J Wood Sci (2004) 50:15–21
DOI 10.1007/s10086-003-0531-0

ORIGINAL ARTICLE

Tomio Takemura · Takashi Taniguchi

Method to estimate the internal stresses due to moisture in wood using transmission properties of microwaves

Received: June 19, 2002 / Accepted: February 13, 2003

Abstract The purpose of this paper is to offer a new method for detecting stress in wood due to moisture along the lines of a theory reported previously. According to the theory, the stress in wood could be estimated from the moisture content of the wood and the power voltage of a microwave moisture meter (i.e., attenuation of the projected microwave). This seems to suggest a possibility of utilizing microwaves in the field of stress detection. To develop such an idea, the stress formulas were initially modified to the form of an uni-variable function of power voltage, and the application method of the formulas to detection was tried. Finally, these results were applied to the data of sugi (*Cryptomeria japonica*) lumber in the previous experiment. The estimated strains showed fairly good agreement with those observed. It could be concluded from this study that the proposed method might be available for detecting stress in wood due to moisture.

Key words Wood · Microwave moisture meter · Detection of stress · Nondestructive testing

Introduction

Stresses in wood are usually measured by various methods, such as mechanical, optical, electrical, ultrasonic, X-ray, and so on. Particularly the fork-sample[1] and slicing[2] techniques are well known for wood drying. These methods are relatively simple and easily put into practice by anyone, but they are inevitably destructive. On the other hand, one of the authors presented a theory to estimate the stress in wood using a microwave moisture meter.[3] However, the stress formulas used were not convenient for nondestructive testing of lumber, as these formulas contain not only power voltage readings from the moisture meter but also the moisture content of wood, which usually must be determined by a destructive method. To avoid this difficulty, the stress formulas should be modified so they require no moisture content factors, and the parameters included in the formulas should be determined by appropriate methods.[4] The present paper deals with these subjects, and a new method to detect the stress in wood due to moisture is proposed, although the studies have not yet reached the goal of actual detection.

T. Takemura (✉)
3-412 Goshikien, Nisshin 470-0105, Japan
Tel. +81-561-73-5645; Fax +81-561-73-5645
e-mail: ttakemra@js6.so-net.ne.jp

T. Taniguchi
Tobishima Kensetsu, Osaka Shiten, Neyagawa 572-0825, Japan

Part of this report was presented at the 52nd Annual Meeting of the Japan Wood Research Society, Gifu, April 2002

Theory

Stress formulas associated with an equilibrium condition of forces

The fundamental formulas of stress due to moisture can be expressed by the equation[3]

$$\sigma = \pm E\alpha u'', \quad \text{or} \quad \varepsilon = \pm \alpha u'' \qquad (\alpha > 0) \tag{1}$$

where + is for late drying (type 3); − is for adsorption and early drying (types 1 and 2); σ denotes stress, ε is the strain, E is Young's modulus, α is the average shrinkage or swelling per unit change of moisture content, u'' is the moisture difference between the moisture u' under stress and the moisture u under nonstress, namely

$$\begin{aligned} u'' &= u' - u \\ u &= av + b \\ u' &= a'v + b' \end{aligned} \tag{2}$$

where v is the power voltage of the microwave moisture meter, and a, a', b, and b' are parameters that can be determined experimentally. Therefore, Eq. (1) might be ex-

pressed as a function of power voltage v instead of moisture difference u''.

$$\sigma = \pm E\alpha a'' V, \quad \text{or} \quad \varepsilon = \pm \alpha a'' V \qquad (a'' = a' - a) \tag{3}$$
$$V = v - v_c \qquad (v_c = -b''/a'',\ b'' = b' - b)$$

where v_c means the v at the intersection point C of the straight lines u and u' given by Eq. (2).

