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BAMBOO BENDING WITH STEAM

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ABSTRACT: The bending of solid wood is a process that has been known for a very long time. The bending of bamboo has rarely been considered. The advantages of bending are material savings (significantly less wood or bamboo waste), reduction of joints, stable construction; as the grain is not interrupted, reduction of the number of materials needed for construction and reduction in the use of adhesives. In the studies presented here, the first tests with bamboo tubes are presented and the results systematically analysed for their material properties.

KEYWORDS: *steam bending of bamboo, bamboo tubes*

1 – INTRODUCTION

Wood is one of the most important renewable raw materials and has been used in Europe for thousands of years. In Asia, next to wood, bamboo is also frequently used as a building and construction material. Unlike wood, bamboo (Bambusoideae) belongs to the family of sweet grasses (Poaceae). Asia has the worlds largest bamboo reserves. China has the largest cultivation area with 1/3 of the world's supply of bamboo [1]. There are about 500 different bamboo families worldwide and hundreds of subspecies. These are native to every continent except Europe and Antarctica (Fig. 1).

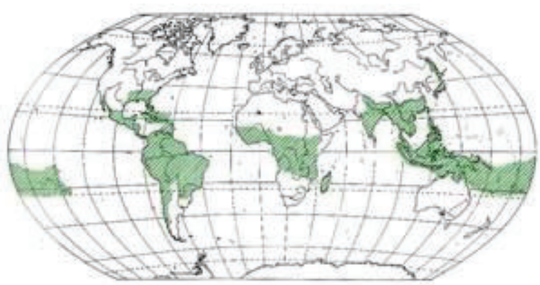

Figure 1 Natural distribution area of bamboo [2]

Wood and bamboo bind not only water but also a great deal of CO_2 as they grow. Bamboo is one of the fastest growing plants on earth and is characterised by its very good mechanical properties. The world record for plant growth is held by Moso bamboo, which can grow up to 114,5 cm per day [3]. Heights of up to 35 m and culm diameters of up to 45 cm are reached. However, the average length growth of all bamboo species is only 25 cm per day [4,5]. Bamboo, like wood is used as a construction material for building houses, bridges and furniture. Wood is usually joined using nails, screws, dowels, etc. Bamboo is traditionally often bonded with ropes, fibres or wires. These joining methods utilize a variety of different materials with different properties. The joints are usually significantly more pronounced than the base structures and frequently disrupt the structure of the base materials. Bending allows structures to be adapted to the loads. Furthermore, significantly less wood or bamboo waste is generated and a reduction in the number of joints is achieved. Constructions made from bent structures are usually more stable than joined constructions because the fiber flow is not interrupted. Bent constructions reduce the amount of material used. Furthermore, the material mix is reduced, thus significantly improving the recyclability of bent structures.

2 – BACKGROUND

For a very long time, solid wood has been bent into a defined shape using hot steam bending or bending by heating. Viking ships with bent wooden planks were found in Denmark. The age of these ships was estimated to be 1000 years [6]. Furniture has been made from bent wooden parts for more than 200 years. MICHAEL

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THONET'S bentwood chairs, also known as Vienna bentwood chairs, made from bent beechwood, became particularly well known. However, THONET was not only concerned with the manufacture of furniture, but also, in his early days, with the manufacture of wheels. Later, he combined his two developments to create the wheel shown in Figure 2.

Figure 2 Thonet wheel with curved spokes from the estate of Viktor Thonet [7]

Steam bending of solid wooden parts is a well established process in a wide variety of applications. Fig. 3 shows a double yoke for draft cattle with U-shaped steam bent wooden yoke bows that were produced in Slovenia approx. 120 years ago.

Figure 3 double yoke with steamd bent yoke bow

Wood steam bending was used in Southern Europe by many non-specialized craftsmen and even farmers to produce complex components quickly and cost-effectively. Figure 4 shows a simple wooden form for bending yoke bows for cattle. This form is approximately 120 years old.

