# Growth stress of *Zelkova serrata* and its reduction by heat treatment

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**Abstract**

Zelkova is one of the tree species that is known to have a very high level of growth stress. During sawing, yield decreases as a result of heart crack and distortion of boards owing to growth stress release. Therefore, the study of growth stress in zelkova is considered to be important for its effective utilization. In this study, six erect trees with diameters at breast height ranging from 25 to 45 cm were felled. Surface growth stress of zelkova was measured by the groove method, using resistant strain gauges. Released surface growth stress of trunks at various tree heights, and the residual growth stress distribution over the radial positions from pith to bark were measured. The steaming method was used in an attempt to decrease growth stress, and the effects of different steaming temperatures and duration times on the decrease of growth stress were examined. There was no obvious relationship between surface growth stress and trunk height. The residual growth stress was tensile for the outer part of the tree trunk and compressive for the inner part, yielding a V-shaped stress distribution. Both the surface growth stress and the internal residual stress were reduced by heat treatment. The reduction of longitudinal growth stress increased with increased heating temperature, and with increased heating time. With a 110°C steam heating temperature and 24- to 48-hour exposure time, over 86 percent of the surface growth stress was released. When 85° or 95°C steam heating temperature and 24-hour exposure time was used, only 50 percent of the growth stress was reduced. However, a heating temperature below 100°C may be most suitable for practical applications.

The cell division of stem cambium results in expansion of secondary phloem and xylem as well as the circumference of a tree's trunk and its branches. Growth stress arises from the deposition of lignin within the secondary walls during the maturation of fibrous cells (Boyd 1972, Yamamoto et al. 1991, Guitard et al. 1999). The annual addition of wood on the outer side of a tree trunk adds to the longitudinal stress and therefore presents a regular distribution along the longitudinal plane through the pith (Archer and Bynes 1974, Kubler 1987, Fournier et al. 1990). The accumulation of growth stress is an unavoidable result of physiological adjustment to environmental stress (Niklas 1992, Mattheck and Kubler 1995).

Greater levels of growth stress generally occur in specific locations of the slanted trunk or branches. The growth stress stimulates the stems to restore a natural erect position of the tree, in order to prevent falling or injury. For example, compression wood forms on the lower side of a leaning tree trunk or branches of softwoods, while tension wood forms on the upper side of the leaning trunk and branches of hardwoods (Panshin et al. 1964, Timell 1986a). It can be seen that the tree ingeniously adjusts its growth stress to satisfy its environment requirements.

Growth stress is of practical importance because it causes failure in wood utilization and lowers the value of wood

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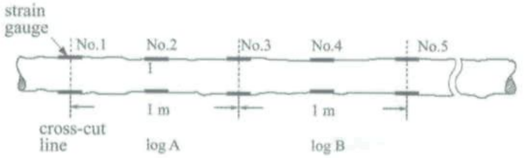


*Figure 1. — Diagram showing how the log samples are cut and strain gauges applied.*

products. The equilibrium state of the standing tree will release its growth stress during wood processing. As a result, logging and cutting may cause heart crack in a log, while sawing may cause warping of lumber. All of these wood failures lower the usability of wood. Therefore, from the standpoint of wood utilization, it is necessary to understand the mechanisms of growth stress in trees and to find proper solutions for releasing or reducing that stress in harvested logs (Okuyama and Sasaki 1979, Archer 1986, Timell 1986b, Okuyama et al. 1988).

Zelkova is a precious hardwood with a beautiful grain, fine texture and great strength. It is mainly used for furniture, flooring, handicrafts, ships, and other structural uses. The plantation area of zelkova in Taiwan is over 6,000 ha. Despite its value, zelkova is one of the species known to have a very high level of growth stress (Sasaki et al. 1978). For this reason, zelkova is one of the most troublesome species for sawing operations in Japan (Okuyama et al. 1987).

