervious to moisture, and increases strength. The outer wall has a power to resist tearing as much as ten times over ordinary cellulose walls.
   The cells are long (0.05-0.1 mm) and thin (0.01 mm).

(1) Cutin = a fatty or waxy protective cuticle (= epidermis, skin) of leaves, stems, etc. of plants (Latin: cutis = skin).

2.5. References

Gordon, J.E.	The New Science of Strong Materials. First edition 1968. Cited edition Pelican 1976.
Gordon, J.E.	Structures. First edition 1978. Pelican.
Grosser and Liese (1971)	On the Anatomy of Asian Bamboos, with special reference to their Vascular Bundles. Wood Science and Technology, vol. 5 (1971), p. 290 - 312.
Jayne, B.E. editor	Theory and Design of Wood and Fibre composite materials. Syracuse 1972.
Kollmann, F.F.P.	Principles of Wood Science and Technology, Berlin (1968) volume 1 and 2.
Parameswaran,N.and Liese,W.	On the Fine Structures of Bamboo Fibres. Wood Science and Technology vol. 10 (1976) p. 231 - 246.

Cited pages

	Gordon Materials	Jayne	Kollmann
par.2.1.	270-274	59-62	(2) 5-9
par.2.2.			
cellulose	128-136	74-77	(1) 58-60, 321
lignin		59, 62	(1) 64-70, 55
hemicellulose			(1) 61-64, 55

Chapter 3

MODELS OF CELL AND CELL WALL

Contents

		page
3.1.	Introduction	30
3.2.	The Cell Wall	31
3.3.	The Cell	32
3.4.	Assumptions	35
3.5.	A Mathematical Model of the Cell	36
3.6.	Numerical Values for E and ν	42
3.7.	The influence of E_T and ν on the resulting w and σ	44
3.8.	Calculations according to the Model	52
3.9.	Verification	59
3.10.	Discussion and comparison with Tests	64
3.11.	Conclusions	67
3.12.	What remains to be done?	67
3.13.	Addition	68
3.14.	Literature	69
3.15.	Appendix: Calculation of E_T	71

3.1. Introduction

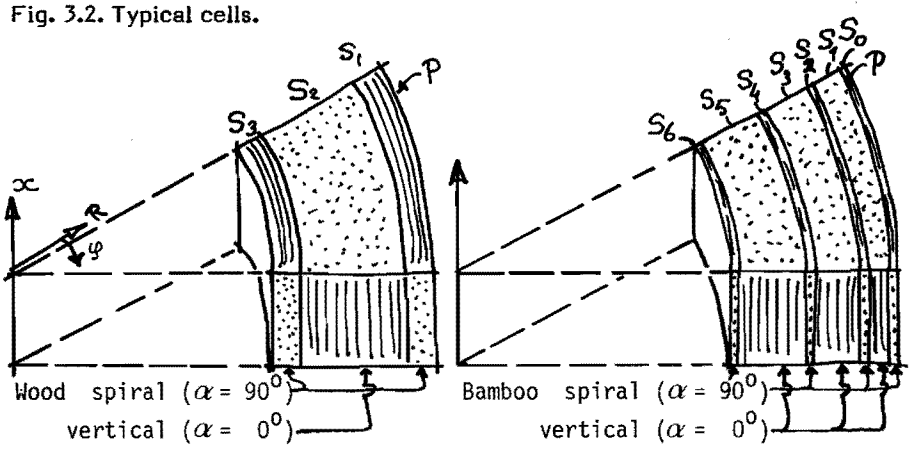
Chapter 1 comprises an introduction into the subject of this thesis, whereas chapter 2 presents a botanical description of the cells and the cellwalls of bamboo and wood. We shall now deal with a study on the mechanical properties of the cell and the cell wall. In this study the mechanical behaviour of the cells of bamboo is compared with that of wood. The chemical composition and the weight per volume of bamboo and softwood are almost the same.
See table 3.1.

Table 3.1. Properties of bamboos and softwoods

	bamboos	softwoods
% cellulose	55	50
% lignin	25	25
% hemicellulose etc.	20	25
weight per volume, kg/m^3, conditioned	600	600

The study was concentrated on the possible influence of the different number of cell wall layers: three in wood, and seven (and even up to fifteen) layers in bamboo.
For this study a mathematical model of a cell was built, and for the cells in both bamboo and wood the stresses in axial, radial and tangential directions, as well as the displacements were calculated.
The sclerenchyma-cells contribute most to the mechanical properties, and so the model was limited to these. These cells can be characterized as thickwalled tubes, e.g. with an outside diameter of 0.03 mm, a wallthickness of 0.006 mm. and an average 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 alternating the cellulose-microfibrils nearly parallel to the cell-axis and nearly perpendicular to the cell-axis.
A layer with cellulose-microfibrils nearly parallel to the cell-axis will be called "vertical", and the other layer with the cellulose-microfibrils nearly perpendicular to the cell-axis will be called "spiral". A sketch of a typical cell of wood and of bamboo is given in fig. 3.2.

Fig. 3.2. Typical cells.



A mathematical model of a cell was built for this study. Fortunately many studies on such models are found in literature. They mainly deal with fibre-reinforced materials (Schwartz and Schwartz, Jones, Williams) or more specifically with the mathematical approach (Lekhnitskii). A very useful book is that by Richard E. Mark (1967). He studies the mechanics of cell walls in tracheids in wood.To start with such a model, data on the composition of cell wall and cell in bamboo and wood were collected.

3.2. 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.

Bamboo

A fibre of common bamboos looks like table 3.3.

(source: Parameswaran/Liese (1967) and Preston and Singh (1950)

Table 3.3. Cross-section of wall of bamboo-cell. Explanation see next page.

← middle lamella ML							Lumen →	
name	P	S0		S1	S2	S3	S4	S5
L or T				L	T	L	T	L
thickness 10^{-6}m	0.06	0.12	0.08	0.60	0.11	1.86	0.30	2.70
α		50^0	35^0	2-5^0	85-90^0	10-12^0	85-90^0	10-20^0
α		35^0	20^0	5-6^0		5-6^0		10^0
lignin content				low	high	low	high	low

in which:

P	= primary wall
SO	= S zero, transition lamella
S1-S5	= secundary wall layers (may be more than 5)
L or T	= longitudinal or transversal orientation of fibrils
α	= angle of fibrils with cell axis, according to Parameswaran/Liese and Preston resp.

Wood

Table 3.4. Cross-section of wall of wood-cell

←Middle lamella						Lumen→
name	P_1	P_2	S_1	S_1/S_2	S_2	S_2/S_3	S_3
L or T			T		L		T
Thick-ness			0.12-				
10^{-6}m			0.35		$\geqslant 5$		$\leqslant$0.08(Kollmann)
idem	0.1		1.0		1-10		1.0(Siau)
α			50-70°		10-30°	20-30°	60-90°(Siau)
lignin content in %	70		40		20		15 (Panshin
hemi-cellulose content in %	20		30		30		40 and De
cellulose content in %	10		30		50		45 Zeeuw)

3.3. The Cell

From the cell wall we now turn our attention to the cell. Data are needed as to the diameter and length, but due to the differences between botanical species, between fibres and other tissues, and between earlywood and latewood, I had to work with mean figures, with a tall standard deviation.

Table 3.5. Diameter and length of cells in 10^{-6} m.

	diameter	length	ref.
bamboo	10 - 30	1000-3000	Liese(1972)
wood	33	3500	Siau

Mark 1967 gives a model how to calculate the overall E-value for a fibre, as a result from given conditions. He uses the following data.

Table 3.6. Proportions of cell-wall substance for wood

layer	% area	% framework (=fibres)	% matrix
P+M	11.2	10.1	89.9
S1	17.5		
S2	61.1	53.1	46.9
S3	10.2		
	100.0		

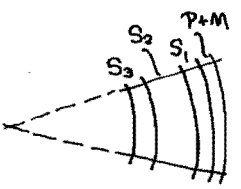


Table 3.7. Elastic constants for wood

framework (= fibres)	matrix
E_{FL} = 137 000 N/mm^2	E_M = 2 040 N/mm^2
E_{FT} = 27 700 N/mm^2	
G_{FLT} = 4 490 N/mm^2	G_M = 785 N/mm^2
ν_{FLT} = 0.10	ν_M = 0.30
ν_{FTL} = 0.011	

ν = Poisson's value.

Fig. 3.8. Bamboo-cell from Parameswaran/Liese

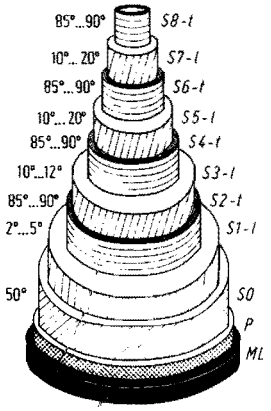


Fig. 24. Model of the polylamellate structure of a thick-walled bamboo fibre. Figures on the left indicate fibril angle, letters on the right terminology of wall lamellae

Fig. 3.9. Wood-cell from Siau

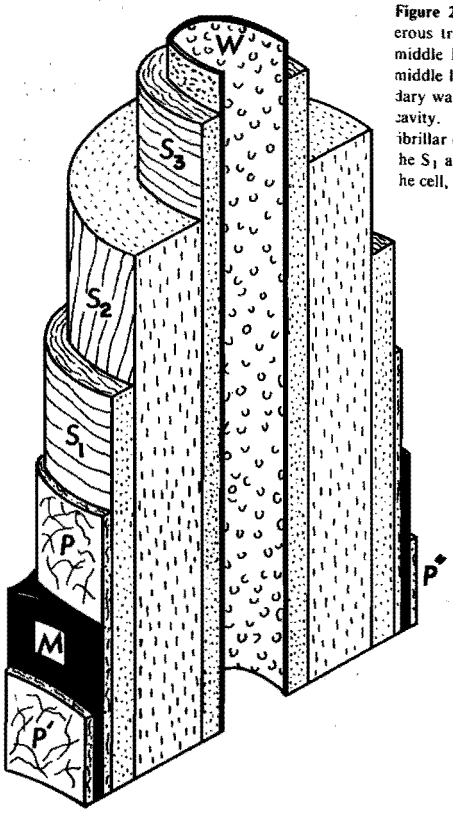
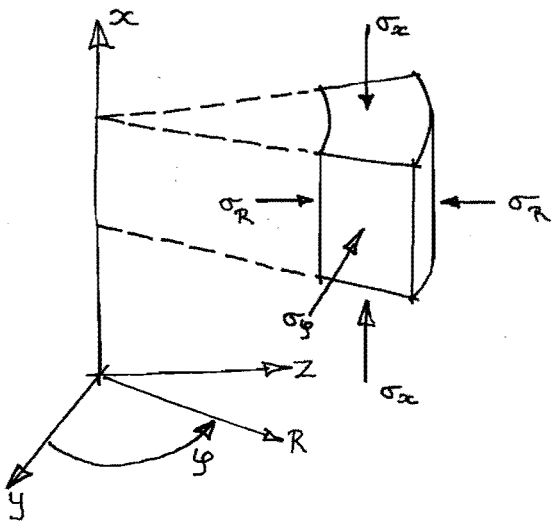


Figure 2.5. Diagrammatic view of the cell wall of a typical coniferous tracheid from Ward *et al.* [20]. P = primary wall; M = middle lamella; S_1 = outer layer of the secondary wall; S_2 = middle layer of the secondary wall; S_3 = inner layer of the secondary wall; W = warty membrane which lines the cell lumen or cavity. P' and P'' = primary walls of adjoining cells. Microfibrillar orientation in the primary walls is indicated as random, in the S_1 and S_3 as approximately perpendicular to the long axis of the cell, and in the S_2, as more or less parallel to the long axis of the cell. (Courtesy of Official Digest.)

3.4. Assumptions

Before building a mathematical model of a cell, certain assumptions were made on a thick-walled tube under an axial stress.



Assumptions:

1. no external forces in R- or φ-direction
2. end-loads in x-direction only, hence

$$\frac{\partial \sigma_x}{\partial x} = 0$$

3. stresses are rotationally symmetrical with respect to the x-axis, (no shear)

$$\frac{\partial}{\partial \phi} = 0$$

4. (according to Lamé) the length of the cylinder $\gg$ diameter and wall thickness.
5. plane cross-sections remain plane
6. elastic behaviour only; no buckling

The difference between Mark's model and this model mainly lies in the three-dimensional deformation of this model.

3.5. A mathematical model of the cell

3.5.0. This paragraph presents the construction of a mathematical model of the cell. The assumptions were mentioned in paragraph 3.4.

The equations for each layer are three constitutive equations and three equations concerning the equilibrium of forces. The three constitutive equations for a vertical layer (with microfibrils nearly parallel with the cell-axis) read:

$$\begin{vmatrix} \varepsilon_x \\ \varepsilon_\phi \\ \varepsilon_R \end{vmatrix} = \begin{vmatrix} \frac{1}{E_L} & \frac{-\nu_{TL}}{E_L} & \frac{-\nu_{TL}}{E_L} \\ \frac{-\nu_{LT}}{E_T} & \frac{1}{E_T} & \frac{-\nu_{TT}}{E_T} \\ \frac{-\nu_{LT}}{E_T} & \frac{-\nu_{TT}}{E_T} & \frac{1}{E_T} \end{vmatrix} \begin{vmatrix} \sigma_x \\ \sigma_\phi \\ \sigma_R \end{vmatrix} \quad - \quad (1)$$

in which

E_L = modulus of elasticity of a cell wall layer parallel to the microfibril direction.

E_T = idem, but perpendicular to microfibril direction.

ν_{LT} = $\frac{\text{contraction in direction T}}{\text{extension in direction L}}$

under stress in direction L (absolute ratio)

ν_{TL} and ν_{TT} are defined similarly.

For a spiral layer the constitutive equations are formed by exchanging the first and second column and line:

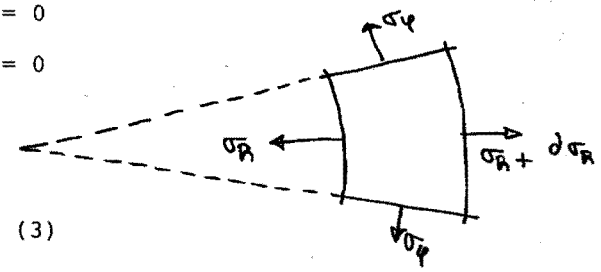
$$\begin{vmatrix} \varepsilon_x \\ \varepsilon_\phi \\ \varepsilon_R \end{vmatrix} = \begin{vmatrix} \frac{1}{E_T} & \frac{-\nu_{LT}}{E_T} & \frac{-\nu_{TT}}{E_T} \\ \frac{-\nu_{TL}}{E_L} & \frac{1}{E_L} & \frac{-\nu_{TL}}{E_L} \\ \frac{-\nu_{TT}}{E_T} & \frac{-\nu_{LT}}{E_T} & \frac{1}{E_T} \end{vmatrix} \begin{vmatrix} \sigma_x \\ \sigma_\phi \\ \sigma_R \end{vmatrix} \quad - \quad (2)$$

Finally, the equations for the equilibrium of forces:

- x - direction: $\frac{\partial}{\partial x} = 0$

- ϕ - direction: $\frac{\partial}{\partial \phi} = 0$

- R - direction:



$$\frac{\partial \sigma_R}{\partial R} + \frac{\sigma_R - \sigma_\phi}{R} = 0 \quad (3)$$

This differential equation is solved for an isotropic layer in par. 3.5.1., for a vertical layer in par. 3.5.2. and for a spiral layer in par. 3.5.3.

3.5.1. The solution for an isotropic layer

The matrix is:

$$E \begin{vmatrix} \varepsilon_x \\ \varepsilon_\phi \\ \varepsilon_R \end{vmatrix} = \begin{vmatrix} 1 & -\nu & -\nu \\ -\nu & 1 & -\nu \\ -\nu & -\nu & 1 \end{vmatrix} \begin{vmatrix} \sigma_x \\ \sigma_\phi \\ \sigma_R \end{vmatrix} \quad (4)$$

and the inverse is:

$$\begin{vmatrix} \sigma_x \\ \sigma_\phi \\ \sigma_R \end{vmatrix} = \frac{E}{(1-2\nu)(1+\nu)} \begin{vmatrix} 1-\nu & \nu & \nu \\ \nu & 1-\nu & \nu \\ \nu & \nu & 1-\nu \end{vmatrix} \begin{vmatrix} \varepsilon_x \\ \varepsilon_\phi \\ \varepsilon_R \end{vmatrix} \quad (5)$$

from which

$$\sigma_R = \frac{E}{(1-2\nu)(1+\nu)} (\nu \varepsilon_x + \nu \varepsilon_\phi + (1-\nu) \varepsilon_R) \quad (6)$$

in which

ε_x = given, a known constant

$\varepsilon_\phi = \frac{w}{R}$ (W positive in outside direction)

$\varepsilon_R = \frac{\partial w}{\partial R}$

Substitution in (3) $\frac{\partial \sigma_R}{\partial R} + \frac{\sigma_R - \sigma_\phi}{R} = 0$

results in:

$$\boxed{\frac{\partial^2 w}{\partial R^2} + \frac{1}{R}\frac{\partial w}{\partial R} - \frac{w}{R^2} = 0} \qquad (7)$$

which equals to

$$\frac{\partial}{\partial R}\left(\frac{\partial w}{\partial R} + \frac{w}{R}\right) = 0 \qquad (R > 0)$$

$$\frac{\partial w}{\partial R} + \frac{w}{R} = C$$

$$R\frac{\partial w}{\partial R} + w = C R$$

$$\frac{\partial}{\partial R}(R w) = C R$$

$$R w = \frac{1}{2} C R^2 + C_4 = C_3 R^2 + C_4$$

$$\boxed{w = C_3 R + \frac{C_4}{R}} \ldots\ldots\ldots (8)$$

Note: C_1 and C_2 are used elsewhere.

3.5.2. The solution for a vertical layer

The flexibility-matrix has already been given as no. 1 at the beginning of par. 3.5.0. The inverse of this matrix reads:

$$\begin{vmatrix} \sigma_x \\ \sigma_\phi \\ \sigma_R \end{vmatrix} = \begin{vmatrix} \frac{1-\nu^2_{TT}}{E_T^2 \Delta} & \frac{\nu_{TL}(\nu_{TT}+1)}{E_L E_T \Delta} & \frac{\nu_{TL}(\nu_{TT}+1)}{E_L E_T \Delta} \\ \frac{\nu_{LT}(\nu_{TT}+1)}{E_T^2 \Delta} & \frac{1-\nu_{TL}\nu_{LT}}{E_L E_T \Delta} & \frac{\nu_{TT}+\nu_{LT}\nu_{TL}}{E_L E_T \Delta} \\ \frac{\nu_{LT}(\nu_{TT}+1)}{E_T^2 \Delta} & \frac{\nu_{TT}+\nu_{LT}\nu_{TL}}{E_L E_T \Delta} & \frac{1-\nu_{LT}\nu_{TL}}{E_L E_T \Delta} \end{vmatrix} \begin{vmatrix} \varepsilon_x \\ \varepsilon_\phi \\ \varepsilon_R \end{vmatrix} \qquad (9)$$

in which $$\Delta = \frac{(1 + \nu_{TT})(1 - \nu_{TT} - 2\,\nu_{LT}\,\nu_{TL})}{E_L\,E_T^2} \qquad (10)$$

$$\frac{\partial \sigma_R}{\partial R} + \frac{\sigma_R - \sigma_\phi}{R} = 0 \qquad (3)$$

$$\sigma_R = \frac{\nu_{LT}\,(\nu_{TT} + 1)}{E_T^2\,\Delta}\,\varepsilon_x + \frac{\nu_{TT} + \nu_{LT}\,\nu_{TL}}{E_L\,E_T\,\Delta}\,\frac{w}{R} + \frac{1-\nu_{TL}\nu_{LT}}{E_L\,E_T\,\Delta}\,\frac{\partial w}{\partial R}$$

$$\frac{\partial \sigma_R}{\partial R} = \frac{\nu_{TT} + \nu_{LT}\,\nu_{TL}}{E_L\,E_T\,\Delta}\left(\frac{1}{R}\,\frac{\partial w}{\partial R} - \frac{w}{R^2}\right) + \frac{1-\nu_{TL}\,\nu_{LT}}{E_L\,E_T\,\Delta}\,\frac{\partial^2 w}{\partial R^2}$$

$$\frac{\sigma_R - \sigma_\phi}{R} = \frac{\nu_{TT} + 2\nu_{LT}\,\nu_{TL} - 1}{E_L\,E_T\,\Delta}\,\frac{w}{R^2} + \frac{1-2\,\nu_{LT}\,\nu_{TL} - \nu_{TT}}{E_L\,E_T\,\Delta}\,\frac{1}{R}\,\frac{\partial w}{\partial R}$$

From which it follows

$$\frac{\partial^2 w}{\partial R^2} + \frac{1}{R}\,\frac{\partial w}{\partial R} - \frac{w}{R^2} = 0$$

with the same solution

$$\boxed{w = C_3\,R + \frac{C_4}{R}} \qquad (8)$$

3.5.3. The solution for a spiral layer

The inverse of the flexibility-matrix (2) is (11) :

$$\begin{vmatrix} \sigma_x \\ \sigma_\phi \\ \sigma_R \end{vmatrix} = \begin{vmatrix} \frac{1-\nu_{TL}\,\nu_{LT}}{E_L\,E_T\,\Delta} & \frac{\nu_{LT}\,(1+\nu_{TT})}{E_T^2\,\Delta} & \frac{\nu_{LT}\,\nu_{TL} + \nu_{TT}}{E_L\,E_T\,\Delta} \\ \frac{\nu_{TL}\,(1+\nu_{TT})}{E_L\,E_T\,\Delta} & \frac{1-\nu^2_{TT}}{E_T^2\,\Delta} & \frac{\nu_{TL}\,(1+\nu_{TT})}{E_L\,E_T\,\Delta} \\ \frac{\nu_{TL}\,\nu_{LT}+\nu_{TT}}{E_L\,E_T\,\Delta} & \frac{\nu_{LT}\,(1+\nu_{TT})}{E_T^2\,\Delta} & \frac{1-\nu_{TL}\,\nu_{LT}}{E_L\,E_T\,\Delta} \end{vmatrix} \begin{Vmatrix} \varepsilon_x \\ \varepsilon_\phi \\ \varepsilon_R \end{Vmatrix}$$

or symbolically (C is mostly called S)

$$\left|\,\sigma\,\right| = \left|\,F\,\right|^{-1} \left|\,\varepsilon\,\right| = \left|\,C\,\right| \left\|\,\varepsilon\,\right|$$

in which

$$\left|\,C\,\right| = \begin{vmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{vmatrix}$$

$$\frac{\partial \sigma_R}{\partial R} = C_{32} \left(\frac{1}{R} \frac{\partial w}{\partial R} - \frac{w}{R^2} \right) + C_{33} \frac{\partial^2 w}{\partial R^2}$$

$$\frac{\sigma_R - \sigma_\phi}{R} = (C_{31} - C_{21}) \frac{\varepsilon_x}{R} + (C_{32} - C_{22}) \frac{w}{R^2} + (C_{33} - C_{23}) \frac{1}{R} \frac{\partial w}{\partial R}.$$

$$\frac{\partial \sigma_R}{\partial R} + \frac{\sigma_R - \sigma_\phi}{} =$$

$$= C_{33} \frac{\partial^2 w}{\partial R^2} + (C_{32} + C_{33} - C_{23}) \frac{1}{R} \frac{\partial w}{\partial R} + (- C_{22}) \frac{w}{R^2}$$

$$+ (C_{31} - C_{21}) \frac{\varepsilon_x}{R} = 0$$

or

$$A \frac{\partial^2 w}{\partial R^2} + B \frac{1}{R} \frac{\partial w}{\partial R} + D \frac{w}{R^2} + E \frac{\varepsilon_x}{R} = 0$$

$$AR^2 \frac{\partial^2 w}{\partial R^2} + B R \frac{\partial w}{\partial R} + D w = - E \varepsilon_x R$$

We substitute $R = e^t$ in which t is a new variable.

$$\frac{\partial w}{\partial R} = \frac{\partial w}{\partial t} \cdot \frac{\partial t}{\partial R} = \frac{\partial w}{\partial t} \cdot \frac{1}{R}$$

$$\frac{\partial^2 w}{\partial R^2} = - \frac{1}{R^2} \frac{\partial w}{\partial t} + \frac{1}{R} \frac{\partial^2 w}{\partial t^2} \frac{\partial t}{\partial R}$$

$$= - \frac{1}{R^2} \frac{\partial w}{\partial t} + \frac{1}{R^2} \frac{\partial^2 w}{\partial t^2}$$

from which follows

$$A \frac{\partial^2 w}{\partial t^2} - A \frac{\partial w}{\partial t} + B \frac{\partial w}{\partial t} + D w = - E e^t$$

The homogeneous equation is:

$$A \frac{\partial^2 w}{\partial t^2} - (A-B) \frac{\partial w}{\partial t} + D w = 0$$

We substitute $w = e^{Ft}$ in which F is a new variable, and t remains the same.

$$F^2 . A - (A-B) . F + D = 0$$

$$F_1, F_2 = \frac{A - B \pm \sqrt{(A-B)^2 - 4AD}}{2A}$$

$$w = C_1 R^{F_1} + C_2 R^{F_2}$$

The particular integral is:

$$w = \alpha R + \beta$$

$$\frac{\partial w}{\partial R} = \alpha \quad \text{and} \quad \frac{\partial^2 w}{\partial R^2} = 0$$

$$B R \alpha + D \alpha R + D \beta = - E \varepsilon_x R$$

This must hold for each R, so $\beta = 0$

For $R \neq 0$:

$$B \alpha + D \alpha = - E \varepsilon_x$$

$$\alpha = \frac{- E}{B + D} \varepsilon_x$$

$$w_p = \frac{- E}{B + D} \varepsilon_x R$$

The complete solution is:

$$w = C_1 R^{F_1} + C_2 R^{F_2} - F_3 R \varepsilon_x . \qquad (12)$$

in which

$$F_1, F_2 = \frac{A - B \pm \sqrt{(A-B)^2 - 4AD}}{2A}$$

in which

$A = C_{33}$

$B = C_{32} + C_{33} - C_{23}$

$D = - C_{22}$

$E = C_{31} - C_{21}$

$F_3 = \frac{E}{B+D}$

3.5.4. The solution of the differential equation now has for each layer two integration constants per layer, so per layer two boundary conditions are needed to solve those constants.

The conditions are:

- on the inner and outer surface a stress in radial direction is impossible, so $\sigma_R = 0$ for $R = R_{inside}$ and $R = R_{outside}$.
- on the surface where two layers meet one another, stresses in R-direction are in equilibrium:

$$\left\{\sigma_{R_i}\right\}_{\text{layer } i} = \left\{\sigma_{R_i}\right\}_{\text{layer } (i+1)}$$

- similarly, there is an equality of displacements:

$$\left\{w_{R_i}\right\}_{\text{layer } i} = \left\{w_{R_i}\right\}_{\text{layer } (i+1)}$$

As a result, for i layers:

- two conditions for $\sigma_R = 0$ on in- and outside.
- (2i - 2) conditions for σ_R and w on the (i - 1) surfaces where layers meet.

Now there are (2 i) equations to solve the (2 i) unknown constants.

This completes the model

After solving the (2 i) equations and thus having found the values for the (2 i) constants, we proceed as follows:

- first, solve w
- second, calculate $\varepsilon_\phi = \frac{w}{R}$ and $\varepsilon_R = \frac{\partial w}{\partial R}$,
- finally, calculate σ_x, σ_ϕ and σ_R.

3.6. Numerical values for E and ν

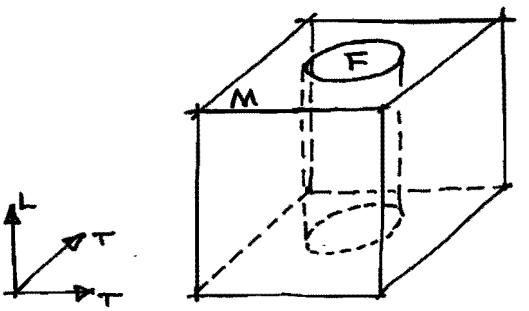
In his book, Mark gives the elastic constants for the microfibrils and the matrix:

- for the microfibrils
  $E_{FL} = 137\,000$ N/mm^2 (see table 3.7.)
  $E_{FT} = 27\,700$ "
  $\nu_{FLT} = 0.10$
  $\nu_{FTL} = 0.011$
- for the matrix
  $E_M = 2\,040$ N/mm^2
  $\nu_M = 0.30$

Based on these constants, values are now calculated for the composite layer for:

$E_L \quad E_T \quad \nu_{LT} \quad \nu_{TL} \quad \nu_{TT}$

The composition of a layer is assumed to consist of 50 per cent cellulose microfibri's and 50 per cent lignin matrix. A sketch of a microfobril in the surrounding matrix is:



E_L If the composite is built up with 50 per cent fibrils and 50 per cent matrix, E_L is simply the mean of E_{FL} and E_M:

$$E_L = \tfrac{1}{2}\,(137\,000 + 2\,040) = \underline{70\,000\ N/mm^2}$$

E_T The calculation of E_T is given in the appendix to this chapter, par. 3.15.
The result is:

$$E_T = 6\,200\ N/mm^2$$

ν_{LT} Similarly as E_L, ν_{LT} is the mean of ν_M and ν_{FLT}:

$$\nu_{LT} = \tfrac{1}{2}\,(0.30 + 0.10) = 0.20$$

ν_{TL} According to Greszuck:

$$\nu_{TL} = \nu_{LT}\ E_T/E_L$$

$$= 0.20\ \ 6\,200/70\,000 = 0.0177$$

ν_{TT}

$$\nu_{TT} = \nu_M = 0.30$$

Note: the cellulose and lignin of bamboo and wood might have different mechanical properties. E.g. Cousins has reported about the different molecular weights of the lignin in bamboo and wood, being 1 700 and 2 600 respectively. This could result in different mechanical properties, about which nothing is known. Therefore all calculations in this chapter are made with Mark's data for both bamboo and wood.

3.7. The influence of E_T and ν on the resulting w and σ

3.7.1. Now calculations are carried out with the mathematical model on two cells, one wood-cell and one bamboo-cell. To study the influence of the different number of cell wall layers, we assume 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. The subdivision of this wall is:

- for wood	spiral layer,	S3	0.001 mm	(cf table 3.4.)
	vertical	S2	0.004	
	spiral	S1	0.001	
			0.006	
- for bamboo	spiral layer,		0.0002 mm	(cf table 3.3.)
	vertical	S5	0.0027	
	spiral	S4	0.0003	
	vertical	S3	0.0019	
	spiral	S2	0.0001	
	vertical	S1	0.0006	
	spiral	S0	0.0002	
			0.0060	

Next, the bamboo-cell has 86 per cent vertical and 14 per cent spiral area, and in the real wood-cell only 70 per cent is vertical. To check this difference, a special wood-cell is created with 86 per cent vertical as in bamboo, which results in:

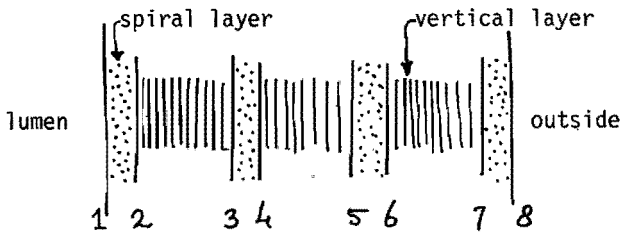
spiral layer	0.00041 mm
vertical	0.00518
spiral	0.00041
	0.00600

At first the influence is studied of the calculated values for E and ν on the resulting stresses and displacements. Since E_L and ν_{TT} are determined with certainty this study is limited to E_T, ν_{TL} and ν_{LT}. These three values have been determined with great difficulties: e.g. depending on different mechanical assumptions E_T varies from 3800 to 17500, but 6200 is the best value.The influence of these different values of E_T on the resulting stresses and displacements is therefore studied as well as those of ν_{TL} and ν_{LT}. The resulting stresses and displacements are plotted in figures 3.10 ... 3.13, i.e.

- the radial displacement w,
- the axial stress σ_x,

- the tangential stress σ_{ϕ},
- the radial stress σ_{R},

all as functions of E_T and ν_{LT} for the different radii (1....8) in a bamboo cell:



(the radii 1...8 are indicated at the right side in each plot).

(Note: ν_{TL} does not have any influences at all, and has therefore not been plotted)

These plots have been calculated with:

E_L = 70 000 N/mm^2 $\quad \nu_{LT}$ = 0.20

E_T = 6 200 $\quad \nu_{TL}$ = 0.0177

ν_{TT} = 0.30

unless these values are varied, as indicated in the figures.

Fig. 3.10. Radial displacement w as a function of E_T for $\varepsilon_x = 10^{-3}$.
Note: radius inside = 10.10^{-6}m, radius outside = 16.10^{-6}m.

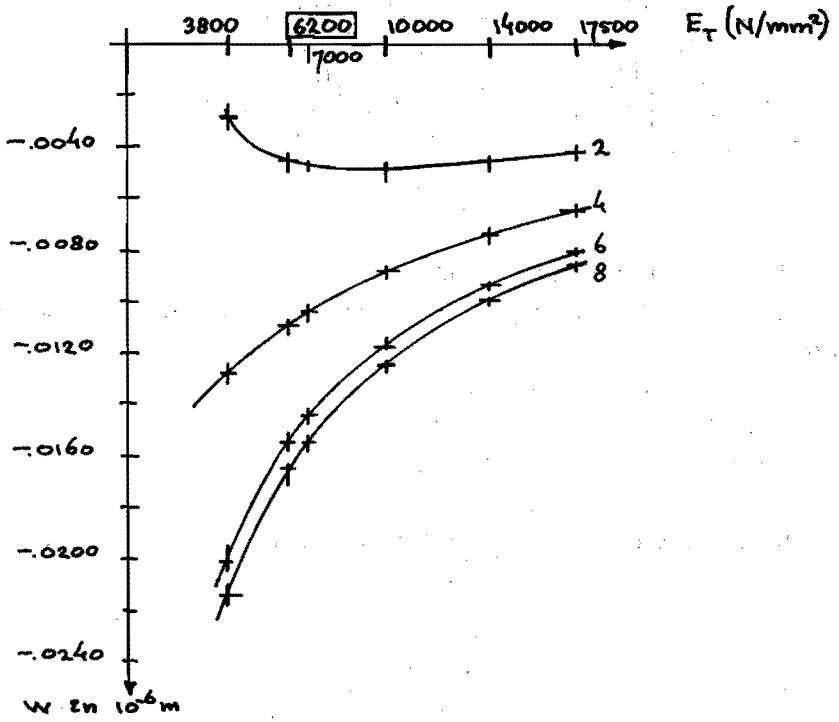


Fig. 3.11. Stresses as functions of E_T for $\varepsilon_x = 10^{-3}$.

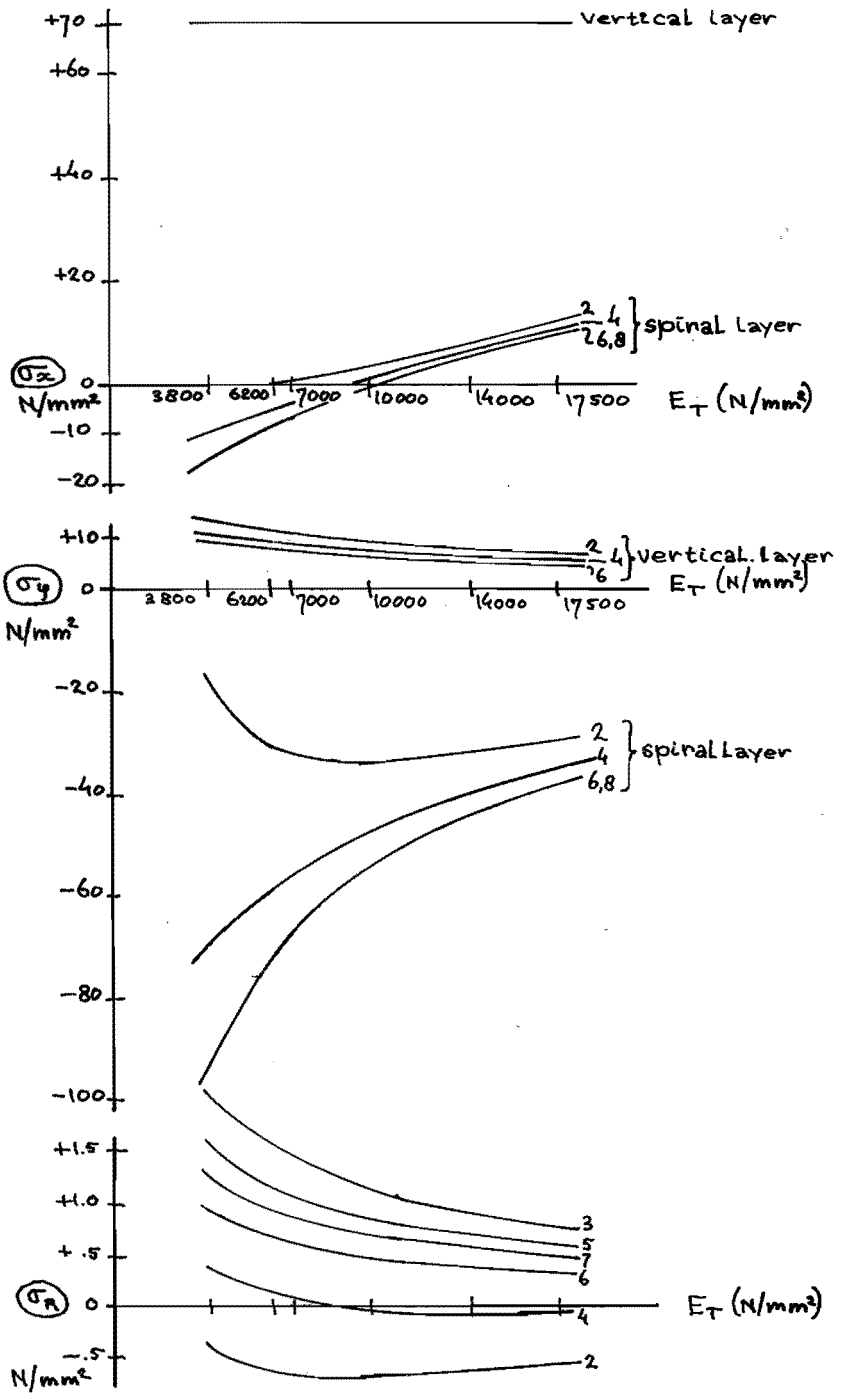


Fig. 3.12. Radial displacement w as a function of ν_{LT} for $x = 10^{-3}$.
Note: radius inside = 10.10^{-6}m, radius outside = 16.10^{-6}m.

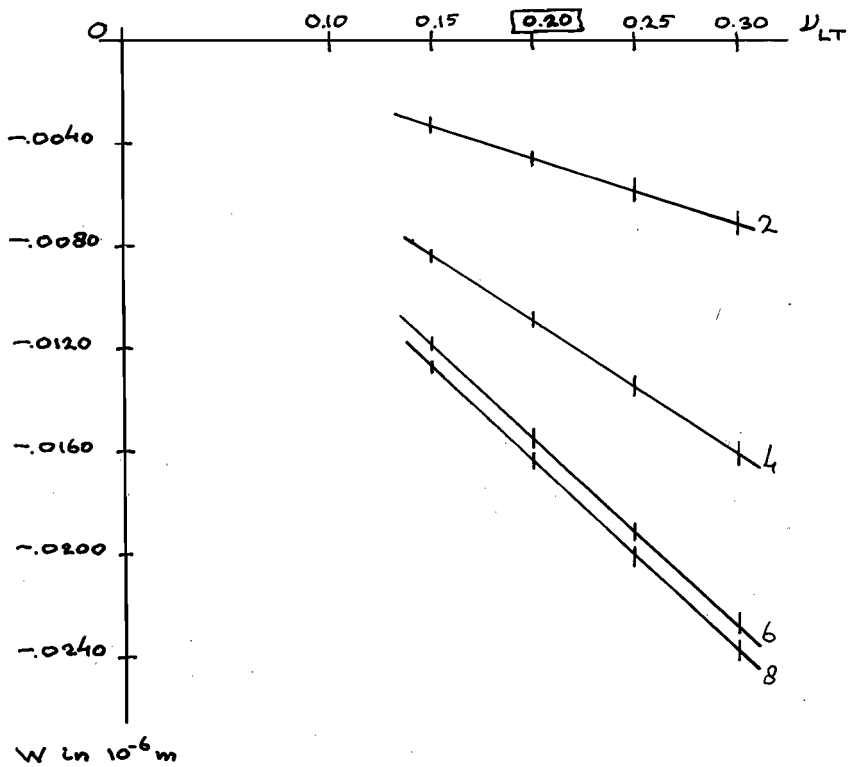
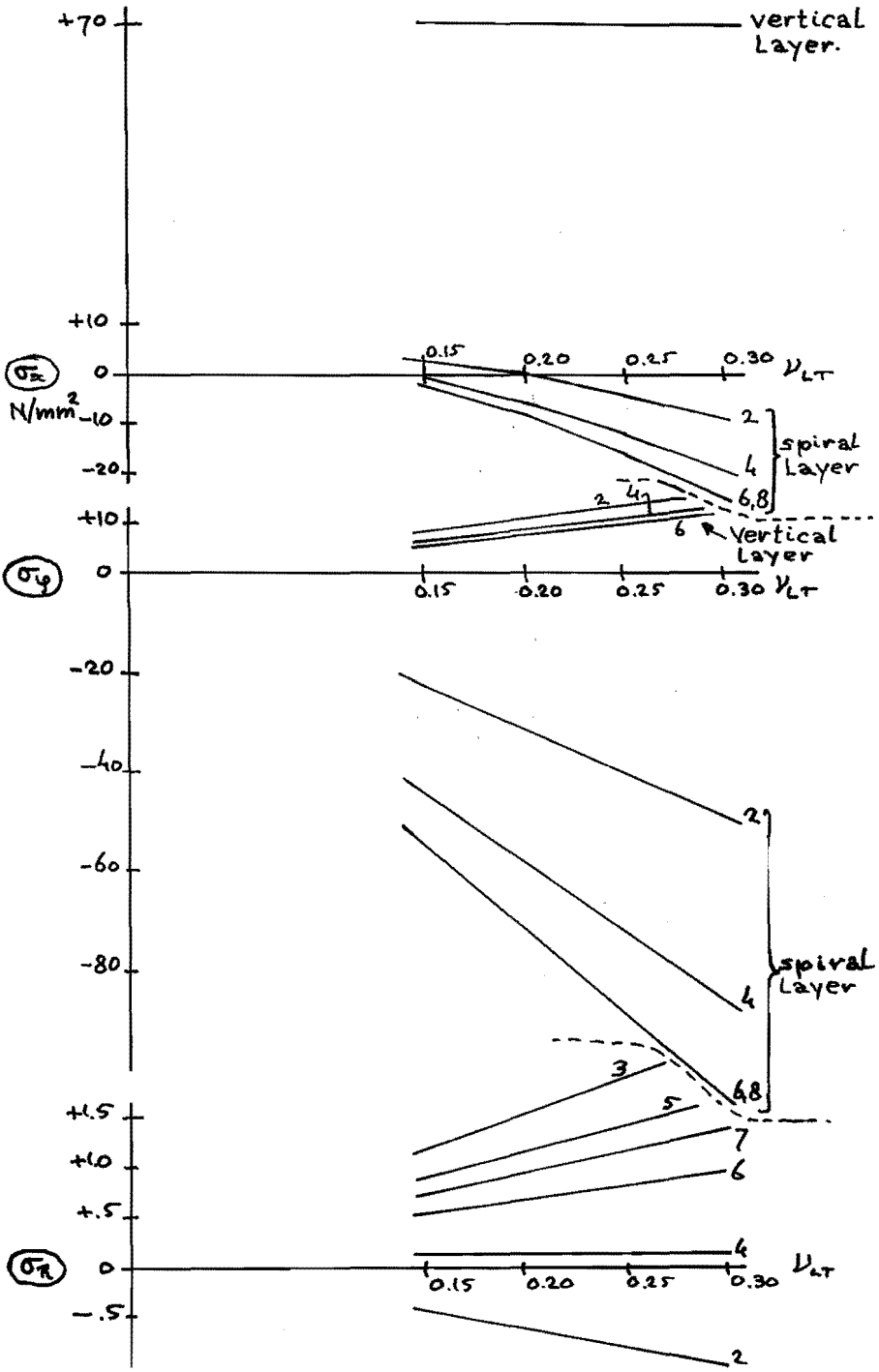


Fig. 3.13. Stresses as functions of ν_{LT} for $\varepsilon_x = 10^{-3}$.



3.7.2. Verification of the results

The results of this computerprogram were verified manually. For briefness'sake, only two examples follow:

- the displacement of w as a function of ν_{LT} (fig. 3.12)
- ν_{TL} has no influence on w.

First, the displacement w as a function of ν_{LT}.

In a vertical layer with no radial deformations

$$\varepsilon_\phi = \varepsilon_R = 0.$$

From the matrix (9) (par. 3.5.2.) follows:

$$\sigma_\phi = \sigma_R = \frac{\nu_{LT}\ (\nu_{TT}+1)}{E_T^{\,2}\ \Delta}\ \varepsilon_x$$

in which

$$\Delta = \frac{(1+\nu_{TT})\ (1-\nu_{TT}-2\nu_{LT}\nu_{TL})}{E_L E_T^{\,2}} \quad - - - \ (10)$$

$$= \frac{1.3\quad \{1-0.3-0.0354\quad (0.15\ \text{à}\ 0.30)\}}{E_L E_T^{\,2}}$$

$$\simeq \frac{0.9}{E_L E_T^{\,2}}$$

and consequently

$$\sigma_R = \sigma_\phi = \frac{\nu_{LT}\ 1.3\ E_L\ \varepsilon_x}{0.9} = \boxed{1.4\ \nu_{LT}\ \sigma_x}$$

However, if the cylinder is completely free in radial movement, then $\sigma_r = \sigma_\phi = 0$. For this rough check, let us take the mean:

$$\sigma_r = \sigma_\phi = 0.7\quad \nu_{LT}\quad \sigma_x.$$

In the matrix (1) (par.3.5.0.) we find:

$$\varepsilon_\phi = \frac{1}{E_T} \left(- \nu_{LT}\, \sigma_x + \sigma_\phi - \nu_{TT}\, \sigma_R \right)$$

$$\simeq \frac{\nu_{LT}\, \sigma_x}{E_T} (- 1 + 0.7 + 0.3 \times 0.7)$$

$$\varepsilon_\phi = - \frac{\nu_{LT}}{2} \frac{\sigma_x}{E_T}$$

$$w = \varepsilon_\phi \times R = - \frac{\nu_{LT}}{2} \frac{\sigma_x\, R}{E_T}$$

With σ_x = 70 N/mm^2 and E_T = 6200 N/mm^2:
$w = - 0.0056\, R\, \nu_{LT}$
from which

ν_{LT}	R(10^{-6}m)	w(manually verified) 10^{-6}m	w(computer outcome, fig.3.12.) 10^{-6}m
0.15	10	-.0084	-.0035
	16	-.0134	-.0078
0.30	10	-.0168	-.0126
	16	-.0269	-.0238

Second example, ν_{TL} has no influence on w:

$$w = \varepsilon_\phi \qquad R = \frac{R}{E_T} \left(- \nu_{LT}\, \sigma_x + \sigma_\phi - \nu_{TT}\, \sigma_R \right)$$

in which ν_{TL} does not occur. From the matrix for a vertical layer ((9)in par.3.5.2.) it can simply be shown that the stresses are hardly influenced by ν_{TL}. Based on several more calculations, I conclude that the mathematical model works properly.

3.7.3. Conclusions

E_T has a considerable influence on w and σ: So it is important to determine E_T carefully. This has been done, see the appendix to this chapter (par.3.15.).

ν_{LT} has a linear influence on w and σ;

ν_{TL} has no influence at all.

With the obtained values for E and ν I now proceed to the calculation of displacements and stresses in cells of bamboo and wood.

3.8. Calculations according to the model

With the values:

E_L = 70 000 N/mm^2
E_T = 6 200 "
ν_{LT} = 0.20
ν_{TL} = 0.0177
ν_{TT} = 0.30

stresses and displacements are calculated in cells of bamboo and wood, shown in fig. 3.14., 3.15. and 3.16. On each page are plotted for $\varepsilon_x = 10^{-3}$:

- a cross section of the wall

- diagrams of σ_x, σ_ϕ and σ_R. In case of axial tension stress, positive stresses are tension, negative compression. Stresses are expressed in N/mm^2.

- a diagram of w = displacement in radial direction. In case of axial tension stress, positive displacement is to the outside, and negative to the inside. w is expressed in 10^{-6}m.

As to E_L = 70 000 N/mm^2, this value holds for microfibrils perfectly vertical (or horizontal, in the spiral layers). However, in bamboo the angle between microfibrils and cell-axis is 10^0, and in wood even 20^0. These values hold for vertical layers; for spiral layers the same angles occur between microfibrils and the horizontal plane.

From Mark (1973) we learn about the influence of this angle on the overall E_L-value:

angle =		E_L =
	0^0	70 000 N/mm^2
	10^0	42 000 N/mm^2 (bamboo)
	20^0	23 000 N/mm^2 (wood)

The value of E_T is hardly influenced by an angle of 10^0 or 20^0. The stresses and displacements calculated with these values of E_L are plotted in figs. 3.17, 3.18. and 3.19.

(The values for E_T and ν are unchanged).

Fig. 3.14. Stresses σ and radial displacement w in a bamboocell.

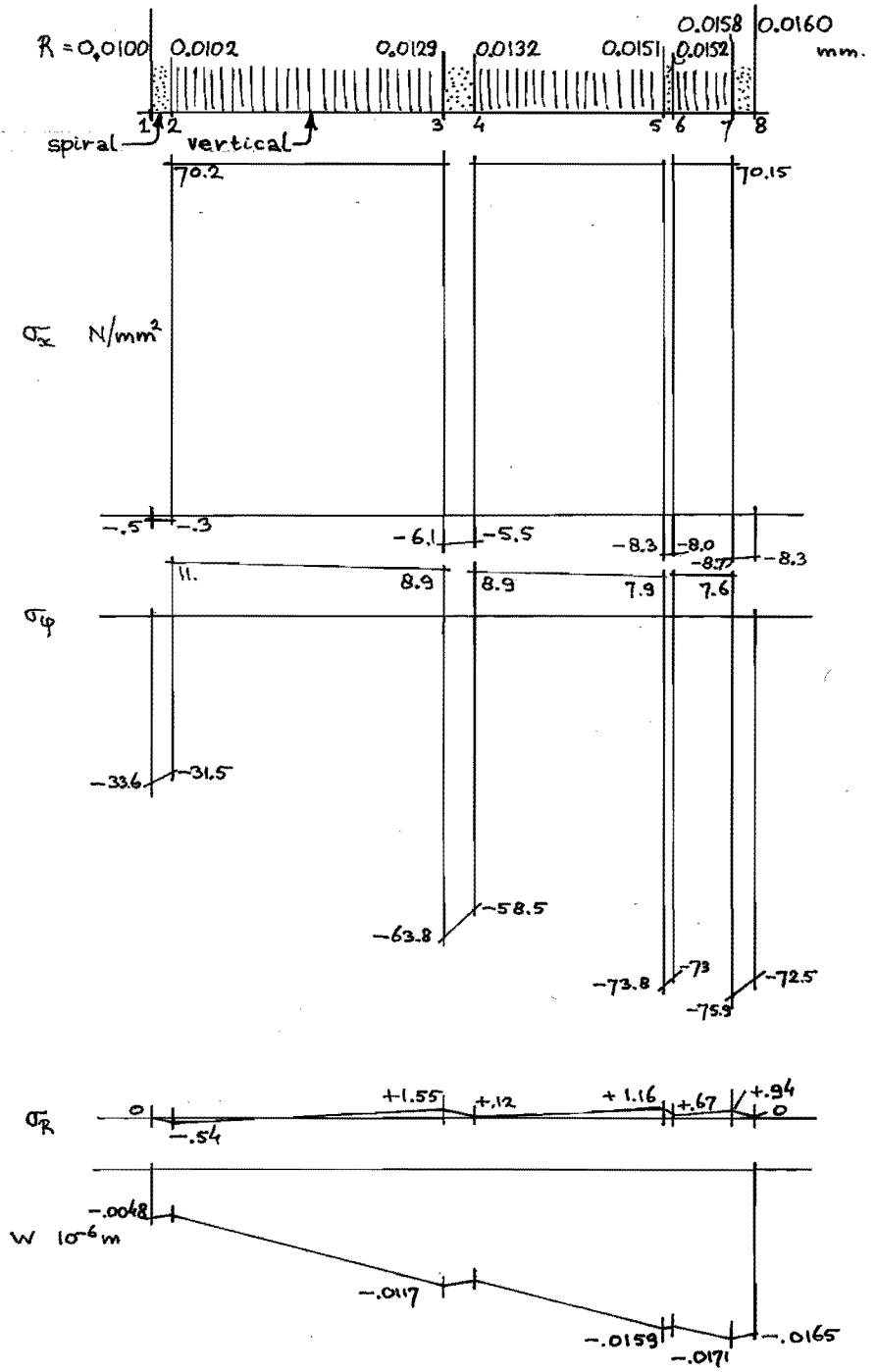


Fig. 3.15. Stresses σ and radial displacement w in a woodcell.

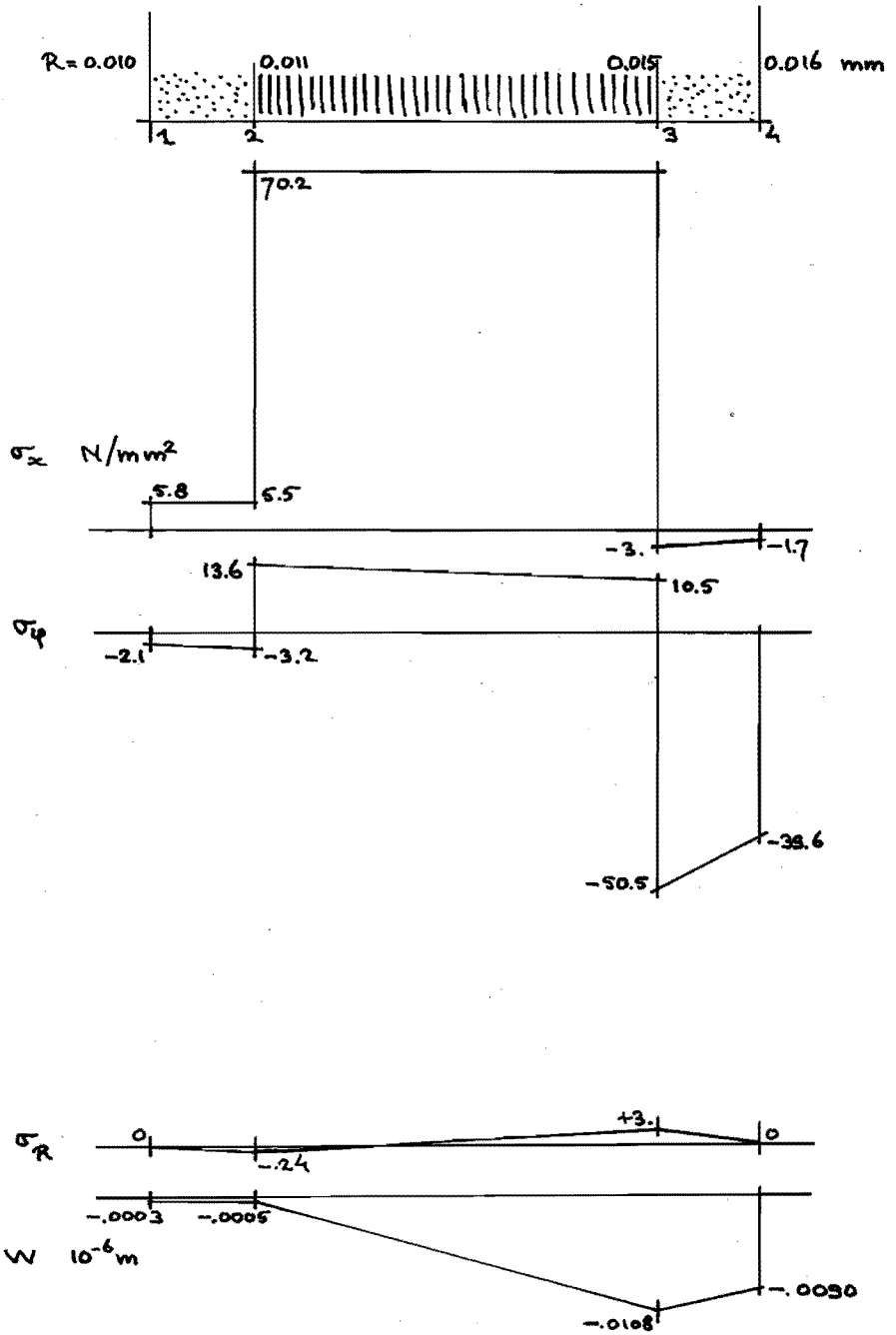


Fig. 3.16. "Special Woodcell".

