Pergamon

Composites Engineering, Vol. 5, No. 7, pp. 743-751, 1995

0961-9526/95 $9.50 + .00

0961-9526(95) 00037-2

INTELLIGENT FUNCTIONALLY GRADED MATERIAL: BAMBOO

Fumio Nogata

Department of Mechanical Engineering, Himeji Institute of Technology, Himeji, 671-22, Japan

and

Hideaki Takahashi

Research Institute for Fracture Technology, Tohoku University, Sendai, 980, Japan

(*Received* 20 *December* 1994; *final version accepted* 23 *February* 1995)

Abstract—Since the shape and ingenious construction of biological hard tissues are the result of a continuous process of optimization, their basic characteristics such as microstructures, functions, and modelling systems fascinate the designers of engineering structures. Through the study of functionally graded materials, we hope to develop new superior material/structure concepts by using or modifying the construction of living organisms. The ingenious construction of bamboo was studied herein to help in the understanding of the principles and the design processes found in biological materials which are multi-phased and functionally graded composites. It was found that the ability of a bamboo cell to generate electrical signals when stressed was an apparently similar function to that of the piezoelectric effect in bone which is stressed. It is also suggested in this paper that the electrical properties play an important role in the modelling/remodelling of the skeletal system in biological hard tissues. It is concluded that a bamboo structure is designed to have uniform strength at all positions in both the radial direction on the transverse section and the lengthwise direction, and that bamboo is a self-optimizing graded structure constructed with a cell-based sensing system for external mechanical stimuli.

INTRODUCTION

Examining some biological load carriers such as plant and tree stems, animal bones and other biological hard tissues, we see that their geometry changes under loading to match mainly stress- or strain-dependent requirements. For example, the interior structure (architecture) of a bone exhibits an optimized shape with respect to the principal stress directions and the shear stress magnitude in the body (Koch, 1917). This indicates that the bone is managed by a self-optimizing system with sensing mechanisms (e.g. piezoelectric effect of bone) that detect external mechanical stimuli to control the modelling/remodelling of the skeletal system. Thus, it can be inferred that the shape and ingenious construction of biological hard tissues are the result of a continuous process of intelligent optimization. The basic characteristics of biological hard tissues such as microstructures, functions, and modelling systems are a source of both fascination and inspiration to the designers of engineering structures. On the other hand, the basic difference between biological and artificial structures is that the former have living organisms which can be characterized by multifunctionality, hierarchical organization, and adaptability (Srinivasan *et al.*, 1991). As a result, biological structures are complicated and nonuniform, which suggests that a judicious combination of elements, materials and components of differing strength in the same structure can lead to acceptable and adequate hybrid systems whose properties are managed for specific purposes.

The purpose of this paper is to examine the ingenious construction and strength of bamboo and derive ideas and guidance for the development of new and superior material/structure concepts, such as composites in multi-phased and functionally graded materials. In particular, we focus herein on the microstructure, strength, and mechanosensing system of the bamboo.

MATERIAL AND METHODS

The material tested was selected from one of the most popular bamboo species in Japan, known as Moso bamboo, *Phyllostachys pubescens* Mazel (Gramineae). Two types of specimens, as shown in Fig. 1, were shaped, using a knife, from a single stem of bamboo