The stress σ in the above is also uni-axial, and associated with the coordinates system $x - \sigma$ where the axis x is taken parallel to the width of the wood with a rectangular section and the axis σ is that for the vertical. Then the stresses distributed along the axis x should satisfy an equilibrium condition of forces

$$\Sigma \sigma dx = 0 \tag{4}$$

where the origin of x is the center of the width of the specimen, and Σ the summation over the width. Substituting the right side of Eq. (3) for the σ in the left side of Eq. (4) yields

$$\Sigma E\alpha a'' V dx \fallingdotseq E\alpha a'' dx\{\Sigma v - \Sigma v_c\} = 0 \tag{5}$$

hence

$$v_c = \Sigma v/n = v_m \tag{6}$$

where n is a total number of the summation, and v_m is the mean of the power voltages along the width of the specimen. In the following, the formula for the strain type in Eq. (1) is mainly used for convenience. Then Eq. (3) can be expressed as

$$\varepsilon = \pm \alpha a'' V \qquad (V = v - v_m) \tag{7}$$

This may be rewritten again as

$$\varepsilon = kV \quad \text{for type 1} \qquad (k = |\alpha a''| > 0)$$
$$= -kV \quad \text{for types 2 and 3} \tag{8}$$

Provided that k is regarded as a constant through all the stress types, Eq. (8) might be expressed as

$$\varepsilon = \pm kV \fallingdotseq \pm k_o V \qquad (k_o = \text{const.} > 0), \text{ or}$$
$$V = \pm q\varepsilon \fallingdotseq \pm q_o \varepsilon \qquad (q = 1/k,\ q_o = \text{const.} > 0) \tag{9}$$

It should be noted here that the observed strain ε_s in the slicing technique is related to the strain ε as

$$\varepsilon = -\varepsilon_s \tag{10}$$

Methods to determine the stress

The stress formulas above can be used in various ways. The following three methods are examples as a prototype for improvement toward the detection of stresses.

Method 1. When the regression lines $u = av + b$ and $u' = a'v + b'$ are known, the moisture difference u'' is merely given by subtraction of u' and u. Hence

$$\varepsilon = \pm \alpha u'' \qquad (u'' = u' - u) \tag{11}$$

Method 2. If the regression line $u = av + b$ is unknown in method 1, it would be determined by using the data (u', v) of the line u' and the relation $v_c = v_m$ in Eq. (6).

$$u_c = u'_c = u'(v_m) = u'_m \qquad (v_m = \Sigma v/n,\ u'_m = \Sigma u'/n)$$
$$\therefore \quad (u_c, v_c) = (u'_m, v_m)$$

Thus, the regression analysis for the paired-data (u'_m, v_m) on the u'-v plane would yield the line u

$$u'_m = av_m + b = u = av + b \tag{12}$$
$$\varepsilon = \pm \alpha a'' V \qquad (a'' = a' - a,\ V = v - v_m) \tag{13}$$

Method 3. When certain series of the paired-data (ε_s, v) are present, the parameters $k_o (\fallingdotseq k)$ and q_o can be obtained from the regression lines between two quantities ε_s and $V (= v - v_c)$:

$$\varepsilon_s = \pm kV \fallingdotseq \pm k_o V \quad (-, \text{ type 1; } +, \text{ types 2 and 3}), \text{ or} \tag{14}$$
$$= \pm(1/q)V \fallingdotseq \pm(1/q_o)V \tag{15}$$

According to the statistics k and q in Eq. (9) are in the relation

$$k = qr^2 < q \qquad (|r| < 1) \tag{16}$$

where r is the correlation coefficient of strain ε_s against voltage V. The magnitude of k_o or q_o should be determined in consideration of the above relationships and as a requisite for the objective of detection.

Experiment

Materials

The specimens used were the same as in the previous experiment.[3] They were made of sugi (*Cryptomeria japonica*) lumber with a pith toward the center of their cross sections, a size of 10.5/11.5 cm × 10.5/11.5 cm × 20 − 45 cm (parallel to the fiber direction) and a specific gravity after air-drying of about 0.42–0.44. A total of 15 specimens were divided into two groups (A) and (B) as shown in Table 1. Group A consisted of 10 specimens for determining mainly a regression line between the moisture content u' and the power voltage v among the specimens. Group B consisted of five specimens for measuring mainly the strains ε_s of each specimen via the slicing technique. Of course the regression line with the u' and the v in each of the specimens was investigated in both groups A and B. The specimens in group A were dried intermittently in both a room and a small kiln kept below approximately 40°C from their green state to the targeted moisture contents (ca. 36%, 22%, 20%, 17%, 15%, 12%, 11.4%, 10.8%, 10.1%, 9.3%). The specimens in group B were humidified in three ways. Two of the five were dried intermittently in a kiln with a humidifier [80%–60%

Table 1. Specimens used[3]

