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INTERNAL STRESS GENERATION IN RATTAN CANES

by

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SUMMARY

Internal stress development was investigated in rattan canes (*Calamus merrillii* Becc.) following the procedures used in trees. Measurements showed that longitudinal compressive stresses existed at the periphery while longitudinal tensile stresses existed at the core. Such stresses originated from the fibers. Fiber MFA was observed to be beyond 20° and the lignin content was above 30%. Considering its similarities to compression wood tracheids, it was assumed that the rattan fibers generated longitudinal compressive stress. The amount of stress varied from base to top and from periphery to core because of the variation in the proportion of fibers along these points. This is why the longitudinal compressive stress that was generated at the base was higher than at the top and high longitudinal compressive stress was developed at the periphery. As a response to this high peripheral stress, longitudinal tensile stress was induced at the core.

Key words: *Calamus merrillii* Becc., internal stress, released strain, lignin content, microfibril angle (MFA), fiber ratio.

INTRODUCTION

The presence of growth stresses within the tree trunk is a natural phenomenon for it is a part of the growth behavior of the tree. Stress provides rigidity to the trunk (Clark 1939; Wilson & Archer 1977) in order for the tree to resist the deleterious effect of external stresses, e.g., strong winds. Stresses are also produced to allow the tree to position itself to its desired vertical orientation. Furthermore, competition compels the tree to develop stress to reorient its crown for better sunlight exposure (Jacob as cited by Kubler 1987; Wilson & Archer 1977).

Some researchers have proposed that stresses are generated during growth and development of trees. Jacob as cited by Kubler (1987), suggested that stress originates at the cambial layer as the tree increases in diameter. As new sheaths of wood are developed, it tends to compress old sheaths, in turn, reducing the tensile stress in the former sheaths. Difference in tissue growth rate could also contribute to growth stress production (Burstrom 1979; Romberger et al. 1993; Mohr & Schopfen 1995). Tissues are composed basically of different types of cells that have the tendency to grow at different rates as they mature. Because these cells are firmly bonded by the cell walls, stresses are developed between adjacent cells.

Previous studies indicated that the production of stress was influenced by the microfibril angle of the fibers, the degree of crystallinity of the cells and the lignin content of the cell walls. Based on this observation, three hypotheses have been formulated; one hypothesis considers the influence of microfibril angle and lignin content (Lignin-swelling hypothesis), another takes into account the influence of microfibril angle and degree of crystallinity (Cellulose-tension hypothesis), and lastly, one hypothesis notes the influence of microfibril angle and the matrix component (Unified hypothesis). These hypotheses will be discussed later.

Indeed the studies of stress in trees have gone a long way, but for a monocot such as rattan, this information has yet to be obtained. In fact whether or not stresses exist within the cane has yet to be determined. If stresses do exist, this information will lead to a better understanding of the behavior of the cane when load is applied. With this in mind, this study aimed to detect the occurrence of growth stresses within the rattan canes and to determine its causes.

MATERIAL AND METHODS

Sample preparation

Palasan (*Calamus merrillii* Becc.), one of the commercially used rattan species in the Philippines was used in this study. This species has a diameter of 35–45 mm and a length of approximately 30 m. However, due to the difficulty in collection, only 11 m long samples were obtained. The canes were collected from Mt. Makiling, Los Baños, Laguna, Philippines. These samples were divided into three height levels; base (0.1 m from the ground), middle (5.5 m from the ground) and top (11 m from the ground). From these height levels, 40 cm long samples were taken. They were immediately soaked in water to prevent them from drying. The samples were transported to Nagoya University, Japan for study.

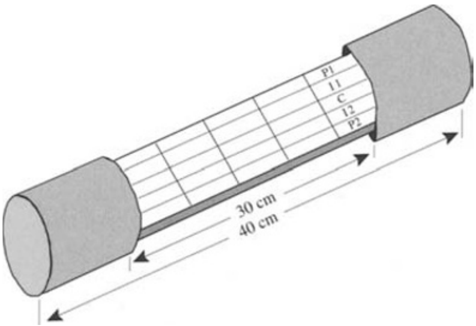


Fig. 1. Diametral flank.

From each height level, two samples were converted into diametral flanks (Fig. 1). One flank was used in the strain release measurements and the other for the longitudinal Young's modulus (E) measurements. On each of these flanks, five zones were delineated namely; peripheral 1, intermediate 1, core, intermediate 2, peripheral 2 (P1, I1, C, I2, P2). In each zone five replicates were made, generating a total of 25 sampling points in each flank. During preparation, the flanks were occasionally placed inside a refrigerator to prevent them from drying. Drying will result to the development of stress, thus, the samples were maintained in green condition as much as possible.

Stress measurement

Following the procedures done in trees, 4 mm strain gauges were attached on the radial surfaces of the individual sampling points of one of the flanks. To release the strain, a transverse cut was made near the tip and base of the strain gauges. The amount of strain released was measured by a strain meter.

