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A new assessment of internal stress within kiln-dried lumber using a restoring force technique on a half-split specimen

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Abstract Due to difficulties in determining modulus of elasticity of wood, only strain or deflection profiles caused by relaxation of internal stress are normally evaluated for industrial kiln-dried lumber. To directly assess the level of internal stress within the lumber, a new technique of measuring the restoring force on a half-split specimen has been presented and the corresponding device has been designed and constructed. Kiln-dried rubberwood specimens with dimensions of 30 or 50 mm (thickness), 130 mm (width) and 50 mm (length) were used in the study. The measured restoring force appears to vary with half-split length and specimen thickness. A mathematical model based on an elastic cantilever beam theory has been successfully developed to describe the restoring force behavior in a flexural response regime. The magnitude of the maximum linearly averaged internal stress σ_m can be derived without prior knowledge of the modulus of elasticity of wood. For the 30-mm-thick lumber, the derived values of σ_m are in general agreement with the ones obtained from the conventional McMillen slice test. Very close agreement is observed when the internal stress is at a relatively low level and its profile is approximately linear. But for the 50-mm-thick lumber, the determination of σ_m is less appropriate because of its relatively short flexural range. A restoring force–internal stress chart has been proposed for practical use in the lumber industry. This assessment was performed to investigate the evolution of internal stress during the conditioning and storage stages of kiln-dried rubberwood lumber.

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Introduction

The drying process always creates internal stress within lumber that continues to exist, even after the lumber is dried (Perré and Passard 2007). The outer layer of kiln-dried lumber is generally under compressive stress, while its inner core layer is under tensile stress (McMillen 1958; Simpson 1999). In practice, these internal stresses are generally relieved by steaming done at the end of the drying process (Wengert 1992). A reliable technique for the assessment of internal stress is therefore essential for effective stress relief and quality control of kiln-dried lumber.

The stress-relaxing techniques of the McMillen slice test (McMillen 1958), the case-hardening test (European Committee for Standardization 2010) and the prong test (Simpson 1991) have been traditionally used to estimate the internal stress magnitude within kiln-dried lumber. These techniques analyze structural deformations in terms of strain or deflection that accompany the stress redistribution which occurs when internal stresses are elastically released by sectioning or splitting. Internal stress can then be determined by analyzing the measured strains or deflections, provided that the elasticity values of the materials are known (Schajer and Ruud 2013; Walton 2002; Rossini et al. 2012). The elastic modulus of wood depends on several factors including moisture content and specific gravity (Bodig and Jayne 1982; Matan and Kyokong 2003; Sonderegger et al. 2013), and it is not practical in the industry to measure every piece of lumber. It is quite common that only strain profiles or deflections obtained from the test methods mentioned above are reported (McMillen 1958; European Committee for Standardization 2010; Fuller 1995).

A novel approach of a restoring force measurement on "half-split" specimens has been proposed by Diawanich et al. (2012). This idea has also been extended to monitor in real time the internal stress during drying, conditioning and storage of lumber (Diawanich et al. 2010; Tomad et al. 2012). In their work, the width of lumber was sawn at half thickness by a half length before being transferred to a device attached to the universal testing machine to measure the force required to restore the specimen back to its initial configuration. However, just a small error in the thickness measurement during restraining of the half-split specimen to its original configuration could lead to a large variation in the measured force. Therefore, further improvement to this technique is required.

The purpose of this research is to design and construct a restoring force measuring apparatus suitable to be used in the lumber industry. An interpretation of the measured restoring force in terms of the internal stress is developed. The derived internal stress is compared with one of the traditional slicing techniques. Finally, a chart for converting the restoring force to the internal stress is proposed for convenience in the industry. Emphasis is placed on estimating the internal stress level within kiln-dried rubberwood lumber.

Materials and methods

Design of restoring force measuring apparatus

The principle of restoring force measurement on half-split specimen was based on the concept proposed by Diawanich et al. (2012). The equipment (Fig. 1a, b) consists mainly of a relatively stiff steel frame, two 56-mm-wide clamping jigs and a load cell (Cooper Instrument, USA). One jig was fixed to the steel frame, and another was attached to a steel rod connected to the load cell. A wood specimen cut to a length (b) of 50 mm was clamped onto the jigs at a distance (g) of 10 mm away from the top end. Care was taken to ensure that optimum torque of 2–3 N m was applied with a contact area of 24 mm^2 to hold the specimen to the jigs without damaging it. While being clamped to the frame, the specimen was half-split at half the thickness for a required length (l). The apparatus was designed so that the width of the specimen clamped to the frame can be sawn with a band saw (Fig. 1c). The kerf from the saw was 2 mm wide. Without restraining the specimen, the relaxation of internal stress would cause the two legs of the half-split specimen to be deformed inward or outward. Since the specimen is restrained to the frame and to a steel rod connected to the load cell, the net force generated as a result of internal stress relaxation within the half-split specimen was transferred to the load cell. The sign and magnitude of the force, displayed on the force reading device (Fig. 1d), was recorded and transferred to the computer in real-time mode during and after cutting.