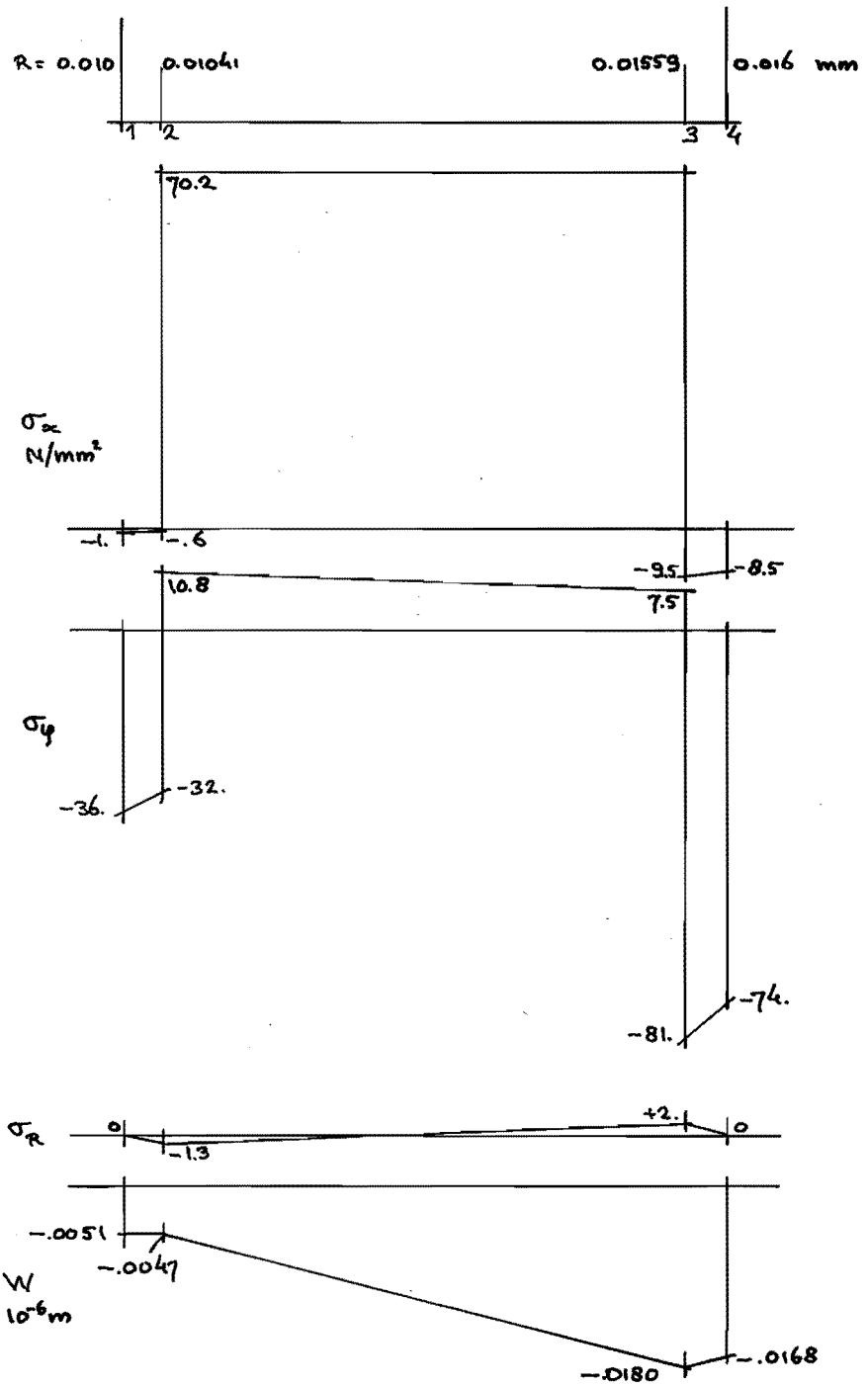


Fig. 3.17. Bamboocell. (fibres at 10^0)

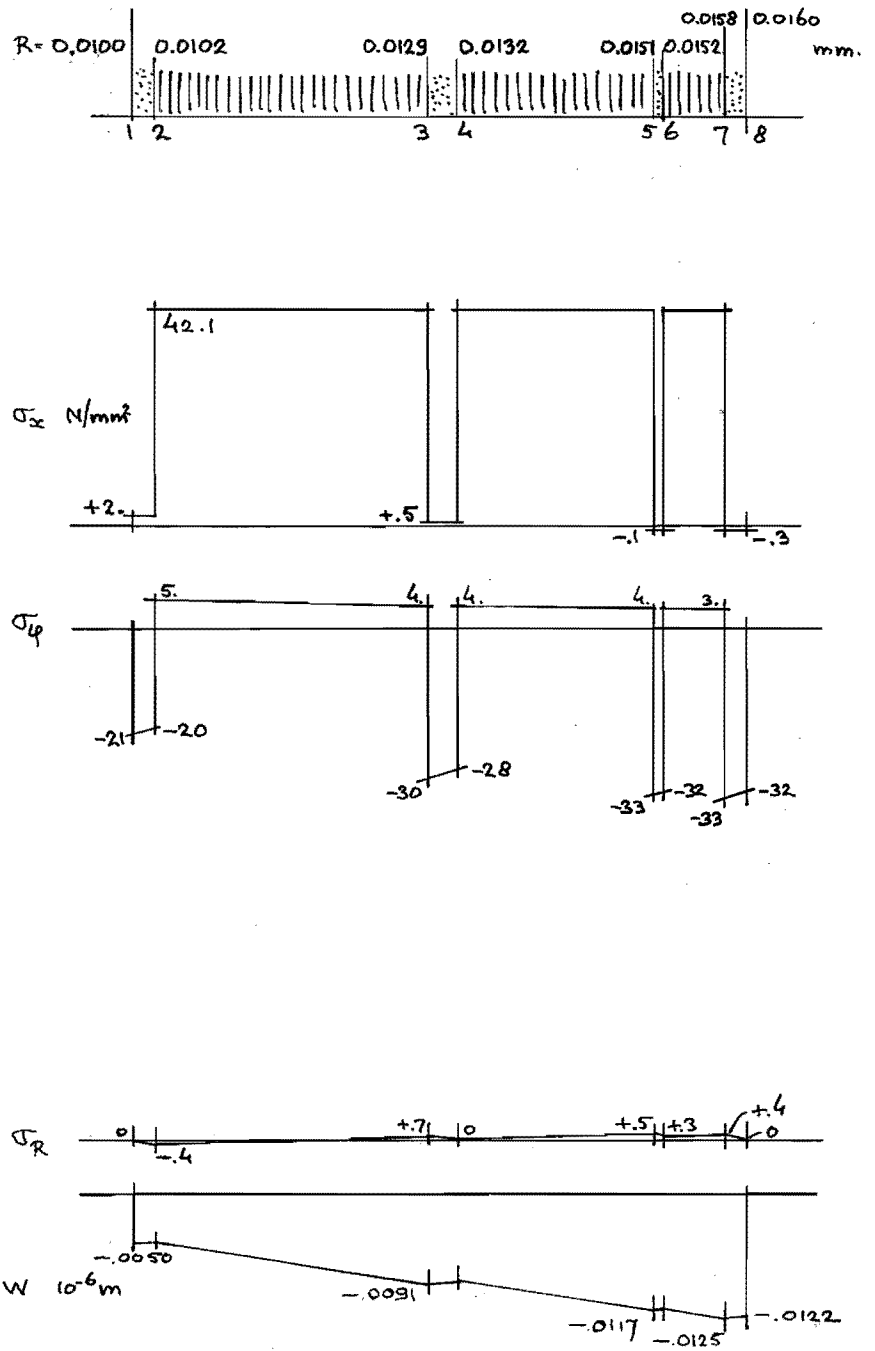


Fig. 3.18. Woodcell. (fibres at 20^{0})

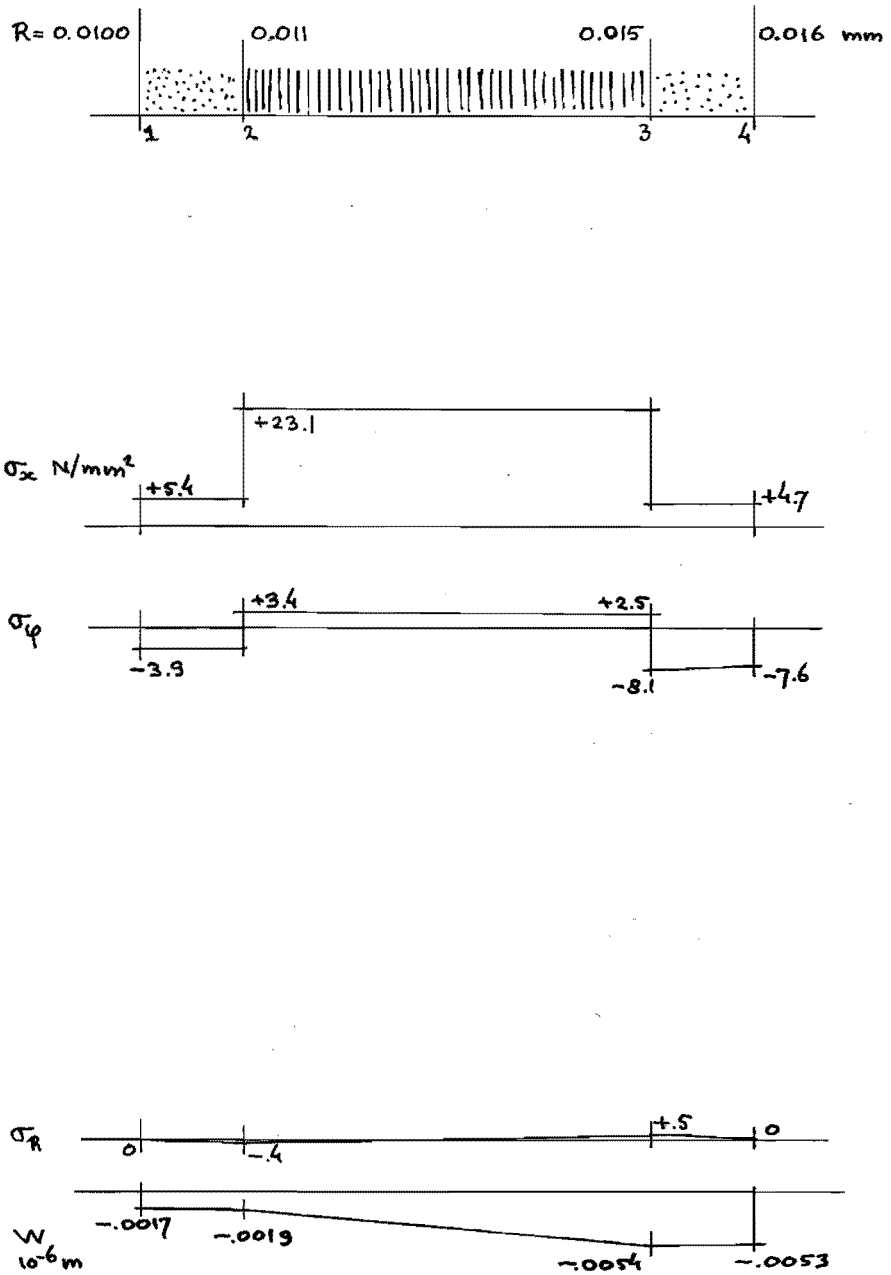
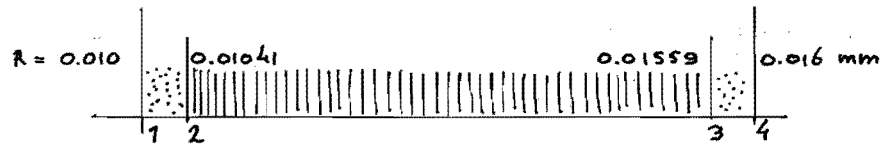
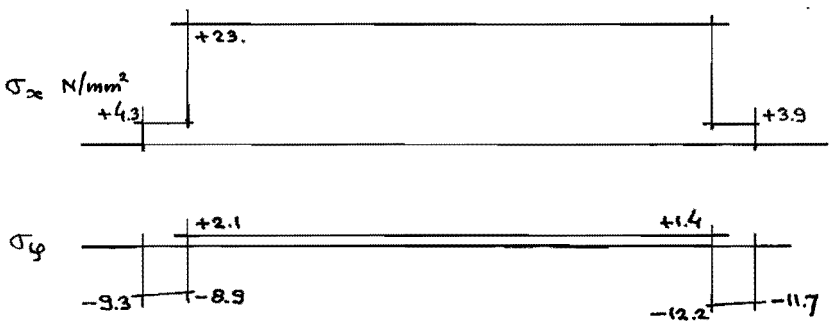
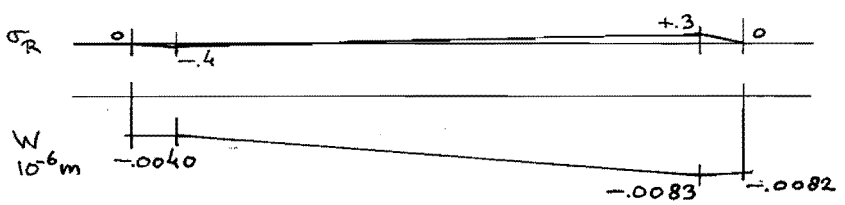


Fig. 3.19. "Special Woodcell". (fibres at 20^{o})







3.9. Verification of σ and w for all cells

3.9.1. σ_x, vertical layer

From $\varepsilon_x = 10^{-3}$ follow means of $\sigma_x = \varepsilon_x E_L$ = 70, 42 and 23 N/mm^2 respectively. In fact, the values of σ_x in the vertical layers do not differ much from these values:

70.2 (figs. 3.14., 3.15., 3.16.), 42.1 (fig. 3.17.) and 23.1 (fig. 3.18.). The explanation of these small differences is as follows.

In par. 3.5.2. the matrix (9) is given for a vertical layer. With the values

ν_{LT} = 0.20

ν_{TL} = 0.0177

ν_{TT} = 0.30

follows (for Δ, see (10), par. 3.5.2.).

$$\frac{1}{E_T^2\ \Delta} = \frac{E_L\ E_T^2}{E_T^2\quad 0.9008} = \frac{E_L}{0.9008}$$

$$\frac{1}{E_L\ E_T\ \Delta} = \frac{E_L\ E_T^2}{E_L\ E_T\ \Delta\quad 0.9008} = \frac{E_T}{0.9008}$$

and the matrix becomes

$$0.9 \begin{vmatrix} \sigma_x \\ \sigma_\phi \\ \sigma_R \end{vmatrix} = \begin{vmatrix} 0.91\ E_L & 0.023\ E_T & 0.023\ E_T \\ 0.26\ E_L & E_T & 0.3\ E_T \\ 0.26\ E_L & 0.3\ E_T & E_T \end{vmatrix} \begin{vmatrix} \varepsilon_x \\ \varepsilon_\phi \\ \varepsilon_R \end{vmatrix}$$

from which

$$\sigma_x = \frac{E_L}{0.9}\left(0.91\ \varepsilon_x + 0.023\ \frac{E_T}{E_L}\ \varepsilon_\phi + 0.023\ \frac{E_T}{E_L}\ \varepsilon_R\right)$$

$$= \frac{E_L}{0.9}\left(0.91\ \varepsilon_x + 0.002\ \varepsilon_\phi + 0.002\ \varepsilon_R\right)$$

$$\simeq 1.01\ E_L\ \varepsilon_x$$

(due to the small coefficients for ε_ϕ and ε_R)

The values calculated in the model fit within this extreme.

They are:

figure	$\bar{\sigma}_x$ vertical mean in $E_L \varepsilon_x$
3.14.	1.0024
3.15.	1.0034
3.16.	1.0024
3.17.	1.0019
3.18.	1.0024
3.19.	1.0013
mean	1.0023

in which again 0.0023 is the improvement of E_L.
So the influence of the actual spirals can be estimated as
$\frac{.0023}{.01}$ = 22 per cent of a infinitely stiff spiral.
In a vertical layer, a rule of thumb for $\bar{\sigma}_x$ is

$$\bar{\sigma}_x = E_L \varepsilon_x$$

3.9.2. $\bar{\sigma}_x$, spiral layer:
For an elongation of $\varepsilon_x = 10^{-3}$ the $\bar{\sigma}_x$ in the vertical layer is a tensile stress, and in the spiral layer in most cases a compressive stress. This is due to the high values for the compressive stress $\bar{\sigma}_\phi$ in spiral layers. Only for a low compressive stress $\bar{\sigma}_\phi$ (figs. 3.18. and 3.19., e.g.), $\bar{\sigma}_x$ in a spiral layer is a tensile stress as well.
It is possible to find a relationship between $\bar{\sigma}_x$ and $\bar{\sigma}_\phi$ in a spiral layer from the matrix, if we take $\varepsilon_x = 10^{-3}$ and if we neglect $\bar{\sigma}_R$:
(compare with the paragraph above)

$$0.9 \begin{vmatrix} \sigma_x \\ \sigma_\phi \\ 0 \end{vmatrix} = \begin{vmatrix} & E_T & 0.26 & E_L & 0.3 & E_T \\ 0.023 & E_T & 0.91 & E_L & 0.023 & E_T \\ 0.3 & E_T & 0.26 & E_L & & E_T \end{vmatrix} \begin{vmatrix} 10^{-3} \\ \varepsilon_\phi \\ \varepsilon_R \end{vmatrix}$$

The latter line yields:

$$\varepsilon_R = -0.3\ 10^{-3} - 0.26\ (E_L/E_T)\ \varepsilon_\phi$$

By substituting this in the first two lines we get:

$$\bar{\sigma}_x = 0.2\ \bar{\sigma}_\phi + 6.25\ \text{N/mm}^2$$

Verification of this rule:

fig.	radii	rule of thumb	exact
3.14.	1-2	- .3	- .5
	3-4	-6.0	-5.8
	5-6	-8.3	-8.1
3.15.	1-2	5.7	5.7
3.16.	3-4	-9.2	-9.0
3.19.	1-2	4.4	4.3

3.9.3. $\bar{\sigma}_\phi$, vertical layer

Similarly, a simple relationship between $\bar{\sigma}_x$ and $\bar{\sigma}_\phi$ in a vertical layer can be found.

Par. 3.9.1. derives:

$$\bar{\sigma}_x = 1.002\ E_L\ \varepsilon_x$$

The first line of the matrix (9) then becomes:

$$0.9\ \ 1.002\ E_L\ \varepsilon_x = 0.91\ E_L\ 10^{-3} + 0.023\ E_T\ (\varepsilon_\phi + \varepsilon_R)$$

from which

$$\varepsilon_\phi + \varepsilon_R = -.3217\ (E_L/E_T)\ 10^{-3}$$

From $\bar{\sigma}_R = 0$ follows:

$$\varepsilon_R = -.26\ (E_L/E_T)\ 10^{-3} - 0.3\ \varepsilon_\phi$$

From these two equations:

$$\varepsilon_\phi = -.09\ (E_L/E_T)\ 10^{-3}$$

$$\varepsilon_R = -.23\ (E_L/E_T)\ 10^{-3}$$

These rules of thumb fit in with the computer-output.

Proceeding with $\bar{\sigma}_\phi$:

$$0.9\ \ \bar{\sigma}_\phi = 0.26\ E_L\ 10^{-3} + E_T\ (-.09\ (E_L/E_T)\ 10^{-3}) + 0.3\ E_T\ (-.23\ (E_L/E_T)\ 10^{-3})$$

from which follows

$$\bar{\sigma}_\phi = 0.11\ E_L\ 10^{-3}$$

Check with figs. 3.14. ... 3.19.:

fig.	rule of thumb	exact
3.14.	7.7	7.6 to 11
3.15.	7.7	10.5 to 13.6
3.16.	7.7	7.5 to 10.8
3.17.	4.6	3.7 to 5
3.18.	2.5	2.5 to 3.4
3.19.	2.5	1.4 to 2.1

3.9.4. σ_ϕ, spiral layer

First, σ_ϕ in a spiral layer can be estimated from the equilibrium of forces in a radial cross section:

σ_ϕ spiral = -(V/S) σ_ϕ vertical

in which

V/S = vertical/spiral ratio in a radial cross-section; e.g. in fig. 3.14. this ratio is based on 0.0052 mm. vertical and 0.0008 mm. spiral.

Verification of this rule of thumb:

fig.	V/S	σ_ϕ spiral	
		rule of thumb	exact mean
3.17.	52/8	27	28
3.18.	4/2	5.9	5.9
3.19.	518/82	11	10.5

Next, seeing the outer spiral layer as a tube with an internal pressure σ_R you will find it rather simple to check the relationship between σ_R and σ_ϕ in this outer layer:

$$\sigma_\phi = \frac{r^2}{R^2 - r^2}\left(1 + \frac{R^2}{r^2}\right)\sigma_r = \frac{R^2 + r^2}{R^2 - r^2}\,\sigma_r$$

in which R = external radius of spiral layer,

r = internal radius

(source: Williams p. 190)

This check holds in all cases.

3.9.5. $\bar{\sigma}_R$, vertical and spiral layer

As stated before $\bar{\sigma}_R$ may be neglected. However, $\bar{\sigma}_R$ can be derived from either $\bar{\sigma}_\phi$ in each layer with the equilibrium in R-direction, as given in formula (3), or from $\bar{\sigma}_\phi$ as stated at the end of the previous paragraph. (the latter method is the best).

3.9.6. w

In par. 3.5.1. is given:

$w = \varepsilon_\phi R$, and in par. 3.9.3. is derived $\varepsilon_\phi = -.09\ (E_L/E_T)\ 10^{-3}$.

This results in

$w = -.09\ (E_L/E_T)\ 10^{-3}\ R$

From a check with figs. 3.14. ... 3.19. is seen that this rule of thumb holds rather well for the outer half of the cellwall, but not for the inner half.

3.9.7. Summary of verifications

The foregoing has shown that the stresses and displacements in a cell under axial deformation can be estimated as:

$\bar{\sigma}_{x\ vert} = E_L \varepsilon_x$ $\qquad$ $\bar{\sigma}_{\phi vert} = 0.11\ E_L \varepsilon_x$

$\bar{\sigma}_{\phi spir} = -\ (V/S)\ \bar{\sigma}_{\phi vert}$

$\bar{\sigma}_{x\ spir} = 0.2\ \bar{\sigma}_{\phi spir} + 6.25$

$$\sigma_R = \frac{R^2 - r^2}{R^2 + r^2}\ \sigma_\phi$$

in which R = outer radius spiral layer

r = inner radius spiral layer

$\bar{\sigma}_\phi = \bar{\sigma}_\phi$ spiral layer

$\bar{\sigma}_R = \bar{\sigma}_R$ on outside of vertical layer

$w = -.09\ (E_L/E_T)\ \varepsilon_x\ R$

for outer half of cellwall.

3.10. Discussion, and comparison with tests

3.10.1. The influence of the vertical/spiral ratio

This ratio is the ratio between the surfaces of the vertical and the spiral layers, in a normal cross-section (for σ_x e.g.) or in a radial cross-section (for σ_ϕ e.g.). The influence of this ratio can best be seen when comparing figs. 3.14. and 3.16. with 3.15., and similarly 3.17. + 3.19. with 3.18., i.e. the bamboocell and the spiral woodcell (with vertical/spiral ratio as in bamboo) with the normal woodcell. The only differences between these cells are σ_ϕ spiral and w. The more spiral layers there are, the lower σ_ϕ spiral is. This relationship is derived numerically in par. 3.9.4. As to w, from figs. 3.15. and 3.18. we learn that w decreases with the vertical/spiral ratio:

fig.	vertical/spiral ratio, normal	E_L	w outside
3.14.	84/16 = 5.25	70 000	-.0165
3.15.	70/30 = 2.33	70 000	-.0090
3.16.	84/16	70 000	-.0168
3.18.	70/30	23 000	-.0053
3.19.	84/16	23 000	-.0082

A numerical relationship has not yet been found.

3.10.2. The influence of the number of layers

Fig. 3.14. and 3.16. differ from each other only in the number of cell-wall layers. We learn from these figures, that the number of layers does not have any influence on the stresses and displacements.

3.10.3. The influence of the angle of the microfibrils

Due to the fact that the angle between the microfibrils and the cell axis has an enormous influence on E_L, and that E_L in its turn has a linear relationship with stresses and displacements, this angle has also influence on stresses and displacements (in the case of imposed axial deformation)

3.10.4. Tensile tests

The tensile strength of bamboo is determined by cellulose, and the theoretical tensile strength of cellulose is 1500 N/mm^2.

We may assume:
- 50% of the vertical layers to be cellulose
- 84% of the cell-wall to be vertical
- 50% of the cell to be cell-wall
- 50% of the bamboo to be sclerenchyma cells.

With these assumptions the overall tensile strength of bamboo is:
1500 0.5 0.84 0.5 0.5 = 160 N/mm^2, a fairly good figure, because it agrees roughly with test results.

As to wood, we learn from figs. 3.17. and 3.18. that under the same axial deformation the overall tensile stresses in the vertical layers are 42 N/mm^2 for bamboo and 23 N/mm^2 for wood, due to the different angles between microfibrils and cell-axis. This means that the overall tensile strength in wood is 23/42 = 55 per cent of that in bamboo.
Next, in wood only 70 per cent of the cell wall is vertical, compared with 84 per cent in bamboo. So we might estimate the overall tensile strength of wood as 160 N/mm^2 0.55 (70/84) = 73 N/mm^2., a fairly good figure for softwood.

However, it is still not possible to use this model to explain the failure of fibres in tensile tests. For this purpose we require microscopic photographs of fibres after failure, plus the dimensions of the cell and the cell-wall layers, the angles between microfibrils and cell axis, the ultimate strength and strain, etc.
Unfortunately, such data are not available for bamboo, and for wood only a few reports (e.g. Saiki a.o., 1972; Mark and Gillis 1970), have been published, but they do not contain all data required.

3.10.5. Compression

The compression strength of bamboo and wood can be estimated by calculating the buckling strength of the vertical layer in a single fibre.
$P_k = \pi^2 EI/L^2$

Calculation	bamboo	wood
E in N/mm^2	42 000	23 000
$I = \pi(R^4 - r^4)/4$		
R in mm	.0158	.015
r in mm	.0102	.011
I in mm^4	4 10^{-8}	2.8 10^{-8}
L of fibre in mm	3.5	3.5
P_k in N for —▸◂—	1.4 10^{-3}	0.5 10^{-3}

Assuming a 1000 cells per mm^2, the overall compression strength becomes 1.4 and 0.5 N/mm^2. However, the compression strength is in fact 80 and 40 N/mm^2 respectively. This means that the overall compression strength cannot be explained by the buckling strength of a single fibre. Naturally, the fibres cooperate: they are placed quite near each other and they stick together with pectin. It can be simply shown that buckling of fibres results in shear stress in the pectin, and this increases the buckling strength considerably. Due to lack of both knowledge of the mechanical properties of pectin and (to lack of) a mathematical model (including instability, and the undulating form of the warty layer!) a numerical calculation of this influence is still impossible. Besides, shear will occur not only in the pectin, but also in the outer spiral layers (S 0 and S 1) In fact, in compression we like to do the same as in tension: to explain the behaviour of a fibre, especially the failure in compression due to the tensile stresses in the spiral layers. But here too data on tests are missing.

3.10.6. Coefficient of Poisson

The coefficient of Poisson in tangential direction is:

$$\nu_{LT} = \frac{\text{contraction in direction T}}{\text{extension in direction L}} \text{ under stress in direction L}$$

in which T = tangential and L = longitudinal.

In the model, this ν on the outer skin of the cell is determined as

$$\nu_{LT} = \frac{\varepsilon_T}{\varepsilon_L} = \frac{\varepsilon_\phi}{\varepsilon_x} = \frac{w/R}{10^{-3}} = \frac{1000 \quad w}{R}$$

For wood (fig. 3.18.) w = -.0053 10^{-3} mm and R = 0.016 mm,

and thus ν_{LT} = 0.33 for a single fibre.

However, in literature (e.g. Kollmann p. 298) ν_{LT} = 0.49 (st.d.0.06)

An explanation for this difference is not known.

For bamboo, the results fit better:

$$\nu_{LT} = \frac{1000 \quad 0.0122 \quad 10^{-3}}{0.016} = 0.76 \text{ for a single fibre.}$$

Assuming as mean values:

- 60 per cent fibres in the outside of bamboo
- 20 per cent fibres in the inside of bamboo
- ν = 0.30 for the lignin

an overall value can be calculated:

- outside: ν_{LT} = 0.6 0.76 + 0.4 0.3 = 0.58
- inside : ν_{LT} = 0.2 0.76 + 0.8 0.3 = 0.39

and these mean values fall within the same range as the measured mean values of 0.51 and 0.31 respectively (see chapter 4.8.).
This confirms the reliability of the model.

3.11. Conclusions

1. In this chapter a mathematical model is created to describe the mechanical behaviour of a sclerenchyma cell under axial deformation in the elastic area.
2. Simple rules of thumb were given for a quick estimate of stresses and deformations (par. 3.9.), but with less accuracy.
3. The coefficient of Poisson for bamboo can be derived with this model; the results fit with the tests. Similarly, the tensile strength for bamboo and wood can be derived.
4. Some conclusions on the mechanical behaviour:
   - the stiffness of the spiral layer on the inside and the outside of the cell can be estimated as 22 per cent of an infinitely stiff spiral.
   - Contrary to the ratio between vertical and spiral layers, the number of cell wall layers does not have any influence on the mechanical behaviour.

3.12. What remains to be done

1. Most essential: the collection of data on tests on fibres, and comparison of these data with the results of the model.
2. Improvement of the model, inserting in the input the correct angles between microfibrils and cell axis, and the correct chemical composition, both different for each layer, and in the output the calculation of the stresses in the microfibrils and in the matrix-material.
3. Collection of mechanical data on cellulose, lignin and pectin.
4. Verification as to whether shear should be taken into account or not. As stated by Schniewind and Barrett:
   "When wood is regarded as a composite of single cells cemented together by the middle lamella, the twisting of cells is effectively restrained. This is caused by the fact that if adjacent cells tend to twist in the same sense, adjacent wall sections would have to undergo circumferential displacements in opposite directions. If the middle lamella has any inherent stiffness, this is clearly impossible. Hence, we will assume that there is complete shear strain restraint so that normal stresses parallel to the cell axis will cause only normal strains".
   But can this assumption be supported quantitatively?

3.13. Addition

After the completion of this chapter I came across two references on this subject. The first is:

Jacek Stupnicki,

Analysis of the behaviour of wood under external load, based on a study of the cell structure. Acta Polytechnica Scandinavia, Civil Engineering, no. 53. Trondheim 1968. 50 + 15 pp.

This author builds a model of several wood cells. This model contains one full annual ring of wood, as to take into account the differences between earlywood and latewood. So the size of the model in radial direction is the width of one annual ring. The sizes in longitudinal and tangential directions are unity. The dimensions of cells and cellwalls are taken from micrographs. The cellwalls in the model are built up with two materials: a material A with E = 200 000 N/mm^2 and G = 70 000 N/mm^2, constituting a load carrying frame, corresponding to the middle lamella, and a material B with E = 570 N/mm^2 and G = 285 N/mm^2, as a filling material, corresponding to the remaining cell wall layers.With these values, overall values for E and G are calculated in three directions; these theoretical values agree very well with the real values for wood. In this model he has calculated the buckling behaviour under a longitudinal compressive force, for the parameters:

- symmetric or asymmetric buckling of cell walls,
- perfect or weak bond between frame and filler, or local separations,
- the inclination of the destruction zone.

The minimum value of the critical stress is reached for asymmetric buckling, local separations, and an inclination of 45^o - 50^o.These fit with observations by microscope. Unfortunately, the average critical stress is ten times the real maximum crushing stress of wood. He assumes, that his model is too regular: in fact wood is irregular (cell walls are corrugated, they have cavities and pits, etc.)From a comparison of his model and mine we learn, that his model is a good method to study buckling of cell walls, whereas my model gives stresses in the cell walls, and deformations. Perhaps in future his model might be adopted to study buckling in bamboo cells.

The second reference is:

Barret, J.D. and Schniewind A.P.

Three-dimensional finite element models of cylindrical wood cells. Wood and Fiber (1973) pp. 215 - 225.

These authors have built a finite-element model of a wood cell, and the resulting strains and stresses agree well with a closed form solution and even with a two-dimensional model. The latter model, however, is incapable of predicting radial stresses and it can be adopted to thin-walled cells only.

3.14. Literature

Barrett, J.D. and Schniewind A.P. — Three-dimensional finite element models of cylindrical wood cells. Wood and fiber (1973) pp. 215-225.

Cousins, W.J. — Elastic Modulus of Lignin as Related to Moisture Content. Wood Science and Technology vol. 10 (1976) p. 9 -17.

Greszcuk, L.B. — Elastic constants and analysis methods for filament wound shell structures. Missile systems engineering, Douglas Aircraft Company (1964)

Jones, R.M. — Mechanics of Composite Materials. Mc Graw Hill (1975)

Kollmann and Côté, — Principles of Wood Science and Technology. Berlin 1968.

Lekhnitskii, S.G. — Theory of elasticity of an anisotropic elastic body. Holden-Day 1963.

Liese,W.and Grosser,D. — Untersuchungen zur Variabilität der Faserlänge bei Bambus. Holzforschung (1972) pp. 202-211.

Mark, R.E. — Cell Wall Mechanics of Tracheids. Yale University Press (1967)

Mark, R.E. and Gillis P.P. — New Models in Cell Wall Mechanics. Wood and Fiber vol. 2 (1970) no. 2 pp. 79 - 95.

Mark, R.E. and Gillis P.P. — The relationship between Fiber Modulus and S_2 angle. Tappi, vol. 56 (1973) no. 4 pp. 164 - 167.

Panshin and De Zeeuw — Textbook of Wood Technology, New York 1970. Cited page 71.

Parameswaran,N and Liese W. — On the Fine Structure of Bamboo Fibres. Wood Science and Technology, vol. 10 (1976) pp. 231-246.

Preston,R.D. and Singh, K. — The fine structures of bamboo fibres. Journal Exper. Botany (1950) pp. 214-230.

Saiki,H. a.o. — An observation on tensile fracture of wood by scanning electron microscope. Bulletin Kyoto University. Forestry (1972) no. 43, pp. 309-319.

Siau, J.F. — Flow in Wood. Syracuse 1971.

Schniewind, A.P. and Barrett J.D. — Cell Wall Model with complete shear restraint. Wood and Fiber (1969) pp. 205-214.

Schwartz R.T. and Schwartz H.S. — Fundamental Aspects of Fiber Reinforced Plastic Composites. New York (John Wiley) 1968.

Stupnicki, Jacek — Analysis of the behaviour of wood under external load, based on a study of the cell structure. Acta Polytechnica Scandinavia, Civil Engineering, no. 53.Trondheim 1968. 50 + 15 pp.

Williams, J.G. — Stress Analysis of Polymers. Longman 1973.

3.15. Appendix

Determination of E_T of composite

As cross-section is assumed:

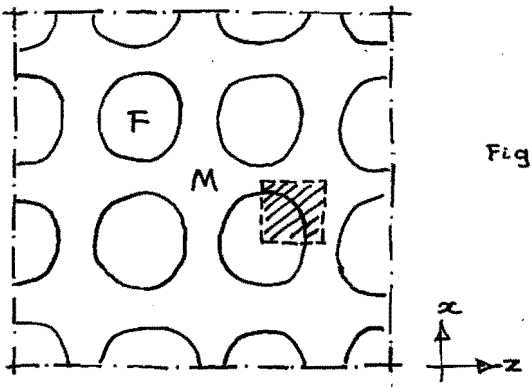


Fig. 3.20

Assumptions:

1. The circles F are the microfibrils, for which a circular cross-section is assumed. In fact the cross-section is rectangular, and the distribution is irregular.
2. The matrix material M is the lignin. Assumed are: 50 per cent. cellulose (= microfibrils) and 50 per cent. lignin.
3. The number of microfibrils is assumed large enough to neglect the influences of the boundaries between cell wall layers.

For the determination of E_T one elementary square piece is taken from fig. 3.20. because of the symmetry. This square is represented enlarged in fig. 3.21.:

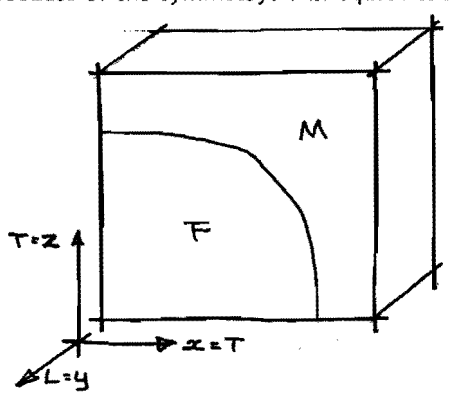


Fig. 3.21.

For the y-axis the assumption "plane strain" is made because of the large E_{FL} = 137 000 N/mm^2. Material-properties in x- and z-direction:

- F: E_{FT} = 27 700 N/mm^2

  ν = 0.3 (this value is unknown; ν = 0.3 is an assumption; if ν = 0.1 it turns out that the influence of this difference on E_T is less then one per cent.).

- M: E = 2 040 N/mm^2

  ν = 0.3

Boundary-conditions at the four edges:

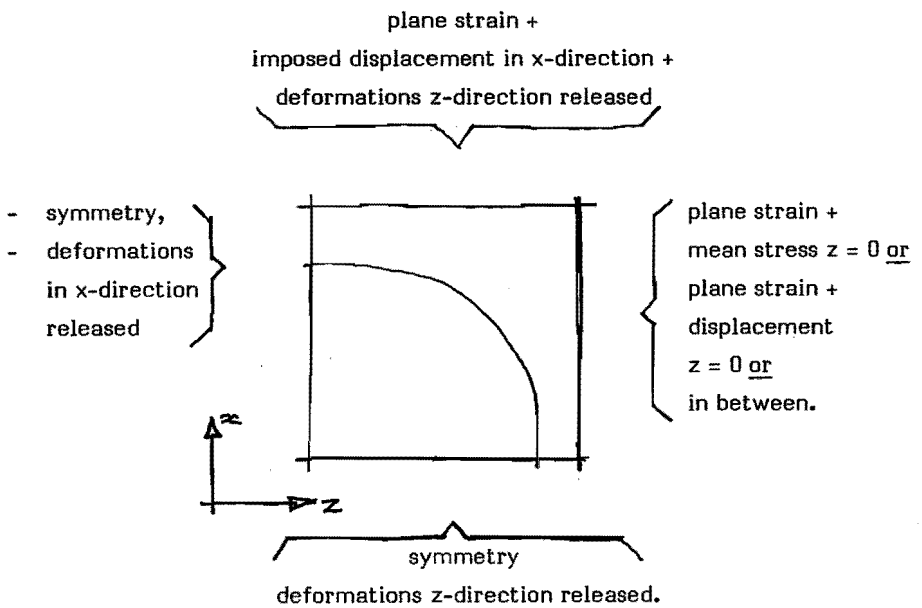


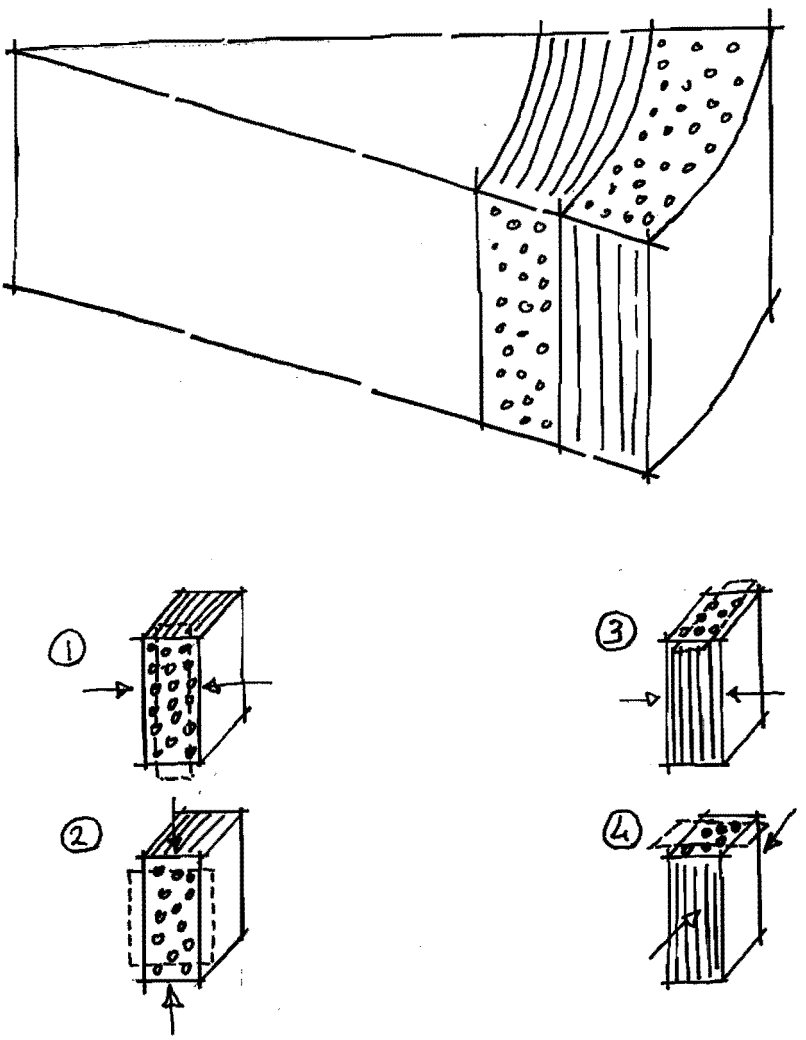
Fig. 3.22.

The E_T is the ratio of the mean stress and the displacement in x-direction. As to the right edge, boundary conditions will vary between:

- plane strain + mean stress = 0 (i.e. mean stress in z-direction is zero, and this edge remains straight, otherwise the pieces cannot fit togehter; the edge displaces in z-direction over a constant)
- plane strain + no deformation in z-direction.

To decide on this choice, four possible situations must be studied: (see fig. 3.23.)

Fig. 3.23.



(1) -spiral layer, imposed displacement radial,
(2) -spiral layer, imposed displacement axial,
(3) -vertical layer, imposed displacement radial,
(4) -vertical layer, imposed displacement tangential.
Only the no. 2 is presented in the result of the model, see fig. 3.14.: the radial stress is about zero under axial displacement. So for case no. 2 "plane stress" is the correct boundary condition. For the other three it is for the moment impossible to estimate which condition should prevail.

With finite element-method the E_T has been calculated:
- E_T = 6200 N/mm^2, mean stress = 0 plus plane strain,
- E_T = 7000 N/mm^2, plane strain plus displacement = 0.

In fig. 3.10. and 3.11. the influence of this difference on the radial displacements of the cell wall and on the stresses in the cell wall has been plotted. E.g. the largest influence on stresses occurs for σ_ϕ in the outside (radius 8); σ varies between 67 and 72 N/mm^2. From fig. 3.14. it can be seen that this difference does not have any significant influence on the conclusions in par. 3.11.

Therefore I have chosen to carry out all calculations with E_T = 6200 N/mm^2. In my opinion more accuracy in data (on microfibrils, their form, pattern, properties, etc.) is needed first, before efforts are made to improve the model from a mechanical point of view. The purpose of this chapter is to build a bridge between the biological structure of the bamboo and its mechanical properties. This purpose will be served better with more accuracy in data first, after which the model can be improved with profit. The finite element method is the proper tool to handle with the data resulting from clear electron-microscopic photographs.

For this moment we should keep in mind that in a natural fibre the range in properties is larger than the range between 6200 and 7000 N/mm^2, and the resulting differences in stresses in the cell wall. Therefore a further mathematical treatment now might suggest a greater accuracy than we would expect from the variations in biological structure.

Chapter 4

MECHANICAL PROPERTIES

Contents

		page
4.1.	Introduction	76
4.2.	An example of a statistical model	76
4.3.	The chosen factors that influence the properties	83
4.4.	Compression	85
4.5.	Bending	109
4.6.	Shear	127
4.7.	Tension	139
4.8.	Poisson's ratio	141
4.9.	Weight by volume; MC versus RH	143
4.10.	References	145
4.11.	Appendix	149

4.1. Introduction

Tests on the mechanical properties of bamboo are necessary to discover the range of applications of this material. For a better understanding, however, one needs both an interpretation of the results by a statistical analysis and a relationship between strength properties and the biological composition of the bamboo. The determination of stresses (for bending, shear, etc.) will allow the study of the effects of the biological structure of bamboo on one hand and on the other hand it will give insight into the range of applications in building structures.

An immediate problem with bamboo is the fact that the first standard on this material appeared in the Indian Standard 6874 as late as 1973. So, before 1973, each researcher tended to postulate his own criteria and developed his own testing-methods, which renders the comparison of results extremely difficult. But if bamboo is to be given an equivalent place among other building materials, one should promote both a standardization of tests methods, a thorough knowledge of the mechanical properties of bamboo and the effect of physical and biological properties on them.

With this series of tests I hope to contribute to the development of bamboo used as a construction material.

After the paragraphs on compression, bending and shear, conclusions follow on the:

- biological effects, which invariably occur, namely:
  1. percentage sclerenchyma fibres;
  2. weight by volume (i.e. cell-wall thickness):
- biological effects, from which one can make his choice:
  3. moisture content; (= MC)
  4. position along the culm
  5. node or internode in the specimen
- effects, chosen by man:
  6. form and size of specimen.
- 7. other effects.

Recommendations for further research will be given as well, but recommendations for standardization and for practical use will be given in chapter 6.

4.2. An example of a statistical model

This research programme starts from a statistical testing scheme enabling to test moisture content and other physical or biological factors together, and calculating the influence of every single factor by an analysis of a linear model.

If e.g. the results of a series of tests look like in fig. 4.2.1. the purpose of the statistical method is to find a mathematical relationship between the physical factor and the test results, e.g. the curved line.

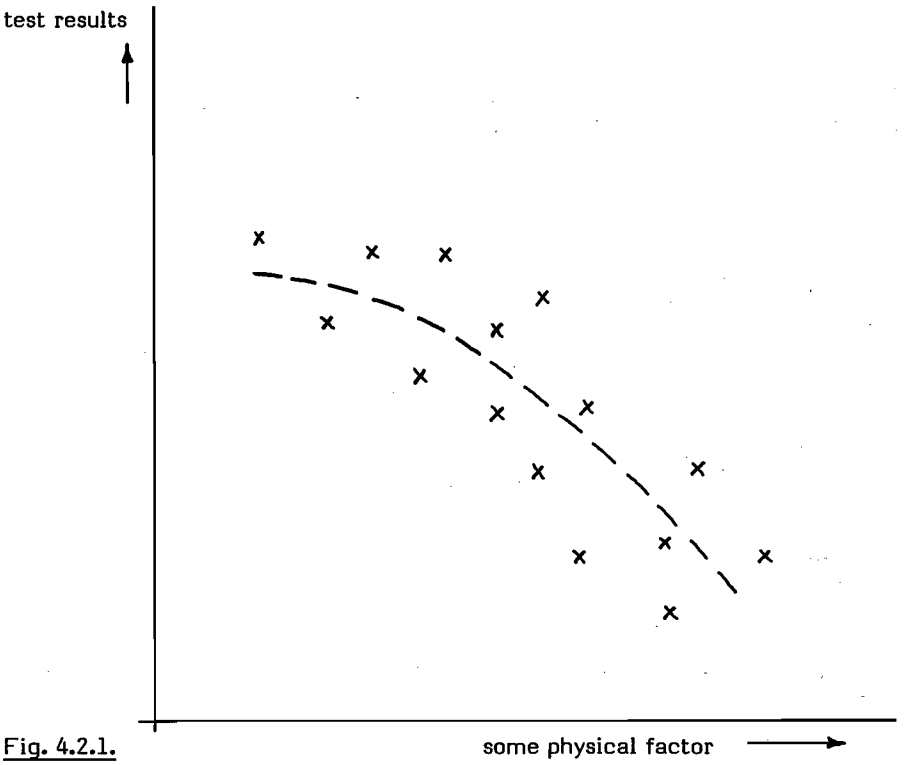


Fig. 4.2.1.

For those who are not familiar with this kind of statistics, the theory of linear models will be explained briefly, followed by a simple numerical example.
It is assumed that a linear model can describe the influences of physical and biological factors on a mechanical property.
In formula:

$$\underline{y} = \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_k x_k + \underline{e}.$$

in which

$\underline{y}$	=	the estimated value of the mechanical property, e.g. ultimate compression stress.
β_i	=	a parameter, to be estimated,
x_i	=	a coefficient, chosen in the test scheme,

$\beta_i x_i$ = the influence of a physical or biological factor (e.g. MC, node or internode) on the mechanical property.

β_1 = the constant; in a fully correct (i.e. orthogonal) test scheme this constant equals the mean value, otherwise it differs slightly from the mean.

x_1 = 1, per definition

$\underline{e}$ = the random error.

If the mechanical property is observed n times, then we might describe them all as:

$$\underline{y}_1 = \beta_1 x_{11} + \dots + \beta_k x_{1k} + \underline{e}$$
$$\underline{y}_2 = \beta_1 x_{21} + \dots + \beta_k x_{2k} + \underline{e}$$
$$\vdots$$
$$\underline{y}_n = \beta_1 x_{n1} + \dots + \beta_k x_{nk} + \underline{e}$$

In order to get reasonable accurate estimates for the parameters n should be considerably larger than k.

In matrix-notation:

$$\underline{y} = X\beta + \underline{e}$$

in which

$\underline{y}$ = a vector, size n, containing all observed mechanical properties, i.e. the test results.

X = a matrix of size n by k, containing all x-values, see later,

β = a vector, size k, has to be estimated,

$\underline{e}$ = a vestor, size n, the random error.

These equation will be solved by the least squares-method, i.e. the parameters $\beta_1 .. \beta_k$ should be estimated in such a way that

$$\sum_{i=1}^{n} (y_i - \beta_1 x_{i1} - \dots - \beta_k x_{ik})^2 = \sum e_i^2$$

is a minimum.

The same in matrix-notation:

$(y - X\beta)' (y - X\beta)$ is a minimum or after differentiating:

$- 2X' (y - Xb) = 0$

in which b is the vector of the estimated values from which

$b = (X'X)^{-1} X'y$

It can be proved that this b is a good value to estimate β.

A simple numerical example: we like to test the compression strength, in connection with the influence of moisture content (MC) at three levels, say 4, 8 and 12 per cent, and the influence if a node is present in the specimen, or if the specimen is an internode. Because each combination of influences should be represented by at least one specimen, we need at least 3 x 2 = 6 specimens, but to improve accuracy 12 specimens are tested.

To simplify calculations, the coefficients x are coded:

MC	x_2	x_3
4	-1	1
8	0	-2
12	1	1

so $x_1 = (MC - 8)/4$

$x_2 = 3x_1^2 - 2$

N/I	x_4
N	-1
I	1

and finally the interactions:

$x_5 = x_2 x_4$

$x_6 = x_3 x_4$

The result is the next table, with the matrix X and the (imaginary) testresults y in N/mm^2:

MC	N	x_1	x_2	x_3	x_4	x_5	x_6	Y
4	N	1	-1	1	-1	1	-1	80
4	N	1	-1	1	-1	1	-1	85
8	I	1	0	-2	1	0	-2	82
8	I	1	0	-2	1	0	-2	79
12	N	1	1	1	-1	-1	-1	70
12	N	1	1	1	-1	-1	-1	75
4	I	1	-1	1	1	-1	1	89
4	I	1	-1	1	1	-1	1	82
8	N	1	0	-2	-1	0	2	74
8	N	1	0	-2	-1	0	2	81
12	I	1	1	1	1	1	1	81
12	I	1	1	1	1	1	1	82

The calculations are:

$$X'X = \begin{pmatrix} 12 & 0 & 0 & 0 & 0 & 0 \\ 0 & 8 & 0 & 0 & 0 & 0 \\ 0 & 0 & 24 & 0 & 0 & 0 \\ 0 & 0 & 0 & 12 & 0 & 0 \\ 0 & 0 & 0 & 0 & 8 & 0 \\ 0 & 0 & 0 & 0 & 0 & 24 \end{pmatrix} \quad X'y = \begin{pmatrix} 960 \\ -28 \\ 12 \\ 30 \\ 12 \\ 12 \end{pmatrix}$$

$$b = (X'X)^{-1} X'y = \begin{pmatrix} 80 \\ -3.5 \\ 0.5 \\ 2.5 \\ 1.5 \\ 0.5 \end{pmatrix} = \begin{pmatrix} \hat{\beta}_1 \\ \hat{\beta}_2 \\ \hat{\beta}_3 \\ \hat{\beta}_4 \\ \hat{\beta}_5 \\ \hat{\beta}_6 \end{pmatrix}$$

and so the equation is now:

$$\underline{y} = 80 - 3.5\, x_2 + 0.5\, x_3 + 2.5\, x_4 + 1.5\, x_5 + 0.5\, x_6$$

If one likes to know the estimated ultimate compression stress for e.g. MC = 4 per cent and internode, this equation gives:

$$\underline{y} = 80 - 3.5(-1) + 0.5\,(+1) + 2.5\,(+1) + 1.5\,(-1) + 0.5\,(+1) = 85.5\ N/mm^2.$$

The relationship between $\underline{y}$ and $\hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \hat{\beta}_3 x_3$ is plotted in fig. 4.2.2. (without physical reality!!)

The next step is: is it possible to simplify this model? E.g. in view of the small differences between the curved line $\hat{\beta}_2 x_2 + \hat{\beta}_3 x_3$ and the straight line $\hat{\beta}_2 x_2$, perhaps the straight line on its own could be accurate enough. For this judgement a criterion is needed. See figure 4.2.3.

The "error" between the model "curved line" $\hat{\beta}_2 x_2 + \hat{\beta}_3 x_3$ and the test results (the little crosses) is SSE_2 = sum of square of error = $a_2^2 + b_2^2 + c_2^2 + d_2^2 + \text{etc.}$ and the "error" between the model "straight line" $\hat{\beta} x_2$ and the test result is $SSE_1 = a_1^2 + b_1^2 + c_1^2 + d_1^2 + \text{etc.}$

If $\hat{\beta}_3 x_3$ really contains valuable information, than SSE_2 must be smaller than SSE_1. The more the difference $SSE_1 - SSE_2$ increases, the more important is $\hat{\beta}_3 x_3$. Because the statistics cannot prove the hypothesis: "x_3 has influence", the so-called null-hypothesis is checked: "x_3 has no influence" or "$\hat{\beta}_3 = 0$".

For this check the null-hypothesis "$\hat{\beta}_3 = 0$" is assumed to be true. If this hypothesis is true, then the variance σ^2 can be estimated from two sources with the same result, i.e. from the complete model, and from the difference $SSE_1 - SSE_2$, or

- σ^2 can be estimated as $s_2^2 = SSE_2^2/(n-k)$
- σ^2 can be estimated as $s_3^2 = (SSE_1^2 - SSE_2^2)/(k-g)$

Fig. 4.2.2.

