J Wood Sci (2012) 58:267–272
DOI 10.1007/s10086-011-1238-2

NOTE

Non-destructive evaluation of surface longitudinal growth strain on Sugi (*Cryptomeria japonica*) green logs using near-infrared spectroscopy

Ken Watanabe · Kana Yamashita · Shuichi Noshiro

Received: 16 September 2011 / Accepted: 9 November 2011 / Published online: 28 December 2011

Abstract A use of near-infrared (NIR) spectroscopy for rapidly predicting the longitudinal growth strain (LGS), as a detector of growth stress, was described. NIR spectra and LGS were measured from peripheral locations of three Sugi (*Cryptomeria japonica*) green logs. Partial least squares regression model for predicting LGS was developed using the spectral range spanning 770–1200 nm. The predicted LGS was correlated with that measured by the strain gauge method. The coefficient of determination and the root mean square error of prediction were 0.61 and 0.013%, respectively. The predicted peripheral LGS distribution moderately fitted with the measured one. Our results indicate that NIR spectroscopy has a potential to evaluate the magnitude of longitudinal growth stresses on green logs.

Keywords Near-infrared spectroscopy · Longitudinal growth strain · Green log · Non-destructive evaluation

Introduction

Growth stresses, self-generated in the cambium during cell maturation in all tree species [1], are one of the most important wood quality criteria. High levels of growth stresses cause end splitting at crosscutting of eucalyptus logs [2–6] and distortion in both eucalyptus and cryptomeria timbers [5–8] during sawing, resulting in the reduction of sawn timber recovery. A better knowledge of the distribution of growth stresses in both standing trees and logs is essential for ensuring wood production of an acceptable quality in the future.

Longitudinal growth strain (LGS) is commonly used as a direct indicator of growth stress and has been measured by many researchers [9]. Operating parameters for several techniques have been comprehensively evaluated [10–12], and recently a new technique for LGS measurement was proposed [13]. All these techniques, however, rely on physically cutting samples to release growth strain and hence cause considerable injury to the cambium. Besides, these time-consuming techniques are not suitable for monitoring a large number of populations or for determining a sawing strategy that optimizes timber value in sawmills. Thus, less invasive and faster methods are being required.

Near-infrared (NIR) spectroscopy has been shown to be a promising technique for the rapid assessment of many physical and chemical properties of wood [14, 15], thereby allowing the use of NIR-based technology in the forest products industry [16]. For the assessment of LGS, Baillères et al. [17, 18] demonstrated that NIR spectroscopy could be used to predict LGS of ground wood-meal of hybridized eucalyptus full-sib families at the moisture content of 6%. They also suggested that LGS depends closely on the chemical composition of wood, and that, because of this, the prediction of LGS was successful. If NIR spectroscopy has a potential to predict LGS of wet solid wood, it could be applied for a rapid non-destructive evaluation of the surface LGS of standing trees or green logs. However, to the best of our knowledge, few studies have focused on predicting LGS of wet wood using NIR spectroscopy. The aim of this study was to examine if NIR spectroscopy has a potential to predict the surface LGS of green logs. The relationship between NIR spectra and wood properties associated with LGS was also discussed.

K. Watanabe (✉) · K. Yamashita · S. Noshiro
Forestry and Forest Products Research Institute, 1 Matsunosato, Tsukuba, Ibaraki 305-8687, Japan
e-mail: kenwatanabe@ffpri.affrc.go.jp

Materials and methods

Sample preparation

A 16-year-old Sugi (*Cryptomeria japonica* D. Don) tree grown in Ibaraki-Prefecture, Japan was felled in March 2011. The tree height and the diameter at breast height were 11.1 and 0.17 m, respectively. The stem was leaning toward the southwest and crooked at the height below 0.7 m (Fig. 1). The north side of the tree was marked before felling. Three logs with a length of 0.35 m and a diameter ranging 0.15-0.18 m were cross-cut from the height between 1 and 2.1 m. The length of the logs (0.35 m) was determined based on a preliminary study that showed crosscutting has no influence on LGS at the middle of the log when the length of the log is over 0.3 m long. The logs were subjected to the measurement of NIR spectra and LGS.