Restoring force and slice test measurements

Six pieces of industrial kiln-dried rubberwood obtained from a local sawmill in Nakhon Si Thammarat, Thailand, were used in this study. The restoring force was measured as a function of the half-split length (l) for thicknesses (d) of 30 and 50 mm (three replicates for each size) in the radial (R) direction. The flat-sawn lumber was 130 mm wide (W) in the tangential (T) direction and approximately 1 m long in the longitudinal (L) direction. For each piece of lumber, two sets of specimens with relatively high levels of internal stress (HS) and low levels of internal stress (LS) were prepared. All specimens were free of defects such as knots and spiral grain. The HS specimens were tested immediately after kiln drying, while the LS specimens were left in ambient air (28 ± 2 °C and 75 ± 6 % RH) for 3 weeks prior to testing. The specimens were cut to a length (b) of 50 mm (Fig. 2a) and marked into a half thickness line at 5-mm intervals (Fig. 2b). For the 30-mm-thick specimens, they were also marked by divided lines so they could be cut into six equal slices according to the McMillen slice test (McMillen 1958) (Fig. 2c). The initial width of each pre-marked slice (W_b) was measured by calipers to an accuracy of 0.01 mm. Specimens were then assembled into the restoring force measuring apparatus and cut through the pre-marked half thickness line. The restoring force was monitored at 5-mm intervals up to 125 mm. They were then cut into slices along the pre-marked lines, and the width (W_a) of each slice was immediately measured. The released strain of each slice (ε) was calculated according to
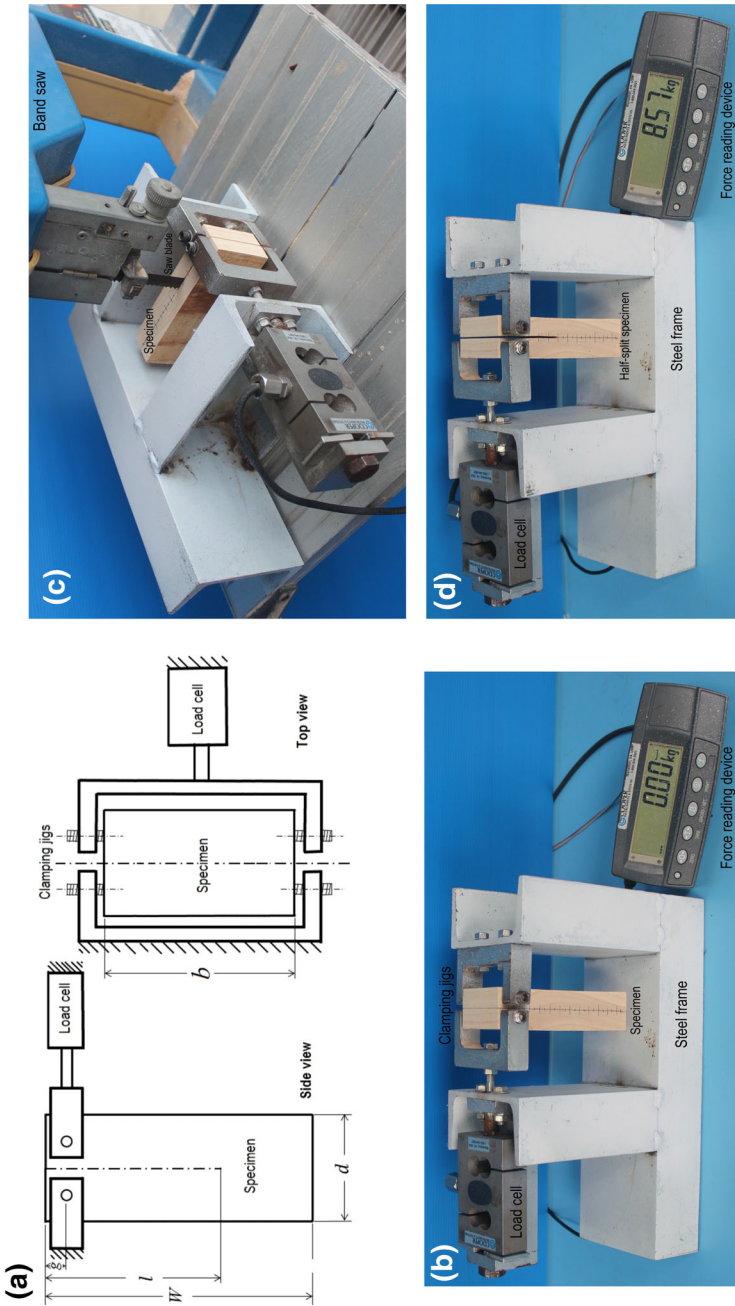
Fig. 1 **a** Schematic diagram of the restoring force measuring apparatus and photographs of the wood specimen installed in the device **b** before, **c** during and **d** after half-split sawing using a band saw

$\varepsilon = \frac{W_a - W_b}{W_b}$. Each slice was then subjected to a tensile test using a universal testing machine (Lloyd 150kN, UK) equipped with a strain gauge (Epsilon Technology, USA) to determine the value of Young's modulus in the tangential direction. After testing, a section of each slice was weighted both before and after oven-drying at 104 °C for 24 h to determine its moisture content.