Specimen no.	Average moisture content (%)	State of moisture
Group A		
36	36.23	Drying
22	21.66	Drying
20	20.00	Drying
31	17.85	Drying
15	15.16	Drying
12	12.20	Drying
11	11.37	Drying
9	9.26	Drying
4	10.79	Air-dry
5	10.06	Air-dry
Group B		
69	68.59	Drying
50	50.22	Drying
18	17.82	Adsorption
14	13.49	Air-dry
9b	11.05	Air-dry

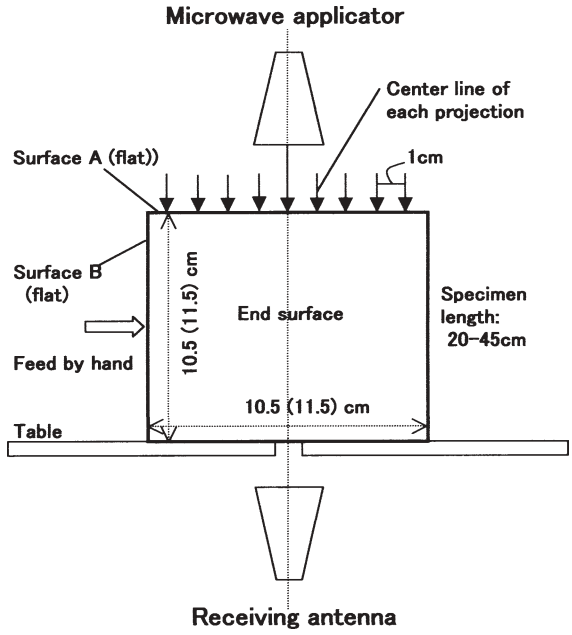

Fig. 1. Microwave projection on the specimen surface A

under the relative humidity (RH)] and temperatures similar to the above. The remaining two were humidified from the air-dried condition to targeted moisture contents of about 18% and 14%, respectively, in desiccators filled with saturated salt-water vapors of 93% and 75% RH at room temperature. The final specimen came from group A 6 months after the end of the first experiment and was used again for the slicing technique.

Apparatus and measuring of power voltage v, moisture content u', and strain ε_s

A microwave moisture meter MM-94L (Kawasaki Kiko Co.) was used for the experiment. A humidified specimen was put on the table of the meter where the axial direction of the specimen was parallel to the electrical field of the microwave. Then microwaves were projected on one of the flat surfaces of the specimen, as seen in Fig. 1. It was directly received by an antenna under the table through a receiving window of 4.0 × 4.0 cm, and the power voltage v of the meter was indicated on its display panel. The specimen was then moved forward by hand, and the projection of microwaves was repeated. Projection and measurement of the microwaves was performed along the width of the specimen at 1.0 cm intervals. At the end of these measurements, a thin section of the specimen 1.0 cm thick was removed for the slicing technique and cut into slices along and at the centerline of the microwave projection. The length of each slice was measured before and after the slicing with a digital caliper that had an accuracy of ±0.01 mm. The moisture content of each slice was also determined by the oven-dried method. An additional section adjacent to the first section was taken from the same specimen and cut into small pieces of 5 × 5 division to acquire a detailed account of the moisture distribution across the cross section. The moisture distribution by 5 × 5 division was investigated for each of the specimens in Table 1.

Results and discussion

Observed data from the specimens

The data for all specimens are too numerous to describe here, so the data from the specimens belonging mainly to group B in Table 1 are shown in Table 2 where specimen 9b lacks the strain data partly because of the presence of a slight crack (there were no cracks in the other specimens). Specimen 69 from group B is also omitted, but specimen 22 from group A is added instead. The reason for this is that it has as high a moisture content as that of specimen 50 in the table.

Regression lines of the specimens

Table 3 shows the parameters a' and b' of the regression line for each of the specimens in Table 2, where r denotes the correlation coefficient of moisture content u' against the power voltage v. The figures of a' and b' in the table indicate a positive (none) or negative status, but the magnitudes of r exhibit fairly high values as a whole except in the case of specimen 9b, which had a shallow crack. The asterisks * and ** by the figures of r denote "statistically significant" in the sense of a significance level beyond 5% or 1%, respectively. The magnitude of r seems to indicate an increasing tendency with increasing moisture content u'_m up to about fiber saturation point, and to continue at nearly a constant level after reaching its maximum.

