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Fracture properties of bamboo

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Abstract

Bamboo is a typical natural composite material, which is longitudinally reinforced by strong fibers. The fibers are distributed densely in the outer surface region, and sparsely in the inner surface region, and their volume fraction changes with respect to radius. The structure of bamboo has been characterized by tensile tests and its mechanical properties have been related to its structure.

This paper presents the fracture toughness of bamboo culms and nodes. A notch is inserted into the culm and node specimens using a razor blade with a thickness of 0.4 mm. Tensile tests are carried out to evaluate fracture toughness. The average value obtained was 56.8 MPa m$^{1/2}$, which is higher than that of Al-alloy. It was concluded that the fracture toughness of the bamboo culm depends on the volume fraction of fibers. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Bamboo; Fracture toughness; Functionally graded structure; Tensile test

1. Introduction

Functionally Graded Materials (FGM) [1] have attracted attention in various fields because they can generate function. Bamboo is a typical, natural FGM and composite material [2–4] with a hierarchical structure [5]. Furthermore it has other positive features, such as a light-weight design based on a hollow cylinder, good flexibility [6] and tough character due to its thin walls with discretely distributed nodes and to its great strength. The most amazing property is a very fast growing speed. Bamboo almost stops growing within one year and stops growing completely within five years [7].

Bamboo has been used as the structural material for steps at construction sites in China, India and other countries because it is a strong, tough and low-cost material. Toughness is the main characteristic which is closely related to resistance to fracture. Fracture of wood microscopically occurs at different levels, for example organ, tissue or cell [8]. Fracture of wood has been discussed and studied for various kinds of fracture mechanism [9]. Fracture toughness K_{IC}, strain energy release rate G, and work of fracture have been measured for various woods [10–13]. But the fracture properties of bamboo have not yet been studied.

This paper presents the fracture properties of bamboo at the macroscopic structural level based on fiber-reinforced composites, and discusses the results obtained based on FGM. When bamboo is covered with heavy snow, it can bend so much that it can touch the ground without breaking. This suggests that bamboo has a higher toughness than woods. The fracture toughness of the bamboo culm and node is measured by tensile tests on the notched specimens. It is discussed from the point of view of a functionally graded structure.

2. Fundamental structure and properties of bamboo

Fig. 1 shows a cross-section of the bamboo culm. The distributed solid dots correspond to fibers. This picture suggests that bamboo is a fiber-reinforced composite material and has the structure of a hollow cylinder with discretely inserted nodes. Let us introduce the coordinate system as shown in Fig. 2. An individual culm is defined as the part of the bamboo culm between two adjacent nodes and culms are numbered from the root to its tip.

2.1. Macroscopic functionally graded structure

Fig. 3(a)–(c) gives the diameter, wall thickness and internodal length of the bamboo culm with respect to culm number. These properties define the macroscopic functionally graded structure, the properties of which change with height.

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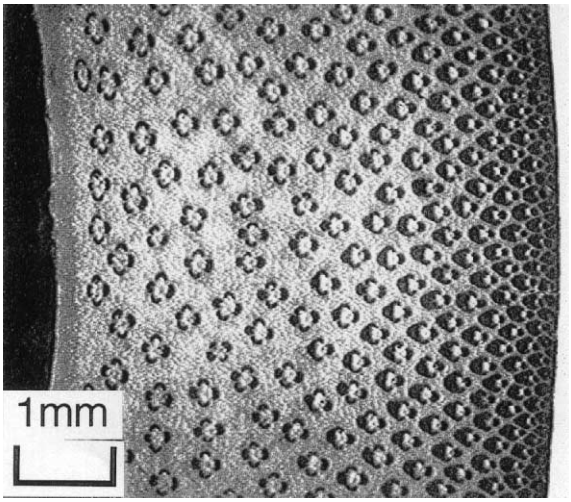


Fig. 1. Cross-section of bamboo culm.

2.2. Microscopic functionally graded structure

As shown in Fig. 1, the fiber in the cross-section of the bamboo culm is distributed densely in the outer layer and sparsely in the inner layer. Fig. 4 shows a typical volume fraction, V_f, of fibers with respect to non-dimensional radius, measured by image analysis. The horizontal axis indicates non-dimensional radius, R, defined by distance from the outer surface divided by the culm thickness, t. Thus $R = 0$ corresponds to the outer surface and $R = 1.0$ to the inner surface. It can be calculated that V_f is about 60% in the outer layer and 20% in the inner layer.

Tensile tests of the thin specimen sliced out of the bamboo culm were carried out at the different radial locations, then the tensile strength and Young's modulus were measured as shown in Fig. 5(a) and (b). These properties change with respect to radius, which corresponds to FGM. This graded structure is the microscopic functionally graded structure.

