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Original Articles

The Mechanical Behaviour and Wood Structure Variation in a Growth Increment in Wood of *Cryptomeria japonica*

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Summary : The effect of wood-structure variation on the mechanical behaviour within growth increments in Sugi (*Cryptomeria japonica*) wood sample was studied by applying a compressive load parallel to the grain. The stress-strain behaviour and the cell wall deformation show that earlywood acts as a plastic body even under the very low stress, while the deformation of the latewood cell walls is elastically recoverable at close to the compression ultimate stress. When the load is applied to a wood specimen, the stress induced in growth increments is mainly initiated in the latewood cell wall. In addition, an increase in the stress induced for the latewood portion of a growth increment was correlated with increased proportion of the cell wall substance and a decrease in the microfibrillar angle of the cell wall. The difference of stresses induced in the cell walls between the latewood and earlywood is greater beyond the stress at the proportional limit. It is apparent that the latewood cell wall performs the function of mechanical support against the load applied. Moreover, the rate of tree growth in diameter affects the stress-resisting function between earlywood and latewood in an increment, when the specimen is compressed. The specific compressive stress varies with the location in a growth increment and shows the maximum value at the transition stage from the earlywood to the latewood. The optimum conditions for mechanical properties may exist at this point.

Key words : *Cryptomeria japonica,* Growth increment, Strain, Stress, Wood structure.

Introduction

Growth features affect wood structure which influences the physical and mechanical behaviour of wood. Hence, the mechanical characteristics of wood as an organic material are essentially shown in elastic and plastic responses of cell walls to applied forces (Kitahara *et al.* 1981 ; Kitahara 1982).

It was suggested by our previous work (Kitahara *et al.* 1981 ; 1984a, Kitahara 1982 ; Kitahara & Tsutsumi 1984b) that differences in the mechanical and morphological behaviour between earlywood and latewood to applied load were considerable. According to our work on the mechanism of failure in timber, the earlywood and latewood zone forming a growth ring in softwood exhibited a quite different pattern of cell wall deformation at air-dried condition when a compressive load parallel to the grain was applied to the end grain of a small clear specimen. The difference in such mechanical behaviour between earlywood and latewood (Raczkowski 1963 ; Tabarsa & Hei Chui 2000 ; Dill-Langer *et al.* 2002 ; Conrad *et al.* 2003) should be associated with the response of the cell wall structure to the applied load.

Further work is necessary to examine the effect of cell wall characteristics in a growth increment on the mechanical behaviour of softwoods. Thus, this study deals with the mechanical response of tracheid

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walls in a growth increment to the compressive load applied parallel to the grain. The following topics are investigated : 1） the detailed stress-strain behaviour of both earlywood and latewood ; 2） the effect of wood structure variation on the stresses induced in a growth increment.

Materials and Methods

Sample trees were selected from a 68-year-old Obi-sugi cultivar （*Cryptomeria japonica* D. Don） forest site in Miyazaki. Wood samples were taken at breast height （1.3 m） from the mature woods in three slow-grown （mean 28.5 cm diameter）, five normal-grown （mean 43.0 cm diameter） and three fast-grown （mean 58.5 cm diameter） trees. The five small clear specimens were prepared from each sample tree and were air-dried （12 % moisture content）.

The wood specimens were loaded in compression parallel to the grain. As shown in Fig. 1, small strain gauges were glued to both earlywood and latewood to measure deformation, while large strain gauges were glued to the wood to measure the deformation of whole specimen. Cell wall deformations and failures caused by compressive stress during/after applying static load were observed by using the techniques of scanning electron microscopy （SEM）.

Stresses induced in both the earlywood and latewood in a growth increment were assessed with 'Prescale' film （Fuji Film Co.）. Red patches appear on the film when pressure is applied and the colour density changes according to the various pressure levels. A Photo-Pattern Analyzer （PPA-250A, Rhesca Co.） was used to read the colour intensity of the loaded Prescale film and to evaluate the stress induced to the specimen. Some structural characteristics, such as percentage of the cross-section area occupied by cell walls, mean microfibrillar angle of tracheid walls, percentage of latewood and annual ring width, were measured by using light microscopy.

