Macroscopic and Microscopic Gradient Structures of Bamboo Culms

Suwat SUTNAUN[1], Siripong SRISUWAN[1], Patcharin JINDASAI[1], Banyat CHERDCHIM[2], Nirundorn MATAN[3], Buhnnum KYOKONG[3]

Visiting High School Students from Princess Chulabhon College Nakhon Si Thammarat[1],Nakhon Si Thammarat 80160, Thailand.
Center for Scientific and Technological Equipments[2]
School of Engineering and Resources[3]
Walailak University, Thasala, Nakhon Si Thammarat 80160, Thailand.

ABSTRACT

This work studied the structure of bamboo culms which is naturally designed to retard the bending stress caused by a wind load. A macroscopic gradient structure (diameter, thickness and internodal length) and a microscopic one (distribution of fiber) of three sympodial bamboo species i.e. Tong bamboo (*Dendrocalamus asper* Backer.), Pah bamboo (*Gigantochloa bambos*) and Pak bamboo (*Gigantochloa hasskarliana*) were examined. From the macroscopic point of view, the wind-load generated bending stress for the tapered hollow tube of bamboo was found to vary uniformly with height, especially at the middle of the culms. Furthermore, the macroscopic shape of bamboo culm is about 2-6 times stiffer in bending mode than one with a solid circular section for the same amount of wood material. Microscopically, the distribution of fiber in the radial direction linearly decreases from the outer surface to the inner surface in the same manner as that of the distribution of the bending stress in the radial direction. Distribution of fiber along the vertical length of bamboos at each height is proportional to the level of bending stress generated by the wind load. Both macroscopic and microscopic gradient structures of sympodial type bamboos were found to be less effective to retard the bending stress than those of monopodial type bamboo.

Key words: Bamboo - Volume fraction of fiber - Bending stress - Gradient structure

INTRODUCTION

Natural design is a continuous refined mechanism over time through a process of natural selection to get the best structure optimized with a particular surrounding environment. Bamboo culm is one example of the naturally designed functional gradient structure to withstand environmental loads especially a wind load. The bamboo culm, cylindrical and hollow, is divided at intervals by nodes. The culm is comprised of exodermis (bark which is heavily overlaid with a waxy covering called cutin to prevent loss of water from the culms), parenchyma cells, vascular bundles and endodermis (inner surface layer). The vascular bundle is made up of vessels (transporting water), sieve tubes (transporting nutrition) and thick-walled fibers (1). The amount and the distribution of the fibers, having comparable mechanical strength with steel (2), determine the overall strength of bamboo culms. Amada et al (2) reported that the distribution of fibers in the monopodial type bamboo decreases in the radial direction from the outer surface to the inner surface in a nonlinear fashion. To the best of our knowledge, there has been no report on the distribution of fibers in the sympodial type bamboo, usually grown in tropical countries such as Thailand. It is the main objective of this work to examine in detail, both macroscopic and microscopic structures of sympodial type bamboo, to gain more understanding on the natural design of bamboos of the sympodial type in comparison with the monopodial one.

MATERIALS AND METHODS

Three species of tropical bamboos, Tong bamboo (*Dendrocalamus asper* Backer.), Pah bamboo (*Gigantochloa bambos*) and Pak bamboo (*Gigantochloa hasskarliana*), cut from Thasala district, Nakon Si Thammarat province, were chosen for this study. The macroscopic structure of bamboo culms was examined by measuring the external diameter (D), wall thickness (t) and internodal length (L) as a function of height from the ground (z) according to the coordinate shown in **Figure 1**. Optical microscopy and Scanning electron microscopy (SEM) were used to examine the microscopic structure of bamboo culms. Quantitative examination of fiber distribution was carried out using a Nikon ME600 optical microscope. Digital image micrographs were taken with a magnification of 50 using 1024×1024 pixels, thus achieving a resolution of ~20 μm per pixel. Typically three micrographs were taken at a particular position. Image analysis was carried out using a technique adapted from that reported elsewhere (2). The digital images were imported into a commercial software package *Mathematica*©. Each image was then transformed into the binary image of black and white pixels as shown in **Figure 2c** to separate the fibers from the matrix of parenchyma cells and the vessels. To ensure that the black pixels in the binary image truly represented the fibers, the vessels, appeared dark in the digital image, were first painted with the white pixels **(Figure 2a and 2b)**. The volume fraction of fiber was measured as a ratio of the number of the black pixels representing the fiber to the total number of pixels.

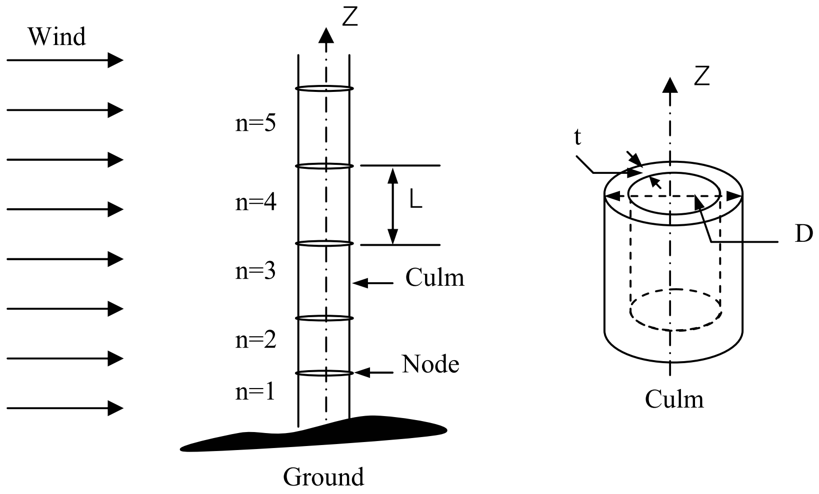


Figure 1. Schematic diagram showing configuration and defined macroscopic parameters of bamboo culms.

