

Ingo Burgert · Takashi Okuyama · Hiroyuki Yamamoto

Generation of radial growth stresses in the big rays of konara oak trees

Received: October 9, 2001 / Accepted: April 22, 2002

Abstract In previous models the distribution of radial tensile stresses in the tree trunk has been explained as a response to the mechanisms of growth stress generation in the longitudinal and tangential directions. We investigated the contribution of ray tissue to growth stress generation in the tree trunk by the origin of the radial stresses during differentiation of parenchyma cells. Measurements on three konara oak trees (*Quercus serrata* Thunb.) were carried out comparing the radial residual strain of big oak rays with the radial residual strain of the axial tissues (containing only uniseriate rays). The results indicated that the ray tissue generated tensile growth stress in the radial direction of the trunk (the axial direction of the parenchyma cells). In contrast to previous assumptions, the growth stresses seem to be variable in relation to the individual tissue types. The mechanical advantage of a radially prestraining effect of the rays is discussed for the living tree.

Key words Radial growth stresses · Ray tissue · Oak · Biomechanics

Introduction

Trees have adapted their shape and structure to terrestrial load conditions.¹ In particular, in the case of wind loads, trees are endangered on their lee side, as the longitudinal compressive strength of wood is only half of its longitudinal tensile strength.² Therefore, the compression side is protected by longitudinal tensile and tangential compressive

stresses at the surface.^{3,4} These growth stresses are generated during the differentiation process of the secondary xylem. Fibers or tracheids, respectively, shorten longitudinally and expand tangentially depending on their microfibril angles and lignin contents.^{5–8} In addition to longitudinal and tangential stresses, radial stresses occur in the tree trunk. Low radial compressive stress in the cambial zone is a basic, necessary condition for regular cell differentiation.^{9,10} In the differentiated xylem the radial compressive stresses change to radial tensile stresses, increasing toward the pith. According to models of the origin of growth stresses in trees, the radial stress distribution is a response to continual generation of longitudinal and tangential stresses of fibers and tracheids in the differentiation zone.^{11,12}

Recently, the mechanical relevance of rays in the living tree was pointed out by several authors.^{4,13,14} The cell wall structure and lignification of ray cells is comparable to that of fibers and tracheids, even though the S₂ layer is less dominant.¹⁵ Because growth stress generation is explained by taking the volume fraction of each secondary wall layer, the microfibril angle, and the lignification into consideration, it seems reasonable to expect that the ray parenchyma cells also generate growth stresses during their differentiation and maturation. Such hints were first found by Schniewind and Kersavage¹⁶ in an investigation on second-order drying stresses in California black oak.

The objective of the present study was to show that models for the distribution of radial tensile stress in the tree trunk in response to the longitudinal and tangential growth stress generation must be expanded, as radial tensile stress generation in the ray tissue must be taken into consideration.

I. Burgert (✉)
Institute of Meteorology and Physics, University of Agricultural Sciences, Türkenschanzstrasse 18, A-1180 Vienna, Austria
Tel. +43-1-4705820-12; Fax +43-1-4705820-60
e-mail: ingo.burgert@mail.boku.ac.at

T. Okuyama · H. Yamamoto
Graduate School of Bioagricultural Sciences, Nagoya University,
Nagoya 464-8061, Japan

Material and methods

Three trunks of konara oak (*Quercus serrata* Thunb.) grown in Gifu Prefecture, Japan were selected. Trunks with a diameter of approximately 20cm were cut to a length of

