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Microstructural characterization of bamboo

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Sophisticated preparation techniques and high production cost of synthetic fibers, like glass, carbon, silica, aluminosilicate, silicon carbide, alumina, etc. limit their use, for the preparation of fiber reinforced composite materials. Low cost, environment friendly, inexhaustible supply and naturally abundant, make natural fibers possible substitutes to synthetic reinforcing fiber materials, especially for polymer matrix composites.

Among many natural fibrous plants, bamboo (botanical name: Bambusa) is one of the fastest growing grass-plants and it is abundantly available in many countries. Unfortunately, in spite of its remarkable tensile and impact strength [1] bamboo fiber has so far been utilized only for making low grade structural materials, that too for short term applications. Recently, a few research groups have scientifically investigated the potential of bamboo fiber as a reinforcing material for polymer matrix composites [2–5].

Bamboo is composed of cellulose materials reinforced with silica [1]. Its anatomical properties and unique structure make it superior to other known natural ligno-cellulose fibers [3]. Since biomaterials have been naturally selected and have evolved for millions of years, their great variety of composite structures could be taken as a reference in biomimetic design of composite materials [6]. If density and mechanical properties were considered along with cost of any functionally graded material (FGM), perhaps bamboo would be the best. The integrated structure of bamboo helps it to withstand extreme natural environment and itself is a unique example of unidirectional fiber reinforced composite. Bamboo is renewable, abundantly available, low cost and environment friendly.

Recently Amada *et al.* [7] have studied the mechanical and macro/micro structural properties of a particular variety of bamboo. The geometry of bamboo's longitudinal profile has a macroscopically functionally graded structure, which can withstand extreme wind loads. It has also been observed that the fiber distribution in the transverse cross-section at any particular height of a bamboo, is dense in the outer periphery and sparse in the inner periphery, as a result, outer surface has higher strength than the inner surface. The fiber strength is reported to be ∼600 MPa which is 12 times higher than the matrix strength [7]; and the Young's modulus of fiber is much higher (46 GPa) than that of the matrix (2 GPa). Whereas the density of fiber is 1.16 and the matrix density [7] is 0.67 gm/cm^3 and the average density of bamboo is 0.8 gm/cm^3 [8]. Therefore, the average volume percentage of fibers in a piece of bamboo is approximately 32%. Amada *et al.* also observed that some fibers deviate from the "culm" (in between two nodes) into the nodes to reinforce the nodes. The fibers in the nodes are not unidirectional but randomly oriented to impart isotropic properties and their main role is to join the nodes and the culm. Therefore, bamboo may be considered as both macroscopically and microscopically functionally graded biomaterial. Both macroscopic and microscopic structure of bamboo is quite complicated. So far very few microstructural studies have been carried out. Therefore, the reasons for very high load bearing capacity of this functionally graded material are not known fully.

The bamboo specimen used in this study was collected from southern part of West Bengal, India and the local name of the particular type of bamboo is "Valki". A typical bamboo specimen was air dried for few months in open atmosphere after collection and then cut into small pieces. The microstructural studies of bamboo specimen were carried out by scanning electron microscope (SEM) using Jeol–JSM 840A, Japan. For this purpose bamboo samples were cut by a slow-speed diamond cutter. The specimen were then polished and etched with 5% NaOH solution for 2–3 min. Micrographs of fibers and fibrils were taken from fractured samples. All the samples were gold coated by ion sputter coating technique and studied by SEM.