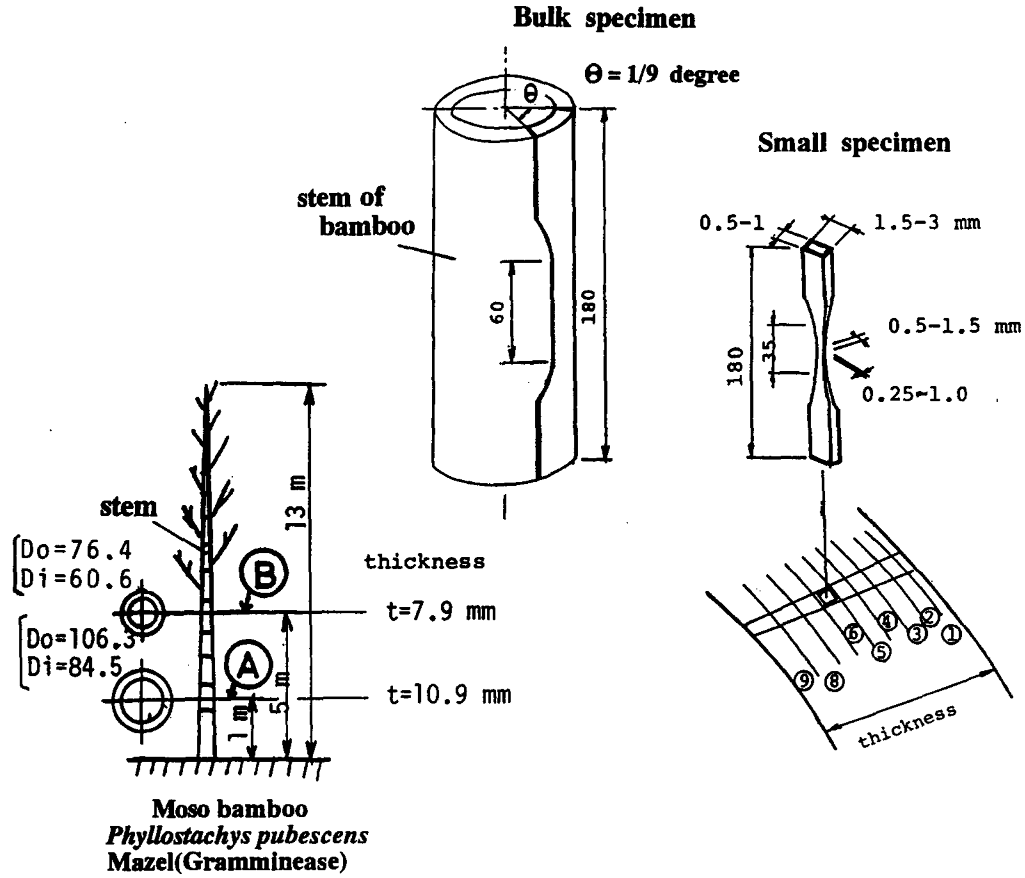

Fig. 1. Specimen geometry for tension test.

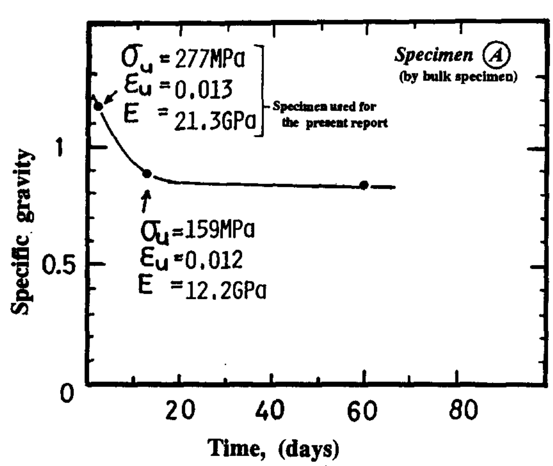

Fig. 2. Change in specific gravity with time after specimen was taken from the field.

which was 13 m long. Tension tests were performed within 48 h after it was taken from the field, to prevent any change in the mechanical properties due to moisture loss (Fig. 2).

RESULTS AND DISCUSSION

Mechanosensing system and adaptive modelling of bamboo

When we cut the transverse section of a stem of bamboo, many beautiful brown dots can be observed (Fig. 3(a)). These dots at the outside and inside of the cross-section have quite different shapes. Figures 3(b) and 3(c) show the enlarged photograph of a dot at the centre and outside of the cross-section. These show a flower shape and a figure eight