Figure 4 Bending toll for yoke bows

Wood is a natural composite material composed mainly of cellulose, hemicellulose, and lignin. The composition of different kinds of wood and bamboo is shown in table 1. The most significant component is cellulose in both wood and bamboo. The bending process of wood is usually divided into three steps: plasticizing (softening) - bending - stabilizing (drying).

Table 1 Composition of wood and bamboo[8,9,10]

Component [%]		Oak	Bamboo	Beech	Pine
Cellulose		47	40,7	41	41
Lignin		29	27.1	27	29
Hemicellulose	Xylan	22	23.6	13	9
	Mannan		0,6	18	18
Pectin				1	3

The glass transition temperature determines the softening temperature of the wood components lignin and hemicellulose. In the dry state, the softening temperatures of hemicellulose and lignin are 167–217 °C and 134–235 °C, respectively, while in the moist state they decrease to approximately 54–142 °C and 77–128 °C, respectively. This transition to the highly elastic state promotes the plasticity of the wood [11]. Processes such as boiling, steaming, and electromagnetic waves are used to soften wood materials. While the mechanism of action is the same in these processes, the method of heat transfer is different. During boiling and steaming, the wood surface is gradually heated, softening the wood core and then bending it into the desired shape. Electromagnetic waves simultaneously heat the core and the outer surface of the wood, ensuring rapid and even heating [12]. Bamboo has a similar chemical composition to wood (see Table 1), but the overall structure is fundamentally different. Bamboo differs from other building materials due to its organic composition and structure, which gives it high strength and relatively low weight. The structure

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of a bamboo stalk is characterized by two main components: the nodes and internodes. Nodes are the thickened nodes on the bamboo stalk where leaves and leaf stalks attach. These nodes divide the stalk into sections and are characterized by a larger diameter than the adjacent sections. A distinctive feature of the nodes is the presence of a diaphragm, a disc-like structure that closes the otherwise hollow cross-section of the stalk. The diaphragm not only stabilizes the stalk against deformation and lateral crushing, but also acts as a distribution point for the supply of nutrients to the stalk and leaves. Internodes are the segments between two nodes and are characterized by their hollowness, although some bamboo species can also have a solid cross-section. The structure of the internodes is characterized by a clearly directed fiber arrangement. During growth, the cells in the internodal region elongate, resulting in longitudinal elongation of the stalk. Together, nodes and internodes form the structural and functional basis of the bamboo stalk [13]. Figure 5 shows the basic structure of bamboo.

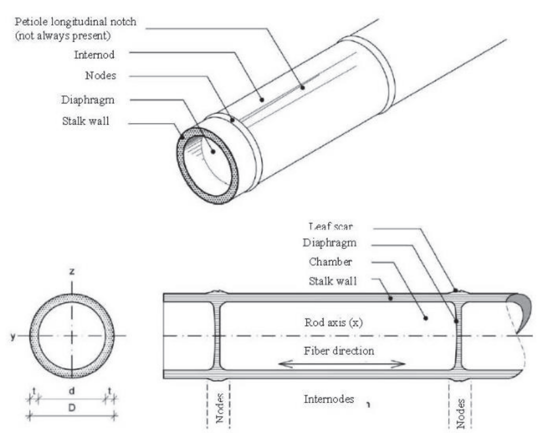

Figure 5 Basic structure of bamboo [according to 13]