Botanically bamboo is categorized as "monocotyledon". In the transverse section of monocots the extreme outer layer is known as "epidermis". Just inside of the epidermis, layer of "hypodermis" is mostly made up of "sclerenchyma cells". In case of bamboo "vascular bundles" are commonly known as bamboo fibers [9]. These vascular bundles are many in numbers and scattered all over any piece of bamboo. The microstructural studies reveal that the population of the fibers varies from outer to inner periphery of a piece of bamboo (Fig. 1). At the outer periphery the fibers are compacted in nature, at the same time they are more in numbers than the fibers at the inner zone. At the inner zone, the volume fraction of bamboo matrix is greater (Fig. 2). Again depending upon the position not only the population of fibers but their size and shape also varies drastically. In general, each vascular bundle (fiber) near the

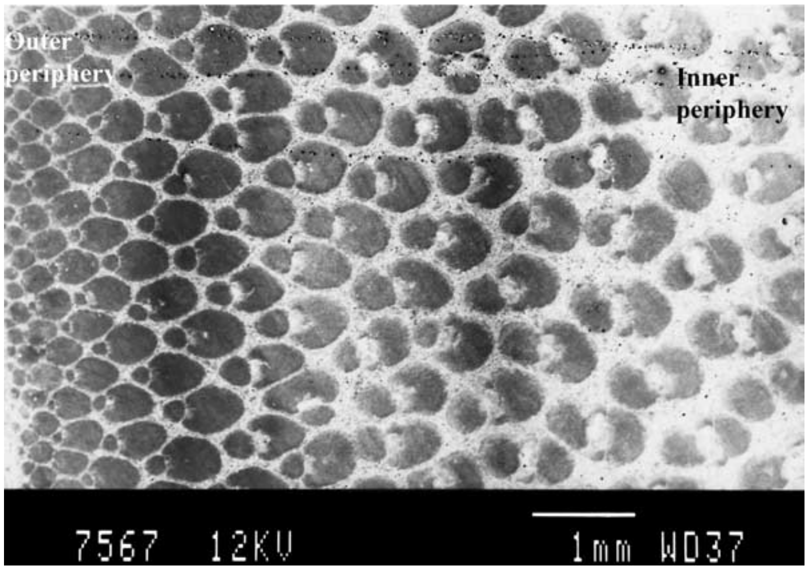


Figure 1 SEM photo microstructure of bamboo showing the population of vascular bundles (fibers).

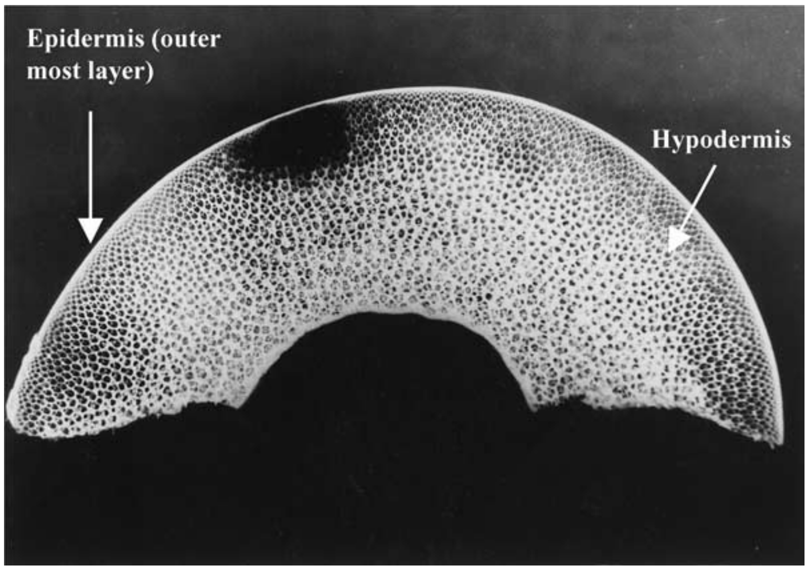
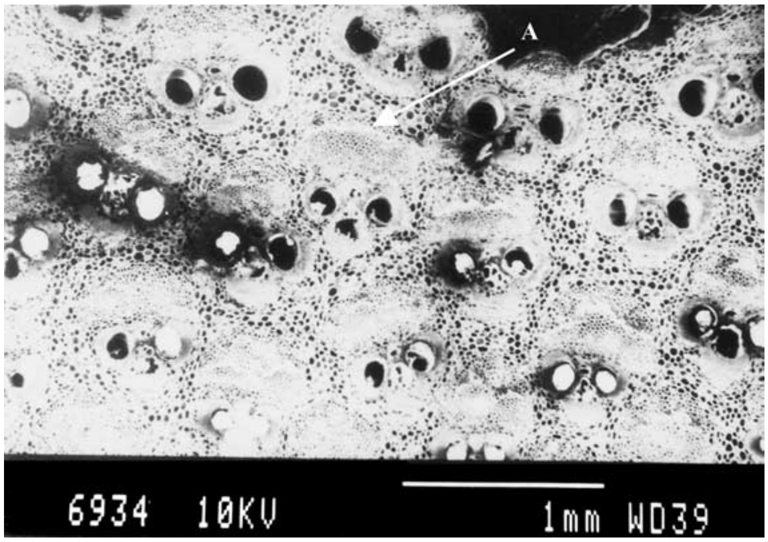


