Bamboo as a composite structure and its mechanical failure behaviour

R. Kappel, C. Mattheck, K. Bethge & I. Tesari
Institute for Materials Research II,
Forschungszentrum Karlsruhe, Germany

Abstract

Bamboo is a renewable resource which is abound especially in tropical areas. It is a very common raw material used within a width range of applications. A lot of research was done to investigate its mechanical properties and improve bamboo as a building material.

Concerning structural mechanics and materials science, bamboo is an excellent example for natural lightweight design and is the opposite to trees; for bamboo a height over diameter ratio of 80 and higher is common and not correlated with cumulated failure. Although bamboo belongs to the botanical group of the graminaceae, some of its characteristics resemble those of wood. But its growth characteristics and microstructure are different from trees. Compared to wood, in bamboo only longitudinally growth and no lateral or radial growth occurs. It has a hollow culm, which is closed at frequent intervals called nodes.

The different failure modes of a bar, a hollow tube and a bamboo culm have been compared to give a better insight into the failure mechanisms of the structure. Geometry data such as height, diameter, thickness of the wall and length of the internodes have been examined and correlated to a calculated bending moment along the culm due to wind. The common failure mode of hollow tubes seems to be cross-sectional flattening with a collapse of the material due to tangential tension stresses perpendicular to the grain. In bamboo the frequent distributed node plates seem to prevent failure due to cross sectional flattening. Therefore the frequency, distribution and mode of action of these node plates have been investigated.

Design and Nature II, M. W. Collins & C. A. Brebbia (Editors)
© 2004 WIT Press, www.witpress.com, ISBN 1-85312-721-3

1 Introduction

Bamboo is a member of the botanical tribe of Graminae with over seventy genera of about 1500 species whose woody stems called culms can have a mature size ranging from 10 to 36 meters with individual culms up to 30 centimetres in diameter [1]. Bamboo grows in a fashion that is quiet different from the way a tree develops. A tree has a layer of living tissue, called meristema, around the outside of its trunk just beneath its bark. This meristema layer adds an ever increasing circle of wood around the central mass which could be recognized as the concentric annual rings in its cross section. The culms of bamboo does not increase their thickness and consequently meristema is only found in each internode to increase its length [2]. The bamboo culm emerge from the ground buds with the same diameter as the final culm. All they do is growing longer in much the same way as a telescope, extending at a very rapid rate that can be in excess of a metre a day in a mature stand [3].

2 Methods and results

2.1 Modes of failure

A rectangular bar, a circular cylinder and a hollow tube under bending load will fail in different ways. Failure behaviour and failure mode are depending on geometric and material properties. Slender bars under compression load may fail by global buckling that finally ends in bending fracture due to compression stress on one side and tension stress on the reverse side. In contrast tubes may fail by local buckling associated with a ovalizing of its cross section. In composites failure due to shear stress or transversal tensile stress is common.

The circular cylinder is equally good or equally poor for all directions of bending. It is not a real light-weight construction, because it is not hollow. In the middle on the neutral fibre of bending the material is non-loaded. If the middle is removed, the bending stresses will scarcely increase. Figure 1 shows the distribution of shear- and bending stress in those bodies. Such a solid cylinder will tend to be used if the weight is not so important and bending load is expected from different directions, just as the wind can also bend a tree in different directions.

2.1.1 Failure due to slenderness

Trees in dense stands normally have a small crown growing very high for phototropic reasons. The trees become increasingly top-heavy and at some time they will fall over even under a moderate load. A field study [4] based on about 2500 trees showed that for mature trees a threshold of Height/DBH (Diameter at Breast Height) $\cong 50$ exists (Figure 2) for solitary growing trees or trees in thinned stands. Trees with higher slenderness have the risk to be first bend sideward by wind and than being pulled down by the weight of their crown. This may get worse by rain or wet snow. But caution, not the absolute height is the problem, ancient tall Seqoias have a favourite slenderness which is about Height/DBH = 20 to 35.