Compared to wood, bamboo is tubular, i.e. hollow inside but reinforced at the nodes. The cellular composition of bamboo, which differs significantly from wood, consists of a heterogeneous network of vascular bundles embedded in a matrix of parenchyma cells. These vascular bundles contain hollow vessels surrounded by fibrous sclerenchyma cells, thus contributing to structural strength. The proportion of these vascular bundles, as well as the solid material within the bundles, increases radially toward the outside of the culm, creating a pronounced radial density gradient in the bamboo culm. This radial increase in density leads to improved mechanical properties such as strength, but at the same time presents a challenge in processing, as harder material is more difficult to machine. The fiber orientation and distribution within the bamboo stalk is not evenly distributed across the cross-section, but is concentrated primarily in areas of highest stress, resulting in varying tensile strength along the stalk. In particular, the outer layers of the bamboo stalk exhibit higher tensile strength than the inner layers due to the increasing fiber density toward the outer edge. This targeted and optimized distribution of the fiber bundles contributes significantly to the mechanical stability of bamboo and increases its tensile strength. The vascular structures of bamboo, characterized by its monocotyledonous nature, feature a special distribution of vascular bundles across the entire stem cross-section, which is essential for the supply of necessary metabolic products. The arrangement of the vascular bundles in bamboo differs from that in trees and means that, unlike trees, bamboo cannot develop secondary lateral growth due to the position of the vascular bundles. This special property of the vascular bundle arrangement and the associated impossibility of secondary lateral growth are key features that distinguish bamboo from other building materials. Nodes, the thickened nodes on the bamboo stalk where leaves and petioles attach, are characterized by a larger diameter than the adjacent areas and divide the stalk into sections. A key characteristic of the nodes is the diaphragm, a disc-like structure that closes the otherwise hollow cross-section of the stalk, not only contributing to stability but also providing protection against deformation. The existence and function of the diaphragm are crucial for maintaining the structural integrity of bamboo, as they play an essential role in protecting and strengthening the overall plant structure [14]. Bending bamboo presents a certain challenge due to the different structure described above, but it is a very interesting process for achieving new technical solutions. The importance of bending wood and bamboo is currently growing due to the optimised use of raw materials and the resulting economic and ecologic advantages.

2.1 - STEAM BENDING PROCESS OF BAMBOO

The technology of steam bending of bamboo is similar to the steam bending process of wood. The biggest challenge is bending a tube, here a bamboo tube with reinforcements through nodes. Table 2 shows the mechanical properties of bamboo, pine and beech. The tensile strength of bamboo can reach values of up to 400 Nmm^{-2}. From a botanical point of view bamboo belongs to the Gramineae (grasses). It can be seen that the tensile strength and bending strength of bamboo are significantly higher than that of wood.

Table 2 Mechanical properties of bamboo, pine and beech [15,16,17,18].

	Young's Modulus N/mm²	Com-pressive strength N/mm²	Tensile strength N/mm²	Flex-ural strength N/mm²	Shear strength N/mm²
Bam - boo	20000	62-93	148-384	76-276	20
Pine	6900-20000	35-94	35-169	41-200	6-14
Beech	10000-18000	41-99	57-180	74-210	6-19
Oak	11500	60	88	95	11,5
Maho-gany	95000	45	100	80	11

3 – PROJECT DESCRIPTION

In a first step, a steam box was designed and built in which bamboo canes up to 2500 mm long could be softened with steam. This setup is shown in Figure 6. This equipment will then be used in a first series of tests to determine whether bamboo can be bent safely at all.

Figure 6 Steam box experimental setup [according to 19]

Using the bending form shown in Figure 7, the first investigations were carried out to determine whether bamboo can be bent by 180° in a relatively large radius.

Figure 7 Bending tool for bending bamboo rods [according to 19]

The design of the tool for bending the bamboo tubes was based on the tools for bending the yoke bows for cattle shown in Figure 4. The mold was deliberately constructed from wood to allow for quick modifications.

4 – EXPERIMENTAL SETUP

After the first successful attempts to bend bamboo sticks by 180°, attempts were made to make coil springs from bamboo using the same experimental setup. The aim was to achieve the smallest possible bending radii. Figure 8 shows a bent bamboo rod with a radius of approx. 250 mm. After 2 days of drying in the bending tool the final shape was achieved. The rod had bent back by approximately 50 mm after removal from the tool.