On the other flank, 5 cm long strips were prepared from each sampling point. On the tangential surfaces of these strips, 8 mm strain gauges were attached. These strips were then mounted on a universal testing machine (UTM) and a tensile test was conducted. With the aid of a computer, the longitudinal Young's modulus (E) at green condition of the individual sampling points were measured.

Stress distributions were then computed using the formula: Stress = E × Strain

Anatomical properties

Fiber area percentage was examined along the transverse direction of the individual sampling point. For this purpose, 25–45 μm thick cross sections were prepared using a sliding microtome. These sections were stained with safranin and fast green and then mounted on a glass slide. With a Kontron Image Analyzer, the area occupied by the fibers within the cross section of the cane was measured. Five measurements were conducted on every sampling point.

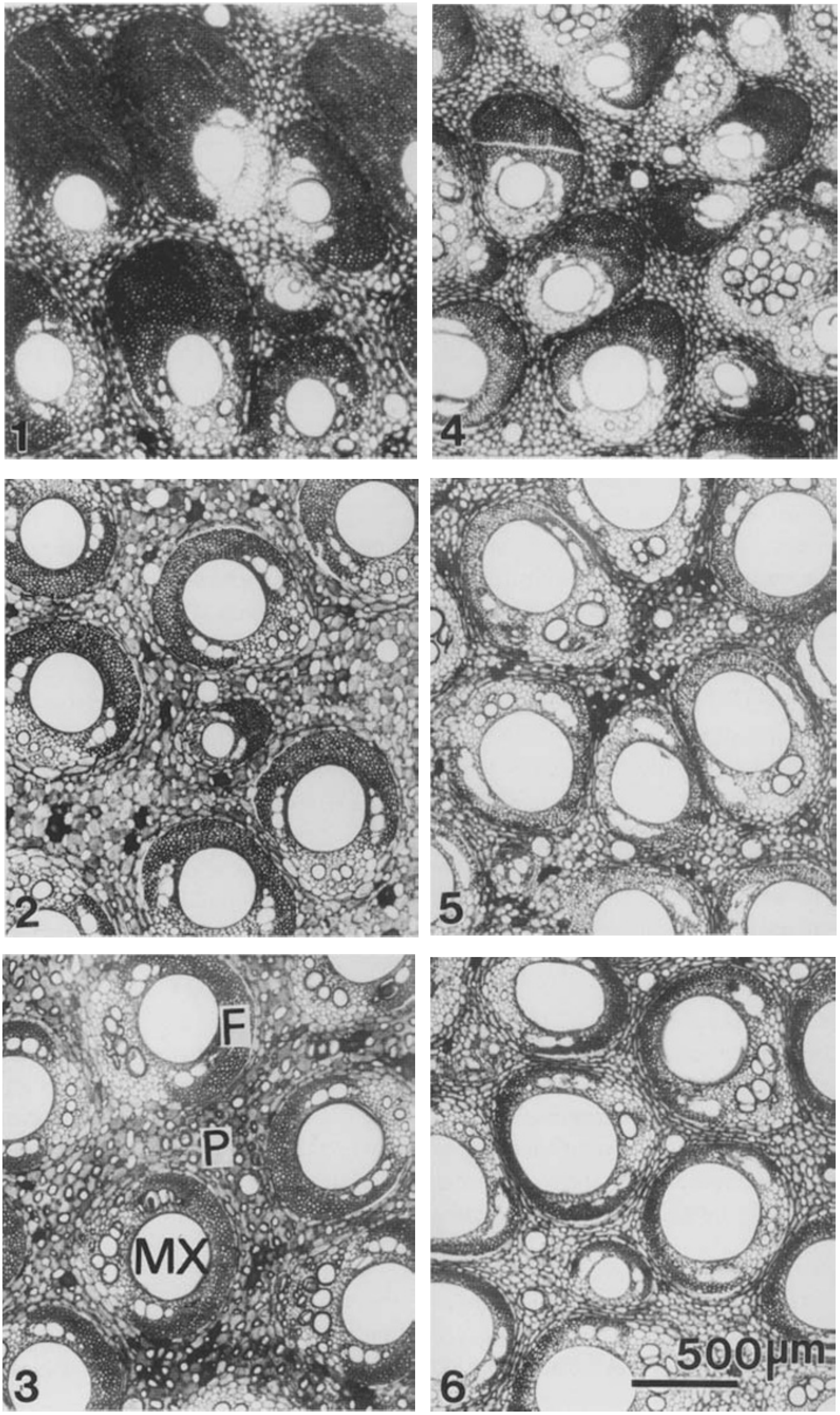
The microfibril angle (MFA) of the fiber surface as well as the average MFA of the individual fiber walls were also evaluated. The iodine staining technique as described by Meylan (1967) was performed for the former measurement while the X-ray diffraction technique as discussed by Cave (1966) was employed for the latter. For this purpose, tangential sections with a thickness of 35–45 μm and 100–120 μm, respectively, were prepared using a sliding microtome. On each sampling point, 35 measurements were conducted to assess the MFA of the fiber surface, and 5 measurements were performed to evaluate the MFA of the fiber walls.