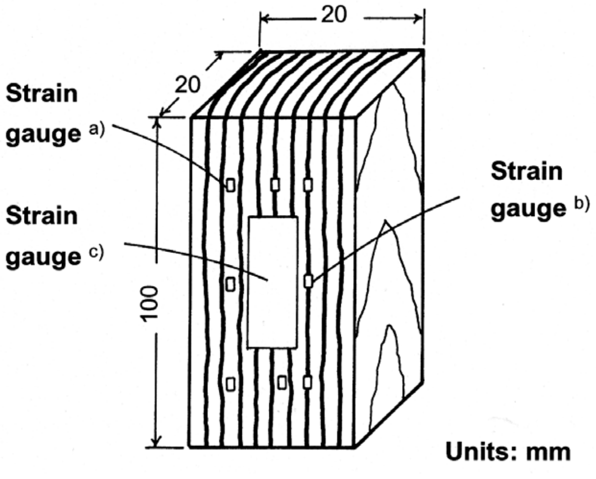

Fig. 1. The specimen with the strain gauges bonded parallel to the grain.

a） : small strain gauges on the earlywood.
b） : small strain gauges on the latewood.
c） : a large strain gauge for the strain induced by the specimen, or both the earlywoods and latewoods.

Results and Discussion

1. Stress-strain behaviour of the earlywood and latewood in growth increments

The stress-strain curves for a wood specimen and both the earlywood and latewood in the wood specimen is shown in Fig. 2. Note that the stress-strain relations exhibit curves from four different locations on a surface of the specimen : the stresses induced in the whole specimen, the earlywood and latewood, respectively, and the strains are based on the strain gauges.

The difference of the stress-strain behaviour between the curves of earlywood （EW） and the curve of latewood （LW） is noticeable in Fig. 2. For the stress-strain curves of earlywood, the linear region is rather short and the curvilinear region is quite long. Note that curvilinear region is found below the order

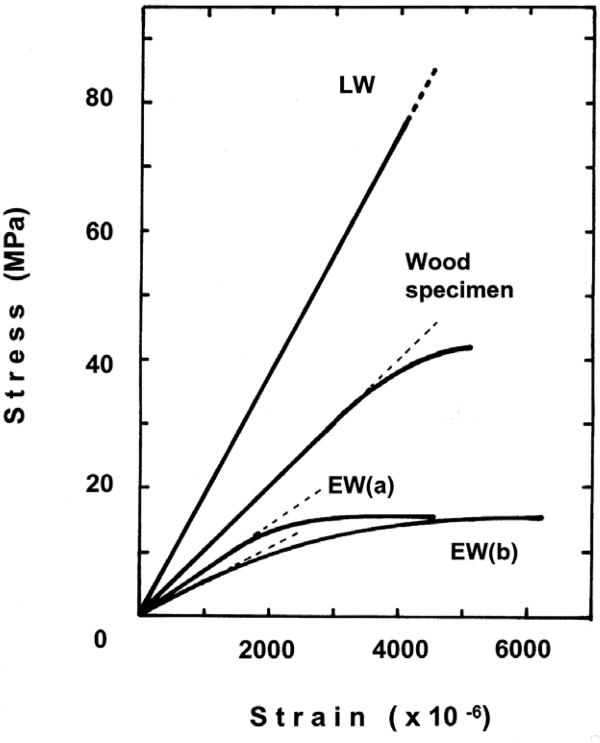

Fig. 2. Stress strain curves for the earlywood （EW）, the latewood （LW） and the wood sample （from a normal-grown tree） subjected to the compressive load parallel to the grain.

of 0.3 of the ultimate stress for the specimen (Fig. 2); the behaviour is concerned with the crease occurring in the earlywood cell (tracheid) walls by loading at the order of 0.3 of the ultimate stress of the specimen (Fig. 3). Microscopic observations reported in previous papers have indicated that the microscopic compression creases (plastic deformation), caused by applying only 0.3 of the ultimate stress, and were visible on the cell walls of the air-dried earlywood after removing the compressive load parallel to the grain (Kitahara 1982, Kitahara *et al.* 1984b). Thus the stress-strain behaviour and the cell wall deformation show that the earlywood acts as a plastic body even under the very low stress. Also, the earlywood has two typical curves (EW(a) and EW(b)) with the different slopes (Fig. 2): the strain measurements induced at location (a) and (b) on the earlywood are different in value because of location (b) being near a crease and the location (a) being far from a crease.

