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Elastic and Shrinkage Deformation of the Cell Wall in the Longitudinal Direction*1

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Keywords: specific Young’s modulus, shrinkage, microfibril angle.

It has been suggested that the elastic deformation of wood is closely related to its shrinkage deformation. However, there are few reports which dealt with this problem. In this report, the relationship between the Young’s modulus and the shrinkage of wood in the longitudinal direction was investigated.

Almost all cells of coniferous wood are tracheids. Therefore, using parallel multilayer model composed of the cell wall and air, the longitudinal Young’s modulus ($E$) of coniferous wood, as first approximation, can be expressed by the following law of mixtures.

$$E = \frac{\sum (\delta_{wi}E_{wi} + \delta_{ai}E_{ai})}{\sum (\delta_{wi} + \delta_{ai})} \approx \frac{\sum \delta_{wi}E_{wi}}{\sum \delta_{wi}}$$

where $E_{wi}$ and $\delta_{wi}$ are the Young’s modulus and the volume fraction of the $i$-th wall layer, while $E_{ai}$ (≡0) and $\delta_{ai}$ are those of the $i$-th air layer. Specific gravity ($\gamma$) is given by $\gamma = \frac{\sum \delta_{wi} \gamma_{wi}}{\sum \delta_{wi}}$, where $\gamma_{wi}$ is the specific gravity of the $i$-th wall layer. When the mean specific gravity ($\gamma_w$) and the mean Young’s modulus of the cell wall ($E_w$) are defined by $\gamma/\sum \delta_{wi}$ and $\sum \delta_{wi}E_{wi}/\sum \delta_{wi}$, respectively, $E_w$ is given by

$$E_w = E(\gamma_w/\gamma). \quad (1)$$

$\gamma_w$ can be regarded as a constant value of 1.45 in the oven dry condition irrespective of wood species, so that the specific Young’s modulus ($E/\gamma$) is proportional to $E_w$.

In the same way, when the longitudinal shrinkage from the wet condition to the oven dry condition of the $i$-th wall layer is denoted by $S_{wi}$ and the mean longitudinal shrinkage of the cell wall ($S_w$) is defined by $\sum \delta_{wi}S_{wi}/\delta_{wi}$, the shrinkage of wood ($S$) corresponds to $S_w$.

These results indicated that $E_w/\gamma$, instead of $E$, should be related to $S$ to examine the relationship between $E_w$ and $S_w$ in the longitudinal direction.

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*2 Laboratory of Property Enhancement.
In this experiment, normal and compression woods of five species, namely: Sugi (Cryptomeria japonica), Hinoki (Chamaecyparis obtusa), Sitka spruce (Picea sitchensis), Agathis (Agathis bornensis), and Igem (Podocarpus imbricatus), were used. The size of the specimens was 5 mm (radial) by 5 mm (tangential) by 100 mm (longitudinal). Three hundred specimens were used. A three-point bending test was conducted to obtain $E$ in the oven dry condition. $S$ was determined from the dimensional changes of the specimens from the wet condition to the oven dry condition.

![Graph showing relationship between $E/\gamma$ and $S$](image)

**Fig. 1** Relationship between $E/\gamma$ (MPa) and $S$ (%) in the longitudinal direction. The solid line shows the correlative equation for 300 specimens.

Fig. 1 shows the relationship between $E/\gamma$ (MPa) and $S$ (%). There was a good correlation between them, yielding the following expression.

$$S = \frac{b}{(E/\gamma)^a}, \quad (R^2 = 0.819) \quad (2)$$

where $a = 2.40$ and $b = 8.18 \times 10^9$. The experimental values of the normal wood samples have larger $E/\gamma$ and smaller $S$, whereas those of the compression wood samples have smaller $E/\gamma$ and larger $S$. The mean microfibril angle ($\theta$) greatly contributes to both $E/\gamma$ and $S$ in the longitudinal direction\(^1\)\(^2\). Therefore, it is considered that $E_w$ is closely related to $S_w$ through $\theta$.

The following expression between $E_w$ and $\theta$ is proposed\(^1\).

$$E_w(\theta) = \frac{E_0}{1 + k\theta^2} \quad (3)$$

where $E_0$ is the Young's modulus of the cell wall at $\theta=0$, $k$ is a factor which depends on both
Mean microfibril angle ($\theta$)

Fig. 2. Comparison between the calculated (solid line) and experimental (▲) values of $S(\theta)$.

Combining (1), (2), and (3) gives

$$S(\theta) = S_0 (1 + k \theta^2)^a$$

where $S_0 = b(\gamma_\infty/E_0)^a$ is the shrinkage at $\theta = 0$. The values of $S_0$ and $k$ were 0.0638 and 0.00735, respectively. In Fig. 2, the calculated values, shown by a solid line, are compared to the experimental values$^2$.

References