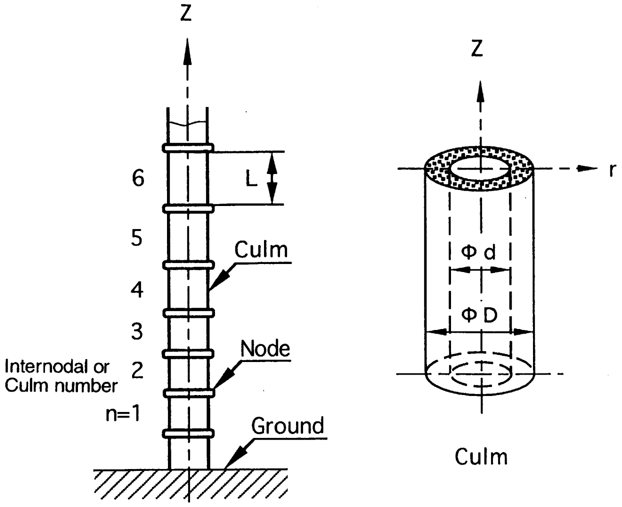


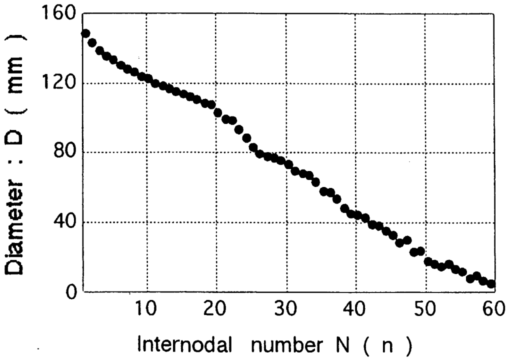
Fig. 2. Coordinate system.

2.3. Material properties

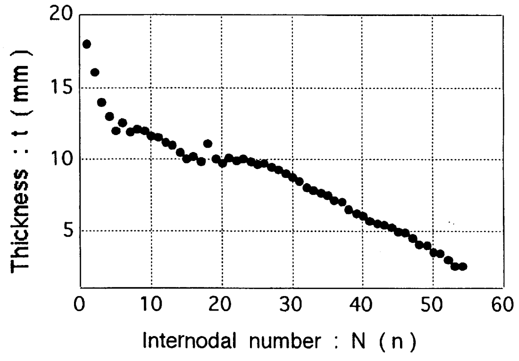
The mixture principle can be written by

$$\Psi_i = \Psi_{if} V_f + \Psi_{im}(1 - V_f) \tag{1}$$

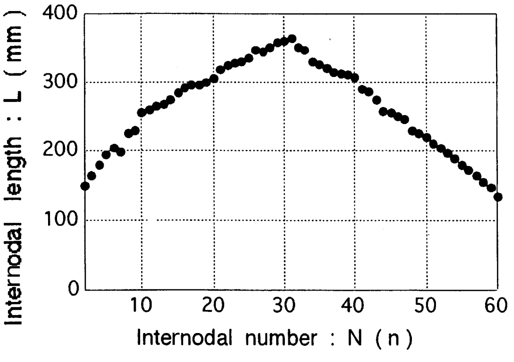
where Ψ_i is an overall material property of bamboo, Ψ_{if} is that of fiber and Ψ_{im} is the matrix property. It is worth noting that the tensile strength of fibers almost corresponds to that of steel. Using the data given in Figs. 4 and 5 and Eq. (1), the properties of bamboo were evaluated. The results obtained for the strength, Young's modulus and density are listed in Table 1.



(a) Diameter



(b) Thickness



(c) Intemodal length

Fig. 3. Diameter, thickness and bamboo culm.

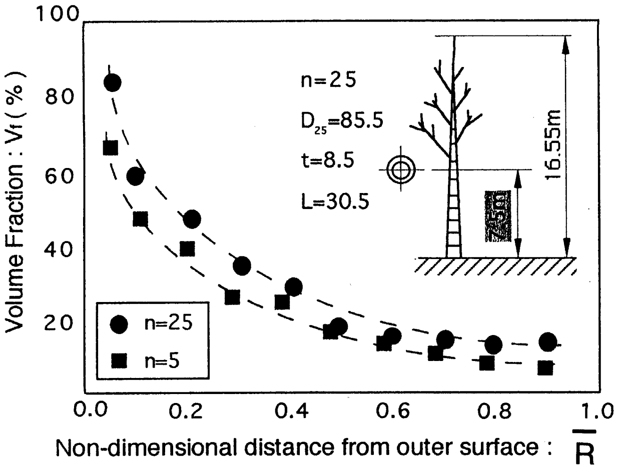
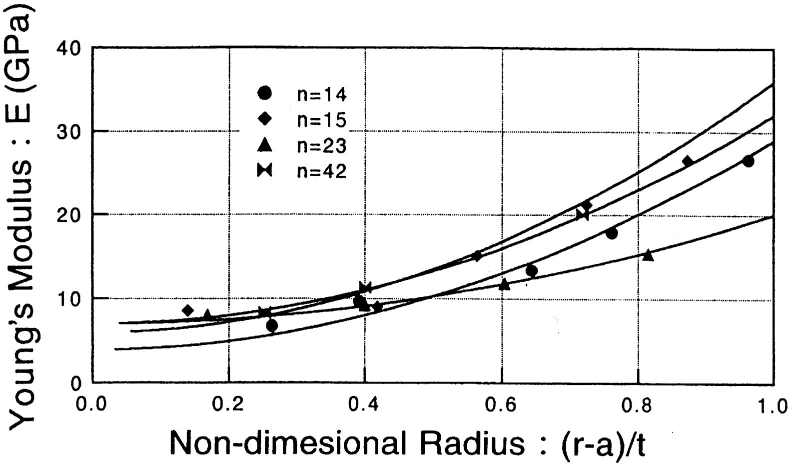


Fig. 4. Volume fraction of fiber with radius.

