Growth strain in coconut palm trees

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Summary Until recently, growth stress studies have been made only on coniferous and dicotyledonous trees. Growth stress of trees is thought to be initiated in newly formed secondary xylem cells. This stress can accumulate for years and is distributed inside the trunk. Major characteristics of the trunk of monocotyledonous trees include numerous vascular bundles scattered inside the ground tissue and the lack of secondary growth for enlarging the diameter of the trunk. We used the strain gauge method to measure the released growth strain of the monocotyledonous woody palm, coconut (Cocos nucifera L.), and to investigate the surface growth strain of the trunk and central cylinder at different trunk heights. The internal strains of both vertical and leaning trunks were measured and compared with those of coniferous and dicotyledonous trees. We found that tensile stress existed longitudinally on the surface of vertically growing trunks, whereas compression stress was found at the bending position of leaning trunks. Compression stress was found in the outer part of the central cylinder, whereas tensile stress is generally found in the outer part of the trunk in coniferous and dicotyledonous trees. The distribution of strain in the palm trunk is similar to that of compression wood of the leaning trunk of a conifer. Specific gravity was greater in the outer part of the trunk than in the inner part of the trunk. This difference may be related to the distribution of growth stress.

Keywords: central cylinder, Cocos nucifera, ground tissue, internal strain, monocotyledonous woody plants, surface growth strain, vascular bundle.

Introduction


Increased growth stress is found at specific locations in the leaning trunk where eccentric swelling growth occurs (Watanabe 1967). Growth stress forces the trunk and branch to grow in a vertical orientation to maximize exposure to sunlight. In conifers, compression wood is formed on the lower side of a leaning trunk where there is strong compression stress, whereas in dicotyledonous trees tension wood is formed on the upper side where strong tensile stress exists (Okuyama et al. 1986, Timell 1986a, 1986b). Even in an upright growing trunk, growth stress forms inside the trunk. In response to environmental stress, such as wind, the sapwood is in danger of compression damage. In both coniferous and dicotyledonous trees, longitudinal tensile stress develops on the peripheral portion of the trunk, whereas compression stress accumulates inside the trunk (Archer 1986).

Three hypotheses have been advanced to account for the initiation of growth stress. The lignin-swelling hypothesis (Boyd 1972) suggests that lignin accumulates between cellulose microfibrils (CMF) of the cell wall, enlarging the cell transversely. Because of the Poisson effect, the cell is constrained in the longitudinal direction by the maturing xylem, thus producing growth stress. This hypothesis could explain the presence of compression stress in compression wood, but it cannot account for the tensile growth stress of normal and tension wood. The cellulose tension hypothesis (Bamber 1978, 1987) postulates that the CMF of the growing cell wall contracts during crystallization. Growth stress is produced in the longitudinal direction of the CMF when the cell is constrained by the maturing xylem. This hypothesis could account for the surface tensile growth stress of normal and tension wood, but again does not explain the presence of compression stress in compression wood. Okuyama et al. (1986) proposed a unified hypothesis that combines the first two hypotheses. The unified hypothesis can be applied to both normal and reaction wood. It claims that the CMF of the maturing cell wall is constrained in the longitudinal direction, thus generating tensile growth stress. At the same time, the CMF create residual compression growth stress because the transverse gap in the CMF is filled.
with lignin. The microfibril angle (MFA) determines the longitudinal growth stress of the trunk and its characteristics.

It is not known if any of these hypotheses can be applied to monocotyledonous woody plants. Vascular bundles are scattered in the ground tissue of the trunk of monocotyledonous trees to form the central cylinder (Tomlinson 1990). This contrasts with the secondary growth of coniferous and dicotyledonous trees, where growth stress originates and accumulates during lignification of newly formed xylem cells inside the cambium. It is of interest to determine whether reaction wood or growth stress also occurs in monocotyledonous woody plants lacking secondary growth. In the only related study on this topic, Abasolo et al. (1999) measured growth stress of the monocotyledonous woody plant, rattan and found that its distribution differed markedly from that of coniferous and dicotyledonous trees. Therefore, we examined the surface and internal growth strain (elongation or contraction per unit length) in the monocotyledonous coconut palm tree (*Cocos nucifera* L.) and compared it with that in coniferous and dicotyledonous trees.