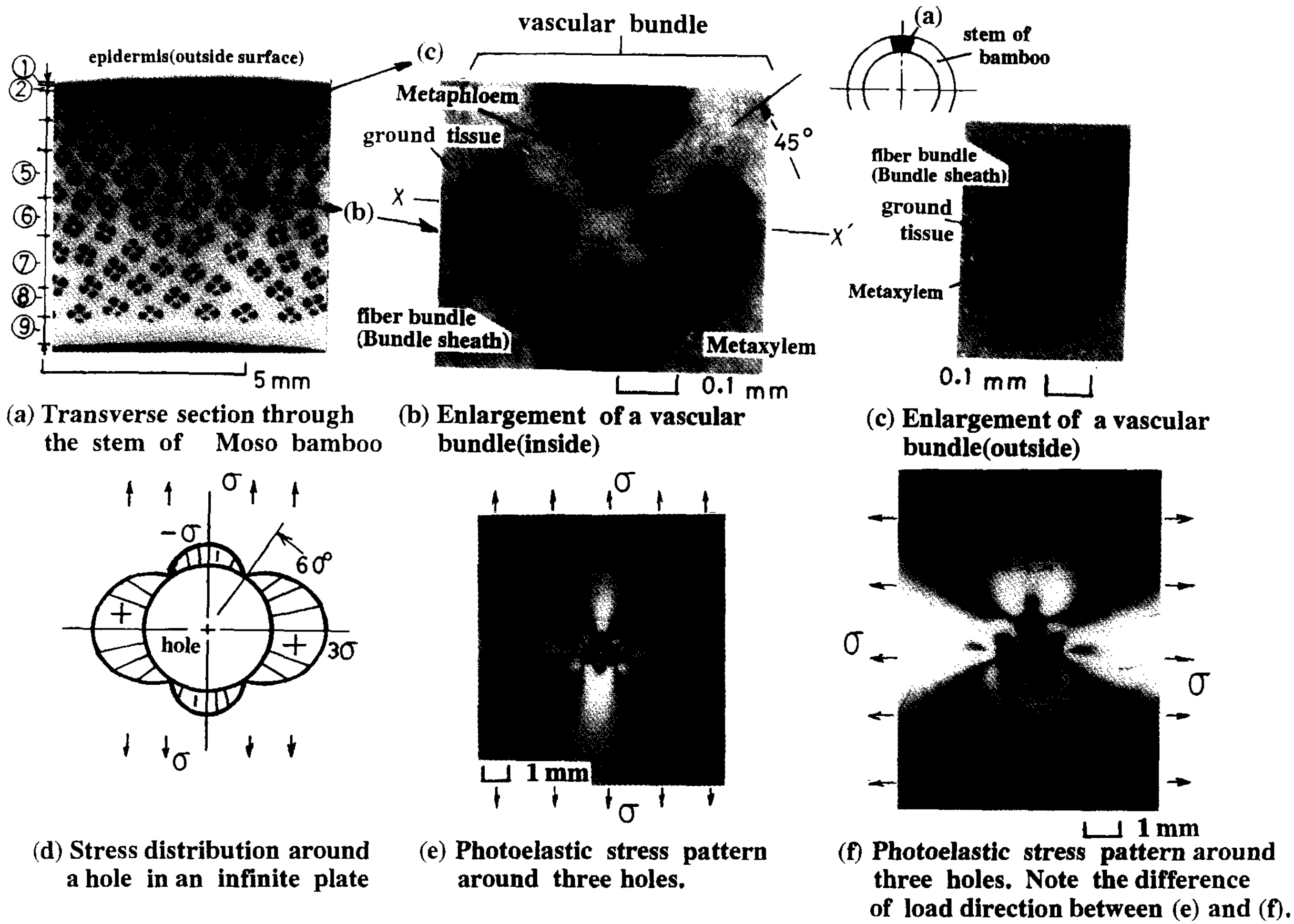

Fig. 3. Transverse section showing the placement of fibre bundles and stress distributions around holes.