NIR measurement

Bark was carefully removed by hand so as not to scratch the xylem surface just before NIR measurement. The excess water was wiped off the surface with a Kim-wipe paper. The diffused reflectance spectra on a spot diameter of approximately 3 mm were collected at 1-nm intervals over the range 770–1200 nm using a MATRIX-F spectrometer (Bruker Optics Inc., Ettlingen, Germany) equipped with a fiber optic probe. The probe tip was carefully adjusted to come into contact at a right angle with the log surface. A piece of commercial resin Spectralon® was used as the reference material. Spectra were collected near the middle of each log at equidistant twenty-four periphery locations numbered from 0 to 23 (Fig. 2). The height of the measuring locations in the tree was 1.2, 1.5 and 1.9 m for the bottom, middle and upper logs, respectively. Fifteen scans were accumulated for each location and were averaged into a single spectrum.

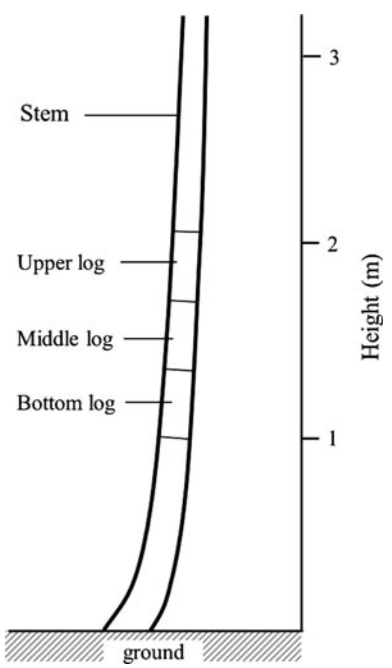

Fig. 1 Profile of the studied tree

LGS measurement

The LGS at twelve periphery locations with an even number (as shown in Fig. 2) was measured by means of the strain gauge method [9–11]. Aligned with the stem axis, 10-mm long strain gauges were glued with cyanoacrylate-based glue and were left in a plastic bag for 2 h to achieve effective adhesion. The logs were completely cross-cut using a table saw at 20 mm distance from the gauge center, so that the LGS of 12 locations could be measured simultaneously (Fig. 3). The LGS of the other 12 locations with an odd number (Fig. 2) was calculated by averaging two LGS values measured at adjacent locations.

Subsequently, a disc with a thickness of 5 cm was cut near the location where LGS was measured, and the disc was oven-dried to obtain the moisture content for each log. As a result, the mean moisture content of the logs was 127.1% with a standard deviation of 2.4%.

Calibration development

The bottom and upper logs were used for calibration, while the middle log was used for validation. Namely, a calibration model was constructed with the 48 data sets of NIR

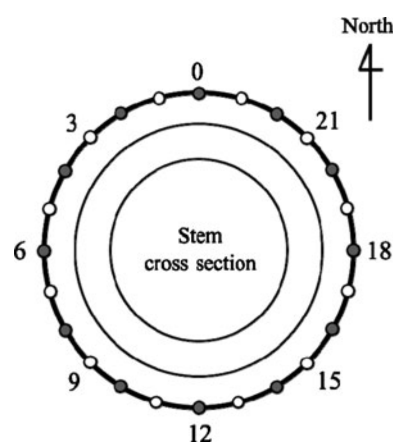

Fig. 2 Twenty-four peripheral locations for the NIR and LGS measurement. *White circles* the location where NIR spectra were measured; *Black circles* the location where both NIR spectra and LGS were measured. 0, 6, 12 and 18 indicate north, west, south and east, respectively

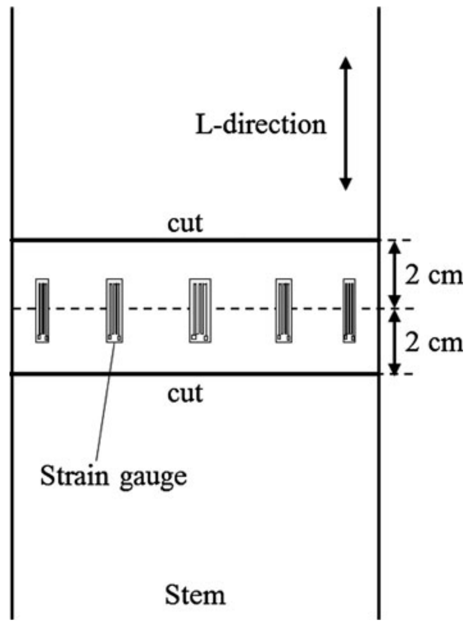

Fig. 3 LGS measurement using the strain gauge method

spectra and LGS, and then the calibration model was validated with the remaining 24 data sets.