Several methods have been developed to control or prevent loses of wood due to stress release in processing of logs by sawing or crosscutting, including driving toothed plates or S-hooks into the ends of the log for end crack reduction and clamping the end or fastening around the end with a band to apply a radial pressure (Archer 1986). Barnacle and Gottstein (1968) described an experimental procedure consisting of cutting circumferential grooves or kerfs at a short distance from one or both sides of a proposed crosscut site; this was found to be effective in reducing end crack development. Storage of logs in water also was found to be effective for a partial relaxation of residual growth stress, but it required too long a time period to be practical (Nicholson 1973). Maeglin et al. (1985) reported the effects of high-temperature drying and equalizing on stress relief in yellow-poplar lumber. Lignin softening was thought to be the main reason for stress release in this treatment. Okuyama et al. (1987, 1988, 1990) investigated the effects of direct heating on the reduction of residual stress in green logs of zelkova, Japanese larch, and Japanese cedar. The purpose of direct heat treatment of logs (smoking method) was to decrease and equalize the moisture content and to reduce residual stress without causing serious damage to the log. Tejada et al. (1997) also reported the merits of smoking logs for the reduction of residual stress. These treatments all had similar results, in that the higher the heating temperature or the longer the duration of heating, the more the reduction of residual stress in the log.

In the present study, released surface growth stress of zelkova trunks at different tree heights, and growth stress distribution over the radial position from pith to bark were determined. The steaming method was used in an attempt to decrease growth stress; the effects of different steaming temperatures and durations on the decrease of growth stress were examined.

## Materials and methods

Two plantation-grown trees of *Zelkova serrata* (Thunb.) Makino, with diameters at breast height ranging from 25 cm to 50 cm, were taken from each of several sites for growth stress measurement. The trees were obtained from 1) the Ta-Fu Station of the Taiwan Forest Bureau; 2) the Ho-Shei Station of the experimental forest, National Taiwan University; and 3) the Lenfa-Chi Station of Taiwan Forestry Research Institute. The surface growth strain of tree trunks was measured using a strain gauge and by the grooving method (Huang et al. 2001, 2002). The felled trunks were sawn transversely to segments of 1 m to 3.5 m in length and longitudinal surface growth strain was measured at the crosscut point of each segment to determine the influence of tree height on growth stress. In addition, disks of wood about 20 cm thick were taken at the measuring position of each segment. Specimens of 1 cm (width) by 1 cm (thickness) by 18 cm (length) were sampled from the disk and used in a static bending test to determine the modulus of elasticity of green wood. The modulus of elasticity was used to calculate the growth stress equal to the product of growth strain and elasticity. Diametral planks, 30 cm (height) by 2 cm (thick), with two log ends remaining intact, were obtained by a chain saw and hand plane for measurement of residual internal stress within the trunk. Strain gauges were glued at the mid-height of each diametral plank, at intervals of 1.5 cm radially, in the longitudinal direction. Longitudinal residual strains on the diametral planks were then measured by crosscutting each plank with a handsaw at 1 cm above the strain gauges and then ripping among the gauges.

As for the grooving method of strain release, after removing the bark at specified positions, electrical resistance strain gauges were attached to the xylem in both longitudinal and transverse directions with cyanoacrylate adhesive. A portable digital strain meter (Model UCAM-1A Kyowa Ltd, Japan) with a 40-channel scanner (USB-11A) was used for measurement. After calibrating the strain gauges to zero, grooves of 1 cm to 1.5 cm depth were made in the xylem around the strain gauge with a handsaw and chain saw and the released strain was determined immediately.

Wood blocks from the positions where surface growth stress was measured were collected for anatomical observation of G-fibers in the wood, which is a structural characteristic of tension wood. For the scanning electron microscopic (SEM) investigation, free-hand sections or sections from the slide method were handled as described by Cho et al. (2001).

Two plantation-grown trees from Ho-Shei Station and two others from Lenfa-Chi Station were used for investigating the effects of heat treatment on the growth stress reduction of logs. After felling the trees, longitudinal and transverse surface growth strains were measured every 1 m along the felled trunk. The trunk was sawn transversely at the points of strain measurement as described above. The average value of the surface strain measured at both ends of the 1-m segment of log was considered as the control value of this log. For example, as shown in **Figure 1**, the average strain values of No. 1 and No. 3, and No. 3 and No. 5 strain gauge were used as the control value to be compared with the value of strain gauge No. 2 and No. 4, representing the released growth strains of log A and log B after treat-