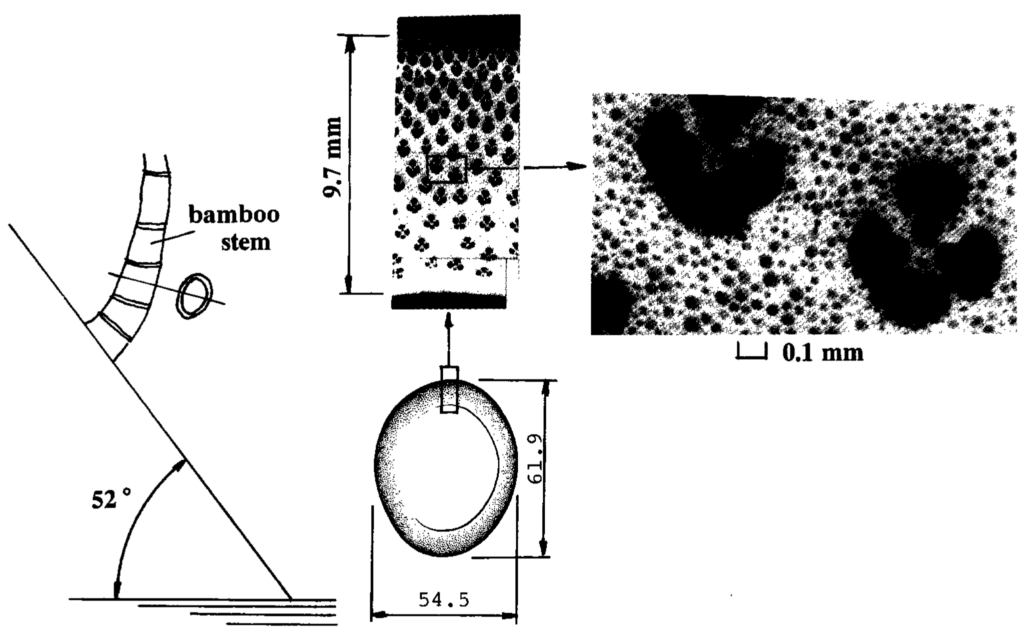

Fig. 5. Transverse section showing the placement of fibre bundles for the stem of bamboo grown on steep ground.

shape, respectively. There are two big holes (vessels in xylem; metaxylem) and a few small holes (sieve tubes in phloem; metaphloem) in the centre. In Fig. 3(b), if we replace these holes by one big hole, the meaning of the flower shape will be realized by comparing the stress distributions around a hole in an infinite plate subjected to a uniaxial tension (Fig. 3(d)).

Figures 3(e) and 3(f) show the photoelastic stress patterns around three holes in a plate model, with similar dimensions to those in a bamboo, which is subjected to two different loading directions, respectively. The best way to reinforce these holes is to set in fibre bundles according to the stress distribution. Therefore, it seems that the placement of the fibre bundle (black areas in Figs 3(b) and 3(c)) indicates a stress situation around the vessels in the xylem and phloem. Mattheck (1990) and Mattheck and Burkhardts (1990) showed that the contour shape of biological structures such as tree stems, red deer antlers, human tibia, and tiger claws are highly optimized in terms of mechanical strength and minimum weight. This implies that biological structures may have mechanical sensing devices. Therefore, in order to gather information and examine the sensing ability of bamboo cells, when stress is induced by external mechanical stimuli, we tried to detect a biological signal which may be induced. We used an electrocardiograph machine for the human body for a measurement system. A half size diagnostic ECG (electrocardiogram) electrode with adhesive paste was used, which was bought from a dealer.

Figure 4 shows an example of the voltage signal curves which were obtained from a bamboo stem subjected to an external bending moment. The curves show the presence of a spike upon loading and upon unloading. The higher voltage signal was recorded on the compression side rather than the tension side of the bamboo stem. These signals may be used as a trigger to organize adaptive growth related to the stress directions. The authors' data, obtained from other plants (rubber plant and palm tree), showed that the characteristic features of the signals depended on the kinds of plants, and there was no voltage signal induced from a specimen boiled in a hot water bath for 1 h or from a dried specimen with a weight loss of one half. Because boiling or drying of specimens means the death of the plant cells, it is clear that the voltage signals recorded were produced from live cells in stressed materials. This indicates that live bamboo cells have the ability to sense some information induced by external mechanical stimuli.

On the other hand, Fukuda and Yasuda (1957) found piezoelectrical properties in bone which was stressed. There are several reports (Martin, 1972; Gjelsvick, 1973; Cowin and Hegedus, 1976; Cowin and Van Buskirk, 1978) which are based on evidence that bone demonstrates a piezoelectric effect. This is used to explain the concept of stress- or strain-induced bone remodelling which is often referred to as Wolff's law (1870). Thus, bone converts mechanical stress to an electrical potential that influences the activity of osteoclasts and osteoblasts (Hayes *et al.*, 1982). It is also known that the interior structure of bone (trabecular architecture) is arranged in compressive and tensile systems corresponding to the principal stress directions (Koch, 1917). The properties of the voltage signals induced in bamboo may also be similar to the piezoelectric effect in bone. Therefore, it may be shown that the electrical properties of bone and bamboo play an important role in the remodelling/modelling of the skeletal system in biological hard tissues.