Physical properties

From each sampling point, two small irregularly shaped samples were obtained. These samples were air dried and their densities were measured using the mercury technique. The average density of these two samples was taken and was considered as the density of that particular sampling point. With a Willey mill, 60–80 mesh powders were prepared. The degree of crystallinity of the individual zone was determined by adopting the X-ray diffraction technique. In every zone, four replicates were made.

Statistical analysis

Analysis of variance was conducted to assess the variation in properties along the length and across the diameter of the cane. For the former analysis, only the peripheral data were used, and for the latter, both data from the periphery and central cane area were analyzed.


1
4
2
5
F
P
MX
3
500 µm
6

Regression analysis was also performed to determine the influence of anatomy on the physical and mechanical properties of the cane, including its effect on the generation of stress within the cane.

RESULTS

Stress distribution

The periphery expanded while the core contracted in the longitudinal direction after the strain was released (Fig. 2). The influence of the height of the stem on the amount of released strain was not distinct in rattan as opposed to the observation of Yao (1979) and Chafe (1981) on several tree species.

Longitudinal Young's modulus decreased from periphery to core as well as from base to top (Fig. 3). This observation conforms with the findings of Bhat and Thulasidas (1992) and Kabir et al. (1994) on some Indian canes.

Results showed that longitudinal compressive stresses existed at the periphery and longitudinal tensile stresses existed at the core (Fig. 4). This is the exact opposite of the stress distribution in tree stems. In trees, longitudinal tensile stresses exist at the periphery while longitudinal compressive stresses exist at the core (Okuyama & Kikata 1975; Okuyama & Sasaki 1978; Sasaki et al. 1981; Okuyama 1993). In addition, the amount of stress at the base was observed to be higher than at the top.

Anatomical observations

The anatomy of the cane was similar to other *Calamus* sp. observed by Weiner and Liese (1992). It was characterized by vascular bundles with one metaxylem vessel and two phloem fields. Bundle diameters varied because of variation in metaxylem vessel diameter and number of fibers (Plate: 1–6). Analyzing the cross section of the cane with a Kontron image analyzer showed that the fiber proportion decreased from periphery to core and from base to top (Fig. 5). This distribution was in agreement with the observations of Bhat et al. (1990) on Indian canes and Siripatanadilok (1996) on Thailand canes.

The microfibril angle of the fiber increased from base to top and from periphery to core. The MFA of the fiber surface (Fig. 6) was more or less equal to the average MFA of the individual walls (Fig. 7). It ranged from 23° to 34°. Comparing this result with previous studies on *Calamus* sp., our findings were lower compared to the 40° MFA reported by other authors (Parameswaran & Liese 1985; Bhat et al. 1990; Bhat & Mathew 1995). These authors used a completely different method from the one employed in this report; thus, different values were obtained. Nevertheless, this further confirmed that the MFA of rattan fibers was higher than the MFA of the fibers in normal wood regardless of its position within the cane.

Plate: 1–6: Cross section of *Calamus merrillii* Becc. – 1–3. Basal portion; 4–6. Top portion. – 1 & 4: Peripheral section. – 2 & 5: Intermediate section. – 3 & 6: Core (F = fiber; P = parenchyma; MX = metaxylem). Vascular bundle diameter varied from periphery to core due to the change in metaxylem diameter and fiber number.

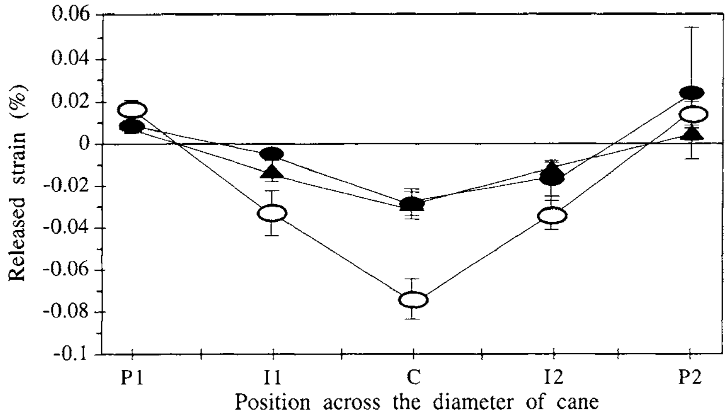


Fig. 2. Released strain distribution across the diameter of the cane. — ○ = base; ▲ = middle; ● = top; I = standard deviation.