**Materials and methods**

Two 20- to 25-year-old coconut palm trees, growing in Hengchun (120°49′ E, 21°57′ N, elevation 230 m), Taiwan, were selected for measurement of surface growth strain and internal growth strain of their trunks. One tree had a straight trunk with a diameter at breast height of 34.5 cm, and a height of about 7 m. The surface growth strains in longitudinal and peripheral directions of the trunk and central cylinder of the trunk were measured at heights of 0.4, 1.4, 2.4, 3.4 and 4.4 m. The other tree was leaning as a result of a typhoon that occurred about 10 years ago. The surface growth strains in longitudinal and peripheral directions of the trunk and central cylinder of the leaning trunk were measured at heights of 0.5, 1.4, 2.9, 3.6, 4.6 and 5.6 m. The profiles of the erect trunk, leaning trunk and measurement locations are shown in Figure 1.

The surface growth strain of each trunk was measured after removing a thin surface layer (1 to 1.5 mm thick), whereas the surface growth strain of the central cylinder was measured after removing the cortex (about 10 mm thick) down to the hard fibrous layer. Strain gauges (10 mm long) were glued with cyanoacrylate adhesive in the longitudinal and circumferential directions (Figure 2). The upper side of the leaning trunk was designated as the starting point (0°) for the measurement of surface growth strain of the trunk. The strain gauges were attached longitudinally and circumferentially on the surface every 22.5° from 0 to 180°.

After calibrating the strain gauges to zero, surface growth strain was measured after release by the kerf method (Sasaki et al. 1978). That is, grooves, 1–1.5 cm deep, were made in the trunk around the strain gauge (the edge of the cut within 5 mm of the edge of the gauge) with a handsaw and a chain saw, and the released strain was determined immediately with a portable digital strain meter (Model UCAM-1A, Kyowa, Tokyo, Japan) with a 40-channel scanner (USB-11A).

To measure the internal growth strain, strain gauges were glued in the longitudinal direction along the diameter of each diametrical plank at intervals of 1.5 cm. A diametrical plank is a radial board, 30 cm tall and 2 cm thick, that is made in the center portion of a log, 1–1.5 m long, with two ends remaining intact (Figure 2). Released strains on the diametrical planks were measured by cross-cutting each plank with a handsaw 1 cm above the strain gauges and ripping among the gauges. The strain was measured as soon as the trunk was felled so that no drying stress occurred. Positive readings of the longitudinal released strain indicate the existence of compression growth stress, whereas negative values imply tensile growth stress.

The distribution of specific gravity in the radial direction, based on green volume and oven dry weight, was also measured to provide information about density variation within the trunk.

**Results and discussion**

**Specific gravity distribution within the trunk**

The diameter of the vertical trunk was larger than that of the...
leaning trunk. The diameter of the vertical trunk was 59.8, 37.5, 34.5, 32.3 and 29.5 cm at heights of 0.4, 1.4, 2.4, 3.4 and 4.4 m, respectively, whereas the diameter of the leaning trunk ranged between 20 and 22 cm. The leaning trunk developed from a horizontal trunk with a diameter of 26 cm. Specific gravity within the central cylinder is shown in Figure 3. The specific gravity of the vertical trunk at a height of 1.9 m above ground was 0.3 on the periphery, and gradually decreased toward the center to only 0.09. The specific gravity of the leaning trunk at a height of 3 m was 0.74 on the periphery, and gradually decreased toward the core to 0.21. Thus, the specific gravity in the center of each trunk was roughly one-third that at the periphery. The specific gravity of the leaning trunk was about 2.4 times that of the vertical trunk. The specific gravity of the cortex was 0.2 and 0.43 for the erect and the leaning trunk, respectively. Because the strength of wood increases with increasing specific gravity (Kollmann and Cote 1968), the leaning trunk, despite having a smaller diameter, obtained its mechanical support from its greater wood strength. However, the greater specific gravity in the outer part of the trunk will provide greater stiffness, and prevent the trunk breaking in response to external forces such as wind. That the peripheral ring of lignified tissue is the main mechanical supporting tissue in the trunk has also been observed in Cuban belly palm (Gastrococos crispa (HBK) H.E. Moore). The density variation in Cuban belly palm showed that the swollen middle region has a much lower density than the shrunken basal part, and the density of the peripheral tissue is greater than that of the center tissue (Fisher et al. 1996). Rich (1987b) has also noted that the physical properties, such as dry density, elastic modulus and modulus of rupture of six species of arborescent palms increased toward the trunk base and at the periphery. These properties also increase as the trunk ages.

We also examined another individual erect coconut palm trunk and found that the specific gravity distribution within the trunk was similar to that described in Figure 3.