Figure 5 shows the enlarged vascular bundle of bamboo which was grown on steep ground. It is clear that the deformed contour shape of the bamboo stem and the asymmetric shape of the fiber bundles are a reflection of biased loading conditions by their environment. Therefore, the electric signals recorded and the location of the fiber bundles are evidence suggesting that bamboo has a stress/strain-induced adaptive modelling system. This system uses cell-based mechanosensors which may be utilized to affect or change their shapes (e.g. placement and volume density of fibre, thickness of stem) which can compensate for applied external loads in order to avoid any localized stress peaks. Thus, the characteristic stress/strain states lead to the modelling of hard tissue and ingeniously customized microstructures in bamboo.

The above considerations also indicate that the volume density of fibres and their distribution give us important information from the mechanical and morphological points of view.

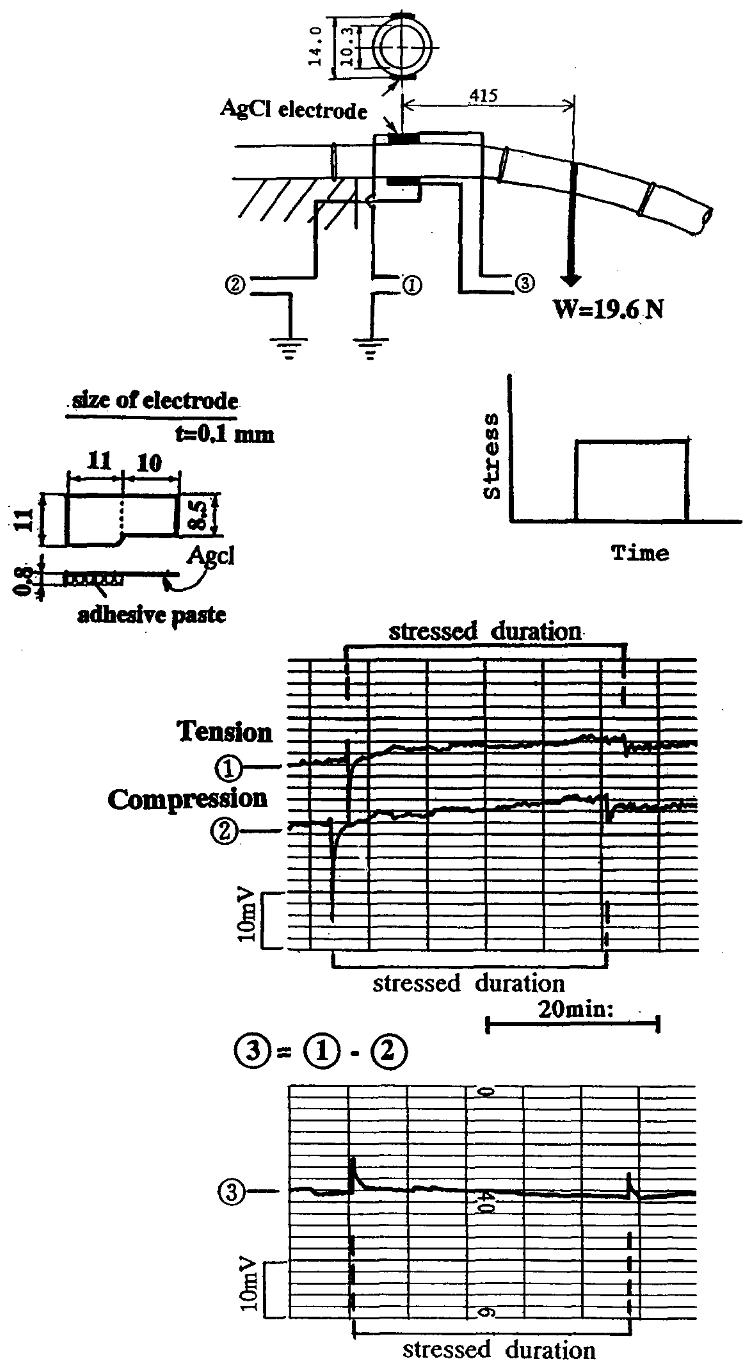

Fig. 4. An example of the voltage signals induced by bending moment for stem of bamboo.