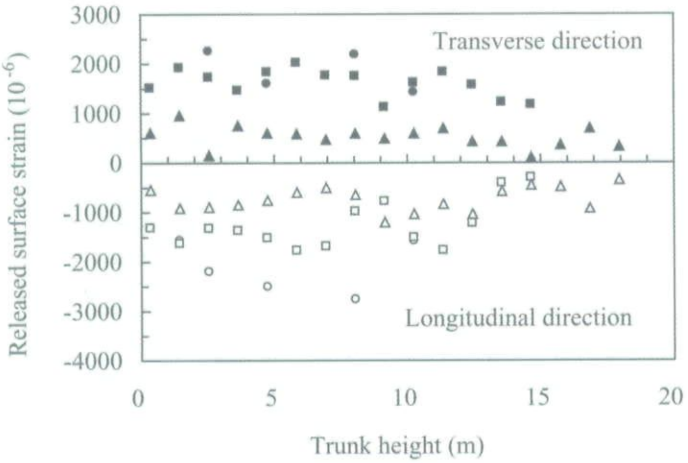


*Figure 2. — Effect of tree height on surface growth strain. Symbols: ○●= Ta-Fu Station; △▲= Ho-Shei Station; □ ■= Lenfa-Chi Station.*

ment, respectively. Eighteen segments of logs from the Lenfa-Chi Station were steam heated in a dry kiln at 85°C for 24 hours, while 17 other segments were steam heated at 95°C for 24 hours. Twelve segments of logs from the Ho-Shei Station were steam heated in a cylinder at 110°C, for 24 hours, while 14 other segments were steam heated at 110°C for 48 hours. The bark was kept intact so that rapid loss of moisture from the surface of the log could be avoided and the extent of surface checks could be lowered. Before heat treatment, logs were end coated to avoid end splitting due to high temperature in the kiln (or cylinder). After treatment, surface strains at the middle portion of the logs were measured. These strains were then compared with the control values. In order to determine the effects of heat treatment on the residual internal growth stress of the logs, segments of the untreated logs and the steam heat-treated logs were selected for testing.

### Calculation of growth stress

A tree trunk can be assumed to be an orthotropic body and surface stresses on the trunk can be considered as biaxial. The direction of principal stress is assumed to coincide with the longitudinal (L) and tangential (T) directions, with the stress in the radial direction (R) being zero. Therefore, the longitudinal and transverse growth stresses ($\sigma_L$, $\sigma_T$) can be calculated as follows (Sasaki et al. 1978):

$$\sigma_L = -E_L(\varepsilon_L + \nu_{TL}\varepsilon_T) / (1 - \nu_{TL}\nu_{LT})$$

and:

$$\sigma_T = -E_T(\varepsilon_T + \nu_{LT}\varepsilon_L) / (1 - \nu_{TL}\nu_{LT})$$

where:

$E_L$ = longitudinal modulus of elasticity

$E_T$ = transverse modulus of elasticity

$\varepsilon_L$ = measured longitudinal released strain

$\varepsilon_T$ = measured transverse released strain

$\nu_{LT}, \nu_{TL}$ = Poisson's ratio

Because $\nu_{TL}$ is very small, longitudinal growth stress can be assumed to be an axial stress and can be simplified as:

$$\sigma_L = -\varepsilon_L E_L$$

In this experiment, only $E_L$ was measured, so only longitudinal growth stresses that relate to the distortion of sawn timber and deformation during processing are discussed.

## Results and discussion

### Influence of tree height on surface growth stress

There was no obvious relationship (**Fig. 2**) between tree height and surface strain in longitudinal and transverse directions. Longitudinal strains were contractive, indicating the presence of tensile stress, whereas transverse strains were extensive, indicating the existence of compressive stress. By comparison, Yao (1979) selected shagbark hickory, water oak, and white ash for a study of growth stress variation with tree height. He found that the longitudinal growth stress for ash reached a peak at a 5-m height, while in oak and hickory, stress reached a maximum at an 8-m height. In a similar study of 39-year-old mountain ash trees, Chafe (1981) found increases in longitudinal growth strain and stress with increasing height up to 7.5 m.