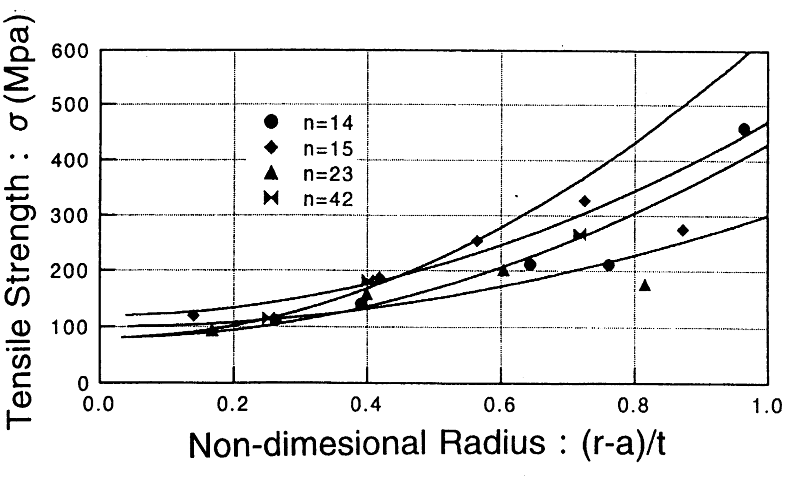
3. Fundamental fracture property of woods

Since woods generally have highly anisotropic characteristics, their fracture property depends on the specimen and the location of the crack. Schniewind and Pozniak [14] classified the specimen type based on the position of the crack relative to the grain of the wood, as shown in Fig. 6. Moreover, the TR- and LR- type are divided into specimens with a crack inserted from the pith-side and bark-side, respectively.

Bamboo is a typical natural composite material which is unidirectionally reinforced by fibers. The fracture property of this kind of material depends on the fracture origin, that is, where a fracture initiates. There are two places where a fracture initiates: the matrix region and fiber region [15]. The former fracture is called first matrix-cracking and is often observed in composite ceramics reinforced by ceramic fibers. The latter is called first fiber-cracking; this material is in the group of fiber reinforced plastics (FRP). For the



a) Young's modulus



b) Tensile strength

Fig. 5. Young's modulus and tensile strength with radius.

Table 1
Mechanical properties of bamboo

Woods	Strength σ_f (MPa)	Young's Modulus E (GPa)	Density ρ (g/cm^3)
Cedar	29.3–48.5	4.4–9.8	0.29–0.46
Fir	30.7–33.8	5.9–6.7	0.31–0.34
Pine	34.0–41.6	6.5–8.8	0.35–0.42
Spruce	31–40	7.3–8.5	0.38
Hickory	62.5–81.0	8.9–11.4	0.56–0.67
Oak	47.7–74.9	7.9–12.4	0.53–0.61
Bamboo (fiber)	610	46	1.16
Bamboo (matrix)	50	2	0.67
Bamboo (composite)	140–230	11–17	0.6–1.1

material of first matrix-cracking, the interface between fibers and matrix must be not so strong as to increase fracture toughness. On the contrary, for materials having the property of first fiber-cracking, a high interface bonding is needed to obtain a high fracture toughness.

A material is estimated to have the characteristics of first matrix-cracking if the following condition is satisfied,

$$\sigma_m \leq (E_m/E_f)\sigma_f \tag{2}$$

where σ_m and σ_f are the strength of matrix and fiber, and E_m and E_f are their Young's modulus, respectively. In the case of bamboo, they have the following values: $\sigma_m = 50$ MPa, $\sigma_f = 610$ MPa, $E_f = 46$ GPa and $E_m = 2$ GPa. Since the right-hand side term becomes 26.5 MPa, the fracture characteristics of bamboo must be first fiber-cracking like FRP. This kind of material often has fiber pull-out features on its fracture surface.

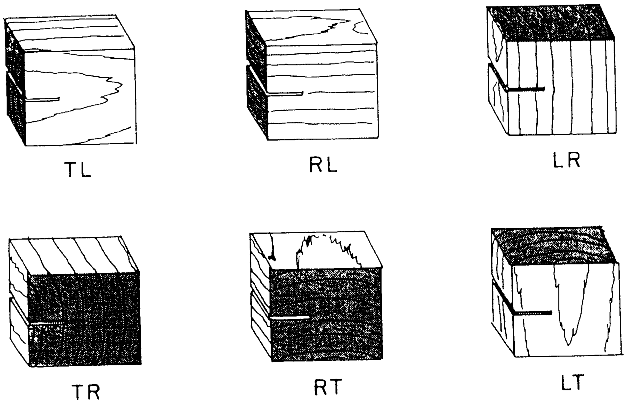


Fig. 6. Orthotropic crack alignments in wood.