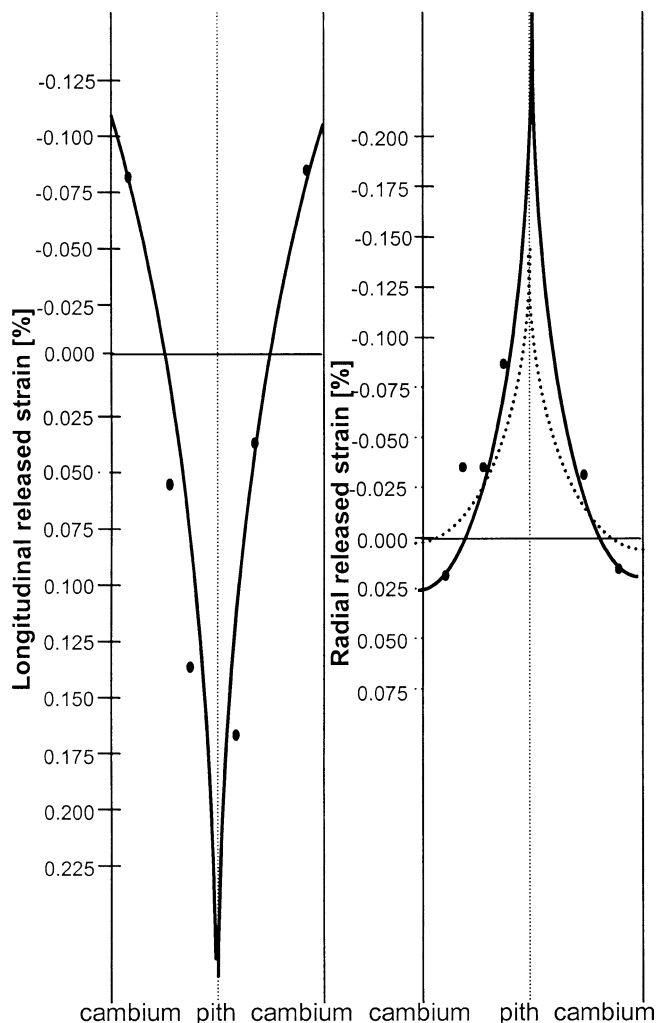


Fig. 1. Longitudinal and radial released strains of the trunk for oak trunk 2. *Straight lines*, measured released strain; *dotted line*, calculated strain, taking Poisson's effect into consideration

120cm. During the entire investigation the wood was kept in the green condition to avoid shrinkage effects. First, the release strain was measured to obtain information on the stress distribution in the whole trunk. The longitudinal and radial released strains were measured, respectively, by pasting wire strain-gauges on the surface of a radial bole and making grooves about 2cm in depth using a hand saw and hand chisel¹⁷ (Fig. 1).

A central trunk section with a length of 40cm was then removed for detailed radial strain measurements. A triangular segment was cut from the trunk section to make the radial surface accessible, as shown in Fig. 2. To avoid radial stress release during the surface preparation a 3cm wide channel depression was shaped with a hand chisel. The distance from the outer side of the depression to the cambium layer along the whole section was 1.5cm (the distance of the strain gauges to the cambium was 3cm) (Fig. 2). This position was chosen because at this position the radial tensile stress and longitudinal stress of the entire wood specimen were rather low (Fig. 1); therefore, the influence of the

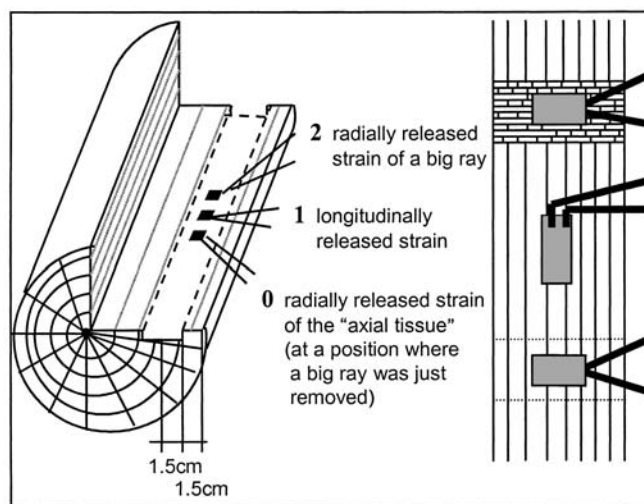


Fig. 2. Procedure to detect radial strains of large rays and "axial tissue" individually. This procedure was repeated for each tree at 15 positions (see Fig. 3, A–O for categories 0 and 2); thus, there were 45 values for each category (0, 1, 2)

axial tissue and the ray tissue seemed to be distinguished more easily. At the bottom of this channel thin slices of fiber bundles were removed surgically with a hand chisel until the radial surfaces of two matched large oak rays were uncovered (Fig. 2).

A 3-mm strain-gauge was glued in its axial direction (radial direction of the trunk) to one of the large oak rays. The second ray was removed totally to measure the released strain in the radial direction of the axial tissue. Because large oak rays always have a minimum distance between them in the tangential direction, this method was suitable for avoiding large rays at this point of measurement. However, the term "axial tissue" must be qualified because "axial tissue" still contains approximately 10% uniseriate rays, because these rays could not be eliminated. A third wire strain-gauge was used to measure the longitudinal strain of the axial tissue at this position, as stress release in the longitudinal direction of the axial tissue influences the radial measurements through Poisson's effect.