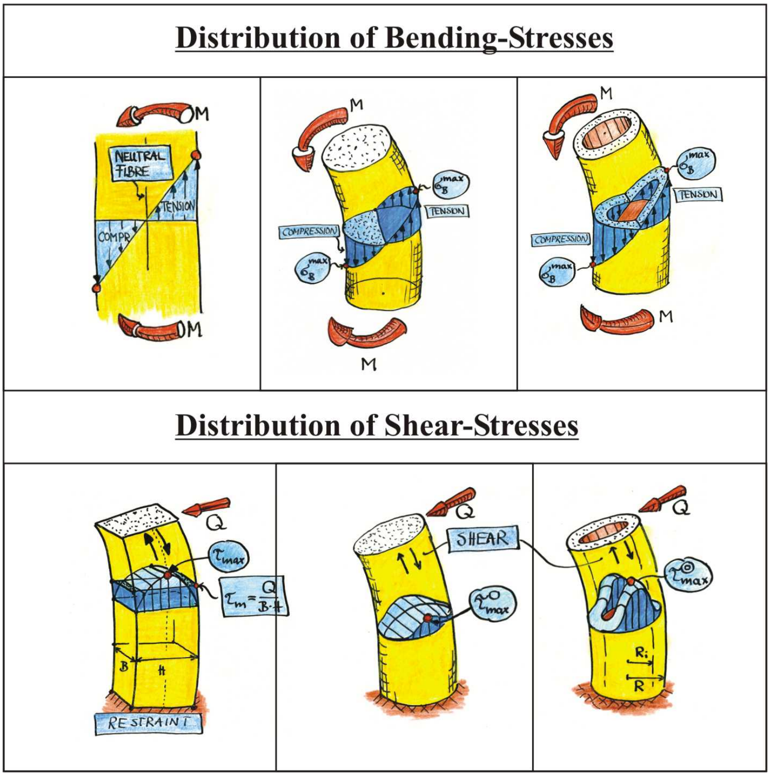

Figure 1: Distribution of bending stresses and shear stresses in cross sections of beam, bar and tube [5].

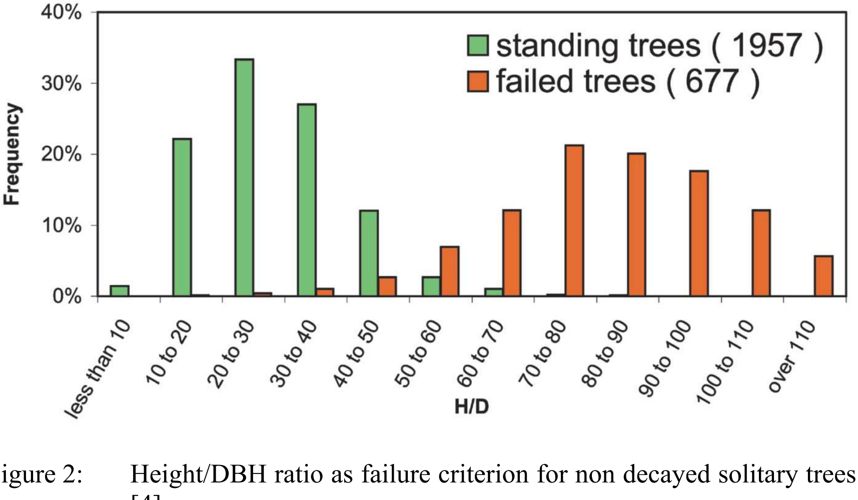

Figure 2: Height/DBH ratio as failure criterion for non decayed solitary trees [4].

Slenderness as a failure criterion means also that the stem of trees have to be well tapered [6]. This means that the stem diameter increases downwards in relation to the increasing bending moment (Figure 3). In a bamboo the thickness of the culm does not increase. There seems to be another kind of adaptation by increasing the wall thickness downwards to adjust the increasing bending moment. Figure 4 shows the alteration of the wall thickness and diameter along a bamboo culm, scaled on the values at the bottom of the culm. Resulting from this the degree of hollowness decreases and therefore the load capacity increases downwards the culm.