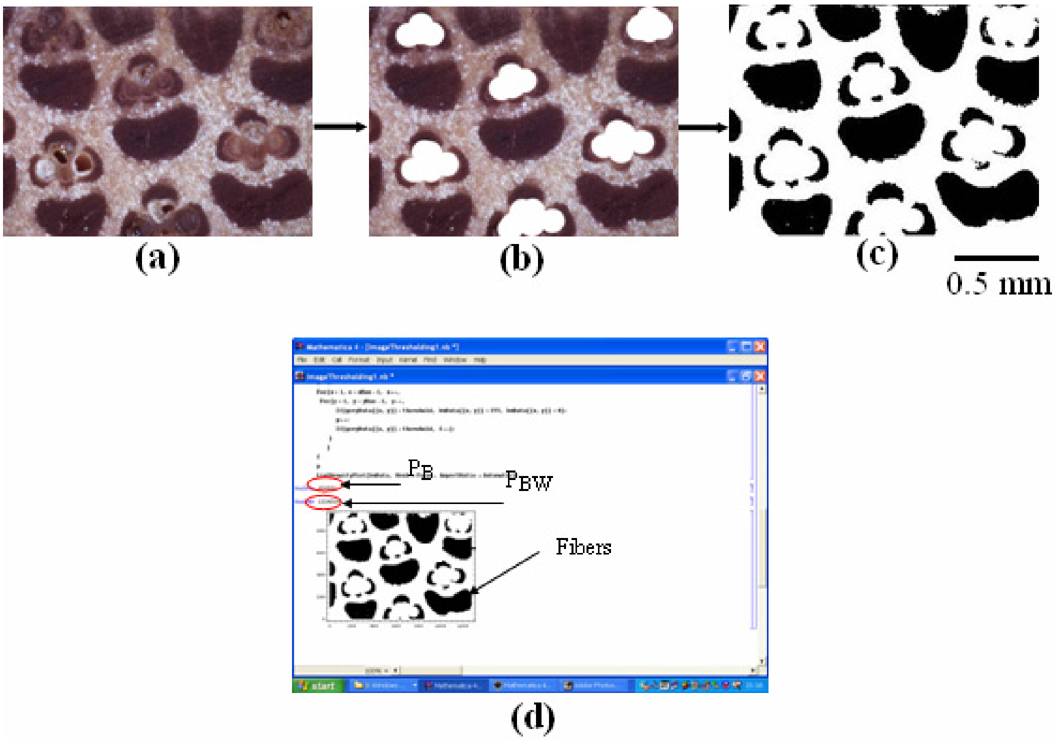
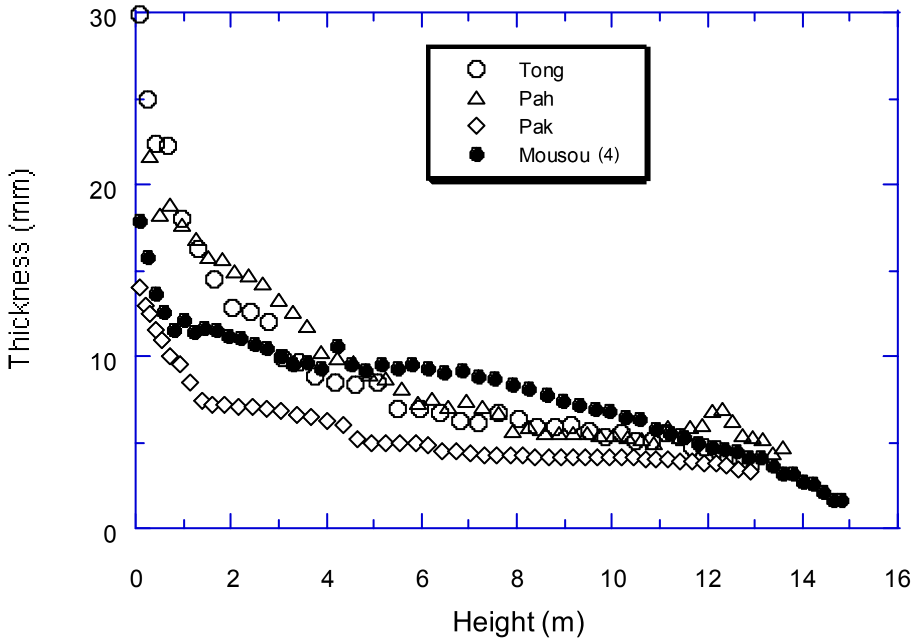
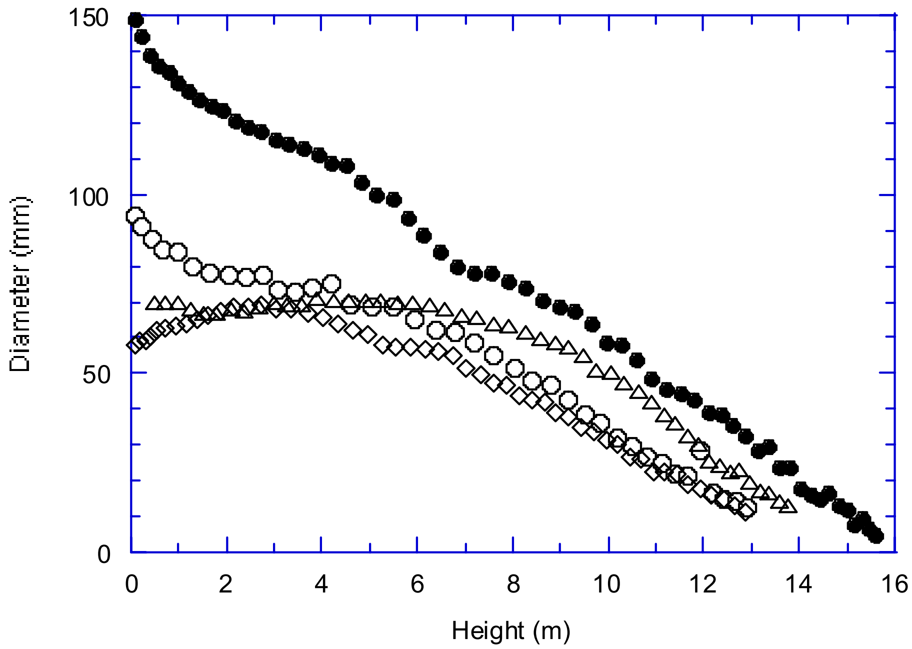


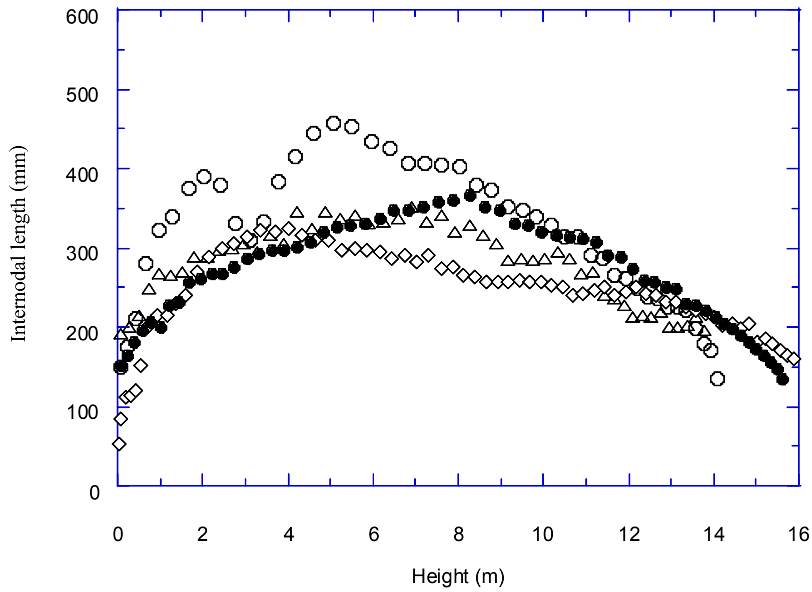
Figure 2. Determination of volume fraction of fiber: (a) typical digital optical micrograph, (b) digital image after painting vessel area with the white pixels, (c) binary image with the black pixels representing the fibers, and (d) calculation of the volume fraction of fiber using the *Mathematica* software (P_B is number of black pixels and P_{BW} is number of total pixels).