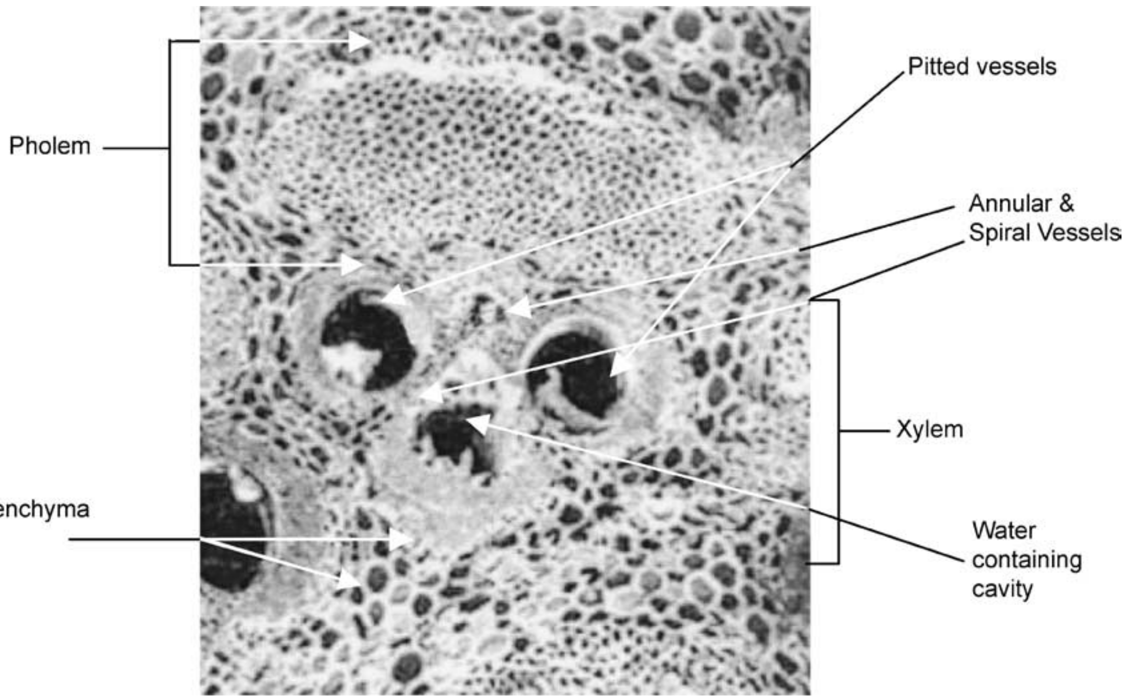
Figure 2 Photograph of transverse section of a piece of bamboo.

hypodermis, that is near the outer periphery, is closely packed or dense (Fig. 1). Each vascular bundle has two distinct parts, i.e., "xylem" and "phloem" (Fig. 3a and b). At the extreme inside of a piece of bamboo the vascular bundles are so broad that it is difficult to identify their boundaries from the matrix (ground tissues).