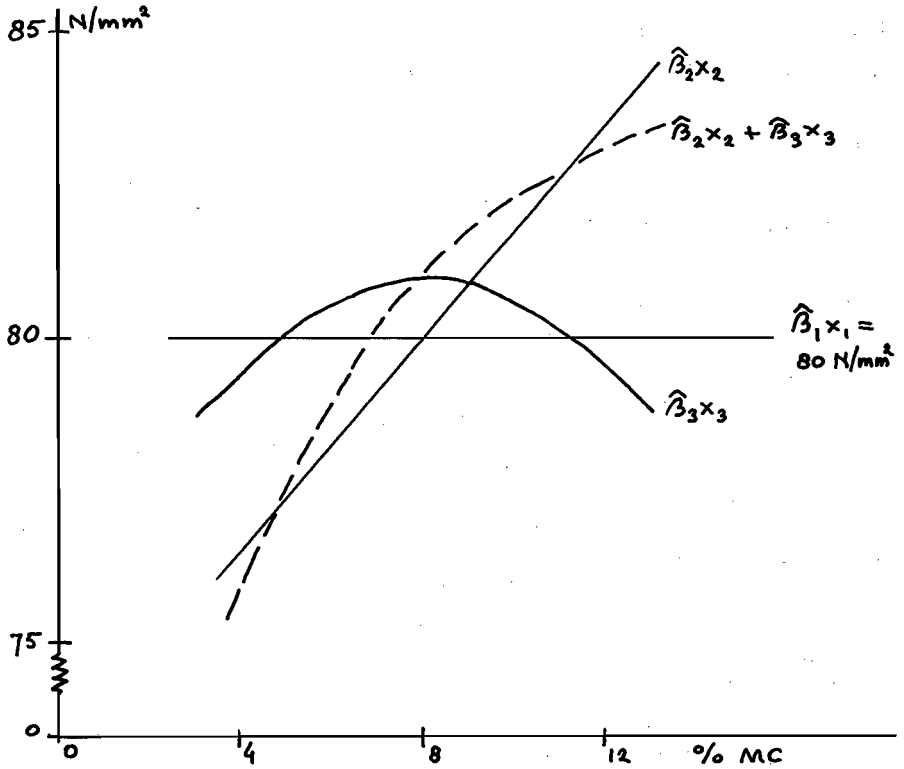
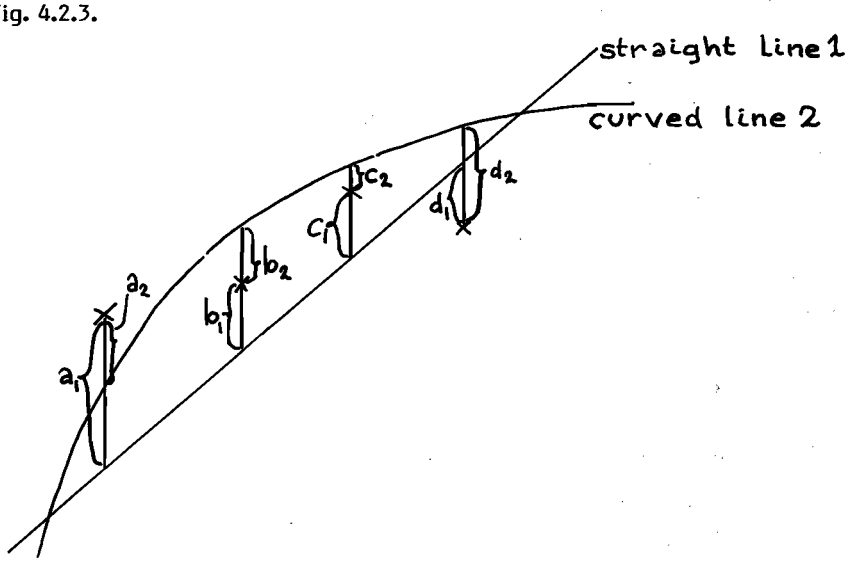


Fig. 4.2.3.



in which:
n = number of tests,
k = number of parameters in complete model,
g = number of parameters in simplified model.

The criterion is now:

$$F = s_3^2/s_2^2$$

and if $\hat{\beta}_3 = 0$ is true, then we will F expect to be about = 1, or at least not to differ to much. On the other hand, if the null-hypothesis is not true, then σ^2 estimated by s_2^2 from the complete model still will do, but s_3^2 will be inflated because $SSE_1^2 - SSE_2^2$ is too large. So, for large values of F we reject the null-hypothesis and in such a case the alternative hypothesis "$\hat{\beta}_3$ has influence" is accepted.
In the numerical example is $SSE_2 = y'y - b'X'y = 77082 - 77003 = 79$ with $n - k = 12 - 6 = 6$.
With the null-hypothesis

$$\beta_3 = \beta_5 = \beta_6 = 0$$

$SSE_1 = 77082 - 76973 = 109$ with $k - g = 6 - 3 = 3$ and

$$F = \frac{(109 - 79)/3}{79/6} = 0.76$$

To decide if F is considered as large, one has to look into any statistical handbook, where tables for critical values of F are given.
As usual in technical sciences, we choose the table with the probability level $\alpha = 0.05$, and read $F_6^3(\alpha = 0.05) = 4.76$.
The found value 0.76 is smaller, so the null-hypothesis is accepted and the model can be simplified to

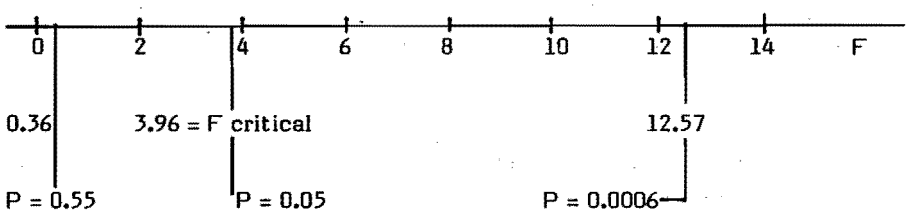
$$\hat{y} = 80 - 3.5\, x_2 + 2.5\, x_4$$

or

$$\hat{y} = 80 - 3.5\,(MC - 8)/4 + 2.5\, x_4$$
$$= 84.5 - 0.875\, MC \text{ in case N and}$$
$$= 89.5 - 0.875\, MC \text{ in case I.}$$

Finally, the comparison of the calculated F with F critical has as disadvantage, that F-values in one table should be compared with $F_{88}^{1} = 3.96$ and in another table with $F_{36}^{4} = 2.65$. For the ease of the reader in this thesis the p-value is used, i.e. the probability that any value could be greater than the calculated value.

An example from table 4.4.4.:



F = 12.57 is the F-value for $\hat{\beta}_2$; F is large and this rejects the null-hypothesis that $\hat{\beta}_2$ has no influence; the alternative hypothesis "$\hat{\beta}_2$ has influence" is accepted.

F = 0.36 is the F-value for $\hat{\beta}_3$; this F is small, and so is accepted "$\hat{\beta}_3 = 0$" (note: this is no prove! e.g. in case of more tests this could change).

So the alternative hypothesis "$\hat{\beta}_i$ has influence" is accepted for $F > F$ critical (different in each table) or for $p < 0.05$ (which is the same in all tables).

Ref.: Mendenhall (1968), mainly chapters 3,6 and 8.

Note in this chapter, calculations are made with a computer-program.

4.3. The chosen factors that influence the properties

In testing the mechanical or physical properties of bamboo, one comes across a series of biological or other effects on such properties. An overall survey of the effects in this study is as follows:

1. Species and age.
   In the testing programme these variables are taken constant. The species named Bambusa blumeana from the Philippines, has been cut at an age of three years, and boiled in seawater and/or sprayed with PCP (= pentachlorophenol) for preservation. After shipment to Holland, the bamboo was stored at 70 ± 5 per cent R.H. and at 295K ± 2 (= 22°C ± 2°).
2. Green or conditioned.
   The bamboo has been conditioned, i.e. dried until the moisture content is in equilibrium with the air (70 % R.H.). (Note: green bamboo is freshly cut, MC = 60 to 100%)

3. Moisture content.
   Most test series were carried out with three different moisture contents, i.e. 4.2, 8.6, or 11.8 per cent by weight, in equilibrium with 30, 50 or 70 per cent R.H. of the air.
4. Form and size of the specimen.
   This means e.g. a full or a split bamboo in compression or bending; or the height of the specimen in compression, etc. The circumstance of the cross-section not being a perfect circle and the bamboo being curved was left out of consideration.
5. Node or internode;
   with node means "the specimen contains a node", otherwise it is cut from an internode; see fig. 4.3.1.

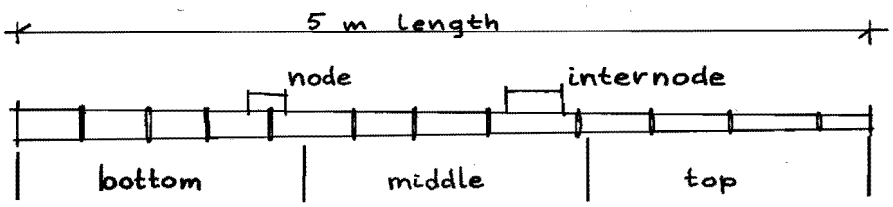


Fig. 4.3.1. (Inter)node, bottom, middle, top.

6. Position along the culm, see fig. 4.3.1.
   To keep the testprogramme simple, specimens were taken from three positions only, bottom, middle or top.
   The position along the culm gives more relevant information than the wallthickness does, because the percentage of sclerenchyma increases from bottom to top.
7. Testing speed. (taken as a constant).
   As far as possible, the speed corresponds with the ASTM- or DIN-standards for timber, or the Indian Standard for bamboo.
8. Short or long-term loading.
   In each paragraph details concerning these influences are dealt with, and sometimes other effects are compared with the tests by other authors. It must be emphasized, that the purpose of our tests is not to determine the mean strength of the bamboo in our stock, but to determine which influences are significant when determining the strength.

N.B. The mass per volume is not mentioned here, because it cannot be chosen as parameter; however it plays an important role when discussing test results.

4.4. Compression

4.4.1. Introduction

Tests on the ultimate compression stress of bamboo have been carried out by several authors. A summary is given in table 4.4.1. The use of this table is to give a quick reference.Other surveys are published by Narayanamurti, and by Sekhar and Bhartari (1960). They are usefull for an overall introduction. A list of factors that have influence on the compression strength has already been given in par. 4.3.

The next paragraphs report on tests on:

- the compression strength of full bamboo;
- idem of split bamboo.

4.4.2. Compression strength of full bamboo

Procedure

The variables given in par. 4.3. are specified as follows:

- species and age: B. Blumeana, three years.
- conditioned
- M.C.: 4,8 and 12 per cent
- form and size of specimen: full bamboo, height 50, 100 and 200 mm. resp.,
- node and internode,
- position along the culm: specimens from bottom, middle and top of culm,
- the stems from which the specimens are cut (a necessary variable for the correctness of the model only).

  To cover each combination, we would need 3 (M.C.) x 3 (height) x 2 (node) x 3 (position) = 54 specimens to be tested. In fact 106 are used, unfortunately not quite evenly distributed to all combinations. The test scheme is not fully orthogonal. The linear model, with which the results have been described, contains 18 parameters. In this way 106 - 18 = 88 degrees of freedom are left, which is sufficient.

Tests.

The specimens were sawn from three culms. This could be a problem if the purpose would have been to determine the mean strength, but the purpose was to detect which factors are significant when determining the strength. The height of the specimens was 50, 100 and 200 mm. resp., the diameter varied from 70 to 90 mm, and the wall thickness from 5 to 9 mm. The roughness of the surfaces in contact with the press was 0.004 mm, according to DIN 52185-1, which prescribes 0.02 mm. for timber.The compression tests were carried out with a hydraulic press, capacity 200 kN, machine-error 0.5 per cent (see picture 4.4.2.).

Table 4.4.1. Summary of literature on compression.

Author	Species	Specimen (size in mm)	MC %	NO of tests	Ultimate compression stress N/mm^2 mean	st.d.	Remarks
Meyer and Ekelund	-	~ 127 / 127	-	4	44	-	Nodes at Several places
Espinosa	Bambusa Spinosa Roxburgh	61 / 356	-	53	57	13	-
Mc Clure	B.Tuldoides	47 / 305	-	21	35	8	-
Glenn	Phyll. Bambusoides	153	-	11	51	13	-
Limaye	Dendr. strictus	36 / 152	64	33	44	-	2½ year old; resp. N/I/N/I.
			61	33	40	-	
			9	33	71	-	
			9	33	74	-	
Atrops	-	77 / 308	-	36	40	-	-
			-	36	43	-	-
			-	36	41	-	-
Sekhar e.a. (1962)	B.Nutans		87	24	46	-	3 years old.
			12	24	85	-	
Sekhar e.a. (1961)	D.Strictus		12	16	54	-	3 years old.

The loading speed was 2.7 up to 3.2 kN/s or about 1.5 N/mm^2s: as the deformation was found to be linear up to at least 50 per cent of the failure load, this measured loading speed agrees with a calculated speed of deformation of 0.02 mm/s.
This speed is higher than ASTM-D143-52 requires for wood, but due to the small cross-section of the bamboo (2000 mm^2) it was difficult to run the press at a lower speed.However, it has been proved that for wood this rather high speed has little influence on the strength (Vermeijden, 1959).
It may be assumed that this is true for bamboo as well. The specimens were visually straight (i.e. not curved). The bamboo was centered visually between the steel plates of the press, the top plate was ball-jointed. The specimens showed no visible defects before testing. The feature of the failure was splitting and/or crushing; a relationship between these and MC was not observed.

Results.
The original results are listed in table 4.11.1. In view of the purpose to contribute to a standard for testing bamboo under compression, the tests were based on a statistical scheme, and a statistical analysis of the results was carried out.The 106 values of the stresses at failure were plotted in order to get a first impression without a statistical analysis, and to see whether a normal distribution had occurred.In case of timber a Weibull-distribution is required in most instances, as explained by Pierce (1976). In the case represented by fig. 4.4.3. a normal distribution seems acceptable.
An interesting detail is that all values are between 60 and 110 N/mm^2, except one value of 176 N/mm^2. Yet we are quite sure about the reliability of the latter figure. Including this figure the skewness of figures is 2.87, which is too much for a Weibull-distribution, and would require a log-normal-distribution. Without the figure of 176 N/mm^2, the skewness is only 0.12, which is fairly good for a normal distribution. This comparison shows how important it can be to omit an extreme value.Table 4.4.4. gives a survey of the results of tests: the factors taken into consideration with their levels and interactions, the estimated parameters β in N/mm^2, and the significance of these, i.e. the P-value.
Also the standard deviation of β is given; if $\beta <$ st. dev., β does not differ significantly from zero. According to the P-value only seven out of the 18 parameters are significant, and consequently the model can be simplified.

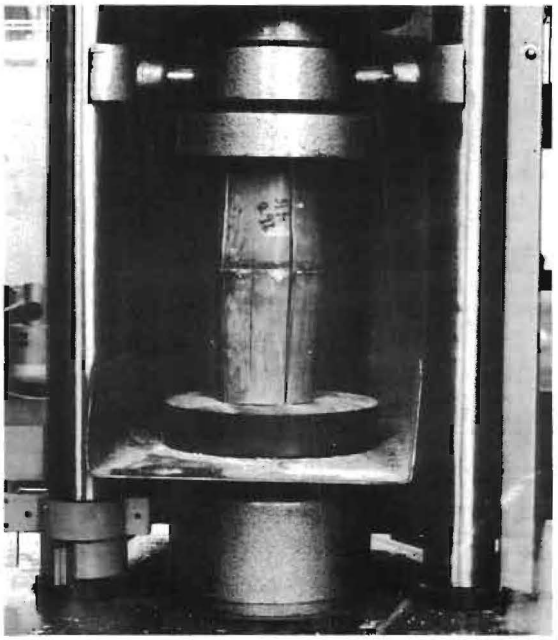
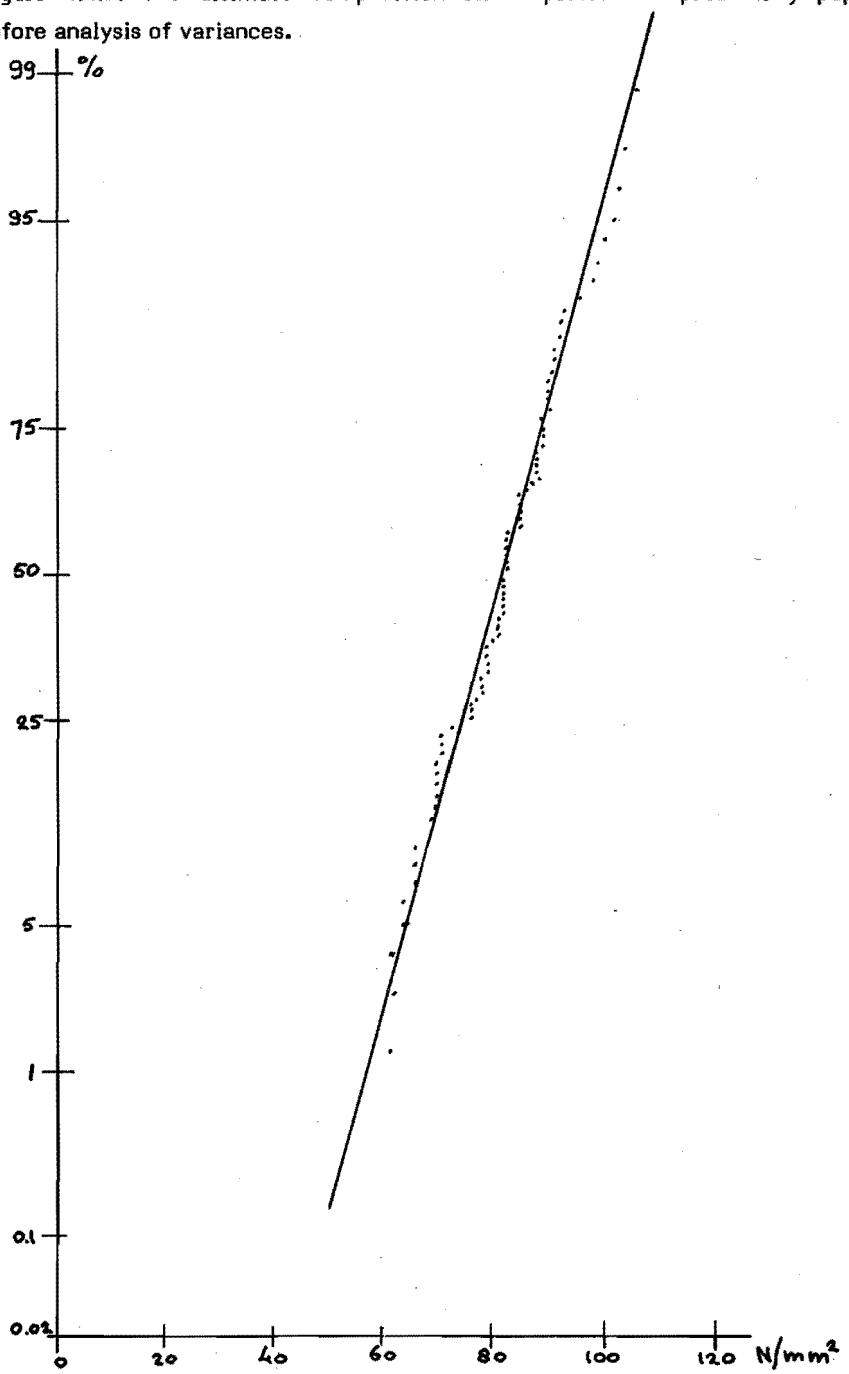


Photo 4.4.2. Compression test on bamboo.

Figure 4.4.3. The ultimate compression stress plotted on probability paper, before analysis of variances.



Another interesting question is how the parameters combined in pairs or in series will behave, see table 4.4.5. From this table, particularly the first line, the conclusion is that only the parameters 3, 4, 5, 6, 11 and 12 might be omitted from the model, i.e. the square of the M.C., the height of the specimen, node or internode, and the interaction of M.C. with (inter)node. (note: the p-values 0.07 and 0.09 are considered as to near to the arbitrarily chosen 0.05-limit) (see 4.11.1.).This reduced model shows up relationships between the compression stress at failure and the parameters M.C., positions along the culm, height and (inter)node respectively. One can deduce these relationships from the linear model by calculating the estimated value of the ultimate stress for each level of the parameters and by keeping the other parameters constant. The results are shown in figures 4.4.6. and 4.4.7. Moisture content and position along the culm are important in practice, and so in figure 4.4.6. are plotted the estimated stresses at failure, as functions of moisture content and the position along the culm, with their interactions, and with 90 per cent area. The other parameters were kept constant, and chosen at random. The bamboo is weaker with increasing moisture content, an obvious conclusion. Likewise the bamboo in the top of the stem is stronger than the bottom. This is due to the increasing percentage of sclerenchyma fibers. Remarkably, bamboo in the position "middle" is as strong as in the position "top" at a MC of 4 per cent, but as strong as in the position "bottom" at a M.C. of 12 per cent. The physical reason for this has still to be studied.

Similarly, figure 4.4.7. shows the estimated stress at failure as a function of the height of the specimen and (inter)node, with interactions. Clearly significant is the influence of the interactions of height and (inter)node ($\beta 17 + \beta 18$), shaded in the figure, while the parameters height of the specimen and (inter)node are not significant. The physical explanation of this effect is still to be investigated.

For mechanical properties of wood and bamboo a variation coefficient of 15 to 20 per cent is common. In this case however, the coefficient is only about 3 per cent. We have calculated the standard deviations after a statistical analysis of the relationship between the ultimate stresses and moisture content or position along the culm. In fact, the standard deviation of 15 per cent mentioned previously is calculated with a residual variance in which all parameters, such as moisture content, position along the culm, the stems, the interactions, etc. are still present, see fig. 4.4.8.A. Figure 4.4.8.C. gives an overall survey of this difference for M.C. only. A comparison with other authors is made in par. 4.4.5.

Table 4.4.4.

factor and levels	value of x	estimated parameter β in N/mm^2	st. dev.	P-value
Constant	$x_1 = 1$	$\beta_1 = 81.1$	-	0.00
M.C.	$x_2 = (8\text{-MC})/4 = +1,0,-1$ resp.	$\beta_2 = 3.5$	1.0	0.00
4,8,12% resp.	$x_3 = 3x_2^2 - 2 = 1,-2,1$ resp.	$\beta_3 = 0.4$	0.7	0.55
height 50,100 200 mm.	$x_4 = H/50 - 2 = 1,0,2$ resp.	$\beta_4 = -0.2$	1.4	0.91
	$x_5 = x_4^2 = 1,0,4$	$\beta_5 = -0.4$	1.0	0.67
node and internode	$x_6 = -1$ or $+1$ resp.	$\beta_6 = 2.3$	1.4	0.11
three stems	$x_7 = -1,0,1$	$\beta_7 = 3.5$	0.9	0.00
	$x_8 = 1,-2,1$	$\beta_8 = 0.2$	0.6	0.69
position along culm; bottom, middle	$x_9 = -1,0,1$	$\beta_9 = 6.8$	1.1	0.00
resp. top	$x_{10} = 1,-2,1$	$\beta_{10} = -0.6$	0.6	0.32
interaction MC and (inter)node	$x_{11} = x_2 \cdot x_6$	$\beta_{11} = 1.1$	1.0	0.29
	$x_{12} = x_3 \cdot x_6$	$\beta_{12} = 0.6$	0.6	0.39
interaction MC and position	$x_{13} = x_2 \cdot x_9$	$\beta_{13} = 0.9$	1.2	0.46
	$x_{14} = x_2 \cdot x_{10}$	$\beta_{14} = -2.3$	0.7	0.00
	$x_{15} = x_3 \cdot x_9$	$\beta_{15} = 0.6$	0.8	0.48
	$x_{16} = x_3 \cdot x_{10}$	$\beta_{16} = -1.1$	0.4	0.01
interaction height and (inter)node.	$x_{17} = x_4 \cdot x_6$	$\beta_{17} = -2.4$	1.4	0.09
	$x_{18} = x_5 \cdot x_6$	$\beta_{18} = 2.3$	0.9	0.02

Significant P-values are underlined.

Table 4.4.5.

factor	parameter β	P-value
height	$\beta_4 + \beta_5$	0.55
stems	$\beta_7 + \beta_8$	<u>0.00</u>
position	$\beta_9 + \beta_{10}$	<u>0.00</u>
interaction		
M.C. and (inter)node	$\beta_{11} + \beta_{12}$	0.46
interactions MC and position	$\beta_{13} + \beta_{14}$	<u>0.00</u>
	$\beta_{15} + \beta_{16}$	<u>0.02</u>
interaction height and (inter)node	$\beta_{17} + \beta_{18}$	<u>0.05</u>

Series of β:

- 3+4+5+6+11+12	0.29
- 3+4+5+6+11+12+15+16	0.09
- 3+4+5+6+11+12 +17+18	<u>0.00</u>
- 3+4+5+6+11+12+15+16+17+18	<u>0.00</u>
- 3 +11+12+15+16	0.07

Significant P-values are underlined.

The meaning of β_4 ... β_{18} is clarified in table 4.4.4.

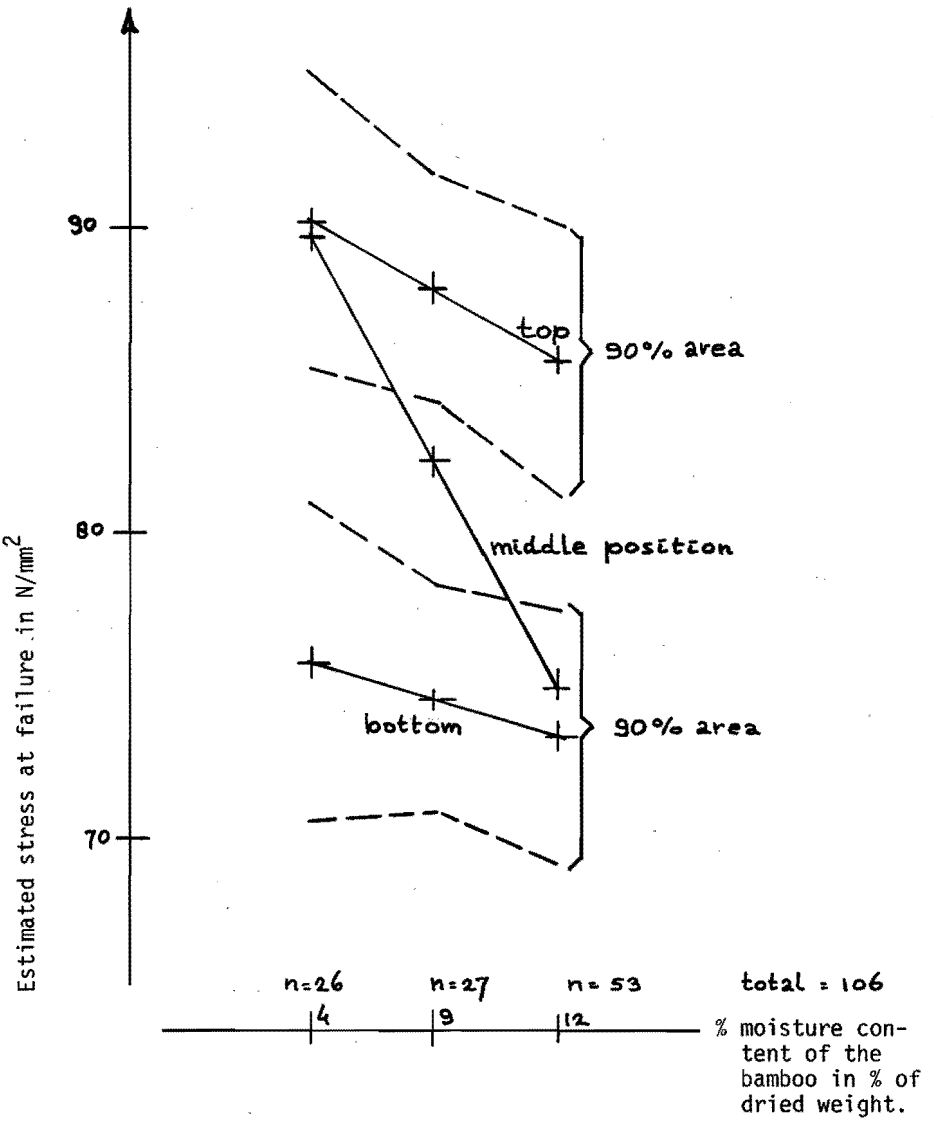


Figure 4.4.6. The estimated stress at failure as a function of the M.C. and the position along the culm, with 90%-areas. Other parameters were kept at a constant level.

For clarity's sake the 90 per cent area of the stresses at the position "middle" has been left out.

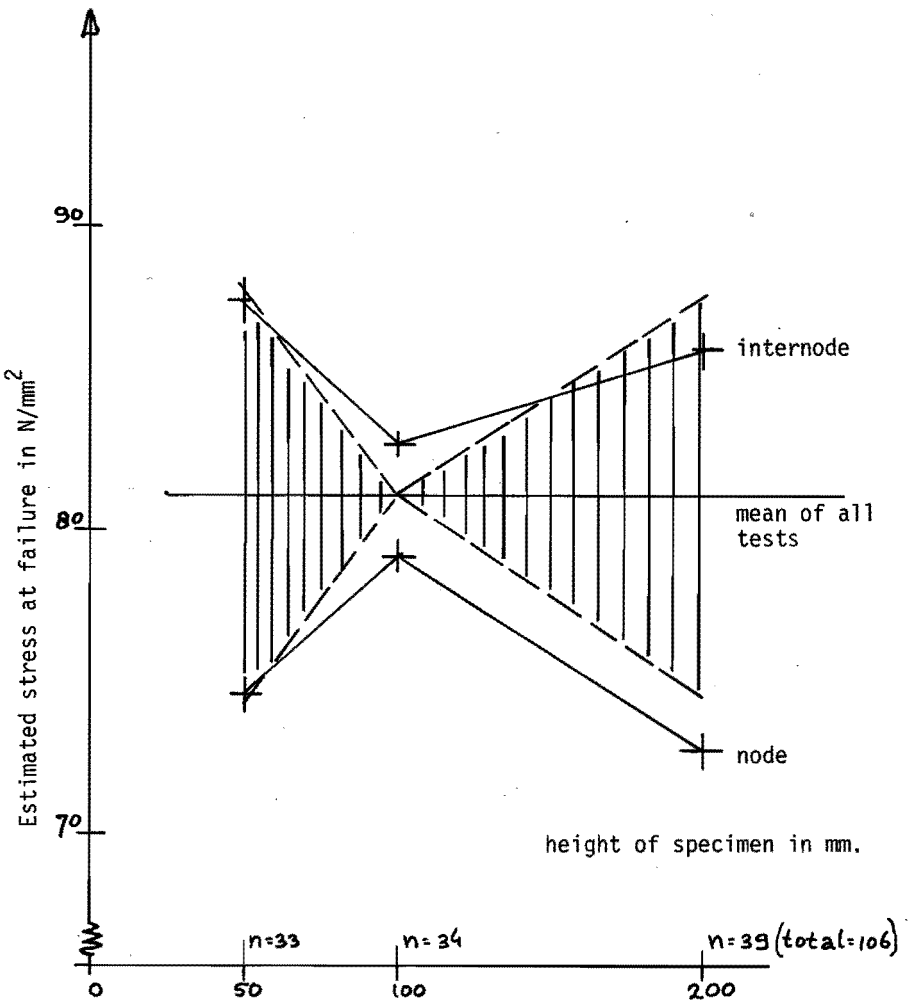
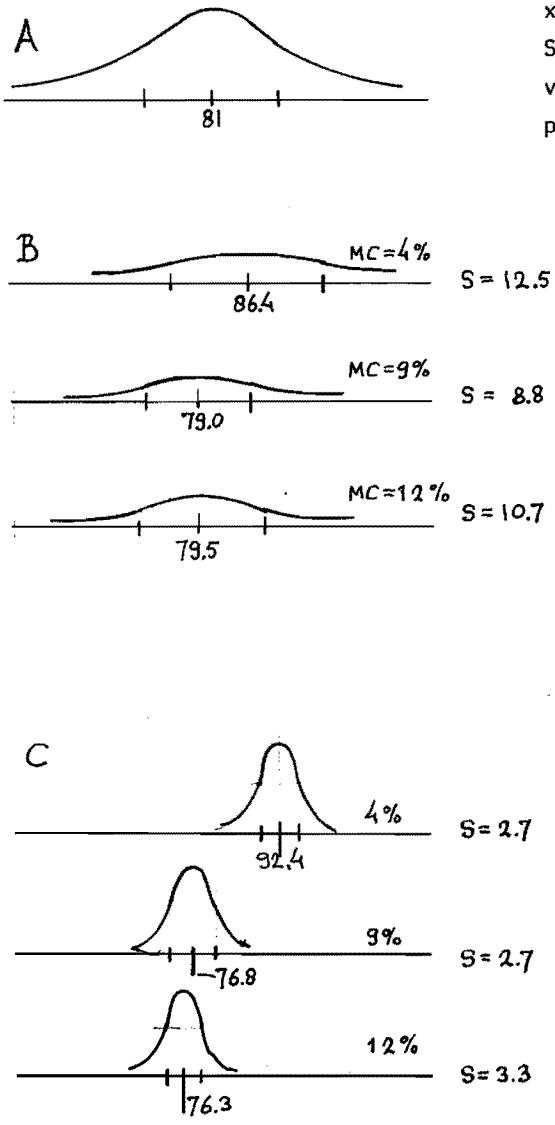


Figure 4.4.7. The estimated stress at failure as a function of the height of the specimen and (inter)node. The shaded parts represent the influence of the interaction (17 + 18) alone.

Figure 4.4.8. Gauss-curves of the ultimate compression stress in relation to M.C., in N/mm^2. A and B are test-results before statistical analysis, and C is a plot of the linear model.



4.4.3. Compression strength of split bamboo

Introduction

Several authors have carried out tests on split bamboo, a survey of which is given in table 4.4.9.

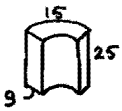
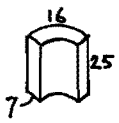
Author	form (mm)	M.C. %	number of tests	σ_u' in N/mm^2 mean	st.dev.
Espinosa		13	25	54	10
Motoi Ota (part 7)	cubes, size = wall thickness	10-13	32	83	-
		12-15	28	82	-
Atrops		dry		62	-
Motoi Ota (part 4)	variable				

Table 4.4.9. Summary of references on compression strength of split bamboo.

Motoi Ota (part 4) has studied the influence of the size (height h, width a and thickness w) on the compression strength of split bamboo. In his opinion the width b of the specimen has no influence, but the height h has a considerable influence.

In fact he finds the empirical formula: (for h/a = 1...8) ultimate compression stress in N/mm^2 = - 90 + 2.5 h/a.

This fits with Kollman and Côté, who mention a relationship between the compression strength of wood and the slenderness of the specimen, due to the friction between the end surfaces of the specimen and the plates of the press. This friction impedes the lateral strain, and as a result the specimen seems to be stronger. The data by Kollmann and Côté fit well with Motoi Ota's:

Kollmann	h/a	0.5	1	3 6	
and Côté	σ_u'(%)	103	100	93	
Motoi Ota	h/a	-	1	3	6
	σ_u'(%)	-	100	94	86

N.B. In the foregoing paragraph the height of the specimens was not significant, but the ratio h:a varied from 7 to 28, i.e. another area.

Similarly the data mentioned above should be higher than tha data found on full bamboos. Espinosa mentions as ultimate stress for split bamboo 54 N/mm^2, and for full bamboos 57 N/mm^2. In view of the fact that the standard deviations are 10 and 13 resp., the conclusion is that there is no significant difference. On the contrary, Atrops gives 62 N/mm^2 for split and 41 N/mm^2 (minimum 36, maximum 54) for full culm. This agrees with my previous statement: higher strength due to impeded lateral strain.

Finally, as early as 1923 Meyer and Ekelund reported about the influence of impeded lateral strain on the compression strength. They carried out tests on full culms, partly with lead plates between the ends of the specimens and the steel heads of the press, however. The results were:

- with lead 34 N/mm^2 (st.dev. 1.6; n = 3)
- without 44 N/mm^2 (st.dev. 5.2; n = 4)

In fact, this is the same subject, and leads to the same conclusion that impeded lateral strain increases compression strength.

Procedure

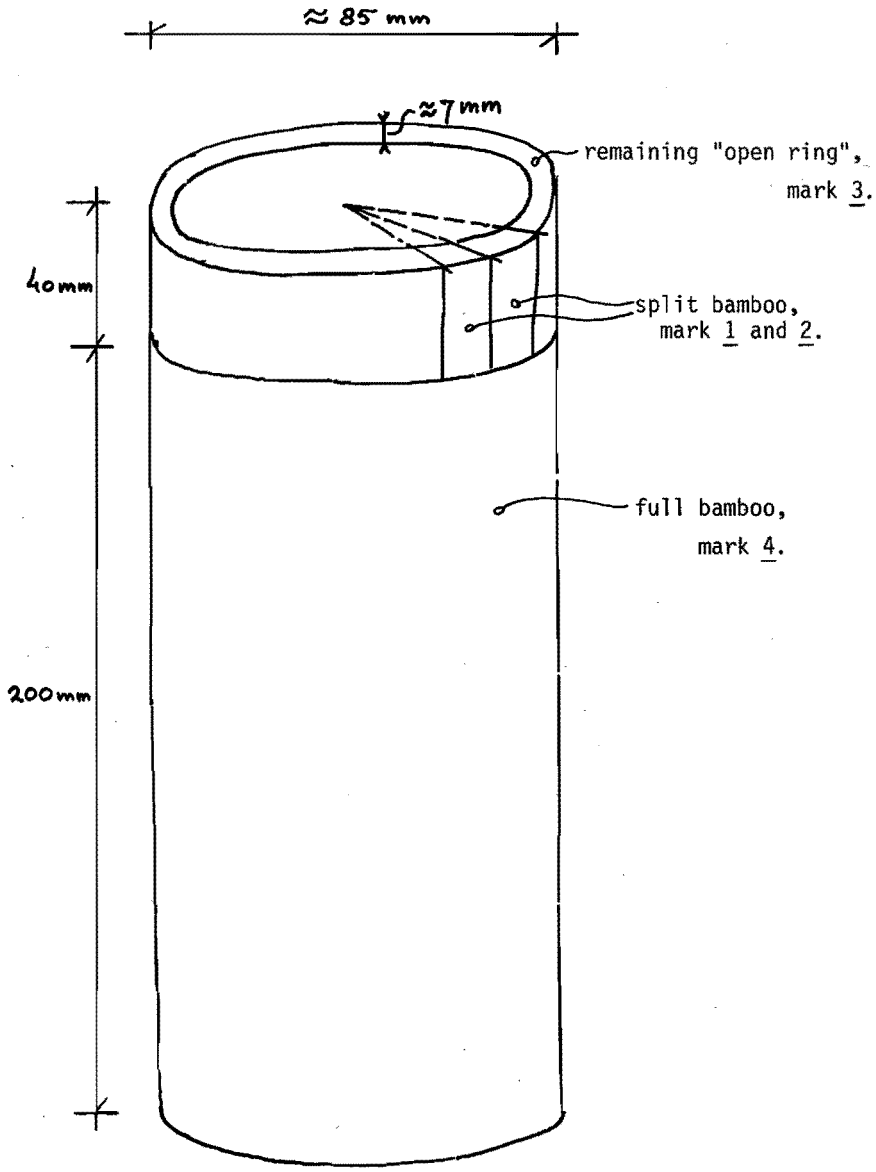
The idea was to study the differences in compression strength between full and split bamboo. Therefore specimens from one stem, and from each internode were cut according to fig. 4.4.10.

In this way 10 samples have been made, each containing four test-specimens belonging together, from which marks 1,3 and 4 have been used for mutual comparison.

All other factors, e.g. position along the culm, are ruled out by this method of sampling; M.C. being 12 per cent.

The full bamboos and the open rings were tested in a 200 kN press, the split bamboo in a 20 kN press. (machine error 0.2 per cent).

Fig. 4.4.10. Test pieces.



Results

The results of the tests read in table 4.4.11.

form	ultimate compr. stress N/mm^2 mean	st.dev.
split bamboo no. 1	70	5.5
open ring, no. 3	68	3.5
full culm, no. 4	64	3.7

Table 4.4.11.

The differences between the several mean values are about as large as the standard deviations or even less, and therefore not significant. This can also be concluded from the 5 per cent lower boundaries, which are important for building practice:

split bamboo no. 1, 5% lower boundary	60 N/mm^2
open ring no. 3,	62
full culm no. 4	58

From table 4.4.4. we see the effect of height on the estimated ultimate stresses:

50 mm σ = -1x(-0.2) + 1x(-0.4) = -0.2 N/mm^2

100 mm = 0 0 0

200 mm = 2x(-0.2) + 4x(-0.4) = -2.0.

The 200 mm. culm is weaker (1.8 N/mm^2) than the 50 mm; similarly the full culm of 200 mm. height (table 4.4.11.) is weaker (4 N/mm^2 however) than the open ring of 40 mm. height, but all these differences are not significant.

Conclusion

As the 5 per cent lower boundaries of the compression strength of split bamboo and full culm are rather equal, small size split bamboo (h = 40 mm, width = 10 mm, thickness $\simeq$ 7 mm.) can be used as a specimen to test the compression strength. In this case a press of smaller capacity will be sufficient..

4.4.4. Discussion

Comparison of results obtained by the various researchers is rather difficult, the statistical basis differing widely. In this comparison, however, three aspects are of particular interest: moisture content, position along the culm, and node/internode. Besides, other factors of interest will be discussed.

A) Moisture content

Several authors mention data on the compression strength of green and dry bamboo, or of bamboo classified into groups with clearly defined values of moisture content. The most valuable data can be found in Limaye (1952), Motoi Ota (part 9) and Sekhar a.o. (1962), because they too derived empirical formulas which are graphically presented in fig. 4.4.12.

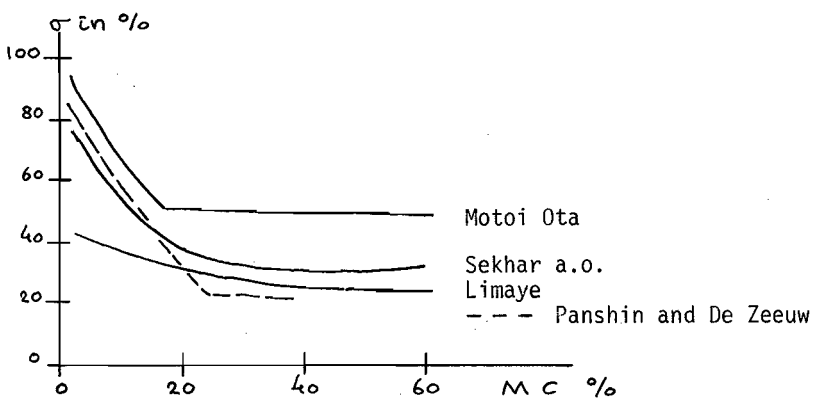


Fig. 4.4.12 Relationship between ultimate compression stress (100 per cent at oven dry) and M.C.

Comments to fig. 4.4.12:

author and species	formula	remarks
Motoi Ota, (part 9)	$\sigma = 0.147 x e^{-0.045xM}$	M.C.<17.2 per cent
for Phyllostachys species	$\sigma = 85 - 4.5xM$	M.C.>17.2 per cent
Panshin and De Zeeuw for wood	graph only	0<MC<35 per cent
Sekhar a.o.(1962) for Bambusa Nutaus	graph only	0<MC<100 per cent
Limaye	$\sigma = 59 x e^{-0.01xM}$	$r^2 = 0.64$
for dendrocalamus strictus	$\sigma = -0.4xM + 57$	$r^2 = 0.70$

σ = ultimate compression stress in N/mm^2
M = M.C. in percentages of dry weight.

The graphs are almost uniform, they differ only by the constant. This may be due to a difference in cellulose content and in its crystalline/amorphous ratio. My own test results give estimated influences of M.C.on ultimate stress, to be compared with the mean value = 81 N/mm^2:

4% MC gives	+ 3.9 N/mm^2
8	- 0.8
12	- 3.1

These three data are not enough to draw a graph; they do not disagree with the given graphs (4.4.12). They cannot be plotted into these graphs because the bamboo was not tested completely dry.
For building practice, a climate change from e.g. 60 to 80 per cent R.H. (dry to wet season) results in a M.C. of 10 to 13% and also in a loss of compression strength of about 7 per cent (in % of strength oven dry).

B) Node or internode

Sekhar and Bhartari write (1960): "Although from the point of view of practical use the disposition of nodes does not seem to be of much importance, it seems to be useful to know the effect of nodes from the point of view of testing".
The general opinion, however, is that this effect is not significant, in our tests (table 4.4.4.), in reports by Limaye (1952) and Atrops (1969). In an isotropic material a diaphragm evidently improves the strength of a cylinder, but in an orthotropic material like bamboo this effect is spoiled because the fibres do not run straight forward in a node.

C) Position along the culm

This influence proved to be significant. From table 4.4.4. we learn the estimated influence of the position on the ultimate compression stress (all other influences having been neglected):
bottom -7.4 N/mm^2
middle +1.2
top +6.2
It is interesting to mention the fact that this significance only appears after an analysis of variances. Before this analysis the variance of position along the culm is mixed up with all other parameters, and therefore the standard deviation exceeds the differences between the mean values:

	bottom	middle	top
mean	75.6	81.4	86.9 N/mm^2
st- deviation	9.1	10.4	11.0

From these data one should not expect any significance. But after analysis of variances the data become:

mean	73.4	75.0	85.6
st. deviation	2.6	2.6	2.7

from which the significance becomes clear.
This might have been the reason for Sekhar a.o. (1962) to state no significance. Their data read for Bambusa nutans, 12% M.C.:

(N/mm^2)	bottom	middle	top
mean	67.7	70.7	69.5
st. deviation	12.1	9.6	9.5

On the contrary, Limaye (1952) reports a significant influence for green bamboo (Dendrocalamus strictus) following an appropriate statistical analysis.

The compression stress increases from bottom to top, which is quite natural, because the percentage of sclerenchyma fibres increases similarly. In table 4.4.13 data on the sclerenchyma-content from Grosser and Liese (1974, table 5) are plotted.

	bottom	middle	top
mean	32.6	40.4	41.4
st. deviation	1.7	1.9	3.1

Table 4.4.13. Percentages of sclerenchyma-fibres.

In figure 4.4.14 the mean values are plotted against the ultimate stresses according to Sekhar and my results.

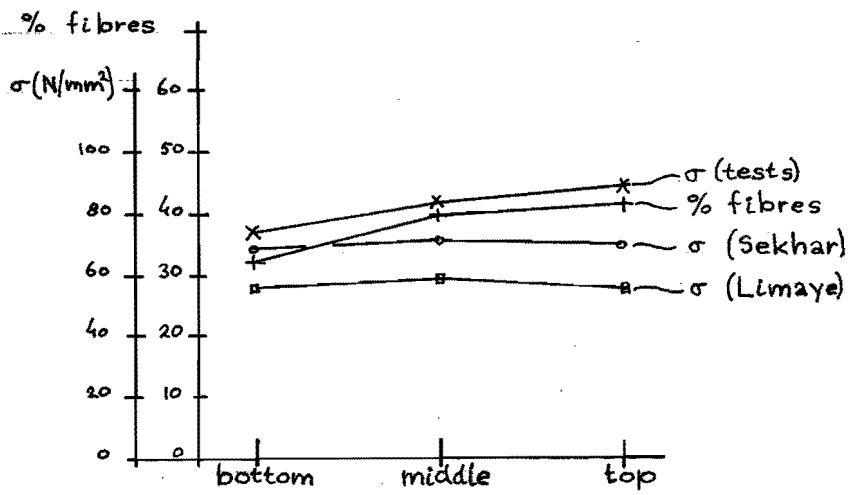


Fig. 4.4.14.

This graph shows the relationship between fibre content, compression strength, and position along the culm: the fibre content increases from bottom to top, and this causes increasing compression stress.
Finally, a comment on a statement by Limaye. He writes: "The discussion on the disposition of nodes and the position of specimens along the culm has an academic interest only. The engineer is generally interested to know a fairly average value for the whole culm as such that can be used in design as loads cannot always be concentrated at particular points. It is, therefore, convenient to take the average strengths from the 2 dispositions of nodes and 3 positions along the culm to represent single mean values of the strength of the culm".
In my opinion this is allowed only with an appropriate safety factor. But modern safety philosophy enables a more economic use of materials. Now the above-mentioned "average strengths" increase the standard deviation. This in its turn diminishes the 5 per cent lower boundary, and an uneconomic use is the result.

D) Age

The age of the bamboo in my tests is a constant. Limaye has found a significant increasing compression strength related to the age of the bamboo from 0.5 to 2.5 year. This is caused by what Young and Haun (1961) describe as "The wood of the culms during the first 2 years is comparatively soft - the fibre cells being at first very thin-walled and filled with sap. During the third year the wood completes its hardening, through the thickening of the walls of the microscopic cells, so that by the end of the third season, and not before, the wood has acquired its maximum strength and durability".
Other researchers, however, are less positive in their reports. A first comment is this: many tests in this field are carried out on green bamboo. However, moisture content in green bamboo varies with age, and therefore it is simpler to study dry bamboo. (Or: one should use a correct analysis of variances).
Likewise the mass per volume varies with age. See figure 4.4.15., where the ultimate compression stress, the mass per volume. and their ratio are plotted against the age of the bamboo. Any relationship between age and compression is not clear, but for practical use this relationship is very important, and, consequently, much research will have to be done as yet.

Fig. 4.4.15.

σ = ultimate compression stress in N/mm^2 (12% M.C.)

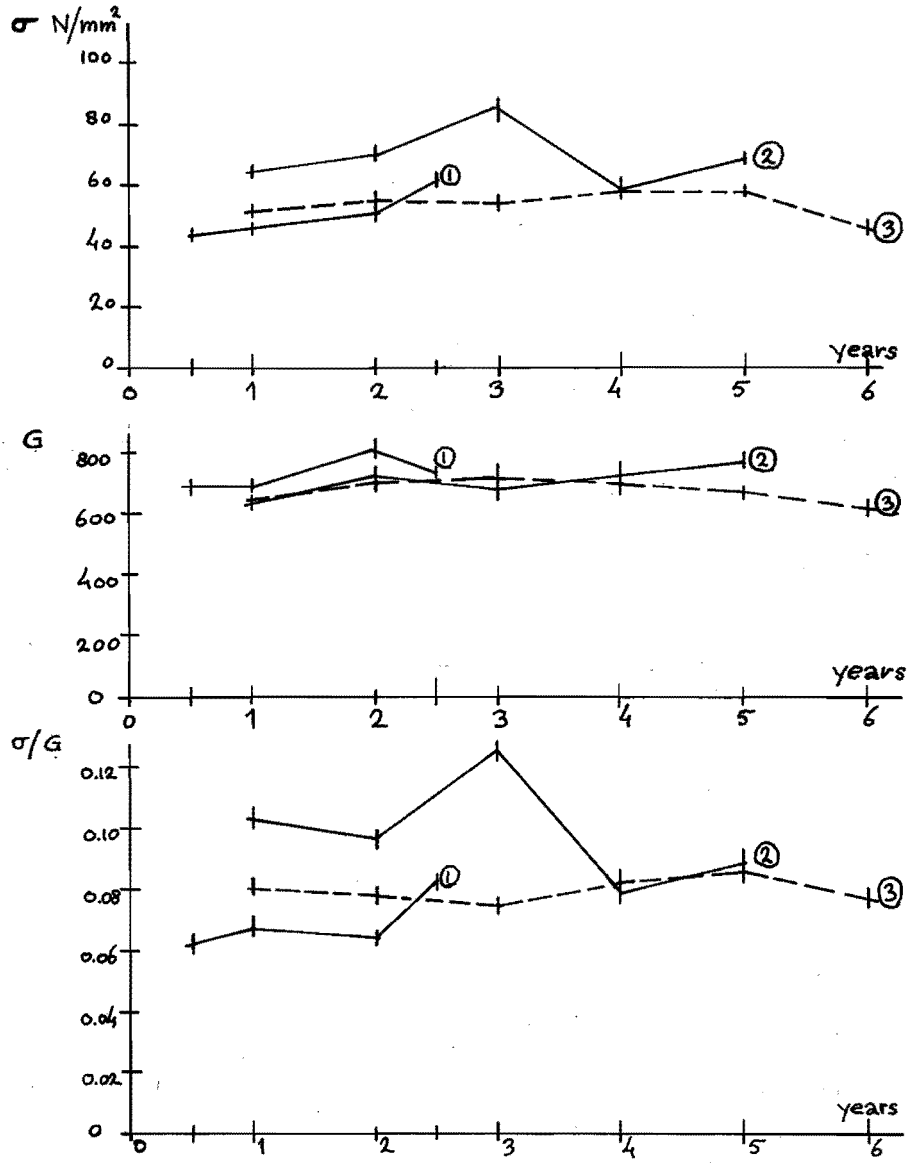
G = mass per volume in kg/m^3.

These two and their ratio plotted against age in years.

1. = Limaye (1952), Dendrocalamus strictus.

2. = Sekhar (1962), Bambusa nutans.

3. = Sekhar and Bhartari (1961), Dendrocalamus strictus.



E. Structure

The relationship between compression strength and structure of the bamboo has been studied mainly by Motoi Ota (part 7, 1950). He has tested split bamboo: outer part, middle part and inner part, the thickness of each specimen being half the thickness of the culm-wall. For these specimens he has tested compression strength and percentage "bundle sheath" (in my opinion this refers to sclerenchyma fibres and vessels together). A summary of these results is given in table 4.4.16.

σ in N/mm^2	Phyll.reticulata	Phyll.edulis
outer part	112	105
middle part	80	76
inner part	67	68
whole	83	82
% bundle sheath = V		
outer part	40	34
middle part	26	23
inner part	17	13
whole	28	22

Table 4.4.16. Ultimate compression stress and percentage of bundle sheath (Motoi Ota 1950).

From these data his calculated relationships are:

$\sigma = 88 + 1.8\ (V - 27)$ corr. coeff. = .86

$\sigma = 85 + 1.7\ (V - 27)$ corr. coeff. = .90

From this data one could simply derive $\sigma = 3.5 \times V$ which however is rather rough. (standard dev. is 0.8). These formulas are empirical, and it would be interesting to verify them theoretically, but unfortunately this cannot be done simply on the basis of the theoretical compression strength of cellulose. Firstly, this was not calculated, and perhaps it could not be calculated at all. The tensile strength of a cellulose chain can be calculated from the bonds between the atoms, but the compression strength is limited by instability.

Furthermore, even if the theoretical compression strength of cellulose would be known, this could not be a basis to explain the compression strength of bamboo, because this in its turn is limited by instability (a cell is not perfectly straight, the inside of the cell wall is corrugated etc.) as pointed out in Chapter 3, in the discussion of Stupnicki's studies (par. 3.13).

F) Mass per volume

The ratio between ultimate compression stress and mass per volume has been studied by several authors, both for wood and bamboo, and in the latter case for the culm as a whole, or for outer and inner part of the culm-wall, or along the internode. The results are summarized in table 4.4.17.

condition	wood		bamboo	
dry	$\sigma = 0.084\ G$	(1)	$\sigma = 0.092\ G$	(2)
			$\sigma = 15.4+0.082 \times G$	(3)
			$\sigma = -77.3+0.165 \times G$	(4)
			$\sigma = 0.096\ G$	(5)
green	$\sigma = 0.046\ G$	(6)	$\sigma = 0.003\ G^{1.5}$	(8)
	$\sigma = 0.047\ G$	(7)	$\sigma = 0.075\ G$	(9)

Table 4.4.17. Ratio between ultimate compression stress σ (N/mm^2) and mass per volume G (kg/m^3).

Sources (all formulas have been translated into ISO-units).

(1) Panshin and De Zeeuw, p. 187
(2) Motoi Ota, part 9, table 7, but calculated by author
(3) Motoi Ota, part 7, page 37,
(4) idem; deviates remarkably.
(5) idem, but calculated by author
(6) Panshin and De Zeeuw, p. 187
(7) Desch p. 175
(8) Sekhar a.o. (1962)
(9) idem, but calculated by author.

The ratios give dry bamboo a slightly higher compression strength: ≈ 0.094 compared with 0.084 for dry wood. This might be caused by the higher cellulose content in bamboo, compared with wood: 55 per cent for bamboo (Motoi Ota part 7, Hidalgo) and 50 per cent for wood (Siau, a.o.). Such relationships are quite sufficient to understand other things. E.g. Sekhar and Gulati (1973) have studied the mechanical properties for Dendrocalamus strictus from eleven different localities. The ultimate compression stress varied from 50 to 79 N/mm^2 (mean 64, var. coeff. 16 per cent). But the compression stress ratio to mass per volume is 0.090, with var. coeff. of 12 per cent. The influence of the different localities has become better understandable now (as an influence of mass per volume).