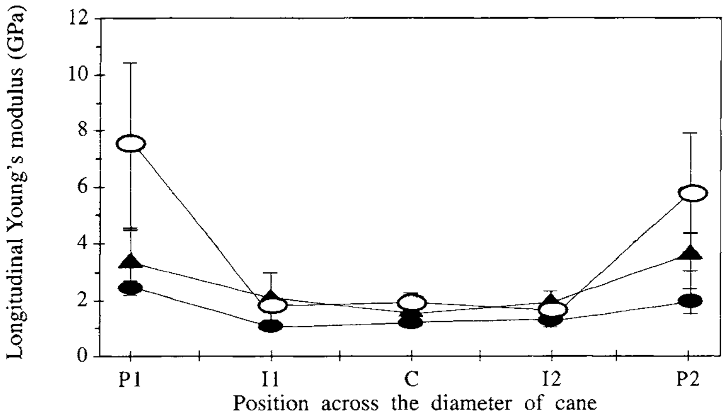


Fig. 3. Longitudinal Young's modulus across the diameter of the cane. — ○ = base; ▲ = middle; ● = top; I = standard deviation.

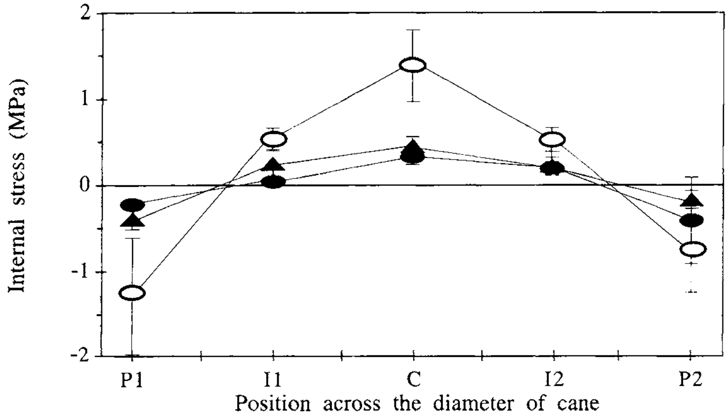


Fig. 4. Stress distribution across the diameter of the cane. — ○ = base; ▲ = middle; ● = top; I = standard deviation.

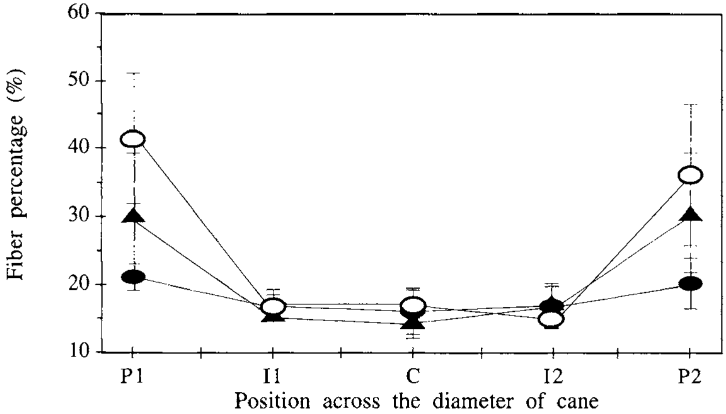


Fig. 5. Fiber percentage across the diameter of the cane. — ○ = base; ▲ = middle; ● = top; I = standard deviation.

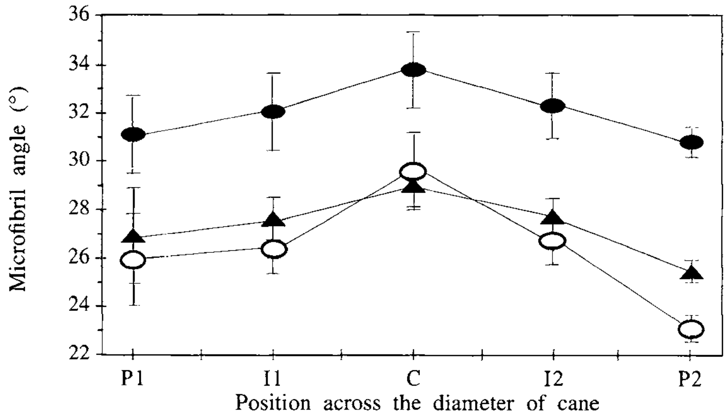


Fig. 6. Microfibril angle of fiber surface across the diameter of the cane. — ○ = base; ▲ = middle; ● = top; I = standard deviation.

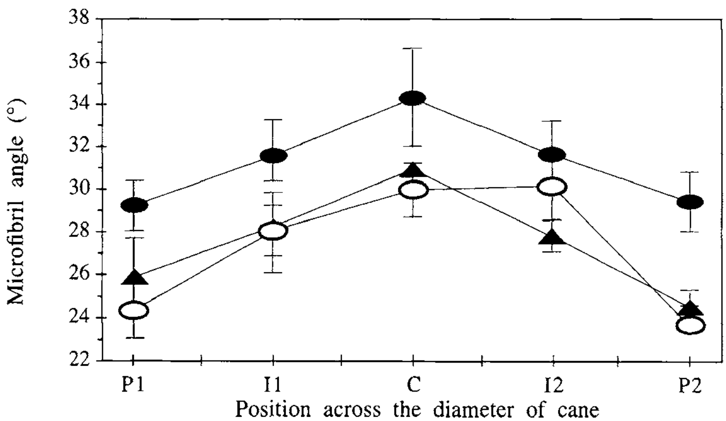


Fig. 7. Average microfibril angle of fiber walls across the diameter of the cane. — ○ = base; ▲ = middle; ● = top; I = standard deviation.