Mechanical properties

Figure 6 shows the distributions of fibre density at two different transverse sections (the lower position is specimen A and upper position, specimen B) in a bamboo stem. This graph shows that the fibre density gradually increases from the inside to the outside surface, as well as from the lower part to the upper part of a bamboo stem. These graded structures will produce a uniform internal stress distribution in both radial and axial directions. In order to examine mechanical properties of the bamboo, tension tests were performed using very small specimens with cross-sectional areas of about 0.25 mm^2. The specimens were taken from nine areas arranged as shown in Fig. 3(a). Figure 7 shows the tensile strength and Young's modulus for A and B specimens along the transverse section

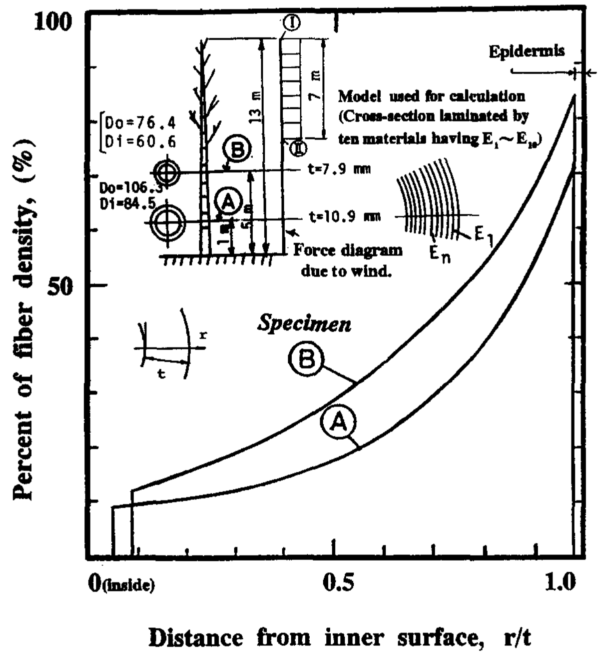

Fig. 6. Distributions of fibre density along the transverse section of a bamboo stem.

of a bamboo stem, which indicates that the strength gradually increases from the inside to the outside, and also that specimen B has higher strength than specimen A. This is the same variation as the variation of volume density of fibres that was mentioned in Fig. 6. Since the extreme inside specimen (No. 9) was made of pure ground tissue, its strength was correspondingly about 25 MPa. Thus, the strength of pure fibre was estimated to be

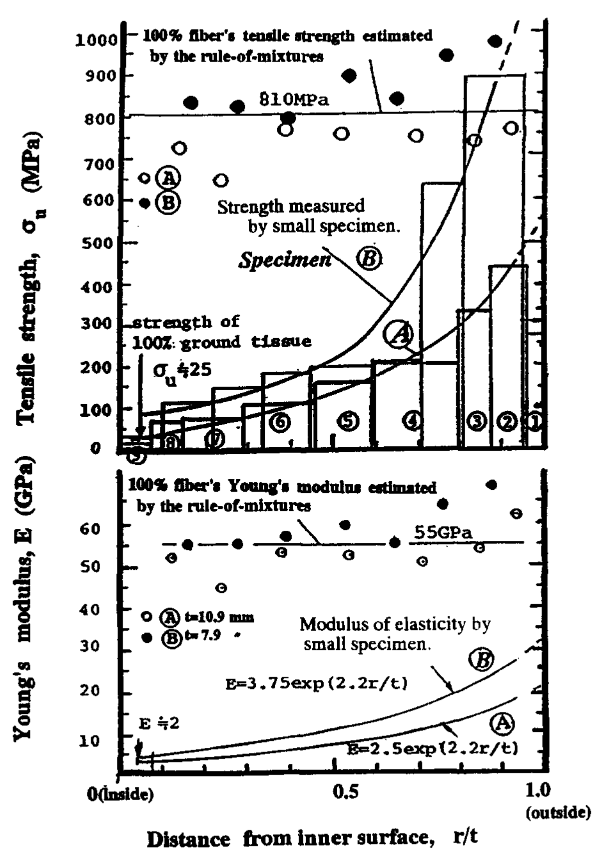

Fig. 7. Distributions of tensile strength and Young's modulus along the transverse section of a bamboo stem.