Unscrambler® software (CAMO, Corvallis, OR, USA) was used for data pre-processing and developing calibration models. The spectral data were smoothed by a 9-point moving average in order to reduce sample noise. In this study, pre-processing techniques used to enhance the quality of calibrations such as first and second derivatives, or multiplicative scatter correction were not used, because little improvement was observed in the calibration models pre-processed by these techniques. Partial least squares (PLS) regression analysis in full cross-validation was applied to construct the calibration model. The number of factors which corresponded to the first minimal residual variance was adopted as optimum.

The LGS in the validation set was predicted using the calibration model. The quality of the model was evaluated by comparing the predicted values with the measured ones. The coefficient of determination (R^2) and root mean square error of prediction (RMSEP) served as the statistical measures of predictive power. RMSEP values were used to measure how well the calibration model predicts the parameter of interest for a set of unknown samples excluding the calibration set.

Results and discussion

Peripheral LGS distribution

The peripheral LGS distribution for each log was shown in Fig. 4. Positive and negative values indicate compressive

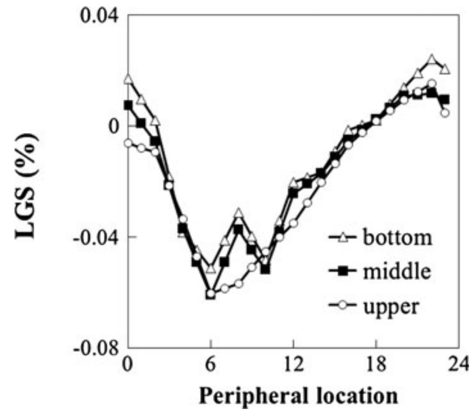

Fig. 4 Peripheral distributions of measured LGS for each log

growth stress and tensile growth stress, respectively. The LGS values varied from −0.061 to 0.024% with a mean of 0.017% and a standard deviation of 0.024%. There was a relatively smaller variation in LGS than that in the Sugi tree containing compression wood [19]. This LGS variation shows that the peripheral growth stress varied from tension to compression, which may result from the adaptation to surrounding environment. It is highly possible that the variation of growth stress has an influence on timber distortion during sawing. Further finite element analyses [20, 21] will be required to confirm the effect of peripheral LGS variation on sawn distortion.

Brown color due to high lignin content was observed on the northeastern side of the tree where compressive stress existed. Okuyama et al. [19] demonstrated that lignin contributes positively to the generation of compressive longitudinal growth stresses in the compression wood of Sugi. The observed brown color associated with high lignin concentration in the compressive stress region is likely to affect the LGS prediction, because lignin content is one of the important chemical properties correlated with NIR spectra [17].

Spectroscopic characterization

The spectra for various LGS obtained from the middle log are shown in Fig. 5. The peaks in this wavelength region are difficult to assign to specific wood components, but can be attributed to second overtones of hydroxyls and third overtones of CH stretching vibrations [22]. The peaks between 1075 and 1250 nm can be assigned to the second overtones of lignin aromatic and aliphatic CH vibrations [23]. The spectra with higher LGS tended to show a lower overall absorbance, and the same trend was observed in the spectra for both bottom and upper logs. The reason is unclear but it may be due to the change in physical and chemical properties related to LGS.