Tong
Pah
Pak
Mousou (4)
Thickness (mm)
Height (m)
0
10
20
30
0
2
4
6
8
10
12
14
16

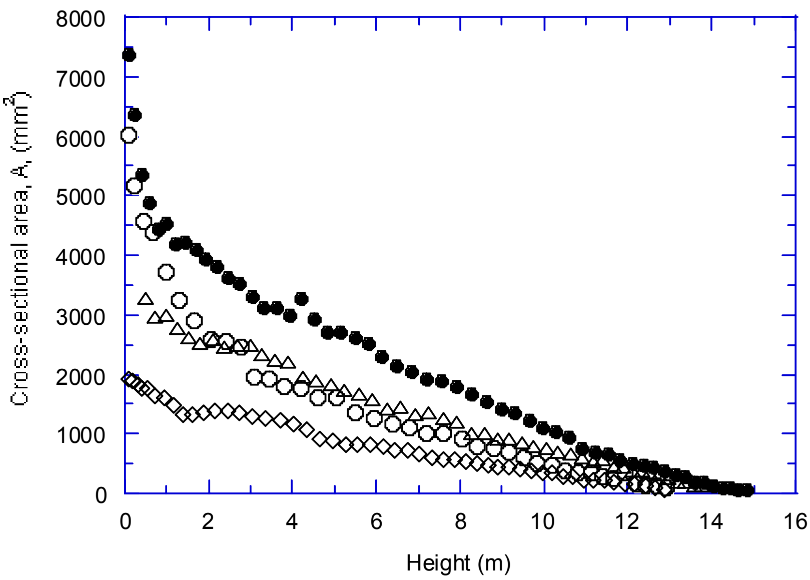
(a)


Diameter (mm)
Height (m)
0
50
100
150
0
2
4
6
8
10
12
14
16

(b)



(c)



(d)

Figure 3. Variations of macroscopic parameters (a) thickness, (b) diameter, (c) internodel length and (d) cross-sectional area along the height of bamboo culms for three bamboo species. Those values reported for Mousou-bamboo (*Phyllostachys edulis* Riv.) (Amada and Untao, (4)) are also shown for comparison.

RESULTS AND DISCUSSION

Macroscopic Structures

Macroscopic shapes of bamboos i.e. diameter, *D*, wall thickness, *t*, internodal length, *L*, and cross-sectional area, *A*, are plotted with respect to height in **Figure 3**. Diameter, thickness and cross-sectional area of bamboos considered were found to gradually decrease with height. This particular pattern forms the macroscopic gradient structure which leads to the increase in bending resistance against the wind load. An internodal length of bamboos reaches its maximum value at the length about 1/3 of the total height measured from the ground. Mousou bamboo, which is monopodial, is larger in diameter and cross-sectional area than the sympodial type bamboos considered here but is smaller in thickness, especially at the bottom half of the culm **(Figure 3a)**.

The second moment of area, *I*, about the axis of bending (the z axis) of a tubular section is given by

$$I_{zz} = \frac{\pi}{32}\left[D^4 - (D-2t)^4\right] \quad [1]$$

The section modulus *Z* is also given by

$$Z = \frac{\pi}{32}\frac{\left[D^4 - (D-2t)^4\right]}{D} \quad [2]$$

Figures 4a and 4b show the plots of the calculated second moment of area I_{zz} and the calculated section modulus *Z* of bamboo culms along the bamboo height, respectively. Both values of the second moment of area and the section modulus gradually decrease from the bottom to the top. Mousou bamboo, monopodial type bamboo, has very high values of the second moment of area and the section modulus with respect to those of sympodial type bamboos, especially at the bottom end.

The bamboos are mainly subjected to wind loads which can be assumed to be uniform over the entire length **(Figure 1)**. The corresponding bending moment, M is given by

$$M = \frac{p}{2}\left(1 - \frac{h}{H}\right)^2 \quad [3]$$

where *p* is the load caused by the wind, *h* is the height and *H* is the total height of the bamboo culm. The surface stress, $\sigma_{surface}$, due to bending at a particular height could then be calculated using

$$\sigma_{surface} = \frac{M}{Z} \quad [4]$$

A ratio of the generated surface stress $\sigma_{surface}$ to the applied wind load *p* can therefore be represented as

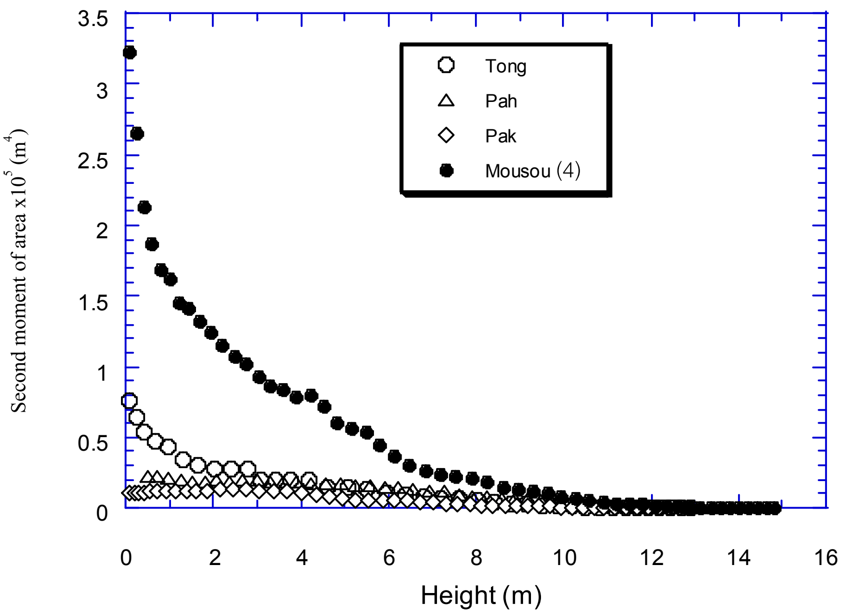
$$\frac{\sigma_{surface}}{p} = \frac{1}{2Z}\left(1 - \frac{h}{H}\right)^2 \quad [5]$$

The structural efficiency of the macroscopic shape of bamboo culms to withstand the wind load can be compared among various types of bamboos using the above ratio $\sigma_{surface}/p$. The $\sigma_{surface}/p$ ratio is plotted against the height of bamboo in **Figure 4c**. Stress generated at the surface per unit load of Tong bamboo is almost constant along the height which is similar to that of Mousou bamboo. Surface stress generated per unit load in Pah and Pak bamboos are very high at the bottom end and gradually decrease to the top. This means that for a given wind load, the bottom end of Pah and Pak bamboos will experience very high stress which may lead to permanent deformation or failure. This may be the reason why Pah and Pak bamboos are sympodial type bamboos. For Mousou bamboo, macroscopic shape is very efficient to withstand the wind load. Generated surface stress caused by wind load is very low and constant for almost an entire length. Tong, although a sympodial type bamboo, has similar surface stress profile along the height to that of Mousou bamboo. The value of the surface stress per unit load of Tong is, however, higher than that of Mousou bamboo.