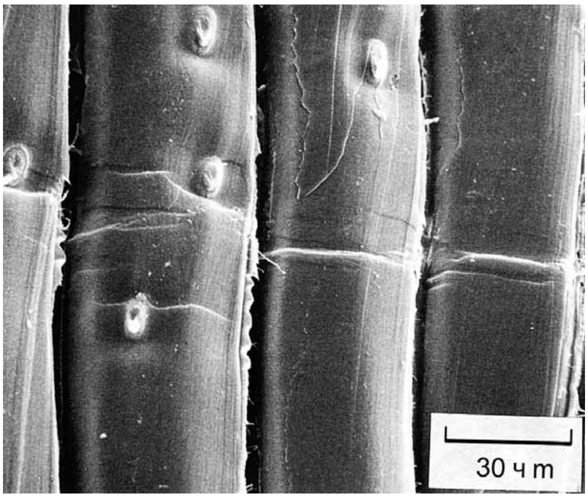

Fig. 3. Minute creases in the earlywood tracheid walls after removing the compression loading in the order of 0.3 of the ultimate stress, radial view. (Micrograph of a filmy replica)

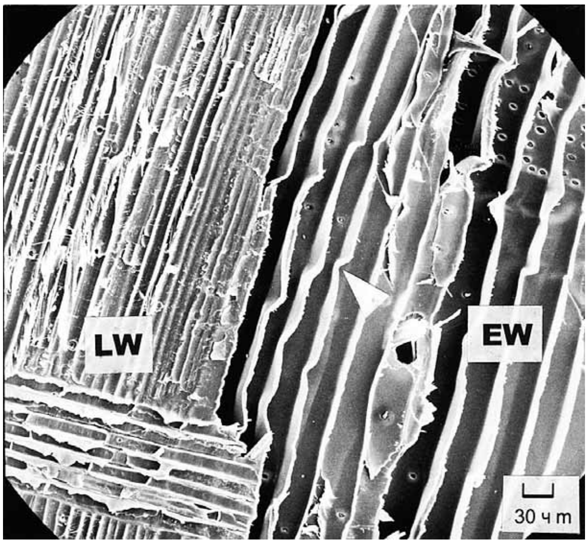

Fig. 4. Cell wall bucklings (arrowhead) in the earlywood tracheid walls under the compression loading in the order of 0.8 of the ultimate stress, radial view (right). No microscopic damage in the latewood tracheid walls (left).

While the stress-strain relation for the latewood extends the linear region in contrast with that for the earlywood as shown in Fig. 2, the stress-strain behaviour agrees with the microscopic observation (Fig. 4): the deformation of the latewood cell (tracheid) walls is elastically recoverable even at close to the compression ultimate stress. The latewood tracheids have thicker walled cells in the wood formed late in the growing season and such wood is denser and stronger than the earlywood tracheids formed at the beginning of the season. Earlywood contains a high proportion of large, thin-walled tracheids compared to latewood, which has thicker walls and sometimes somewhat narrower and frequently flattened tracheids.

2. Relationship between stresses induced within growth increments and wood structure variation

It was suggested by the results in the preceding clause that the differences in the mechanical behaviour between earlywood and latewood were considerable. As for the details of the effect of cell wall characteristics in a growth increment on the mechanical behaviour of wood, further work is necessary.

For a slow diameter-grown tree, the variation in stresses induced within a growth increment in the mature wood under applied load-levels is shown with percentage of cell wall area and mean microfibrillar angle in Fig. 5. The stresses induced within a growth increment increase from the inception of earlywood across the increment, then increase sharply in the transition zone, and reach a maximum in the latewood. The amount of cell wall substance present in wood, expressed as specific gravity, is an important indicator of many of the physical and mechanical properties of wood. The magnitude of the specific-gravity differences across the growth increment is determined by the percentages of the cross-section area occupied by cell walls (i.e. the percentage of cell wall area). We have correlated an increase in the stress induced for the latewood portion of a growth increment with increased proportion of the cell wall substance and a decrease in the microfibrillar angle of the cell wall. Furthermore, the difference of stresses induced in the cell walls between the latewood and the earlywood is greater beyond the stress at the proportional limit. It is apparent that the latewood cell wall performs the function of mechanical support against the load applied (Mott *et al.* 2002b). Wood is built up of functional cell types ; the tracheids are considered to be the mechanical support tissue, and the mechanical properties and behaviour of timber are therefore affected by the cell wall characteristics of tracheids.