On the other hand the specimens of group A in Table 1 yielded the following regression line, which was already described in a previous paper[3]

Table 2. Observed data of power voltage, moisture content, and strain of group B in Table 1

x (cm)	v (v)	u' (%)	ε_s (%)
Specimen 18			
−5	1.553	18.69	−0.008
−4	1.508	18.81	−0.110
−3	1.133	17.97	−0.034
−2	1.142	17.50	−0.051
−1	1.151	17.33	0.110
0	1.169	17.15	0.144
1	1.285	17.19	−0.017
2	1.230	17.63	0.059
3	1.132	17.81	−0.136
4	1.233	18.71	−0.051
5	1.247	18.49	−0.248
Specimen 14			
−5	0.956	12.70	0.068
−4	0.824	13.60	0.282
−3	0.735	14.12	0.017
−2	0.695	14.03	0.017
−1	0.631	13.81	0.291
0	0.581	13.81	0.221
1	0.602	13.75	−0.043
2	0.636	14.01	0.059
3	0.717	13.63	0.068
4	0.872	13.32	0.411
5	0.946	12.91	0.034
Specimen 22			
−4	1.179	14.42	
−3	1.472	18.99	
−2	1.641	23.55	
−1	1.860	25.98	
0	2.139	28.41	
1	1.759	27.78	
2	1.915	27.15	
3	1.546	21.02	
4	1.324	14.89	
Specimen 50			
−5	0.934	20.00	−0.359
−4	1.335	25.57	−0.047
−3	1.619	48.90	0.018
−2	1.976	73.95	0.094
−1	2.082	73.65	0.113
0	2.081	64.71	−0.028
1	2.022	66.26	−0.047
2	1.946	67.07	−0.065
3	1.525	50.12	−0.131
4	1.213	37.20	−0.385
Specimen 9b			
−5	0.645	9.64	0.31
−4	0.625	10.73	0.48
−3	0.524	10.91	0.06
−2	0.510	11.20	0.07
−1	0.598	11.59	–
0	0.634	11.59	–
1	0.605	11.59	–
2	0.622	11.59	–
3	0.841	11.21	−0.21
4	1.158	10.44	0.18

x, measuring position on the width of the specimen; $x = 0$, middle point of the width; v, voltage; u', moisture content; ε_s, strain

$$u' = 9.6408v + 6.0521(\%) \quad (r = 0.9810) \quad (u' < 30) \tag{17}$$

where u' represents the moisture content of the middle layer (1.0 cm wide) of each specimen (Fig. 1), and v is the power voltage of the same layer. Lines similar to those in Eq. (17) had been found also by Okada.[5]

Table 3. Values of parameters a′ and b′, correlation coefficient r, mean moisture content u'_m, and mean power voltage v_m for each specimen

Specimen no.	a' (%/v)	b' (%/v)	r	v_m (v)	u'_m (%)
18	2.7837	14.447	0.6402*	1.253	17.93
50	45.839	−23.960	0.9560**	1.673	52.74
14	−2.8224	15.711	−0.8332**	0.745	13.61
9b	−1.0423	11.754	−0.3113	0.676	11.05
22	16.962	−5.493	0.9486**	1.648	22.47

* Significant at the 5% significance level
** Significant at the 1% significance level

$$\begin{aligned} &y = 8.5262v + 5.6634(\%) \ (r = 0.9715) \\ &\quad (y < 25) \ (\text{sugi: } 11.8 \times 11.8\,\text{cm}) \\ &y = 10.2220v + 3.8779 \ (r = 0.9440) \ (y < 30) \end{aligned} \tag{18}$$

where y denotes the moisture content of the middle portion (7.8 cm wide) of the width of sugi lumber. These three equations are somewhat different from each other but not substantially so. Therefore Eq. (17) could be regarded as representative of them and might be employed as the line under nonstress in the sense of a temporary meaning.

$$u \fallingdotseq u' = 9.6408v + 6.0521 \ (\%) \quad (u < 30) \tag{19}$$

To ascertain the relation described by Eq. (12), the regression line for the paired-data of (v_m, u'_m) in Table 3 was determined under the condition of a moisture content below 30%.

$$u = u'_m = 10.8420v + 4.5501 \ (\%) \quad (r = 0.9887) \quad (u < 30) \tag{20}$$

This line is similar to the temporary line (Eq. 19), but the correlation coefficient $r = 0.9887$ is somewhat higher than those in Eqs. (18) and (19). The aptness of Eq. (20) is explained later.