In the present study, both the longitudinal and the transverse growth strains were greatest in wood from the Ta-Fu Station and least in wood from the Ho-Shei Station (**Fig. 2**). The average values of longitudinal growth strain measured from the Ta-Fu, Lenfa-Chi, and Ho-Shei Stations were –2124, –1328 and –740 $\mu\varepsilon$, respectively, while the corresponding values for transverse growth strains were 1872, 1637, and 520 $\mu\varepsilon$, respectively. By the analysis of variance, there were significant differences ($p = 0.01$) between the measurements at the three stations, except for transverse growth strain between Ta-Fu and Lenfa-Chi Stations. The reason for these significant differences may be related to the different habitats. At the Ta-Fu Station, zelkova trees grew on a hill, whereas at the Lenfa-Chi and Ho-Shei Stations, they grew in a valley and on the flat ground, respectively. The relationship between habitat and growth stress of trunks needs to be further studied.

### Effect of log diameter on longitudinal surface stresses

There was no significant relationship between surface growth stress and log diameter in the range from 23 cm to 53 cm (**Fig. 3**). Because the logs were cut from various heights along the trunk, this relationship more or less reflects the influence of tree height. As tree height increases, the age of cambium decreases. This result revealed that xylem differentiated from young or old cambium had little influence on the formation of growth stress.

### Distribution of residual growth stress within the trunk

In regard to the distribution of internal stress within the trunk (**Fig. 4**), tensile stress was found outside and compressive stress occurred inside. The maximum residual stress near the peripheral surface was 314 kgf/cm$^2$ (tension) and 250 kgf/cm$^2$ (compression) at a position 7 cm to 10 cm to the right of pith. Growth stress accumulates in the trunk each year, and the distribution of stress and growth rings are closely related. According to many studies (Archer and Byrnes 1974, Okuyama and Kikata 1975, Sasaki and Okuyama 1983, Ar-

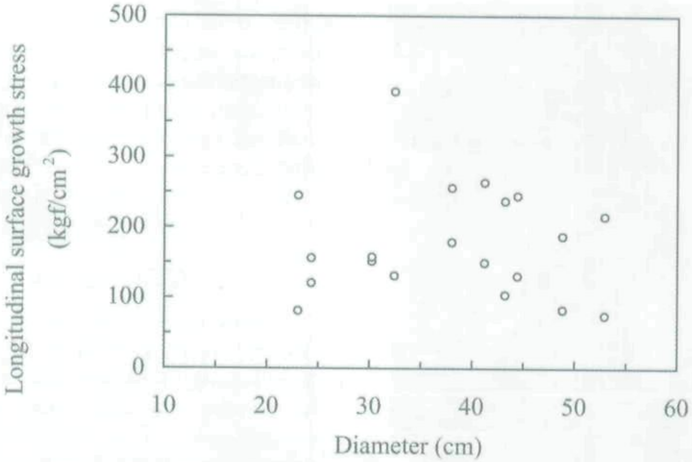


*Figure 3. — Effect of log diameter on surface growth stress.*

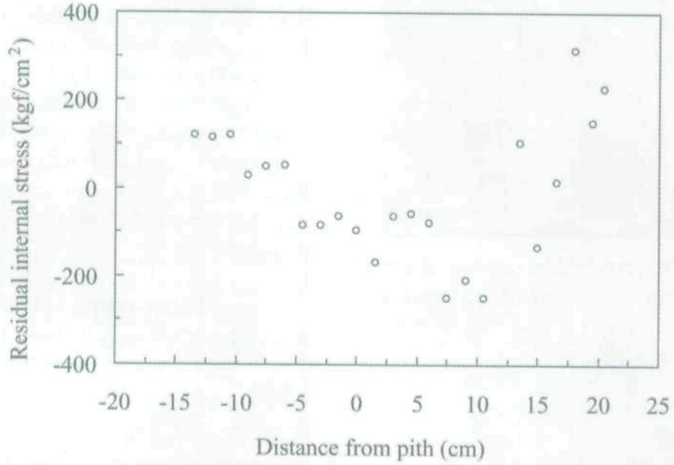


*Figure 4. — Distribution of residual internal stress in trunk.*

cher 1986), in the case of longitudinal residual stress in normal wood, tensile stress is found close to the bark, while large compressive stress occurs toward the pith. This distribution of stresses leads to warping of lumber during processing because of stress release. The trunk had an elliptical cross section with long and short axes of 36 cm and 32 cm, respectively. The trunk also had eccentric growth with the pith deviated from the center of the ellipse (**Fig. 4**). Tension wood appeared on the eccentric side (right), indicating maximum tension growth stress at this end. A direct relationship between the gradient of the stress distribution curve and the amount of lumber crooking is anticipated. The steeper the curve is, the greater the amount of crooking (Okuyama and Sasaki 1979).