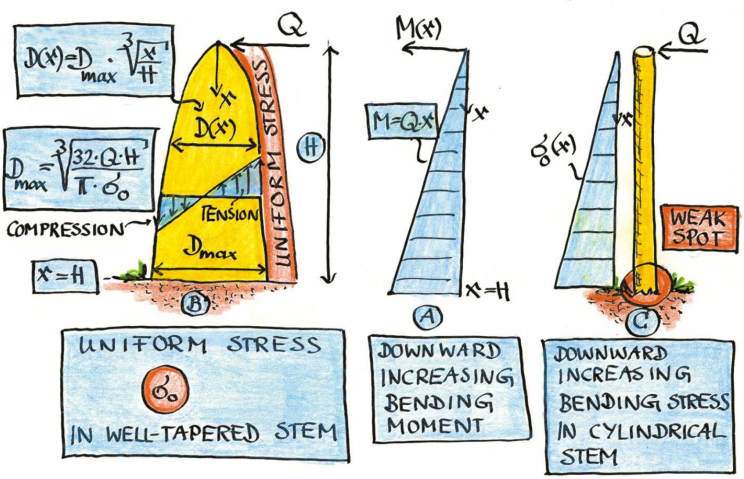

Figure 3: Adaptation of trees to the applied load by tapering [5].

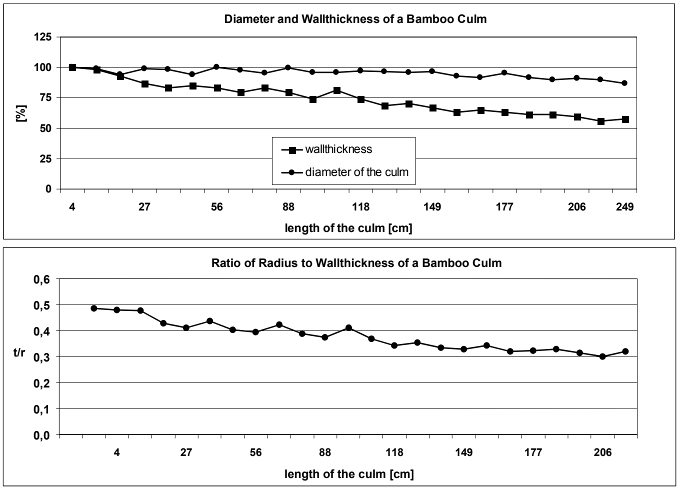

Figure 4: Tapering by variation of the wall thickness and degree of hollowness along a bamboo culm measured from base.

Design and Nature II, M. W. Collins & C. A. Brebbia (Editors)

2.1.2 Failure due to hollowness

Older ancient tress usually become more and more hollow by the work of wood destructing fungi. By the way tubes are also equally good for all directions of bending, and are really light-weight structures as only the underloaded middle has been removed. Figure 5 illustrates the results of a field study worked out in the USA, Europe and Australia. The histogram shows hollow trees in relation to their degree of hollowness divided in standing and broken trees [4].

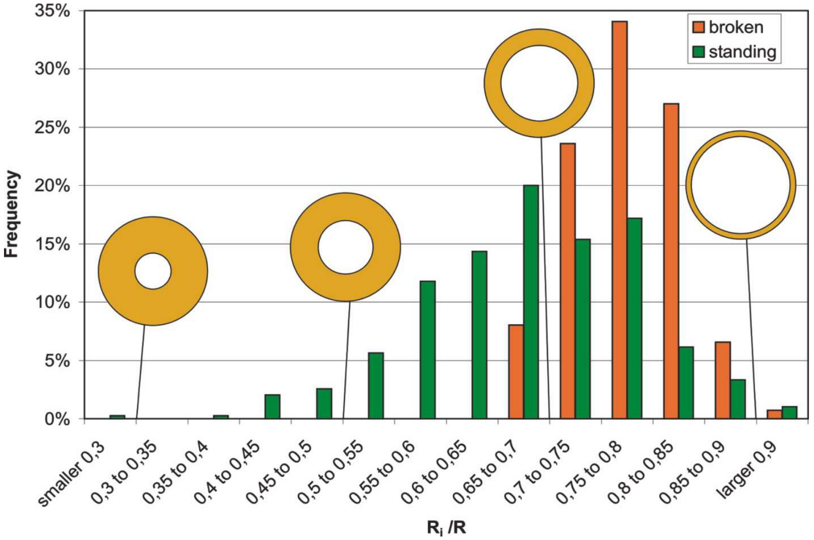

Figure 5: Field study on hollow trees [4].