The residual strain was released by making thin grooves in the wood with a depth of approximately 1 mm. The longitudinal cuts were made first followed by the radial cuts.

The whole procedure was repeated 15 times for each oak trunk (each with individual positions for categories 0/1/2) to collect enough data for a sufficient comparison between the rays and the axial tissue.

Results and discussion

Residual strain distribution of the radial surface

The three oak trees showed more or less the same distribution of residual strains in the entire wood samples. Oak trunk 2 is an example (Fig. 1).

The released strain in the radial direction near the log surface showed expansion of about 0.02%, and the longitudinal released strain had approximately -0.076% contraction. Taking Poisson's effect into account, longitudinal contraction generates expansion in both the radial and tangential directions. Poisson's ratio, ν_{LT} , of *Quercus serrata* Thunb. is 0.44¹⁷; thus, ν_{LR} might be smaller than ν_{LT} based on the anisotropy of wood. Assuming that Poisson's ratio ν_{LR} is 0.2–0.3, the radial expansive strain induced by the longitudinal contraction could be 0.014%–0.028%. The radial released strain near the log surface shown by the dotted lines in Fig. 1 should then be considered more or less zero strain at the surface, and less contraction would appear near the pith.

This pattern of residual strain coincides with the theoretical model of residual stress in the radial direction,^{11,12} so it can be said that the results indicate a normal distribution. Thus, one can be sure that the special measurements on the ray tissue were carried out on trees with regular growth stresses.

Released strains of ray tissue and axial tissue in the radial direction

The three oak trees showed similar results regarding the examinations of the radial strain of ray tissue and axial tissue for the 90 measurements (Fig. 3). The large rays contract with release of the stresses, so the results indicate the presence of radial tensile stresses. The released strains in the radial direction of the axial tissues indicate small tensile or compressive stresses.

The released strain in the axial direction of the ray tissue was measured by grooves made across the ray tissue; therefore, Poisson's effect of the longitudinal released strain of the axial tissue does not influence the result. On the other hand, the influence of Poisson's effect must be taken into consideration for category 0 (Fig. 2), where the radial strain of the "axial tissue" was examined. However, measurements in the longitudinal direction (position 1) (Fig. 2) indicate rather low longitudinal strain. Combining results for the three oak trunks, a mean value of -0.0066% can be calculated for the longitudinal direction. Therefore, Poisson's effect in the radial direction is rather small (approximately 0.002%), and the difference between the radial released strains of ray tissue and axial tissue is not affected substantially. Furthermore, it is difficult to estimate the influence of the uniseriate rays remaining in the "axial tissue." However, it is possible that these small rays also generate small tensile stresses, influencing somewhat the radial strain of the "axial tissue".

To assume the growth stress levels in the tissues from the released strains, their individual stiffness must also be taken into consideration. Kawamura^{18,19} investigated the radial elastic modulus of large rays and axial tissue (containing uniseriate rays) for three oak species. For the large rays of the investigated oak species the radial modulus of elasticity (MOE) was in the range of 2.38–4.00 GPa, whereas for the axial tissue (containing uniseriate rays) the radial MOE was