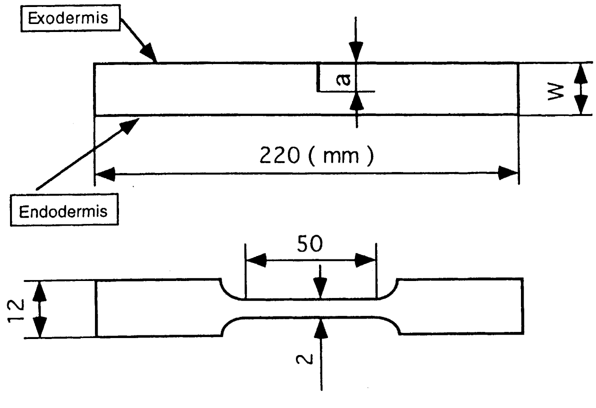


Fig. 7. Bamboo specimen with crack.

4. Specimens and tensile tests

The bamboo used for experiments is two-year old Mousou bamboo (*Phyllostachys edulis* Riv.). A tensile specimen is longitudinally cut out of the bamboo culm as shown in Fig. 7. The specimen width, W, is equal to the wall thickness, t, of the bamboo culm, which changes with

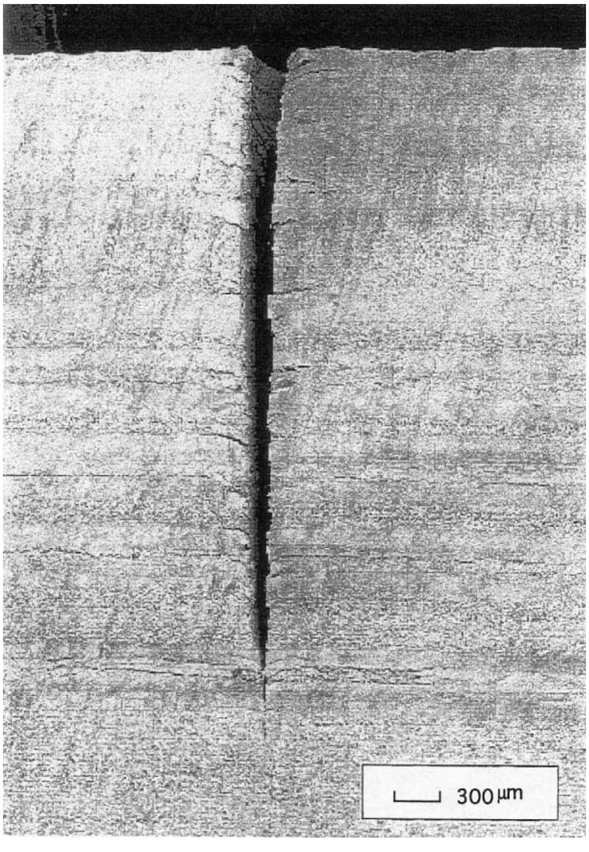


Fig. 8. SEM photograph with inserted crack.

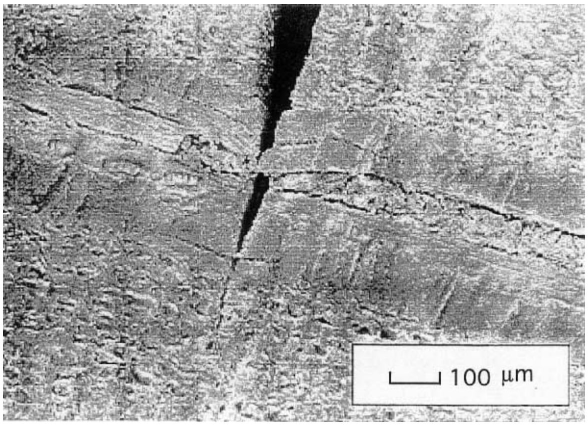


Fig. 9. Magnified notch front.

height, i.e. culm number. On the exodermis side, a slit is inserted using a razor blade with a thickness of 0.4 mm. The notch front for small notch depth stays at the location where the fiber distributes densely. With an increase in notch length, a, the notch front is located in the region where the fibers are sparsely distributed.

A typical SEM photograph of the notched part is shown in Fig. 8. The magnified notch front is shown in Fig. 9. Judging from this picture, the root radius of the crack tip is several tens of µm. This means that a crack extends further into the front of the blade tip when it is inserted, as shown in Fig. 10. Let a' be the insert depth of the razor blade and Δa be the extended crack length measured from SEM photographs. Fig. 11 shows the change in Δa with respect to insert depth a'. A true crack length is denoted by a and given by the sum of both lengths, i.e.

$$a = a' + \Delta a \tag{3}$$

It can be observed that Δa increases with the insert depth a' of the razor blade, and saturates with larger insert depth. A true crack length is adopted for an evaluation of fracture toughness.