With a cavity equal to 70% of the radius the risk of failure increases immediately. Accordingly, large bones are often hollow, so they are lighter, for they are moved and it would require more energy to move a solid cylinder than a tube. Currey and Alexander have shown that most bones of mammals are less than 70% hollow [7]. With a cavity of 70% and over, full-crowned trees are endangered by failure.

A hollow tree does not fail primarily by bending fracture i.e. by fibre kinking on the compression side of the bending (Figure 6). Transverse forces are responsible, which first ovalize the tree's cross section and then kink it like a hosepipe [5]. This usually causes four cracks, but in the early stage of failure only the two on the neutral fibres of the bending can be seen externally which are created also by shear stresses. In practice there are four bending points where cracks develop, distributed over the stem's circumference, approximately described by four hinges as shown in figure 7. It is bending tensile stress in the circumferential direction which starts the failure. First longitudinal cracks and splits occur and then the cross-section buckles in.

Design and Nature II, M. W. Collins & C. A. Brebbia (Editors)
ISBN 1-85312-721-3

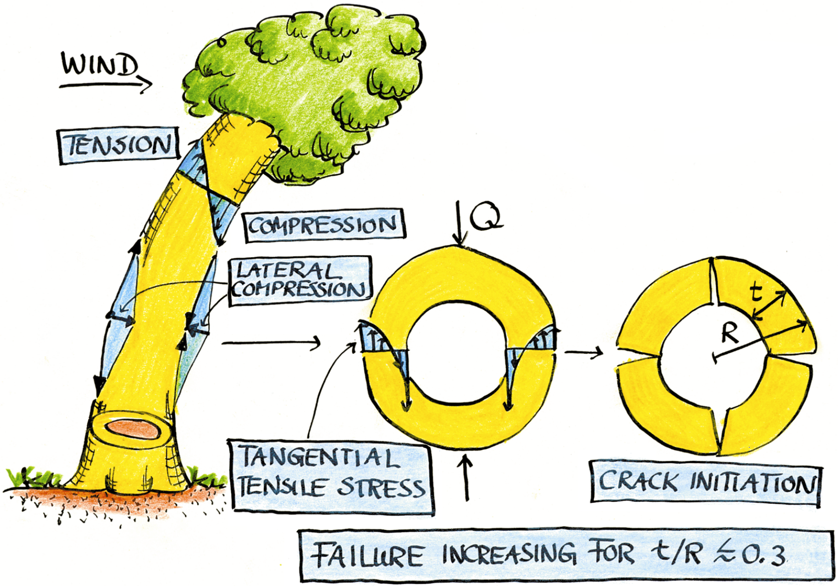

Figure 6: Failure mechanism of hollow trees [4].

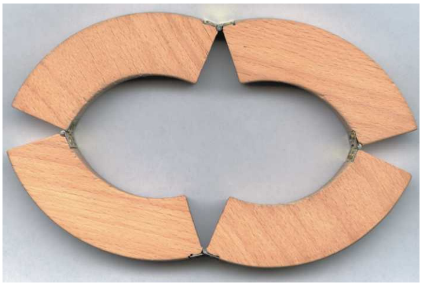

Figure 7: Collapse of the cross section by four hinges [5].

The culms of some bamboo species have Height/DBH ratio of 80 and higher. Bamboo culms are hollow tubes divided by nodes into sections called internodes. Those nodes support the culm to prevent failure due to local buckling. The length of the internodes along the culm increases from the base of the culm towards somewhere below the middle, and then decreases till top of the culm (Figure 8). For a culm of a giant bamboo *dendrocalamus giganteus* with a length of 13,02 meter and a diameter of 90 Millimeter this means a Height/DBH ratio of 144. The length of the internodes along the culm is shown (Figure 9).