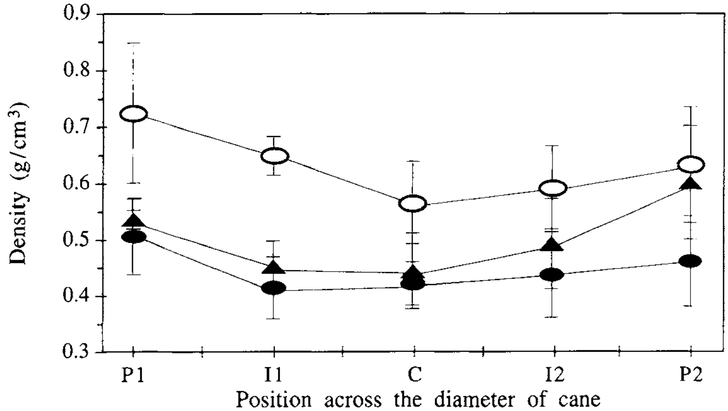


Fig. 8. Density distribution across the diameter of the cane. — ○ = base; ▲ = middle; ● = top; I = standard deviation.

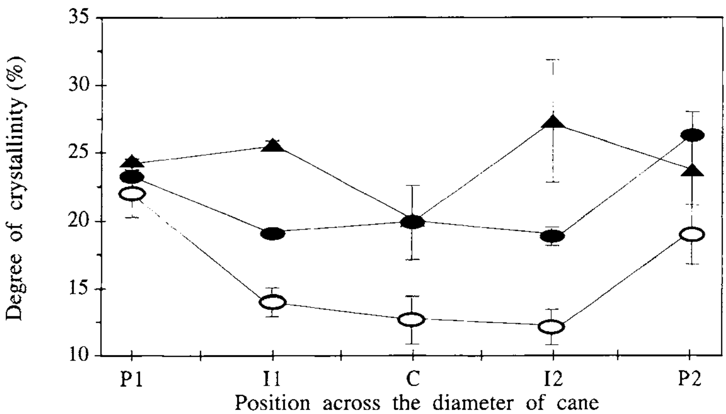


Fig. 9. Cellulose crystallinity distribution across the diameter of the cane. — ○ = base; ▲ = middle; ● = top; I = standard deviation.

Physical properties

Air dried density decreased from base to top as well as from periphery to core (Fig. 8). Density ranged from 0.40 g/cm^3 to 0.72 g/cm^3. This trend was consistent with the density distribution of some Indian canes as observed by Bhat and Renuka (1988). Similarly, percent crystallinity decreased from periphery to core (Fig. 9). Crystallinity ranged from 12% to 26%, very much lower than the crystallinity of wood fibers as observed by Lee (1961).

Statistical analysis

Table 1 shows the result of the one-way analysis of variance (ANOVA). The analysis indicated that except for peripheral release strain, the mechanical, anatomical, and physical properties of the cane varied significantly from base to top and from periphery to core. The amount of strain released at the periphery was more or less constant along the length of the cane.

Regression analysis showed that the anatomy of the cane strongly influenced its physical and mechanical properties (Table 2). The amount of fibers was directly proportional to the longitudinal Young's modulus and the density of the individual sampling points. Fiber ratio also had a strong influence on the generation of stress. As the amount of fiber increases, compressive stresses were produced.

Table 1. Results of Analysis of Variance (ANOVA).

Parameter		Peripheral						
		Base	Middle	Top	F-test	Periphery	Core	F-test
Released strain (%)	av.	0.0161	0.0079	0.0148	ns	0.0129	–0.0418	***
	n	10	10	10		30	15	
	CI (±)	0.015	0.003	0.004		0.005	0.013	
Longitudinal Young's Modulus (GPa)	av.	2.17	3.49	6.48	***	4.04	1.56	***
	n	10	10	10		30	15	
	CI (±)	0.30	0.56	1.76		0.89	0.20	
Stress (MPa)	av.	–0.31	–0.27	–0.97	***	–0.52	0.71	***
	n	10	10	10		30	15	
	CI (±)	0.24	0.13	0.44		0.20	0.28	
Fiber (%)	av.	20.8	30.5	38.8	***	30.0	16.1	***
	n	50	50	50		150	75	
	CI (±)	2.01	5.88	6.88		4.01	1.54	
MFA (°) (Iodine Staining)	av.	30.9	26.2	24.6	***	27.2	30.8	***
	n	350	350	350		1050	525	
	CI (±)	0.81	1.05	1.27		1.15	1.32	
MFA (°) (X-ray diffraction)	av.	29.2	25.1	23.9	***	26.1	31.6	***
	n	50	50	50		150	75	
	CI (±)	0.75	0.92	0.71		0.94	1.24	
Density (g/cm^3)	av.	0.48	0.56	0.68	***	0.57	0.47	***
	n	20	20	20		60	30	
	CI (±)	0.05	0.05	0.08		0.05	0.05	
Crystallinity (%)	av.	24.0	23.8	20.8	***	22.8	16.8	***
	n	8	8	8		24	12	
	CI (±)	1.93	2.02	1.78		1.34	2.64	

*** = significant at 1%; ns = not significant; av. = average; n = number of observations; CI = confidence interval.

Table 2. Regression analysis.