Stress types of the specimens

According to the previous theory[3] the types of stress of the specimens can be classified by the parameters a and a' of the regression lines u and u'.

$$\text{Type 1: } a > a' > 0; \text{ type 2: } a' > a > 0; \text{ type 3: } a' < 0 \tag{21}$$

The data of a' in Table 3 and the values of a in Eq. (19) or (20) result in stress types such as the following.

$$\begin{aligned} &\text{Type 1: no. 18} && (a = 9.64, \text{ or } 10.84 > a' = 2.78 > 0) \\ &\text{Type 2: nos. 50 and 22} && (a' = 45.84,\ 16.96 > a > 0) \\ &\text{Type 3: nos. 14 and 9b} && (a > 0 > a' = -2.82,\ -1.04) \end{aligned} \tag{22}$$

The parameters a' and a are not known at first in method 3, so more information is needed to discern the stress type of each specimen. Generally, it would be the information on the moisture histories of the specimens and the data of

Table 4. Parameters a″, b″, and k for each specimen and all specimens

Specimen no.	a'' (%/v)	b'' (%/v)	v_c (v)	ε_s*
Method 1				
18	−6.8571	8.3949	1.224	
50	36.1982	−30.0121	0.829	
14	−12.4632	9.6589	0.775	ε_{s1}
9b	−10.6831	5.7019	0.534	
22	7.3212	−11.5451	1.577	
Method 2				
18	−8.0583	9.8969	1.228	
50	34.9970	−28.5101	0.815	
14	−13.6644	11.1609	0.817	ε_{s2}
9b	−11.8843	7.2039	0.606	
22	6.1200	−10.0431	1.641	
	$\lvert a''\rvert$ (%/v)	k_o (%/v)	q_o (%/v)	ε_s*
Method 3				
18–22	3.784	0.3784	–	ε_{sk}
18–22	13.259	–	0.7542	ε_{sq}

ε_s*, type of estimated strain; v_c, $= -b''/a''$; k, $\fallingdotseq k_o$ or $1/q_o$ (see the text)

power voltages, as shown in Tables 1 and 2. The data of v for each specimen in Table 2 would draw a broken line concave upward (nos. 18, 14, 9b) or downward (nos. 50, 22) against axis x, but specimen 18 is unique in the process of adsorption (Table 1). Hence specimen 18 can be separated from specimens 14 and 9b, and it turns out to be of type 1. In contrast, specimens 50 and 22 might be of type 2 because of their high moisture contents beyond/toward the fiber saturation point, and their broken lines concave downward. The residual specimens 14 and 9b might be of type 3 because of their low moisture contents near or at the air-dried condition, and their broken lines concave upward. These results perfectly coincide with the stress types shown in Eq. (22).

Obtaining parameters a'' and k

Parameters a'' and k of the specimens can be determined after determining the stress type of each specimen.

Method 1. The parameter a'' can be easily attained from the subtraction $a'' = a' - a$, though it is not always needed for calculating stress. Using the data of a' in Table 3 and a in Eq. (19) $u = 9.6408\ v + 6.0521$ (%), the value of a'' for each specimen was calculated as shown for method 1 in Table 4, where the values of b'' $(= b' - b)$ and v_c $(= -b''/a'')$ are also shown.

Method 2. The parameter a in Eq. (20) $u = 10.8420\ v + 4.5501$ (%) is used, and the results for this are again exhibited for method 2 in Table 4 together with the values of b'' and v_c. The figures of a'' in this case are somewhat different from those in method 1 but not substantially so. Similarly, the figures of v_c for each specimen in the table resemble each other for the same specimen. Furthermore, they also resemble the figures of the average power voltages v_m in Table 3 except in the case of specimen 50, which shows an abnormally large figure. Perhaps this abnormality can be attributed to the moisture content of specimen 50 (ca. 50%), which is far beyond the fiber saturation point. Therefore, the relation expressed by Eq. (6) might be regarded as existing in the specimens under the restriction of moisture content below 30% for Eq. (20) or (19).