Vascular bundles in coconut palm trunk
Vascular bundles are scattered in the ground tissue of the coconut palm trunk to form a central cylinder that is similar in anatomy to the stem of other woody monocotyledonous plants. The percentage area of vascular bundles in the erect trunk at 2 m above ground was 57.1 and 9.9% at the periphery and in the core, respectively, whereas it was 64.0 and 22.4%, respectively, in the leaning trunk 3 m from the trunk base. For both erect and leaning trunks, the density of vascular bundles in the outer trunk was higher than in the center. Large amounts of sclerenchymatous fiber were found in the vascular bundles. Fibers have a higher cell wall density than parenchymatous cells. The percentage of area of vascular bundles in the outer part of the leaning trunk was only 1.1 times (64.0/57.1) higher than in the erect trunk, whereas the specific gravity was 2.5 times higher (0.74/0.3). This is because the fiber cells in the leaning trunk had thicker cell walls and smaller lumens than the fiber cells in the erect trunk.

We also examined another individual erect coconut palm trunk and observed that the percentage of area of vascular bundles at the periphery and in the core within the trunk was similar to that described for the two intensively studied trees.

Surface growth strain of trunk
Surface growth strain in the longitudinal direction of the trunk was negative (Figure 4), indicating the existence of tensile stress. The absolute value of strain decreased with increasing tree height. Growth strain in the transverse direction of the trunk was slightly above zero at heights below 1.5 m. Growth strains became negative with increasing trunk height (Fig-
The cortex of coconut palm trunk has similar growth stress to the inner bark of coniferous trees. Okuyama et al. (1981) found that both longitudinally and transversely released strains are negative in the inner bark of Cryptomeria japonica (L.f.) D. Don. They also reported a longitudinal stress in tension of about 2.6 MPa. However, the inner bark of dicotyledonous and coniferous trees differs from the coconut palm cortex in both structure and growth. The inner bark is composed of living secondary phloem, whereas the cortex of coconut palm is composed of parenchyma cells, fibers and incomplete vascular bundles.

Both the longitudinal and transverse directions of the central cylinder showed positive values of surface growth strain (Figure 4), indicating the presence of compression stress. Although longitudinal growth strain decreased with increasing tree height, no significant relationship was observed between transverse growth strain and tree height. The surface growth strain on the periphery of the central cylinder of the coconut palm trees resembled the compression wood of conifers. A similar finding was reported for rattan (Abasolo et al. 1999).

The surface growth strain on the upper side of the leaning trunk is shown in Table 1. Locations A, B, E and F denote the linear parts of the trunk where surface growth strains were negative, as in the erect trunk. Transverse strains in locations B, E and F were positive, whereas those in Locations A and C were negative. Longitudinal strains at the leaning portions C and D were positive, in contrast to those in the erect trunk but similar to compression wood.

The distribution of circumferential surface strain of the leaning trunk at Location C is presented in Figure 5. Longitudinal strain was positive (expansive), between $496 \times 10^{-6}$ and $2054 \times 10^{-6}$. The strain on the lower side of the leaning trunk was greater than on the upper side, indicating the existence of greater compression stress. Transverse strains were negative (contractive), ranging from $-148 \times 10^{-6}$ to $-682 \times 10^{-6}$.

The mechanism of reorienting leaning coniferous tree stem to the vertical has been explained as the expansion of compression wood on the lower side pushing the trunk into the vertical position (Timell 1986b, Niklas 1992, Mattheck and Kubler 1995). Therefore, we assume that the greater compressive strain on the lower side of leaning coconut palm trunk is responsible for the righting of stem.

**Internal growth strain in trunk**

Figure 6a shows the longitudinal strain of the central cylinder in a diametrical plank with the cortex removed for the erect trunk at a height of 2.9 m, where diameter equaled 33 cm. Internal strain in the peripheral portion was positive, indicating the existence of compression stress. Both positive and negative strains were observed in the inner part, whereas positive strain ($+229 \times 10^{-6}$) was seen at the center. The maximum strain in the outer part was $+815 \times 10^{-6}$, whereas the minimum strain in the inner part was $-408 \times 10^{-6}$, indicating the existence of some tensile stress in inner parts of the trunk. Figure 6b shows the longitudinal strain of the central cylinder in a diametrical plank including the cortex in the erect trunk at a height of 1.9 m, where trunk diameter equaled 35.5 cm. The internal strain in the cortex showed negative values of $-480 \times 10^{-6}$ and $-131 \times 10^{-6}$ (open circles in Figure 6b), indicating the existence of tensile growth stress in cortical tissue.