In the xylem there are two "pitted vessels", one "annular vessel", one "spiral vessel" and one "water containing cavity"; these are arranged in 'Y' shape. The pitted vessels, annular vessel, spiral vessel and water-containing cavity are all surrounded by a solid structure (Fig. 4). The over all area of this solid structure in a particular vascular bundle is more when the bundle is close to outer periphery (Fig. 5). Apart from two pitted, one annular, one-spiral vessels and water-containing cavity, there are large number of sclerenchyma cells (fibrils) around any vascular bundle (Fig. 3b). The pitted vessels and water containing cavity in the vascular bundles, situated near the inner periphery gradually become far apart, thus the vascular bundle around that place is less dense (Fig. 5). In other words, the bundles close to the inner periphery contain more "ground tissues" (matrix) which have less strength. The fibers or vascular bundles close to epidermis are so dense that it is difficult to differentiate the parts of xylem such as pitted vessels, water-counting cavity, annular and spiral vessels. The xylem becomes much smaller than the phloem. From outer to inner periphery xylem changes from small circular to bigger flower like shape. In contrast, towards the outer periphery phloem looks almost elliptical, and more towards the inner periphery it becomes rounded (Fig. 2) and at the extreme inner periphery it merges with the matrix (Fig. 1). Near the outer periphery the cross-section of vascular bundles are almost circular, whereas towards the center it becomes elliptical. It has also been observed that the xylem portion of vascular bundles is always facing towards outer periphery, whereas phloem is facing towards the inner periphery of a bamboo piece (Fig. 1).



(a)



(b)

Figure 3 (a) Microstructure of bamboo showing the xylem and phloem in fibers. (b) An enlarged (×2.8) photo micrograph of A in Fig. 3a showing parts of the vascular bundle.

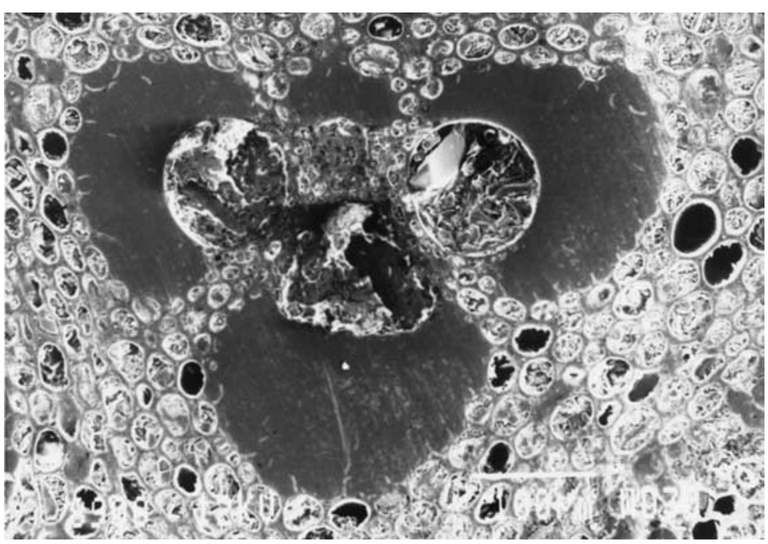


Figure 4 Microstructure of bamboo shows the solid structure around different vessels.

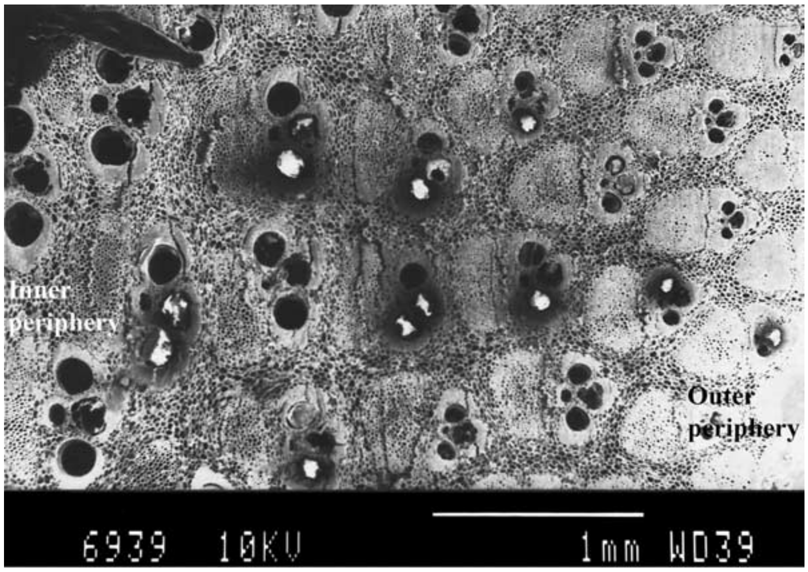


Figure 5 The micrograph shows the nature of vascular bundles at inner and outer periphery of bamboo.