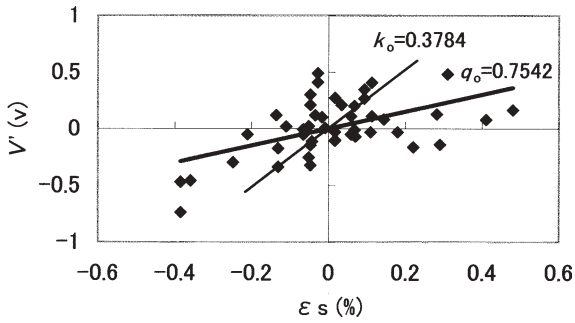

Fig. 2. Plots for the observed data (ε_s,V') of the specimens and regression lines of V' versus ε_s and v.v. where $V' = +V$ for drying and $V' = -V$ for adsorption; ε_s, observed strain; V, voltage difference $(v - v_c)$

$$v_c \fallingdotseq v_m \qquad (u' < 30) \tag{23}$$

The parameter a'' for method 2 in Table 4 displays an increasing tendency with increasing v_m, and the following equation presents the regression line determined from these data.

$$a'' = 18.272\ v_m - 26.615\ (\%/\mathrm{v}) \quad (r = 0.9318) \quad (u' < 30) \tag{24}$$

Method 3. The parameter $k \fallingdotseq k_o$ or q_o can be determined from the paired-data of (v, ε_s) in Table 2 where the missing data for ε_s in specimen 22 can be obtained from those of specimen 50, which indicates that there is the same stress type as that for specimen 22. Preliminary investigations revealed that this has little effect on parameters k_o and q_o. The paired data of (v, ε_s) of each specimen were then converted to the form of (V', ε_s) where V' denotes merely the voltage difference V $(= v - v_m)$ for the specimen during drying but is denoted as $-V$ for the specimen during adsorption. Based on these data of (ε_s, V'), the diagram to determine the parameters k_o and q_o was drawn as shown in Fig. 2, where the dark points in the figure represent the plotted points of all the specimens, the bold line is the regression line of $V'(v)$ against strain ε_s (%), and the solid line is the regression line of strain ε_s against V'. Thus it follows that

$$q \fallingdotseq q_o = 0.7542\ (r = 0.5333), \quad k \fallingdotseq k_o = 0.3784\ (r = 0.5300) \tag{25}$$

Here if we assume $\alpha = 0.1$[6] it follows that

$$\lvert a''\rvert \fallingdotseq k_o/\alpha = 3.784\ (k_o = 0.3784), \quad (\alpha = 0.1) \tag{26}$$

$$\fallingdotseq 1/(q_o \cdot \alpha) = 13.259\ (q_o = 0.7542) \tag{27}$$

It is remarkable that the values of $|a''|$ in Eqs. (26) and (27) roughly coincide with those of 6.12 and 13.66, which repre-