Parameter	Correlation coefficient
Fiber % vs. Density	0.56***
Fiber % vs. Young's Modulus	0.87***
Fiber % vs. Stress	–0.65***

*** = significant at 1%.

DISCUSSION

Variation in properties

When fiber percentage was correlated to Young's modulus and density, it was observed that as the ratio of fibers in the tissue increases, Young's modulus and density also increased. Thus, the variations in mechanical and physical properties of the cane were attributed to its variation in anatomy.

Bhat and Thulasidas (1992) obtained similar results. After identifying the factors that influence strength, e.g., species, age, stem position, fiber proportion, specific gravity and moisture content, they observed that fiber proportion has the greatest influence on the strength of the cane. Density, on the other hand, was observed to be highly affected by fiber percentage/fiber wall thickness, lumen diameter ratio and metaxylem vessel diameter (Bhat & Verghese 1989, 1991). In this case, fiber percentage / fiber wall thickness was observed to be the most important parameter that influences density.

The number of fiber wall layers can also influence strength and density. Fibers have the ability to produce additional cell wall layers as they mature because they live throughout the life cycle of the cane (Tomlinson 1990). In fact, it was observed that the fibers of *Calamus manan* have as many as 7 layers of alternating broad and narrow sheets (Parameswaran & Liese 1985). The addition of new layers does not only contribute to the stiffness of the cane (Bhat et al. 1990), it also increases the cell wall substance of the fibers. Nevertheless, its effect is only secondary to the influence of fiber ratio on the strength and density of the cane.

Stress distribution

The periphery expanded while the core contracted in the longitudinal direction after the stress was released. This proved that, eventhough the growth characteristics and growth behavior of rattan are completely different from that of trees, stress will still be produced. One interesting fact obtained from the result of this study is that the stress pattern in rattan is the exact opposite of that in trees. Whether this pattern is true for all monocotyledons is still uncertain.

The amount of peripheral release strain was more or less constant along the three height levels, but because of the steady decrease in Young's modulus from base to top, the resulting stress also decreased from base to top. This implies that the strength of the material has a major influence on the generation of stress. Because fiber percentage dictates the magnitude of the strength, it follows that it will also have a direct impact on the amount of stress produced. As proof to this claim, when fiber percentage was correlated with the amount of stress, it showed that an increase in fiber proportion resulted in the production of compressive stresses.

Origin of stress

As early as 1938, the significance of the supportive tissues, i.e., fibers and tracheids, in the production of stress had been established (Munch as cited by Clark 1939). Munch specifically noted the influence of the microfibrils and the amount of lignin in the tracheids. He suggested that during lignin deposition, the secondary wall of the tracheids undergo irreversible swelling. Such swelling will exert radial pressure on the outer layers of the walls. Because of this swelling, the spiral coils of the fibrils will be compressed resulting in the longitudinal shortening of the cells (Lignin-swelling hypothesis). Boyd (1972) supported Munch's claim. He reported that stress was indeed generated within the wood tissues during lignin deposition.

Bamber (1978) also noted the significance of the supportive tissues in the generation of stress. However, he contested Munch's claim stating that, if stress was dependent on lignin deposition, it remained unclear why tension wood which has low amounts of lignin possesses high tensile stresses. He therefore suggested that tensile stresses in fibers were generated naturally in the cellulose crystallites. Tension arises from the contraction of the crystallizing cellulose due to a high degree of lateral order of crystals (Cellulose-tension hypothesis).

Okuyama et al. (1986) and Yamamoto et al. (1995), on the other hand, proposed that stress was produced by the combined stress due to the contraction of the microfibrils along the axial direction and the compressive stress generated in the matrix component (Unified hypothesis). In this theory, they took into account the influence of the microfibrils and the matrix component as a whole. Yamamoto et al. (1995) provided quantitative proof for this claim. Although opinions vary on how stress is produced, all these theories take into account the significance of the properties of the fibers or the tracheids. Specifically, they all recognize the influence of the microfibril angle, and the role of either lignin or cellulose crystallinity or the cell wall matrix as a whole in the production of stress. Fibers and tracheids differ in their ultrastructure. Nevertheless, these differences were not considered in any of the theories discussed because of their irrelevance in the generation of stress. In the present study, the properties of the rattan fibers, e. g., microfibril angle, lignin content and cellulose crystallinity etc., were also assessed.

a. Microfibril angle

Observations revealed that MFA exceeding 20° produces compressive stresses (Yamamoto et al. 1991; Okuyama 1993). This generalization was based on the study of compression wood tracheids because high MFA in tension wood fibers seldom occurs. However, considering the results of Okuyama et al. (1990), when the MFA of tension wood fibers is beyond 20° the stress produced tends to shift toward the compression side. Therefore, if high MFA does occur in tension wood fibers, it is more likely that these fibers will also generate compressive stresses.