## Effects of tension wood on surface strains

Wood structure of zelkova was investigated by SEM and transmission electron microscopy (TEM) (**Figs. 5a** and **5b**). Images indicate that the cell wall of G-fibers contained S1, S2, and gelatinous layers. However, the normal fibers (**Figs. 5c** and **5d**) contained a normal thick S2 layer between the thin S1 and S3 layers of the secondary cell wall. The observation of wood structure on the surface-strain-measured wood blocks indicated that G-fibers were scattered in all the studied erect trunks. This fact may be related to the high growth stress of zelkova. Nevertheless, tension wood (tissues with dominant G-fibers) displayed larger surface strain than normal wood (tissues with just a few or no G-fibers). **Figure 6** compares surface growth strain between tension wood and normal wood (significantly different at $p = 0.01$). The average surface strains of tension wood and normal wood were −1080 and −613 με, respectively. It has been reported that longitudinal growth stress is related to the G-fiber of tension wood (Okuyama et al. 1994). The G-layer of the fiber is almost entirely cellulose. The microfibril angle of the G-layer is nearly parallel to the direction of the fiber axis. This small microfibril angle is related to the high tension stress observed in tension wood.

## Effect of heat treatment on growth stress reduction

When logs were steam heated at 85°C for 24 hours, average released longitudinal strain decreased to 50 percent of that in the controls (**Fig. 7a**); a significant difference was observed at $p = 0.01$. The result of 95°C heating for 24 hours was not significantly different. With heating at 110°C for 24 hours, average released longitudinal strain decreased to 14 percent of that in the control (significantly different at $p = 0.01$). Furthermore, under the 110°C/48-hour condition, average released strain decreased to −1 percent of that of the controls (significantly different at $p = 0.01$). Under the 110°C heat treatment, surface stresses of many logs changed from tension to compression. This phenomenon was also observed by Okuyama et al. (1987).

There were somewhat different effects of heat treatment (**Fig. 7b**) on the transverse surface growth strain. When logs were steam heated at 85°C for 24 hours, or at 95°C for 24 hours, average released transverse strain decreased to 85 or 64 percent of that in the controls, respectively (different at $p = 0.05$ and $p = 0.01$, respectively). It is interesting to note that at a heating temperature of 110°C, the transverse surface strain increased to 171 percent (24 hr.) and 200 percent (48 hr.) of that in the controls (both different at $p = 0.01$). The reason may be that surface cracking of logs occurred under high temperature and compressive drying stress resulted from case-hardening; this was then superimposed on the original growth stress. The same explanation is suitable for the longitudinal surface stress that changed from tension stress to compression stress under high temperature.

**Figure 8** shows the distribution of residual longitudinal strain across the diameter of heat-treated logs and control logs; the internal stress of heat-treated logs was very small compared with that of the control. It is assumed that the steeper the strain gradient, the more severe is the crook of sawing (Okuyama and Sasaki 1979). It was reasonable that the strains in the logs changed to such a condition that the crook at the time of