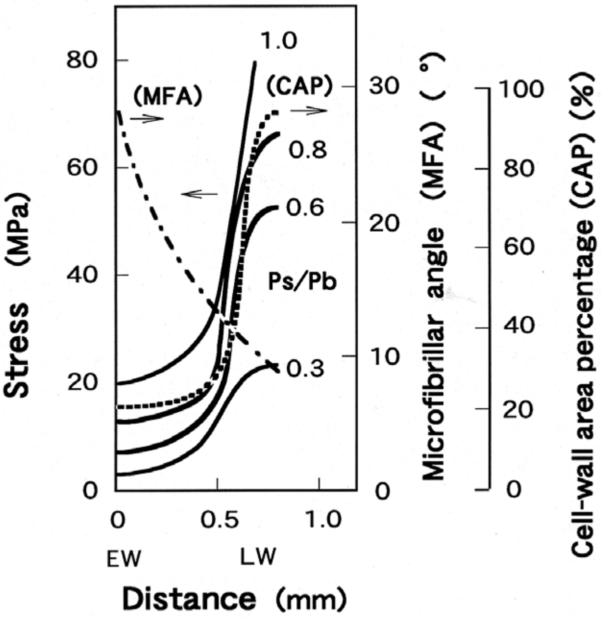

Fig. 5. Stresses induced under applied load-levels (P_s/P_b), cell-wall area percentage and mean microfibrillar angle from earlywood to latewood with-in a growth increment in the mature wood for a slow-grown tree.

P_s is the static load applied to the wood specimen ; P_b, the ultimate load of the control specimen.

It is suggested that the rate of tree growth in diameter affects the stress-resisting function between earlywood and latewood in a growth increment when the specimen is compressed. In a fast-grown tree, as shown in Fig. 6, the difference is rather small in the stress-resisting function between earlywood and latewood, while the larger difference was found in a slow-grown tree (Fig. 5). Also, for juvenile wood with wide annual rings, a pattern of the variation in stress induced within a growth increment was very similar to that for the fast-grown tree. In any case, the influence of growth rate on the mechanical behaviour and properties of softwoods must be examined by further work.

The specific strength, i.e. strength on a unity specific gravity basis, is important for the assessment of mechanical performance of materials. Thus, for the assessment of wood quality in a growth increment, the variations in specific compressive stress (compressive stress/specific gravity) within a growth increment in the wood specimen under some applied load level is shown with cell-wall area percentage in Fig. 7. The specific compressive stress varies with location in a growth increment and shows the value of a maximum at the transition stage from the earlywood to the latewood. The optimum conditions for mechanical properties may exist at this point.

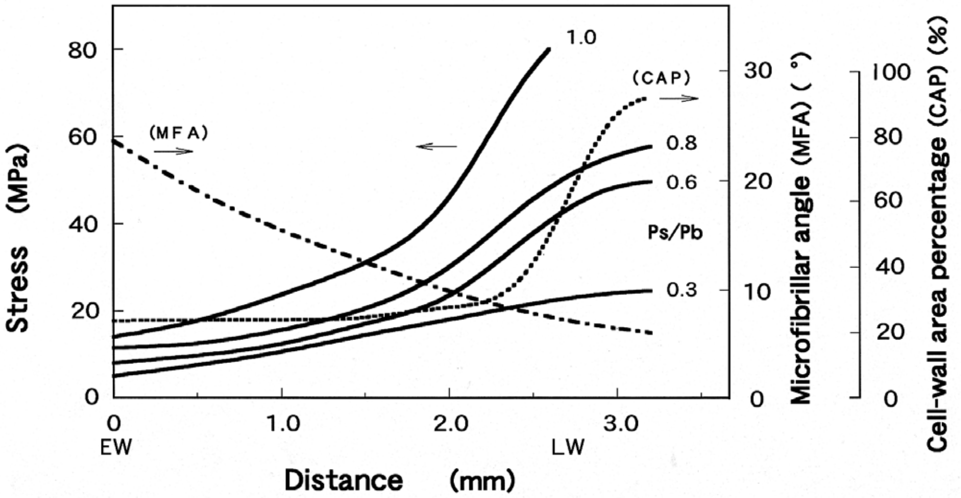

Fig. 6. Stresses induced under applied load-levels, cell-wall area percentage and mean microfibrillar angle within a growth increment in the mature wood for a fast-grown tree.

