# 木材の応力～ひずみ関係の挙動をとらえる一つの考えかた : 繊維方向の荷重と関連させて

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# A Concept on Stress-Strain Behaviour of Wood Effect of Compressive Stress Parallel to the Grain

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## Abstract

This study deals with the mechanical response of the cell-wall to the compressive load applied parallel to the grain. The results from the analysis of sugi-wood (*Cryptomeria japonica*) were used to introduce a concept on stress-strain behaviour of wood.

The differences in the mechanical behaviour between earlywood and latewood were remarkable at air-dried condition, while the water-saturated wood had much less difference in stress/strain behaviour between the earlywood and the latewood than the air-dried wood.

The mechanical properties and behaviour of timber are affected by the cell-wall characteristics of tracheids. The difference between the latewood and the earlywood in the stress induced increased considerably with increased stress level. It is apparent that the latewood performs the function of mechanical support against the load applied.

## Introduction

Wood is composed of several types of cells and most fundamental properties of wood are the characteristics of cell wall structure. Hence the deformation/failure of timber is essentially under the influence of the elastic and plastic responses of the cell wall to applied forces.

According to our work on the mechanism of wood failure (KITAHARA *et al.*, 1981) (KITAHARA *et al.*, 1982) (KITAHARA *et al.*, 1984 a) (KITAHARA *et al.*, 1984b), 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. In water-saturated wood, on the other hand, microscopic cell-wall damage or failure was rarely observed either in earlywood or latewood after the test. The difference in such mechanical behaviour between earlywood and latewood (RACZKOWSKI, 1963) or between the air-dried and the water-saturated condition should be associated with the response of the cell-wall structure to the applied load.

It is the purpose of this study to provide further knowledge of the mechanical response of the cell wall to the compressive load applied parallel to the grain.

## Material and Methods

Small clear specimens were prepared from the mature wood of an 81-year-old tree

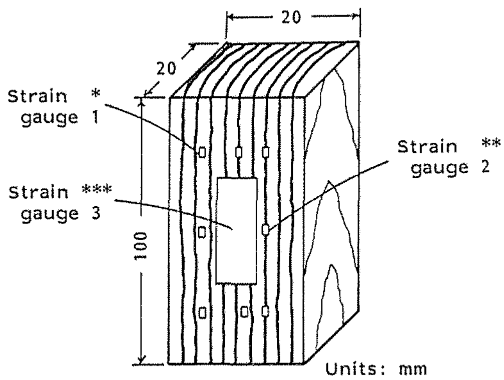


Fig. 1 The specimen with the strain gauges bonded parallel to the grain.
* : the strain gauges on the earlywood.
** : the strain gauges on the latewood.
*** : a strain gauge for the strain induced by the specimen, or the earlywood and latewood.

of sugi (*Cryptomeria japonica* D. Don), and were tested in the water-saturated or air-dried condition.

As shown in Fig. 1, small strain gauges (grid width : 0.5~1 mm×grid length : 1~8 mm) were glued to each of the earlywood and latewood to measure deformation, while a large strain gauge (grid width : 5 mm×grid length : 20 mm) was glued to the wood to measure the deformation of whole specimen. The "Pre-scale" film of Fuji Film Co. was used to assess the stress induced in the earlywood and latewood by the applied load. A photo-pattern analyser (PPA-250A, Rhesca Co.) was used to read the colour intensity of the loaded Pre-scale film and to evaluate the stress applied to the specimen.

## Discussion and Conclusions

### 1. On air-dried wood

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, were visible on the cell walls of the air-dried earlywood after removing the compressive load parallel to the grain, while the deformation of the latewood-cell walls was elastically recoverable even at close to the compression ultimate stress (KITAHARA *et al.*, 1982) (KITAHARA, 1984b). The set of springs shown schematically in Fig. 2 illustrates the responses of the earlywood and the latewood to