G) Procedure of tests on compression

Only one standard on bamboo exists: the Indian Standard 6874 (1973), which has been preceded by the standards of the Forest Research Institute (Sekhar and Rawat 1956). Specimens are taken from the lowest 3.3 m. of each culm of the sample, and half has to be tested green and half in 12 $\pm$ 2 per cent by weight M.C. The test on compression parallel to the grain should be carried out on internodes only. The length of the specimen equals 10 x wall-thickness. The loading-rate is 0.011 mm/s. (ASTM requires 0.005 mm/s).All variables, which according to my investigation are significant, have been fixed in this standard. The loading-rate, although twice as high as prescribed by ASTM, agrees very well with our experience (see 4.4.2. tests) that a lower speed is impossible due to the small cross-section of bamboo compared with that of wood, and because it is impossible to run the press at a lower speed.

4.4.5. Conclusions

Effects on the ultimate compression stress σ are given in the nrs. 1 ... 6:

1. The percentage of sclerenchyma fibres is significant.
2. The mass per volume G is significant:
   bamboo with 12% M.C. σ (N/mm^2) = 0.094 x G (kg/m^3),
   green bamboo σ = 0.075 x G
   (G is not significant for the differences between bamboo and wood).
3. The M.C. is significant.
4. Position along the culm is significant.
5. Node or internode in the specimen is not significant.
6. Height of the specimen within the area (1 à 3) x diameter is not significant.
7. Instead of a full bamboo, a small piece of split bamboo may be used to predict the 5 per cent lower boundary.

4.4.6. What remains to be done

- Failure is mainly due to splitting, i.e. an excess of the tensile strain of the pectin sticking the fibres together. If we could determine the tensile strain, it seems possible to explain the compressive strength of bamboo.
- Buckling, taking into account that a bamboo culm is curved and tapered, and contains nodes.
- Creep in compression.
- Further test series on the influence of the age of the bamboo.
- Study on the interaction between moisture content and position in the culm.

4.5. Bending

4.5.1. Introduction

For its use in structures the behaviour of bamboo in bending is very important, because this use is limited in many cases just on account of bending. This opinion is confirmed by Limaye (1952) and Karamchandani (1959). As a result many tests on bending strength and E-modulus were carried out. A summary of these tests is presented in table 4.5.0. From this table one might see the state of the art.

A still interesting report is that by Trojani (1930), a French officer in Indo-China. He gives an empirical rule of thumb for the bending strength of bamboo:

$$F = \frac{100\,n}{3}$$

in which F = total load in kg.

n = exterior diameter in cm.valid for a span up to 3 metres.

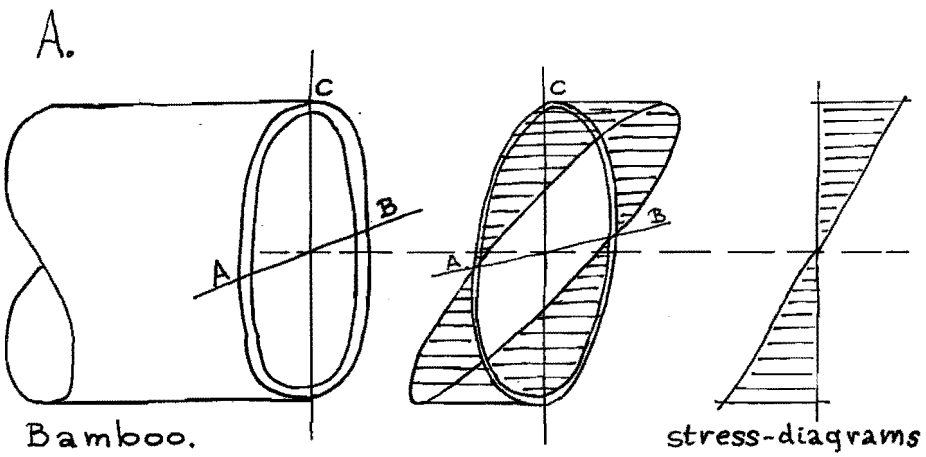
A simple calculation shows a stress of 25 N/mm^2 as a basis for this rule of thumb. He even published a nomogram: given the wall thickness and outer diameter, one can read the maximum load for a free span from 1.50 up to 4 metres. This nomogram was based on an ultimate stress of 20 N/mm^2. Here this author is cited to show a good example of working with bamboo already in 1930. Unfortunately he does neither mention how these rules have been derived, nor does he report on the deformation. The next paragraphs report about our tests on bamboo, concerning the ultimate bending stress and the E-modulus, in short and long-term loading.But prior to these reports, an introduction on the bending phenomenon is given. Fig. 4.5.1.A. shows a piece of bamboo with stresses due to a bending moment. In the neutral layer A - B the shear stress is at maximum, and this is a risk of failure in bamboo. In the top C the bending stress is at maximum, and in case of a positive bending moment this is a compression stress, which results in lateral strain. This lateral strain, acting transversely to the fibres, is an additional risk of failure in bamboo.

If bamboo were isotropic, this lateral strain could be calculated with Boussinesq, but bamboo is orthotropic, and now such a calculation is very difficult. Besides, bamboo is a thick-walled tube, and not thin-walled, which makes calculations even more difficult.Next, the difference between a three- and a four-point bending test. From fig. 4.5.1.B. we can see, that in a four-point bending test the centre third part is free from transversal forces and subject to a constant pure bending moment. But in a three-point bending test failure will most certainly occur in the centre (point C) where the bending moment reaches its maximum and the transversal forces change rapidly as well. Therefore the three-point bending test is less reliable: the deviation in the results being much too large.

Table 4.5.0.

author, year, species	sketch size in mm, culm or split	σ N/mm²	E N/mm²	no.of tests	M.C.	age years	remarks
Meyer+Ekelund 1922, sp.?	c 1800	90					
	c 2100	88					
	c 2100	96					
Teodoro, 1925, B.Spinosa	c 3000	55	10 300		dry		90 days curing shade dry season
B.Vulgaris	idem	33	18400		dry		
Espinosa, 1930, B.Spinosa R.	c 1250				dry		
	c 700				dry		
	s 300	143		43	dry		
	s 300	113		43	dry		
Glenn, 1950, Phyllost.	s	146	14 800	19	? (seasoned)		also tests on ( ) ⊂ etc.
	s	143	14 300	15	?		
Limaye 1952, Dendroc.str.	c 700	68	12 000	240	green		mean values for ½,1,2 and 2½ years
		107	15 600	240	dry		
Sekhar/Bhartari 1960							summary of other researchers
idem, 1961 Dendroc.str.	c 700	96	16 000	14	12%	1	
		96	15 300	16	"	2	
		92	15 150	16	"	3	
		95	14 500	15	"	4	
		94	14 200	17	"	5	
		97	13 700	17	"	6	
Sekhar a.o. 1962 Bambusa Nutans	c 700	96	13 900	24	dry	1	
		83	9 300	24	dry	2	
		92	13 100	21	dry	3	
		76	11 000	21	dry	4	
		100	15 400	23	dry	5	
		61	9 400	24	green	1	
		56	8 800	24	green	2	
		59	9 400	21	green	3	
		67	10 800	21	green	4	
		79	13 000	23	green	5	
Atrops 1969, sp.?	c 3600	107		40	dry		
	s 300	142			dry		
	s 300	113			dry		
Sekhar+Gulati 1973, dendr.str.		scattered					from different localities.

Fig. 4.5.1.



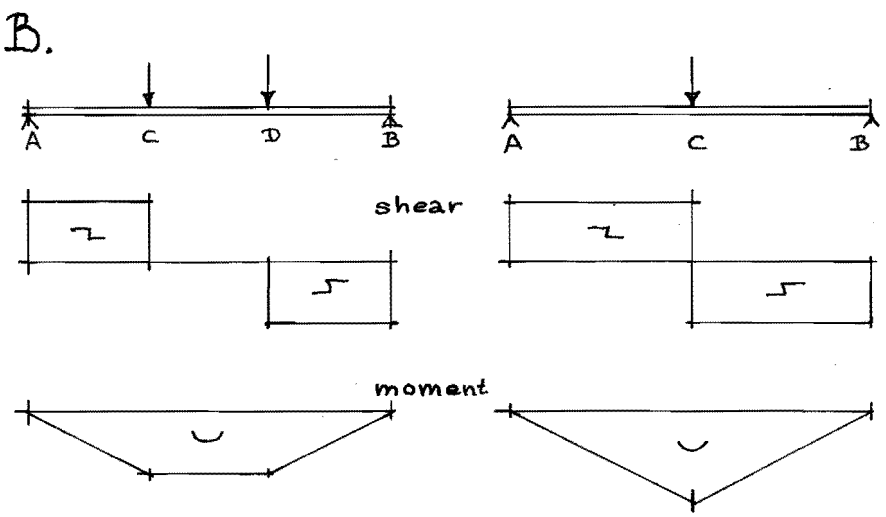
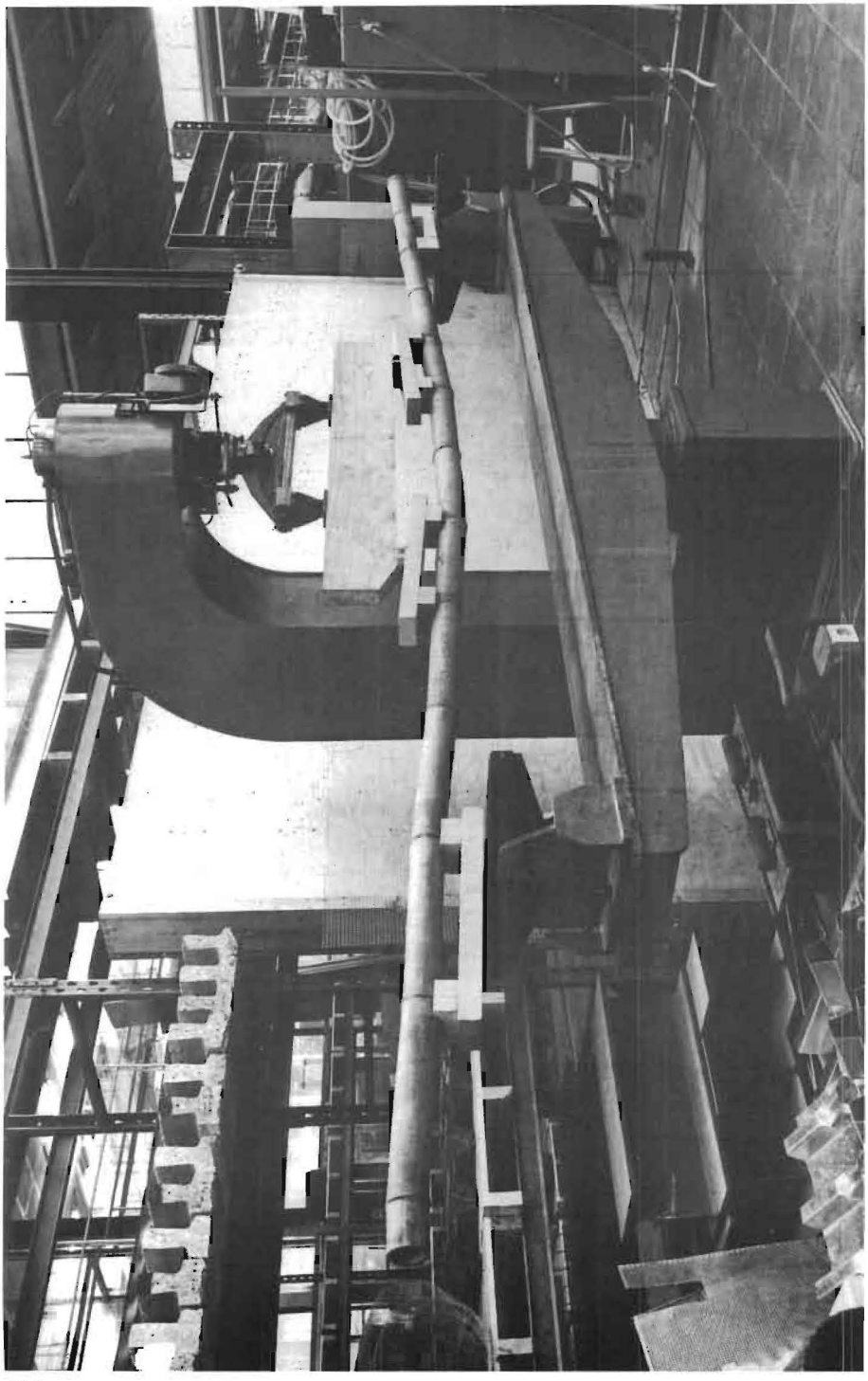


Photo 4.5.2. Bending test.



4.5.2. Short-term tests

The variables, as in par. 4.3., are as follows:

- species and age: Bambusa Blumeana, three years old,
- conditioned,
- M.C.: only 12 per cent by weight (equilibrium with 70 per cent R.H.)
- form and size of specimen: full culm, length 5 m, free span 3.60 m, four-point-bending test, see picture 4.5.2.
- node or internode: loads and supports are always fixed at a node by wooden saddles, see picture 4.5.2.
- position along the culm: only full culm of 5 m. length.
- machine-error 0.2 per cent.
- testing speed: for bending stress 0.3 N/mm^2.s (mean), with variation coefficient 20%; for deformation 0.5 mm/s with variation coefficient 8 per cent. In our experience the E-modulus remains constant till just before failure.

The standards (ASTM D143-52, DIN 52186 and IS 6874) prescribe a three point bending test on a free span of 0.7 m, with a speed of 0.7 till 0.8 N/mm^2 s (DIN) or 0.04 mm/s (ASTM and IS). Tests were carried out on split bamboo in order to compare three- and four-point bending tests, and the three-point test was found less reliable. This is caused by the complicated change in stresses under the central load, and by the transversal forces which are rather large on a short span. On the contrary, with a rather long free span (3.60 m) the transversal forces are relatively smaller, and in a four-point bending test the stresses change in a more continuous way. Cf fig. 4.5.1.B.

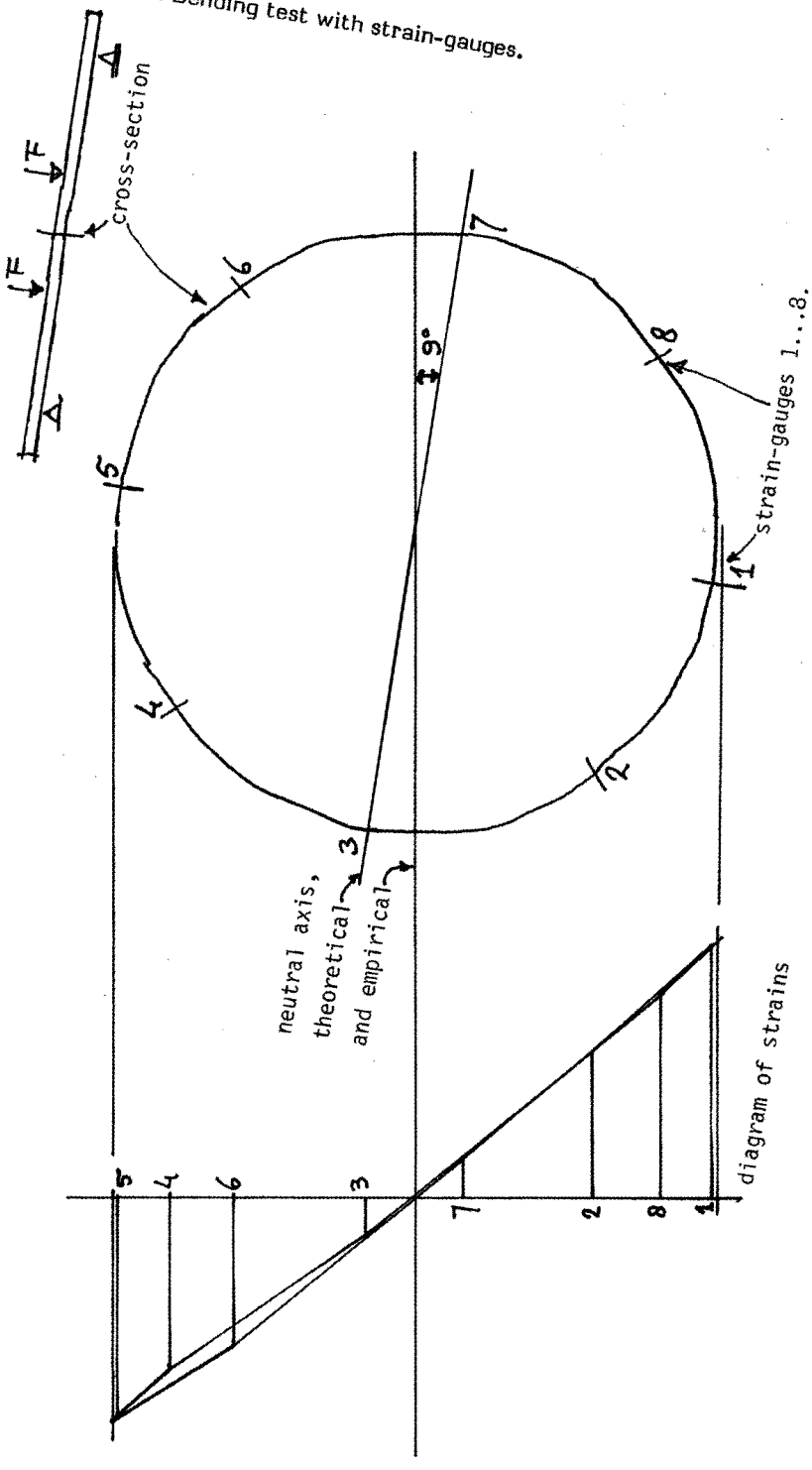
As to the differences in speed, the speed of stress was lower than the DIN figure, and the speed of deformation was higher than those figuring in ASTM + IS. These differences agree with the different free spans. Vermeyden (1959) reports about the possible influence of speed on test results: between 0.2 and 0.8 N/mm^2s there is hardly any influence on strength and no influence at all on E-modulus. This is true for wood, and I assume it is for bamboo too.

Table 4.5.3. Results of short-term bending tests, N/mm^2.

	mean	st.dev.	no. of tests
ultimate bending bending stress	84	26	9
E-modulus	20 500	3 400	9

The ultimate stress is calculated by working on the assumption that the tensile strains in the beam are equal to the compressive strains a equal distances from the neutral axis, i.e. the so-called modulus of rupture.

Fig. 4.5.4. Bending test with strain-gauges.



This statement has been checked with eight strain-gauges around the circumference of a culm, all in one cross-section; this statement was correct; see fig. 4.5.4., where a linear diagram of strains is shown. The neutral axis has been turned 9^{0}, but presumably the bamboo has made this movement during the test. No ovalization was not found whatsoever.

The main goal of the said tests was to become familiar with the phenomenon of bending in bamboo. A statistical analysis of variances for bending on full culm lies outside our scope, because in our laboratory it is impossible to condition full culms at 30 or 50 per cent R.H.

Failure was described already in 1922 by Meyer and Ekelund: "The collapse of the bamboo was always sudden and the material was split into pieces parallel to the longitudinal axis, none of the fibres being torn.This fact indicated that the collapse was caused by the shearing force".

Accordingly, the shear stress in the neutral layer at the moment of failure is calculated: 2.25 N/mm^2 with st. dev. 0.65 N/mm^2. This stress is much lower than in the case of pure shear (7.3 N/mm^2 estimated for 12% M.C., 80 mm height and node), but this could be caused by the more complicated stresses in the case of bending (also transversal shear and bending stresses). According to the theory in par. 4.5.1. I observed not only splitting of the culm in the neutral layer, but also in the top of the cross-section (picture 4.5.5.). Here, the longitudinal compressive bending stress causes tensile stress in a direction transversal to the fibres, which is followed by buckling of the fibres.

Consequently it was tried to improve this weak point in the bamboo by a circular prestressing, by wrapping sisal rope tightly around each internode and then wetting it. The result was bad: the ultimate bending stress was only 82%! (69 N/mm^2, st. dev. 22 N/mm^2, E = 20 400 N/mm^2 with st. dev. 2860, and n = 4).

On the contrary, De Jonge (in the discussion with Meyer and Ekelund, 1922) reports about prestressed bamboo for masts and spars of sailing yachts:

"I made a number of experiments with wire band which were wound round the bamboo tightly and were soldered up. With these bands the bamboo's strength was completely changed, the shear being much increased and therefore the bamboo's strength was vastly improved. The maximum spacing of such bands for 4-in. to 6-in. bamboo mast was found to be between 10 to 12 times the diameter. If the spacing was about 7 to 8 times the diameter the torsion stress to which masts are subjected was well taken up by the strengthened bamboo".

My bad experience could be explained by the not perfectly circular circumference of our bamboo. To end up with, in building prestressed bamboo is no practical solution, due to the swelling and shrinking of the bamboo in wet and dry weather.

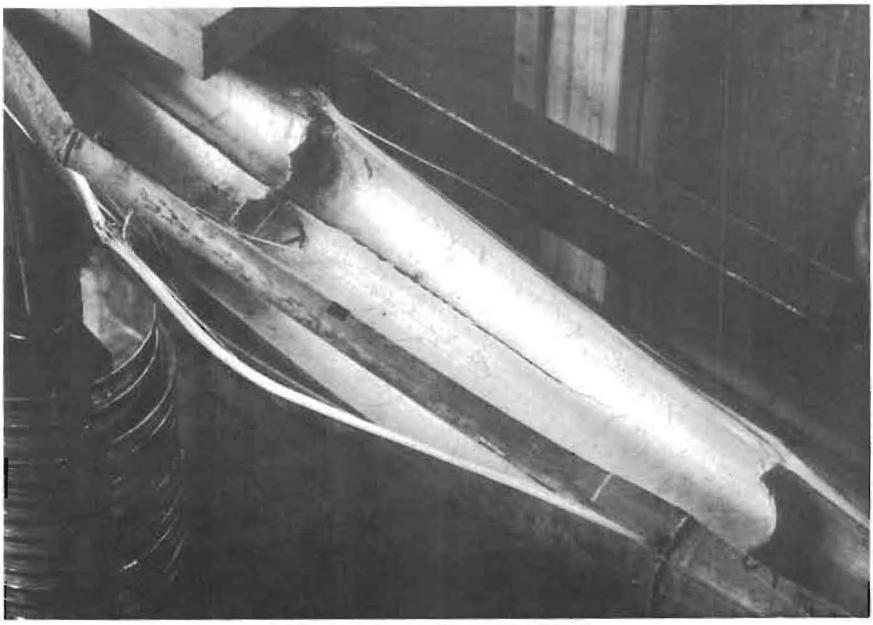
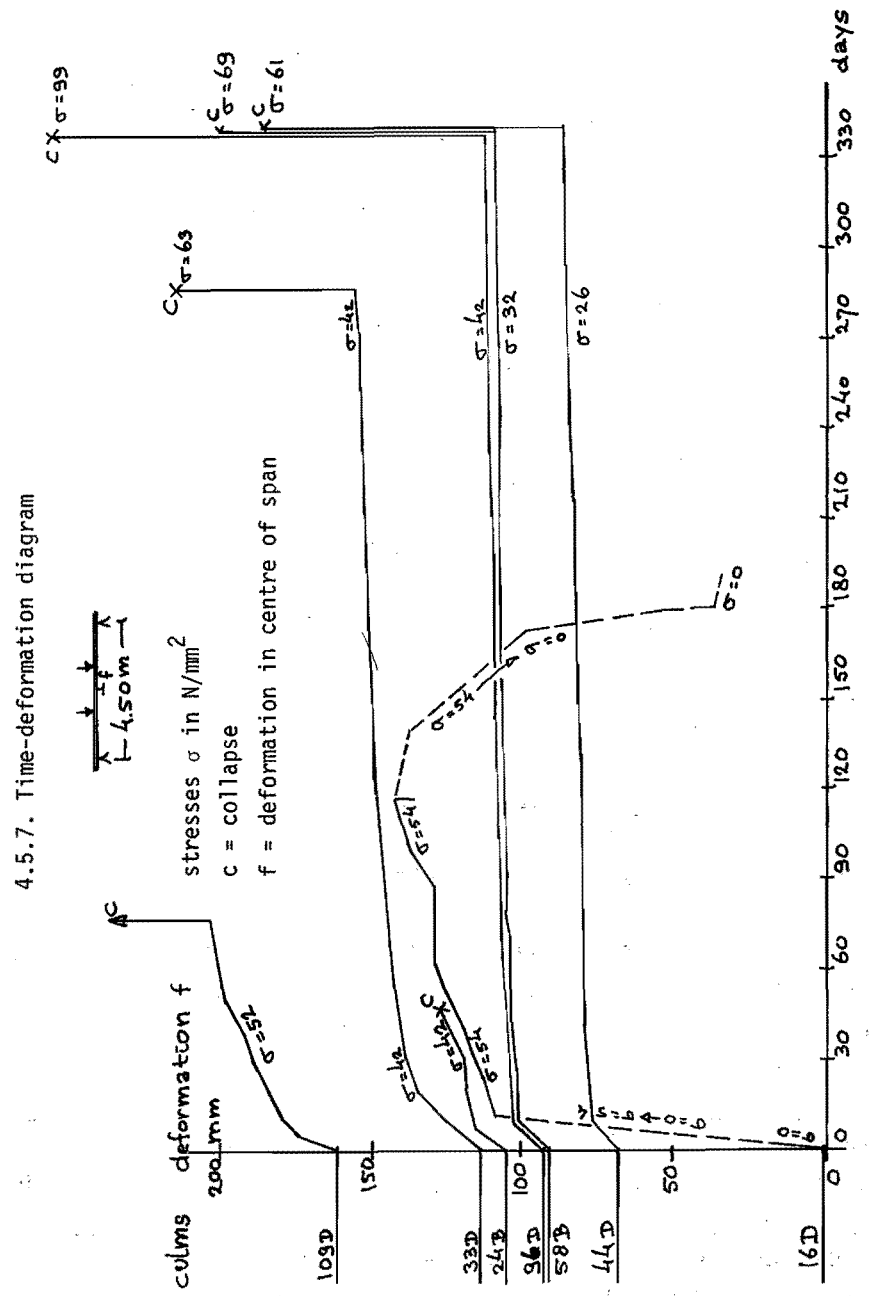


Photo 4.5.5. Collapse in bending
Photo 4.5.6. Long-term bending

Fig. 4.5.7.


4.5.7. Time-deformation diagram
stresses σ in N/mm²
c = collapse
f = deformation in centre of span
4.50m
culms deformaton f
200 mm
150
100
50
0
0 30 60 90 120 150 180 210 240 270 300 330 days
16D
44D
58D
96D
24D
33D
109D
σ=99
σ=69
σ=61
σ=63
σ=42
σ=42
σ=32
σ=26
σ=0
σ=54
σ=41
σ=54
σ=54
σ=42
σ=42
σ=0
σ=0
σ=0
σ=0
σ=0
σ=0

4.5.3. Long-term tests

Short-term bending tests are rather well described in literature. Conversely, long-term tests can hardly be found. Only Atrops mentions the effect of time on the bending behaviour. He studied four-point bending tests, free span 3.60 m, stress 16 N/mm^2 (i.e. 15 per cent of short-time strength). The load was removed every 24 hours for a short while in order to measure the remaining deformation, and the load was replaced. The total deformation after 20 days is 165 per cent of the immediate deformation. The total deformation can be divided into 64 per cent of plastic and 36 per cent of elastic deformation.

After 20 days the culms were loaded to failure, which occurred at 75 per cent of the ultimate stress in short-term loading.

My tests were carried out in sevenfold times as four-point bending tests, free span 4.50 m, with a load (concrete blocks or steel discs) on two points, see picture 4.5.6. The results are shown in figure 4.5.7.: the deformation in mm is plotted against the time in days and, in addition, the calculated bending stress for each culm is given.

The results are shown in the next table (4.5.8.)

culm	time days	σ long N/mm^2	σ fail N/mm^2	deformations (in relation to immediate)		initial ε in 10^{-3}
				long	at failure	
fail by their own:						
24B	47	42	42	1.12	?	1.95
109D	76	52	52	1.26	?	3.23
loaded to failure:						
33D	285	42	63	1.36	1.88	2.39
96D	337	42	99	1.22	2.76	1.74
58B	337	32	69	1.19	2.18	1.87
44D	337	26	61	1.26	2.71	1.50
unloaded:						
16D	115	54	--	1.31	---	2.15
mean		41(n=7)		1.25(n=6)	2.4(n=4)	2.12(n=7)
st.dev.		10		0.08	0.4	0.57

Table 4.5.8. Results of long term bending tests.
"long" = before failure; "fail" = at failure. M.C. = 12%.

Discussion: for wood the long-term bending strength is about 55 per cent of short term. If this is valid for bamboo too, the long term strength could be 0.55 x 84 = 46 N/mm^2, which is not in contradiction with the figures above (mean 41, st. dev. 10 N/mm^2). The corresponding shear is 1 N/mm^2 (st.dev. 0.27 N/mm^2) which is only 45 per cent of the short-term shear strength.
The four stems, loaded to failure after having been loaded for 285 or 337 days already, failed at a stress of 73 N/mm^2 (with st.dev. 18), also at only 87 per cent of the short-term strength of 84 N/mm^2.
The deformation after a long period of loading is 1.25 times the immediate deformation; Atrops has found 1.65 times, but the time-schemes are different.
Discussion of these results follows in the next paragraph, mainly sub E.

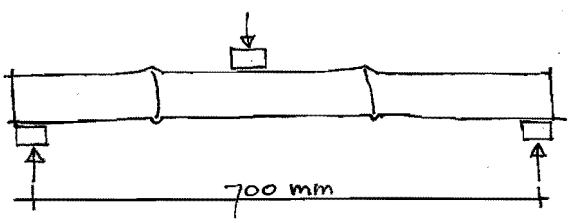
4.5.4. Discussion

A) Moisture content

Comparative tests on the bending strength of green and dry bamboo were carried out by Limaye (1952) and Sekhar a.o. (1962). In green bamboo the M.C. is about 80 per cent (st. dev. 24), in dry bamboo about 12 per cent. For dry bamboo the ultimate bending stress is 1.5 times the stress for green bamboo. A further analysis is not possible.

B) Node or internode

In view of the fact that most tests have been done on a free span of 700 mm, i.e. about two internodes long, the factor node or internode had a significant influence in the tests by Limaye (1952). Consequently the Indian Standard 6874 (1973) has standardized the position of nodes in the bending test:



As argued in par. 4.5.2., I did not follow this standard, but I carried out four-point bending tests with a free span of 3.60 m (short term) or 4.50 m (long term).

C) Position along the culm

This influence has been studied by Limaye (1952) and Suzuki (1948). Limaye has found for green bamboo the results given in table 4.5.9.

	bottom	middle	top	st.dev.
ultimate bending stress N/mm^2	73	65	66	1
E-modulus N/mm^2	10700	11850	13800	300

Table 4.5.9. Limaye's results on bending along the culm.

These differences are significant. But here is a remarkable apparent contradiction: the bending stress decreases with height, and the E-modulus increases. This happens likewise in dry condition. This contradiction can be explained, however. The ultimate bending stress decreases with height in correlation with the shear (fig.4.6.9.): bending stress is, in fact, weakness in shear! And as to the E-modulus: this increases with height, since the percentage of sclerenchymafibres increases.

D) Age

Bending in relationship with the age of the bamboo has been studied by Limaye (1952), Sekhar a.o. (1962) and Sekhar/Bhartari (1961). A summary of their results is plotted in fig. 4.5.10.

The bending-strength increases with age in Limaye's reports, but not in those by Sekhar. Even occur some ups and downs, which cannot be explained by comparing with mass per volume. A clear conclusion is not possible.

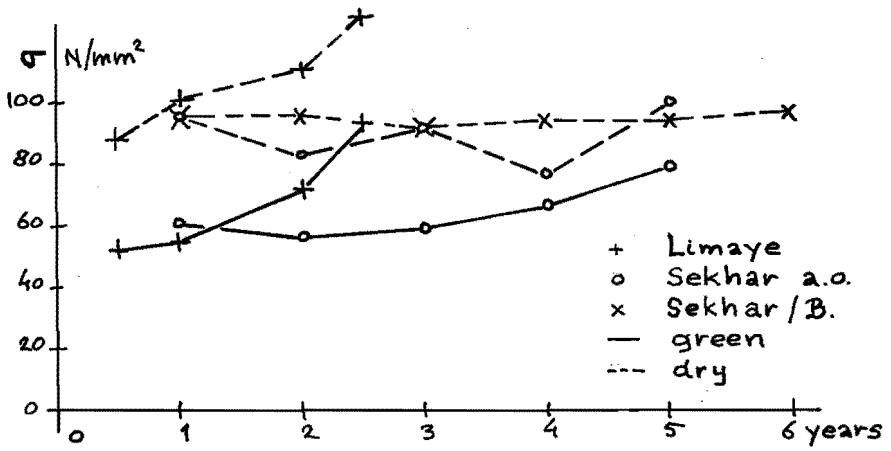


Fig. 4.5.10. Ultimate bending-stress plotted against age.

E) Structure of bamboo

By structure is meant the chemical composition, e.g. the percentages of cellulose, lignin, etc., and the crystalline/non-crystalline ratio of the cellulose. These data are important for the creep of bamboo (and wood as well).

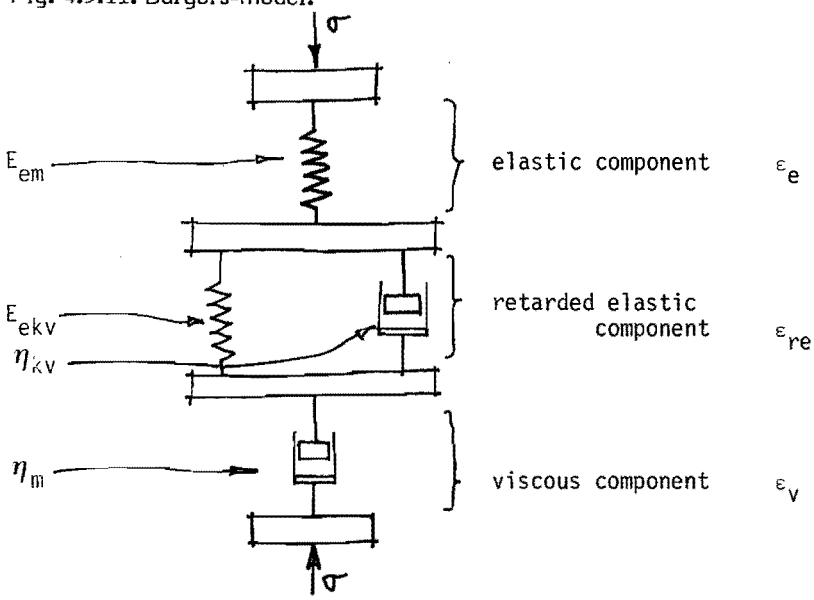
For wood creep is described by a Burgers-model, see figure 4.5.11. According to Kollmann: "Highly crystalline cellulose regions in an isolated state would have the properties of a spring. Amorphous lignin would have the properties of an isolated dashpot".

As to the influence of the amorphous and crystalline parts of the cellulose, Gordon writes:

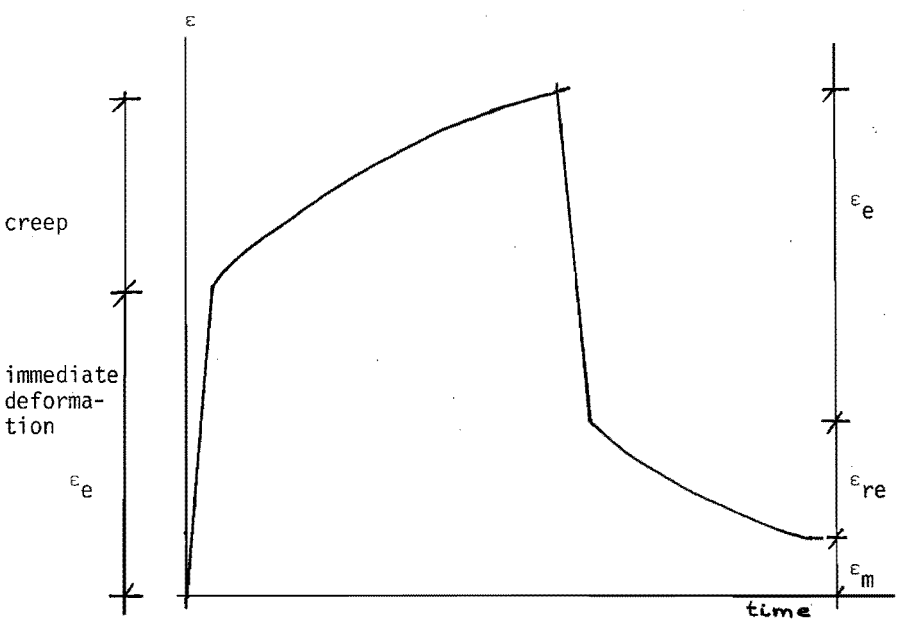
"The cause of the creep is most probably simply that, in the amorphous part of the cellulose, the rather badly stuck hydroxyls take advantage of changes in moisture and temperature to shuffle away from their responsibilities. It is unlikely that the crystalline part of cellulose creeps to any measurable extent".

In my opinion, the Burgers model might be used as well to describe creep in bamboo, because the compositions of wood and bamboo do not differ very much, as can be seen from tables 4.5.12 and 4.5.13.

Fig. 4.5.11. Burgers-model.



e = elastic
kv = kelvin-voigt
m = maxwell



percentages	bamboo	deciduous wood	conifer wood
cellulose	55	50	55
other polysacharides	20	25	15
Lignin	25	25	30
Source	Hidalgo p.32	Siau p.11	

Table 4.5.12. Compositions of bamboo and wood.

species	crystallinity %	
wood		
Pinus radiata,		
5th annual ring	72	
10th annual ring	58	mean = 62
15th annual ring	57	st.d. = 8
bamboo		
Melocanna bamb.	50	
Bambusa arund.	55	
Bambusa polym.	62	
D.strictus	62	mean = 58
D.strictus	62	st.d. = 5
D.strictus	58	

Table 4.5.13. Crystallinity percentage (Preston a.o. 1950).

The relationship between crystallinity and creep has been studied by El-Osta and Wellwood (1972). If:

Y = total creep in $\mu = 10^{-6}$

X = relative degree of cell wall crystallinity,

than

Y = 1160 - 16.5 x if initial strain = 3000μ,

Y = 2580 - 36 x if initial strain = 6000μ,

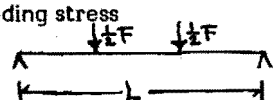
(for Douglas fir and Sitka spruce, time of creep 60 minutes)
The relative degree of crystallinity is between 52 and 64 per cent.

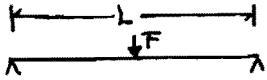
They also report that the microfibril angle has an influence, and this angle differs for bamboo and wood; as a result this could cause a different creep behaviour.
Unfortunately, the creep after 60 minutes of loading has not been observed, and so a comparison between my tests and their formula is not possible.
The creep is 65 per cent (Atrops) or 25 per cent (author). 50 per cent is normal for wood. The low creep of 25 per cent could be explained by the high percentage of cellulose (table 4.5.12), and especially by the steeper angle of the microfibrils (10^{o}, compared with 20^{o} in wood), but the crystallinity is lower than in wood (table 4.5.13.). And this explanation makes it even more difficult to understand Atrop's results.
More research in this field will be necessary.

F) Mass per volume

The relationship between bending strength (σ) and mass per volume (G) can be described by the ratio σ/G, but because failure in bending is due to shear in the neutral layer, the ratio σ/G might be replaced by the ratio between this shear stress and the mass per volume τ/G.
The ratio between the ultimate bending stress σ and the shear stress τ in the neutral layer is 2L/3d in case of a four-point-loading, and L/d for a 3-point-loading, since:

$$\sigma = \frac{M.\frac{1}{2}D}{I} \qquad \text{and} \tau = 2\frac{\frac{1}{2}F}{A}$$

in which
σ = ultimate bending stress
M = 1/6 FL for 

M = 1/4 FL for 

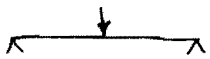
D = outer diameter of bamboo
d = inner diameter of bamboo

$$I = \pi (D^4 - d^4)/64$$

$$A = \pi (D^2 - d^2)/4$$

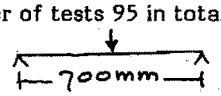
from which follows

σ/τ = 2L/3d for

σ/τ = L/d for 

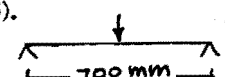
Unfortunately, among all authors listed in table 4.5.0., only Sekhar and Bhartari (1961) and Sekhar and Gulati (1973) mention both the inner diameter of the culm and the mass per volume. The calculations follow in tables 4.5.14 and 4.5.15.

age years	σ N/mm^2	d mm	$\tau=\sigma d/L$	mass per volume G	σ/G	$(\tau/G) \times 10^3$
1	96	20	2.74	646	0.149	4.25
2	96	22	3.02	703	0.137	4.29
3	92	24	3.15	718	0.128	4.39
4	95	24	3.26	706	0.135	4.61
5	94	25	3.36	672	0.140	5.00
6	97	18	2.49	608	0.160	4.10
		mean			0.141	4.44
		st.dev.			0.011	0.32
		var.coeff.in per cent			8	14

Table 4.5.14. Bending stress and shear, as by Sekhar and Bhartari (1961). Dry bamboo. Numer of tests 95 in total, about equally divided over the six ages.
Scheme: 

The continuously increasing τ/G for the ages to 5 years might be regarded as an improving quality of the bamboo during these years of growth. The six-years old bamboo should be considered as over-ripe then. It is regrettable that tests are not continued for bamboos older than six years.

	$\sigma N/mm^2$	σ/G	τ/G
mean	120	0.161	5.79×10^{-3}
st.dev.	37	0.028	1.64×10^{-3}
var.coeff.in %	31	17	28

Table 4.5.15. Bending-stress and shear in Dendr.Str. from 7 different localities; Sekhar and Gulati (1973).
Dry bamboo. Scheme: 

The ratio τ/G has a variation coefficient which in both tables is higher than that of σ/G. However, from a mechanical point of view the τ/G-ratio is a better one. Its greater variation coefficient might be caused by an accumulation of errors in σ, d, L and G. The ratio between σ and G can be compared with the results by other authors, see table 4.5.16.

Green bamboo		σ/G		no.of
author	mean	st.dev.	var.coeff.	tests
Limaye (1952)	0.117	0.017	15%	240
Sekhar a.o. (1962)	0.107	0.014	13%	120
Sekhar/Gulati (1973)	0.115	0.026	23%	?
dry bamboo				
Limaye (1952)	0.146	0.021	14%	240
Sekhar a.o. (1962)	0.127	0.019	15%	120
Sekhar/Bhartari (1961)	0.141	0.011	8%	?
Sekhar/Gulati (1973)	0.161	0.028	17%	?

Table 4.5.16. The relationship between the ultimate bending stress σ (in N/mm^2) and the mass per volume G (in kg/m^3); three-point tests.

A conclusion might be that the relationship between ultimate bending stress and mass per volume is about .11 for green and about .14 for dry bamboo.

4.5.5. Conclusions

1. A relationship of bending-strength with sclerenchyma content is not known.
2. The ratio between the ultimate bending stress in N/mm^2 and the mass per volume in kg/m^3 is .11 for green bamboo and .14 for bamboo with 12% M.C.
3. The effect of M.C. is significant for the difference between green and dry bamboo.
4. The position along the culm is significant: bending-strength decreases from bottom to top. E-modulus increases.

5. The question whether there is a node or an internode in the centre of the span is significant if the free span equals about two internode-lengths.
6. Form and size of the specimen, i.e. a full bamboo or a split bamboo, are presumably significant.
7. The ultimate bending strength is determined by the ultimate shear stress in the neutral layer and by the ultimate tensile strain transversal to the fibres in the top of the cross-section.
8. Creep in bamboo could be described with a Burgers-model.

4.5.6. What remains to be done

- Studies on creep (and recovery)
- Studies on the effects of free span and type of test (three- or four-point) on test results.
- Studies on the influence of age.

4.6. Shear

4.6.1. Introduction

Shear is important in bamboo, because it is the weakest point. Already in 1922, Meyer and Ekelund gave a summary of the tension-, bending- and shear-strength of beech, oak, pine, fir and bamboo, demonstrating that bamboo is as strong as wood in tension and bending, but much weaker in shear.
In their opinion the shear strength of the mentioned woods is between 20 and 30 per cent of the compressive strength of the wood in question, but of bamboo the shear strength in their tests is only 8% of the compressive strength (Comment:par.4.6.5.)
This lack of shear may be a disadvantage for the structural use of bamboo, it is, however, a great advantage for the use of bamboo by farmers and other people to make baskets, matting, and all kinds of handicraft in which split bamboo is used. We should realise that our problem is their luck. In the use of bamboo in structures, shear is a problem in bending and in joints. In bending, failure does not occur due to an exceeded tensile strength of the fibres, but on account of a loss of cohesion between the fibres, in which shear sometimes plays a role.
Joints always correlate with holes, which introduce shear into the bamboo.
In literature the publications on shear in bamboo are not abundant, see summary in table 4.6.1. It is rather difficult to discuss this literature, because the data (species, age, etc.) are far from sufficient, and because all test methods are different. Therefore, we shall not try to find any conclusion.

Table 4.6.1. Summary of literature on shear.

author	ultimate shear stress in N/mm^2	test method	no.of tests	remarks
Meyer and Ekelund	3.1	3- and 4-point bending test.	150	no data on species, age,humidity,etc.
idem	7.1	fig.4.6.2.	4	green bamboo,internode
	8.1	fig.4.6.2.	2	green bamboo,node
	8.1	fig.4.6.2.	6	dry bamboo,internode
	8.0	fig.4.6.2.	8	dry bamboo,node
ibidem,Chow	13.8	description	?	no data on species,etc. Values appear high. node
	18.9	is not clear	?	internode Values appear very high
ibidem, Dickerson	8.9	?	3	green bamboo
Motoi Ota		fig.4.6.3.		Phyllostachys pubescens Mazel,moisture content 15.2%
	12.5	fig.4.6.3.	5	highest values,with H=20mm and W=20mm
	10.5	fig.4.6.3.	5	lowest values, H=40mm and W=30mm. Phyllostachys reticulata C.Koch;moisture content 14.6%
	14.9	fig.4.6.3.	5	Highest val.]W en H
	11.7	fig.4.6.3.	5	Lowest val.]as before
Sekhar e.a.		fig.4.6.3. but: W=12,25,37,50mm H=25,37,50mm		Bambusa nutans, green,MC.75-109 per cent
	6.7		24	age 1 year
	7.7		36	age 2 years
	7.9		36	age 3 years
	9.8		33	age 4 years
	7.9		48	age 5 years
Atrops	19.8	fig.4.6.4.A	32	dry bamboo
	16.7	fig.4.6.4.B	32	dry bamboo Shear-strength decreases with increasing wall-thickness

Fig. 4.6.2.
A bar through the hole A is forced towards the hole B.
Shear area is dashed.

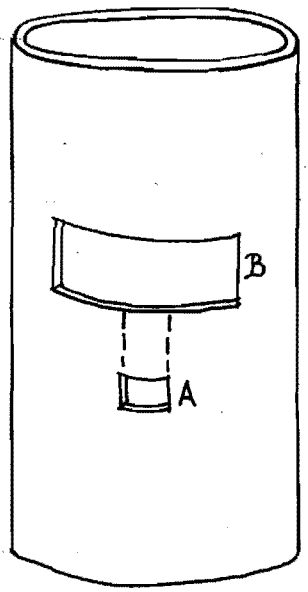


Fig. 4.6.3. Motoi Ota's type of specimen.
w = 10, 20, 30 mm. resp.: H = 10, 20, 30, 40 mm. resp.

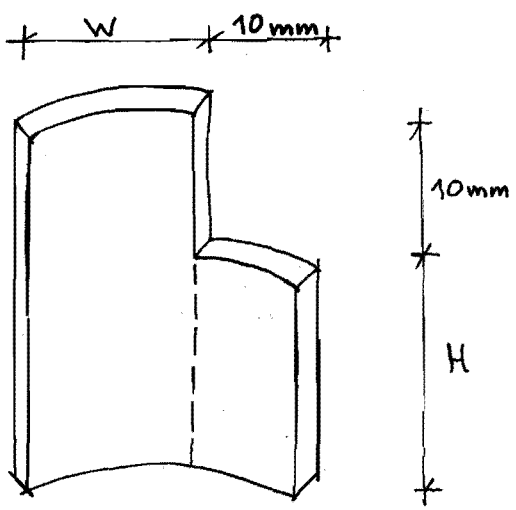


Fig. 4.6.4. Shear test by Atrops.
Measures in mm.

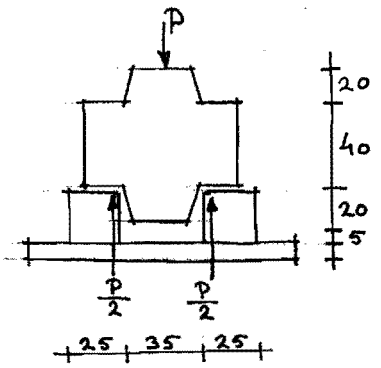
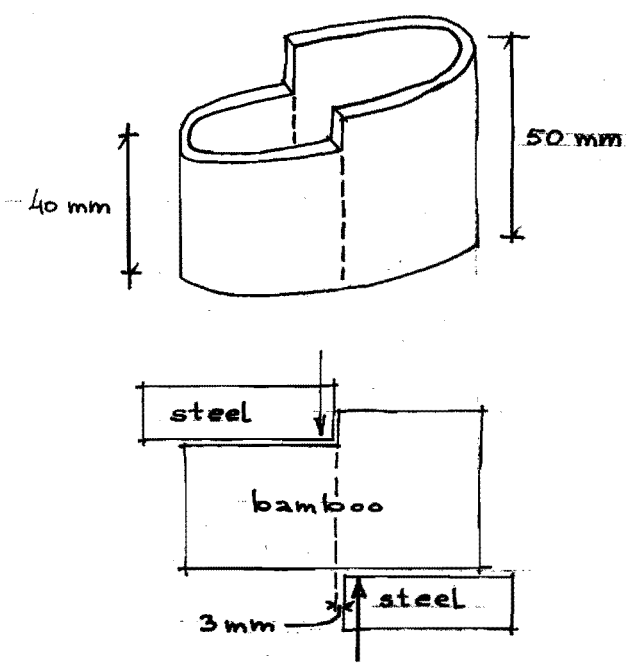


Fig. 4.6.5. Shear specimen no. 1 in my research.



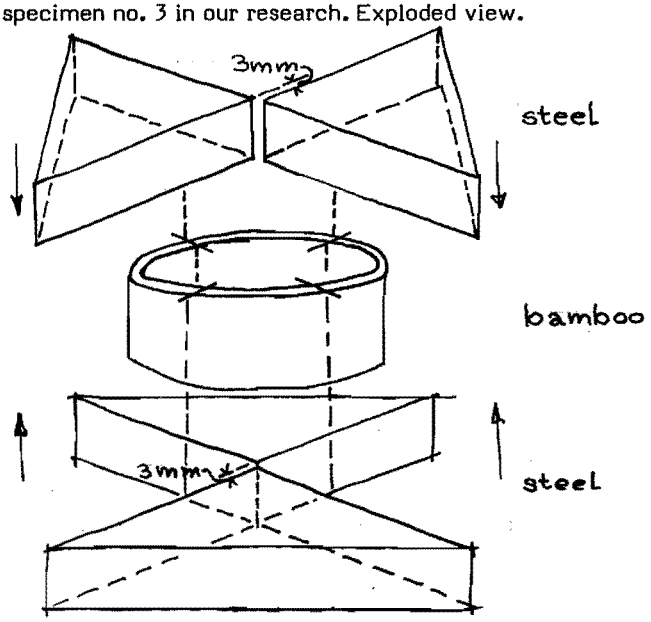
4.6.2. Purpose of shear-tests

The purpose of tests is to determine which factors are significant and which not. As stated in par. 4.3., this research was restricted to one species (Bambusa Blumeana), one age (three years), and the conditioned state. We are interested in the influences of moisture content, position along the culm and (inter)node, because these three might be significant. The remaining factors are the form and size of the specimen, the distance between two shear forces, and the testing-speed. For these tests the next forms are chosen:

1. As figure 4.6.3., from Motoi Ota, but with two shear areas, because this resembles more a practical situation, see figure 4.6.5., as prescribed for wood by ASTM D143-52, par. 88 and fig. 16.
2. As Atrops, see fig. 4.6.4.B, as prescribed for wood by DIN 52187.
3. A simple form, designed by myself see fig. 4.6.6.

The testing-speed has been taken from DIN 52187, which prescribed a loading speed for wood of 0.1 N/mm^2s. The specimens for these tests were taken from one stem with 12% moisture content. From each of the twelve internodes three specimens were made. From these specimens three samples of 12 specimens each were systematically chosen in order to avoid any influence of differences between culms, moisture content, position along the culm, size (height) of the specimen and (inter)node.
The results are listed in table 4.6.7.

Fig. 4.6.6. Shear specimen no. 3 in our research. Exploded view.



tested form	figure	ultimate shear force in N per shear area	var. coeff.	ultimate shear stress in N/mm^2	variation coeff.
1	4.6.5.	2910	16%	8.70	16%
2	4.6.4.	1690	22%	5.90	22%
3	4.6.6.	2825	15%	10.26	26%

Table 4.6.7. Results of shear tests.

In this case of shear, I consider also the forces and not only the stresses, because the shear force is determined by failure in one, two or three out of the four shear areas and, after failure, in one or two areas another greater shear force can be applied to the specimen before another area fails and the specimen is considered as lost.

First of all the shear forces are considered. The shear forces of 1 and 3 are about equal. Their variation coefficients are equal too. Form no. 2 has a lower force and a larger variation coefficient. So we reject no. 2, and from the nos 1 and 3 we take no. 3 because it is simple to make.

Next come the shear stresses. Again, no. 2 is lower, and is therefore rejected, because in my opinion this low value is due to harm in the specimen, caused by sawing. The variation coefficient of no. 1 is equal in shear force and stress, but for no. 3 the variation coefficient is 15 for force and as much as 26 for stresses. This is due to the fact that specimen no. 3 has four shear-areas, and the shear stress is determined as the shear force divided by the sum of the four shear-areas. Specimen 1 has only two areas, and so this problem is simpler with no. 1. Considering stresses alone, one would chose no. 1, but in my experience the form of no. 1 is rather difficult to make. Considering also the forces, and the simpleness of form no. 3, I have chosen this form, because in structures shear forces in a joint with a number of shear areas are more interesting than shear stresses. However, I agree with everybody in stating that this choice is questionable.

4.6.3. Methods of our tests

Apart from the shear tests on the form as explained in 4.6.2., one can calculate an ultimate longitudinal shear stress from bending tests on culms. Thus we get two series of shear tests.

a) Shear tests in the form as represented by fig. 4.6.6. As stated previously, the interest is in the influences of moisture content, position along the culm, the height of the specimen, and (inter)node.
These factors are taken as follows:
- moisture content: 4, 9 and 12% resp.
- position along the culm: bottom, middle and top,
- height of the specimens: 40, 80 and 120 mm.,
- (inter)node: internode or node.

So we need at least 3 x 3 x 3 x 2 = 54 specimens, which can be made out of three stems. The influence of the differences between the stems is taken as a parameter, and consequently the remaining factors are free from this influence. These tests were done with a hydraulic press, capacity 200 kN, machine-error 0.2%, loading-speed 0.1 N/mm^2s. The number of specimens was 54.
b) Second, from the bending tests on full culms the ultimate shear stress can be calculated in the many cases where shear was the reason for failure. Moisture content 12%. Failure occurs in the middle of a stem, and in an internode. The number of specimens is 11 on short-term tests and 7 on long-term tests (i.e. a half up to a full year of loading time). The moisture content is always about 12%, in equilibrium with a R.H. of 70%. Each specimen is a full culm, length 5 m, tested in a four-point bending test, free span 4.50 m. The loading-speed is 0.3 N/mm^2s, whereas DIN 52186 prescribes 0.7 to 0.8 N/mm^2s for wood. In my opinion this is too fast for bamboo. Because the E-value remains linear, this loading-speed corresponds with a deformation-speed of 0.5 mm/s; ASTM D143-52 prescribes 0.04 mm/s for wood, but this has already been discussed in par. 4.5.2.