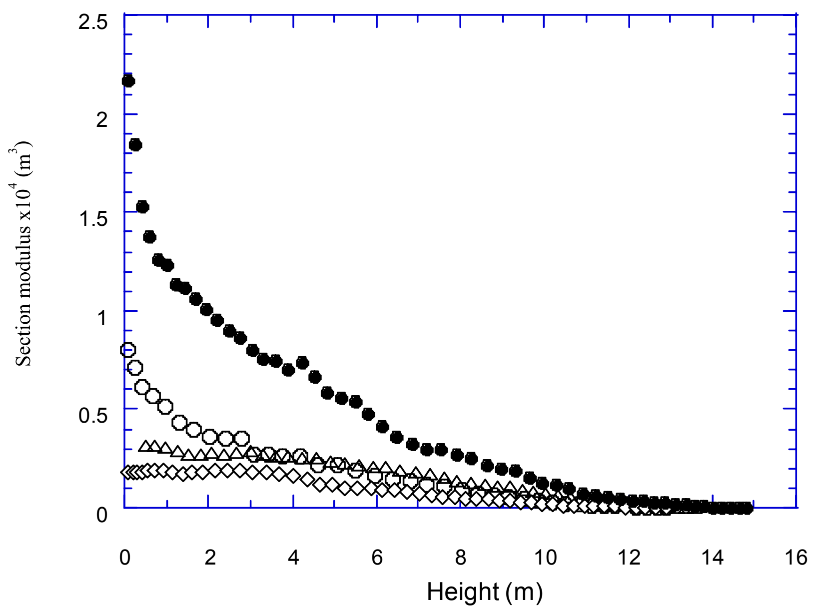
The efficiency of materials used to produce bending resistance can be characterized using a shape factor proposed by Ashby (3). The shape factor is defined so that it is equal to 1 for a solid bar with circular cross-section. The shape factor for elastic bending of tubular section, ϕ^e_B, is expressed by

$$\phi^e_B = \frac{r}{t} = \frac{D-t}{2t} \qquad [6]$$

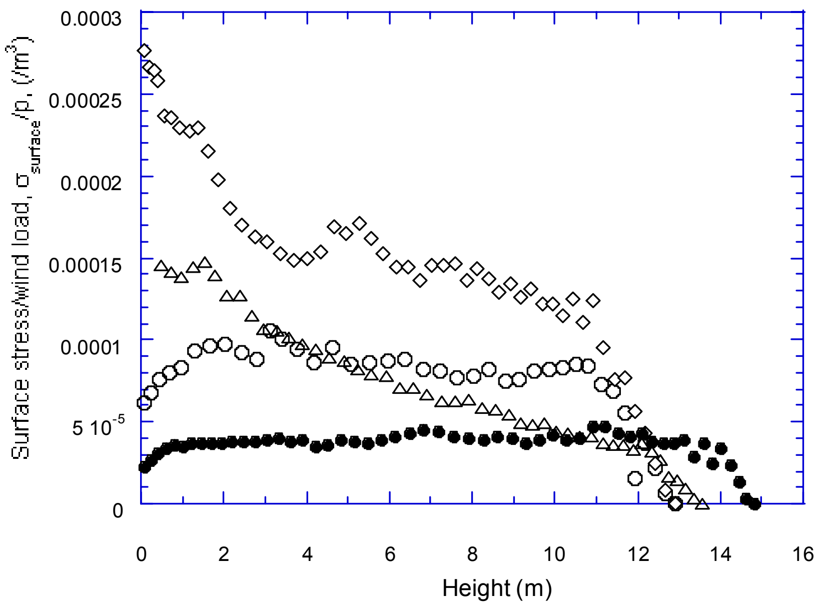
Figure 4d shows the variations of shape factors in elastic bending mode along the height of bamboos considered. The shape factor of Mousou bamboo is fairly constant at about 4-6 along the height. This indicates that the Mousou bamboo culm is about 4-6 times stiffer in the mode of bending than one with a solid circular section for the same cross-section area. The values of the shape factor of all sympodial type bamboos considered here increase from the value of about 2 at the bottom end to the value about 5-6 at the middle of the culm and then decrease to the value of 2 up to the top.



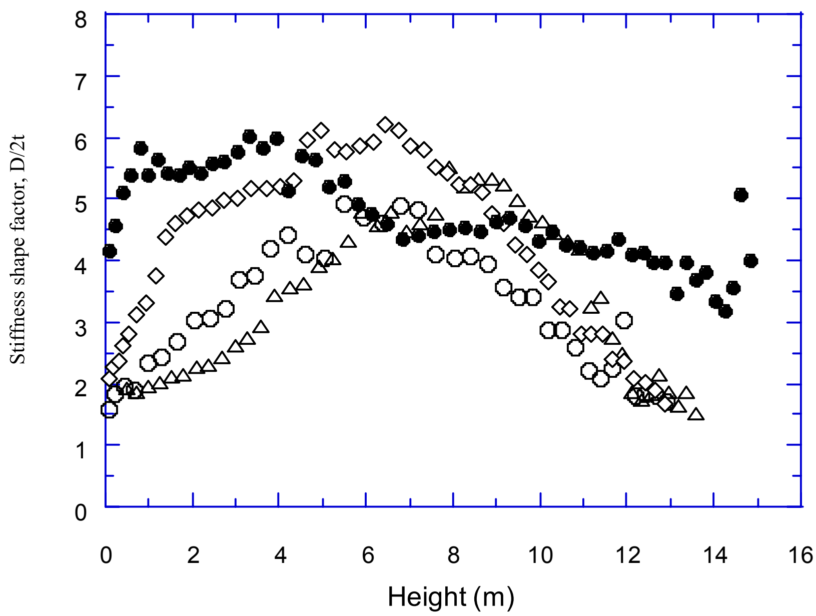
(a)


Section modulus x10^4 (m^3)
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
Height (m)

(b)


Surface stress/wind load, σsurface/p, (/m^3)
0.0003
0.00025
0.0002
0.00015
0.0001
5 10^-5
0
0
2
4
6
8
10
12
14
16
Height (m)

(c)



(d)

Figure 4. Variations of bending parameters (a) second moment of area, I_{zz}, (b) section modulus, Z, (c) generated surface stress per unit load, $\sigma_{surface}/p$, and (d) shape factor in elastic bending mode ϕ^{e}_{B} along the height of bamboo culms for three bamboo species. Those values reported for Mousou-bamboo (*Phyllostachys edulis* Riv.) (Amada and Untao, (4)) are also shown for comparison.