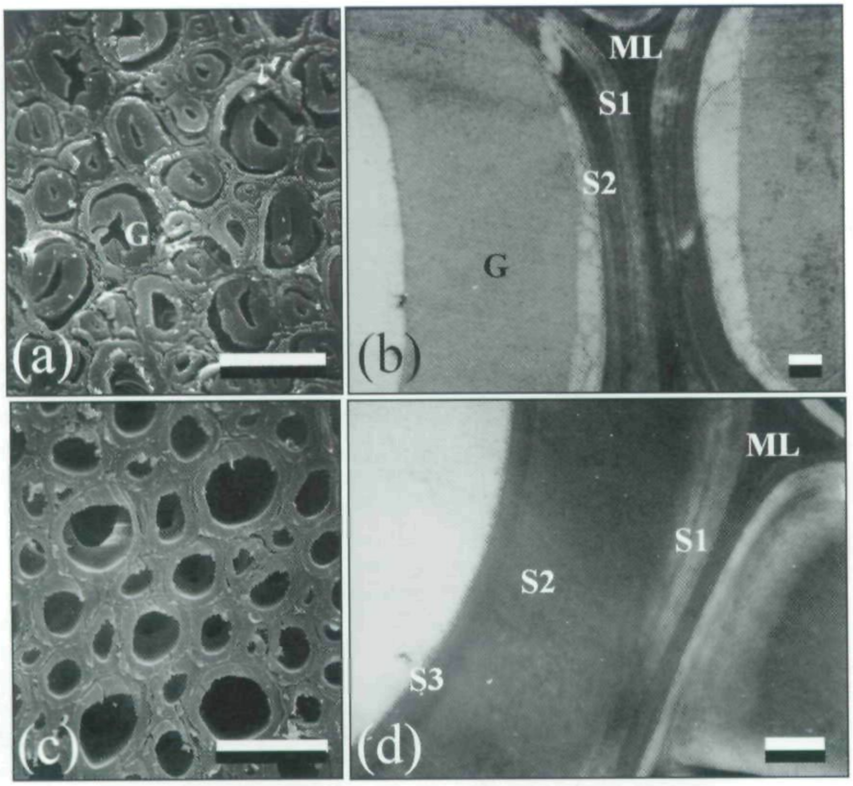


*Figure 5. — Wood structure of zelkova by SEM (a and c) and TEM (b and d); a and b show G-fibers with dominant gelatinous layers; c and d show normal fibers with thick S2 layer between thin S1 and S3 layers of the secondary cell wall; ML = middle lamella; in a and c, the bar = 20 μm; in b and d, the bar = 500 nm.*

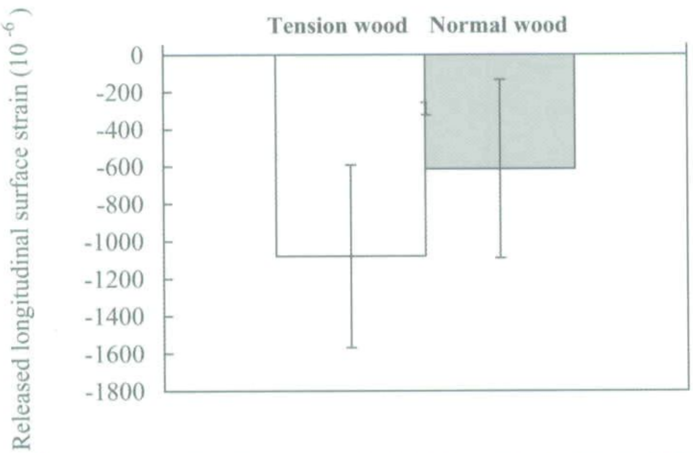


*Figure 6. — Comparison of surface growth strain between tension wood and normal wood.*

sawing would be reduced. It follows that any method that makes the residual strain distribution uniform in the log will improve the lumber quality of sawing, because more stress-balanced boards are obtainable. It was obvious from the result obtained that the heat treatment had a positive effect in reducing the growth stress in logs, resulting in a reduction of the amount of deformation (Tejada et al. 1997).

The reason for stress reduction by wet heating of logs is understood to be a thermal degradation of wood, resulting from softening of lignin and solubilization of hemicellulose under high temperature and high moisture content (Maeglin et al. 1985, Okuyama et al. 1990). The advantages of steam heat treatment of logs are relaxation of growth stress, to reduce the distortion and heart crack in sawn timber, and subsequent increased timber yield. However, the disadvantages of high-temperature treatment are dry cracks of log surfaces and darkening of the wood. Thus, some decrease in value of timber is unavoidable. Based on the results of this study, a steam heat treatment with a temperature below 100°C is suggested.

## Conclusions

There was no obvious relationship between surface growth stress and tree height. Longitudinal surface stress was tensile and transverse surface stress was compressive. The residual internal growth stress was tensile near the outer part of the trunk and compressive in the inner part, yielding a V-shaped distribution. Both the longitudinal surface growth strain and the internal residual strain were reduced by heat treatment. The reduction of longitudinal growth strain increased with increased heating temperature, and with increased heating time. For practical applications, a heating temperature below 100°C is recommended.