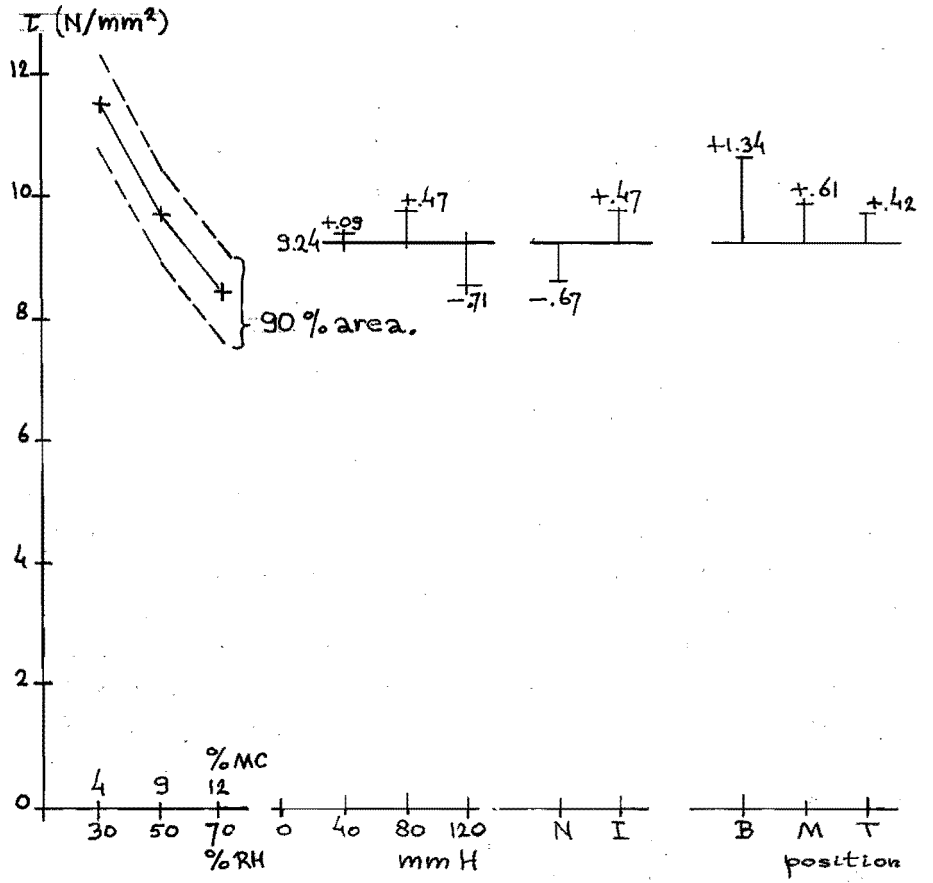
4.6.4. Results

The first series of tests (on the form of fig. 4.6.6.) was set up as an orthogonal scheme, and thus an analysis of variances was very easy. The statistical model has been dealt with in par. 4.2. The results are listed in table 4.6.8. and they are graphically presented in fig. 4.6.9. Table 4.6.8. contains the factors and interactions with their respective P-values. It can be seen that only the interaction between moisture content and position can be neglected.
In fig. 4.6.9. the estimated values of the ultimate shear stress are plotted as functions of moisture content, while the remaining factors were kept constant during this calculation. The influences of height of the specimen, node or internode and position along the culm are plotted at the right. The second series of tests concerns the bending tests on full culms. The calculated longitudial shear stress is listed in table 4.6.10.

parameter no.	factors	estimated parameter β in N/mm^2;	st.dev.	P-values	
1	constant	9.2	-	0.0000	
2	moisture	1.0	0.1	0.0000	0.0000
3	content	-0.1	0.1	0.0885	
4	height of	-0.1	0.1	0.4215	0.0005
5	specimen	-0.3	0.1	0.0001	
6	(inter)node	0.8	0.1	0.0000	
7	culms	0.6	0.1	0.0000	0.0000
8		0.4	0.1	0.0000	
9	position along	-0.5	0.1	0.0001	0.0004
10	culm	-0.1	0.1	0.2315	
11	interaction moisture x	0.5	0.1	0.0006	0.0023
12	(inter)node	0.0	0.1	0.6332	
13		-0.1	0.2	0.5440	
14	interaction	-0.0	0.1	0.8670	0.4920
15	moisture x	-0.0	0.1	0.6265	
16	position	-0.1	0.1	0.1011	
17	interaction height x	0.5	0.1	0.0005	0.0015
18	(inter)node	0.0	0.1	0.3452	

Table 4.6.8. Results from shear test. Underlined P-values are significant. For original data see table 4.11.2.

Fig. 4.6.9. Estimated values of ultimate shear stress as functions of moisture content, with 90% areas, and influences of other factors.



	short term	long term($\frac{1}{2}$-1 year)
no. of tests	11	7
ultimate shear stress mean, N/mm^2	2.25	1.01
standard deviation, N/mm^2	0.65	0.27

Table 4.6.10. Ultimate longitudinal shear stress in bended full culms.

4.6.5. Discussion

As to the foregoing tests on shear we learn from table 4.6.8. that all factors (moisture content, height of the specimen, (inter)node and position along the culm) are significant, and in figure 4.6.9. we see their influence on the shear stress. The significance of the moisture content fits in with the studies by Motoi Ota (1956). It is a matter of common sense: the strength of a material decreases with increasing moisture content. From the height of the specimen follows that the best shear stress is reached at 80 mm. height. A lower stress at a shorter length might be understood as a result of local irregularities. A lower stress at a greater length is logical because the central part does not react as effectively as 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 cannot go on straight forward because many vessels cross them to reach the diaphragm inside the node. The last relationship between shear stress and position along the culm, indicates a shear stress slightly decreasing from bottom to top. This is not in conformity with Atrops and Suzuki who both found that the shear strength increases with decreasing wall-thickness, i.e. from bottom to top. My results on shear are controversial, but I cannot find any mistake. An explanation could be the different statistical treatment: Atrops draws his conclusion from the observed values, and I draw my conclusion only after an analysis of variance.

I do not agree with Atrops, in that the shear stress correlates with the percentage of sclerenchyma-fibres. It is true that this percentage increases too from bottom to top (Grosser and Liese, 1974, p. 479), but shear occurs in a radial plane, parallel to most of the fibres. Consequently, it is the thickness of the cell-wall that determines the shear stress, and the weight by volume is the property concerned. This increases also with height (Suzuki).

From the second series of shear stresses, in bending of culms, we see a rather low value, which, however, fits in with Meyer and Ekelund. This shear stress is not a pure shear stress, but it is interwoven with bending stresses in the wall of the culm. These stresses are due to the fact that the action forces are carried by the top of the cross-section of the culm, and the reaction forces by the lower side of the cross-section.

Finally, there is the possible relationship between shear strength and percentage of rays, see table 4.6.11.

We should keep in mind that the shear strength is determined also by the thickness of the cell-walls, i.e. by the weight by volume. Table 4.6.11. is therefore extended with data on the weight by volume. From these data follows a relationship between the ultimate shear stress τ, the percentage rays R and the weight by volume G:

$$\tau = GA + BR$$

in which according to table 4.6.11.:

$\tau = GA + RB$

$11 = 467A + 7B$

$14 = 660A + 17B$

from which A = 0.0268 B = -0.2181

with st.dev. = 0.0067.

So the percentage of rays has a negative influence on the shear strength! After all this is evident: rays consist of parenchyma tissue, for food storage, not for strength. For bamboo this formula becomes τ = 0.0268 x G. This has been checked for the data of table 4.6.1., see table 4.6.12.

table 4.6.11.	softwoods mean	softwoods st.dev.	hardwoods mean	hardwoods st.dev.	source
percent ray volume (R)	7	-	17	-	Panshin and De Zeeuw
ultimate shear stress (τ) N/mm^2	11	1.9	14	3	B.R.E.
weight by volume (G) kg/m^3	467	88	660	154	B.R.E.

author	ultimate shear stress(τ) in N/mm^2	weight by volume (G) in kg/m^3		A=τ/G
Chow	18.9	862		0.0220
Motoi Ota	11.8	722		0.0163
	13.8	787		0.0175
Atrops	19.8	730		0.0271
	16.7	730		0.0229
			mean =	0.0212
			st.dev.=	0.0044

Table 4.6.12. Relationship between shear stress and weight by volume. Air-dry, internode.

The mean value for A is 0.0212, and its standard deviation is 0.0044. Taking into account the roughness of the data, this fits fairly well in with the A for wood (0.0268) with its st. dev. 0.0067.
If this ratio τ = 0.0212 x G is compared with the ratio for compression σ= 0.094 x G (table 4.4.17.), a ratio τ = 0.22 x σ follows, instead of the 8%-ratio stated by Meyer and Ekelund (see par. 4.6.1.)

4.6.6. Conclusions

1. There is a relationship between shear strength and fibre content, but seemingly without a physical meaning.
2. A relationship between shear strength and mass per volume exists:
   τ = 0.021 x G.
3. M.C. is significant for shear strength.
4. Position along the culm: idem.
5. Node or internode: idem
6. Height and form of the specimen: idem.
7. A shear area in a joint should be made from an internode, because the ultimate shear stress in a node is lower. It is true that the wall-thickness in a node is greater then that in an internode, but this difference is not enough to make the shear strength per length of the culm better for the internode (except if we consider the e.g. 50 mm. length of a node only).
8. Pure shear and shear in bending are to be determined in different tests.

4.6.7. What remains to be done

1. Study of the form of the shear specimen, including shear specimens with one shear area only.
2. A theoretical calculation of the shear strength of pectin, and a comparison of this value with the shear strength found on macroscale.
3. Long-term tests on shear.
4. Standardization of test methods.

4.7. Tension

The tensile strength and the modulus of elasticity in the case of tension are important for bamboo suspension bridges, e.g. in China and the Andes, for joints in bamboo trusses in which lashings are used to keep the bamboo together (Duff, 1941), and for reinforcement in concrete. Several authors describe methods to test the tensile strength of bamboo, but I met many problems when we tried to follow their prescriptions. The problem is that the tensile strength of bamboo is rather high, e.g. 200 - 300 N/mm^2, but the E-modulus in compression transversal to the fibre is very low, and this low E-value causes considerable problems in the grips. The problem of tensile testing grows even worse due to the low shear stress. Therefore, failure in tensile tests of bamboo is in many cases caused by longitudinal shear or by transversal compression in the grip.

I have carried out some tests on tensile strength, with a method similar to that described by Atrops. But due to the limited strength of the joints, the tensile strength is not important for building practice, however. Even for reinforcement in concrete the tensile strength is not a critical point for the bamboo, but the durability and the bond are.

So I refrain from reporting on tensile strength tests. The interest in the tensile strength of bamboo has changed to another topic. 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. 4.7.1. shows two diagrams, both in a cross-section of a wall of a culm.

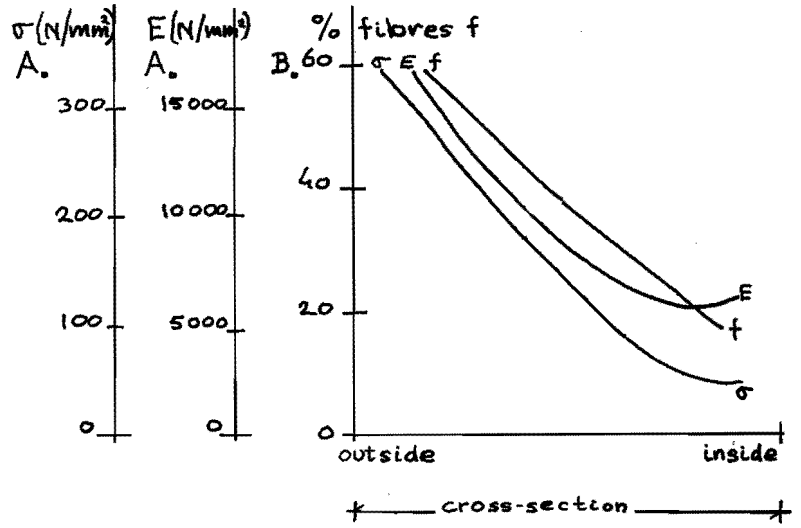


Fig. 4.7.1. Ultimate tensile stress, E-values and percentages of fibres in cross-section of wall of culm. (A from Duff, B from Grosser and Liese 1974).

Diagram A gives the ultimate tensile strength and the E-value, and diagram B the percentage of fibres. These diagrams are obviously similar, and they suggest rules of thumb like:

"ultimate tensile stress in N/mm^2 = (4 - 5) x percentage sclerenchymafibres" or a similar rule for the E-value. This statement is slippery, because diagram A holds for Phyllostachys pubescens from Shanghai in China, and diagram B for Phyllostachys Makinoi from Taiwan.

I have therefore tried to collect data on tensile strength together with data on the sclerenchyma or cellulose content for several species. This research into litterature does not give results which are sufficiently comparable, because data are collected from many different authors, and each of them has used a different test method.

Another entrance to this problem is the theoretically calculated tensile strength for cellulose of 1500 N/mm^2 (Kollmann p. 321). A sclerenchymacell in bamboo contains:

40 per cent lumen;

50 per cent cell wall layer with cellulose fibrils nearby parallel to the cell axis;

10 per cent cell wall layer with cellulose fibrils in a spiral.

For the tensile strength I neglected the lumen and the spiral layer. The remaining 50 per cent layer consists of 50 per cent cellulose and 50 per cent lignin. For the tensile strength I neglected the lignin.

Evidently, the tensile strength of a sclerenchyma fibre in this case is 0.5 x 0.5 x 1500 N/mm^2 = 375 N/mm^2, so rounded of to 4 in the rule of thumb, falling in the range expected. As to the E-value there are similar problems. In chapter 3 an E-value of 70 000 N/mm^2 is derived for the layers in the cell wall in which the microfibrils are nearby parallel to the cell-axis. Assuming a 50 per cent for these layers and another 50 per cent for the spiral layers, the lumen and the primary layer, an overall E-value for the sclerenchyma-cell becomes
.50 x 70 000 = 35 000 N/mm^2.
With this value, a rule of thumb for the overall E-value of a bamboo culm can be formulated:
"E-value (N/mm^2) = 350 x percentage of sclerenchyma".
A control of this rule of thumb with data from literature is given in table 4.7.2.

species	sclerenchyma %	E-value measured N/mm^2	E-value from rule of thumb
Bambusa tulda	45	19300	15750
Dendrocalamus strictus	43	17400	15000
Source	Grosser/Liese	Hidalgo	

Table 4.7.2., See text.

The E-values fit rather well, but further study is desirable, similarly as to the tensile strength in relationship with the structure of bamboo.

4.8. Poisson's ratio

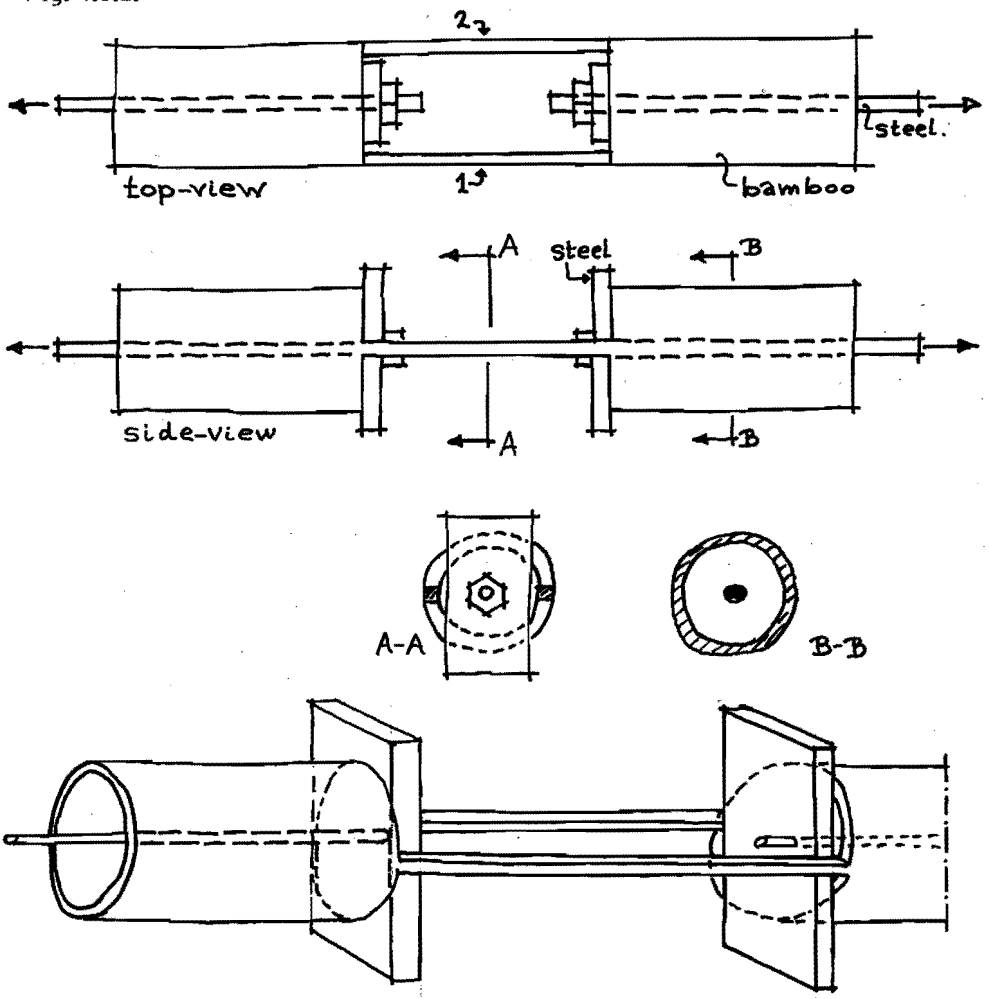
In literature only one reference (Cox, 1969) is found on the Poisson's ratio. Cox measured the ratio between axial elongation and transverse contraction on 11 tensile specimens, with strain gauges. His results are: mean value 0.317, standard dev. 0.052, variation coeff. 16 per cent. Similarly, I have determined Poisson's ratios in a tensile test, as in figure 4.8.1. In the bamboo in cross-section A the Poisson's ratio is measured with strain-gauges on the outer skin, over the wall-thickness and at the inner side of the culm.Due to the enormous amount of work needed for this kind of test, only one specimen was tested. The results were:

	side 1	side 2	mean
outer skin	0.49	0.54	0.51
wall thickness	0.32	0.31	0.31
inner side	0.34	0.28	0.31

The Poisson's ratio for wood for longitudinal-tangential is about 0.49 (st.dev. 0.06) and for longitudinal-radial it is about 0.41 (st.dev. 0.07) (Kollmann, page 298).

The results of the tests on wall-thickness and innerside (ratio = 0.31) fit well in with those reported by Cox and with the theoretical value of 0.3 for lignin. The measured value on the outer skin (0.51) is as high as the longitudinal value for wood, but contrary to wood, the outer skin has a high silica content and a high percentage of cellulose.More study is needed to explain this.

Fig. 4.8.1.



4.9. Weight by volume; M.C. versus R.H.

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 1580, and that of lignin 1400 kg/m^3. For bamboo this is 50 per cent of each. With 44 per cent material (the remaining 56 per cent being lumens and vessels) the weight by volume can be estimated as:

$$0.44 \times \frac{1580 + 1400}{2} = 660 \text{ kg/m}^3 \text{ (dry)}$$

which agrees fairly well with the tests.

The relationship between moisture content of the bamboo, and the relative humidity of the air, can be explained similarly. Fig. 4.9.1. gives the moisture content of wood and bamboo in relationship with the relative humidity of the air. For 100 per cent R.H. is plotted the fibre saturation point. To explain this figure, we assume that bamboo contains 55 per cent cellulose, which in its turn is crystalline (58%) or amorphous (42%) (Preston a.o.) In other words, the composition of bamboo is:

32 per cent crystalline cellulose;

23 per cent amorphous cellulose;

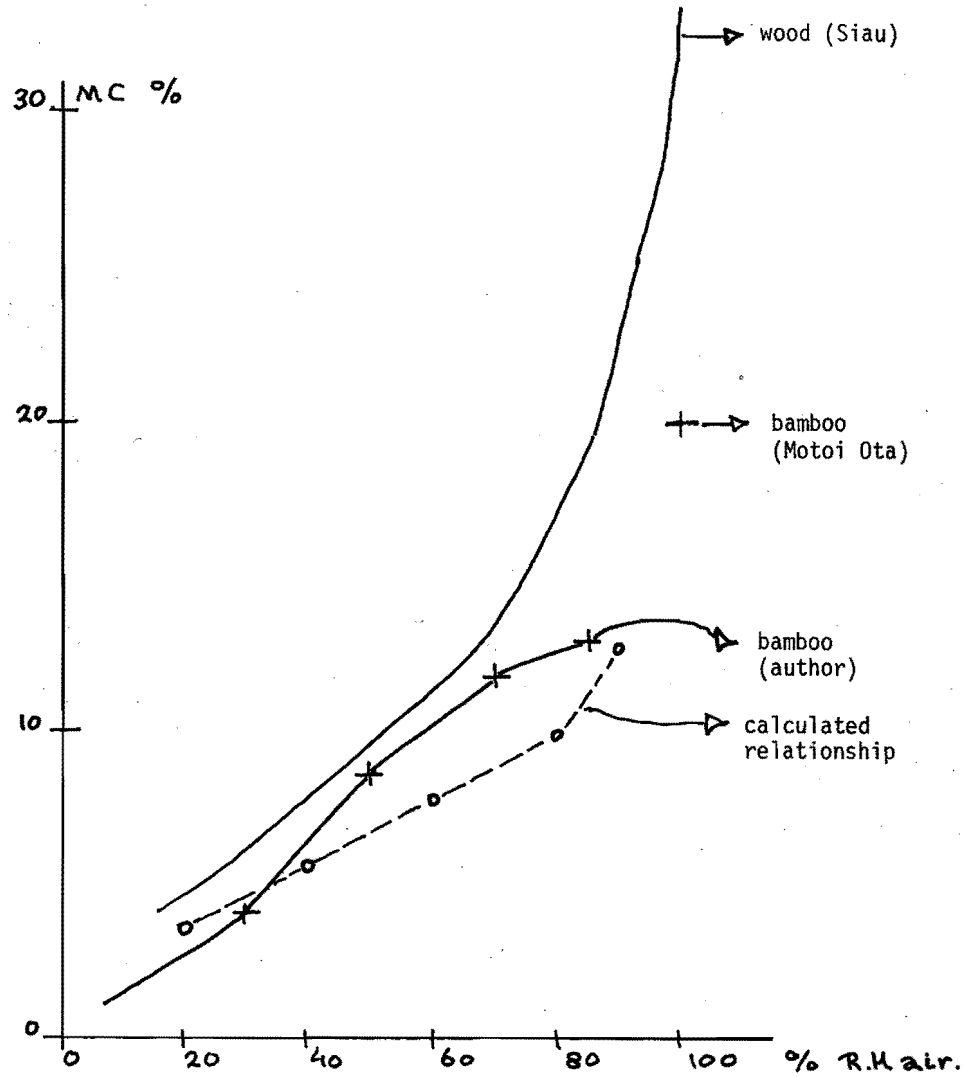
45 per cent lignin etc.

The crystalline cellulose does not absorb any water. The amorphous cellulose does, and its sorbtion ratio is 1.85, which means that it absorbs 1.85 times as much water as native cotton. The M.C. of native cotton is given in line (2) of table 4.9.2. The contribution of the amorphous cellulose of the M.C. of bamboo is given in line (3). Similarly, lines (4) and (5) reveal the contribution of the lignin. The theoretically calculated M.C. of bamboo is given in line (6), and plotted as -0-0-0- in fig. 4.9.1. This looks quite acceptable. In my opinion such explanations are useful to understand what is going on, and they may build bridges between biological and mechanical researchers.

(1)	R.H. air	20	40	60	80	90
(2)	MC native cotton	3	5	7.3	10.5	15
(3)	Amorphous cellulose in bamboo,MC=0.23x 1.85xline (2)	1.3	2.1	3.1	4.5	6.4
(4)	lignin, MC (Cousins)	5	8	10.5	12	14
(5)	0.45xline (4)	2.3	3.6	4.7	5.4	6.3
(6)	(3)+(5)=MC bamboo	3.6	5.7	7.8	9.9	12.7

Table 4.9.2. Theoretical calculation of the M.C. of bamboo, in percentages.

Fig. 4.9.1. Relationship between M.C. and R.H. for wood and bamboo.
Line -0-0-0-: see text.



4.10. References

ASTM-D-143-52(1972) Standard Methods of testing, small clear specimens of timber.

Atrops J.L. Elastizität und Festigkeit von Bambusrohren. Der Bauingenieur (1969), vol 44, pp. 220...225.

B.R.E. The Strength Properties of timber. Princes Risborough 1974. Cited are the data on pages 18 ... 61, for these woods for which the number of results for shear tests is 100 or more.

Cox and Geymayer Expedient Reinforcement for Concrete for use in S.E. Asia. Part 1: preliminary test of bamboo. Vicksburg (U.S.) 1969. Cited is page 30, and table 6 (in par. 4.8.)

Cousins, W.J. Elastic Modulus of Lignin as Related to M.C. Wood Science and Technology, vol. 10 (1976) pp. 9 ... 17.

DIN-52180...190, Prüfung von Holz.

Duff, C.H. Bamboo and its structural use. The Engineering Society of China, Session 1940-41, paper no. I.C.E.1. Shanghai 1941, 27 pp. Cited are pp. 5 and 6, and figure 9 (in par. 4.7.)

El-Osta and Wellwood Short-term creep as related to cell-wall crystallinity. Wood and Fiber (1972) p. 204...211.

Espinosa, J.C. Bending and Compressive strengths of the common Philippine Bamboo. The Philippine Journal of Science (1930) vol. 41 no. 2 pp. 121...135.

Glenn, H.E. Bamboo reinforcement in portland cement concrete. Engineering Experiment Station, Clemson, South Carolina, Bulletin no. 4, May 1950.

Gordon, J.E. The new science of strong materials. New York 1976. (p. 141).

Grosser, D and W.Liese Verteilung der Leitbündel und Zellarten in Sproszachsen verschiedener Bambusarten. Holz als Roh- und Werkstoff (1974) vol. 32 pp. 473...482.

Hidalgo, Bambu, Columbia (1974) (page 32)

Indian Standard 6874 (1973)

Karamchandani, K.P. — Role of Bamboo as a constructional material. National Building Organisation of India. Proceedings Symposium Timber and Allied Products. New Delhi (1959) pp. 430 ... 435.

Kollmann and Côté — Principles of Wood Science and Technology. Berlin 1968. Cited is p. 336 (par. 4.4.) p. 318 (p.4.5.)

Kumpe. George — An Experimental Bamboo Truss. The Military Engineer (1937) vol. 29 no. 166 pp. 288-289.

Limaye, V.D. — Strength of bamboo. The Indian Forester (1952) vol. 78, pp. 558...575; reprinted in Indian Forest Records (New Series) vol. 1 no. 1, Dehra Dun (1952).

McClure, F.A. — Some preliminary tests on the longitudinal Crushing Strength of Bambusa Tuldoides. Lingnan Science Journal (1938) vol. 17 no. 1. See B.R.S. Library Archive no. 161, Watford, U.K.

Mendenhall, W. — Introduction to linear models and the design and analysis of experiments. Wadsworth, 1968.

Meyer, H.F. and B. Ekelund — Tests on the mechanical properties of bamboo. Proceeding Engineering Society China, (1922-23) vol. 22 paper 7 pp. 141 ... 169.

Motoi Ota — Studies on the properties of Bamboo Stem. Bulletin of the Kyushu University Forestry. Cited are:

- year unknown, but before 1950, part 4, pp. 65 ... 69.
- 1950, part 7, vol. 19, pp. 25 ... 47
- 1953, part 9, vol. 22, pp. 87 ... 108
- 1955, part 11, vol. 24, pp. 61 ... 72
- 1955, part 12, vol. , pp. 73 ... 84
- 1956, part 13, vol. , pp. 121 ... 131.

Narayanamurti, — Editor of: The Use of Bamboo and Reeds in Building Construction, United Nations New York (1972)

Panshin and De Zeeuw, — Textbook of Wood Technology, New York 1964 (2) In par. 4.6. are cited pp. 112 and 152.

Parrat, N.J.	Fibre Reinforced Materials Technology (1972). Cited is p. 70.
Pierce, C.B.	The Weibull distribution and the determination of its parameters for application of timber strength data. Building Research Establishment, Current paper (1976) no. 26, Garston, Watford, U.K.
Preston, R.D. and K. Sing	The fine structure of bamboo fibres. Journal Exper. Botany (1950) pp. 214 ... 227 and (1952) pp. 162 ... 169.
Sekhar, A.C., and R.K. Bhartari	Studies on Strength of Bamboos: a note on its mechanical behaviour. Indian Forester (1960) pp. 296 ... 301.
Sekhar, A.C. and R.K. Bhartari	A note on strength of dry bamboo (Dendrocalamus Strictus) from Madhya Pradesh. Indian Forester (1961) pp. 611...613.
Sekhar A.C. B.S.Rawat and R.K.Bhartari	Strength of bamboos: Bambusa Nutans. Indian Forester (1962) pp. 67 ... 73.
Sekhar, A.C. and A.S. Gulati	A note on the physical and mechanical properties of Dendrocalamus strictus from different localities. Van Vigyan (1973) vol. 11 no. 3 + 4 pp. 17...22.
Sekhar, A.C. and B.S.Rawat	Strength tests on bamboo (1957) Indian Forest Leaflet nr. 147
Siau	Flow in Wood. Syracuse (1971) page 11 is cited in par. 4.5. and page 5 in par. 4.9.
Suzuki, Y.	Distribution of Specific gravity and bending strength along the culm. Bul. Tokyo Univ. For. 36, 188 (1948)
Teodoro, A.L.	A preliminary study of the transverse strength of structural bamboos. Agricultural Engineering vol. 6 no. 11 pp. 266.7 (1925)
Trojani, F	Passerelles en bambous. Bull. Econ. Indo-China (1930) April pp. 369B-373B. Libr.: Kew Gardens (Museum), London.

Vermeijden, P. Literatuuronderzoek betreffende het tijdeffekt van verschillende factoren op hout en houtverbindingen. (Literature survey on the time effect of several factors on timber and joints). (Orig. Dutch) Delft 1959.

Young, R.A. and J.R.Haun Bamboo in the United States: Description, Culture and Utilization. Agricultural Handbook nr. 193. U.S. Department of Agriculture, Washington 1961. (Cited: page 53).

4.11. Appendix

4.11.1. Compression

MC	H	N/I	Culm1			Culm2			Culm3		
			B	M	T	B	M	T	B	M	T
		N		70				82			83
	50							74			
		I	87	79	88	82	89	104	82	90	81
				68				91	87		
		N		69		62					91
12	100					62					
		I	71	70	77	61	91	88	89		99
			71	69		60	77		77		80
		N	71		68		77		58	71	87
	200				70				73		82
				72				100			
		I			83	75		93	85		88
				77				86			94
		N				64					
	50										
		I	79	90			78	89	71	85	
			85								
		N	81				70		86		
8	100										
		I	83	66			80	102	85		89
				78			78				
		N			70		81		66	70	
	200										
		I	69			81				82	
						76					
		N	62								
	50										
		I	79	105	90	76		103	83	95	
									83		
		N		82				83			98
4	100										
		I	64	88				91	79		111
			82	92							
		N		90				66		91	
	200							72			
		I	85	92						104	

Table 4.11.1., results of compression-tests, N/mm^2.

M.C. = Moisture Content, 12%, n = 53; 8%, n = 27; 4%, n = 26 } 106

H = Height of Specimen, 50 mm. n = 33; 100 n = 39; 200 n = 34 } 106

N/I = Node or Internode, N n = 33; I n = 73 } 106

B/M/T = Bottom, Middle, Top B n = 38; M n = 34; T n = 34 } 106

Remarks to table 4.11.1.

1) The number of 106 specimens is not equally divided in the cases moisture content and node/internode, due to physical reasons: many specimens split when being dried from 12 to 8 or 4 per cent, and each culm contains only about 12 nodes, whereas from each internode more than one specimen can be sawn.
The correlation between 2 and 6 (these two factors, MC and N/I) is only -.0011, so this error is negligible, because in both cases the ratio of the group-sizes is 2:1 (M.C. 53 to (27 or 26), and N/I 33 to 73).

2) As to the simplified model, with the parameters 3,4,5,6,11 and 12 omitted, it is interesting to check the simplified model, with the 24 duplo-values and the triplo-value. From the computer output it follows that for these six parameters $SSE_3 = 420$ with DF = 6, and F = 1.24.
So

$$F = 1.24 = S_3^2/S_2^2 = \frac{420/6}{SSE_2/88}$$

$$\text{from which } SSE_2 = \frac{70 \times 88}{1.24} = 4968$$

which has increased with $420 = SSE_3$, and from this
$SSE_1 = 5388$ with DF = 94 in which:
SSE_1 = sum of squares pure error, complete model
SSE_2 = idem, simplified model
SSE_3 = idem, drop of sums (=SSLF, sum of squares due to lack of fit)
From SSE, follows

$s^2 = 57.32$ and $s = 7.57$

From the 24 duplos and the triplo follows s = 6.47, which confirms rather well the correctness of the calculations. Another method to check eventual differences between the complete model and the duplos + triplo:

- complete model: $SSE_1 = 5388$ with DF = 94,
- 24 duplos plus one triplo:
  SSPE = 1090 with DF = 26,
- SSLF = 5388 - 1090 = 4298 with DF = 68,
- $F = \frac{4298/68}{1090/26} = 1.51$
- and F critical = $F_{26}^{68}(\alpha = 0.05) = 1.8$
- so the differences between the two models is not significant, which confirms again the reliability of the calculations.

4.11.2. Shear

MC	H	N/I	Culm1			Culm2			Culm3		
			B	M	T	B	M	T	B	M	T
		N							7.9	10.8	6.1
	40	I				7.9	7.0	7.5			
		N	8.1	8.4	7.6						
12	80	I							11.1	9.2	8.8
		N				7.3	6.9	7.0			
	120	I	8.3	8.3	7.7						
		N				7.6	7.1	7.1			
	40	I	10.5	10.2	10.9						
		N							11.5	10.2	9.8
8	80	I				9.8	9.9	9.5			
		N	9.4	8.2	8.2						
	120	I							11.6	10.3	9.3
		N	6.7	7.7	6.1						
	40	I							13.1	13.1	11.4
		N				9.9	9.3	8.5			
4	80	I	12.7	12.3	11.4						
		N							11.2	10.7	8.9
	120	I				10.1	9.9	8.9			

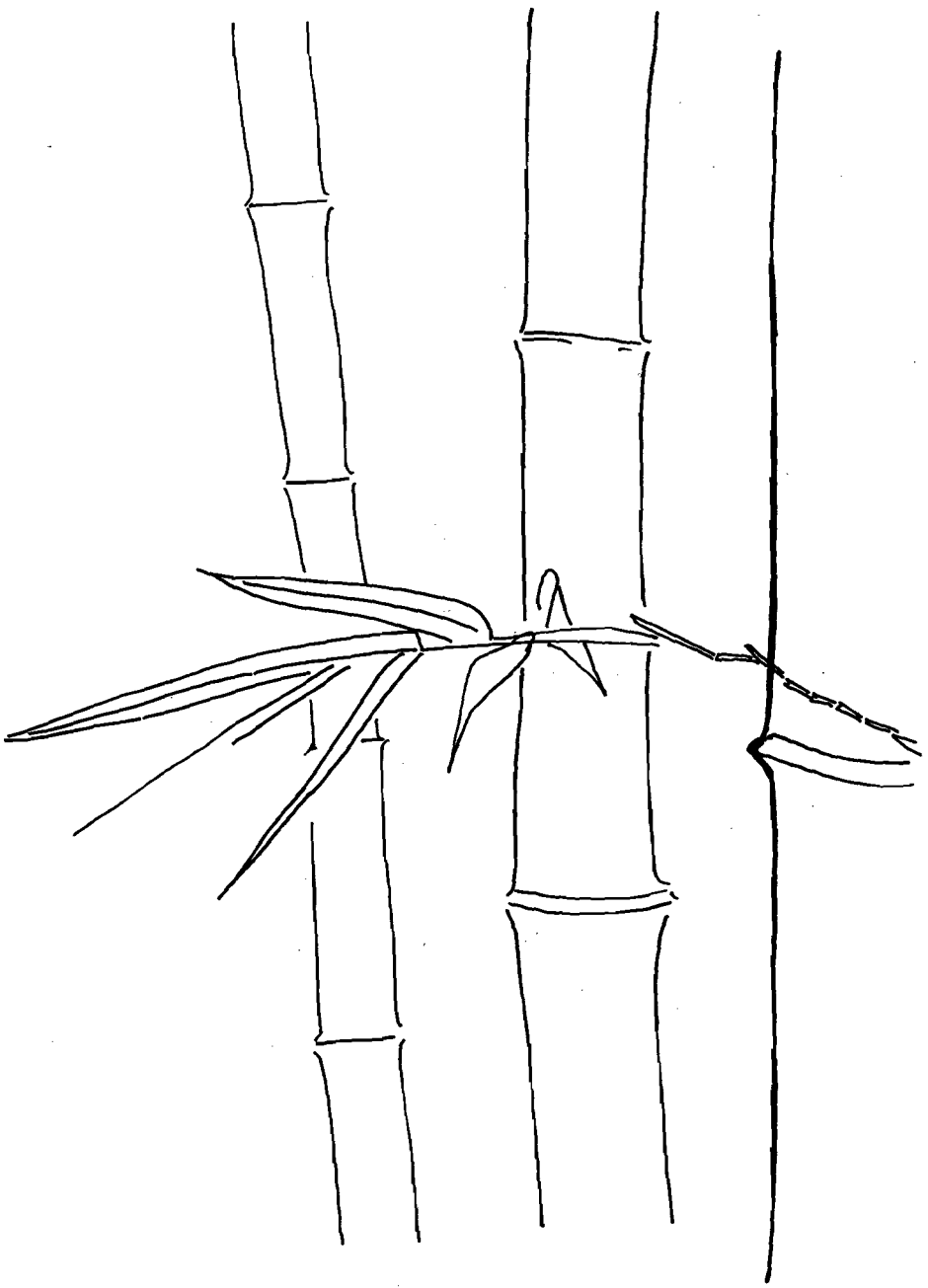
Table 4.11.2. Results of the shear-tests, N/mm^2

MC = Moisture - Content, 12%, n = 18; 8%, n = 18; 4%, n = 18 } 54

H = Height of Specimen, 40 mm, n = 18; 80, n = 18; 120, n = 18 } 54

N/I = Node or Internode, N, n = 27; I, n = 27 } 54

B/M/T = Bottom, Middle, Top B, n = 18; M, n = 18; T, n = 18 } 54



Chapter 5

JOINTS AND TRUSSES

Contents

		page
5.1.	Introduction	154
5.2.	Bolts in bamboo	154
5.3.	Bamboo pins	158
5.4.	Joints, design	165
5.5.	Joints, test methods	178
5.6.	Joints, results	185
5.7.	Trusses	205
5.8.	Results of tests on trusses	206
5.9.	Conclusions	225
	References	226

5.1. Introduction

This chapter reports on research into joints and trusses. The purpose was to study how to design and build trusses of bamboo for roofs with a free span of 8 m. Such roofs are needed for schools, medical centres, storehouses for agricultural products , etc. Before building a truss I have tested and selected joints that form part of a truss.

Consequently, this chapter reports firstly on joints and secondly on trusses.

5.2. Bolts in bamboo

This paragraph and the next one are in fact a transition from the mechanical properties mentioned in chapter 4 to the joints and structures in this chapter. Steel bolts, the subject matter of this paragraph, are often used as connectors in bamboo joints. In literature several examples are described, like the experimental bridge of the American Army on the Philippines in 1937 (Kumpe). There is no literature on any systematic research in this respect. The number of influences to be studied (listed in par. 4.3.) should be enlarged with the diameter of the steel bolts, and the direction of the force.

Some preliminary tests have been done, the purpose of which was in fact to learn about the mechanical behaviour of a steel bolt through a hole in bamboo, and therefore the next variables are taken as constant values:

- species: Bambusa Blumeana
- age: three years
- conditioned
- moisture content 12%
- form and size of the specimen, fig.5.2.1. and 5.2.2.
- internode only
- position along the culm: specimens are chosen at random from the whole culm
- bolt: 12 mm. diameter
- direction of force: axial, towards the end of the bamboo, and the only variables in the tests are:
  - the distance from bolt to the end of the bamboo, see figs. 5.2.1. and 5.2.2.
  - short and long term loading, the short term as represented in fig. 5.2.1. under a hydraulic press of 10 kN capacity, and the long term as shown in fig. 5.2.2., loaded by a cantilever system. There are in fact differences between the stresses occurring in these two methods: compressive stress between support and bolt in the short-term loading and between the two bolts in the long-term tension. The results of the short-term series read in fig. 5.2.3., plotted as shear stresses.

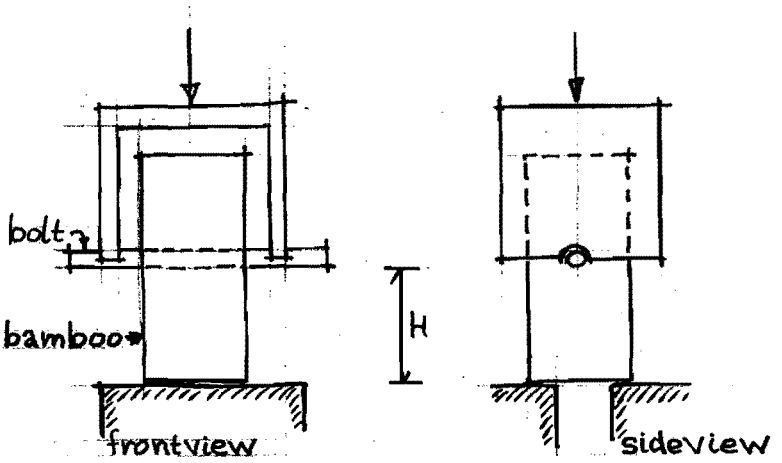


Fig. 5.2.1. Short term bolt test. H = 40, 60, 80 mm.

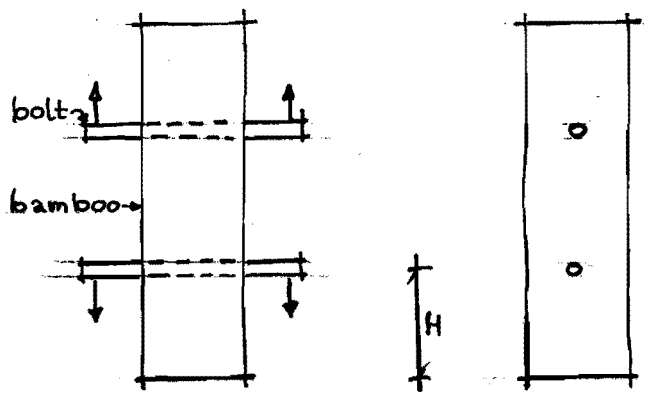


Fig. 5.2.2. Long term bolt test. H = 40, 60, 80 mm.

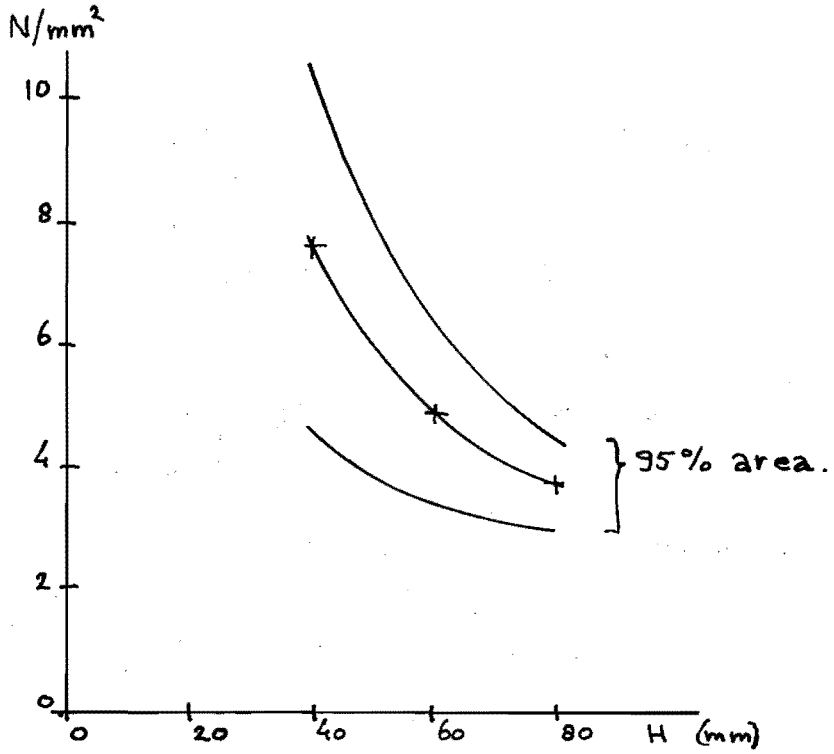


Table 5.2.3. Results of short term bolt tests (expressed as shear stress) 24 specimens in 3 samples of 8 each, 12% M.C.

This is a simple way to present the results, but in fact we have a mixture of shear, compression and cleavage, see fig. 5.2.5. So it is difficult to explain why the shear stress increases with decreasing distance from bolt to end, fig. 5.2.3. Local irregularities may be reponsible for the increase of the 95% area with shorter distances. For structural purposes a distance of 80 mm. (or more?) appears to be better, because the safety is determined by the standard deviation. The results of the long-term tests are plotted in fig. 5.2.4., as shear stresses against log time, up to 4 000 hours (nearly half a year). This time is too short for extrapolations. The shear-stress is independent from the wall-thickness. A conclusion might be, that a joint in bamboo with a steel bolt in circumstances as in our test and 80 mm. or more distance to the end of the bamboo could be calculated with a shear stress of 3 N/mm^2 (short term!) at a 5 per cent. level of probability.

If the long-term strength of bamboo is 55 per cent. of the short term strength, as with wood, a long-term stress reads 1.65 N/mm^2, yet without safety factor. Interesting as a steel bolt may be, the next paragraph will deal with bamboo pins instead of steel bolts, which are a promising connector.

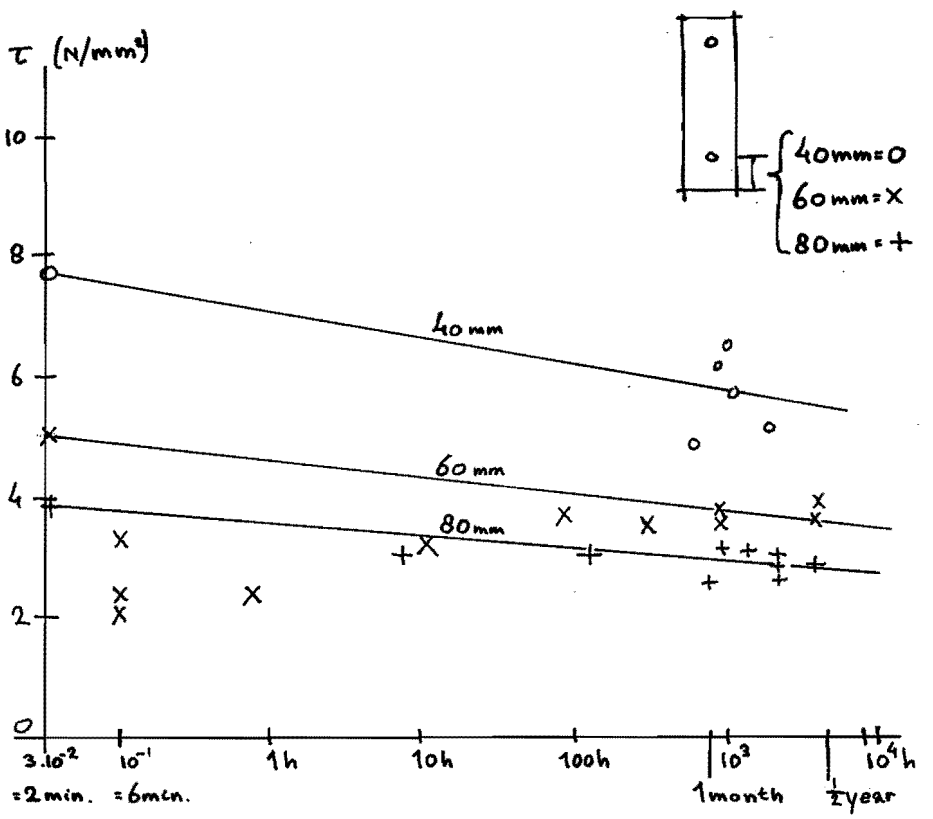


Fig. 5.2.4. Result of long-term bolt tests, expressed as shear stress. No. of specimens: 24 on the 2-min-axis, and 29 on long-term.

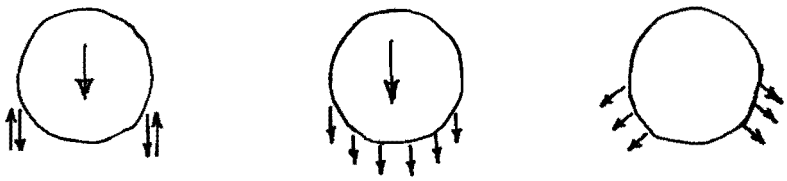


Fig. 5.2.5. Shear, compression and cleavage by a steel bolt in bamboo.

5.3. Bamboo pins

5.3.1. Introduction

As stated in the previous paragraph, steel bolts are interesting connectors in bamboo joints. But my impression is that a bamboo pin might do as well. In literature I could not find any information on this topic, only on bamboo nails. But these are much smaller, and loaded in a different way. I studied the usefullness of bamboo pins and how to test them. Possibilities for bamboo pins are sketched in fig. 5.3.1.: detail A is a proposed tension joint, detail B is a joint of a single diagonal with a double beam in a truss, and details C_1 and C_2 are supports for purlins.

5.3.2. Purpose of the tests

The purpose of the tests is to estimate which pins are best for use in trusses. In fact, the strenght of pins is determined by an interaction between the bamboo pin and the bamboo culms which are connected by the pins.

To begin with, pins are tested by steel "culms" on the assumption that this method would select the best pins in a similar way as bamboo culms would do. The factors that are of influence, are defined as follows. Species, age and conditioned or green bamboo are constant values throughout the programme. The form and size of the specimen is a difficult one. Fig. 5.3.1. presents sketches of four details. Since detail C2 is estimated to be weaker than C1, it is abandoned. Detail A is enlarged: in fig. 5.3.3. the distance between the culm and the two bamboo strips outside the culm is important and therefore detail A is defined as "with a distance between" (being 12 mm.) and a detail D is added, which differs from detail A only in having a small intermediate distance of 2.5 mm.

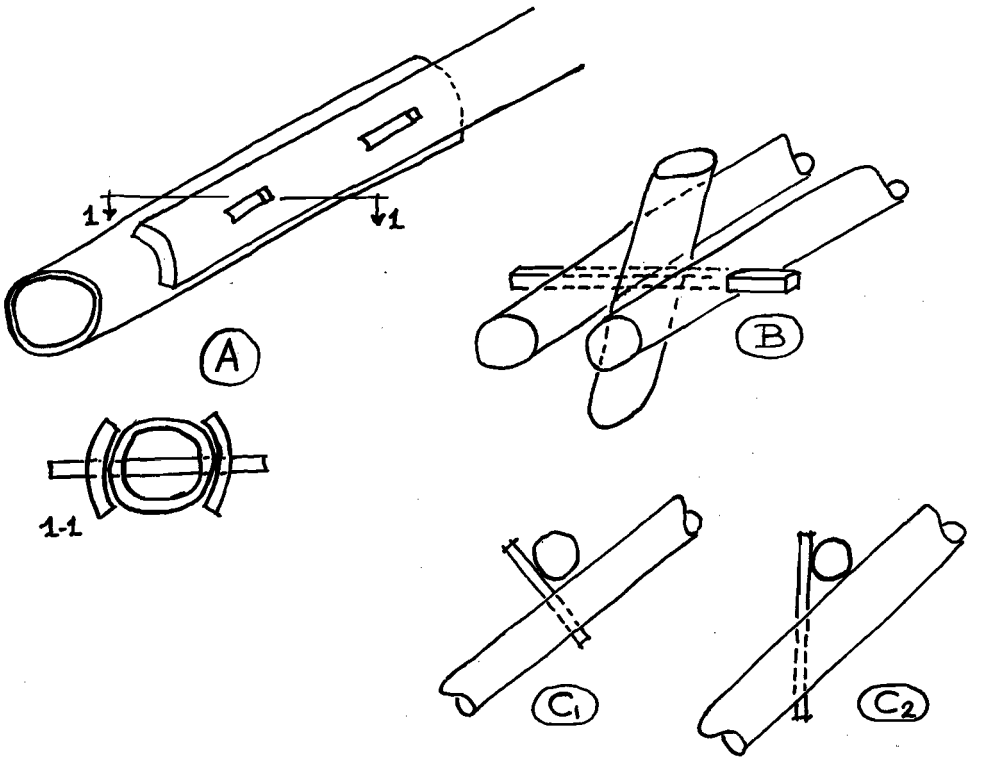


Fig. 5.3.1. Bamboo pins, see text.

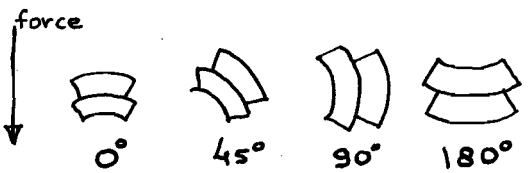
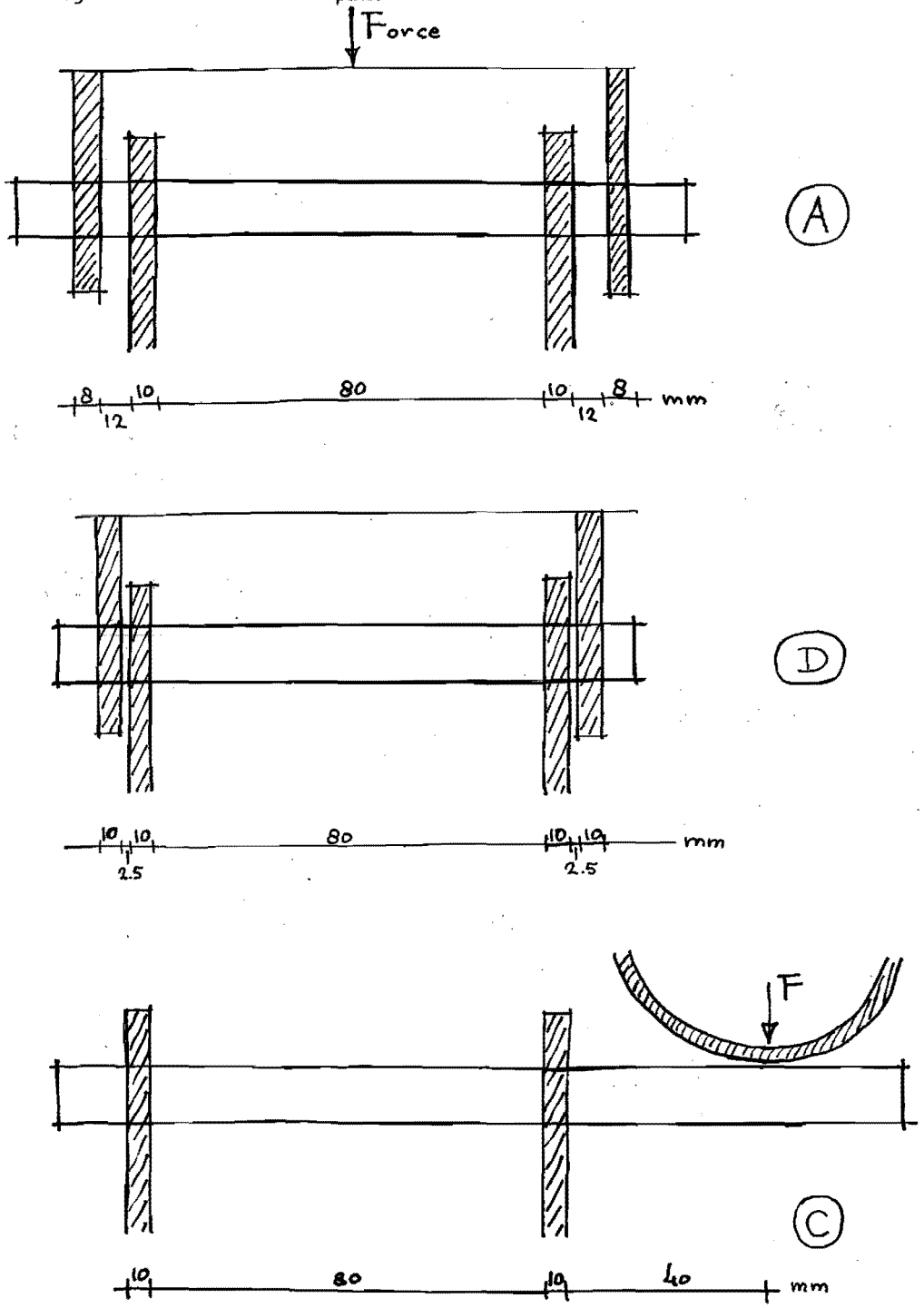


Fig. 5.3.2. Cross-section of bamboo pins.