Microscopic Structures

The bamboo culm is comprised of exodermis (outer surface layer), parenchyma cells, vascular bundles and endodermis (inner surface layer). The vascular bundle is made up of vessels (transporting water), sieve tubes (transporting nutrition) and fibers **(Figure 5)**. The bamboo culm can be considered to be a composite material comprising high strength and rigid fibers embedded within the low strength but more ductile parenchyma matrix. Mechanical properties of bamboo culm therefore relate very strongly to volume fraction of the fiber (and volume fraction of the matrix). As can be seen from **Figures 5a and 5b**, the amount of fibers gradually decreases from the outer surface to the inner surface. This configuration forms a gradient structure on the microscopic level. Typical distribution of fibers in Tong bamboo is shown in **Figure 6**. The volume fraction of fiber of Tong bamboo decreases from about 60% to about 20% from the outer surface to the inner surface at the internode number. Distribution of fiber can be best represented by plotting fibers volume fraction against a non-dimensional distance from the outer surface, *R* defined as

$$R = \frac{r_o - r}{r_o - r_i} \qquad [7]$$

where r is the radius, r_o and r_i are the radius of the outer and inner surfaces, respectively. It should be noted that $R=0$ at the outer surface and $R=1$ at the inner surface. As a result, distribution of fibers from the outer to the inner surfaces at various internodes of all bamboos considered can be compared. **Figures 7a-d** show the distributions of fibers in Tong, Pah, Pak and Mousou bamboos, respectively. Interestingly, distribution of fibers from the outer to the inner surfaces of all internodes in each type bamboo seems in fall into a single master curve. This implies that in each type of bamboo, distributions of fibers from the outer to the inner surfaces of all internodes, i.e. despite having different thicknesses, follow the same form of function. The distribution is a linear function for the tropical bamboos considered, Tong, Pah and Pak. The equations obtained by linear curve fitting to measured data are also shown in the plots in **Figure 7a-c**. The distribution is nonlinear in Mousou bamboo. Approximately, the volume fraction of fibers decreases exponentially from the outer to the inner surface. The fitted equation is also shown in **Figure 7d**. It should also be noted that volume fraction of fiber in all tropical bamboos considered decreases linearly from about 60% at the outer surface to about 20% at the inner surface whereas that in Mousou bamboo logarithmically decreases from about 80% at the outer surface to about 10% at the inner surface. Natural design of Mousou bamboo, which is monopodial type bamboo, is to strengthen the outer surface whereas that of tropical bamboo, which is sympodial type bamboo, is to reduce strength at the outer surface but to strengthen more within the culms. Average volume fractions of fiber within all internodes were also calculated. **Figure 8** shows a plot of average volume fractions of fiber against heights of all bamboo species considered. On average, the distribution of fiber correlates with the stress generated within the culms at each height. The higher average volume fraction of fiber is to compensate for the less effectiveness in macroscopic shape which experiences higher level of stress. For example average volume fraction of Pak bamboo is highest at the bottom end and gradually decreases along the height of the culms that corresponds very well with the distribution of generated surface stress/wind load along its height **(Figure 4c)**. Indeed, average volume fraction and calculated surface stress/wind load follow a linear relationship as shown in **Figure 9**. This is another smart structure of bamboo. Fibers are distributed in such a way to strengthen the culms against bending stress caused by wind load. Slope differences in **Figure 9** amongst bamboo species might be a result of the different mechanical strength of bamboo fibers of various species. This warrants further study on the mechanical properties of bamboo culms.