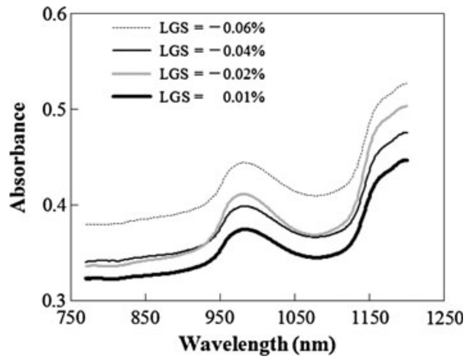

Fig. 5 NIR spectra for various LGS obtained from the middle log

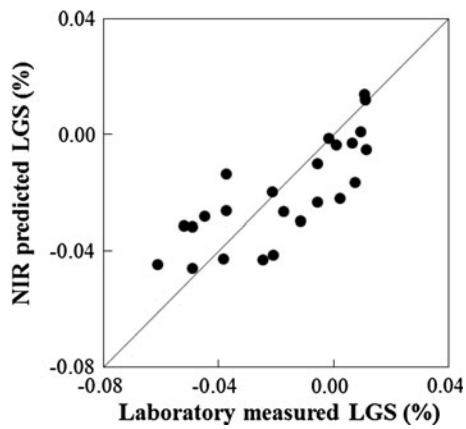

Fig. 6 Laboratory measured versus NIR predicted LGS in the validation set. The number of factor used was 3. *Solid line* a one to one relationship between measured and predicted values. ($R^2 = 0.61$, RMSEP = 0.013%)

Prediction of LGS

The predicted LGS was correlated with laboratory measured ones (Fig. 6). The calibration model with the number of factors of 3 yielded R^2 of 0.61 with RMSEP of 0.015%. The results of predictive performance of the model is comparable with those obtained from ground wood-meal of hybridized eucalyptus under constant moisture content ($R^2 = 0.64$, standard error of prediction = 0.020%) [17].

The measured and predicted peripheral LGS distributions were plotted in Fig. 7. The fitted line calculated by 3-point moving average of the predicted LGS moderately fitted with the laboratory measured one. These results indicate that NIR spectroscopy has a potential to predict the surface LGS of green logs as well as LGS of dried ground wood-meal, and to detect the compression wood that causes timber distortion during sawing.

This approach of using NIR spectroscopy for predicting LGS affords a rapid and simple method without any sample preparation. NIR spectrum was obtained from the xylem surface after debarking, so no invasive procedure is

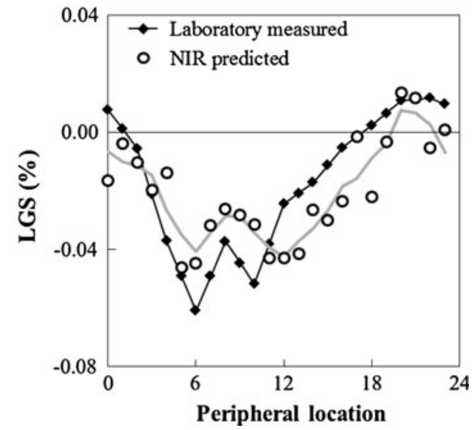

Fig. 7 Measured and predicted peripheral distributions of LGS. The *gray line* the fitted line of predicted LGS calculated by 3-point moving average

necessary to release the growth strain. This is an advantage over other conventional methods described by Yang et al. [11] On the other hand, there are a few limitations that should be considered with regard to potential future applications. As with all NIR methods, the calibration model is dependent on the calibration set used, which in this study includes the LGS that was measured from a single tree. In practice, several factors affecting NIR spectra, such as moisture content, density, and earlywood/latewood ratio, vary considerably depending on tree age and growing season, as well as species. Thus, further research with a larger number of samples is required to examine if NIR spectroscopy can be used to predict LGS of green logs grown under different seasons and conditions.

Significant wavelengths for predicting LGS

Regression coefficients of the PLS analysis can be used to construct the predictions and to determine important spectral regions that are responsible for the correlation with LGS prediction. In the spectral plots of the regression coefficients (Fig. 8), highly negative and positive impact on the calibration model was found in the wavelengths between 1070 and 1150 nm. These wavelengths can be attributed to second overtones of hydroxyls and third overtones of CH stretching vibrations [22].