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**Table 1. Released surface strain at different positions of a leaning trunk including the cortex as shown in Figure 1.**

<table>
<thead>
<tr>
<th>Location</th>
<th>Height (m)</th>
<th>Longitudinal</th>
<th>Transversal</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5.6</td>
<td>$-430$</td>
<td>$-40$</td>
</tr>
<tr>
<td>B</td>
<td>4.6</td>
<td>$-345$</td>
<td>$100$</td>
</tr>
<tr>
<td>C</td>
<td>3.6</td>
<td>$931$</td>
<td>$-640$</td>
</tr>
<tr>
<td>D</td>
<td>2.9</td>
<td>$202$</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>1.4</td>
<td>$-467$</td>
<td>$452$</td>
</tr>
<tr>
<td>F</td>
<td>0.5</td>
<td>$-2061$</td>
<td>$624$</td>
</tr>
</tbody>
</table>

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**Figure 4. Effects of trunk height on surface growth strain determined by measuring the erect trunk surface (●, longitudinal direction; and ○, transverse direction), and by measuring the outside of the central cylinder (▲, longitudinal direction; and △, transverse direction).**

**Figure 5. Peripheral distributions of surface growth strain on a leaning trunk taken at Location C in Figure 1. Symbols: ●, longitudinal direction; and ○, transverse direction.**

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**Figure 6a. Longitudinal strain of the central cylinder in a diametrical plank with the cortex removed for the erect trunk at a height of 2.9 m, where diameter equaled 33 cm.**

**Figure 6b. Longitudinal strain of the central cylinder in a diametrical plank including the cortex in the erect trunk at a height of 1.9 m, where trunk diameter equaled 35.5 cm.**
Expression stress (positive strain values) was found mostly inside the central cylinder where tensile stress was limited (negative strain values).

Another individual erect coconut palm trunk was examined, and the trend of the internal growth strain at the periphery and in the core within the trunk was again observed.

Figure 7 shows the strain of the central cylinder in a diametrical plank including the cortex in the leaning trunk at Location D (20 cm in diameter at 3 m height). Growth strain of the cortex was positive, with values of $+498 \times 10^{-6}$ and $+202 \times 10^{-6}$ at the two ends (open circles in Figure 7), indicating that compression stress prevailed, in contrast to the tensile stress of the erect trunk. Positive values were also observed toward the inner part of the trunk on the lower side, but both positive and negative values were found on the upper side. The outermost part of the central cylinder of the upper side had a strain value of $+22 \times 10^{-6}$, indicating slight compression stress, similar to the compression wood found on the lower side of leaning conifer trunks (Huang et al. 2001). With respect to the central cylinder, the outermost portion of both vertical and leaning trunks exhibited compression stress. This is strikingly different from coniferous and dicotyledonous trees, which show tensile stress at the trunk periphery and compression stress in the inner trunk. Measurements on rattan by Abasolo et al. (1999) showed that longitudinal compression stress existed at the periphery, whereas longitudinal tensile stress was found at the core.

Growth stress in the stems of dicotyledonous and coniferous trees is generated at the locations of the vascular cambium and newly formed xylem. Growth stress accumulated over the years shows a specific distribution pattern (Boyd 1950). The distribution of growth stress in the palm trunk, which lacks secondary growth or annual rings, is probably generated during one period and changes with time as a result of the thickening of the cell walls of the vascular tissue, fibers and parenchyma. We speculate that if the fibers of the vascular bundles swell in the longitudinal direction during maturation because of thickening of fiber cell walls, this swelling will be constrained by the ground tissue. This constraint would be greater at the periphery than in the inner trunk because the area percentage of vascular tissue at the periphery is greater. Also, the periphery of the central cylinder has a high density of small fiber bundles that are lacking in the center (Tomlinson 1990). As a result, compression stress will be induced in the outer part of the trunk. In response, tensile stress in the inner trunk will develop to achieve equilibrium. That is, the distribution of growth stress in the palm trunk changes during maturation of the fibers of vascular bundles, thus providing mechanical support. Further investigation is needed to clarify the relationship between growth stress and the microstructure of palm. Also, increased lignification of cell walls of fiber and ground tissue as the tree ages may affect the stiffness and strength of the trunk (Rich 1987a, Fisher et al. 1996).

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**References**