Internal stress relaxation of kiln-dried rubberwood lumber

Six pieces of kiln-dried rubberwood lumber (30 mm thick, 130 mm wide and approximately 1 m long) were taken from a local sawmill in Nakhon Si Thammarat, Thailand. The growth ring orientation was selected such that the lumber thickness aligned in the radial direction (Fig. 2a). Defect-free specimens measuring 50 mm long were cut at least 50 mm from the end of each lumber. Restoring force measurement was then carried out on the half-split specimens at cutting lengths
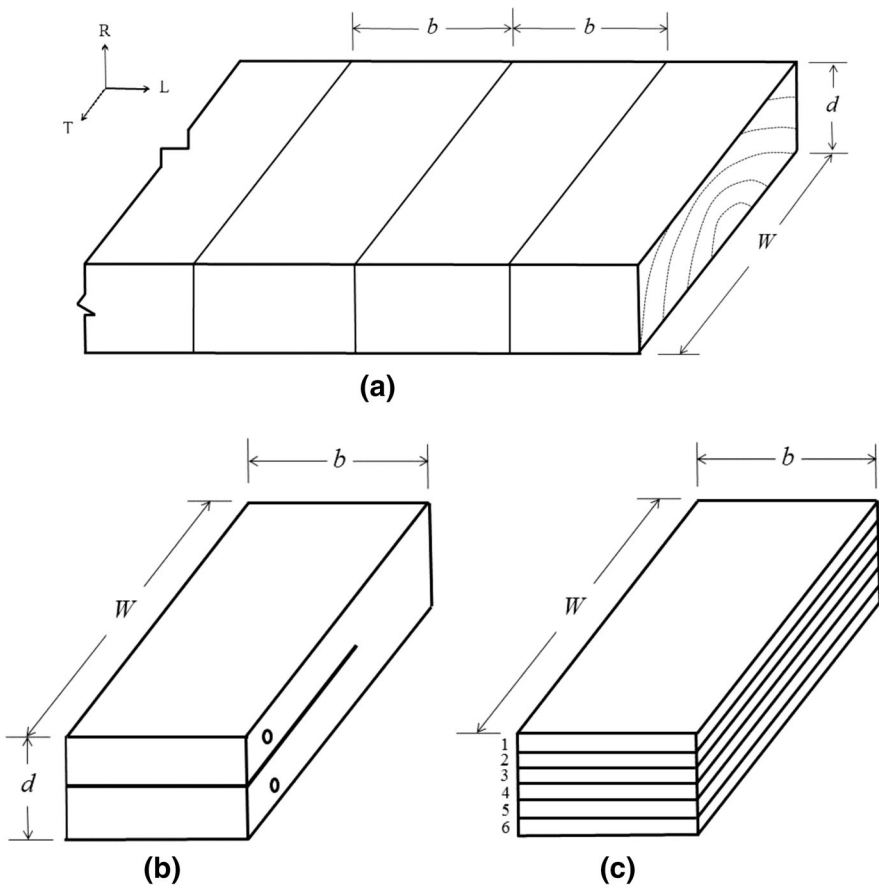

Fig. 2 Sample layouts of **a** the test specimens cut from the lumber, **b** the half-split specimen for the restoring force measurement and **c** the specimen for the McMillen slice test

from 60 to 100 mm. The remaining pieces of lumber were coated with aluminum paint at both ends. Three pieces of lumber were placed in a conditioning chamber (Binder, Germany) at 85 °C and 80 % RH. Another three pieces were left in ambient air at 28 ± 2 °C and 75 ± 6 % RH. Assessments of internal stress were later performed after 30 and 90 min of conditioning and at 10 and 20 days of storage, respectively.

Results and discussion

Restoring force measurement on half-split specimens

Internal compressive and tensile stresses often remain in both an outer layer and an inner core of lumber after kiln drying (McMillen 1958; Simpson 1999). A resultant force generated due to relaxation of these internal stresses tends to bend the two legs of the half-split specimen inward. This behavior is similar to the prong response of kiln-dried lumber which is commonly observed in sawmill industry; however, the deflection degree of half-split specimens is relatively small. According to the prong test, the central portion accounting for about one-third of the thickness is generally removed (Simpson 1991) so that the deflection of the two legs could be easily measured. However, removing a bigger central portion of lumber would lead to a larger error in quantifying the internal stress level because the degree of prong deflection is only caused by redistribution of the internal stresses within the remaining portion of lumber. Fuller and Hart (1994) also reported an ambiguous reading on the internal stress level of the prong test as a result of the amount of the wood removed.

   Within this work, the apparatus was designed to hold the half-split specimen to the initial position at the clamping points. As a result, a tensile (positive) restoring force was detected on the load cell. Figure 3a shows typical evolution of the force value reading on the load cell before, during and after half-split sawing. Before cutting, the force was set to zero. The force increased during the sawing to a required length. A slight fluctuation in the force value as a result of saw blade vibration can be observed. An instantaneous elastic response of the restoring force was recorded immediately after half-splitting the specimen to the required length and removing the specimen from the saw blade. Thereafter, the force value slightly increased with time as a result of viscoelastic creep. Mechano-sorptive creep should also play a role over time as moisture could easily diffuse into or out of the inner section of the specimen via the saw kerf. Creep response of the specimen could affect the measured values of the restoring force when multiple sawing at various half-split lengths was performed (Fig. 3b). To minimize such an effect from creep to <3 %, the multiple sawing on each specimen was completed in a short time of <3 min. Detailed analysis of the creep response is beyond the scope of the present paper and should be explored in the future.