Limited information is available on NIR absorption bands and wood properties, such as microfibril angle (MFA) and lignin content, which have been shown to be associated with the generation of LGS [24]. Yamamoto et al. [25] investigated the relationship between LGS and MFA of Sugi and showed that LGS increased with increasing MFA. Kelly et al. [22]. reported that MFA was successfully predicted using a spectral range spanning 650–1150 nm, and that the wavelengths at around 1150 nm significantly had a positive impact on the prediction model

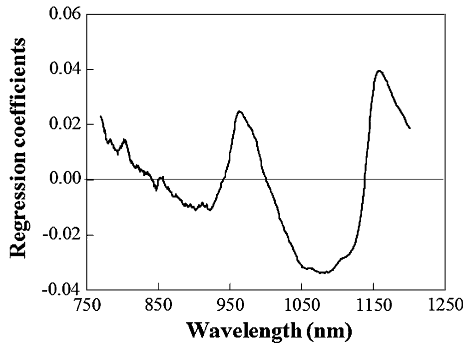

Fig. 8 Spectral plots of the regression coefficients

of MFA. The plots of the regression coefficients in this study indicate that the wavelengths at around 1150 nm positively and highly contribute to predicting LGS. Therefore, it is speculated that the regression coefficients in both the prediction models of MFA and LGS show a positive peak in the same wavelengths at around 1150 nm because of the positive correlations between MFA and LGS.

In the regression coefficients, there was an abrupt change from negative to positive at around 1120–1150 nm, meaning that the spectral change in this region had an impact on predicting LGS. The wavelengths in this range have been affirmed to be associated with lignin content. The wavelength at 1143 nm is assigned to aromatic group [26], and the wavelength at 1130 nm pre-processed by second derivatives had a strong relationship with lignin content [27]. Thus, it is hypothesized that LGS seems to be influenced by lignin content, and that this spectroscopic analysis complements the finding by Okuyama et al. [19] that lignin contributes to the generation of compressive longitudinal growth stresses.

Since no measurement of chemical and physical properties associated with LGS was carried out in this study, the relationship between NIR spectra and these properties was discussed using the limited information in the literatures. Experimental investigation of NIR spectra and wood properties, as well as LGS, is further required for rational interpretation of their relationships.

Conclusions

NIR spectra were collected from peripheral locations of three Sugi green logs, and a PLS regression model for predicting LGS was constructed. Although the sample size was very limited, our results indicate that this approach provides a non-destructive, rapid and simple method for assessing the magnitude of longitudinal growth stress, without any sample preparation.

Acknowledgments The authors would like to thank Mr. J. Akutsu for his assistance in the experiments. This research was partially supported by a Grant-in-Aid for Scientific Research (No. 21300332) from the Japan Society for the Promotion of Science (JSPS).