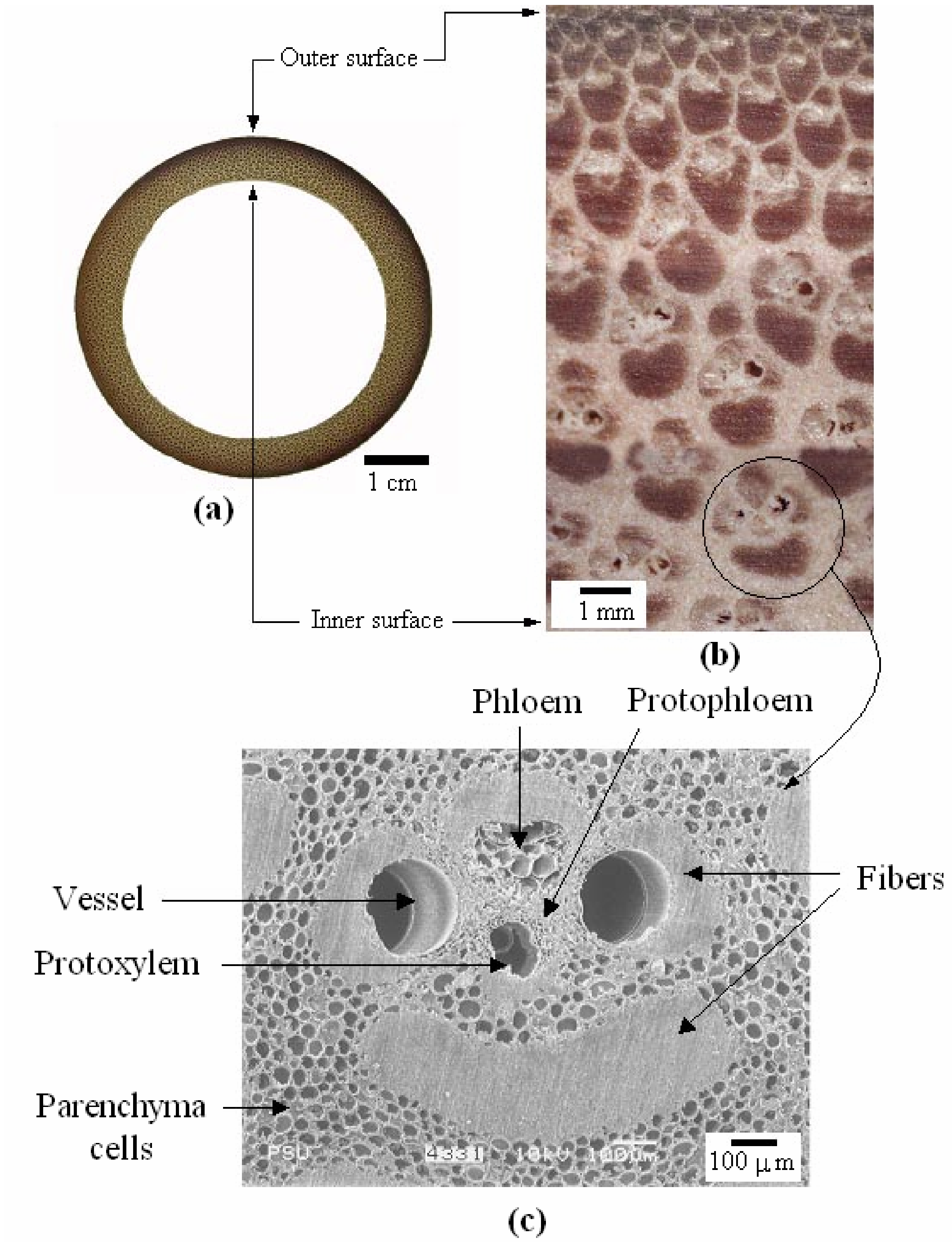


Figure 5. Microstructure of Tong bamboo (a) Photograph showing culm circular cross-section, (b) Optical micrograph showing distribution of vascular bundles from the outer to the inner surface, and (c) SEM micrograph showing parenchyma cells and vascular bundle which consists of vessels, phloem and fiber.

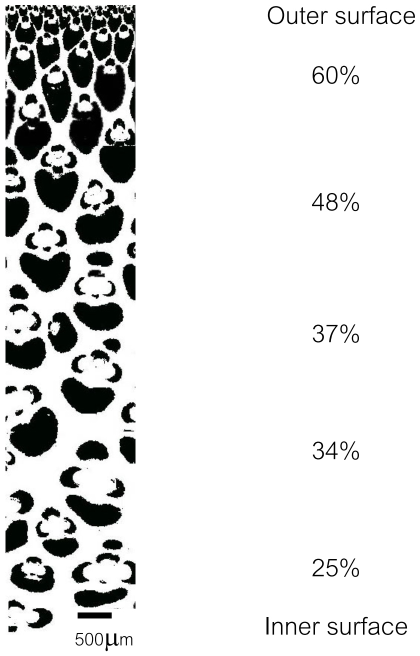
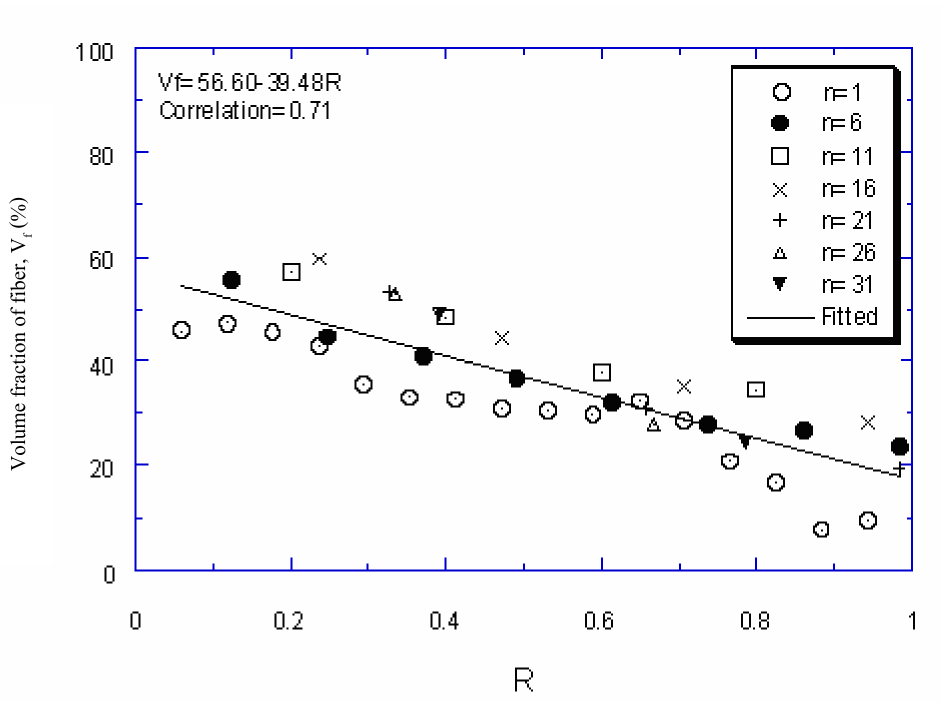
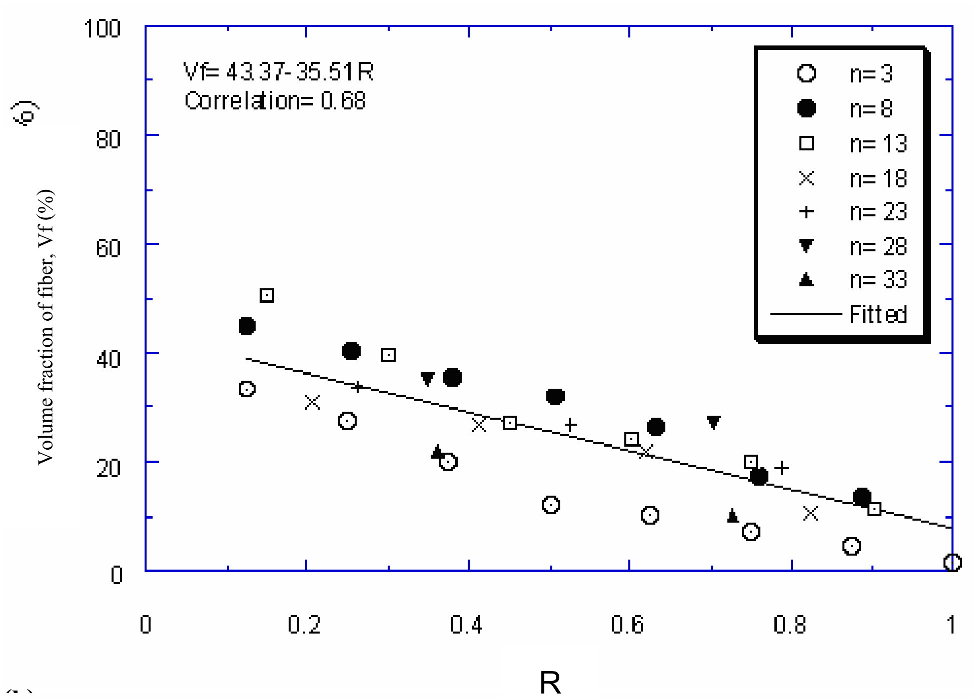
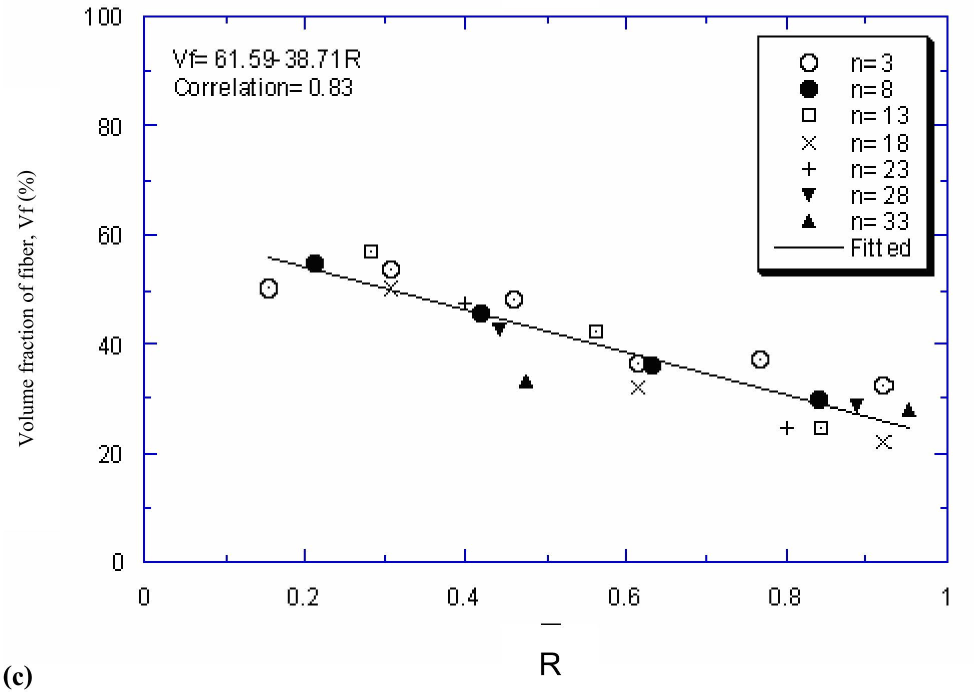