   The curves of the restoring force as a function of half-split length obtained from the 30- and 50-mm-thick specimens are shown in Fig. 4a, b, respectively. For the 50-mm-thick HS specimens, measurements could be taken up to the half-split length
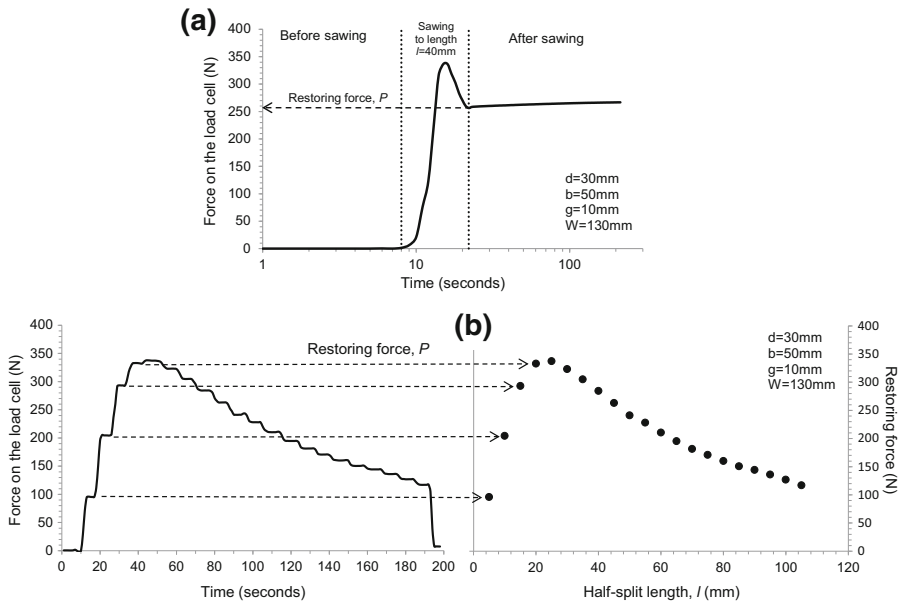
Fig. 3 Typical evolution of the detected force on the load cell before, during and after half-split sawing of the specimen fixed to the restoring force measuring device using **a** a single sawing at 40-mm and **b** multiple sawing at 5-mm intervals. Some values of the derived restoring force are also indicated in the *graphs*

of 100 mm (Fig. 4b) because of the presence of cracks at the tip of the kerf. For both lumber thickness sizes, the magnitude of the restoring force varied with the half-split length. The restoring force first abruptly increased and reached the maximum values at the half-split lengths of around 25 mm for the 30-mm-thick specimens and around 35–45 mm for the 50-mm-thick specimens. After exceeding the maximum value, the restoring force gradually decreased with the increase in the half-split length. The magnitude of the restoring force appears to reflect the internal stress level within the specimen. The restoring forces of the HS specimens are clearly higher than those of the LS specimens. However, the observed force values should also be influenced by the specimen's geometry. As shown in Fig. 4, higher restoring force levels were detected in the thicker specimens. In the following section, an attempt was made to relate the magnitudes of the restoring force to the level of the internal stress within the lumber.

Estimation of the internal stress

By assuming a linear distribution of internal stress across half thickness of lumber (Fig. 5a), the maximum linearly averaged internal stress σ_m was assumed to be equal at the outer surface and at the inner core. This can be calculated by a deflection of the half-split specimen (Fig. 5b) as expressed by

Fig. 4 Experimental restoring force profiles as a function of half-split length of **a** the 30-mm and **b** the 50-mm-thick kiln-dried rubberwood specimens with widths of 130 mm and lengths of 50 mm containing high levels (HS) and low levels (LS) of internal stress
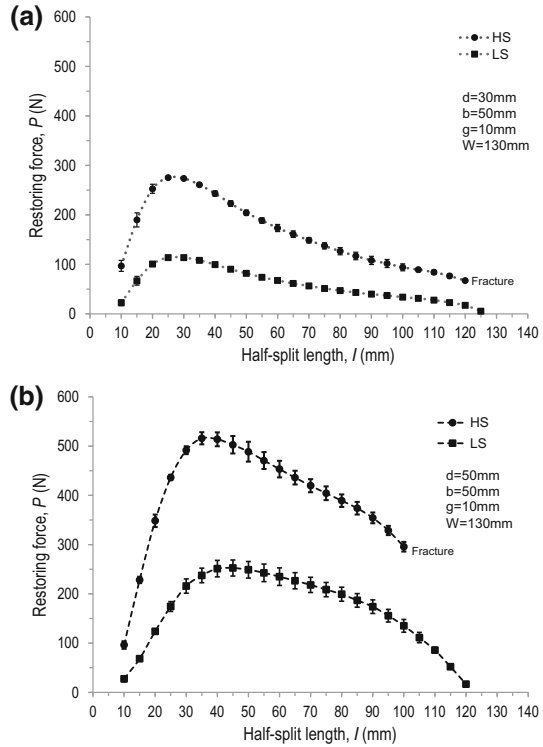
$$\sigma_{\mathrm{m}} = \frac{E \cdot \Delta\delta \cdot d}{4l^2} \qquad (1)$$

where E, $\Delta\delta$, d and l are Young's modulus in the tangential (T) direction, mouth opening, thickness and sawed depth of the specimen, respectively (Walton 2002). A restoring force (P) is applied at distance a away from the end of the kerf (or at distance g away from the specimen end) to keep the half-split specimen in the original configuration prior to sawing (Fig. 5c). According to Lados and Apelian (2006), the restoring force (P) can then be expressed as

$$P = \frac{E \cdot \Delta\delta \cdot b}{S} \qquad (2)$$

where b is the sample length and S is the geometrical shape factor.