## Literature cited

Archer, RR. 1986. Growth Stresses and Strains in Trees. Springer-Verlag, New York. pp. 150-151.

__________ and F.E. Bynes. 1974. On the distribution of tree growth stresses. Part I: An anisotropic plane strain theory. Wood Sci. and Tech. 8:184-196.

Barnacle, J.E. and J.W. Gottstein. 1968. Control of end splitting in round timber. Tech Note 7. Div. Forest Prod., Commonwealth Scientific and Industrial Research Organization (CSIRO), Melbourne, Australia. 4 pp.

Boyd, J.D. 1972. Tree growth stresses. V. Evidence of an origin in differentiation and lignification. Wood Sci. and Tech. 6:251-262.

Chafe, S.C. 1981. Variations in longitudinal growth stress, basic density and modulus of elasticity with height in the tree. Aust. Forest Res. 11:79-82.

Cho, C.H., T.P. Lin, and L.L. Kuo-Huang. 2001. Ultrastructural study on the recalcitrant seeds of *Machilus thunbergii* Sieb. & Zucc. Taiwania 46(2):125-134.

Fournier, M., P.A. Bordonne, D. Guitard, and T. Okuyama. 1990. Growth stress patterns in tree stems. Wood Sci. Tech. 24:131-142.

Guitard, D., H. Masse, H. Yamamoto, and T. Okuyama. 1999. Growth stress generation: A new mechanical model of dimensional change of wood cells during maturation. J. Wood Sci. 45:384-391.

Huang, Y.S., S.S. Chen, T.P. Lin, and Y.S. Chen. 2001. Growth stress distribution in leaning trunks of *Cryptomeria japonica*. Tree Physiology 21:261-266.

__________, __________, __________, and __________. 2002. Growth strain in coconut palm tress. Tree Physiology 22:261-266.

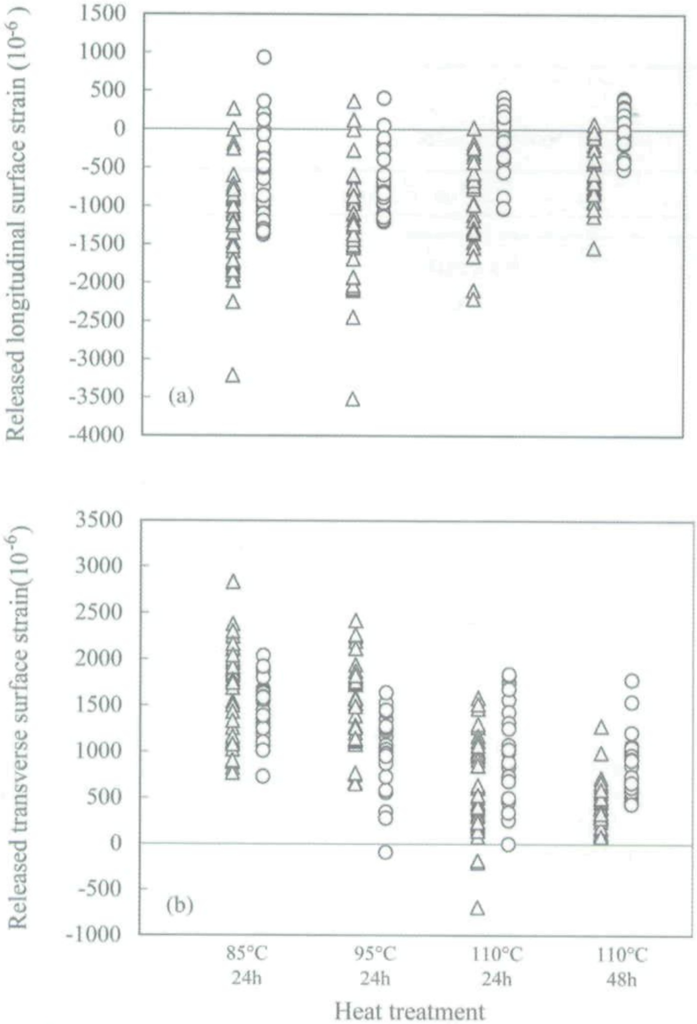


*Figure 7. — Effect of heat treatment on the released surface strain. Symbols: △ = control; ○ = heat treatment.*