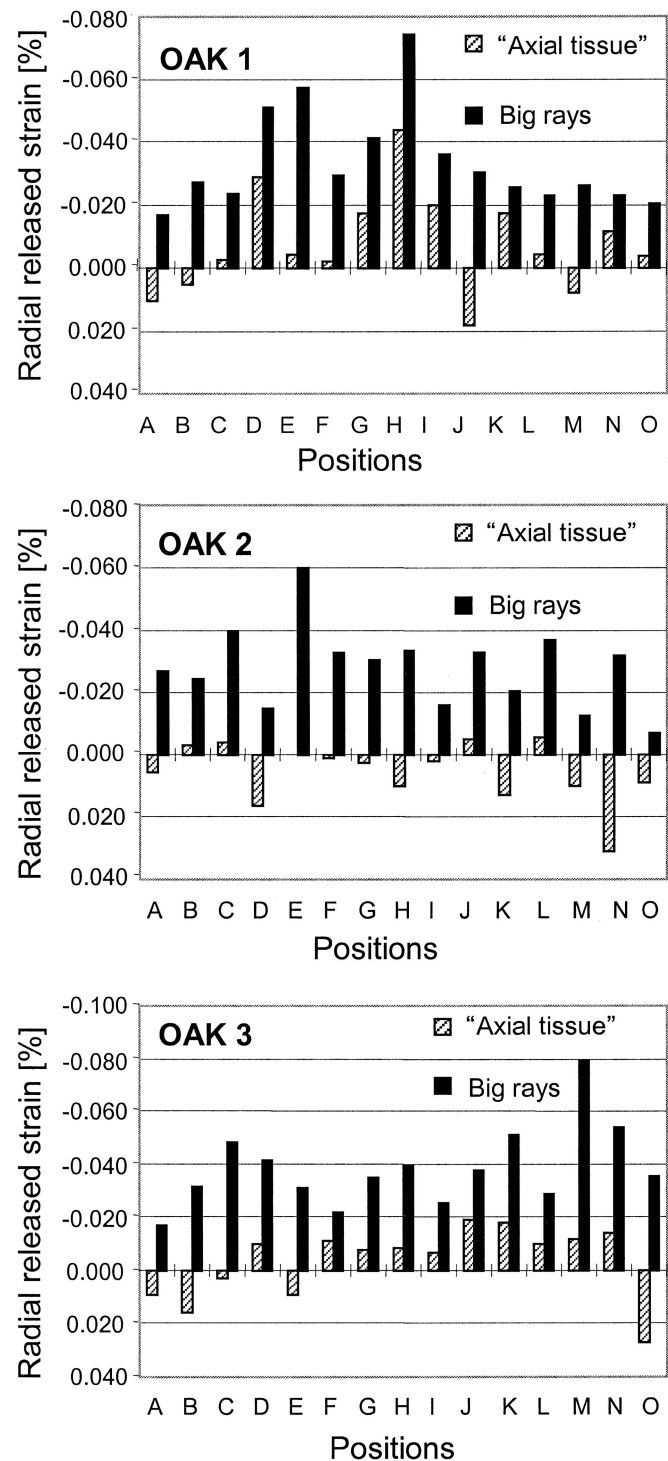


Fig. 3. Release of radial strains of the large rays and the "axial tissue" for three oak trees at 15 positions (A–O) each. For the measurement procedure, see Fig. 2

1.03–1.86 GPa. In view on the fact that the radial stiffness of the large rays is approximately three times as high as the radial stiffness of the axial tissue (with uniseriate rays), it can be assumed that the difference in growth stresses between ray tissue and axial tissue is much higher than the difference in the released strain distribution. Whether the

axial tissue itself holds radial compressive stresses, such as those calculated by Schniewind and Kersavage,¹⁶ has not yet been determined.

Kawamura¹⁸ provided data on the microfibril angle of the ray tissue. Using the X-ray diffraction technique, Kawamura measured microfibril angles of about 60° to the cell axis (radial direction in the trunk). However, these values must be qualified regarding their interpretation according to growth stress generation. Calculations by Yamamoto⁸ indicate that the microfibril angle in the S₂ layer correlates with the generation of growth stresses. Therefore, a cell with a large microfibril angle of about 60° might generate compressive stress in its axial direction, resulting in expansive released strain. In fibers and tracheids, the volume of the S₂ layer may be approximately 20 times that of the S₁ and S₃ layers together. In the ray parenchyma cells of beech (*Fagus crenata*) Harada¹⁵ detected a cell wall structure comparable to that of fibers. However, the ratio of the volumes of the layers was about 1:2:1 (S₁:S₂:S₃); therefore the S₂ layer is less dominant than that in fibers and tracheids. Measurements of the microfibril angle using the X-ray diffraction technique produced integrated values of the entire cell wall. In the case of a dominating S₂ layer (fibers, tracheids), the influence of the S₁ and S₃ layers on the results can be ignored.²⁰ Considering these facts on the measurements of ray parenchyma cells, it seems reasonable to assume that the S₁ and S₃ layers, which are known to have large microfibril angles, influence the results of the X-ray diffraction substantially, leading to overestimation of the microfibril angle in the S₂ layer. Therefore, further investigations on the cell wall structure of ray parenchyma cells are needed to determine whether the released strains of the big oak rays correlate with the cell wall structure, particularly with the microfibril angle of the S₂ layer. This argument raises the fundamental question of the role of the S₁ and S₃ layers in growth stress generation during cell differentiation, particularly in the case of a high volume fraction of these layers in the cell wall (e.g., in parenchyma cells).