Figure 8: Increasing length of the internodes along the culm from the bottom part upwards.

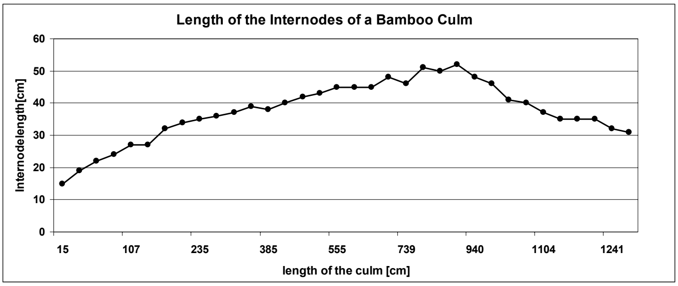

Figure 9: The length of the internodes over the height.

The results are in a good agreement with the distribution of the internode length along the culms of many other bamboo species [8] and the induced bending moment along the culm.

Specimen with a length of 30 Millimeter have been taken from the culm and loaded under radial compression in an Instron testing machine. The applied load and the distance have been recorded. Figure 10 shows the tested specimen.

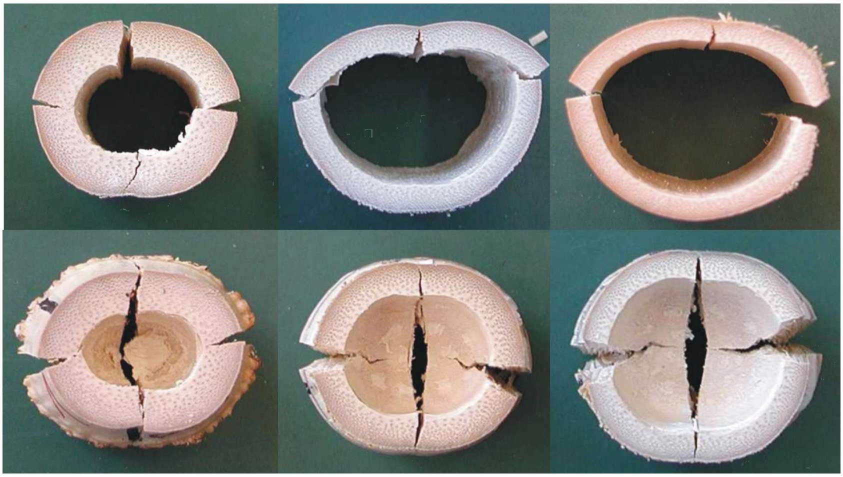

Figure 10: Specimen of nodes and internodes along the culm failed due to radial compression showing different failure modes.

Design and Nature II, M. W. Collins & C. A. Brebbia (Editors)
© 2004 WIT Press, www.witpress.com, ISBN 1-85312-721-3

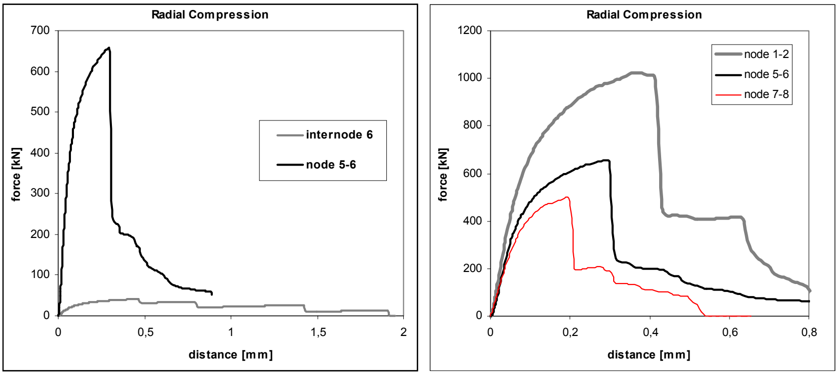

Figure 11: Force-elongation graphs of nodes and internodes of a green bamboo loaded radially by compression.