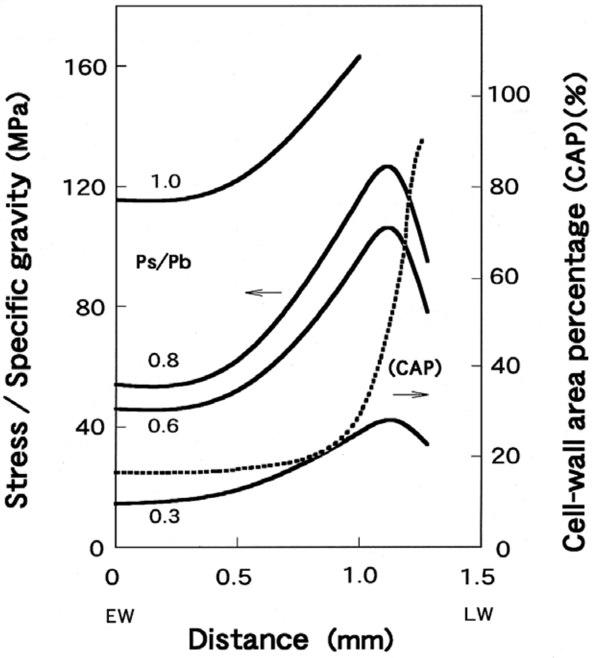

Fig. 7. Variation in the specific compressive stress (compressive-stress / specific gravity) under applied load-levels and cell-wall area percentage within a growth increment in the mature wood for a normal-grown tree.

References

Conrad, M. P. C., G. D. Smith, G. Fernlund (2003) Fracture of solid wood : A review of structure and properties at different length scales. *Wood & Fiber Sci.* **35,** 570-584.

Dill-Langer, G., S. Lutze, S. Aicher (2002a) Microfracture in wood monitored by confocal laser scanning microscopy. *Wood Sci. Technol.* **36,** 487-499.

Kitahara, R., J. Tsutsumi, T. Matsumoto (1981) Observations on cell wall response and mechanical behaviour in wood subjected to repeated static bending load (in Japanese). *Mokuzai Gakkaishi* **27,** 1-7.

Kitahara, R. (1982) Effect of loads on the mechanical and morphological behaviour in wood (in Japanese). Doctoral thesis, Kyushu University, Fukuoka, pp.1-159.

Kitahara, R., J. Tsutsumi, T. Matsumoto (1984a) Effect of static bending load on the mechanical behaviour of wood (in Japanese). *Mokuzai Gakkaishi* **30,** 522-529.

Kitahara, R. & J. Tsutsumi (1984b) Responses of tracheids in wood to applied forces. Proceedings of Pacific Regional Wood Anatomy Conference, IUFRO S5.01 and IAWA, Tsukuba, Japan, 16-18.

Mott, L., L. Groom, S. Shaler (2002b) Mechanical properties of individual southern pine fibers. Part II. Comparison of earlywood and latewood fibers with respect to tree height and juvenility. *Wood & Fiber Sci.* **34,** 221-237.

Raczkowski, J. (1963) The toughness of earlywood and latewood from Douglas-fir of Polish origin. *Holzforschung* **17,** 189-190.

Schmitt, U., H.G. Richter, B. Wittke (1996) Fracture morphology of Hickory (Carya spp., Juglandaceae) under single-blow impact loading. *IAWA J.* **17,** 151-160.

Tabarsa, T. & Y. H. Chui (2000) Stress-strain response of wood under radial compression. Part I. Test method and influences of cellular properties. *Wood & Fiber Sci.* **32,** 144-152.

スギ材の力学的挙動と年輪構造

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要　約

この研究では，スギ材を用いて，繊維方向に圧縮荷重を加えたとき，年輪内早材部と晩材部の応力－ひずみ挙動を実験的に明らかにするとともに，年輪内応力分布への年輪構造の影響を検討した．その結果，木材が荷重を受けたとき，年輪内の早材部と晩材部との間に著しく異なる挙動を認めた．すなわち，早材部仮道管壁が低い応力レベルでも塑性的な挙動を示すのに反して，晩材部仮道管壁では木材ブロックの破壊直前まで弾性的な挙動を示した．つまり，小さなミクロフィブリル傾角と大きな細胞壁率をもつ晩材部仮道管壁が，負荷によって，早材部仮道管壁よりも主体的に荷重を負担することが判明した．その傾向は，比例限度以上の大きな応力レベルで著しかった．また，林木の肥大成長速さの相違が，年輪内の早材部仮道管壁と晩材部仮道管壁の応力負担分布に影響をもたらした．さらに，年輪内の部位ごとにもとめた比応力度（比重を１に換算したときの応力度）の分布において，早材部仮道管壁と晩材部仮道管壁との境界付近に比応力度の最大値が存在した．要するに，木材が荷重を受けたとき，この付近の仮道管壁が最も効率よく力学性を発揮できることが示唆された．

キーワード：応力，スギ材，組織・構造，年輪，ひずみ．