Table 1. The structural efficiency in terms of weight-cost for some selected materials

Materials	E (GPa)† (E/ρ	σ_u (MPa)‡ (σ_u/ρ)	ρ (Mg/m^3)§	Remarks
Mild steel	200 (25.6)	400–500 (51–64)	7.8	
Carbon steel	200 (25.6)	450–700 (58–90)	7.8	
CrMo Steel	200 (25.6)	800–1200 (102–154)	7.8	
Al alloys	73 (26)	140–550 (50–196)	2.8	
Ceramics:				
SiC	260 (81)	400 (125)	3.2	
XrO_2	170 (146)	160 (43)	3.7	
Al_2O_3	390 (100)	500 (128)	3.9	
Bamboo:				
bulk	15 (12.7)	22 (18.6)	1.18	Authors
matrix	2 (1.47)	25 (18.4)	1.36	Authors
pure fibre	55 (52.3)	810 (770)	1.05	Authors
Wood (pine)	11 (27.5)	100 (250)	0.4	Gordon (1988)
Mollusk shell:				
purplish Wa. clam (nacre)	32.4 (11.8)	44.1 (16)	2.75	Authors
Bone:				
rhino (humerus)	13 (6.5)	150 (75)	2.01	Currey (1991)
antler	14 (7.3)	200 (105)	1.9	Gordon (1988)
Leaf shaft:				
palm tree (Butia Yatay)	2 (1.8)	4 (3.6)	1.1	Authors
Feather shaft:				
stanley crane	7.2 (10.7)	310 (462)	0.67	Authors
duck	12 (16.2)	245 (331)	0.74	Authors

$^{\dagger}E$, Young's modulus, E/ρ = GPa/(Mg/m^3).
$^{\ddagger}\sigma_u$, tensile strength, σ_u/ρ = MPa/(Mg/m^3).
$^{\S}\rho$, density.

about 810 MPa (using rule-of-mixtures), which is equivalent to that of steel (600–1000 MPa). Furthermore, Young's modulus of pure fibre was 55 GPa. This value is about one quarter of the value of steel, which is 200 GPa. This data shows that the bamboo has high strength but low rigidity.

In order to examine the meaning of the graded structures and strengths, we

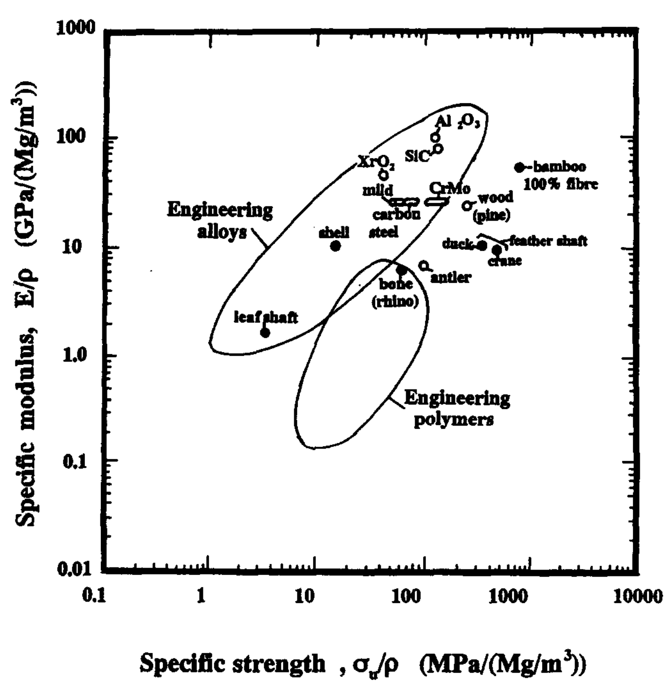

Fig. 8. Specific modulus, E/ρ, plotted against specific strength, σ/ρ, for some selected biological hard tissues.

performed stress analysis as on a composite beam made of ten different materials having a hollow cross-section. The model was considered as a cantilevered beam carrying a uniformly distributed load (which simulated the wind on the branches and leaves) between points I and II (see Fig. 6). The results showed that the ratio between measured strength (σ_u : see Fig. 7) and calculated strength (σ_i), σ_u/σ_i, had almost the same values (about 25 ~ 30), for all test points in the composite beam for both specimens A and B. This means that a bamboo structure is designed to have uniform strength at all positions in both the radial direction on the transverse section and the axial (lengthwise) direction. So, it is found that bamboo is a self-optimizing graded structure constructed with a sensing system of external mechanical stimuli; we may call this an intelligent adaptive modelling system.