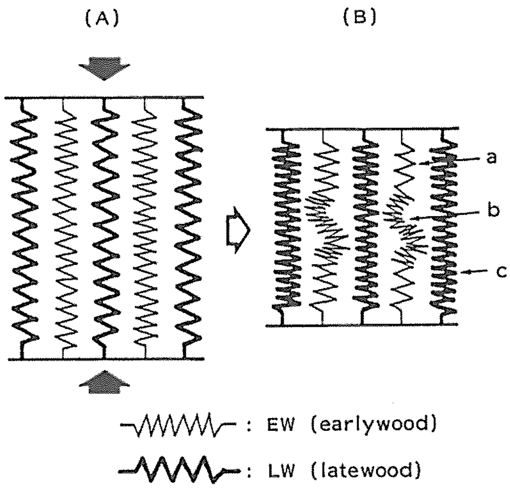


Fig. 2 Schematic illustration of the mechanical behaviour in the earlywood and the latewood; (A) at the beginning of loading, (B) during/after the loading: a: shows the place with small deformation, b: crease, c: elastic deformation.

the applied compressive load parallel to the grain. The microscopic creases occur locally in a weak spring for earlywood (Fig. 2(B)b), and the progress of deformation is considerably smaller in other locations than the creased portion (Fig. 2(B)a). In the latewood-cell wall, on the other hand, the deformation is elastic and no microscopic creases occur as shown in Fig. 2 (B) c.

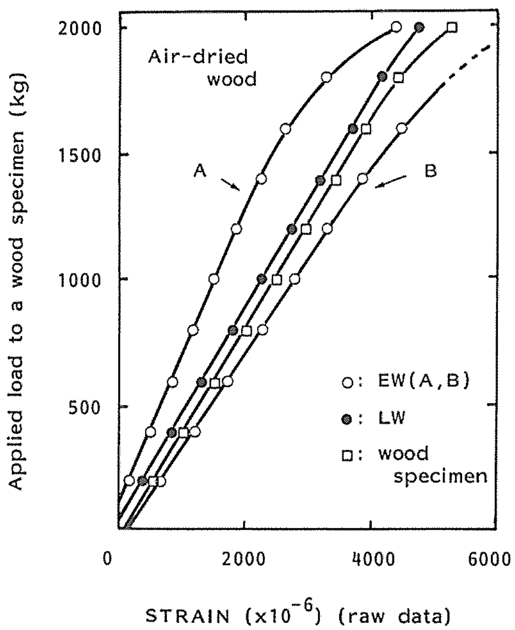


Fig. 3 Relationship of the applied compressive load to the strain induced in the earlywood (EW), the latewood (LW), and the wood-specimen at air-dried condition.

—Strain behaviour—

The strain behaviour both in the earlywood and the latewood in the wood specimen is shown in Fig. 3. Note that the load-strain relations exhibit curves from four different locations on a surface of the specimen: the loads both in the earlywood and the latewood are cooperated for the loads applied to the specimen, and the strain are based on the strain gauges shown in Fig. 1. The difference of the slope between the

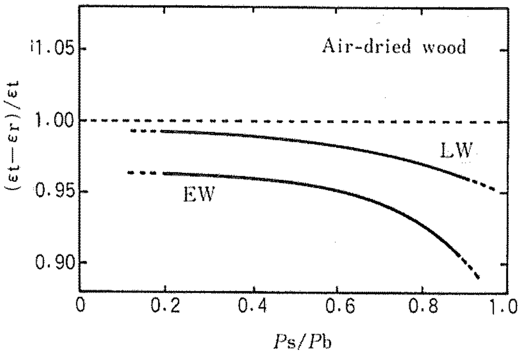


Fig. 4 Effect of the applied-load level ($P_s/P_b$) on the instantaneous strain recovery ($\varepsilon_t-\varepsilon_r/\varepsilon_t$) of the earlywood and the latewood at air-dried condition: $\varepsilon_t$ is the strain during loading; $\varepsilon_r$ the residual strain after unloading; $P_s$ the static load applied to the wood-specimen; $P_b$ the ultimate load of the control specimen.

curve A and the curve B is noticeable in Fig. 3: the strain measurements induced at the location A and the loacation B on the earlywood are different in value as shown in Fig. 2 (B).

The effect of the applied load level on the instantaneous strain recovery in both the earlywood and the latewood is shown in Fig. 4. There was a difference in the strain recovery between the earlywood and the latewood: the strain in the latewood was fully recoverable and remained very small after removing the load.