References

1. Jacobs MR (1938) The fibre tension of woody stems, with special reference to the genus *Eucalyptus*. Commonwealth Forestry Bureau, Australia, Bulletin No. 22, p 37
2. Okuyama T, Dolán J, Yamamoto H, Ona T (2004) Heart splitting at crosscutting of eucalypt logs. J Wood Sci 50:1–6
3. Raymond CA, Kube PD, Pinkard L, Savage L, Bradley AD (2004) Evaluation of non-destructive methods of measuring growth stress in *Eucalyptus globulus*: relationships between strain, wood properties and stress. For Ecol Manage 190:187–200
4. Valencia J, Harwood C, Washusen R, Morrow A, Wood M, Volker P (2011) Longitudinal growth strain as a log and wood quality predictor for plantation-grown *Eucalyptus nitens* sawlogs. Wood Sci Technol 45:15–34
5. Yang JL (2007) Investigation of potential sawlog quality indicators—a case study with 32-year-old plantation *Eucalyptus globulus* Labill. Holz Roh Werkst 65:419–427
6. Muneri A, Leggate W, Palmer G (1999) Relationships between surface growth strain and some tree, wood and sawn timber characteristics of *Eucalyptus cloeziana*. South Afr For J 186: 41–49
7. Yang JL, Fife D, Waugh G, Downes G, Blackwell P (2002) The effect of growth strain and other defects on the sawn timber quality of 10-year-old *Eucalyptus globulus* Labill. Aust For 65:31–37
8. Okuyama T, Sasaki Y (1979) Crooking during lumbering due to residual stresses in the tree. Mokuzai Gakkaishi 25:681–687
9. Yang JL, Baillères H, Okuyama T, Muneri A, Downes G (2005) Measurement methods for longitudinal surface strain in trees: a review. Aust For 68:34–43
10. Yoshida M, Okuyama T (2002) Techniques for measuring growth stress on the xylem surface using strain and dial gauges. Holzforschung 56:461–467
11. Yang JL, Baillères H, Evans R, Downes G (2006) Evaluating growth strain of *Eucalyptus globulus* Labill from SilviScan measurements. Holzforschung 60:574–579
12. Jullien D, Gril J (2008) Growth strain assessment at the periphery of small-diameter trees using the two-grooves method: influence of operating parameters estimated by numerical simulations. Wood Sci Technol 42:551–565
13. Chauhan S, Entwistle K (2010) Measurement of surface growth stress in *Eucalyptus nitens* Maiden by splitting a log along its axis. Holzforschung 64:267–272
14. Schimleck LR, Raymond CA, Beadle CL, Downes GM, Kube PD, French J (2000) Applications of NIR spectroscopy to forest research. Appita J 53:458–464
15. Tsuchikawa S (2007) A review of recent near infrared research for wood and paper. Appl Spectrosc Rev 42:43–71
16. So CL, Via BK, Groom LH, Schimleck LR, Shupe TF, Kelley SS, Rials TG (2004) Near infrared spectroscopy in the forest products industry. Forest Prod J 54:6–16
17. Baillères H, Davrieux F, Ham-Pichavant F (2002) Near infrared analysis as a tool for rapid screening of some major wood characteristics in a eucalyptus breeding program. Ann For Sci 59:479–490
18. Baillères H, Davrieux F, Ham-Pichavant F (2003) Growth strains assessment of various *Eucalyptus* species by near infrared spectroscopy. In: Proceedings of IUFRO all division 5 conference:

forest products research—providing for sustainable choices, Rotorua, New Zealand, p 216
19. Okuyama T, Takeda H, Yamamoto H, Yoshida M (1998) Relation between growth stress and lignin concentration in the cell wall: ultraviolet microscopic spectral analysis. J Wood Sci 44:83–89
20. Ormarsson S, Dahlblom O, Johansson M (2009) Finite element study of growth stress formation in wood and related distortion of sawn timber. Wood Sci Technol 43:387–403
21. Johansson M, Ormarsson S (2009) Influence of growth stresses and material properties on distortion of sawn timber—numerical investigation. Ann For Sci 66:604
22. Kelly SS, Rials TG, Snell R, Groom LH, Sluiter A (2004) Use of near infrared spectroscopy to measure the chemical and mechanical properties of solid wood. Wood Sci Technol 38:257–276
23. Huang A, Li G, Fu F, Fei B (2008) Use of visible and near infrared spectroscopy to predict klason lignin content of Bamboo, Chinese Fir, Paulownia, and Poplar. J Wood Chem Technol 28:194–206
24. Yamamoto H, Okuyama T, Yoshida M (1995) Generation process of growth stresses in cell walls VI. Analysis of growth stress generation by using a cell model having three layers (S1, S2, and I+P). Mokuzai Gakkaishi 41:1–8
25. Yamamoto H, Okuyama T, Sugiyama K, Yoshida M (1992) Generation process of growth stresses in cell walls IV. Action of the cellulose microfibril upon the generation of the tensile stresses. Mokuzai Gakkaishi 38:107–113
26. Shenk JS, Workman JJ Jr, Westerhaus MO (2008) Application of NIR spectroscopy to agricultural products. In: Burns DA, Ciurczak EW (eds) Handbook of near-infrared analysis, 3rd edn. CRC Press, Boca Raton, p 356
27. Jones PD, Schimleck LR, Peter GF, Daniels RF, Clark A III (2006) Nondestructive estimation of wood chemical composition of sections of radial wood strips by diffuse reflectance near infrared spectroscopy. Wood Sci Technol 40:709–720