Fig. 5.3.3. Tests on bamboo pins.



Steel tubes are now used to test the pins, and since detail B is almost equal to A we have as a result three details: A, C and D. The width of the pins is taken at 10 mm., the wall-thickness varying along the culm, interwoven with its position along the culm. To get a first impression of the influence of the sclerenchyma content, the bottompart of another culm is taken as well, with a similar wall-thickness as the top-part of the first culm. The number of pins in each joint was fixed at two. The cross sections are sketched in fig. 5.3.2., where four positions of two pins are shown, with the indexes 0^0, 45^0, 90^0 and 180^0. In fact, all cross-sections are cut into a rectangular form. The pins are taken systematically from the circumference of the culm, to study eventual differences in the cross-sections of the culm. The remaining influences taken are: internode, moisture content (12 per cent.), wall-thickness and position along the culm as mentioned previously.

5.3.3. Methods of tests

As said previously, the bamboo pins are tested in steel tubes, see fig. 5.3.3. The edges of the holes in the steel tubes are rounded off. The tests are statistically organized as an imcomplete Greek-Latin square:

- four quarters of the circumference of the culm (called 1, 2, 3, 4),
- four positions along the culm: bottom, middle and top of one culm, and bottom of another culm, (called B, M, T, b resp.)
- four positions of the pins: 0^0, 45^0, 90^0, 180^0
- three details: A, C and D.

In a scheme for each of the positions B, M, T and b:

	first internode	second intern.	third intern.	fourth intern.
1	A 0^0		C 90^0	D 180^0
2		A 180^0	D 0^0	C 45^0
3	C 180^0	D 90^0	A 45^0	
4	D 45^0	C 0^0		A 90^0

This scheme is repeted four times, for B, M, T and b respectively, in total 16 internodes. The tests were carried out 48 times. The results have been calculated as mean transversal shear stresses.

5.3.4. Results

The results are listed in table 5.3.4. and plotted in fig. 5.3.5.

	P-value
details A,C,D	0.0000
positions of the pin (0,45,90,180^{o}	0.18
position along the culm (B,M,T,b)	0.15
four quarters of the culm (1,2,3,4)	0.41

Table 5.3.4. Results of tests on pins.

From table 5.3.4. we learn that only the details are significant, but none of the remaining factors. In fig. 5.3.5. the results are plotted as estimated mean shear stresses in N/mm^{2}.

At the left, the estimated stresses with 90% areas are given for the details A, C and D. Obviously, a pin is stronger as the distance between the shear areas becomes smaller, due to the decreasing bending moment.

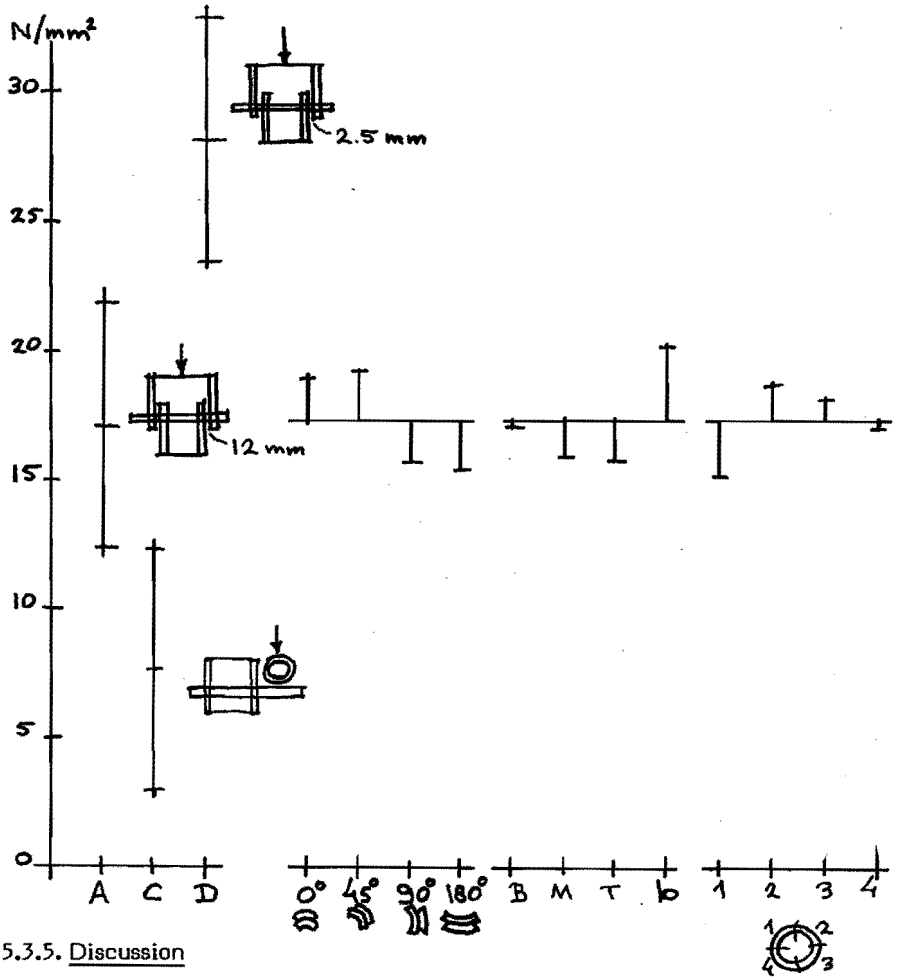
At the right side of fig. 5.3.5. we see the influences of the remaining factors. The position of the pins has a slight positive influence in 0^{o} and 45^{o}, due to the hard outer skin of the bamboo culm in the tension area of the bent pin.

From the position along the culm follows that a bottom part will do better than middle or top part of the culm, and a thin bottom part will do best. There is no relationship with the percentages parenchyma, sclerenchyma and vessels.

The influence of the quarters is rather small. A relationship between these differences and wall-thickness cannot be found.

One should remember that all these factors are not significant, and that these tests are carried out with steel "culms".

Fig. 5.3.5. Results of tests on pins. Explanation in text.



5.3.5. Discussion

From the results we learn that a bamboo pin can function as a connector. A rough calculation might be interesting. We need two assumptions: the first is that specimens are taken mainly from one culm, and for this rough calculation this has to be considered a correct sampling. The second assumption is, that the relationship 0.55 between short and long-term results which is valid for wood and for stresses parallel to the fibre, is now used for bamboo and for stresses transversal to the fibre. With these two assumptions a bamboo pin as in detail D could be calculated at a 5% shear stress of 0.55 x 23 N/mm^2 = 12 N/mm^2. This is a promissing value indeed.

It is mostly important for the strength of a pin to keep the shear areas as close together as by all means possible: detail D with 2.5 mm. distance is better than detail A with 12 mm. However, in the case of a support of a purlin (detail C) this remark is rather useless for practice.
The distance between shear areas is half the diameter of the purlin, and this is a fixed value. Deformations were great in our tests with purlins, especially with 0^{o} and 180^{o}; 90^{o} seems to be better.
For other details, a bamboo pin in the position of 0^{o} is easy to make in a joint, and this is the best solution for practice. It does not matter from which part of the culm the pins are taken.
Finally, I have tested also some pins with a cross-section as in this sketch:

So with the outer skin on both sides. Results read in table 5.3.6.

position along culm	detail D, 45^{o}	detail A (fig.5.3.3.) 0^{o}
B	69 per cent.	100 per cent.
M	104	73
T	96	78
b	103	160

Table 5.3.6. Results of tests on pins as percentages from tests on pins , 8 specimens.

From this table a series of tests on this form of pins seems attractive. This form is not added to our scheme in order not to enlarge this series of tests any more.

5.3.6. Conclusions

1. A bamboo pin seems to be a promissing connector in a joint instead of steel bolts.
2. It is important to keep the shear areas as close together as possible.
3. In detail with short shear distance (e.g. a few mm.) (detail A in fig. 5.3.1.) bamboo pins should be placed with their outer skin facing to force (0^{o}). To support a purlin (detail C fig. 5.3.1.) their outer skin should be parallel with the force. (90^{o}, in fig. 3.5.2.)

5.3.7. What remains to be done

1. Tests on bamboo pins in bamboo culms (my tests were carried out with steel "culms").
2. Long-term tests.
3. Tests on pins with cross-section 8 .
4. Relationship between the strength of pins and the structure of the bamboo.
5. A method to calculate bamboo pins on shear and bending.

5.4. Joints, design

In literature many references on bamboo joints are found. Some of them repeat each other, others contain new suggestions, sometimes even built on full scale or built in practice. References are given below: in this introduction I make an exception for Oscar Hidalgo Lopez, from Columbia. He has published an excellent book on bamboo. This book contains descriptions of two designs (made by himself) of bamboo buildings, up to a 21 m. diameter free span. Cross-section:

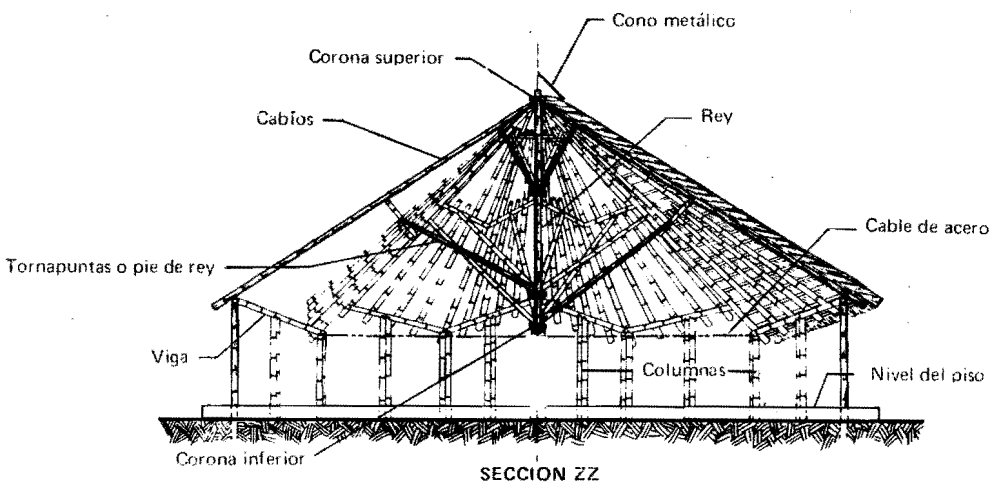
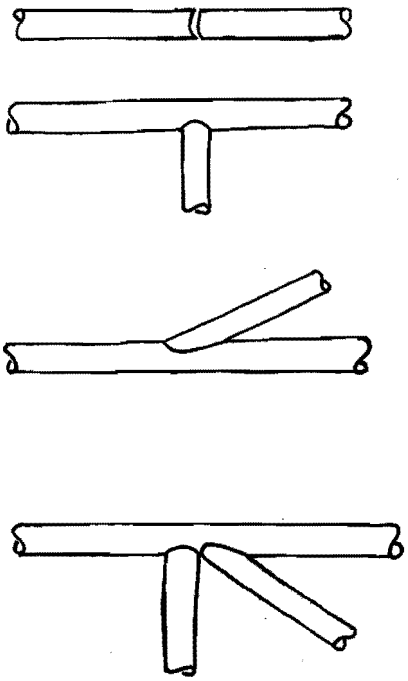


Figure 5.4.1.

For my tests on bamboo joints, I have designed a systematic approach on how to join bamboo.The underlying variety of bamboo joints is as follows:



These four construction models are not used systematically, because in my opinion the method how to join them is more important.

A joint between two pieces of bamboo can be made either by contact between the full cross-sections of both bamboos, or by collecting forces from one cross-section to a joining element, which in its turn transfers the forces to the other bamboo.

"Collecting the forces" may occur:

- from a node
- from the inside of the bamboo culm,
- from the cross section,
- from the outside of the bamboo culm.

"The joining element" may have the appearance of:

- a point which is technically of no use,
- a linear element (bolt, pin, etc.), to be divided into
  "parallel with the bamboo" // and
  "transverse to the bamboo" ⊥
- a plane (but this possibility coincides with "contact between full cross-section").

Summary

group 1, full cross-section	
group 2, from a node	to a line //
group 3, from a node	to a line ⊥
group 4, from inside	to a line //
group 5, from inside	to a line ⊥
group 6, from cross-section	to a line //
group 7, from cross section	to a line ⊥
group 8, from outside	to a line //
group 9, from outside	to a line ⊥

However, groups 2 and 3 coincide with all other groups, because a joint is preferably made at a node; at an internode the culm is too weak for a strong joint.

These groups include possible solutions, found as:

A. a structural design based on an analysis of forces.

B. tradition,

C. references, other than tradition,

D. resemblance with joints in timber or in steel tubes.

After this, groups 5 and 9 remain empty, due to lack of design. We will now report on the other groups.

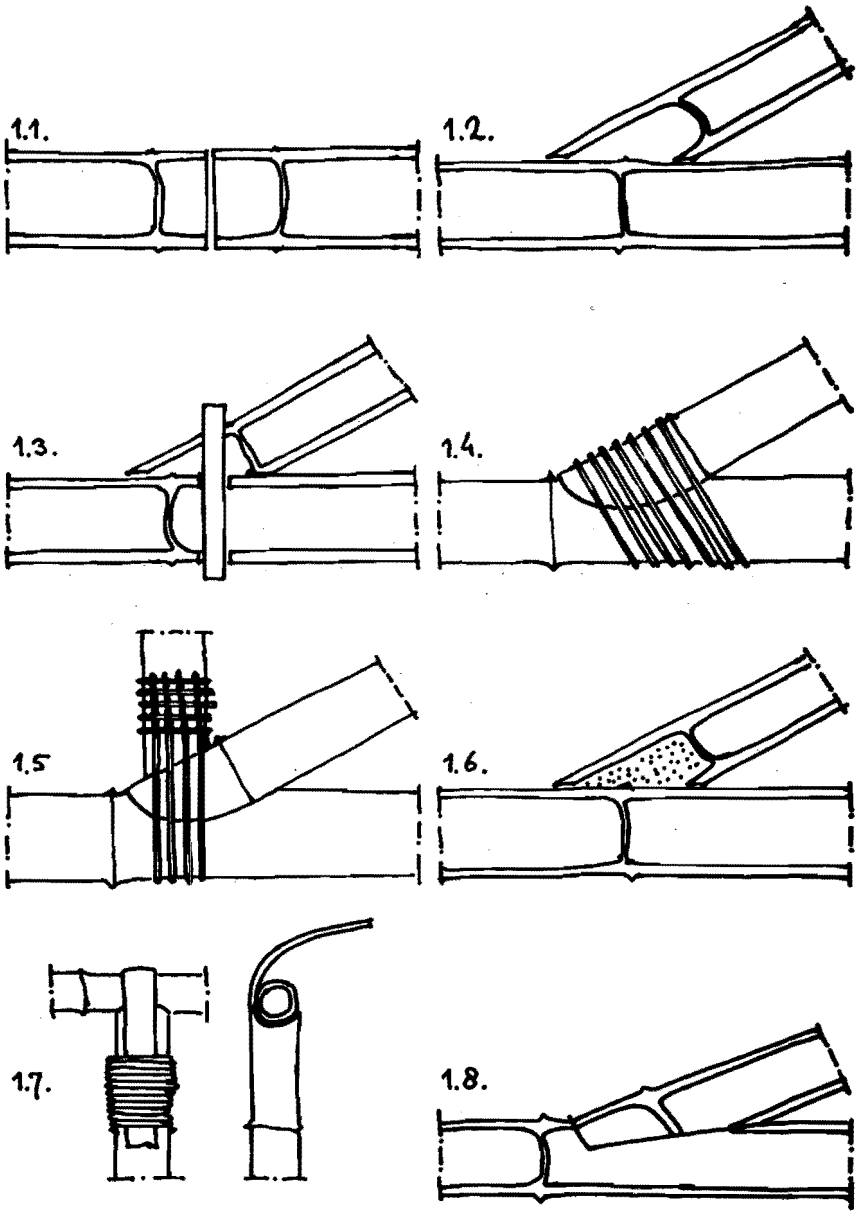
Joints are selected with these criteria:

- can the joint be made by local people,
  - with their traditional craftmanship,
    and with their available materials?
- is it a simple joint?
- does it look strong and stiff enough?

The following references are abbreviated:

Mc Clure	= C
Narayanamurti	= N
Mathur	= M

Fig. 5.4.2.



Group 1. Contact between full cross-section of both bamboos.

- Joint 1.1. is the most simple joint, only for a compression member. For stability and shear, a glue is necessary; for tension this is ineffective, however.

- In joint 1.2. the upper part meets the lower part at an angle, as occurs in trusses. The end of the upper member is hollowed out so as to fit around the lower part. For a perfect contact between both members and for shear a glue is used. The waxy outer-skin is a problem for the glue. Tension is not allowed.

- Joints 1.3. and 1.4. solve the shear-problem of 1.2. with a pin through both members, or with a tight lashing (e.g. split bamboo, cane, tough vines, barks of certain trees, or shrubs, or even soft galvanised iron wire, Karamchandani p. 432). In fact these two joints belong to groups 7 and 9 resp.as well. As to 1.4., deformations are expected to be great. (ref. to 1.4.: N, p. 66)

- In joint 1.5. a vertical tension member in the truss is used to hold the compression diagonal; this shifts the problems to the lashing (8.2.)

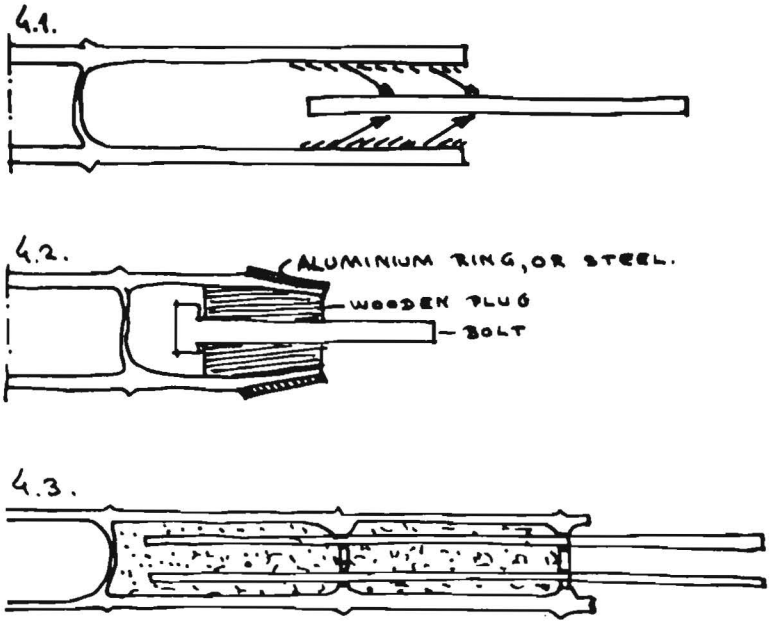
- If the end of the upper member is too weak, it might be filled with mortar or with wood- or bamboo-pulp, joint 1.6.

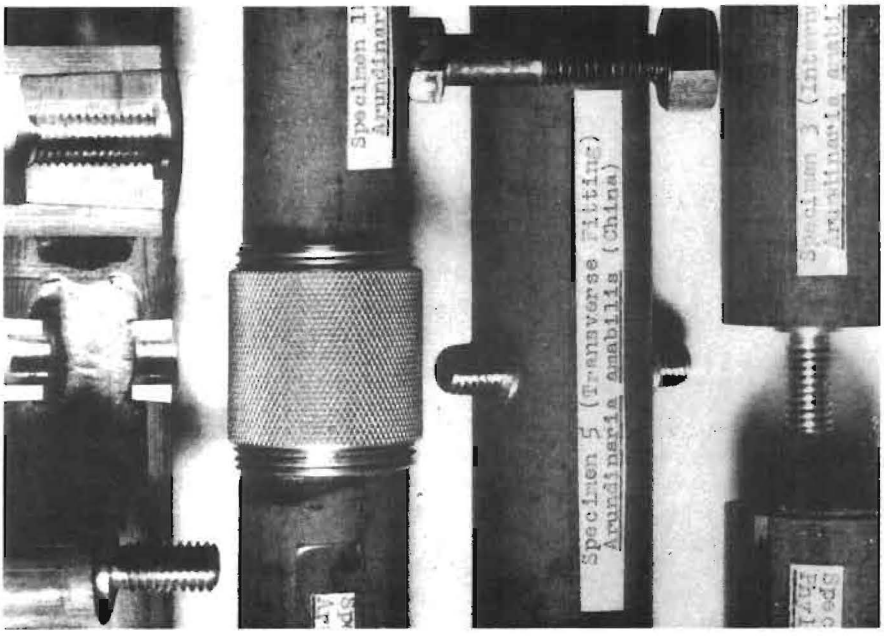
- Joint 1.7. is very well known in the tradition of Asia; part of one cross-section is folded as a tongue around the other member, and tightly lashed. (ref. N. p. 64 and C. p. 17)

- Finally, 1.8. is similar to the tooth-joint in timber, but timber is massiv. This joint in bamboo looks like an "air-to-air-joint", without strength.

Chosen: 1.3. and 1.7., because these look better than the other joints, see above.

Fig. 5.4.3.


4.1.
4.2.
ALUMINIUM RING, OR STEEL.
WOODEN PLUG
BOLT
4.3.
4.4.


Specimen 5 (Transverse fitting)
Arundinaria anabilis (China)

Group 4. Forces collected from the inside of the culm to a line.

- In 4.1. the principle is given: the forces are collected from the inside of the bamboo culm, and transferred by a filling to a linear element (e.g. a bolt or steel bar) in the axis of the culm.

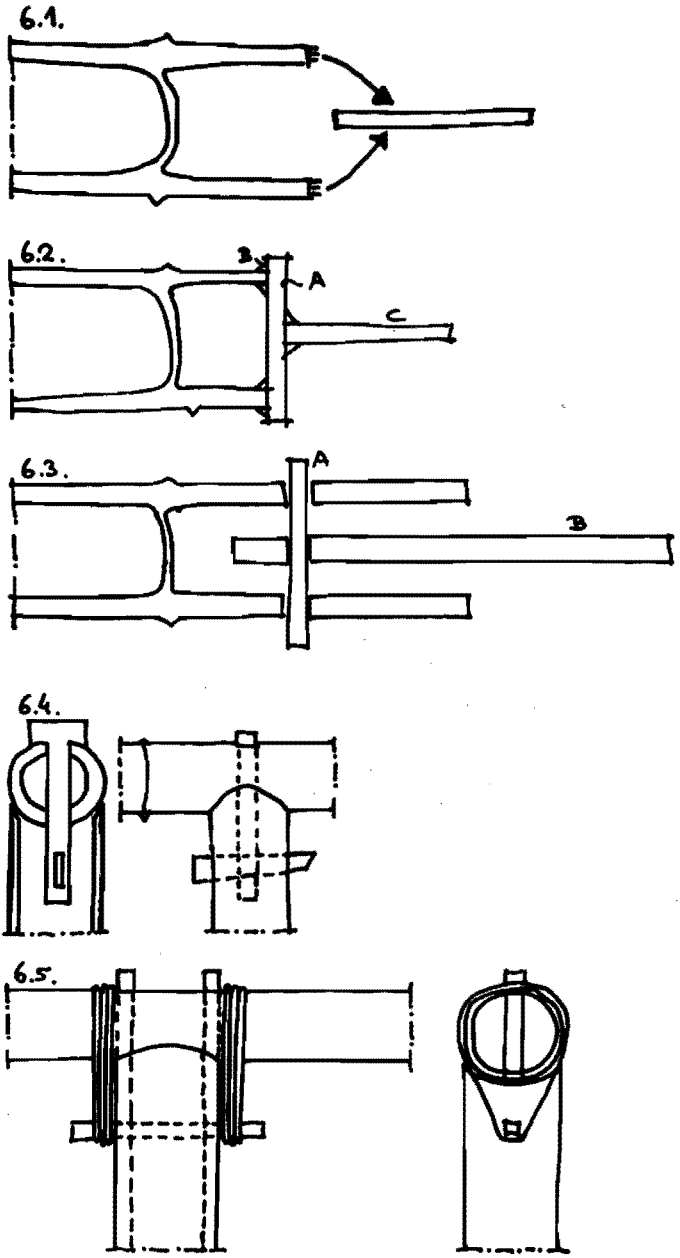
- Joint 4.2. is a practical solution, from Duff (1941): the end of the bamboo is filled with a tapered wooden plug, and surrounded by a tapered steel ring. With these two parts a steel bolt is fastened. It looks like a Western solution. He reports a strength of 27 kN in tension for a 64 mm. diameter bamboo.

- Joint 4.3. is a Russian proposal (N.N., 1961) for the trusses (span 15 metres) on the building of the Building Materials Research Institute in Tbilisi.
  "Two holes were drilled through the last two diaphragms of either member and short rods of reinforcement steel of various cross-sections were passed through these holes to join both members.The cavities around the steel rods were filled with cement grout, poured through holes in the walls of the bamboo. Nodes were designed in a similar way, but in addition to steel rods, bolts were also used for joining the beams and spars verging in the node".
  They report that this joint is as strong in tension as the bamboo member itself. But I wonder about the splitting of the bamboo due to the seasonal changes in relative humidity.
  (The shrinkage of concrete from 75 to 55% R.H. is 2 10^{-4}. The radial shrinkage of bamboo from airdry to ovendry is 3%, from which one quarter is assumed as shrinkage from 75 to 55%, i.e. 0.75% = 75 10^{-4}).

- Next, a picture on a joint from Hodge (1957), similar to that of 4.2. The aluminium rings here are "seated in place by induction heating" (a tapered form is then not necessary). As possible uses are mentioned "furniture, ladders, sporting equipment".

Chosen: none.

Fig. 5.4.4.



Group 6. Forces collected from cross-section of culm-wall to a line //.

- The principle is given in 6.1.

- 6.2. Gives a possible solution: part A sticks with the bamboo by the glue B. A and C can form one part, of steel or of plastic, or A can be a wooden part and C a steel bolt. The problem is the glue B.

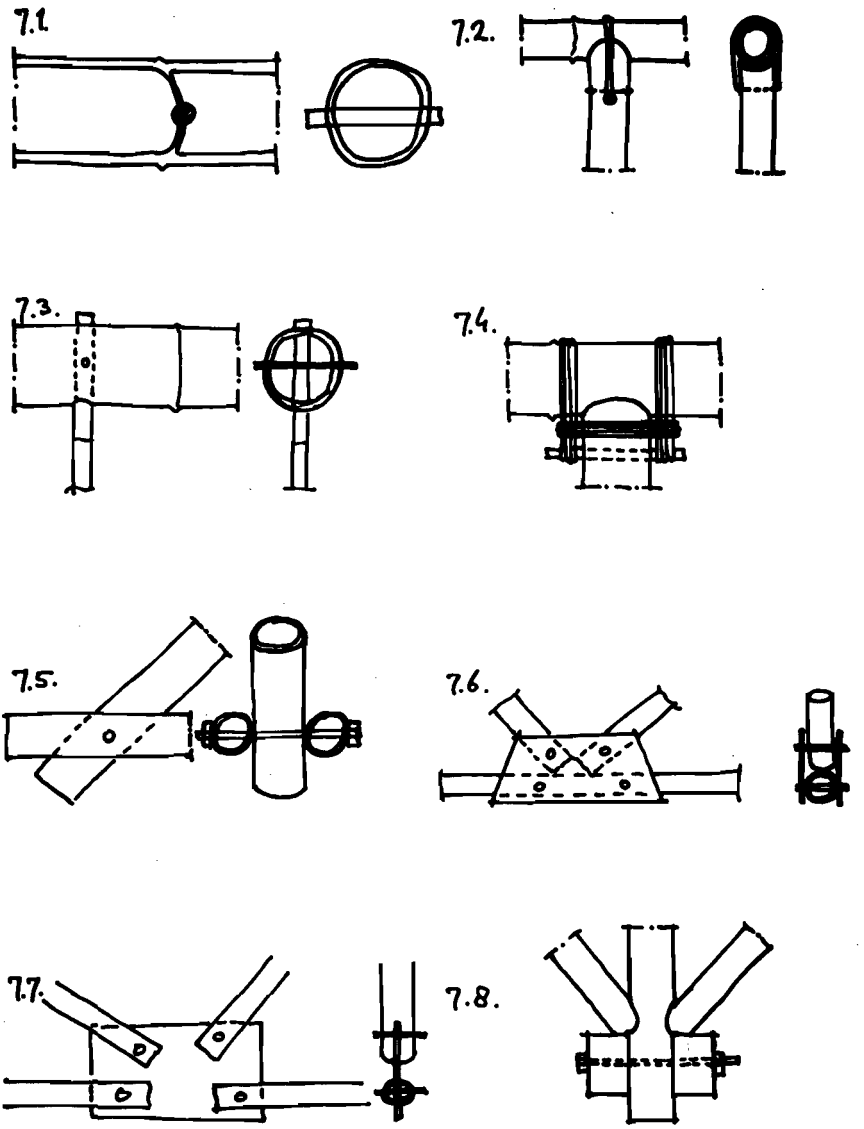
- In 6.3. the forces from the bamboo-culm are transferred by a pin A to a part B. Materials for A and B might be steel, plastic, wood or bamboo. Disadvantages of the first two materials are the price and their availability; a disadvantage of the latter two is the shear.

- Joint 6.4. is found many times in literature (N. p. 64, M. p. 27, C. p. 17). Due to shear problems the strength for tension in vertical direction must be low.

- Joint 6.5. has the two "horns" for shear, the rope for tension, and the contact-area for compression. (N. p. 67) In fact, only the horns belong to this group; the rope and the pin belong to the next group.

Chosen: 6.5.

Fig. 5.4.5.



Group 7: Forces collected from cross-section of culm-wall to a line ⊥.

- 7.1. Gives the principle. A node is taken as the best place because of the greater wall-thickness.

- Joint 7.2. is a solution with rope only. Shear is not possible. Common joint in a fence or as a support of a beam or waterpipe. (N. p. 64, C. p. 16+17, M. p. 27).

- In 7.3. a thick bamboo is connected with a thin one. For fences; not for structural use (the thin member could act as a tension member only) (C. p. 17,, N. p. 64, M. p. 27)
- Joint 7.4.: for pin and rope see joint 6.5. This joint looks well for compression and tension (ref.: K.N.I.L.).

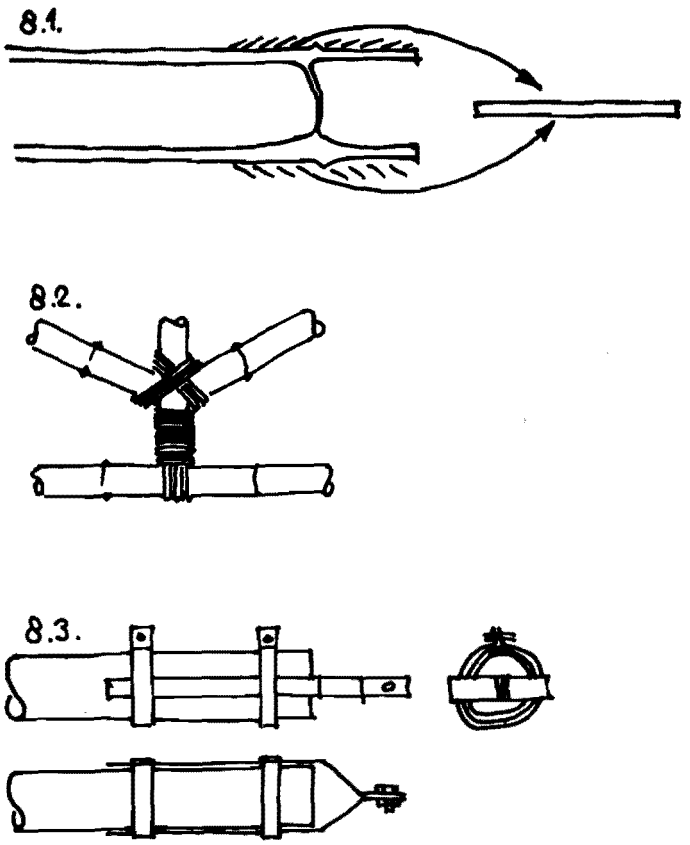
- Joint 7.5., with a steel bolt, has been used many times, by the U.S. Army in the Philippines and by the former Royal Dutch Indian Army (ref. Kumpe and Van der Maaten resp.)
  A similar bolt is present in picture 5.4.3. It looks like a strong, stiff and simple joint.

- Joint 7.6. and 7.7. are alternatives, with plywood and steel bolts. The 7.6. is very strong and simple; the 7.7. looks cumbersome.

- Joint 7.8. Shows two wooden blocks, bolted to the vertical bamboo, and giving support to two bamboo diagonals. (Hidalgo, p. 204).

Chosen: 7.5. and 7.6.

Fig. 5.4.6.



Group 8: Forces collected from the outside of the culm to a line //.

- 8.1. Shows the principle.

- An ancient traditional solution is given in joint 8.2. (N. p. 66 and others). Duff tells about good lashings: "The bamboos are lashed together with thin bamboo-skin thongs which ... are especially suited to this purpose on account of their strength and flexibility; the thongs, which are soaked in water before use, shrink upon drying, thus forming a very tight lashing".(Duff 1941 pp. 5+6).

- A kind of metal clip is used in joint 8.3., cited by Lowson from a Peruvian building company, who are said to have built a 15 m. roofing span with this system in 1949. The strength of the joint is reported to be 10 kN.

- Finally, the recommendation by Narayanamurti (p. 79): "Metal ring and plate connectors have proved their worth in timber construction. Hollow plastic T and L fasteners using wedges may be the answer. Perhaps specially developed screws and bolts with rounded toothed washers will prove most efficient".

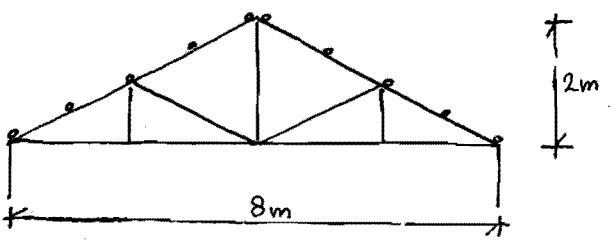
Chosen: none.

Summary of this par. 5.4.: chosen are the type 1.3., 1.7., 6.5., 7.5. and 7.6.; further selection in par. 5.6.

5.5. Joints, test methods

Motto: "No one knew how to run a stress analysis on a bamboo knot".
(page 215 in Proceedings 17th Annual Conference of the Society of Experimental Test Pilots, 1975).

I got this quotation from the Royal Aircraft Establishment in Farnborough in 1976, when I contacted them about some RAF-hangars built with bamboo in older times. The quotation refers to the problems in building a replica of a Curtiss plane from 1911. In my research on bamboo joints, no stress analysis was carried out; only forces and deformations were measured, and from these I tried to calculate stresses.
The purpose of my research programm was to build the joints, selected in the foregoing paragraph, on full scale, and to test them with respect to strength and stiffness as if they were part of a truss.
For this a truss had to be designed and calculated. As a basis for calculation is chosen the Indian Code of Practice for structural safety on building (875/1964, revised 1976).
The chosen truss is a king-post type:

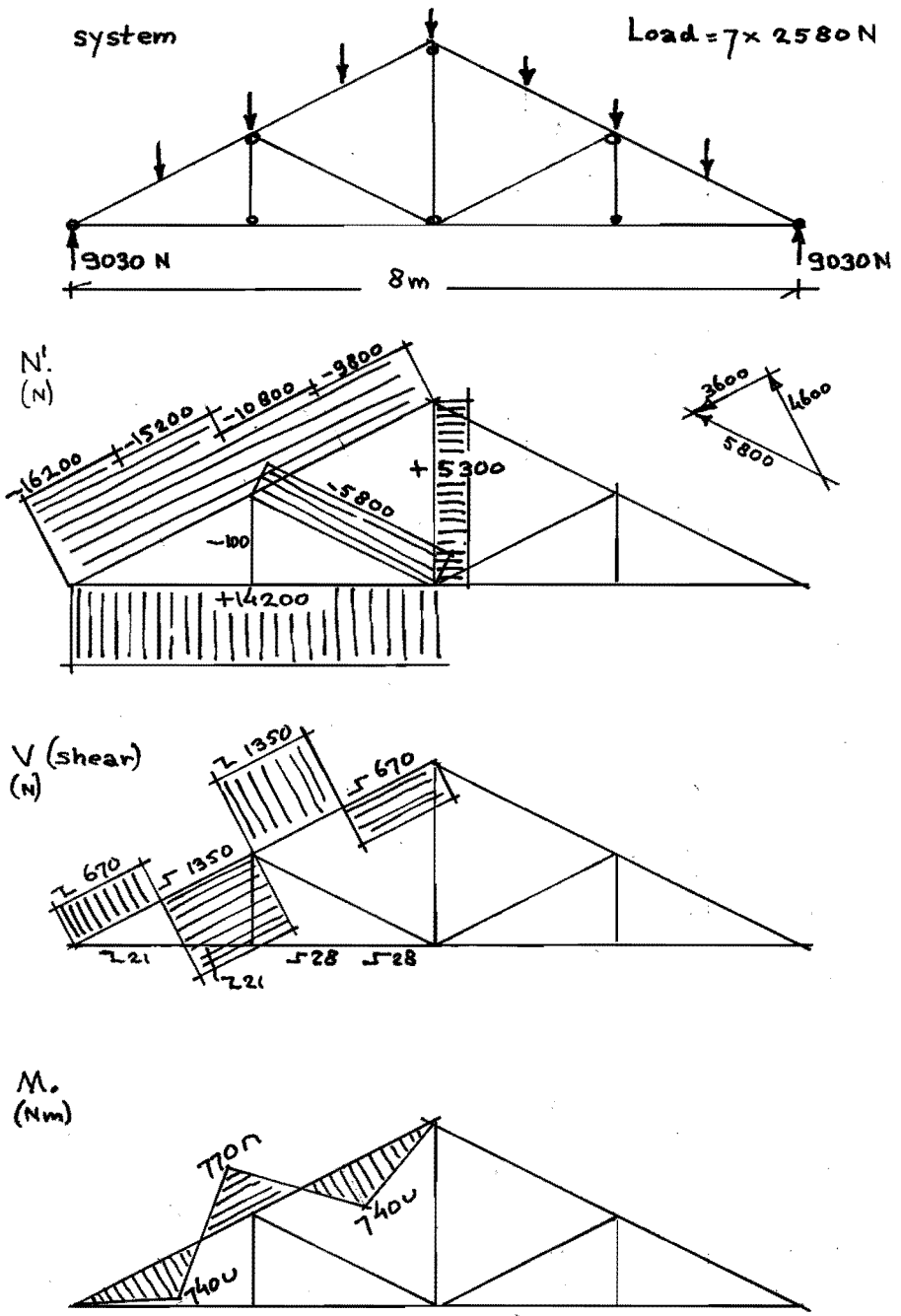


Distance center-to-center 3 m.

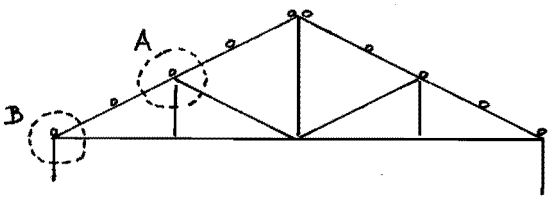
Dead weight (roofing sheets, purlins)	360 N/m^2 plan
Live load	500 N/m^2 plan
	860 N/m^2 plan

The resulting moments and forces in the truss are given in figure 5.5.1.
(calculations with ICES-STRUDL computer programme; E = 17 000 N/mm^2, A = 2 900 mm^2, I = 3.2 10^6 mm^4).

Fig. 5.5.1. Bamboo-truss; M-, N-, and T-lines.



The truss mentioned ahead contains four different joints. Two of them were chosen to select the designed joints, viz. as follows:

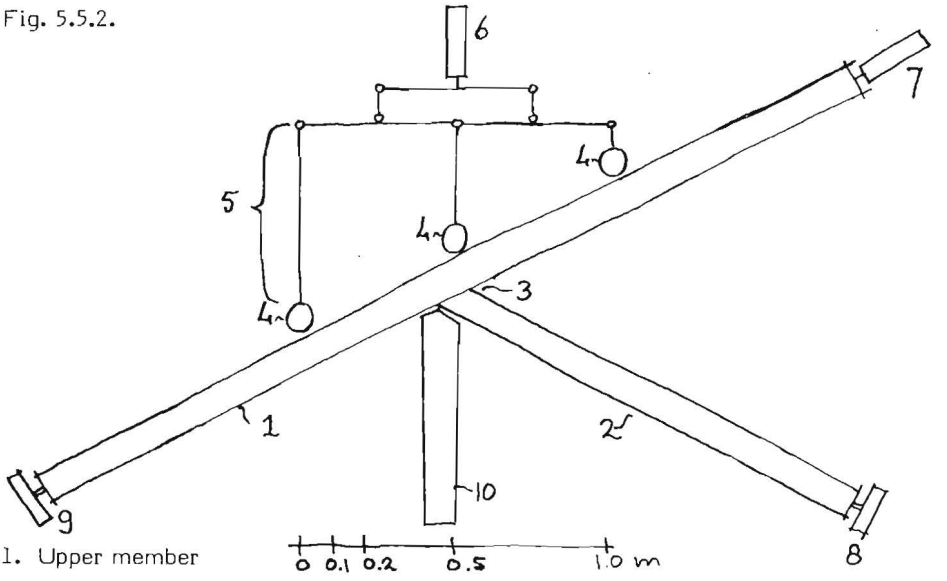


Joint A is the joint between diagonal and upper member, and in joint B the truss is supported by the column. Figure 5.5.2. and picture 5.5.3. shows how the first mentioned joint was tested.

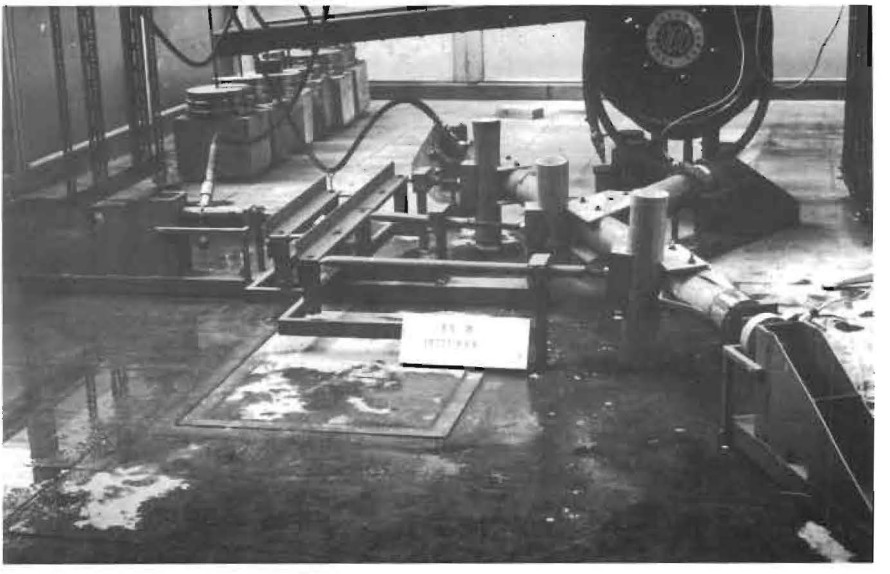
In this test system the forces are simulated as if this joint were part of a complete truss. In this procedure the axial force in the diagonal is considered critical for the joint, see fig. 5.5.4. In the upper member the axial force is fairly well simulated, which is not the case with the bending moment and the shear. It is tried to simulate these two also, but without success. This is considered not critical for the joint to be tested. If this truss is loaded according to the Indian Standards, an axial force results in the diagonal of 5800 N, which means a normal force of 4600 N and a shear force of 3600 N in the joint. These forces are taken as a reference level and are called "100 per cent.". One should keep in mind that this does not mean that this truss would satisfy the Standards, because the load of "100 per cent." is the load under use, still to be multiplied by a safety factor, which must be determined as yet with these tests, however.

The procedure of these tests is, that the load is brought on to the joints in steps of 20 per cent. each, with three minutes between each step. Forces and deformations are read immediately after each step and again after three minutes, just before the next step. Sometimes strain gauges are used as well. It is found that eight strain gauges around a culm (in one cross-section) are sufficient to determine a bending moment and/or an axial force. To verify the possible influence of the differences between one place of the culm and another, a test is made on one piece of bamboo, 240 mm. high, with three circles of eight strain gauges each around it, see figure 5.5.5. and picture 5.5.6. This cylinder was tested in compression up to 20 N/mm^2, which equals "200%". The E-modulus found was 17 600, 17 300 and 17 200 N/mm^2 respectively, with coefficients of variation of 18 ,6 and 9 per cent. These differences are not significant.

Fig. 5.5.2.

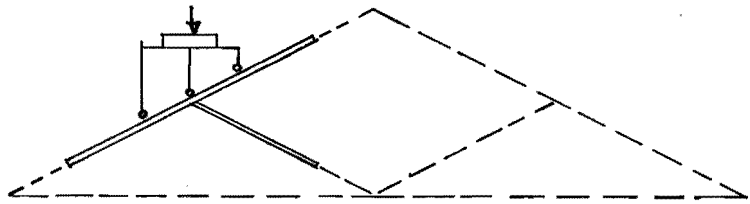


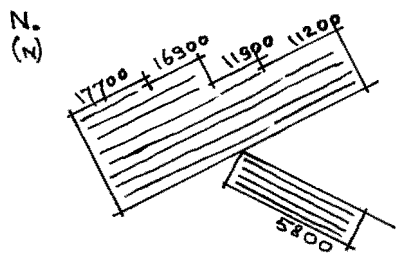
1. Upper member
2. Diagonal
3. The joint to be tested
4. Three purlins
5. Cantilever system
6. and 7. Hydraulic jacks
8. and 9. Pressure gauges
10. Vertical, not present in all specimens.

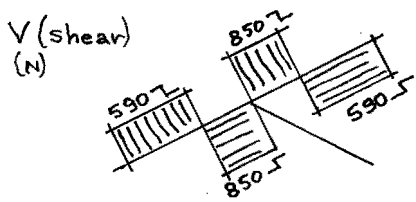


Picture 5.5.3. Test on joint.

Fig. 5.5.4. Joint to be tested; M-, N- and T.
(to be compared with figure 5.5.1.)







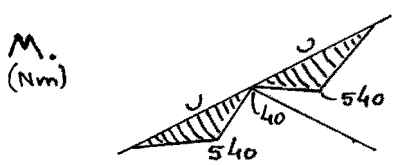
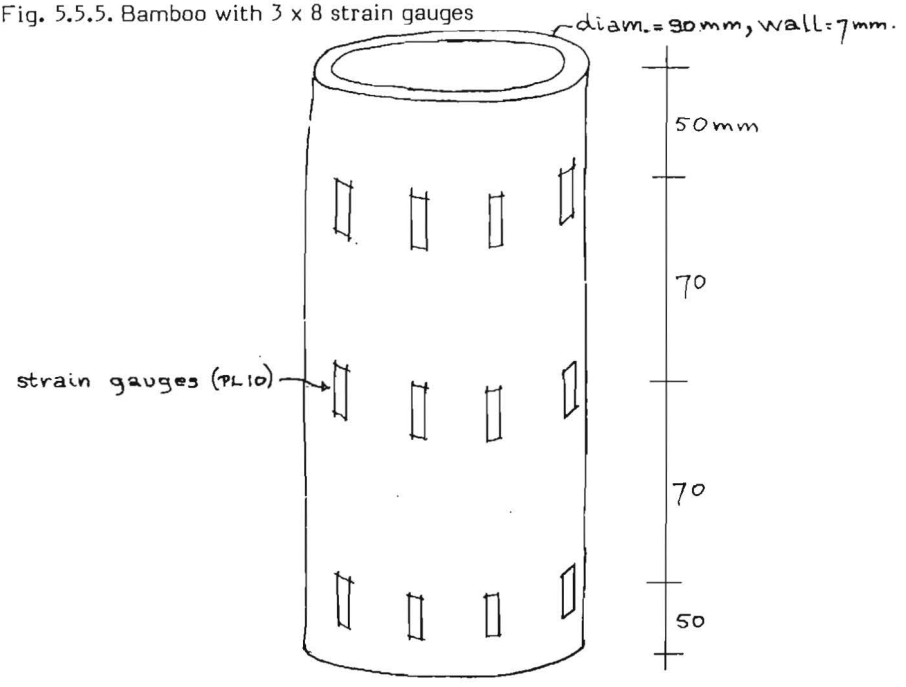


Fig. 5.5.5. Bamboo with 3 x 8 strain gauges



Picture 5.5.6. Bamboo cylinder with 3 x 8 strain gauges tested in compression.

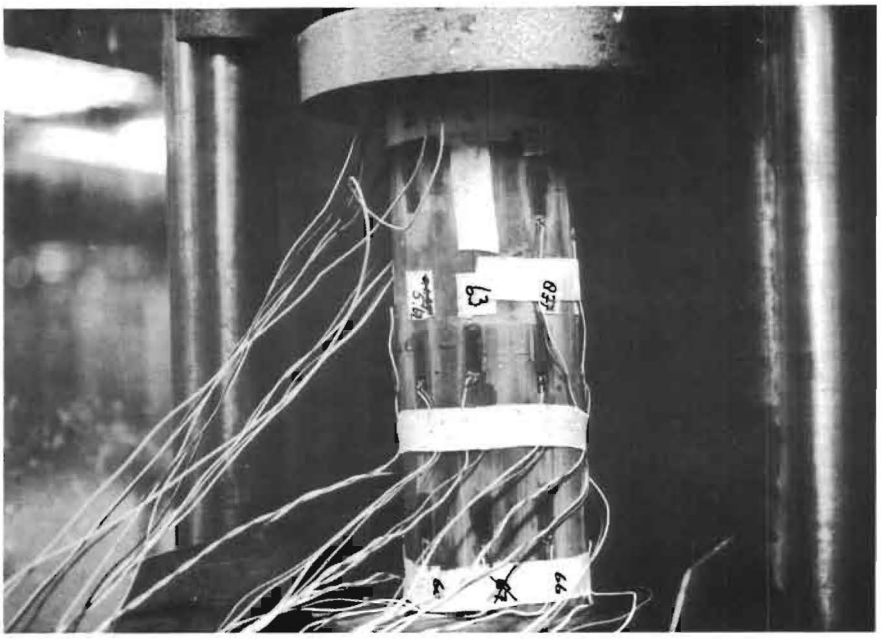
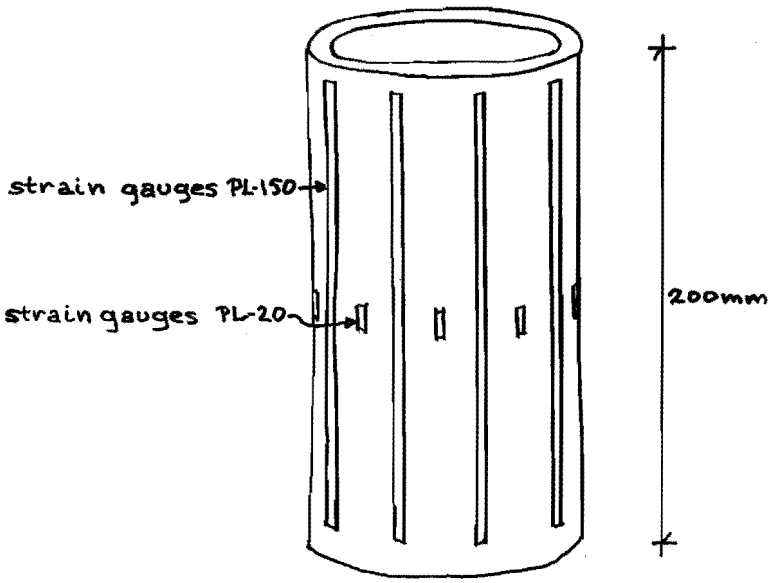


Fig. 5.5.7. Bamboo with long and short strain gauges.



A correlation between the readings of the strain gauges on one hand and the wall thickness or the unevenness of the top- or bottom-surfaces on the other hand was not found. Next, the cylinder was split into eight pieces, each piece containing three strain gauges, in a vertical row. The split bamboo was hold together with tape, and tested again. The E-modulus decreased from 17 300 to 16 600 N/mm^2, due to the lost contraction. Its variation coefficient increased from 11 to 28 per cent.: in the full culm weak places are supported by shear from stronger places, but in a split culm this does not happen.

Finally, the possible influence of the length of the strain gauges was studied: normal is 20 mm., and they were compared with one of 150 mm. length. In a piece of a culm of 200 mm. height eight of each kind were glued around the circumference, see figure 5.5.7. The E-modulus, tested up to a stress of 43 N/mm^2, was in the case of the 150 mm. strain gauges 98 per cent. of that with the 20 mm. strain gauges. The variation coefficients are 6 and 9 per cent. respectively. So tests were continued with the cheap 20 mm. strain gauges.

5.6. Joints, results

This paragraph reports about the results of the tests on joints.

First the diagonal joints:

5.6.1. type 7.6., plywood with steel bolts;

5.6.2. type 1.3., diagonal rests against bamboo pin;

5.6.3. type 6.5. + 7.4., bamboo "horns" and rope;

5.6.4. type 7.5., diagonal between double upper members and steel bolt through all three;

5.6.5. selection of joints.

Then the column joints in 5.6.6.

(note: type 1.7. will be used as improved column joint, see par. 5.8.2.)

5.6.1. Diagonal-joint, type 7.6.

This joint is built with plywood and steel bolts, see picture 5.6.1.
Figure 5.6.3. and table 5.6.4. report about the tests.
Seven specimen, called A...G, have been built and tested. If a specimen was tested more than once, this will be reported as A1, A2, etc. The result of all tests is that the joint never failed, but the purlins failed. They are steadily improved, see figure 5.6.3. at the right: detail A is used in specimen A, details B + C, for the specimens B and C, and so on.

Accuracy of tests:

The normal force in the diagonal should have been 5800 N. at the reference level of 100 per cent., but due to friction losses and errors this force was:

mean 5500 N(= 95%)
with standard dev. 700 N(= 12%)

This has been incorporated in the results.

Results of tests:

The slip of the diagonal along the upper member at the reference level is:

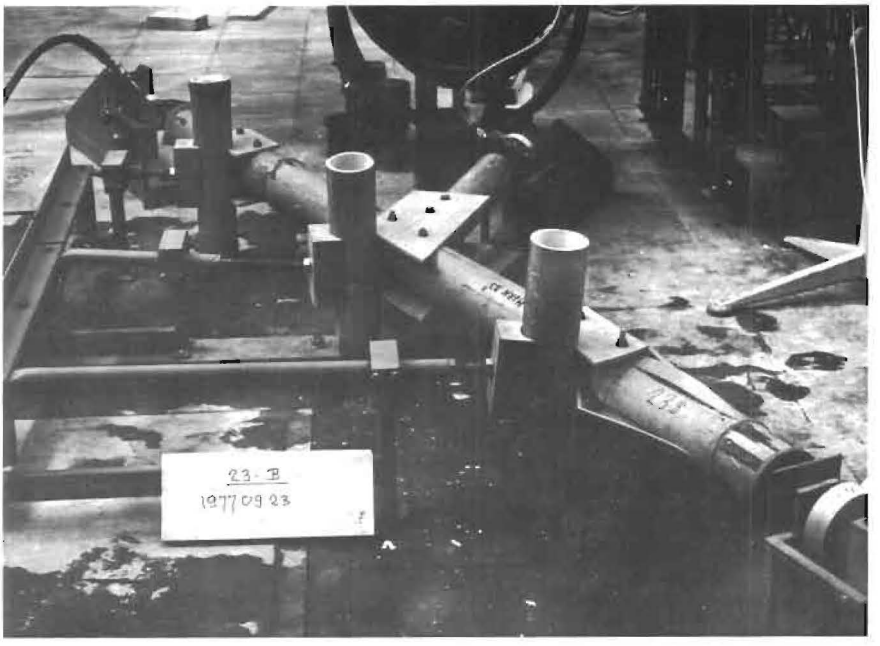
mean 3.9 mm.
with standard dev. 2.2 mm.