—Stress behaviour—

When the load is applied to a given wood specimen, the stress induced in the wood specimen may be written as $\sigma=E\cdot\varepsilon$, where $E$ is Young's modulus and $\varepsilon$ is strain. The strains in the earlywood and the latewood are shown schematically in Fig. 2. In addition, it is experimentally confirmed by a number of researchers (RACZKOWSKI, 1963) that Young's modulus of the latewood ($E_L$) is much greater than that of the earlywood ($E_E$). Thus it could be expected that the stress induced in the latewood ($\sigma_L$) is greater than that in the earlywood ($\sigma_E$).

The compressive load parallel to the grain was applied to the specimen, and the stress induced in each of the earlywood and the latewood under the given load level was obtained by using Pre-scale film and is shown in Fig. 5. A larger stress was found in the latewood than in the earlywood even at lower load levels as expected. In

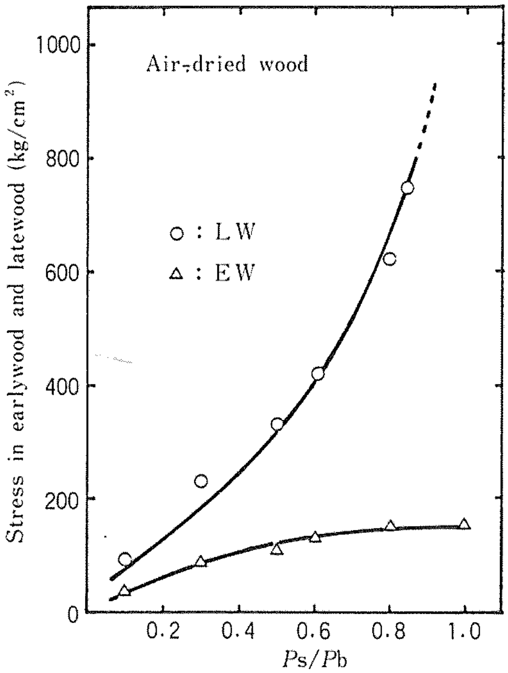


Fig. 5 Relationship between the load level ($P_s/P_b$) and the stress induced in the earlywood and the latewood at air-dried condition : $P_s$ is the static load applied to the wood-specimen ; $P_b$ the ultimate load of the control specimen.

addition, the difference between the latewood and the earlywood in the stress induced increased considerably with increased stress level. It is apparent that the latewood performs the function of mechanical support against the load applied.

On the basis of the stress behaviour shown in Fig. 5, assuming that the longitudinal strains induced in both the earlywood and the latewood were equal to that of the specimen as shown in Fig. 2(B). For the stress-strain curve of the earlywood given in Fig. 6, the linear region is rather short and the curvilinear region is quite long as shown in Fig. 6. Note that the curvilinear region is found below the order of 0.3 of the ultimate stress for the specimen ; the behaviour is concerned with the creases occuring in the earlywood-cell walls by loading at the order of 0.3 of the ultimate stress of the specimen. Thus the cell-wall deformation and the stress-strain behaviour showed that the earlywood acts as plastic body even under the very low stress. The stress-strain relation for the latewood extends the linear region in contrast with that for the earlywood as shown in Fig. 6. The stress-strain behaviour agrees with the microscopic observation which have been discussed in the previous papers (KITAHARA *et al.*, 1981) (KITAHARA *et al.*, 1984b).

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

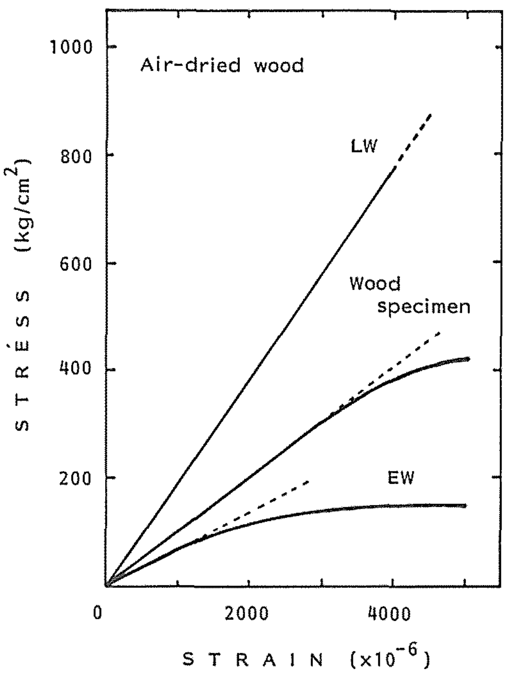


Fig. 6 Stress-strain curves for the earlywood (LW), the latewood (EW), and the wood-specimen subjected to the compressive load parallel to the grain at air-dried condition.