It can be considered that each leg of the half-split specimen acts as a cantilever beam that is rigidly fixed at one end and free at the other end. In addition, it is assumed that the internal stress is fully relaxed across the thickness of the specimen and the effects of other stress components (including stresses in the thickness and the length directions, shear stresses and stress concentration around the end of the kerf) are negligible. The restoring force (P) is calculated using the cantilever beam equation (Hibbeler 2012) according to
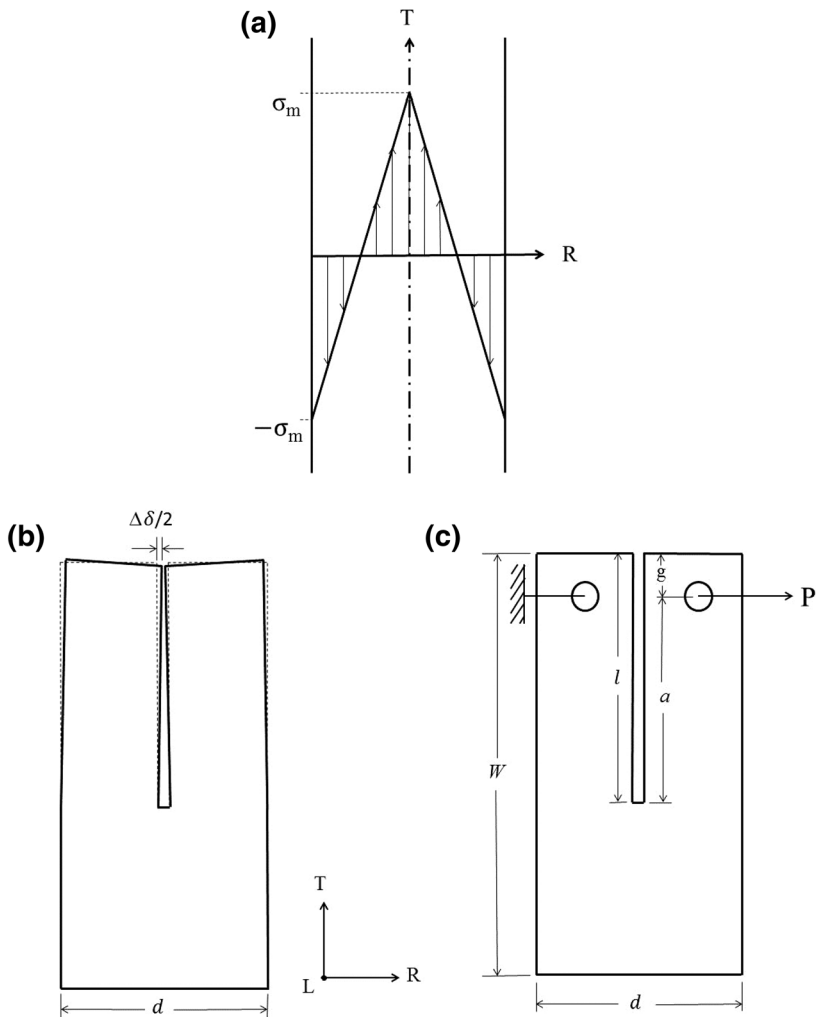
Fig. 5 **a** Linear distribution of through thickness internal stress within lumber, **b** deflection of half-split specimen caused by internal stress after sawing and **c** application of restoring force to restrain the half-split specimen in original configuration prior to sawing

$$P = \frac{6EI}{a^2(3l-a)}\frac{\Delta\delta}{2} = \frac{6EI}{(l-g)^2(2l+g)}\frac{\Delta\delta}{2} \tag{3}$$

where I is the second moment of area which is equal to $\frac{bd^3}{96}$. By combining Eqs. (1), (2) and (3), the restoring force P can be expressed as

$$P = \frac{4bl^2}{Sd}\sigma_m \tag{4}$$

where the geometrical factor is $S = \frac{32(l-g)^2(2l+g)}{d^3}$. It should be emphasized that according to Eq. (4), the magnitude σ_m can be straightforwardly calculated from the measured restoring force without prior knowledge of the Young's modulus E of the wood.