The average microfibril angle of rattan fibers ranged from 23° to 34°. Taking into consideration the previous premise that the cell ultrastructure has no role in the production of stress, we postulate that the rattan fibers will behave in the same way as compression wood tracheids; thus, it will generate longitudinal compressive stress.

b. Degree of crystallinity

A report by Sugiyama et al. (1993) indicated that an increase in the degree of crystallinity in wood tends to create tensile stresses on the radial walls of the cells. The average degree of crystallinity of rattan fibers was high at the periphery and low at the core. However, because it was relatively small compared to the degree of crystallinity of wood, we believe that its influence in the generation of stress in rattan is very small.

c. Lignin content

Yamamoto et al. (1991) and Sugiyama et al. (1993) observed that lignin content above 30% produces longitudinal compressive stresses. Gonzales (1980) reported that the lignin content of *Calamus merrillii* Becc. decreased from base to top. She found that it was 33.22% at the base, 32.91% at the middle and 27.78% at the top. The lignin content at both the base and the middle part of the cane was more than 30%; thus, it was deduced that the rattan fibers at these portions will generate longitudinal compressive stress. At the top portion on the other hand, the lignin content was below 30%, but because the MFA at this region was very high (29° to 34°), longitudinal compressive stress will still be developed.

Stress generation mechanism

Following Munch's hypothesis, it was assumed that the fibers produce stress in the following manner:

> "When lignin is deposited between the microfibrils, it will push the fibrils outward causing the fibers to swell. As lignin pushes away the fibrils, it will cause an increase in fiber length due to a high microfibril angle. However, because of adjacent cells, this longitudinal expansion will be inhibited resulting to the production of longitudinal compressive stress."

This hypothesis was proved quantitatively by Okuyama et al. (1986), Yamamoto et al. (1991) and Yamamoto (1998).

All the fibers will generate longitudinal compressive stress. The amount of stress will vary slightly because of the variation in the number of fiber wall layers among fibers. It was speculated that, as the number of fiber wall layer increases the Young's modulus of the fiber will also increase, resulting in an increase of the amount of stress produced.

The number of fibers will also have an influence on the amount of stress produced. The arrangement of the fibers in rattan is not like that in trees, where they are more or less evenly distributed throughout the structure of the stem. In rattan, the fibers are grouped together in a particular way. More fibers are situated at the base of the cane than at the top and there are more fibers at the periphery than at the core. When more fibers are grouped together at a particular point, the stiffness of that point will increase. This increase in Young's modulus will result to the production of high compressive stress. This is why the longitudinal compressive stress that was created at the base was higher than at the top. And also why high longitudinal compressive stress was generated at the periphery. As a response to this high peripheral stress, longitudinal tensile stress must have been induced at the core.

Observing the form of the vascular bundles, the longitudinal compressive stresses generated by the fibers might cause buckling of the bundles. Nevertheless, we believe that the parenchyma cells surrounding the bundle will prevent such buckling. While the bundles bend because of the compressive stress, the flexible parenchyma cells will absorb such bending, in turn, preventing the bundles from being damaged.

CONCLUSION

The longitudinal Young's modulus and the density of rattan cane varied significantly from base to top and from periphery to core. This variation was attributed to the variation in the proportion of fibers along the length and across the diameter of the cane.

Palasan cane (*Calamus merrillii* Becc.) was stressed at varying degrees from periphery to core and from base to top. Longitudinal compressive stress existed at the periphery while longitudinal tensile stress existed at the core.

The rattan fibers were responsible for the production of stress. Because the MFA of the fibers was beyond 20° and the lignin content of the cell walls was higher than 30%, considering its similarities to compression wood tracheids, it was assumed that the fibers generated longitudinal compressive stress. The amount of stress produced varied because of the variation in fiber number. More fibers resulted in an increase in Young's modulus which resulted in the production of high compressive stress. This is why longitudinal compressive stress produced at the base was higher than at the top. This is also why high longitudinal compressive stress was generated at the periphery. As a response to this high compressive stress at the periphery, longitudinal tensile stress was induced at the core.