therefore affected by the cell-wall characteristics of tracheids.

## 2. On water-saturated wood

The previous studies (KITAHARA *et al.*, 1982) (KITAHARA *et al.*, 1984b) proved that microscopic failures were rarely observed on the water-saturated cell walls even under high stress level. The aggregation of microfibrils forms the cell wall as the framework of the stress-resisting system (OHTA *et al.*, 1968) (SCALLAN, 1974), and water taken up by wood makes the system loosen.

—Strain behaviour—

The load-strain curves for the wood specimen, the earlywood, and the latewood are shown in Fig. 7. The curves for water-saturated wood, shown in Fig. 7, are much different from those for air-dried wood shown in Fig. 3. It should also be noted that there are no significant differences among the slopes of the curves for the water-saturated wood.

The effect of the applied-load level ($P_s/P_b$) on the instantaneous strain recovery both in the earlywood and the latewood after the load removal is shown in Fig. 8. The two curves for earlywood and latewood show a similar tendency, in that little strain induced by loading both the earlywood and the latewood remains.

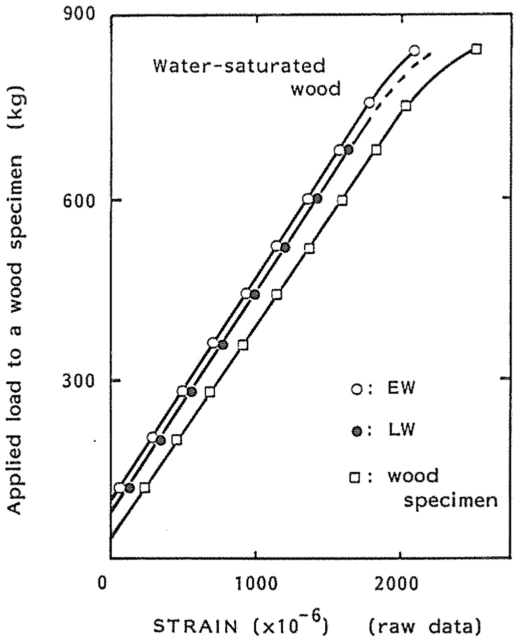


Fig. 7 Relationship of the applied compressive load to the strain induced in the earlywood (EW), the latewood (LW), and the wood-specimen at water-saturated condition.

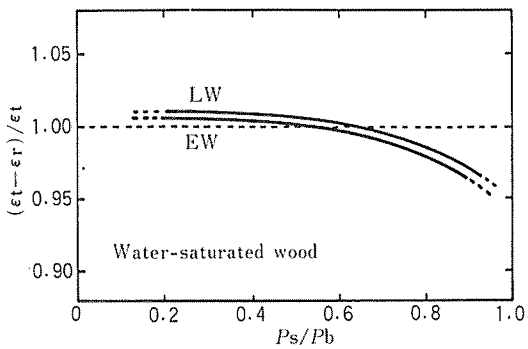


Fig. 8 Effect of the applied-load level ($P_s/P_b$) on the instantaneous strain recovery ($(\varepsilon_t - \varepsilon_r)/\varepsilon_t$) of the earlywood and the latewood at water-saturated condition: the abbreviations are the same as in Fig. 4.

—Stress behaviour—

The stresses induced in both the earlywood and the latewood under the given load level for the water-saturated wood are shown in Fig. 9. The difference in stress between the earlywood and the latewood was much smaller than that for the air-dried wood.