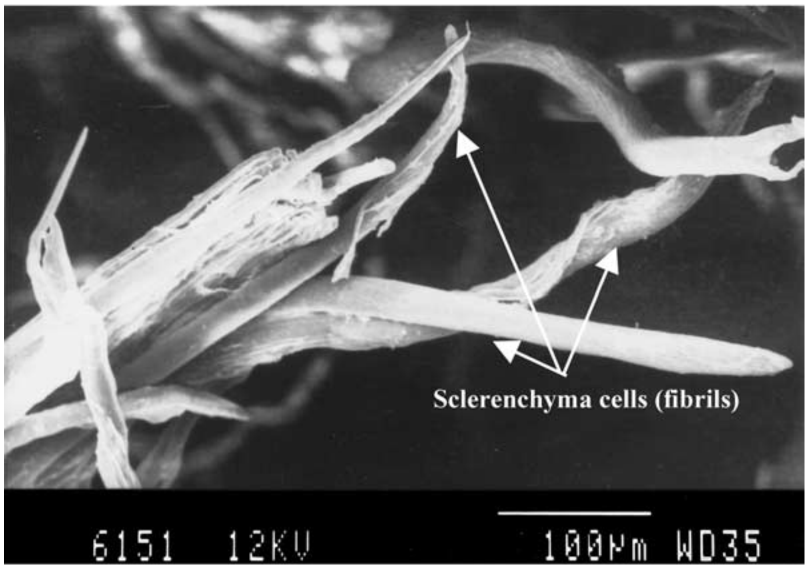


Figure 6 Fractured vascular bundle (fiber) shows the sclerenchyama cells (fibrils).

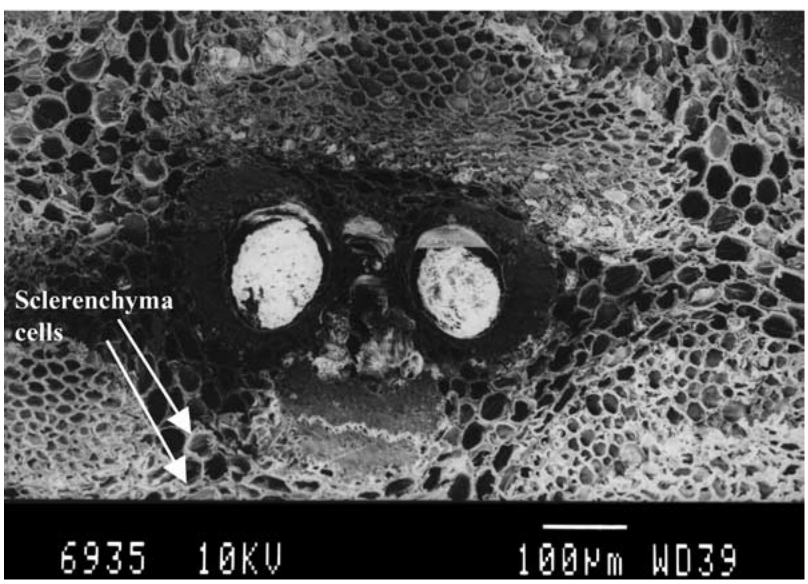


Figure 7 Pentagonal and hexagonal sclerenchyma cells, around xylem and phloem are arranged in honeycomb pattern.