By plotting the restoring force (P) against the term $\frac{4bl^2}{Sd}$, the value of σ_m can then be deduced from the slope of the graph. It appears that the model well describes the experimental restoring data at relatively small values of $\frac{4bl^2}{Sd}$. In this flexural response regime, the restoring force is proportional to the term $\frac{4bl^2}{Sd}$ (Fig. 6a, b). Alternatively, one could plot the term $\frac{PSd}{4bl^2}$ against the half-split length (l) and the maximum, and constant value of the term $\frac{PSd}{4bl^2}$ is the value of σ_m (Fig. 6c, d). The magnitudes of σ_m derived from the graphs are 2.90 and 1.08 MPa for the 30-mm-thick HS and LS specimens, respectively (Fig. 6a, c), and are 3.37 and 1.67 MPa for the 50-mm-thick HS and LS specimens, respectively (Fig. 6, d). It should be noted that the presence of other stress components especially in the thickness direction could also affect the measured restoring force value. For the purpose of this study, all pieces of flat-sawn lumber were selected such that stresses in thickness direction were relatively small compared to those in the direction of width. In the future, the effects of other stress components could be included in the calculations.

According to Eq. (4), the calculated restoring forces at those magnitudes of σ_m derived are compared with the experimental values in Fig. 7a, b. As expected, a good agreement between the calculated and the measured restoring force values is obtained in the flexural response regime between the half-split lengths from 60 to 100 mm in the 30 mm-thick and 130-mm-wide specimens (Fig. 7a). Outside this range, the calculated restoring forces overestimate the experimental values. At half-split lengths <60 mm, it is expected that the internal stress was not fully relaxed across the whole specimen thickness, and the presence of stress field around the tip of the kerf had not yet been taken into account in the calculation. At the half-split lengths more than 100 mm, stress field generated by the deep kerf should have covered across the end of specimen with a width of 130 mm. Therefore, one end of a half-split specimen leg cannot be considered to be fixed to a rigid support. A modification of Eq. (4) to cope with such behaviors outside the flexural response regime warrants further investigation and is a subject of future work. This is crucial for thicker lumber such as the 50-mm-thick specimens where the flexural response range was rather small of 80–95 mm (Fig. 7b). Estimation of the internal stress within thicker lumber using the purely flexural model proposed is still possible but is no longer appropriate. Analysis in the following section is therefore restricted to the 30-mm-thick and 130-mm-wide rubberwood lumber.

Validation of σ_m derived from the restoring force technique

The released strain and Young's modulus in the tangential direction plus moisture content distributions within the 30-mm-thick HS and LS specimens obtained from the McMillen slice test are shown in Fig. 8a–c. The elastic strains due to the release of internal stresses were not uniform (Fig. 8a). After slicing of the surface layer,
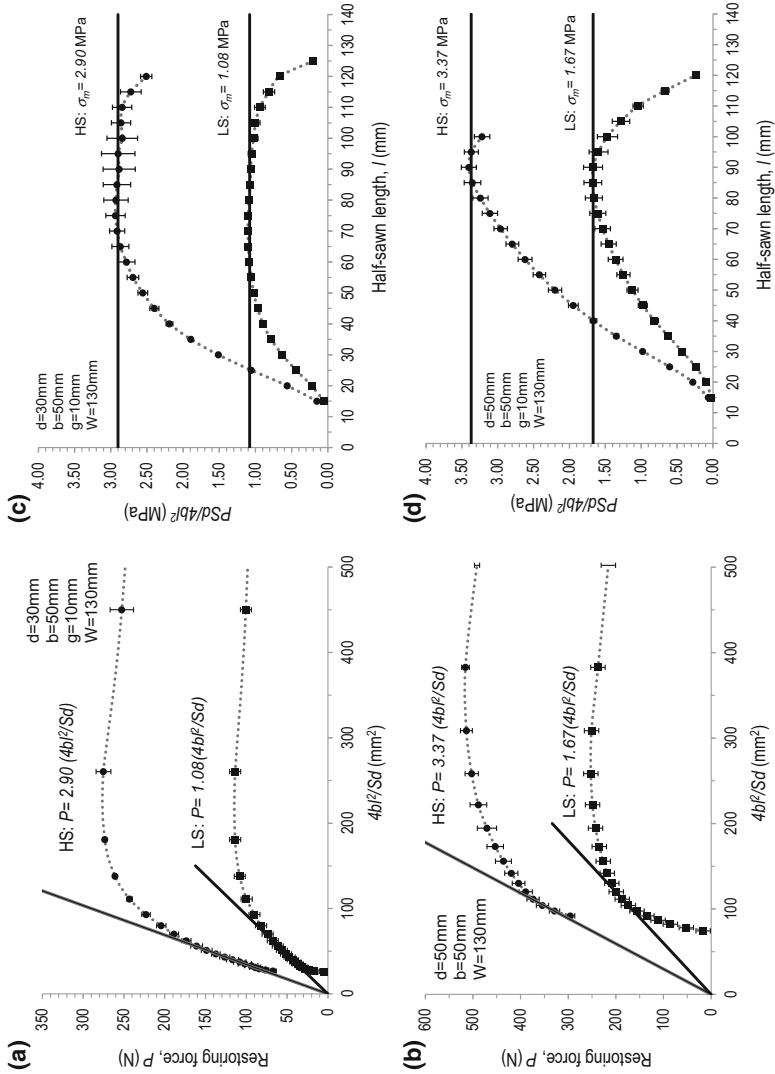
Fig. 6 Plots of the restoring force versus $\frac{4bl^2}{Sd}$ for **a** the 30-mm and **b** the 50-mm-thick half-split rubberwood specimens and plots of $\frac{PSd}{4bl^2}$ versus the half-split length for the **c** 30-mm and **d** the 50-mm-thick half-split rubberwood specimens containing relatively high (HS) and low (LS) levels of internal stress. *Solid lines* represent the best fits to the experimental data in the flexural response regime