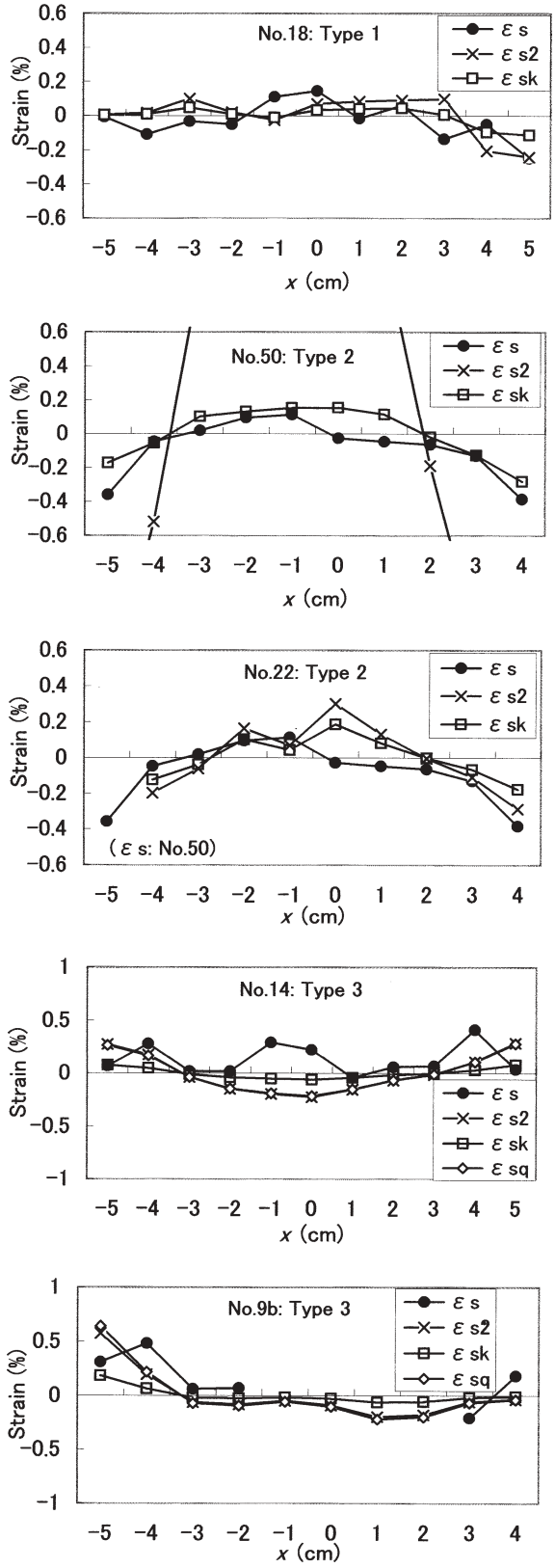

Fig. 3. Strain distributions in each of the specimens. ε_s, observed strain; ε_{s2}, ε_{sk}, ε_{sq}, estimated strains (see Table 4); x, measuring position along the line of the specimen width

sent the lower and upper limits of $|a''|$ for method 2 in Table 4 with the exception of specimen 50.

Estimated strains and their accuracy

Strains in the specimens can be calculated using the parameters a'' or k in Table 4; the results obtained are plotted in the diagrams of Fig. 3 where the strain symbols ε_s, ε_{s1}, ε_{s2}, ε_{sk}, and ε_{sq} denote the following meanings, respectively:

ε_s: observed strain
ε_{s1}: strain by method 1
ε_{s2}: strain by method 2
ε_{sk}: strain by method 3 ($k_o = 0.3784$)
ε_{sq}: strain by method 3 ($q_o = 0.7542$; i.e., $k_o = 1/q_o = 1.3259$)

but broken lines of ε_{s1} are omitted in Fig. 4 because of their similarities to those of ε_{s2} and their appearances in the previous paper.[3] The broken lines of ε_{s2} in Fig. 3 lie along or toward the lines of ε_s in each diagram except for specimen 50. The reason for this can be attributed again to the approximately 50% moisture content of the specimen, which is far beyond the upper limit of Eq. (20). The broken lines of ε_{sk} in Fig. 3 display fairly good agreement with the observed lines of ε_s in all cases; the broken lines of ε_{sq} in Fig. 3 are omitted from the diagrams of specimens 18, 50, and 22 for simplicity and because their behavior more or less diverges from the observed lines more than the broken lines of ε_{sk}. However, the lines of ε_{sq} in the other diagrams for specimens 14 and 9b appear rather close to those observed, in comparison to the lines of ε_{sk}. These behaviors of both broken lines of ε_{sq} and ε_{sk} would be mostly explained by the relation $k < q$ in Eq. (16).

The fitness of the estimated strains to the observed strains could be expressed by a method other than the one described above. That would be a direct comparison between the estimated and observed strains. The regression line between the two yields the following equations.

$$\varepsilon_{sk} = 0.2895\,\varepsilon_s - 0.0013\,(\%) \quad (r = 0.5417) \quad (k_o = 0.3784)$$
$$\varepsilon_{sq} = 1.0009\,\varepsilon_s - 0.0014\,(\%) \quad (r = 0.5334) \quad (q_o = 0.7542) \tag{28}$$

These equations indicate that the estimated strain ε_{sk} produces too small values when compared to the observed values, and that the strain ε_{sq} yields fairly good results all along their magnitudes. A concept of strain accuracy is also another important method.