Figure 6. Distribution of fiber from the outer surface to the inner surface of Tong bamboo at the 11th internode.

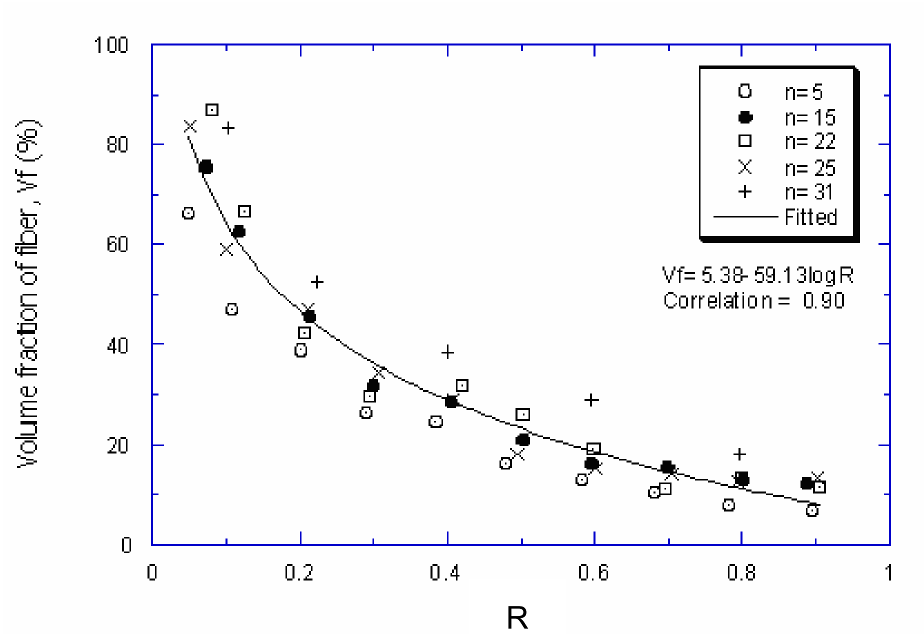


(a)


Vf= 43.37-35.51R
Correlation= 0.68
n=3
n=8
n=13
n=18
n=23
n=28
n=33
Fitted
Volume fraction of fiber, Vf (%)
R


Vf= 61.59-38.71R
Correlation= 0.83
n=3
n=8
n=13
n=18
n=23
n=28
n=33
Fitted
Volume fraction of fiber, Vf (%)
R

(c)



(d)

Figure 7. Distributions of volume fraction of fiber from the outer to the inner surfaces of (a) Tong bamboo (*Dendrocalamus asper* Backer.), (b) Pah bamboo (*Gigantochloa bambos*), (c) Pak bamboo (*Gigantochloa hasskarliana*), and (d) Mousou-bamboo (*Phyllostachys edulis* Riv.) (Amada and Untao, (4)).

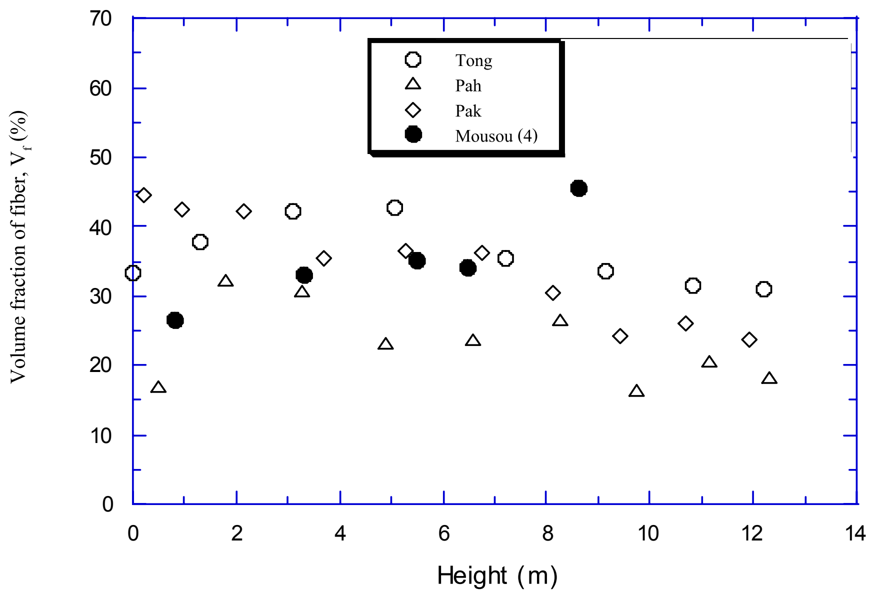


Figure 8. Plots of average volume fraction of fiber versus the height of various bamboo species.