Fig. 7 Comparison of experimental (*symbols*) and calculated restoring force (*solid lines*) profiles of the **a** 30-mm and **b** 50-mm-thick half-split rubberwood specimens containing relatively high (HS) and low (LS) levels of internal stress at various half-split lengths
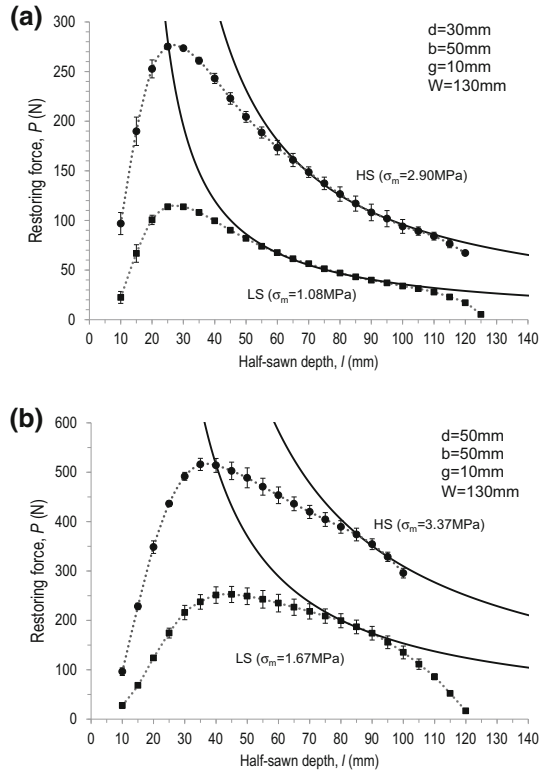
lengthening with a positive value of released strain indicates that the wood in this layer was under compressive internal stress before being sliced. On the other hand, a negative released strain observed at the core layer indicates a tensile internal stress. This behavior has been reported for casehardening of kiln-dried lumber by various authors (McMillen 1958; Simpson 1999). Moisture content was approximately uniform across the lumber thickness with the average values of 6.2 ± 0.4 % and 10.2 ± 0.5 % in the HS and LS specimens, respectively (Fig. 8b). Since moisture content was lower in the HS specimens, Young's modulus in these specimens (585 ± 112 MPa) was higher than that in the LS specimens (477 ± 91 MPa) (Fig. 8c).

Corresponding internal stress profiles, product of the released strain and the Young's modulus for each slice, are shown in Fig. 8d, e. The Poisson's ratio effect is assumed to be negligible. A linear average to the stress data was performed across the thickness. Corresponding maximum stresses σ_m obtained were 2.10 and 0.97 MPa for the HS and LS specimens, respectively. These values are in general agreement with those derived from the restoring force technique of 2.90 and 1.08 MPa for the HS and LS specimens, respectively. A very close agreement is observed in the LS specimens where the internal stress profile is relatively low and roughly linear (Fig. 8e). At higher levels of internal stress, the stress profile deviates from the linear distribution. The maximum stresses at the surface and the core layer
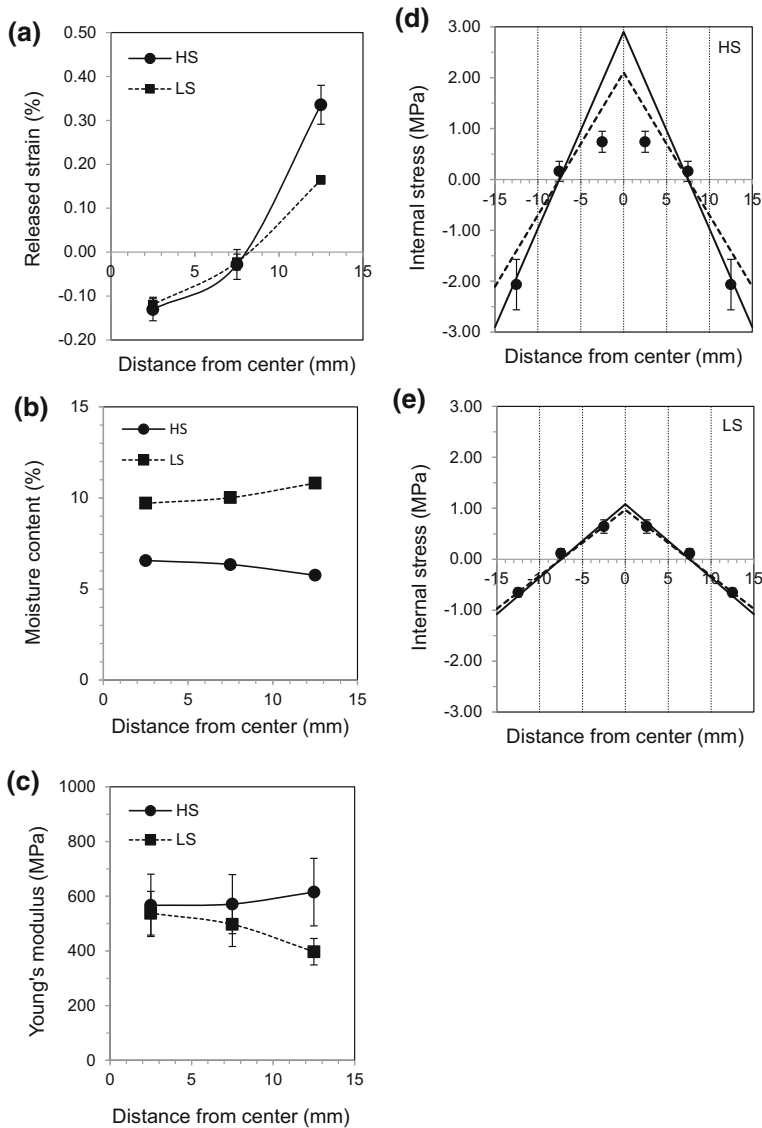
Fig. 8 Distributions of **a** released elastic strain, **b** moisture content, **c** Young's modulus within the HS and LS specimens and distributions of the calculated internal stresses within **d** the HS and **e** the LS specimens. Linearly averaged internal stress profiles obtained from the slice test (*dashed lines*) and the proposed restoring force technique (*solid lines*) are also displayed for comparison