The error of strain δ is defined here by this equation.

$$\delta = \varepsilon_s^* - \varepsilon_s\text{: error of strain } \varepsilon_s^*$$
$$\varepsilon_s^*\text{: estimated strains } \varepsilon_{s1},\ \varepsilon_{s2},\ \varepsilon_{sk} \text{ and } \varepsilon_{sq} \tag{29}$$

It is then considered for the parameters m, $r\varepsilon_s$, $s.d.$, and z.

$$m\text{: mean of } \delta; \quad r\varepsilon_s = \varepsilon_{smax} - \varepsilon_{smin}\text{: range of strain } \varepsilon_s$$
$$s.d.\text{: standard deviation of } \delta;$$
$$z = s.d./r\varepsilon_s\text{: index for strain accuracy} \tag{30}$$

where ε_{smax} and ε_{smin} denote the maximum and the minimum of strains ε_s, respectively. Figure 4 shows the broken lines of

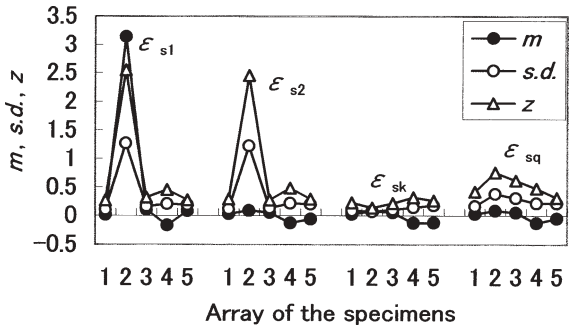

Fig. 4. Characteristics of strain errors. m, mean of errors δ; $s.d.$, standard deviation of δ; z, ratio of m to $r\varepsilon_s$; $r\varepsilon_s$, range of observed strain ε_s; array numbers *1*, *2*, *3*, *4*, and *5*, specimens 18, 50, 22, 14, and 9b; ε_{s1},ε_{s2}, ε_{sk}, and ε_{sq}, estimated strains ε_s*(see Table 4); δ, $\varepsilon_s^* - \varepsilon_s$

the quantities m, $s.d.$, and z, respectively, for each of the strains ε_s* where array numbers 1, 2, 3, 4, and 5 on the horizontal line refer to specimens 18, 50, 22, 14, and 9b, respectively. The broken lines of the quantities m, $s.d.$, and z in the Fig. 4 apparently explain the characteristics of each of the strains ε_s* more quantitatively than those in Fig. 3. For instance, sharp peaks of the broken lines in Fig. 4 occur only at the array number 2 (i.e., specimen 50 in the strains ε_{s1} and ε_{s2}. This tells us that the strain or stress estimation by methods 1 and 2 are not apt for specimen 50, which has a high moisture content. The negative sign of m in Fig. 4 appears exclusively in specimens 14 and 9b. It is also apparent that the broken lines of m, $s.d.$, and z lie more adjacent to the horizontal axis in strains ε_{sk} than do the others as a whole, and that the strain accuracy z for the strain ε_{sk} amounts to 0.14–0.32 throughout all the specimens. Based on these results method 3 may have the highest potential among the three methods discussed here as a technique for nondestructive detection of strain or stress in wood.

Conclusions

It can be concluded from this study that the methods offered here may have the possibility of detecting stresses in wood under a few assumptions of the theory. However, further studies on determining experimental parameters and increasing the strain/stress accuracy are advocated to facilitate the practical detection of stresses in the future.

Acknowledgment The authors wish to thank Dr. Okada of The Kawasaki Kiko Co. for his help with the instrumental affairs.

References

1. Kollmann FFP (1968) Kiln drying. In: Kollmann FFP, Côté WA Jr (eds) Principles of wood science and technology. Springer-Verlag, Berlin, pp 438–460
2. McMillen JM (1955) Drying stresses in red oak. Forest Prod J 5:71–76
3. Takemura T (2003) Theory to estimate the stress in wood due to moisture by using a transmission-type microwave moisture meter. J Wood Sci 49:11–17
4. Takemura T, Taniguchi T (2002) Measurement of uni-axial stresses in sugi lumbers by using a transmission-type microwave moisture meter (in Japanese). In: Abstracts of the 52nd annual meeting of the Japan Wood Research Society, p 74
5. Okada T (1999) Measuring of wood moisture by using a transmission-type microwave moisture meter (in Japanese). In: Abstracts of the Mokuzai to Mizu symposium of the Japan Wood Research Society, pp 5–10
6. WTAJ (1966) Japanese woods (in Japanese). Wood Technological Association of Japan, Tokyo, pp 26–27