The stiffness of the joint for the shear along the upper member is (for specimens D-): (expressed in unit force per mm. displacement)

mean 1170 N/mm.
with standard dev. 365 N/mm.

The strength of the joint is not known, because other parts (e.g. purlins) fail earlier. >16500 N?

Picture 5.6.1. Joint type 7.6., plywood with steel bolts.



Picture 5.6.2. Joint type 7.6., specimen B-2, failure at purlin 1.

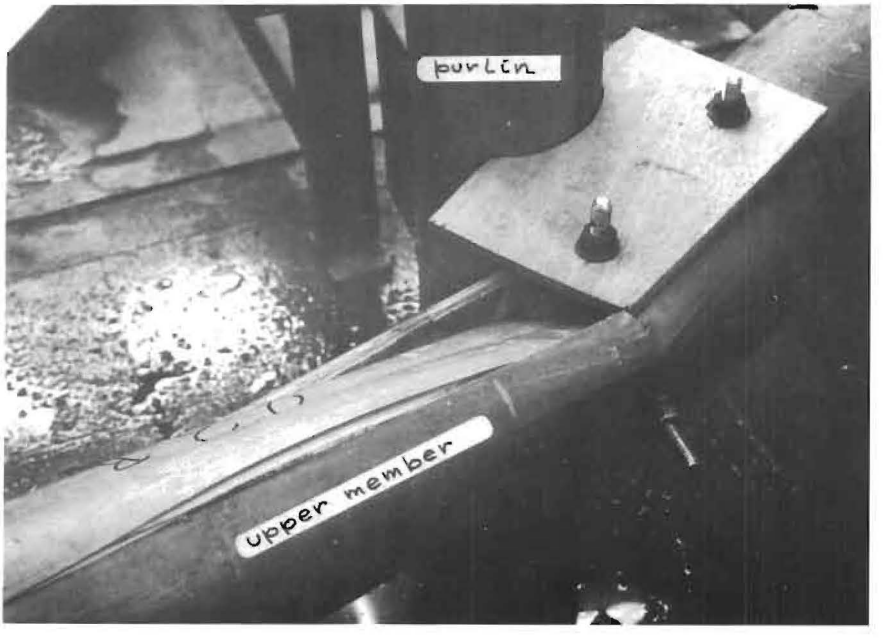


Figure 5.6.3.
Joint 7.6.

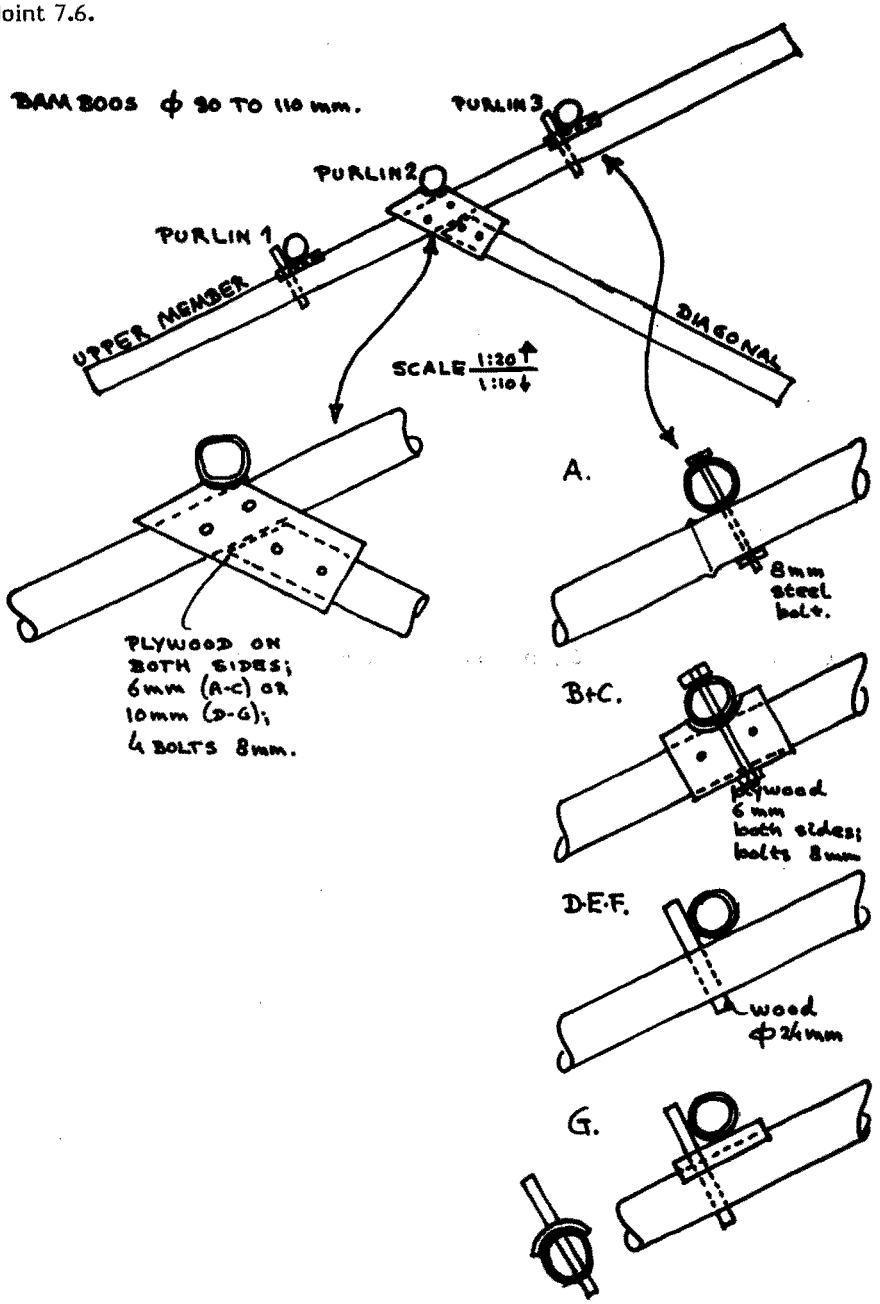


Table 5.6.4.
Joint 7.6.
Plywood and steel bolts

specimen no.	purlin detail no.	failed at	what happened	what has been improved
A.1	A	60%	load system failed	load system
A.2	A	100	the bolts with which purlins 1 and 3 were fixed, failed (sketch A)	purlins placed in plywood, similar as diagonal in sketch "B+C".
B.1	B+C	100	Purlin 2 failed	Take purlins with node instead of internode
B.2	B+C	180	Upper member failed at purlin 1. See picture 5.6.2; σ = 55 N/mm^2.	New upper member
C.	B+C	160	Plywood under purlin 2 failed.	Plywood 10 mm (was 6 mm).Purlins 1 and 3 supported by wooden pins $\varnothing$ 24 mm. See sketch "D-E-F".
D.	D.E.F.	200	Upper member failed at top. Splitting by shear, should not occur in real truss; because the fixed ends in this test introduce greater shear than a real truss	Circular prestressing around both ends of upper member
E.	D.E.F.	220	Load system failed by shear force in upper member	Shear force in upper member in this test is greater than in a real truss; length upper member now 3 m (was 2 m) for lower shear,
F.	D.E.F.	160	Purlin 1 penetrated into upper member (due to hole for pin $\varnothing$ 24 mm).	Add split bamboo as a mediate between purlin and upper member, see sketch G.
G.1	G	160	Wooden pin to support purlin 3 failed	New pins
G.2	G	260	Purlin 2 failed	Renewed.
G.3	G	180	Idem (purlin damaged by beetles)	Idem
G.4	G	300	Buckling of upper member. Joint was still good. End of tests.	

Note: "100%" means: 5800 N compression in the diagonal.
Note: σ is due to N' and M in upper member; transversal forces by purlin and/or diagonal not taken into account!

Conclusion: in none of the specimens the joint itself failed. So we do not know the strength of the joint. Because the joint is stronger than other parts (purlins, upper member) the tests were stopped. The result of these testsd is in fact an improved purlin detail. For further conclusions see par. 5.6.5.

5.6.2. Diagonal-joint, type 1.3.

In this joint the diagonal rests against pins through the upper member, see fig. 5.6.6.

Fig. 5.6.6. and table 5.6.7. report about the tests on eight specimens of this joint.

Accuracy of tests:

The normal force in the diagonal should have been 5800 N. at the reference level of 100 per cent., but due to friction losses and errors this force was:

mean 5400 N = 93%
with standard ev. 600 N = 10%

This has been incorporated in the results.

Results of tests:

The slip of the diagonal along the upper member at the reference level was:

mean 8.5 mm.
with standard dev. 2.4 mm.

The stiffness of the joint for shear along the upper member was:

mean 430 N/mm.
with standard dev. 160 N/mm.

Strength of joint, expressed as force in diagonal, based on specimens C-H (A and B fail elsewhere)

mean 10 500 N.
with standard dev. 1 640 N.

Picture 5.6.5. Joint 1.3., specimen G, after failure.

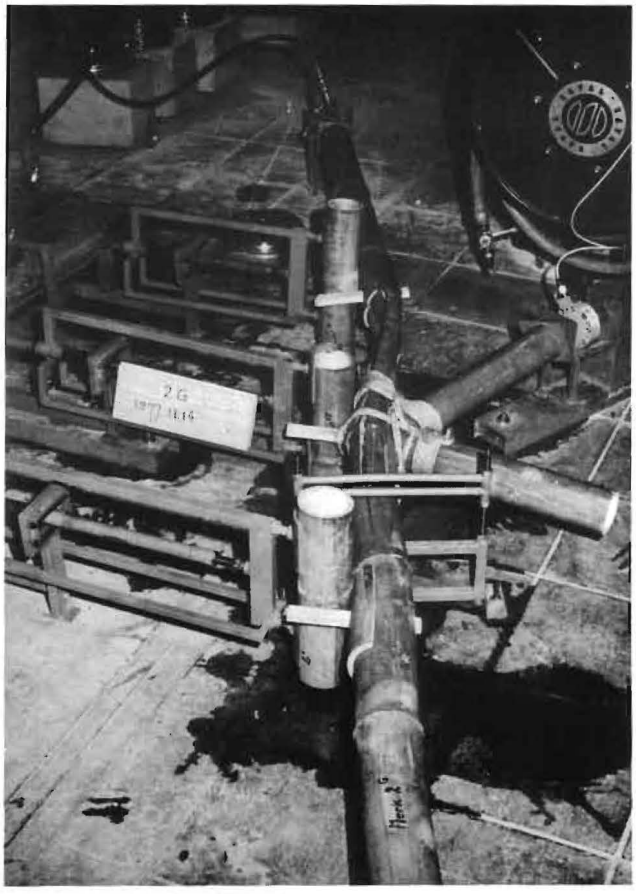


Fig. 5.6.6.
Joint 1.3.

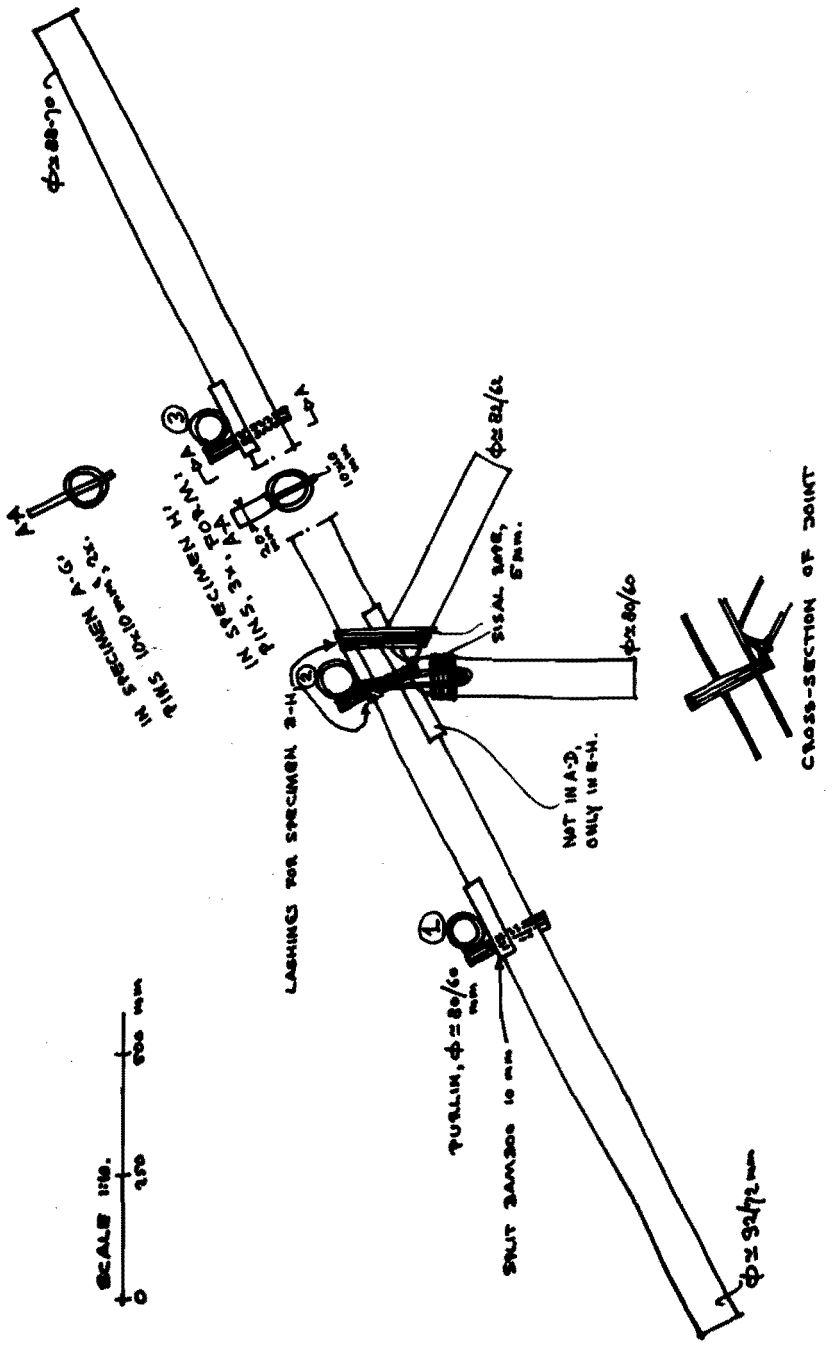


Table 5.6.7.
Joint 1.3.
Diagonal rests against bamboo pins

Specimen no.	failed at per.cent.	what happened	what has been improved
A	160	upper member failed at joint 2, weakened by hole, σ= 19 N/mm^2	vertical and diagonal were lashed around purlin 2, further only around upper member, to diminish lateral forces on upper member.
B	170	upper member failed at purlin 3, at hole, σ= 25 N/mm^2	
C	180	diagonal split at 120 and failed at 180 per cent.	
D	180	upper member and diagonal split at joint	split bamboo between diagonal and upper member.
E	200	upper member failed at holes at purlin 1 and 2, σ= 47 and 33 N/mm^2 resp.	
F	140	idem, σ = 35 N/mm^2.	
G	200	upper member split at 180 per cent. from purlin 2 to purlin 3, and failed at 200 per cent. σ = 30 N/mm2. See picture 5.6.5.	Bamboo pins were two, now 3, and easier form.
H	200	upper member flattens between purlin 2 and diagonal. Tests considered to be sufficient.	

Note: σ was calculated from the normal force and the bending moment in the upper member only; this stress has to be enlarged with the influence of the transversal forces by the purlin and/or diagonal.

Conclusions: par. 5.6.5.

5.6.3. Diagonal joint type 6.5. + 7.4.

Bamboo "horns" and rope.

This test series has been a "trial-and-error" improvement of the original joint. This original one resembles that shown in fig. 5.6.10., specimens A-B-C, and pictures 5.6.8. and 5.6.9. The results were the collapse of the upper member at the joint. To try out if the lashings might have contributed to this collapse, specimens D-E-F were tested without lashings, but the strength did not increase. Similarly the purlin no. 2 (at the joint) was omitted in specimens G-H-I, also without better strength. Conclusions are listed below.

Accuracy of tests:

The normal force in the diagonal should have been 5800 N. at the reference level of 100 per cent., but due to friction losses and errors this force was:

mean 5100 N. = 88%
standard dev. 500 N. = 9%

This has been incorporated in the results.

Results of tests: (specimen A excluded)

The slip of the diagonal along the upper member at the reference level is:

mean 3.7 mm.
standard dev. 1.6 mm.

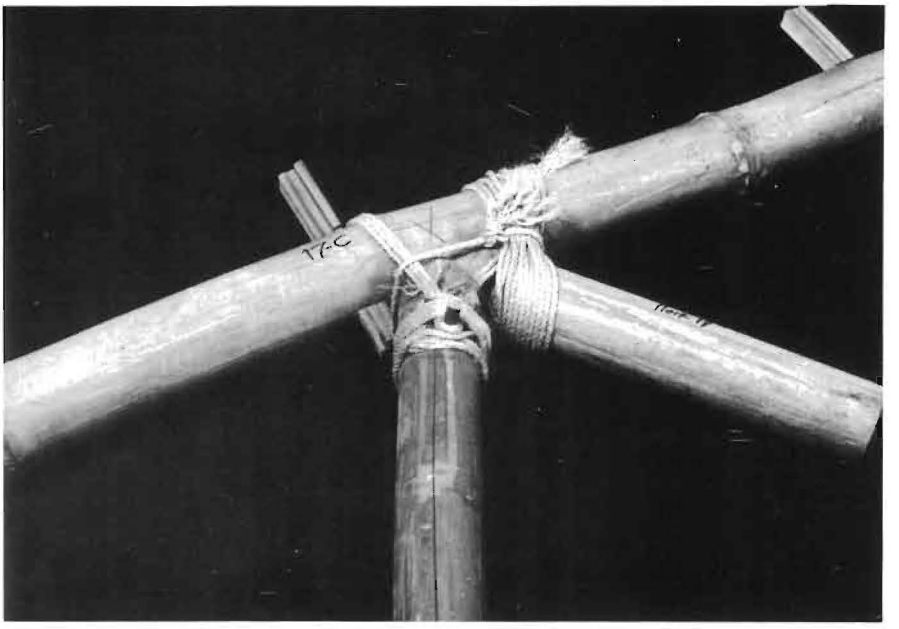
The stiffness of the joint for shear along the upper member is:

mean 980 N/mm.
standard dev. 350 N/mm.

Strength of the joint, expressed as force in diagonal:

mean 8 000 N.
standard dev. 2 000 N.

Picture 5.6.8.
Joint with bamboo horns (inside) and sisal lashing.



Picture 5.6.9.
Joint with bamboo horns; lashings and vertical left away.

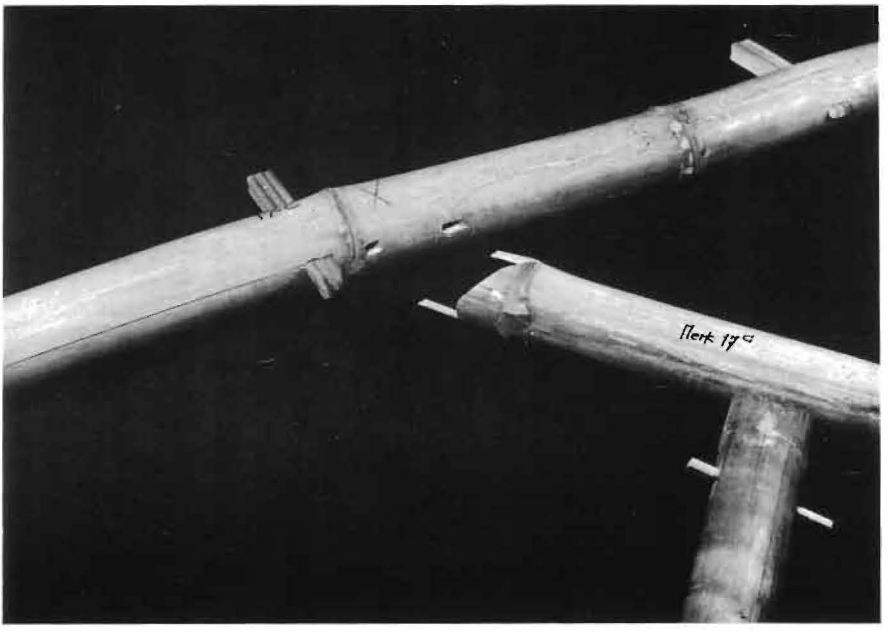


Fig. 5.6.10.
Joint 6.5. + 7.4.

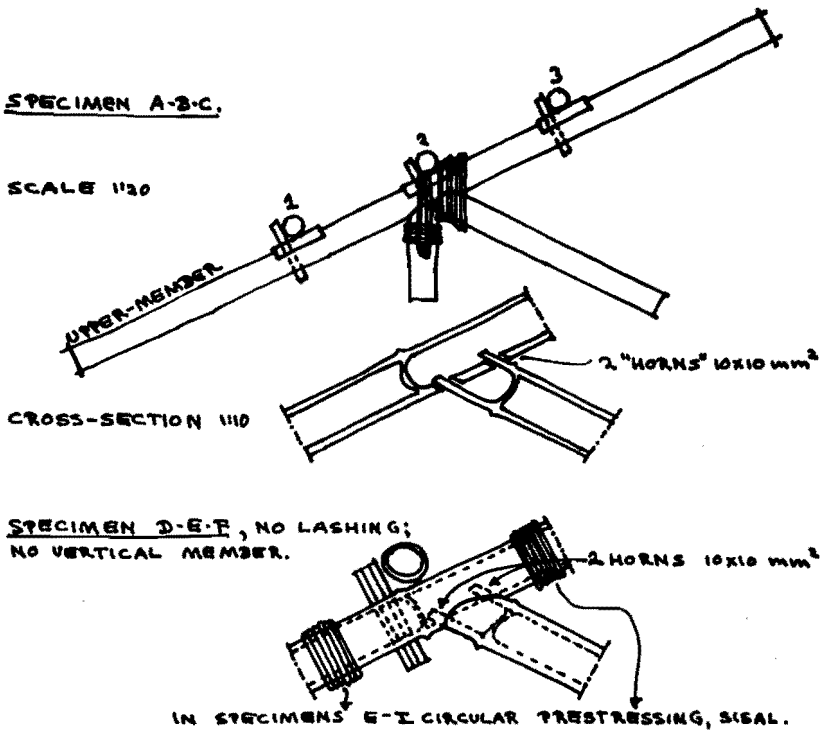


Table 5.6.11.
Joint 6.5. + 7.4.

Bamboo horns and sisal lashing

specimen no.	fails at per cent.	what happened	what has been proved
A	80	purlin 1 pushes into uppermember (thin-walled, 6 mm)	heavier upper member
B	180	upper member compressed between purlin 2 and diagonal; horns defect.	
C	200	idem see pictures 5.6.8. and 5.6.9.	lashing around diagonal and upper member left away.
D	120	upper member splits from joint to purlin 3; horns defect.	
E	180	purlin 2 pushes into upper member; joint still good.	
F	160	idem as B and C	purlin 2 left away.
G	100	upper member compressed at joint; horns defect.	
H	160	purlin 1 pushes into upper member; joint still good.	
I	140	purlin 3 pushes into upper member; joint still good.	

Conclusions: par. 5.6.5.

5.6.4. Diagonal joint, type 7.5.

Diagonal between double upper members.

The original concept for this joint contains a steel bolt through all three bamboos, but this is replaced by bamboo pins.

Accuracy of tests:

The normal force in the diagonal should have been 5800 N. at the reference level of 100 per cent., but due to friction losses and errors this force was:

mean 5250 N. = 91%
standard dev. 560 N. = 10%

This has been incorporated in the calculations.

Results of tests:

The slip of the diagonal along the upper member at the reference level is:

mean 5.6 mm.
standard dev. 2.4 mm.

The stiffness of the joint for shear along the upper member is:

mean 665 N/mm.
standard dev. 250 N/mm.

Strength of the joint, expressed as force in diagonal:

mean 11 300 N.
standard dev. 300 N.

Picture 5.6.12.
Joint 7.5. specimen E, opened after failure.

Fig. 5.6.13.
Joint 7.5.

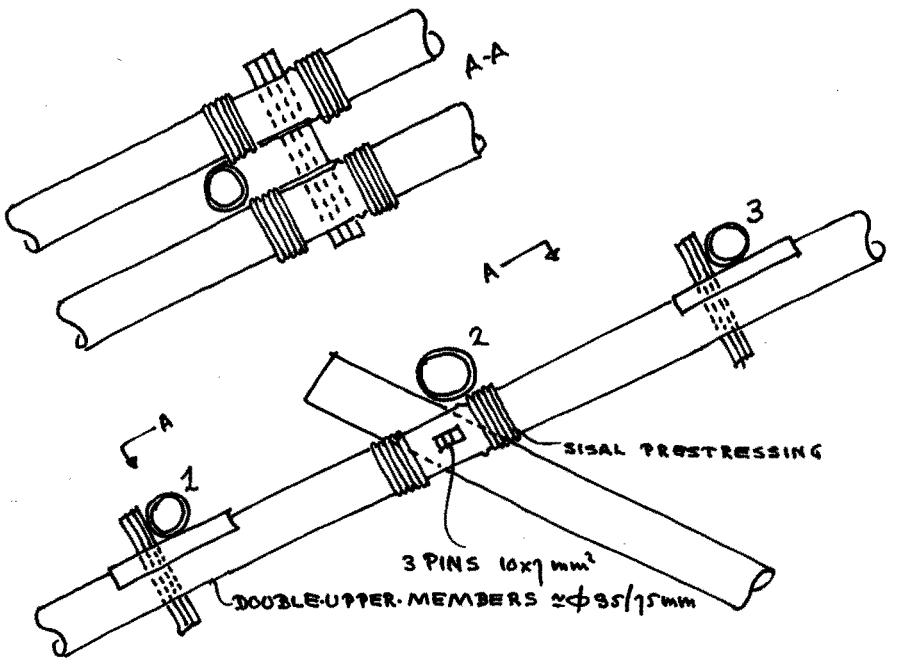


Table 5.6.14.
Joint 7.5.

Diagonal between double upper members

specimen no.	failed at per cent.	what happened	what has been improved
A	200	both upper members split at joint	
B	240	idem	prestressing of upper members on both sides of joint.
C	160	purlin 3 fails!	
D	260	diagonal + upper member + pins in joint all fail, see picture 5.6.12.	
E	240	pins in joint failed.	

Conclusions: par. 5.6.5.

5.6.5. Selection of joints; conclusions

Summary:

joint-type	stiffness for shear		strength	
	mean	st.dev.	mean	st.dev.
	N/mm	N/mm	N	N
7.6.,plywood and bolts	1170	360	16500?	-
1.3.,bamboo pins	430	160	10500	1640
6.5. (+7.4.),bamboo horns	980	350	8000	2000
7.5.,double upper member	665	250	11300	300

Table 5.6.15, Summary of joint-tests.
"Stiffness for shear" is expressed in unit force per mm. displacement.

The order is, as seen from the next viewpoints:

- strength : 7.6., 7.5., 1.3., 6.5.
- stiffness : 7.6., 6.5., 7.5., 1.3.
- simpleness : 1.3., 6.5., 7.5., 7.6.
  (with simpleness is meant: simpleness in construction with local materials and local craftmanship).

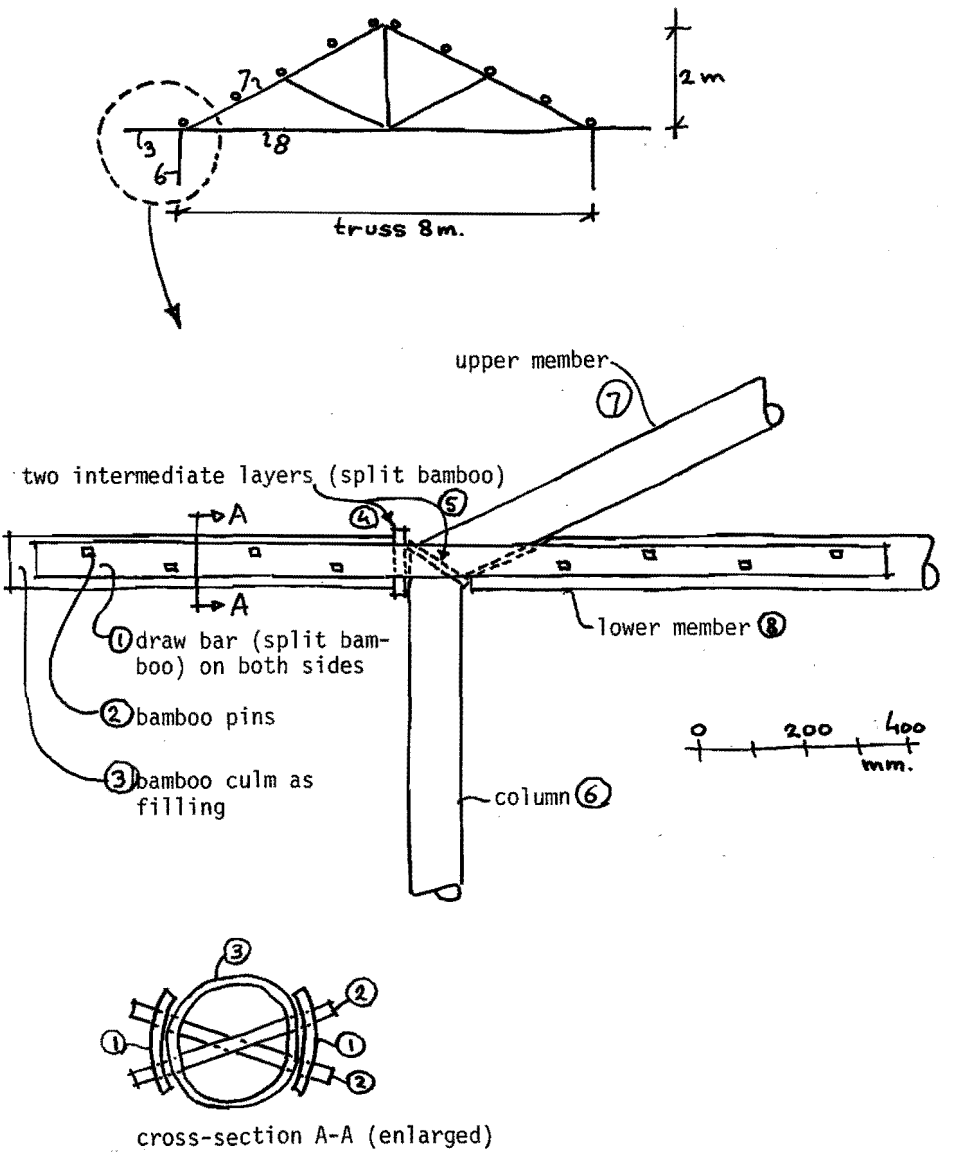
Comments:

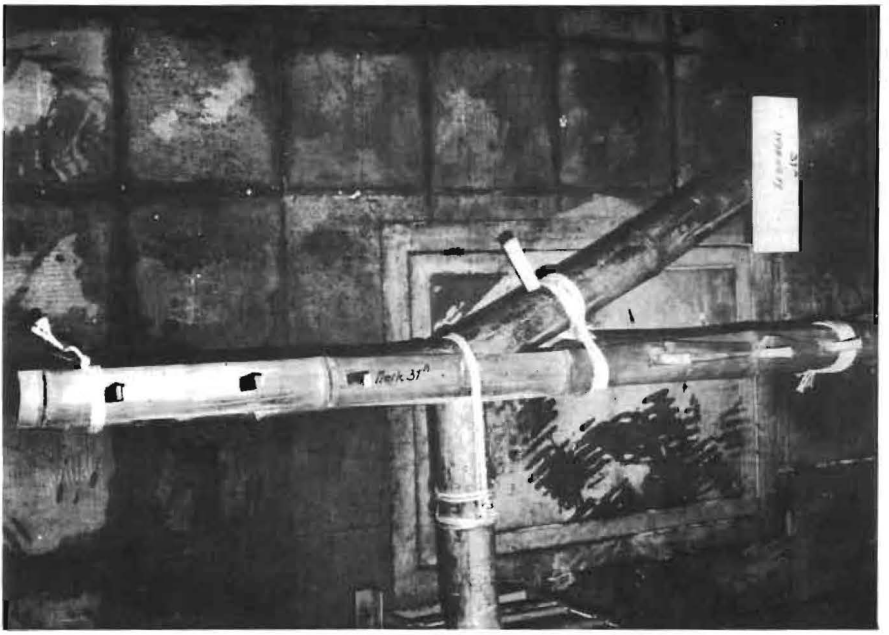
- Joint 7.6. is the strongest and stiffest one, but because of the plywood and steel bolts it is considered to be hard to make and therefore it has been rejected, which admittedly is an arbitrary judgement.
- Joint 7.5. is second in strength, and third in stiffness and simpleness; as an additional disadvantage the double upper member requires much bamboo; so this joint was rejected.
- Joint 6.5. is the second in stiffness and simpleness, and the worst in strength, and all together not considered a good choice.
- Joint 1.3. is the first in simpleness. Its third place in strength is almost an ex aequo with no. two, and its fourth place in stiffness is regretted but accepted.
  Joint 1.3. is chosen mainly because its first place in simpleness.

5.6.6. Tests on column joints

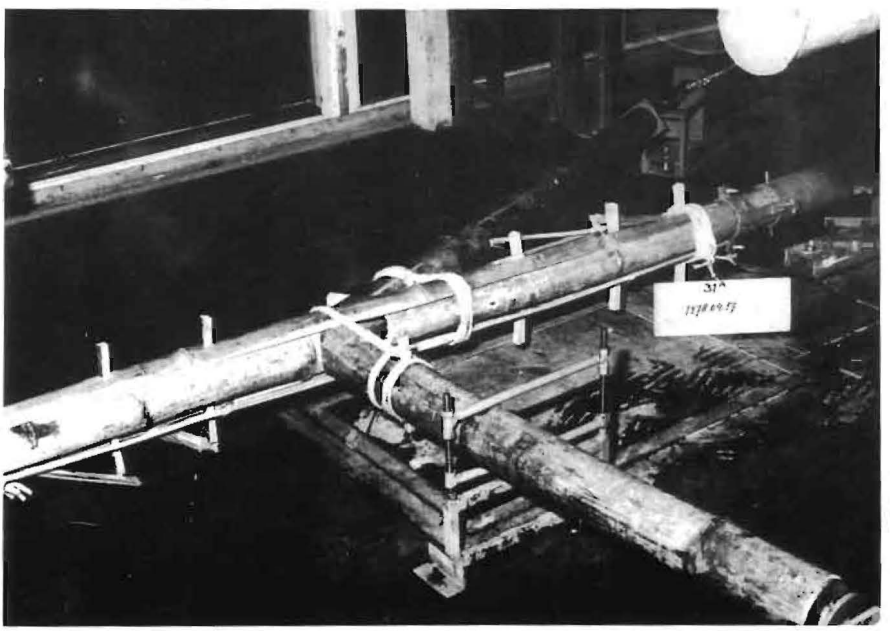
The culm joint is the place where the truss rests on the column, and the upper member of the truss (with its compression force) is connected with the lower member (with its tension). Sixteen tests were carried out on three different types, with many trials and errors in order to improve the designs.The joint represented in fig. 5.6.16. and pictures 5.6.17 and 5.6.18 finally was chosen. This joint is composed as follows: the upper member 7 rests upon the column 6 with a split bamboo layer 5 between them. But the main problem is the connection of the horizontal component of the compression force in upper member 7 with the tensile force in lower member 8. This is solved because the upper member 7 rests upon the column 6 and both on the filling bamboo culm 3 (with again an intermediate layer 4). This filling 3 is connected with the lower member 8 by the draw bars 1 and pins 2. The bamboo pins and the draw bar can be calculated, according to chapter 4.Failure occurs at about 200% loading (= 13 kN in lower member).Pictures 5.6.17. and 5.6.18. show this joint after failure by shear.
(P.S.: an improved column joint is designed and tested in the trusses 2 and following, see par. 5.8.2.).

Fig. 5.6.16. Column joint;





Pictures 5.6.17. and 5.6.18.: column joint after failure.



5.7. Trusses

5.7.1. Introduction

The tests on trusses are limited to:

- a free span of 8 m,
- distance c.o.c. 3 m,
- slope of roof 1:2,
- king-post type truss,
- leight-weight roof (galvanised iron sheets, or fibre reinforced cement sheets)
- dead weight of roof, purlins and trusses 330 N/m^2 floor area,
- joints as in par. 5.6.2. and 5.6.6.

The purpose of the test is to test a bamboo truss on full scale, in order to see:

- if a bamboo truss might be possible;
- how strong and stiff such a truss is;
- if the ultimate stresses fall within the range of ultimate stresses of chapter 4;
- if failure occurs in a joint or in the bamboo between the joints.

5.7.2. Test method

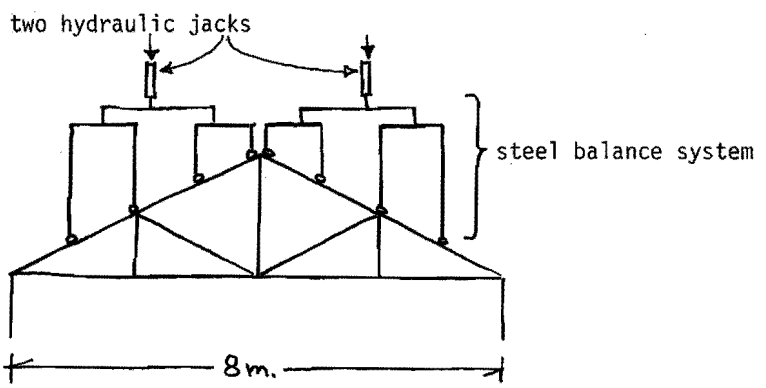


Fig. 5.7.1. Bamboo truss with loading system.

The load on the truss is brought on by two hydraulic jacks and a steel balance system. The jacks are electronically controlled to reach a greater accuracy. (error 0.5 per cent.). The steel balance system brings an equal load on each of the purlins; the double purlin in the ridge is exposed to the same load. Similarly as in par. 5.5. the load of 860 N/m^2 (according to Indian Standards) has been taken as a reference and called "100 per cent.". This load agrees with 2580 N on each of the seven purlins.

As it is rather difficult to test a truss in vertical position, the truss is laid down on the floor with ball-bearings in the balance system, and (starting with truss no. 2) teflon on the supports of the truss, to reduce friction losses. The friction losses are measured, and the calculations take account of these.
Now the truss has been laid down in a horizontal position, additional stresses occur in the truss due to its own weight. But these stresses are only 0.1 N/mm^2, which can be neglected when compared with the 50 or 80 N/mm^2 caused by the load. A disadvantage is that the stability in this position (fixed to the floor) is greater than in reality.
The time-schedule for loading is as follows. The load is brought on (or released) in steps of 20 per cent. Readings of strains and deformations were made immediately after each step, and again after a 3 minutes rest, whereupon the next step followed. On the first day a last rehearsal took place: the load was brought to 20 and 40 per cent., and down to 20 and to zero. Every detail was checked.
On the second day the load was brought up to 100 per cent. and down to zero, and after a full hour of rest again to 100 per cent. During five hours, creep was observed at this level (of 100 per cent.), whereupon the load was removed.
On the third day the truss was loaded again in steps of 20 per cent. until failure.
Measured were:

- the reaction forces in the two columns, by pressure gauges;
- the displacements of upper and lower members, by ten-turn potentiometers;
- the strains in the bamboo, by strain gauges, eight of which were required in order to determine the bending moment and the normal force in one cross-section.

It is important to check beforehand, if the chosen system of measuring displacements and strains would satisfy so as to calculate deformations, moments and forces afterwards.

5.8. Results of tests on trusses

5.8.1. Truss no. 1

Truss no. 1 is represented in figure 5.8.2. and picture 5.8.3., and the joint between diagonal and upper member is shown in picture 5.8.4.
The measuring system (potentiometers, pressure-gauges, strain-gauges) is also shown in fig. 5.8.2., and it can be seen also from the two pictures just mentioned.
Figure 5.8.5. shows the loading-deformation diagram, from which one can see the deformations between zero and 100% loading:

- first time, from 5 to 56 mm = 51 mm (permanent 10);
- second time, from 15 to 59 mm = 44 mm (permanent 8);
- third time, from 23 to 74 mm = 51 mm.

So the immediate deformation under a load of 18 kN is about 50 mm (= 1/160 of span), of which about 40 mm. is elastic and 10 mm. is plastic.The internal forces (axial forces, shear forces and bending moments) and the displacements have been both calculated and measured. They are considered representative if the displacements, resulting from calculations and from measurements, are equal. Results are as follows:

- the calculated deformation of the truss
  without displacements in the joints, is (see par. 5.5.) 7 mm;
- idem, with displacements in the joints,
  based on the stiffness derived before, (par. 5.6.) 24 mm;
- measured deformation 50 mm.

(so 85% of the deformation is due to the joints and only 15% to the elasticity of the material).By trial and error it was found that the calculated deformation can be enlarged from 24 to 50 mm. only by a lower stiffness of the joints between lower member and column. In fact, a stiffness of 1000 N/mm will do. Unfortunately the displacement in this joint was not observed, neither when testing this joint (par. 5.6.6.) nor in this truss.Fig. 5.8.6. shows a comparison between calculated and measured forces and displacements. During the test the reaction forces in the columns have been recorded as 88% of the action forces, due to friction losses. It is assumed, that the truss has been loaded by 90%, and this error has been accounted for in fig. 5.8.6. The measured axial forces are lower than the calculated ones, in fact 84%, for which an explanation could be found in the statical redundancy of the upper member, and the deformation of the truss. The measured bending moments agree fairly well with these calculated, but one might assume that the negative bending moment of 580 Nm is much less, or perhaps zero, which is usual in wooden trusses (based on personal information from specialists in wooden trusses). The forces in the diagonals and verticals have not been plotted; the number of strain-gauges is not enough to measure internal forces, presumably because of bending moments (perhaps due to eccentricities in the joints).As to the strain gauges, eight of them are enough to measure a moment plus an axial force. Readings might correspond to those given in 5.8.7.A. But these strains have to be gauged in order to calculate stresses from these strains. So all pieces of bamboo with strain-gauges were sawn out of the truss after the test, and gauged in a hydraulic press. Surprisingly, strains under an axial force sometimes might be as those in fig. 5.8.7.B.: they are not always constant around the circumference! The right procedure now is to draw a stress-strain diagram for each strain-gauge during gauging, and to find the stress for each strain in fig. 5.8.7.A., see fig. 5.8.7.C., from which bending moment and axial force can be calculated, see fig. 5.8.6.

Ø 103/87 means: outer Ø 103 mm, inner Ø 87 mm.

diagonals etc. ~ Ø 83/69

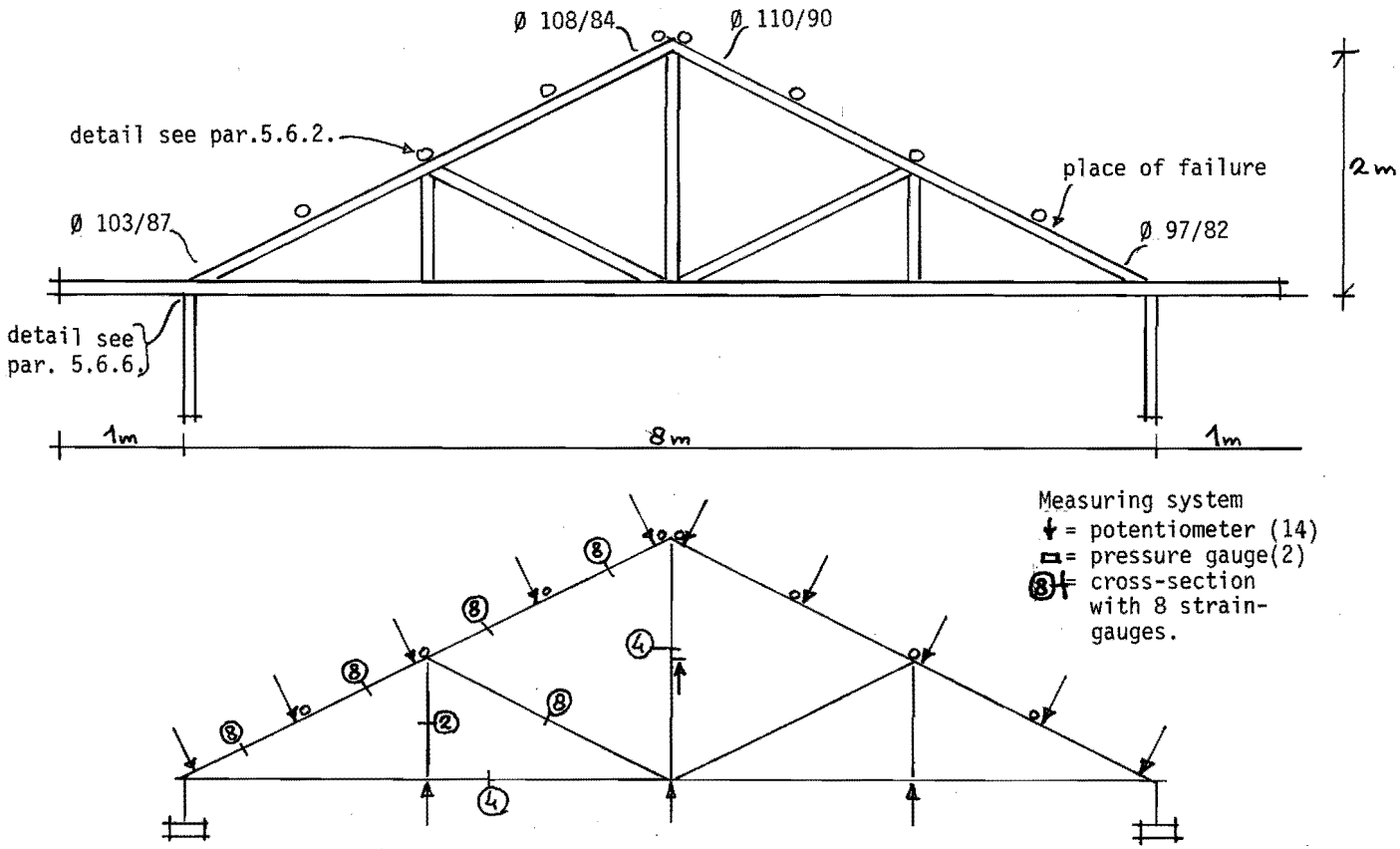
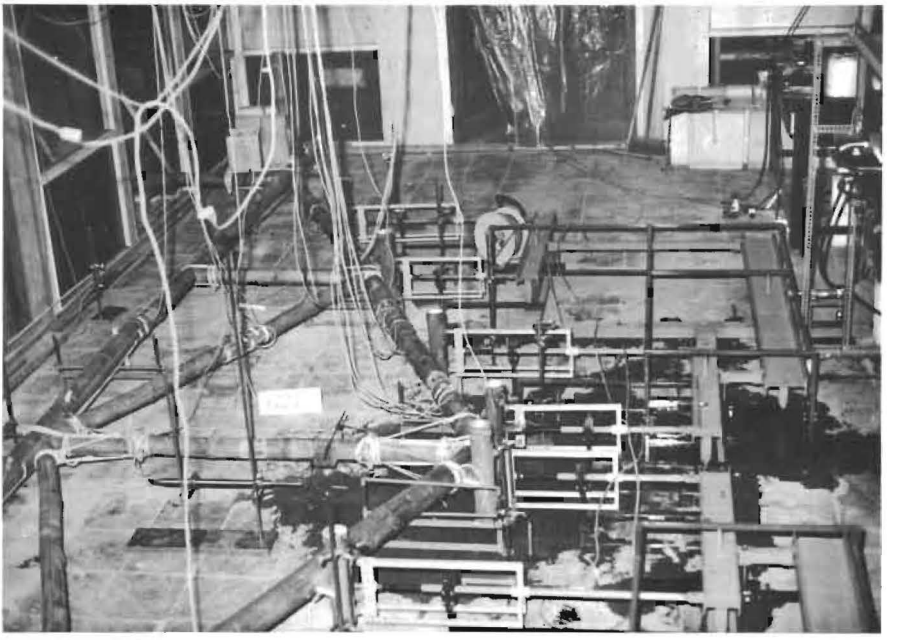


Fig. 5.8.2. Truss no. 1

Picture 5.8.3. Truss no. 1



Picture 5.8.4. Detail

Fig. 5.8.5. Loading-deformation diagram

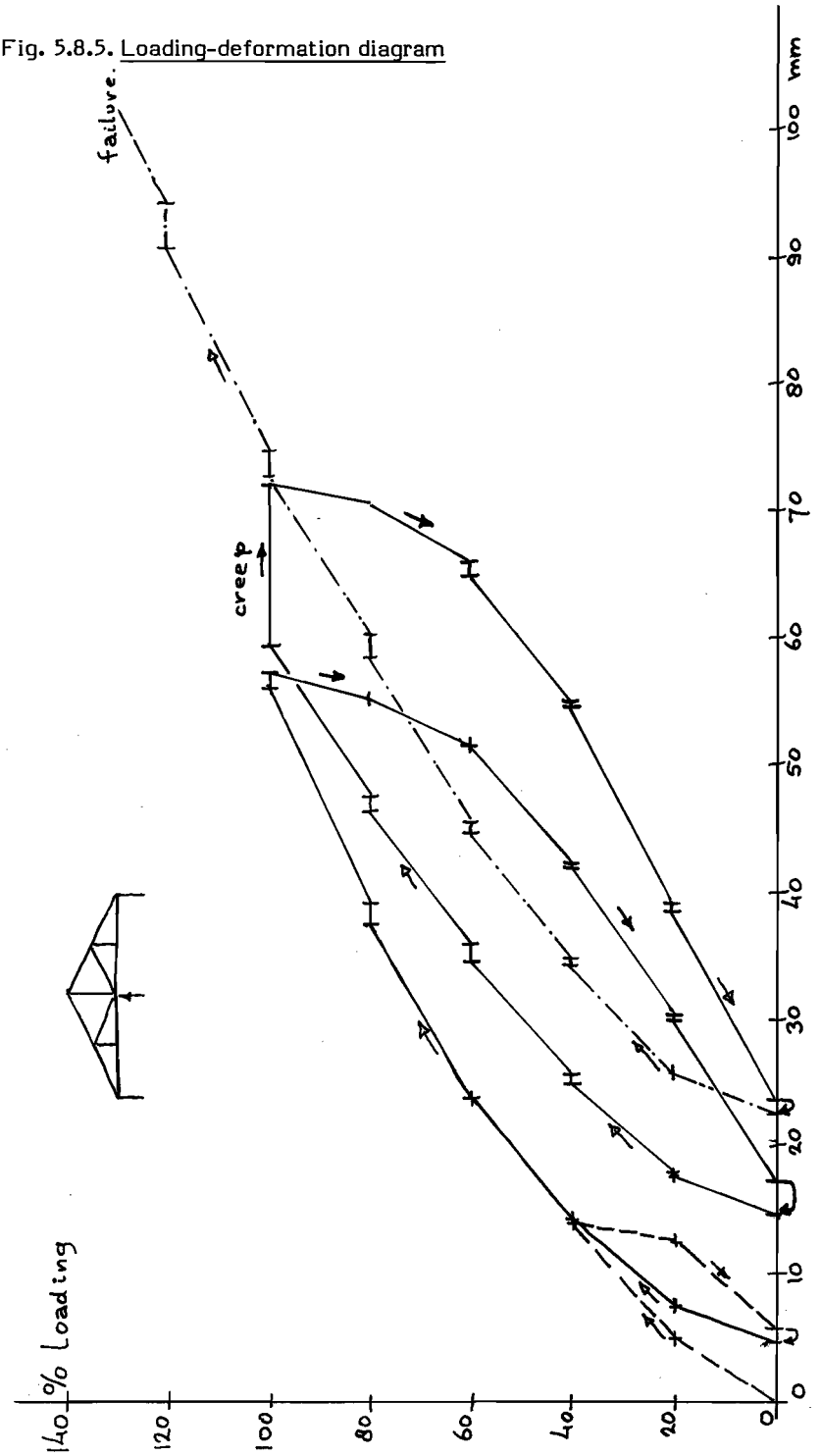


Fig. 5.8.6. Calculated and measured forces and displacements, truss 1
(calculations were linear)

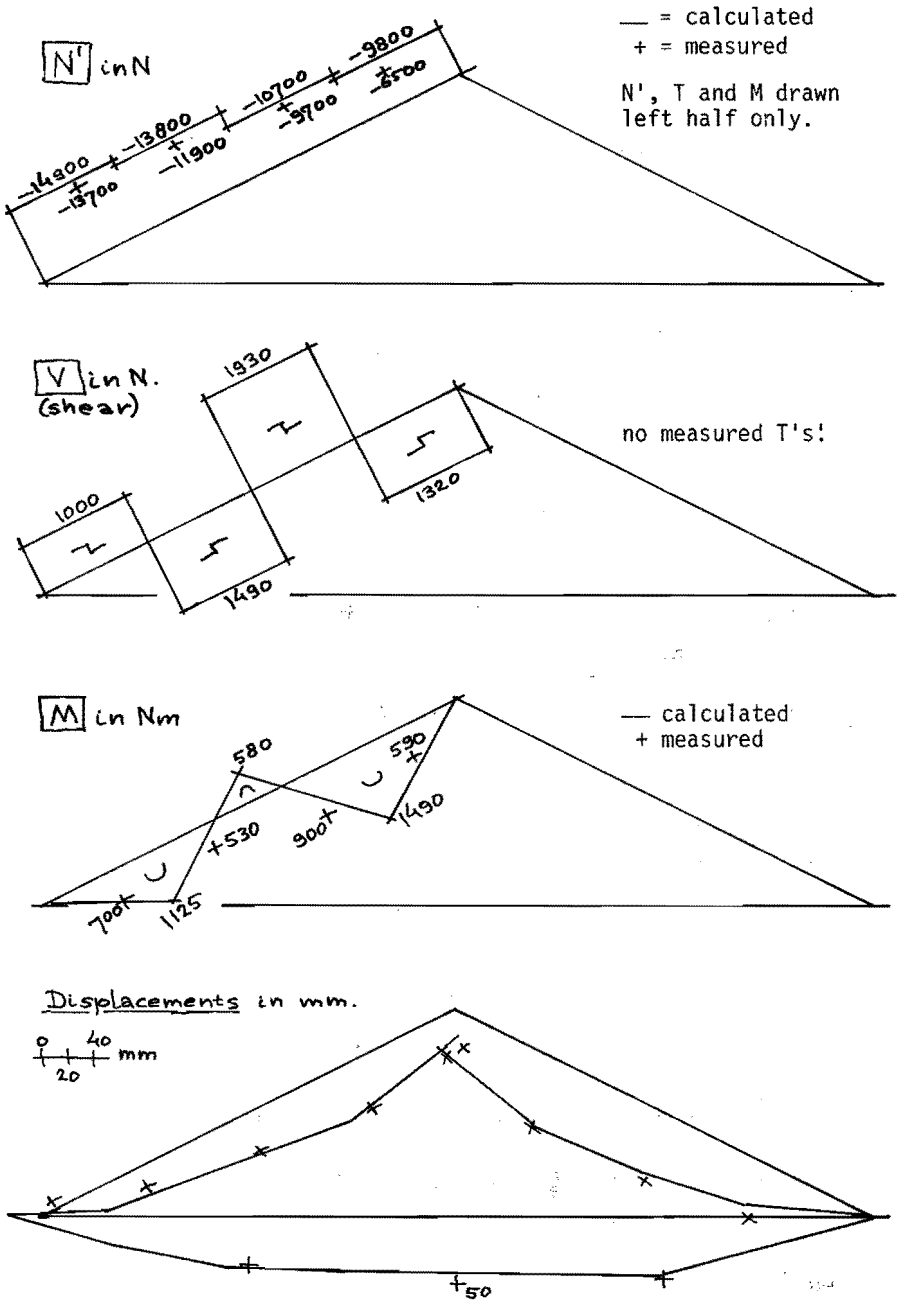


Fig. 5.8.7.A. (see text)

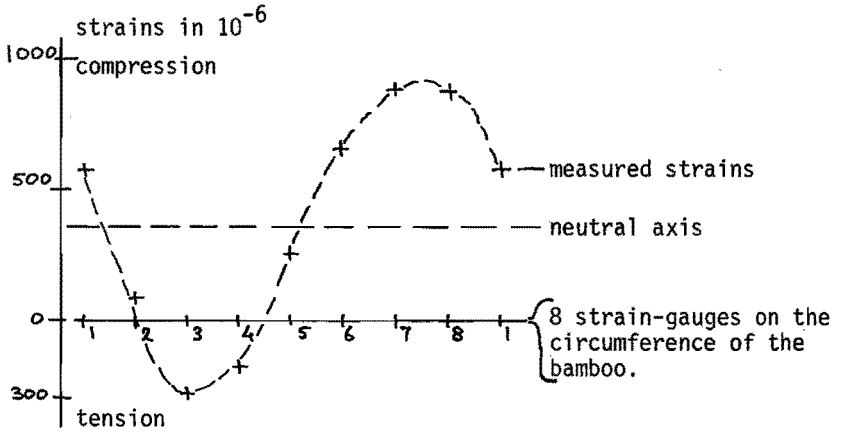


Fig. 5.8.7.B.