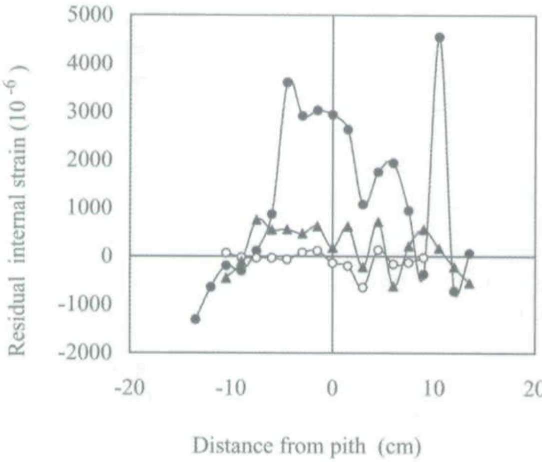


*Figure 8. — Effect of heat treatment on the residual internal strain in the logs. Symbols: ● = control; ○= 110°C/48 hours; ▲ = 110°C/24 hours.*

Kubler, H. 1987. Growth stresses in trees and related wood properties. Forestry Abstracts 10:61-118.

Maeglin, R., J. Liu, and R.S. Boone. 1985. High-temperature drying and equalizing effects on stress relief in yellow-poplar lumber. Wood and Fiber Sci. 17(2):240-253.

Mattheck, C. and H. Kubler. 1995. Wood - The Internal Optimization of Trees. Springer-Verlag, New York. pp. 63-89.

Nicholson, J. 1973. Effect of storage on growth stress in mountain ash logs and trees. Australian Forestry 36(2):114-124.

Niklas, K.J. 1992. Plant Biomechanics: An Engineering Approach to Plant Form and Function. The Univ. of Chicago Press, Chicago, IL. pp. 420-423.

Okuyama, T. and Y. Kikata. 1975. The residual stresses in wood logs due to growth stresses. Mokuzai Gakkaishi 21:326-327.

__________ and Y. Sasaki. 1979. Crooking during lumbering due to residual stress in the tree. Mokuzai Gakkaishi 25(11):681-687.

__________, Y. Kanagawa, and Y. Hattori. 1987. Reduction of residual stresses in logs by direct heating method. Mokuzai Gakkaishi 33(11):837-843.

__________, H. Yamamoto, and I. Kobayashi. 1990. Quality improvement in small log of sugi by direct heating method (2). Mokuzai Kogyo 45(2):12-16.

__________, __________, and Y. Murase. 1988. Quality improvement in small log of sugi by direct heating method. Mokuzai Kogyo 43:359-363.

__________, __________, M. Yoshida, Y. Hattori, and R.R. Archer. 1994. Growth stresses in tension wood: Role of microfibrils and lignification. Annals of Forest Sci. 51:291-300.

Panshin, A.J., C. DeZeeuw, and H.P. Brown. 1964. Textbook of Wood Technology. McGraw-Hill Book Co., New York. pp. 257-276.

Sasaki, Y. and T. Okuyama. 1983. Residual stress and dimensional changes on heating green wood. Mokuzai Gakkaishi 29(4): 302-307.

__________, __________, and Y. Kikata. 1978. The evolution process of the growth stress in the tree: The surface stress on the tree. Mokuzai Gakkaishi 24:149-157.

Tejada, A., T. Okuyama, H. Yamamoto, and M. Yoshida. 1997. Reduction of growth stress in logs by direct heat treatment: Assessment of a commercial-scale operation. Forest Prod. J. 47(9):86-93.

Timell, T.E. 1986a. Compression Wood in Gymnosperms. Vol. 1. Springer-Verlag, New York. pp. 63-89.

__________. 1986b. Compression Wood in Gymnosperms. Vol. 3. Springer-Verlag, New York. pp. 1757-1791, 1799-1824.

Yamamoto, H., T. Okuyama, M. Yoshida, and K. Sugiyama. 1991. Generation process of growth stresses in cell walls. Growth stress in compression wood. Mokuzai Gakkaishi 37(2):94-100.

Yao, J. 1979. Relationships between height and growth stress within and among white ash, water oak, and shagbark hickory. Wood Sci. 11:246-251.