The decreasing wall thickness from the base upwards can be seen clearly as well as the cracks occurring under radial compression for nodes and internodes. The maximum radial force where failure starts is much higher at the nodes than at the internodes (Figure 11). The nodes and internodes are numbered starting from the base of the culm upwards. Node 1-2 means the node between internode 1 and internode 2. Figure 11 shows the maximum radial compression force of different nodes along the culm. The values decrease rapidly from the base to the top of the culm.

The mode of failure of the nodes with this stiffening rings due to radial compression indicates that node plates act as a kind of lateral tensile ropes which are preventing the cross section against flattening (Figure 12).

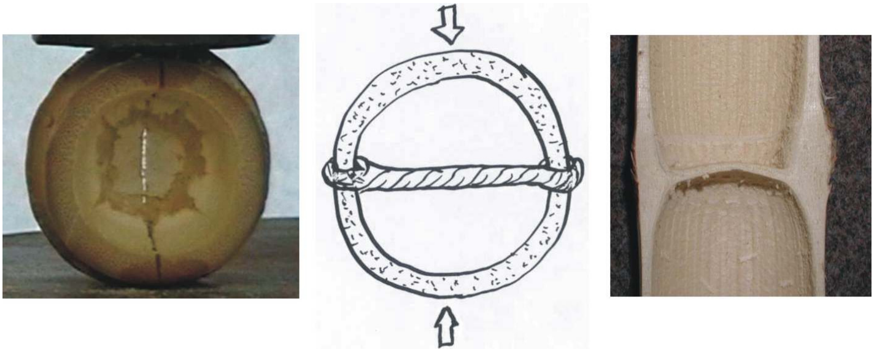

Figure 12: Failure of a compression loaded node plate due to tensile stresses and a analogous model which demonstrates the bamboo as a structure stiffed by a lateral tension rope.

3 Conclusion

Even Bamboo is from the botanical point of view a giant grass with tall and slender culms it is very well adapted to the bending moment due to external loads like wind. In a bamboo the thickness does not increase and the culms with a Height/DBH ratio up to 140 have a nearly constant diameter over a wide range. Tall and slender tubes will fail due to local buckling which is starting with an ovalization of its cross section. Bamboos prevent this cross-sectional flattening by their supporting nodes. The distance between those supporting nodes decreases downwards the culm according to the increasing bending moment due to external loads, mainly wind. Also the maximum radial compression force, which is responsible for cross sectional flattening increases at the nodes downwards and reaches its highest values at the base of the culm. The mode of failure of the nodes due to radial compression indicates that node plates act as lateral tensile ropes which are preventing the cross section against flattening.

Additionally the wall thickness increases from the top downwards to the base of the culm which is similar to the tapering of a also mechanically well designed stem of a tree. Those results are indicating that the culms of bamboo are adapted very well to their loading.

References

[1] Dart, D. The Bamboo Handbook – Australian / International Issue. Nemea Pty Ltd. Queensland, Australia, 1999.

[2] Janssen, J. *Bamboo in building structures*. Thesis, Eindhoven University of Technology, Eindhoven, Netherlands, 1981.

[3] Recht, C., Wetterwald, M., Simon, W. *Bambus*. Verlag Eugen Ulmer, 2. Auflage, Stuttgart, 1988.

[4] Mattheck C. *Tree mechanics – explained with sensitiv words by Pauli the bear*. www.mattheck.de, Verlag Forschungszentrum Karlsruhe, Karlsruhe, 2002. Karlsruhe, 1999.

[5] Mattheck C. *The face of failure - Form and Failure in Nature and Engineering*. www.mattheck.de, Verlag Forschungszentrum Karlsruhe, Karlsruhe, 2004.

[6] Mattheck, C., Bethge, K., Tesari, I., Kappel, R., *A new failure criterion for non decayed solitary trees*. Arboricultural Journal, Vol 26, pp 43-54, 2002.

[7] Currey, J. D., Alexander, R. Mc N., The thickness of the walls of tubular bones, J. Zool. Lond. 206, pp 453-468, 1985:

[8] Janssen, J., *Mechanical properties of Bamboo*. Kluwer Academic Publishers, Dordrecht, Boston, London, 1991.

Design and Nature II, M. W. Collins & C. A. Brebbia (Editors)