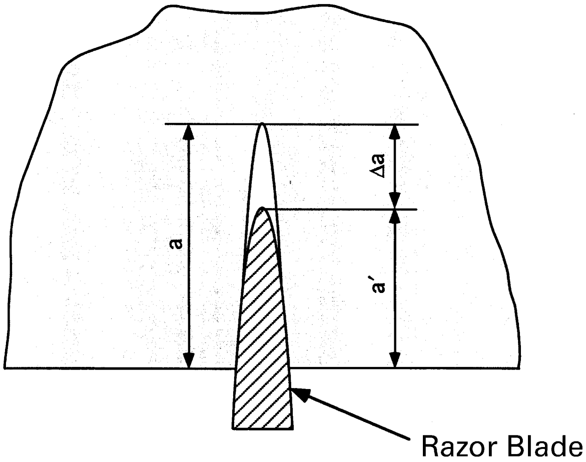


Fig. 10. Extended notch length.

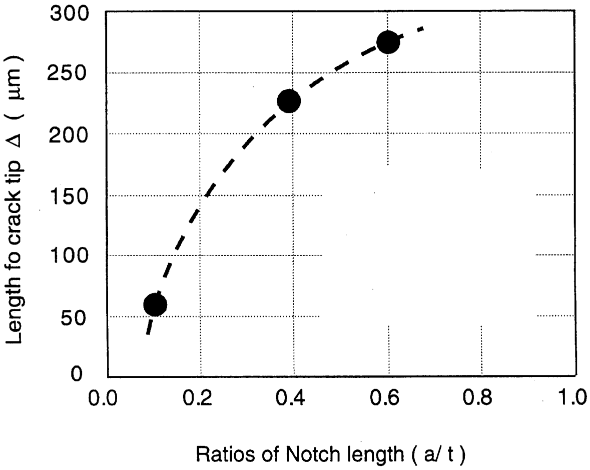


Fig. 11. Change of extended notch length.

The fracture stress, σ_C, is measured by tensile tests. A typical recorded stress–strain curve is shown in Fig. 12. Beyond the maximum stress, several step-like stress drops are recorded, which correspond to successive fracture behaviors of fibers.

Fig. 13 shows a typical SEM photograph of the fracture surface after the tensile test, where several pull-out fibers are observed, which is a typical feature of the fiber-reinforced materials with first fiber-cracking. The fracture surface of a fiber bundle around the parenchum is shown in Fig. 14.

Fracture toughness is calculated by the following formula [16],

$$K_{IC} = \sigma_C \sqrt{\pi a} / F(\xi) \tag{4}$$

where ξ is defined by a/W. The function, F, depends on the notch size, notch- and specimen-shape, and is given by,

$$F(\xi) = 1.12 - 0.231\xi + 10.55\xi^2 - 21.72\xi^3 + 30.39\xi^4 \tag{5}$$

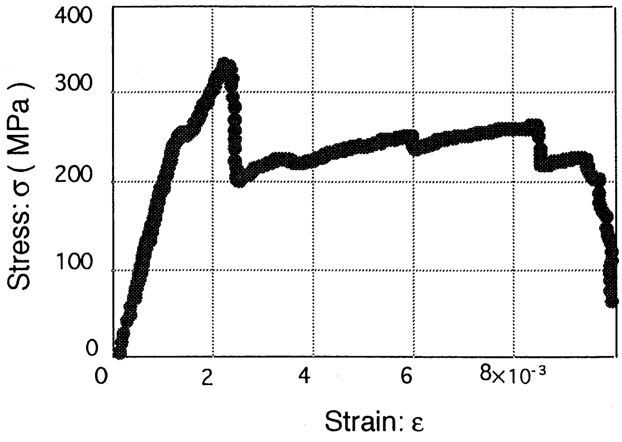


Fig. 12. Stress–strain curve ($n = 22$).

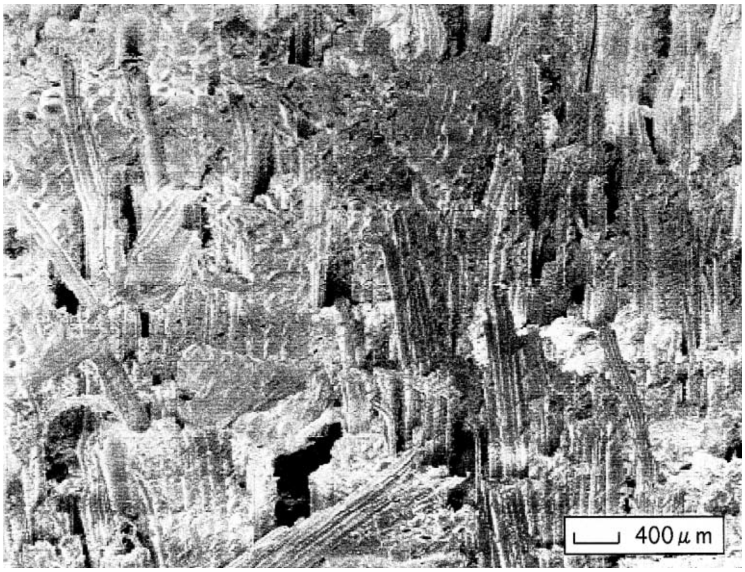


Fig. 13. SEM photograph of fracture surface.