Figure 8 Bent bamboo rod (diameter apprx. 500mm)

The tests were conducted with bamboo tubes of two different dimensions: Type X with a diameter of 12-14 mm and a length of 180 cm, and Type Y with a diameter of 18-20 mm and a length of 210 cm. Tests 1-5, 19, and 20 focused on a bending radius of 10 cm, with the bamboo canes being bent around a DN 200 KG pipe with an outer diameter of 20 cm. In the course of the failed experiments, it was decided to increase the bending radius to 14 cm (outer diameter 28 cm). This adjustment was implemented in tests 6, 7, and 16. A further increase to an outer diameter of 40 cm (DN 400 KG pipe, bending radius 20 cm) was made for tests 8 to 15, as well as 17 and 18. Table 3 shows the test parameters for the conducted tests. Various soaking times, steaming times, and diameters of the bamboo sticks were tested at different bending radii. For the tests marked with the letter z, fresh garden bamboo with a diameter of about 12mm was used to test whether the samples used so far were too dry. The fixed bamboo tube remains in the bending tool for at least one day to release additional moisture and minimize springback. Any protruding ends of the bamboo tube can be further adjusted and fixed to achieve optimal curvature.

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Table 3 Overview of the test parameters

Test	Radii [mm]	Bamboo type	Soaking time	Steam time
1	100	Y	-	30min
2	100	X	-	1h
3	100	X	19h 30min	2h
4	100	X	-	2h
5	100	X	-	2h
6	140	Y	8h 30min	2h
7	140	X	5h 50min	2h
8	200	Y	10h 40min	2h
9	200	X	10h 40min	2h 10min
10	200	X	-	2h 10min
11	200	X	3d 12h 20min	2h 10min
12	200	Y	3d 12h 20min	2h 10min
13	200	Y	4d 12h 40min	3h 15min
14	200	X	4d 12h 40min	3h 15min
15	200	X	3d 50min	3h 20min
16	140	X	3d 50min	4h 20min
17	200	Z	6d 20h 50min	4h 45min
18	200	Y	6d 15h 20min	4h 45min
19	100	Z	6d 15h 20min	5h 30min
20	100	X	2d 23h 10min	5h 30min

5 – RESULTS

The results of samples 1 to 5 show the following characteristics in the fracture and deformation patterns of the bamboo canes:

- Deep longitudinal cracking: Several canes exhibit deep, longitudinal cracks along their structure. These cracks indicate loading, resulting in distinct parting lines and a bulging, porous structure at the fracture ends.
- Dryness and brittleness of the material: The fractures on various canes reveal consistent dryness and brittleness of the bamboo fibers, which protrude from the main body and form a rough, frayed surface.
- Irregular and frayed fracture surfaces: The fracture surfaces are irregular and often frayed, indicating abrupt and significant mechanical loading, reflecting shear and tensile forces.
- Emphasis on hollow areas as weak points: The fractures occur mainly in the hollow areas between the nodes, with the majority being concentrated in the areas adjacent to the nodes. Although the bars in these areas exhibit noticeable cracks and fractures, mechanical stress, the nodes themselves generally show no damage and prove to be structurally stable.

Figure 9 Sample 6, kink [20]

Figure 10 Broken area sample 6 [20]

The results of samples 6 to 10 show the following characteristics in the fracture and deformation patterns of the bamboo canes:

- Deformations: The bamboo cane continues to be severely deformed. The deformations occur primarily in the form of bends and twists, which significantly alter the natural straight structure of the cane.
- Breaks: Similar to the previous samples, the breaks are characterized by complete separations as well as deep and superficial cracks. This damage often occurs in the hollow segments of the bamboo.
- Nodes: While the areas between the nodes are more severely damaged, the nodes themselves often remain unaffected or show only minor damage.
- Fiber splitting: The splitting of the bamboo fibers is particularly noticeable at several break points. The fibers protrude from the fracture edges, giving the break a torn, frayed appearance.