Conclusions

It can be deduced from our results that rays and axial tissue contain different growth stresses. Therefore, it must be questioned that at any point in the stem various tissues have the same stress levels.²¹ Our findings, in fact, suppose that the tissue types prestrain each other in the living tree. Therefore, the generation of radial tensile stresses in large oak rays is a clue to the mechanical relevance of the ray tissue. In addition to their high strength¹³ and stiffness,^{14,18,19,22} they contribute actively to the generation of stresses for tree protection. A mechanical explanation for the importance of radial stresses in rays might be given in combination with the previous models on growth stress distribution. The generation of longitudinal and tangential stresses additionally leads to radial tensile stresses, so these stresses endanger the tree because its axial tissue is weak against transverse stresses. Provided the rays generate

tensile stresses during parenchyma differentiation, the matched axial tissue will be stressed while in compression and therefore would be protected against tensile failure.

Acknowledgments This research was carried out during a 2-month short-term stay of the first author at Nagoya University. The financial and organizational support by Monbusho Foundation is gratefully acknowledged.

References

- Niklas KJ (1992) Plant biomechanics. Chicago University Press, Chicago
- Kollmann F (1982) Technologie des Holzes und der Holzwerkstoffe, vol 1, 2nd edn. Springer, Berlin Heidelberg New York
- Boyd JD (1950) Tree growth stresses. I. Growth stress evaluation. Aust J Sci Res B 3:270–293
- Mattheck C, Kubler H (1995) Wood – the internal optimization of trees. Springer, Berlin Heidelberg New York
- Boyd JD (1950) Tree growth stresses. III. The origin of growth stresses. Aust J Sci Res B 3:294–309
- Bamber RK (1979) The origin of growth stresses. Forpride Dig 8:75–79, 96
- Yamamoto H, Okuyama T, Yoshida M (1998) Growth stress generation and microfibril angle in reaction wood. In: Butterfield BG (ed) Microfibril angle in wood, IAWA/IUFRO, University of Canterbury, Christchurch, pp 225–239
- Yamamoto H (1998) Generation mechanism of growth stresses in wood cell walls: roles of lignin deposition and cellulose microfibril during cell wall maturation. Wood Sci Technol 32:171–182
- Brown CL, Sax K (1962) The influence of pressure on the differentiation of secondary tissues. Am J Bot 49:683–691
- Makino R, Kuroda H, Shimaji K (1963) Callus formation, and effects of applied pressure to the cultured cambial explant of sugi (*Cryptomeria japonica* D. Don). Wood Res 69:1–11
- Archer RR, Byrnes FE (1974) On the distribution of tree growth stresses. 1. An anisotropic plane strain theory. Wood Sci Technol 8:184–196
- Okuyama T, Kikata Y (1975) The residual stresses in wood logs due to growth stresses (in Japanese). Mokuzai Gakkaishi 21:326–327, 335–341
- Burgert I, Eckstein D (2001) The tensile strength of isolated wood rays of beech (*Fagus sylvatica* L.) and its significance for the biomechanics of living trees. Trees 15:168–170
- Burgert I, Bernasconi A, Niklas KJ, Eckstein D (2001) The influence of rays on the transverse elastic anisotropy in green wood of deciduous trees. Holzforschung 55:449–454
- Harada H (1965) Ultrastructure of angiosperm vessels and ray parenchyma. In: Côté WA (ed) Cellular ultrastructure of woody plants. Syracuse University Press, Syracuse, NY, pp 235–249
- Schniewind AP, Kersavage PC (1961) A quantitative evaluation of second order drying stresses. For Prod J 11: 523–530
- Sasaki Y, Okuyama T, Kikata Y (1978) The evolution process of the growth stress in the tree: the surface stresses on the tree. Mokuzai Gakkaishi 24:149–157
- Kawamura Y (1984) Studies on the properties of rays. II. Mean micelle angles and physical properties of broad rays. Mokuzai Gakkaishi 30:201–206
- Kawamura Y (1984) Studies on the properties of rays. III. Influence of rays on anisotropic shrinkage of wood (2). Mokuzai Gakkaishi 30:785–790
- Lichtenegger H, Reiterer A, Tschegg SE, Müller M, Riekel C, Paris O, Fratzl P (2000) Microfibril angle determined by X-ray scattering and the correlation with the mechanical properties of wood. In: Spatz HC Speck T (eds) Plant biomechanics 2000. Thieme, Stuttgart, pp 436–442
- Kubler H (1987) Growth stresses in trees and related wood properties. For Prod Abstr 10:61–119
- Badel E, Perré P (1999) Détermination des propriétés élastiques d'éléments individuels du plan ligneux du chêne par des essais de traction sur micro-éprouvettes. Ann For Sci 56:467–478