5. Measured results

5.1. Culm

Fig. 15 shows, using the symbol ●, measured K_{IC} with respect to non-dimensional radius a for culm number $n = 5$, which is located near the bamboo root. $a = 0$ corresponds to the outer surface and $a = 1$ to the inner surface. K_{IC} has a large value of 96 MPa m$^{1/2}$ in the outer surface layer, decreases towards the outer surface and approaches 12 MPa m$^{1/2}$ at $a = 0.8$. Therefore, K_{IC} has a graded structure. The volume fraction of fibers is simultaneously represented by the symbol ∇. It can be easily seen that the distributions have approximately the same pattern. This leads to the conclusion that fracture toughness of the bamboo culm is proportional to the volume fraction of fibers.

Fig. 16 also gives the K_{IC} distribution for $n = 15$. The K_{IC} in the outer surface layer has a slightly higher value of 106 MPa m$^{1/2}$ than that for $n = 5$. Again, K_{IC} and V_f are distributed similarly. Figs. 17 and 18 represent the measured results of K_{IC} for $n = 22$ and 31, respectively. Since the culm

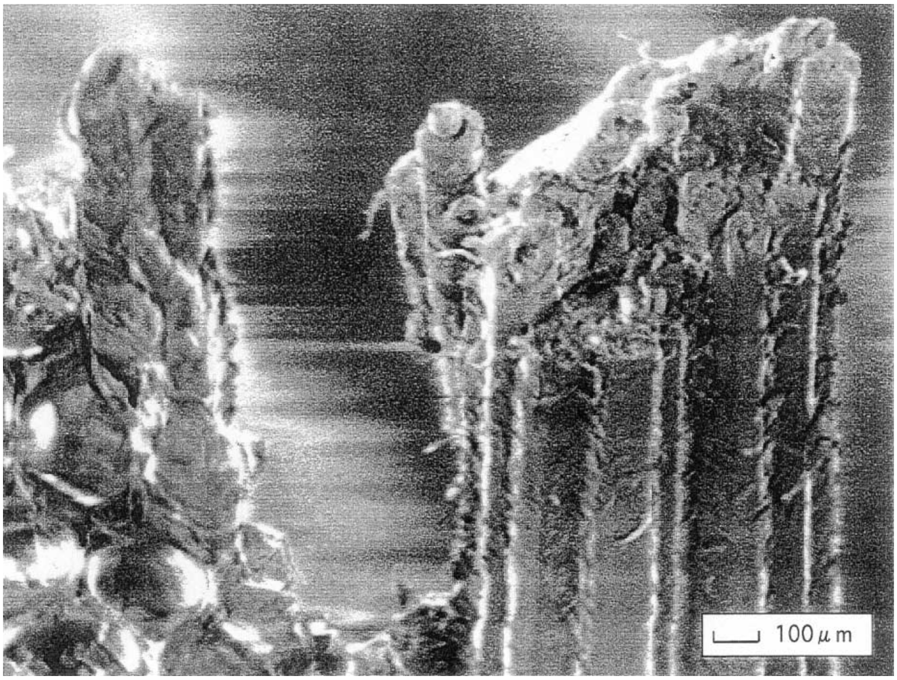


Fig. 14. SEM photograph of fractured fiber bundle.

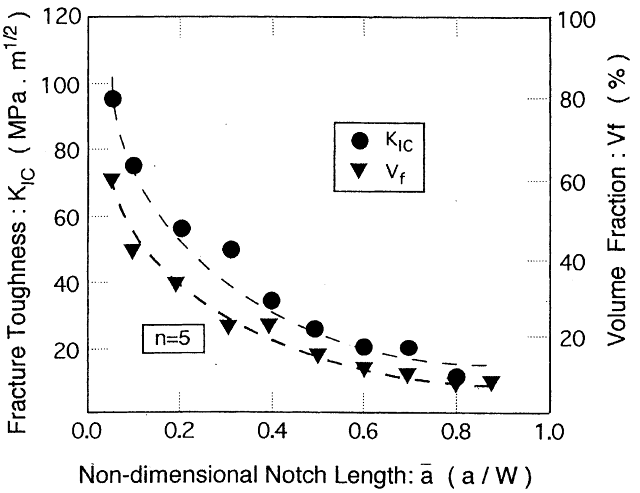


Fig. 15. Fracture toughness with radius for $n = 5$.