The structural efficiency in terms of weight-cost (Gordon, 1978, 1988) for some selected materials is summarized in Table 1. Some of these data are plotted in Fig. 8 which shows the relationship between the specific modulus, E/ρ, and the specific strength, σ/ρ (Ashby, 1991). It is seen that the pure fibre of bamboo, the feather shaft, and wood have excellent specific strengths comparable with engineering alloys and ceramics, and that bone and antler have almost the same strengths as engineering alloys. Also, in terms of E/ρ, which governs the weight-cost of overall deflections, bamboo fibre is even better than steel.

CONCLUDING REMARKS

The ultimate goals of this work are to gain an understanding of the principles of design and processes found in biological materials and to apply these findings toward developing new superior material/structure concepts, such as composites in multi-phased and functionally graded materials, by using and/or modifying those models which are found in living organisms. We showed, as a typical example, the ingenious construction and sensing abilities of a bamboo structure which was described in this paper. We showed that bamboo is a self-optimizing graded structure constructed with a cell-based sensing system for sensing external mechanical stimuli.

There was no pretense that we could cover all the fascinating characteristics of bamboo. The authors believe that the examples show us that it would be better to spend more time and money on developing functionally graded materials which are governed by uniform strength; for example, structures using the optimal placement of fibres, various microstructures, porous or cellular structures, etc., rather than developing new materials with high-stiffness.

REFERENCES

Ashby, M. F. (1991). *Materials Selection in Mechanical Design*, p.35. Pergamon Press, Oxford.

Cowin, S. C. and Hegedus, D. H. (1976). Bone remodeling. I: Theory of adaptive elasticity. *J. Elastic.* **6**, 313-326.

Cowin, S. C. and Van Buskirk, W. C. (1978). Internal bone remodeling induced by a medullary pin. *J. Biomech.* **11**, 269-275.

Currey, J. D. (1991). Private communication.

Fukuda, E. and Yasuda, I. (1957). On the piezoelectric effect of bone. *J. Phys. Soc. Japan* **12**, 1158-1162.

Gjelsvik, A. (1973). Bone remodelling and piezoelectricity—I. *J. Biomech.* **6**, 69-77.

Gordon, J. E. (1978). *Structures or Why Things Don't Fall Down*, p. 17. Penguin Books, London.

Gordon, J. E. (1988). The science of structures and materials. *Scient. Am. Library* **25**, 176.

Hayes, W. C., Snyder, B., Levine, B. M. and Ramaswamy, S. (1982). Stress-morphology relationships in trabecular bone of the patella. In *Finite Elements in Biomechanics* (Edited by Gallagher, R. H. *et al.*), pp. 223-268. John Wiley, New York.

Koch, J. C. (1917). The laws of bone architecture. *Am. J. Anat.* **21**, 177-198.

Martin, R. B. (1972). The effects of geometric feedback in the development of osteoporosis. *J. Biomech.* **5**, 447-455.

Mattheck, C. and Burkhardts, S. (1990). A new method of structural shape optimization based on biological growth. *Int. J. Fatigue* **12**(3), 185-190.

Mattheck, C. (1990). Engineering components grow like trees. *Mat.-wiss. 11, Werkstofftech* **21**, 143-168.

Pauwels, (1948). Bedeutung und Kausale Erklarung der Spongiosaarchitektur in neuer Auffassung. *Arztl. Wschr* **3**, 379.

Srinivasan, A. V., Haritos, G. K. and Hedberg, F. L. (1991). Biomimetics: advancing man-made materials through guidance from nature. *Appl. Mech. Rev.* **44**(11), 463-481.

Wolff, J. (1870). Ueber die innere architecture der knochen und'ihre Bedeutung fur die Frage von Knochenwachstun. *Uirchows Arch.* **50**, 389-450.