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REFERENCES

Bamber, R.K. 1978. Origin of growth stresses. Proc. IUFRO Conf. FORPRIDECOM, College, Laguna, Philippines.
Bhat, K.M., W. Liese & U. Schmitt. 1990. Structural variability of vascular bundles and cell wall in rattan stem. Wood Sci. Tech. 24: 211–224.
Bhat, K.M. & A. Mathew. 1995. Structural basis of rattan. Biomechanics, Biometrics 3: 67–80.
Bhat, K.M. & C. Renuka. 1988. Variation in physical characteristics of Kerala grown rattans of Peninsular India. Malaysian Forester 49: 185–197.
Bhat, K.M. & P.K. Thulasidas. 1992. Strength properties of ten South Indian canes. J. Trop. For. Sci. 5: 26–34.
Bhat, K.M. & M. Verghese. 1989. Anatomical basis for the physical behavior of rattan. IAWA Bull. n.s. 10: 334–335.
Bhat, K.M. & M. Verghese. 1991. Anatomical basis for density and shrinkage behavior of rattan stem. J. Inst. Wood Sci. 12: 123–130.
Boyd, J.D. 1972. Tree growth stresses V. Evidence of an origin in differentiation of lignification. Wood Sci. Tech. 6: 251–262.
Burstrom, H.G. 1979. In search of a plant growth paradigm. Am. J. Bot. 66: 98–104.
Cave, I.D. 1966. X-ray measurement of microfibril angle. Forest Products J. 16: 37–42.
Chafe, S.C. 1981. Variations in longitudinal growth stress, basic density and MOE with height in the tree. Austral. For. Res. 11: 79–82.
Clark, S.H. 1939. Stresses and strains in growing timber. Forestry 13: 68–79.
Gonzales, E.V. 1985. Chemical properties of some Philippine rattan species. PCARRD Philippines. Unpublished terminal report.

Kabir, M.F., D.K. Bhattacharjee & M.A. Sattar. 1994. Variation of physical and mechanical properties of Calamus erectus. Bangladesh J. For. Sci. 23: 43–47.
Kubler, H. 1987. Growth stresses in trees and related wood properties. Forest Products Abstracts 10 (3): 61–119.
Lee, C.L. 1961. Crystallinity of wood cellulose fibers. Forest Products J. 11: 108–112.
Meylan, B.A. 1967. Measurement of microfibril angle by X-ray diffraction. Forest Products J. 17: 51–58.
Mohr, H. & P. Schopfen. 1995. Plant physiology: 99–109. Springer-Verlag, Berlin Heidelberg.
Okuyama, T. 1993. Growth stresses in tree. Mokuzai Gakkaishi 39: 747–756.
Okuyama, T., A. Kawai, Y. Kikata & H. Yamamoto. 1986. The growth stresses in reaction wood. Proc. XVIII IUFRO World Congress, Yugoslavia: 249–260.
Okuyama, T. & Y. Kikata. 1975. The residual stresses in wood logs due to growth stress. Mokuzai Gakkaishi 21: 326–327.
Okuyama, T. & Y. Sasaki. 1978. The residual stresses in wood logs due to growth stresses. IV. Mokuzai Gakkaishi 24: 77–84.
Okuyama, T., H. Yamamoto, M. Iguchi & M. Yoshida. 1990. Generation process of growth stresses in cell walls. II. Growth stresses in tension wood. Mokuzai Gakkaishi 36: 797–803.
Parameswaran, N. & W. Liese. 1985. Fiber wall architecture in the stem of rotan manau (Calamus manan). Proc. Rattan Seminar, 1984, Kuala Lumpur, Malaysia: 123–129. Rattan Information Center.
Romberger, J.A., Z. Hejnowicz & J.F. Hill. 1993. Plant structure: Function and development: 45–65. Springer-Verlag, Berlin, Heidelberg.
Sasaki, Y., T. Okuyama & Y. Kikata. 1981. Determination of the residual stress in a cylinder of inhomogeneous anisotropic material. I. Mokuzai Gakkaishi 27: 270–276.
Siripatanadilok, S. 1996. Anatomical characteristics relating to the quality of large-cane rattan. Kasetsart J., Nat. Sci. 30: 118–130.
Sugiyama, K., T. Okuyama, H. Yamamoto & M. Yoshida. 1993. Generation process of growth stresses in cell walls: Relation between longitudinal released strain and chemical composition. Wood Sci. Tech. 27: 257–262.
Tomlinson, P.B. 1990. The structural biology of palms: 52–59. Clarendon Press, Oxford.
Weiner, G. & W. Liese. 1992. Cell types and fiber lengths within the stem of various rattan genera. Holz als Roh- u. Werkstoff 50: 457–464.
Wilson, B.F. & R.R. Archer. 1977. Reaction wood: Induction and mechanical action. Annual Review Plant Physiol. 28: 23–43.
Yamamoto, H. 1998. Generation mechanism of growth stresses in wood cell walls: role of lignin deposition and cellulose microfibril during cell wall maturation. Wood Sci. Tech. 32: 171–182.
Yamamoto, H., T. Okuyama & M. Yoshida. 1995. Generation process of growth stresses in cell walls. VI. Analysis of the growth stress generation by using a cell model having three layers (S_1, S_2, and I+P). J. Japan Wood Res. Soc. 41: 1–8.
Yamamoto, H., T. Okuyama, M. Yoshida & K. Sugiyama. 1991. Generation process of growth stresses in cell walls. III. Growth stresses in compression wood. Mokuzai Gakkaishi 37: 94–100.
Yao, J. 1979. Relationship between height and growth stresses within and among white ash, water oak and shagbark hickory. Wood Sci. 11: 246–251.