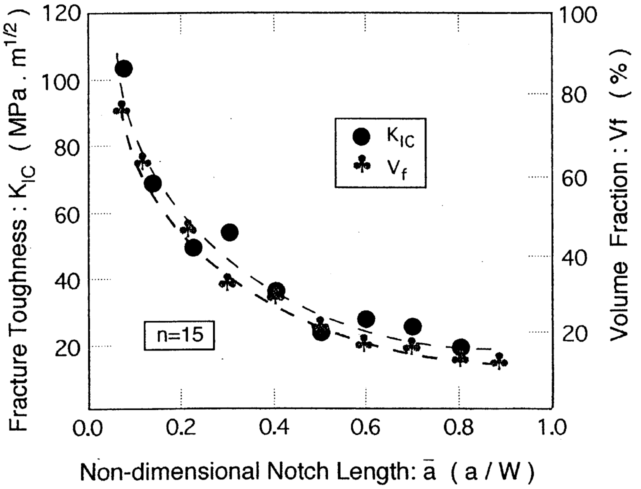


Fig. 16. Fracture toughness with radius for $n = 15$.

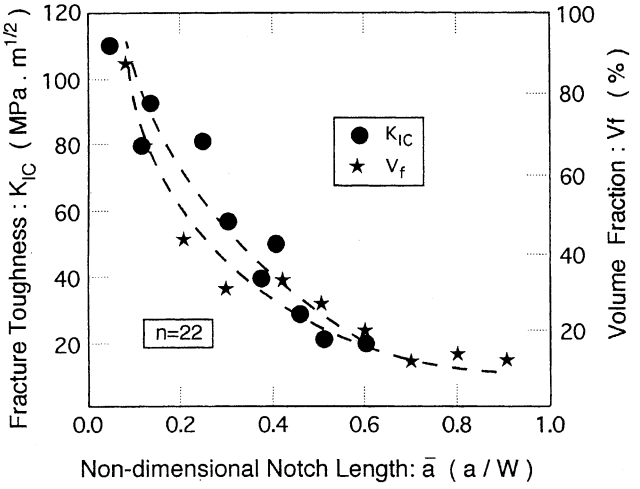


Fig. 17. Fracture toughness with radius for $n = 22$.

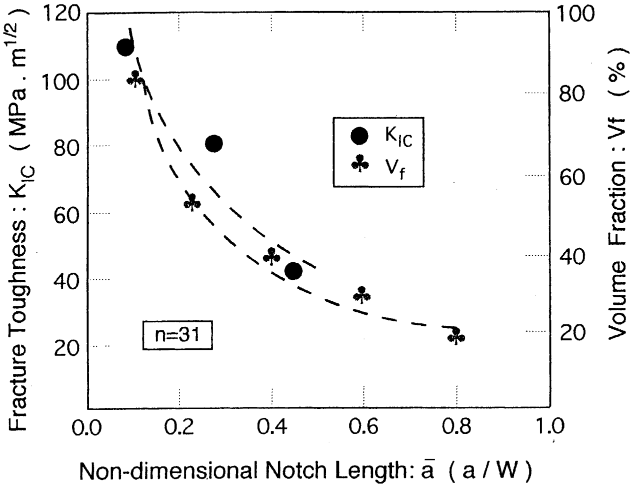


Fig. 18. Fracture toughness with radius for $n = 31$.

number $n = 31$ is located at the upper part of the bamboo, only three specimens could be made due to the small diameter and thickness of the culm. Even so, the distribution of $K_{IC}$is similar to that of other culm numbers.

From these results, it was concluded that the fracture toughness is proportional to the volume fraction of fibers and forms a functionally graded structure in the culm cross-section. Let $K_{IC,max}$ and $K_{IC,AV}$ be the maximum value of K_{IC}, which is obtained at the outer surface layer, and the average value in radius, respectively. Both $K_{IC,max}$ and $K_{IC,AV}$ are plotted in Fig. 19 with respect to culm number n. Both $K_{IC,max}$ and $K_{IC,AV}$ slightly increase with n.

It was concluded that bamboo provides a higher fracture toughness at the culm surface where external force is subjected and fracture is expected to occur easily. Bamboo has great resistance to an impact load on its outer surface layer.

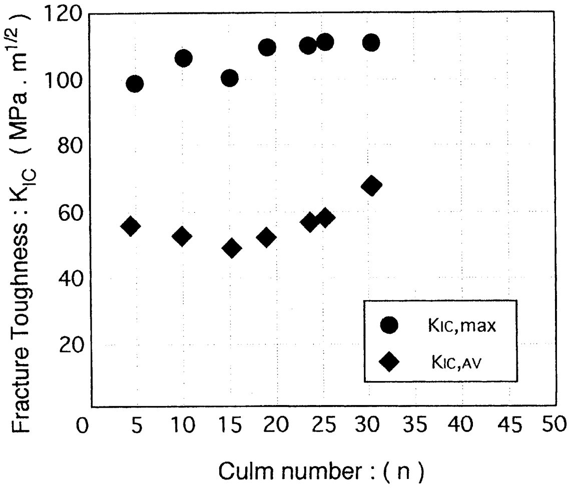


Fig. 19. Fracture toughness with culm number.