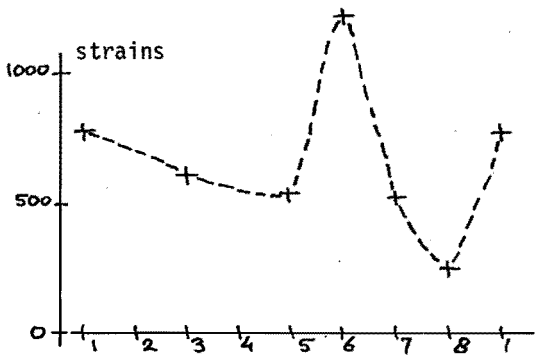
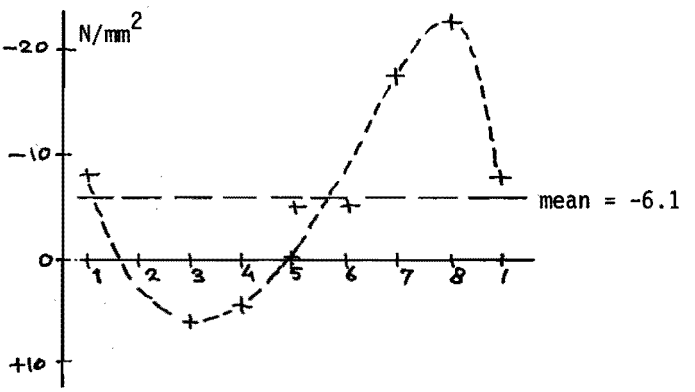
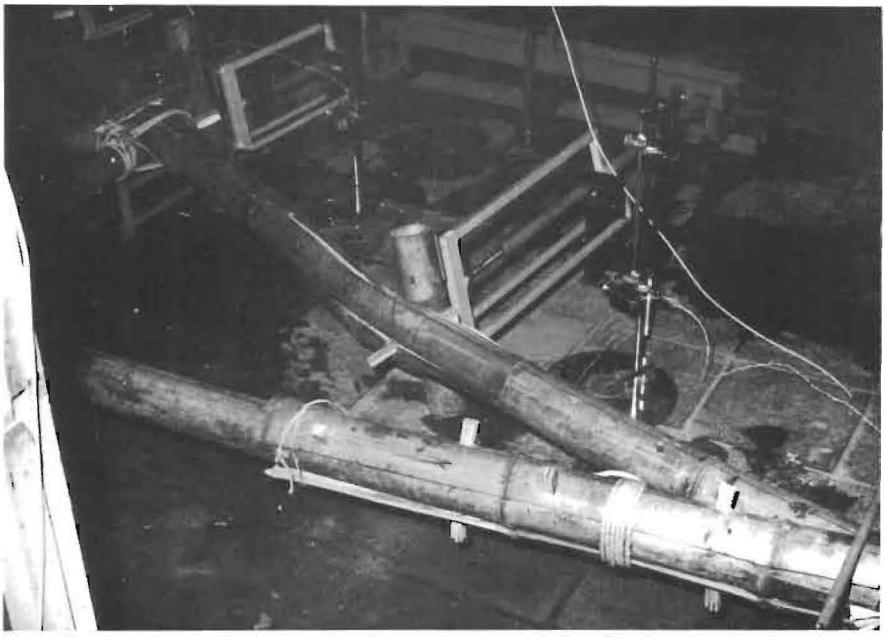
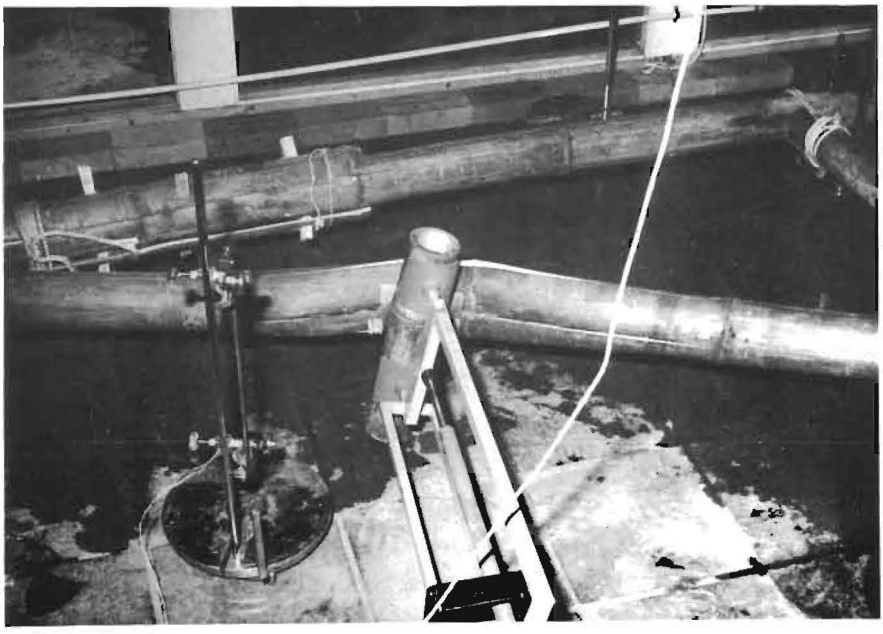


Fig. 5.8.7.C.





Pictures 5.8.8. and 5.8.9.; detail of failure.

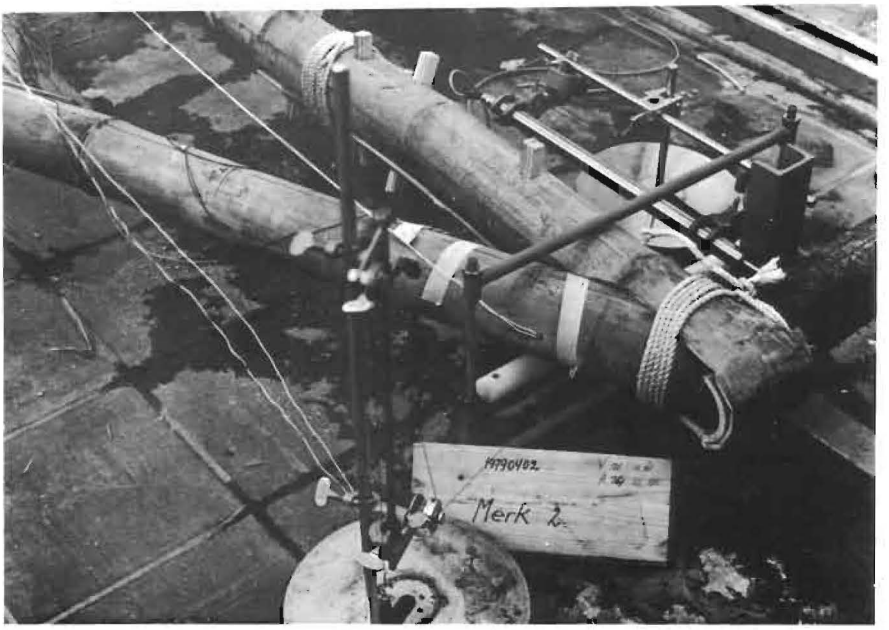


The hysteresis can already be seen in the loading-deformation diagram, fig. 5.8.5. The hysteresis has been recorded too in the reaction forces in the columns: the difference between loading and unloading is 14%, but it is not possible to divide this between the truss and the friction losses.
The creep, observed during four hours, is 12 mm, under a load of 18 kN. (The estimated creep in 5 hours is 14 mm). Ultimate stresses under this load are about 30 N/mm^2. (This creep in the first hours cannot be used to predict creep on the long term, but it might be useful for a comparison between the structures.)
Finally, failure occurred at a load of 140%, i.e. 23 kN, or 3.25 kN on each purlin. The failure occurred at the arrow in fig. 5.8.2. at the right, where a purlin causes a bending moment, the axial force is high, and the cross-section is weakened by the holes (for the pins to support the purlins). See picture 5.8.8. and 5.8.9.
Due to contradictionary results of the measurements with strain-gauges and with potentiometers, it is difficult to determine the stress at failure, but the best estimated value is about 50 N/mm^2.
This is a compression stress, due to bending moment plus axial force, taking into account the weakening of the cross-section by the holes, but neglecting the stress-concentrations near these holes and the stresses caused by the purlin.

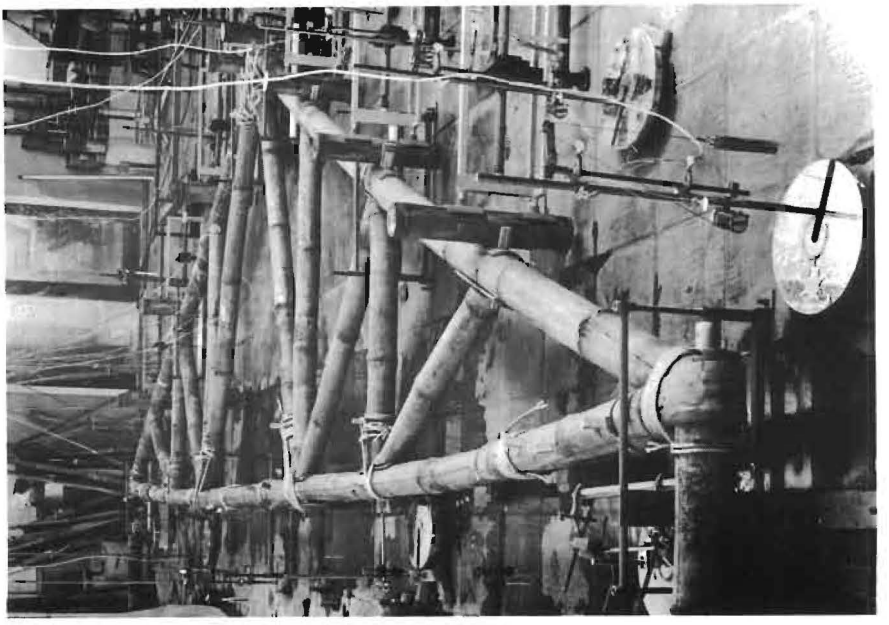
5.8.2. Truss no. 2

Based on the experience with the first truss, several improvements have been carried out:

- more diagonals and verticals, in order to support each purlin, and in order to reduce the bending moments and the deformation;
- as few tensile joints as possible, because compressive joints are easier, stronger and stiffer;
- a better column-joint, easier to make and hopefully stiffer, see picture 5.8.10. (This has come true, see page 217)
- the horizontal displacements of the column-joints will be measured.
- to reduce friction-losses, the truss is laid on the teflon, which reduces friction-losses from 12 to 2% (as measured);
- this process of improvement was carried out with the same computer-model as used for truss no. 1. Several configurations of verticals and diagonals have been studied, which resulted in the choice of the truss as represented by picture 5.8.11. and in figure 5.8.12. It is predicted that moments and displacements will decrease to 75% of those in truss no. 1. (this has been confirmed in practice).

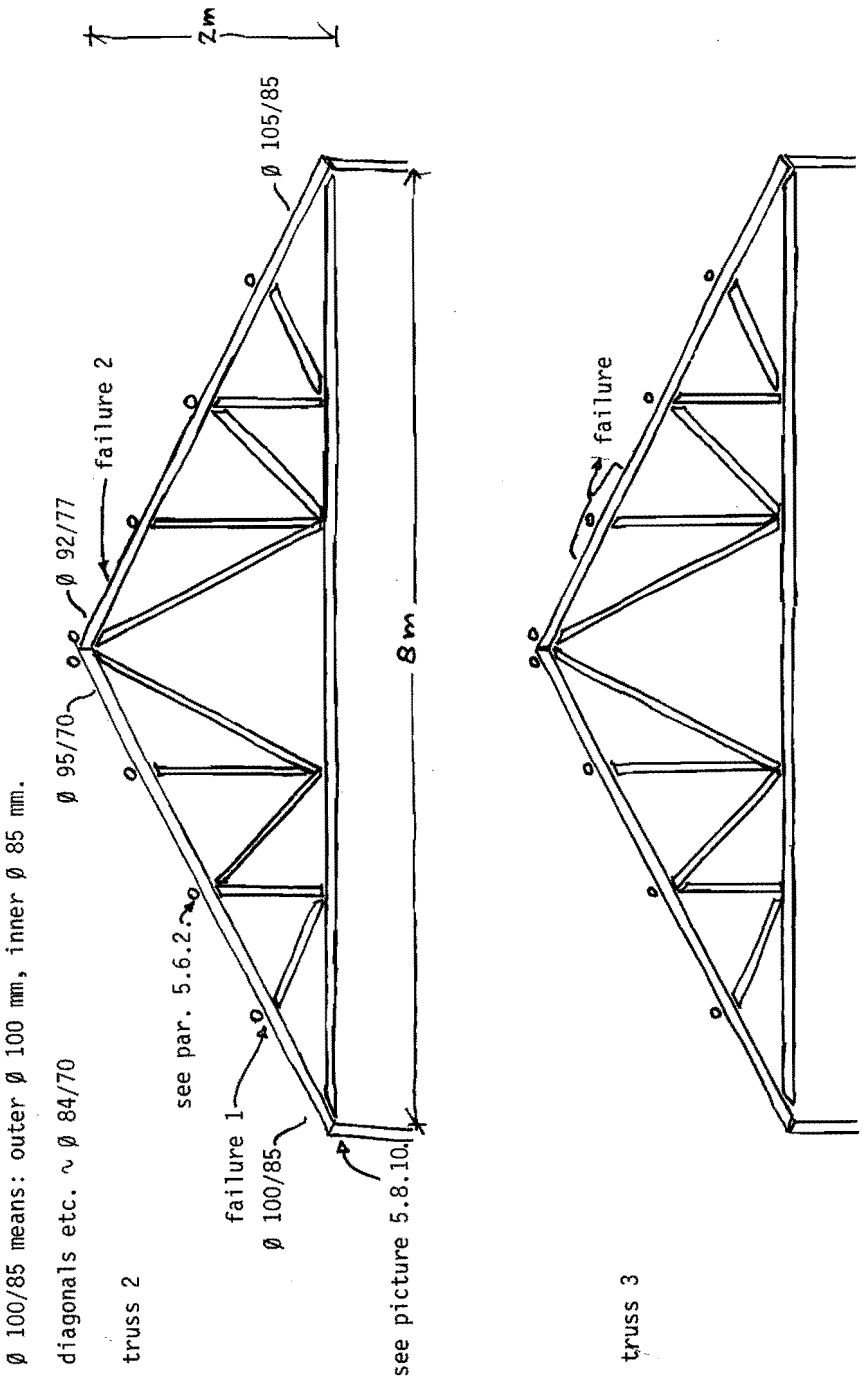


Picture 5.8.10. Improved column-joint



Picture 5.8.11. Truss no. 2

Fig. 5.8.12. Truss no. 2 and 3



The measuring system (strain-gauges, potentiometers, pressure-gauges) is about the same as that for truss no. 1, only more strain-gauges are used at the upper member, for better measurement of moments and forces.
The loading deformation diagram is very similar to that of the first truss (fig. 5.8.2.), only the deformations between zero and 100% loading are now:

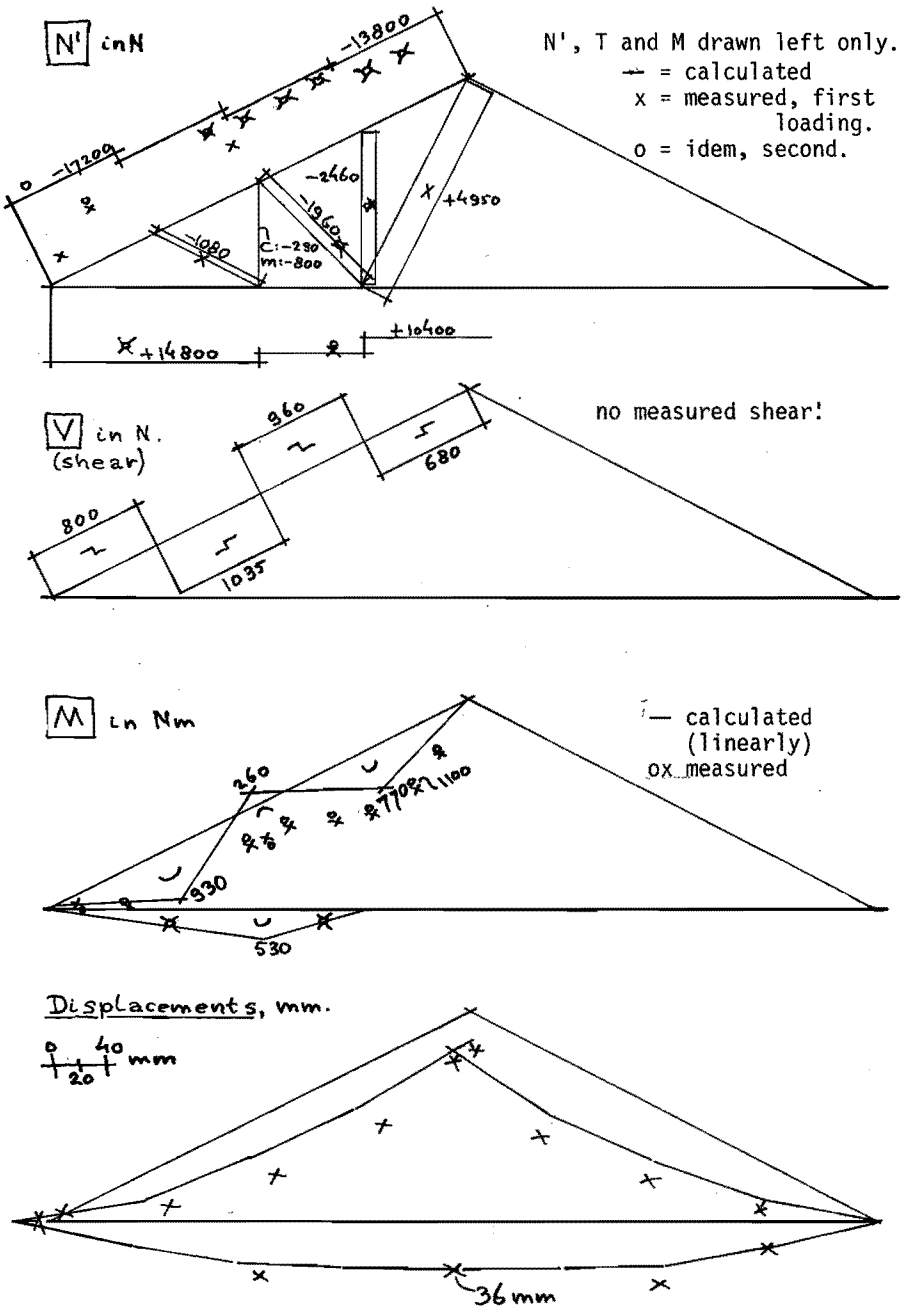
- first time, 50 mm, permanent 14 mm;
- second time, 36 mm, permanent 3 mm;
- third time, 39 mm.

So the deformation predicted by the computer-model of 37.5 mm. has been confirmed only at the second and third time of loading. But in the first loading the joints still have to set themselves (presumably the permanent 14 mm.).
The internal forces (axial forces, shear forces and bending moments) and displacements, both (linearly) calculated and measured, are given in fig. 5.8.13.
The normal forces in the truss are smaller in reality than in the calculation, presumably because the deformation of the upper member is greater. This is because in this upper member there are no negative, but only positive moments. These might be caused by a smaller stiffness of the joints of verticals and diagonals. The maximum moments are about 1100 Nm (measured), which indeed is less than those in the first truss (1500 Nm, estimated). The stiffness of the column joints is 1650 N/mm, which is indeed better than the 1000 N/mm estimated in the first truss. The hysteresis in the deformations is similar tot that in first truss, fig. 5.8.5. The hysteresis in the reaction forces (= the difference between loading and unloading) is 15%. The creep, observed during five hours under 18 kN, is 12 mm, under a maximum stress of about 25 N/mm^2.
Failure occurred at 160% = 29 kN at two places, see the arrows in fig. 5.8.12. In point 1 failure occurs by compression in the upper member at the place weakened by the hole; stress = 37 N/mm^2, to be increased with the stress concentration around the hole, and with the influence of the purlin. At point 2 failure occurs by splitting at a compressive stress of 46 N/mm^2.
A brief comparison with truss 1:

	truss 1	truss 2	ratio 2:1
- material quantity in this truss	27 m'	30 m'	1.11
- number of joints	8	13	1.63
- load at failure	23 kN	29 kN	1.26
- deformation at 100%	48 mm	42 mm	0.88

As a mattter of fact, in view of the large amount of material and joints (i.e. labour) the small improvement in load at failure was felt as a disappointment. Truss no. 2 has therefore been built again, see truss no. 3.

Fig. 5.8.13. Calculated and measured forces and displacements, truss 2.



5.8.3. Truss no. 3

The third truss is almost a copy of the second, and therefore a summary of the results is given in table 5.8.14, and the moments and axial forces are graphically represented in fig. 5.8.15. Table 5.8.14. is clear on its own, only the failure needs some explanation. This truss failed twice, being repaired after the first time. The first failure occurred in the ridge, at a load of 25 kN (140%). The two upper members, meeting one another in the ridge, pressed into each other.
The lesson from this type of failure is an intermediate layer of split bamboo between the two upper members at the ridge. The second failure occurred in the right upper member, see fig. 5.8.12., when the load was brought from 29 to 32 kN, at a stress of about 41 N/mm^2 (compression, to be increased with the stress concentrations around the hole and the stress due to the purlin).

	truss 1	truss 2	truss 3	units
Mean $\varnothing$ upper beams	104/86	98/79	102/82	mm
Deformation at 18 kN loading, elastic/permanent,				
first time	51/10	50/14	37/15	mm
second	44/8	36/3	26/4	mm
third	51	39	30/-	mm
fourth	-	-	40	mm
mean	48	42	33	
stiffness column joint	-	1650	1000	N/mm
Creep in 5 hours	14	12	9	mm
Load at failure	23(140%)	29(160%)	29(160%)	kN
σ at failure	50?	37/46	41	N/mm^2

Table 5.8.14. Comparison of truss 1, 2 and 3.

In fig. 5.8.15. at first the axial forces N' have been plotted. Skipping the extreme high and low values, because I do not trust the strain gauges at these places, the results are:

truss 2, first loading, n = 8, N = 10600 N, st.dev. 1500 N
truss 2, second loading, n = 7, N = 11000 N, st.dev. 1100 N
truss 3, first loading, n = 7, N = 9400 N, st.dev. 1700 N

Secondly, the moments M are represented. A conclusion might be, that the upper member in this type of truss might be calculated at 11 kN axial force plus 1100Nm bending moment, as failure load for trusses 8 m. span, 3 m. c.o.c., dead load 360 N/m^2, live load 500 N/m^2. This means that the upper members are the weak spots of this type of truss. In practice haevier bamboos should be taken for these upper members (e.g. outer diameter 125 mm instead of 100 mm as in our tests).

Fig. 5.8.15. M and N' measured in truss 2 and 3.

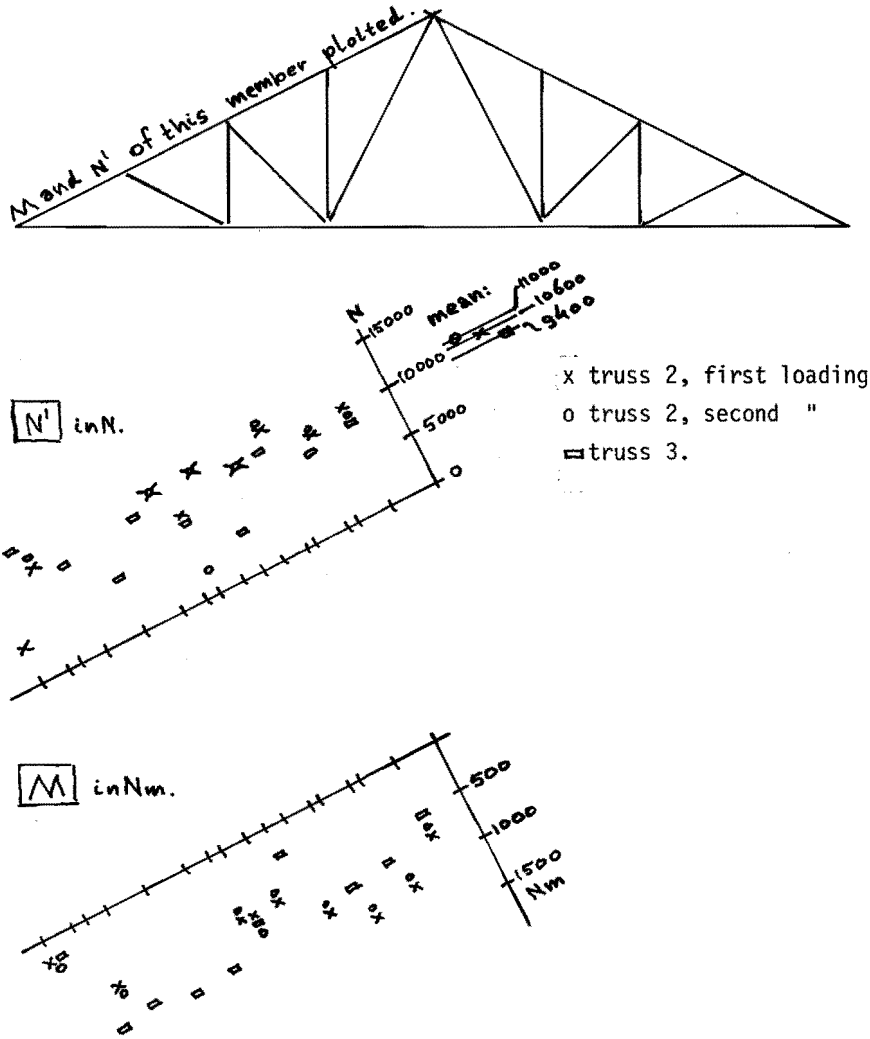
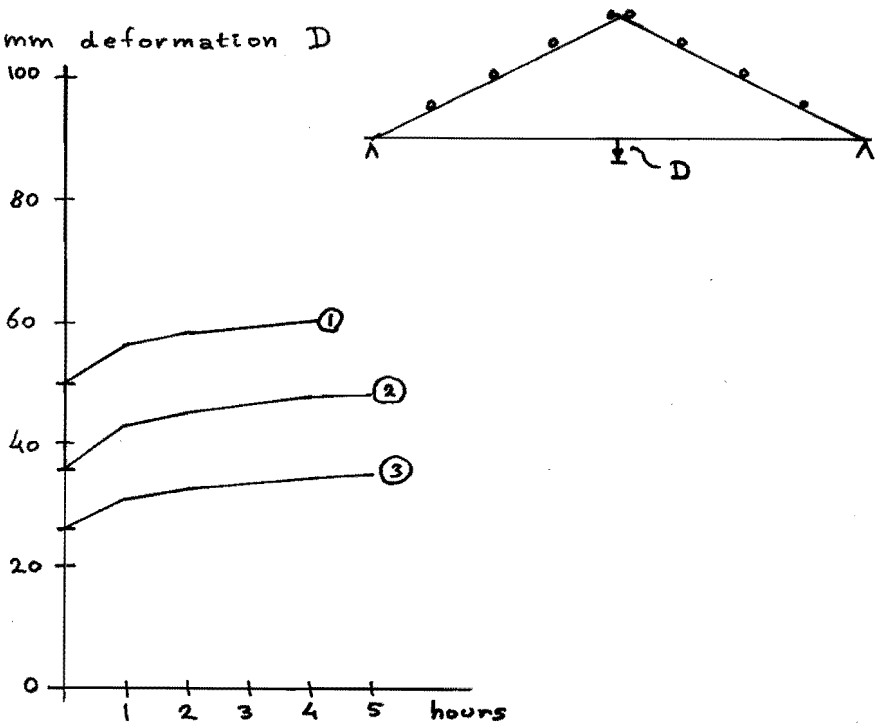


Fig. 5.8.16. Creep in the first three trusses.



5.8.4. Truss no. 4

After these three tests on short-term loading, a need was felt for a test on long-term loading in order to study creep and recovery. Creep had been observed already, see fig. 5.8.16., but only during four or five hours. A summary which also refers to stresses and strain and to truss no. 4, is given in table 5.8.17.

truss no.	mean δ upper member mm.	deformation immediate mm.	creep, 5 hours mm.	at maximum moments max. stress, N/mm^2	strain, initial, 10^{-6}	strain, increase, %
1	104/86	50	14	30	1400	16
2	98/97	36	12	25	1150	17
3	102/82	26	9	20?	950	22
4	94/78	50	11	43	2000	22

Table 5.8.17. Creep during first five hours.

One should keep in mind, that the improvement from truss no. 1 to no. 2 is reached by a better design, and from no. 2 to no. 3 by heavier bamboo. As to truss no. 4, this is the same type as nos. 2 and 3. Because the nos. 2 and 3 failed between 160 and 180%, say 170% loading, and because one might assume the longterm strength of bamboo to be 55% of the short term strength, similarly as with wood, it was decided to load truss no. 4 with 0.55 time 170% = 94%, rounded off to 100% = 18 kN. However, when measuring the outer diameters and wall thicknesses of truss no. 4, by mistake the sizes of the upper members of truss no. 3 (i.e. 102/82 mm) were taken to determine the moment of inertion, instead of the sizes of the upper members of truss no. 4 (i.e. 94/78 mm only) (see table 5.8.17.).Consequently, the maximum stress in truss 4 was as high as 43 N/mm^2, and the initial strain at the maximum moments 2000.10^{-6}, both of which values are higher than for trusses no. 2 and 3. The truss failed after 100 hours, see fig. 5.8.18.

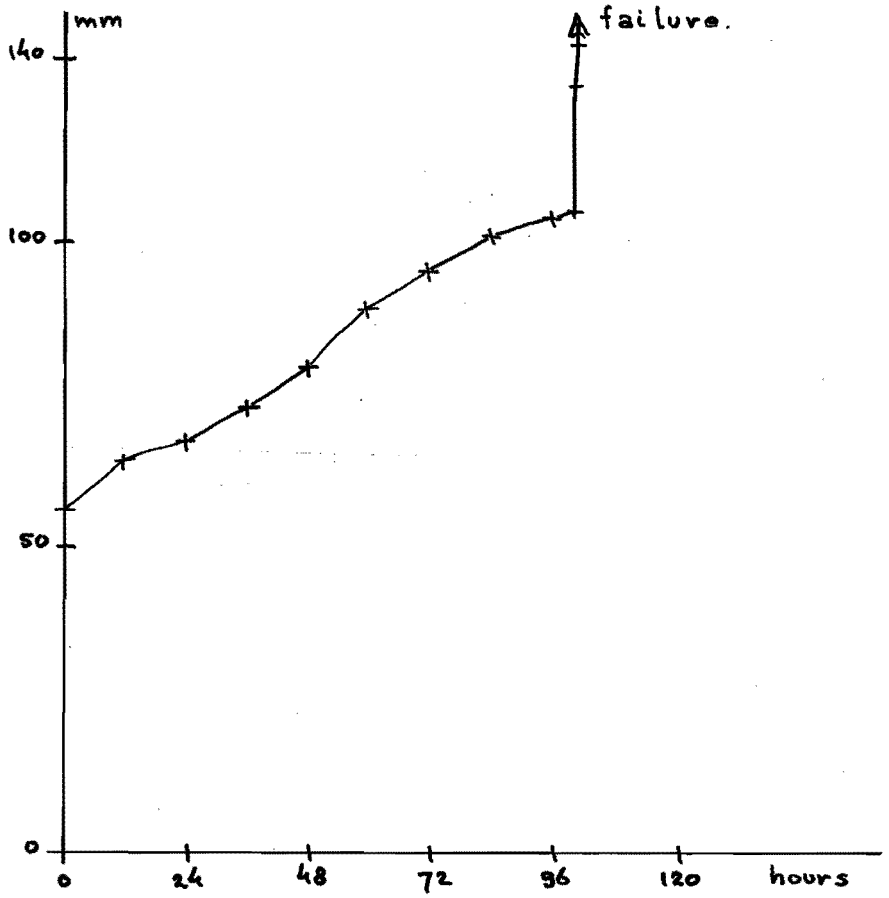


Fig. 5.8.18. Creep in truss no. 4.

The stress of 43 N/mm^2 agrees fairly well with the 46 N/mm^2 in the case of long-term pure bending, see par. 4.5.3.
A final remark: the measuring systems contains no straingauges, because these do not behave well in a moist condition during a long time. Because moisture can reach the strain-gauges through the bamboo, they are spoiled after about one or two months.
A really long-term test was made with the fifth truss.

5.8.5. Truss no. 5

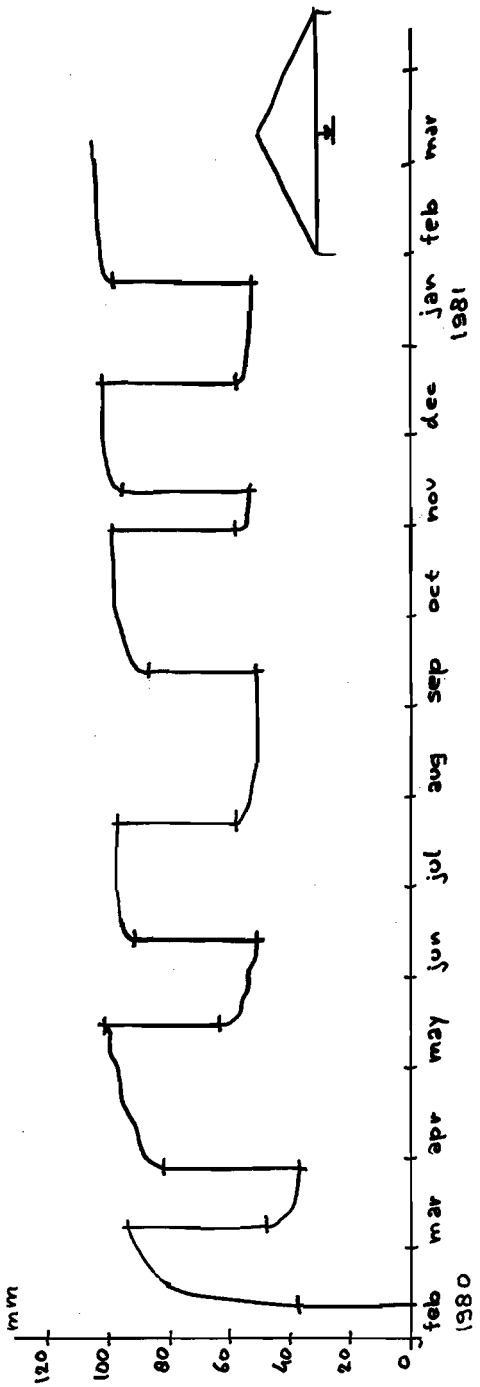
To give truss no. 5 a longer lifetime than that of truss no. 4, it was loaded with 14.4 kN only, instead of 18 kN. This lower load resulted in an estimated maximum stress of about 25 à 30 N/mm^2. The creep and recovery, as observed until February 1981, are given in fig. 5.8.19. One should know that the creep and recovery during the first 50 days had been influenced by setting of the joints. This test had to be continued till creep and recovery have been observed five times. At this moment five times lead to the next conclusions:

- the immediate deformation in the first loading is 37 mm., and in the next loadings 43, 41, 36 and 43 mm. resp., i.e. an average of 41 mm (n = 4);
- the creep in the first loading was 56 mm, and in the next 3 loadings 19, 6, and 12 mm;
- the total deformation was about 100 mm, to be divided into:
  - permanent deformation 50 mm. (viscous);
  - immediate deformation 40 mm. (elastic);
  - creep 12 mm. (retarded elastic).

These deformations are the consequences of compression, bending and shear, and therefore it is nearly impossible to compare it with wood or with cristallinity.

A note from this test series: in our laboratory all diagonals and verticals under compression were not lashed, so as to keep the work simple. But in the first unloading, all of them fell apart onto the floor. (due to permanent deformation). So we still had to add lashes. In building practice lashings are always necessary to cope with wind suction.

Fig. 5.8.19. Creep and recovery, truss no. 5



5.9. Conclusions

The introduction promises a report on joints and trusses, to support roofs with 8 m. free span. Joints have been designed, selected, and tested on full scale, and as a result their strength and stiffness is known, see table 5.6.15. With one of these joints five trusses have been built and tested on full scale, three on short-term loading (including 5 hours creep), one during 100 hours, and one during 380 days until February 1981.

As a result, their strength and stiffness on short and long-term can be determined, see tables 5.8.14 and 5.8.17. The sample is very small, too small as a basis for practice, however.

The reason for this research on trusses is given in the introduction (par. 5.1.): trusses are required for schools, medical centres, storehouses for agricultural products, etc. However, after completion of the research mentioned in this chapter, it is felt, that firstly it should be tried out if the expected need for this type of trusses in practice is a reality, and if so, secondly, if such trusses should be tested in a field situation as well.

A important fact remains, that the trusses fail due to limits to material strength in the upper members, and not on account of joint strength. This means that the problem of bamboo joints in fact has been solved for this type of truss. However, much research on other joints (see par. 5.4.) and trusses is still necessary.

As to the truss, described in this chapter, a design-rule is given at the end of par. 5.8.3.

5. References

McClure — Bamboo as a building material.Department of Housing and Urban Development. Washington D.C. Reprinted 1972, 52 pp.

Duff, C.H. — Bamboo and its structural use. Institution of Civil Engineers, Shanghai (1941). Cited pp. 2...27.

Hidalgo Lopez, Oscar. — Bambu. Cali (Columbia) 1974, 318 pp. Cited pp.195...204.

Hodge, W.H. — Bamboos, their economic future in America. The garden journal, (1957) pp. 124...128 + 131.

Karamchandani, K.P. — Role of bamboo as a constructional material. National Buildings Org., India. Proceedings Symp. Timber and allied products. New Delhi (1959) pages 430...435.

K.N.I.L. — Former Royal Dutch Army in Dutch East Indies, manual (in dutch) "Civil Structures with Bamboo", reprint 1939, fig. 4.c.

Kumple, G. — An experimental Bamboo Truss. The military Engineer (1937) vol. 29 no. 166 pp. 288-289.

Lowson, Jack — Master degree report, faculty of architecture, Cambridge, ± 1975.

Van der Maaten, K. — Pionierskunst en versterkingskunst. (in dutch); manual for the engineers of the Former Royal Dutch Army in Dutch East Indies. Haarlem 1894. Fig. 172.

Mathur, G.C. — Bamboo for House Construction. National Building Organisation, New Delhi (1964), 37 pp.

Narayanamurti, — The use of Bamboo and Reeds in building construction. United Nations, New York, 1972. 95 pp.

N.N. — Technical Digest (Prague) (1961) vol. 3 no. 5 p. 72.

After completion of this thesis I came across the thesis by the late Klaus Dunkelberg, called "Bambus als Baustoff" (Bamboo as a Building Material). Edited by Rudolf Habelt Verlag, Bonn, Germany, 1980. It is really an excellent study on bamboo in building.

CONCLUSIONS AND RECOMMENDATIONS

6.1. Retrospective view on chapters 3 and 4

The chapters 3 (Models of cell and cell wall) and 4 (Mechanical properties) have a more fundamental character, contrary to chapter 5 (Joints and trusses) which is more a practical one.

The chapters 3 and 4 contain conclusions on the subjects dealt with in those chapters; here the most important conclusions of chapter 4 will be summarised and discussed. These conclusions concern compression (par.4.4.), bending (par.4.5.) and shear (par.4.6.), see table 6.1.

influence of ↓ on →	compression	bending	shear
percentage fibres	significant	stress: unknown relationship E: significant	significant without physical meaning
weight by volume, (G) moisture content (MC)	12% MC: σ = 0.094 G, green: σ = 0.075 G.	12% MC: σ = 0.14 G, green: σ = 0.11 G.	12% MC τ = 0.021 G --
position along culm	significant, top is stronger	significant, top is weaker, but stiffer.	significant, top is weaker.
node or internode	not significant	short span: significant, long span: not significant (see par.4.5.5.)	significant, internode is stronger

σ or τ = ultimate stress in N/mm^2.
green = freshly cut bamboo, MC = 60 to 100%.

Table 6.1. Summary of conclusions of chapter 4.

Tension is not a limit for the possibilities of bamboo and it is therefore not taken into consideration. Table 6.1. is based on own research and other authors.
From this table we learn the next rules.

- Bamboo with many fibres prevails.
- The haviest bamboo is the best (i.e. bamboo with the greatest dry mass per volume).
- Next, the bamboo should be conditioned, i.e. not green, but dried until in equilibrium with the relative humidity of the air. (e.g. in green bamboo the M.C. is 60 to 100 per cent, but in 70 per cent R.H. the equilibrium M.C. is 12 per cent). The more humid the climate, the worse the mechanical properties.
- The choice between a bottom part of a culm or a top-part is important, the more so as the cross-section decreases.
- As to node or internode, the differences in mechanical properties are not important, contrary to structural details, where a node is much stronger than an internode.
- The bamboo should be ripe; (i.e. 3 years old) however, this is not found neither in the table nor in chapter 4. It is based on the tradition of the people of South-East-Asia.

Compared with wood, bamboo seems to be more regular: problems as to knots or slope of grain do not occur. But the influences of decay by rot and insects (bubuk!), and those of splitting, must be studied, as well as their influences on the mechanical properties.

Quite another way to look at the mechanical properties of bamboo is to make a list of all points of interest for any material, and then to complete this list for bamboo. This list is:

1. Shear $\perp$ axis.
2. Tension $\perp$ axis, clearage.
3. Compression $\perp$ axis.
4. Shear // axis
5. Tension // axis
6. Compression // axis.
7. Torsion
8. Bending
9. The form of the cross-section.
10. Stress-concentrations around holes.

Discussion of this list for bamboo, to find out the strong and weak points for bamboo.

1. Shear ⊥ axis.
2. Tension ⊥ axis, cleavage.
   These points never have been the subject of research in the case of bamboo.
3. Compression ⊥ axis.
   Atrops has found a significant difference between a node and an internode as to compression ⊥ axis, the internode being much weaker. This agrees with the results in bending (par.4.5.) and chapter 5, where the same result was found. A force perpendicular to a bamboo culm should be positioned at a node, but this remains a problem: it is hardly impossible to position a bamboo culm in a structure in such a way that all joints take place at a node. A study on how to improve an internode for lateral forces would be very useful (e.g. by filling with some mortar, or pulp of bamboo or wood). "Compression ⊥ axis" is a weak point for bamboo.
4. Shear // axis.
   Shear is a problem in bamboo, however, not because the shear strength of bamboo is lower than that of wood. On the contrary, as a material bamboo has a better shear strength than wood. Bamboo is not weakened by rays. The problems with shear in bamboo result from its shape. The cross-section of bamboo is hollow, and wood is massive.The interior part of the wood cross-section hardly contributes to the moment of inertia I, but to the shear area in the neutral layer.
   An example: a common bamboo culm e.g. has an outer diameter of 100 mm and a wall thickness of 7 mm. From this follows $I = 2.22 \times 10^6$ mm^4 and the area of the cross section A = 2300 mm^2. In timber for these values cross-sections are required of 72 x 72 mm^2 or 48 x 48 mm^2 resp. These cross-sections have a shear area per mm. length in the neutral layer of 72 or 48 mm, but the shear area of the bamboo is only 2 x 7 = 14 mm, which is about one fifth of that of wood.
   And this, the hollow shape, is the cause of the problems with shear in bamboo. Consequently, shear is a weak point in bamboo.
5. Tension // axis does not limit the possibilities of bamboo, because the tensile strength of bamboo can be compared with that of mild steel, and the difficulties arise in connecting the bamboo under high tension with other structural parts.
   Tension // axis is a strong point.

6. Compression // axis is better in bamboo than in wood. As to buckling, the hollow shape is a great advantage, but buckling might occur rather rapidly if the bamboo is not straight. Buckling, however, has hardly been studied. Compression without buckling is a strong point.
7. Torsion has not been studied sofar. For practical use it does not seem to be of much importance, except masts. (The hollow shape is very good now).
8. Bending: the ultimate bending stress as well as the hollow shape make bending a strong point for bamboo.
9. The shape of the cross-section, a hollow thick-walled tube, stiffened by nodes at regular intervals, is a great advantage in buckling and bending, and only a disadvantage in shear.
10. Stress concentrations around holes were a problem in chapter 5; they will have to be studied as yet.

Summary:

strong points	weak ponts	unknown
tension//axis	compression⊥axis	shear⊥axis
compression//axis	shear//axis	tension⊥axis
bending		torsion
form of cross-section		stress concentr. around holes.

Recommendations how to build with bamboo:
Make your designs based on the strong points, avoid the weak ones, and do research on the unknown points.

6.2. Retrospective view on chapter 5

Looking back to the joints and trusses in chapter 5, it appears that the weak points just mentioned are responsible for the problems we have had, similarly as the stress concentrations around holes. As a result the problem of joining bamboo can be defined as the sum of compression ⊥ axis, shear // axis and stress concentrations around holes.
One might cope with these three or by avoiding them in the design or by improving them by research.
The compression⊥axis, (the first point) should be improved by research not only because this research looks promissing, but also because compression ⊥ axis in the design can hardly be avoided.
The second point, shear//axis, should be solved (or at least improved) in the design, as research does not seem to be an outlet.
The third and last point (i.e. stress concentrations around holes) must be studied from the beginning, since we do not know anything about it.

Another question is, how a bamboo culm should be positioned as an upper member in a truss: the top in the ridge, or the top down, because the cross section diminishes from bottom to top, similarly as bending and shear strength, contrary to compression strength and bending stiffness which increase from bottom to top. In my opinion this choice does not matter as far as strength is concerned, because in chapter 5 the axial forces and bending moments are found to be equal along the upper member of this type of truss.
Finally, as the strength of this truss turns out to be limited by material strength and not by joint strength, the problem of joining bamboo has been solved in this type of truss. It is to be hoped that many other solutions for this problem will follow.

6.3. Safety

This thesis contributes to the know-how for testing mechanical properties of bamboo, and trusses of bamboo. With this know-how and with adequate sampling, it will be possible to determine mean strengths and standard deviations, just as in the current practice of building materials and structures.
The Indian Standard 6874 (1973) "Methods of tests for round bamboos" already gives such prescriptions; in my opinion, however, this standard might be more valuable if the bending test should be studied further (four-point or three-point test, and longer span, see par.4.5.2.) and if statistical methods were adapted (e.g. standard deviation, five per cent lower boundary). However, it is still a long way from test results to building regulations. Even if one does not go that far, but simply wants to write a manual for field practitioners how to build with bamboo (as I envisage to do), even then safety must be guaranteed as well as in building regulations.
The International Standard ISO 2394 (1973) shows this procedure. This Standard defines "the characteristic strength":

$$R_k = R_m - k.s$$

where

R_m = the arithmetic mean of the different test results.
S = the standard deviation
k = a coefficient depending on the probability, accepted a priori, of obtaining test results less than R_k".
(note: e.g. for a five per cent lower boundary k = 1.64).
Next is defined the design strength:

$$R^x = R_k/\gamma_m$$

"The reduction coefficient, γ_m, is in principle a function of two coefficients γ_{m1} and γ_{m2}.

γ_{m1} is intended to cover the possible reductions in the strength of the materials in the structure as a whole as compared with the characteristic value deduced from the control test specimen;

γ_{m2} is intended to cover possible weakness of the structure arising from any cause other than the reduction in the strength of the materials allowed for γ_{m1}, including manufacturing tolerances".

Similarly, a design load is defined, and evidently for a satisfactory design the following relation must be defined:

$$R^x \geqslant S^x$$

design strength $\geqslant$ design load.

As to the design strength R^x for bamboo, it is possible to determine the characteristic strength R_k, e.g. as a 5 per cent lower boundary. But the reduction coefficients γ_{m1} (differences between reality and test) and γ_{m2} (e.g. determination, manufacturing tolerances, and the like) still need much research. Besides, the design load S^x has to be defined statistically, and this also is a long way to go.

In the meantime, one might help oneself with the well known British Standard Code of Practice 112 (1971), which prescribes for timber a permissible stress f_p:

$$f_p = \frac{x - 2.33\sigma}{FS} \cdot K_G \cdot K_D$$

where

fp = permissible stress

x = mean ultimate stress from tests, short term loading

σ = standard deviation, e.g. 15 per cent

$x - 2.33\,\sigma$ = the 1 per cent lower boundary

FS = factor of safety, taken as 2.25, which converts the characteristic strength to a basic strength, and which includes an allowance for the effect of long term loading.

K_G = modification factor for grade, e.g. 0.5.
(difference between laboratory quality and practice)

K_D = modification factor for duration of load:
1.0 for long term (permanent load)
1.25 for medium term (permanent + temporary)
1.5 for short term (the above plus wind)

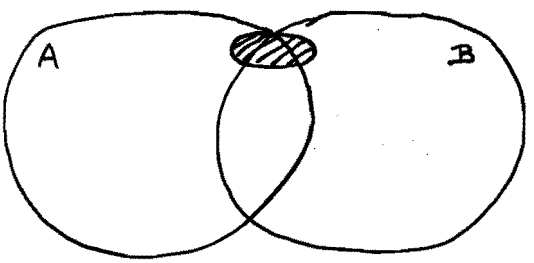
As long as the ideal way of ISO 2394 (1973) not has been completed, this British Standard gives a perspective of how to proceed from tests results to rules for building practice in bamboo.
As the standard deviation is about 15 per cent, the allowable stress is:

$$f_p = \frac{x - 2.33\ 0.15\ x}{2.25}\ 0.5 \quad 1.0 = 0.14\ x$$ (x = mean ultimate stress)

so the allowable stress for permanent load is 14 per cent of the short term strength.

6.4. Our knowledge about bamboo

A diagram of our knowledge on bamboo might look like:



- Circle A is the symbol of all knowledge on mechanical properties, presently available about bamboo. Most of this knowledge is present in the references to this thesis.
- Circle B is the symbol of all knowledge we need in order to exploit bamboo to the full. A summary is given below in the "Recommendations".
- The common area of A and B symbolises that the new knowledge about bamboo (circle B) will even change the meaning of the present knowledge (circle A).
- The shaded area is the contribution of this thesis.

We have to define the boundaries of circle B, and we have to develop methods to "conquer" this circle with the least effort.
As a matter of course, the more knowledge we have of bamboo, the more possibilities we will find. The durability remains a limit.

6.5. Recommendations

The introduction stated: "Bamboo must be exploited to the full". For this purpose we need much more knowledge then is available now. Nearly each paragraph of the chapters 3 and 4 of this thesis ends with recommendations; here follows a list of the most important recommendations. They are sometimes not based on this thesis, but they are considered necessary for the promotion of bamboo.

1. Durability. What is the natural durability of the different species? How can this be improved, preferably with local possibilities.
2. Mechanical properties. For timber, tables with e.g. allowable stresses are widespread. For bamboo we need these too. To achieve this goal we need:
   - a thorough insight into botanical or physical factors having a significant influence on the mechanical properties.
   - with this knowledge, more standartdized tests can be developed,
   - and, finally, tables could be made of stresses that can be used in engineering practice.
3. The reason why the mechanical properties are as they are, based on the relationship with the biological and chemical composition of the bamboo. E.g.
   - Cells: size, geometry, chemical composition.
   - Sclerenchyma fibres: distribution along the culm, in node and internode, and in thickness of the wall of the culm.
     Relationship with stresses and strain.
   - Mathematical models of cell and cell walls, containing the geometry of cell and cell wall, and the mechanical properties of cellulose, lignin and pectin. With such models the mechanical properties on macroscale can be explained or predicted.
4. A method for the conveyance of the results from the laboratories into actual practice. E.g. manuals, clearly written with many sketches, how to solve building problems with the bamboo around a village, in a simple and safe way.

These recommendations have been chosen by the author, and they were accepted by the IDRC-IUFRO workshop of bamboo researchers, held in Singapore, May 1980, and they now appear in the reports of this workshop.

References

Atrops, J.L. Elastizität und Festigkeit von Bambusrohren. Der Bauingenieur vol. 44 (1969) no. 6 pp. 220 - 225.

British Standard
Code of Practice 112 (1971)

Indian Standard 6874 (1973) Methods of Tests for Round Bamboos.

International Standard
ISO 2394 (1973) General Principles for the verification of the safety of structures.

STELLINGEN

Behorend bij het proefschrift van

J.J.A.Janssen,

promotiedatum 19 mei 1981.

1. De maximale druk-, buig- en schuifspanningen in bamboe zijn een funktie van de volumieke massa. De gemiddelde verhouding is:

	druk	buig	schuif
groene bamboe (vochtgehalte 60 à 100%)	$\sigma = 0.075G$	$\sigma = 0.11G$	
droge bamboe (vochtgehalte 12%)	$\sigma = 0.094G$	$\sigma = 0.14G$	$\tau = 0.021G$

G = volumieke massa in kg/m^3
σ en τ in N/mm^2

Dit proefschrift, par. 4.4.5., 4.5.5. en 4.6.6.

2. In tegenstelling tot wat algemeen wordt gedacht, is bamboo niet zwak met betrekking tot afschuiving. Integendeel, het is in dit opzicht sterker dan hout.
De praktijkproblemen met betrekking tot het afschuiven van bamboe worden veroorzaakt door de holle vorm van bamboe, in tegenstelling met de massieve vorm van hout.
Dit proefschrift, par. 4.6.5. en 6.1.

3. Het is mogelijk om tenminste één bamboekonstruktie te bouwen, die niet meer bezwijkt op de verbindingen (zoals gebruikelijk) maar op materiaalsterkte.
Deze konstruktie kan dus berekend worden, met behulp van resultaten van materiaalonderzoek.
Dit proefschrift, par. 5.9.

4. Een proevenserie, die niet gebaseerd is op een statistische proefopzet, kan niet leiden tot konklusies en hoeft dus niet beproefd te worden.

5. Samenwerking tussen biologen, materiaaldeskundigen en konstrukteurs is nodig om het gebruik van bamboe in alle mogelijkheden te ontplooien.

6. De eindige elementenmethode leidt tot bewonderenswaardige resultaten, maar ook tot minder begrip dan de oude methode van continue vergelijkingen.
Het is te verwachten dan wel te hopen dat er een evenwicht tussen beiden tot stand zal komen.

7. Zoals al reeds is voorgeschreven voor technische berekeningen in de praktijk, dienen wetenschappelijke berekeningen, gemaakt met een computer, vergezeld te gaan van zodanige handberekeningen, dat de juiste werking van het programma aannemelijk wordt gemaakt.

8. De overdracht van zachte aangepaste technologie gaat uitstekend via harde en commerciële verkoop.
International Development Review, (1979) no. 1 p. 45.

9. Een bamboepijp begraven in de grond boven de grondwaterspiegel, als waterleiding, is een tegenstrijdige zaak, omdat de grond onder andere tot taak heeft het afbreken van dood organisch materiaal. Onder de grondwaterspiegel blijft de bamboe goed, maar is het drinkwater veelal onbetrouwbaar.

10. Omdat men tegenwoordig veel gebruik maakt van fotokopieën van tijdschriften, en omdat op een fotokopie van een microscopische foto in zo'n tijdschrift niets meer te zien is, dient zo'n foto vergezeld te gaan van een lijntekening, die de wezenlijke informatie van de foto bevat.
Zie bijv. Tono en Ono, J. Jap.Wood.Res.Soc., (1962) pp. 240-1.

11. Het boek "De bevrijding van Sollidee" (Olivier B.Bommel) is verplichte lectuur voor ieder die te maken heeft met ontwikkelingssamenwerking, omdat het de problematiek van ontwikkelingslanden zeer juist weer geeft.

12. Bamboe is hol, is glanzend, schiet snel omhoog, en buigt met alle winden mee, en daarom wordt het wel eens spottend als symbool voor diplomaten gebruikt. Dit gebruik miskent het nut van bamboe.