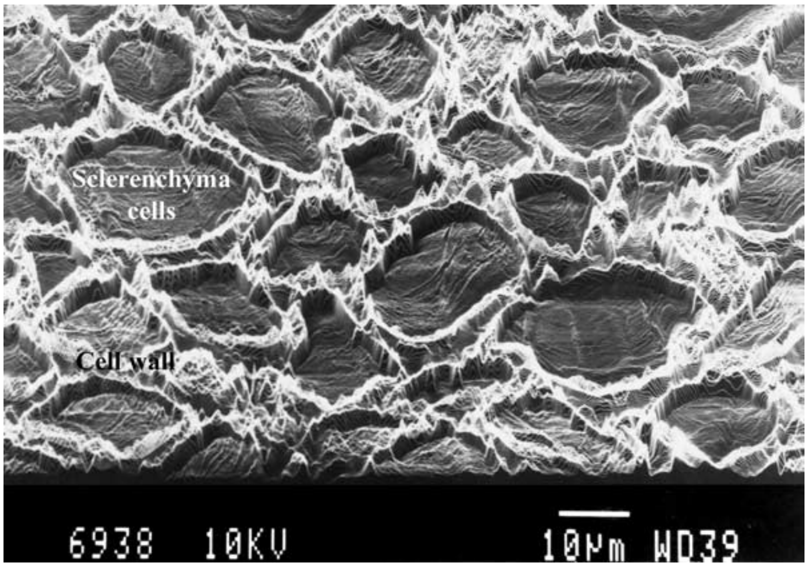


Figure 8 Topographical SEM micrograph shows the sclerenchyma cells and the wall thickness in between the cells.

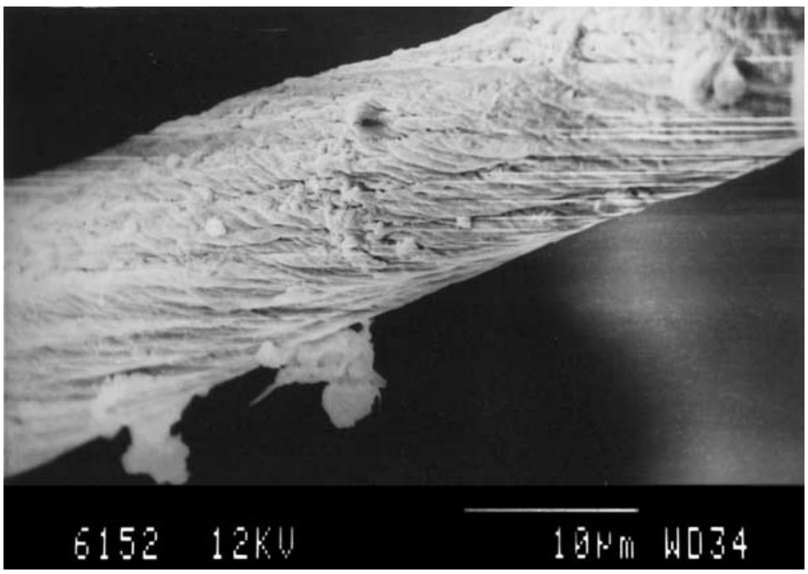


Figure 9 Microstructure of single sclerenchyma cell (fbril).

The fracture of a fiber (vascular bundle) shows that each fiber, irrespective of its position, contains many sclerenchyma cells (fibrils) (Fig. 6). The cross-section of these fibrils is either pentagonal or hexagonal and they are arranged in honeycomb pattern, separated by thin walls of matrix (Fig. 7). The wall thickness in between two sclerenchyma cells ranges from 1 to 5 μm and the width of the same varies from 10 to 20 μm (Fig. 8). Again a fibril contains many continuous elongated cellulose, which are staggered in twisted nature, like a metal cable formed by many twisted wires (Fig. 9). Thus a bamboo fiber contains several fibrils which are composed of many twisted and elongated cellulose. As a result a small fiber of $\sim$1 cm length can be bent 180° or more. The complicated nature of a bamboo fiber accounts for its better strength than other natural fibers. The unique microstructures of bamboo as a whole help it to withstand the strong wind or other adverse natural conditions.

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