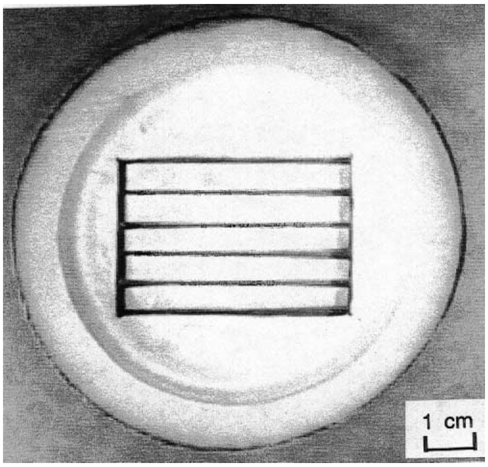


Fig. 20. Specimen positions in node.

5.2. Nodes

The bamboo culm is reinforced by fibers along its axis, but fibers run almost randomly in the nodes. It is expected that the fracture property is different from that of culm. The node $n = 5$, with a flat disc part, provides several specimens as shown in Fig. 20. The tensile tests give an average fracture toughness of 18.4 MPa m$^{1/2}$,which is lower than the minimum value of the bamboo culm. Carefully observing the cross-section and side surface shown in Fig. 21, there are quite a few fibers which are weakly reinforced at the nodes and are randomly directed. Fig. 22 shows the fracture surface where the holes pulled out the fibers can be seen. These features suggest that fibers made no contribution to the fracture resistance of the nodes. So this value is close to the K_{IC} value of the parenchyma.

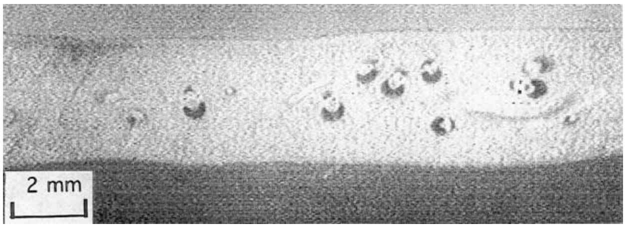


Fig. 21. Side and cross-section surfaces of specimen.

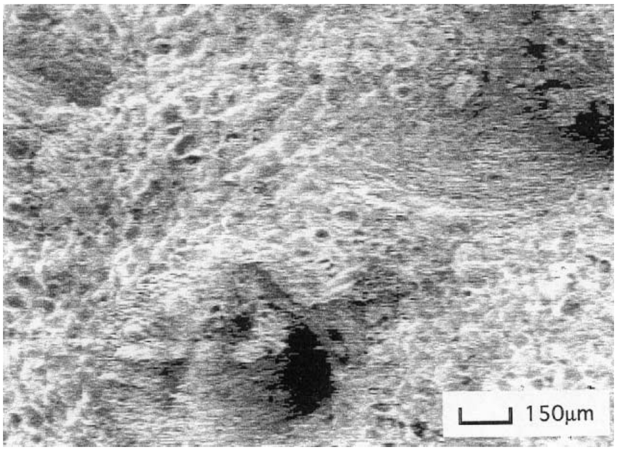


Fig. 22. SEM photograph of fractured surface of node specimen.

Table 2
Measured fracture toughness of bamboo

Materials	K_{IC} (MPa m$^{1/2}$)
Bamboo: culm (maximum value)	116.2
Bamboo: culm (average value)	56.8
Bamboo: node	18.4
Steel	217
Al-Alloy	33
Douglass fir	1.64
Spruce	7.0

Summarizing the results, the obtained fracture toughness, $K_{IC,max}$ and $K_{IC,AV}$, are listed in Table 2 where the values of other woods and typical metals are also given. The K_{IC} value of bamboo is not as high as that of steel, but is higher than that of Al-alloy. Also, it has a considerably higher fracture toughness than other woods.

6. Conclusions

In order to evaluate fracture toughness of the culm of the bamboo specimens, a so-called LR-type specimen was provided, by inserting a crack perpendicular to the fibers from the outer surface. Tensile tests were carried out and the following results were obtained.

1. Fracture toughness K_{IC} of the bamboo culm has a high value in the outer surface layer and decreases towards the inner surface. It forms a functionally graded structure as well as the volume fraction of fibers, Young's modulus and tensile strength with radius. These results suggests that bamboo provides a higher fracture toughness on the outer surface, where the most dangerous and external force is exerted.
2. The distribution of K_{IC} with radius agrees well with that of the volume fraction V_f of the fibers. This means that the fracture toughness is proportional to V_f.
3. The fracture toughness, $K_{IC,max}$ in the outer surface layer and $K_{IC,AV}$, increase slightly with height.
4. The average value of fracture toughness $K_{IC,AV}$ becomes about 56.8 MPa m$^{1/2}$, which is higher than that of the Al-alloy and far higher than that of other woods.
5. The fracture toughness of the bamboo nodes is about 18.4 Mpa m$^{1/2}$, which is lower than that of bamboo culm in the inner surface layer.

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