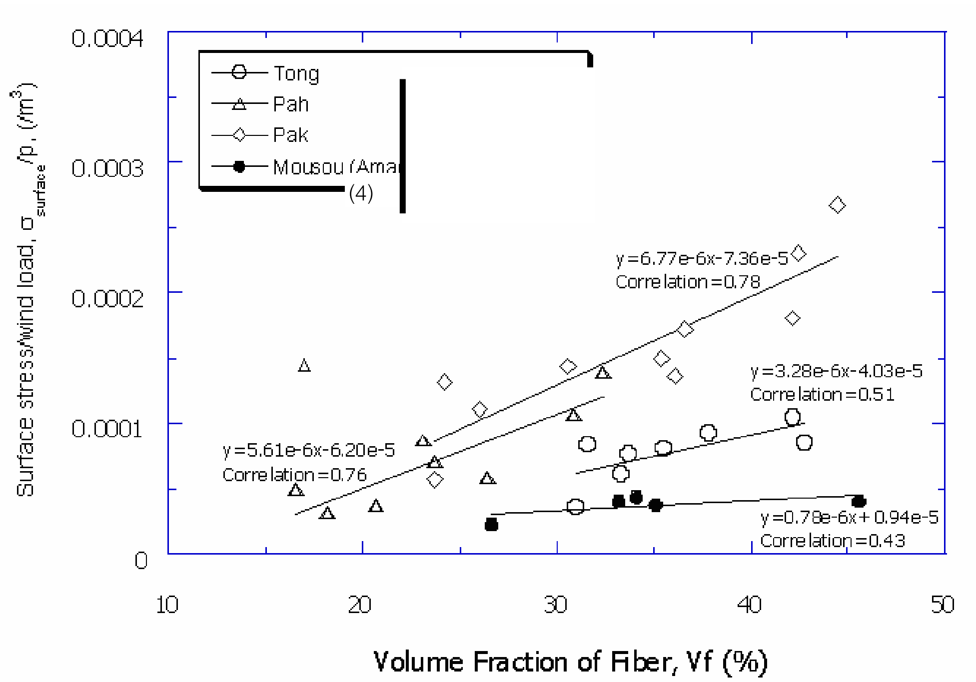


Figure 9. Plots of average volume fraction of fiber versus the ratio of surface stress/wind load of various bamboo species.

CONCLUSIONS

The following conclusions can be drawn from this work:

1. The tapered hollow tube of bamboo culm, is a smart macroscopic gradient structure in such a way that the generated bending stress, caused by the wind load, distributes uniformly along the height, especially at the middle part of the culms. The amount of bamboo wood material is effectively used to create a structure that withstands the bending stress caused by the wind load.
2. Distribution of fiber in the radial direction is a smart microscopic gradient structure in such a way that it decreases from the outer to the inner surfaces with respect to distance normalized by culms thickness, in the same manner as the distribution of generated bending stress in the radial direction.
3. Distribution of fiber along the height of bamboos is proportional to the level of bending stress generated by the wind load at each height.
4. Both macroscopic and microscopic gradient structures of sympodial type bamboos are less effective to withstand the wind load than those of monopodial type bamboo.

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บทคัดย่อ

สุวัฒ สุทธิ์นวล[1], ศิริพงษ์ ศรีสุวรรณ[1], พัชรินทร์ จินดาไส[1], บัญญัติ เฉิดฉิ้ม[2], นิรันดร มาแทน[3], บุญนำ เกี่ยวข้อง[3]
โครงสร้างลาดชันระดับมหภาคและระดับจุลภาคของลำไม้ไผ่

งานวิจัยนี้ศึกษาโครงสร้างของลำไม้ไผ่ซึ่งธรรมชาติได้ออกแบบไว้ให้สามารถต้านทานความเค้นอันเกิดจากแรงลม สิ่งที่ตรวจสอบคือโครงสร้างลาดชันระดับมหภาค (เส้นผ่าศูนย์กลาง ความหนา และความยาวปล้อง) และโครงสร้างลาดชันระดับจุลภาค (การกระจายตัวของไฟเบอร์) ของไม้ไผ่ชนิดเป็นกอสามชนิด ได้แก่ ไผ่ตง (*Dendrocalamus asper* Backer.) ไผ่ป่า (*Gigantochloa bambos*) และไผ่ผาก (*Gigantochloa hasskarliana*) จากการวิจัยระดับมหภาคพบว่าความเค้นอันเกิดจากแรงลมในไม้ไผ่ที่มีลักษณะเป็นท่อกลวงและมีเส้นผ่าศูนย์กลางของลำไผ่เล็กลงจากโคนลำสู่ปลายลำมีค่าสม่ำเสมอตามความสูงของลำไม้ไผ่ โดยเฉพาะอย่างยิ่งบริเวณกลางลำ นอกจากนี้โครงสร้างระดับมหภาคดังกล่าวมีค่าความแกร่งต่อความเค้นบิดคิดเป็น 2-6 เท่าของโครงสร้างที่มีรูปร่างเป็นทรงกลมตันในปริมาณเนื้อไม้ที่เท่ากัน ปริมาณของไฟเบอร์ซึ่งเป็นโครงสร้างระดับจุลภาคมีการกระจายตัวในแนวรัศมีลดลงแบบเป็นเชิงเส้นจากผิวด้านนอกสู่ผิวด้านในซึ่งเป็นไปในลักษณะเดียวกันกับการกระจายตัวของความเค้นบิดที่เกิดขึ้นในแนวรัศมี การกระจายตัวของปริมาณไฟเบอร์ในแนวดิ่งที่ระดับความสูงหนึ่ง ๆ ของไม้ไผ่มีค่าแปรผันตรงกับปริมาณความเค้นที่เกิดขึ้นจากแรงลม ทั้งโครงสร้างลาดชันระดับมหภาคและระดับจุลภาคของไม้ไผ่ชนิดเป็นกอมีประสิทธิภาพในการต้านทานแรงลมที่มากระทำด้อยกว่าโครงสร้างดังกล่าวในไม้ไผ่ที่มีลักษณะเป็นต้นเดี่ยว

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[1] นักเรียนภาคฤดูร้อน โรงเรียนจุฬาภรณราชวิทยาลัย นครศรีธรรมราช อำเภอเมือง จังหวัดนครศรีธรรมราช 80000
[2] ศูนย์เครื่องมือวิทยาศาสตร์และเทคโนโลยี มหาวิทยาลัยวลัยลักษณ์ อำเภอท่าศาลา จังหวัดนครศรีธรรมราช 80160
[3] สำนักวิชาวิศวกรรมและทรัพยากร มหาวิทยาลัยวลัยลักษณ์ อำเภอท่าศาลา จังหวัดนครศรีธรรมราช 80160