Figure 11 Kink and break point, sample 9 [20]

In figures 11 and 12 it can be seen that the nodes are usually not destroyed, but that the destruction of the structure of the bamboo canes often begins at the nodes or starts from them when bending.

Figure 12 Break point sample 10 [20]

The specimens exhibit pronounced fracture and deformation features in the hollow segments of the cane, while the nodes remain largely undamaged. It is striking that the crack and fracture growth of the fracture point begins at the node. The cracks in the bamboo occur primarily longitudinally, revealing individual layers of the bamboo. The visible fibers are severely torn in places, indicating severe disruption of the material. Samples 14 and 15, shown in Figure 13, demonstrate successful bending in the shape of a spiral spring, extending beyond 360°.

Figure 13 sample 14 and 15, successfully bent samples [20]

During the bending, the canes achieved a largely uniform curvature without breaking. However, it is noticeable that the ends of the bamboo canes are no longer bent into a perfectly circular shape, but instead transition into a straight shape.

The comprehensive examination of the bamboo canes in samples 1 to 20 reveals a wide range of fracture and deformation patterns. The results show that the majority of the canes exhibit deep, longitudinal cracks, producing significant split lines and a bulging, porous structure at the fracture ends.

The fracture surfaces of the canes exhibit a consistent dryness and brittleness. The surfaces are rough and frayed, which is particularly evident in the irregularly frayed fracture surfaces.

A recurring observation is the emphasis on hollow areas as weak points, where noticeable fractures frequently occur. Although the areas between the nodes are severely damaged, the nodes themselves often remain intact or show only minor damage.

A particular feature that stands out across the sample series is the splitting of the bamboo fibers at the fracture points. This is particularly pronounced and gives the fractures a torn and frayed appearance. In summary, the investigations of samples 1 to 20 provide a detailed picture of the diverse mechanical stresses and the resulting damage to the bamboo stick, clearly highlighting the natural structure and load limits of the material.

6 – CONCLUSIONS AND RECOMMENDATIONS

The analysis of the tests confirms the previous observations. Longer soaking times and a larger bending radius are crucial for successfully bending bamboo without breakage or cracking. The influence of soaking time appears to be an important factor, with longer soaking times of 8 to 12 hours combined with an appropriate steaming time producing the best results. A smaller bending radius of 10 cm and 14 cm, regardless of the soaking and steaming time, more frequently leads to increased stresses and associated fractures in the material. Future tests must continue to focus on optimizing these parameters to ensure reproducible and break-free bends. To make future tests more successful and reproducible, the results of the two successful tests must serve as basis. In tests 14 and 15, a nearly circular bend was achieved, which can be attributed to the optimized parameters.

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The key parameters for successful bending are:
• Bending radius: 20 cm
• Soaking time: 3 days (Test 15)
• Steaming time: 3 hours 15 minutes (Test 14)
• Bamboo rod: Type X
Recommendations for further tests:
1. Maintaining the bending radius of 20 cm: This has proven suitable in successful tests to achieve a uniform and break-free bend.
2. Optimizing the soaking time: A soaking time of at least 3 days significantly improved the flexibility of the bamboo stick. It should be investigated whether shortening the soaking time can lead to similar results.
3. Steaming time: A steaming treatment of over 3 hours in combination with the soaking time produced the best results. Future tests should determine whether shortening the steaming time achieves the same effect to reduce the effort.
4. Bamboo rod type X: This stick type showed better bending properties in the successful tests compared to other types and should continue to be used.

Steam bending bamboo offers excellent opportunities for creating optimized and sustainable structures. However, compared to steam bending wood, the process of soaking and plasticizing bamboo is significantly more complex. This is due, on the one hand, to the structure of bamboo (a hollow material with structurally reinforcing nodes) and, on the other, to its slower water-absorbing outer waxy layer. Further research is needed to optimize the soaking and plasticizing processes.

7 – ACKNOWLEDGEMENTS

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