The stress-strain relationships in water-saturated condition for wood specimen, the earlywood, and the latewood are given in Fig. 10 which is based on Fig. 9. The

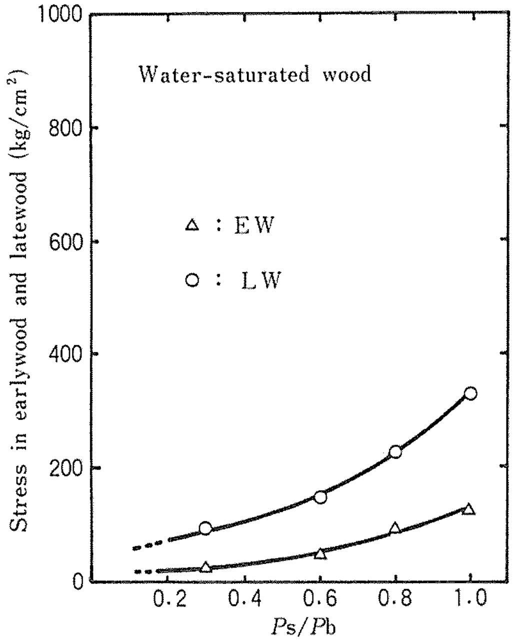


Fig. 9 Relationship between the load level ($P_s/P_b$) and the stress induced in the earlywood and the latewood at water-saturated condition: the abbreviations are the same as in Fig. 5.

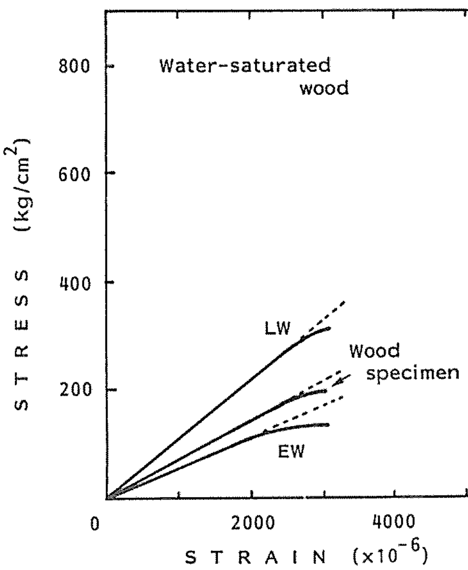


Fig. 10 The stress-strain curves at water-saturated condition: the abbreviations are the same as in Fig. 6.

stress-strain curves of the earlywood and latewood in water-saturated condition differ in the shape from those for air-dried wood: the linear portion on the curves for the water-saturated specimen was more extensive than that for the air-dried one.

The water-saturated wood had much less difference in stress/strain behaviour between the earlywood and the latewood than the air-dried wood. Furthermore, it was apparent that microscopic plastic deformation rarely occurs in the earlywood as well as in the latewood when the cell wall is saturated by water. These result indicate why the stem of living tree does not suffer mechanical damage even under severe growth stresses.

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# 木材の応力～ひずみ関係の挙動をとらえる一つの考えかた
## 繊維方向の荷重と関連させて

北　原　龍　士・堤　　　壽　一

## 要　　　旨


木材は数種類の細胞で構成され，それぞれの細胞には異なった役割りが負わされている．いわゆる繊維は樹木に強さを与え，たとえば針葉樹材の主要構成要素である仮道管は，典型的な強固組織と見なすことができる．

一方，木材の力学的性質に関連して，弾性定数や破壊現象が実験的成果として得られてきた．

ところが，木材の破壊現象や荷重を受けたときの変形現象を，強固組織の力学的挙動と関連させた研究は極めて少なく，十分な知見が得られていない．

以上のようなことを踏まえ，この研究ではスギ（*Cryptomeria japonica* D. Don）材を使って，繊維方向に荷重を与えたときの木材の変形とその挙動，仮道管の変形とその挙動を実験的に検討した．その結果，つぎのことが明らかになった．

(1) 気乾材では，負荷時と除荷時のいずれでも，早材部と晩材部の間で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試験片の破壊直前まで弾性的な挙動が認められた．

(2) 飽水材では，早材部と晩材部のいずれの仮道管壁でも，荷重と変形の関係に気乾材ほどの著しい相違を認めなかった．