are different. Values of σ_m both underestimate and overestimate the maximum compressive stress at the surface layer and the maximum tensile stress at the core layers, respectively (Fig. 8d). Nevertheless, a single value of σ_m, representing the average maximum magnitude of the internal stress within the kiln-dried lumber, should be a simple and convenient stress indicator to be used in lumber industry.

Validation of σ_m obtained from the restoring force technique should be performed against other well-developed internal stress measurement techniques (Schajer and Ruud 2013) in the future.

The restoring force–internal stress chart

Intended for practical use in the lumber industry, the chart of restoring force versus half-split length plotted at different levels of internal stress is created in Fig. 9a, b. The demonstration was made in this work for 30-mm-thick lumber with length in the longitudinal direction of 50 mm and the restraining point at 10 mm from the top end. Two sets of three 30-mm-thick industrial kiln-dried rubberwood lumber were used. Stress relaxation of the kiln-dried lumber during conditioning at 85 °C and 80 % RH inside the conditioning chamber and during storage in ambient air at

Fig. 9 Determination of σ_m using the restoring force–internal stress chart by plotting the measured values of the restoring force as a function of the half-split length of the 30-mm-thick and 130-mm-wide kiln-dried lumber during **a** conditioning at 85 °C and 80 % RH and **b** storage in ambient air at 28 ± 2 °C and 75 ± 6 % RH
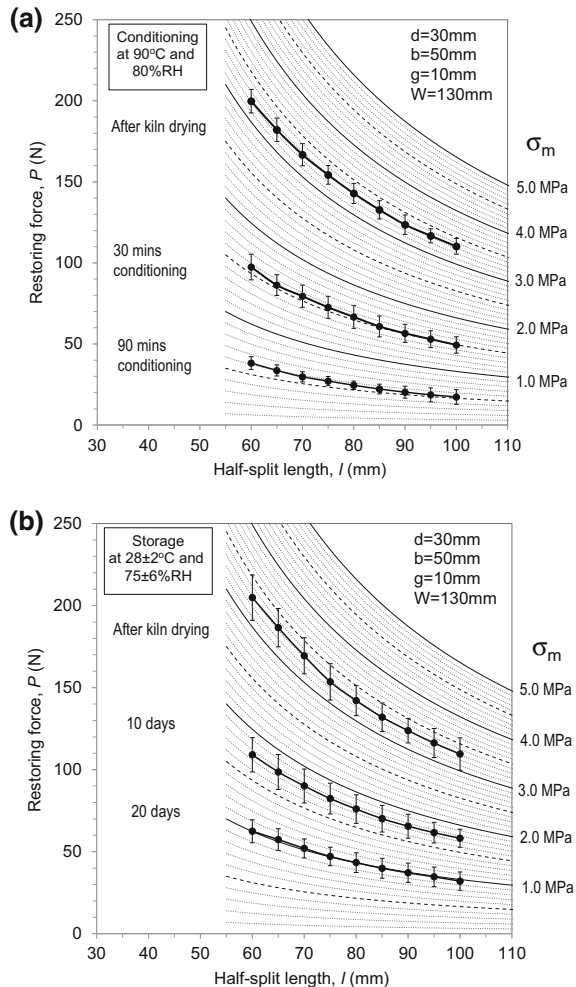
28 ± 2 °C and 75 ± 6 % RH was investigated using the chart. The half-split length employed was from 60 mm to 100 mm, a suitable range as mentioned in "Estimation of the internal stress" section.

The measured restoring forces obtained from each group of lumber roughly follow a particular stress level line. The magnitude of σ_m can be directly assessed through the chart. Figure 9a shows that after kiln drying, σ_m was 3.3 MPa and after conditioning for 30 and 90 min, it was reduced to 1.5 and 0.6 MPa, respectively. For the second set of kiln-dried lumber, storage in ambient air for 10 and 20 days reduced σ_m to 1.8 to 1.0 MPa, respectively (Fig. 9b).

The restoring force measurement on the half-split specimens together with the use of the proposed restoring force–internal stress chart should be a useful tool in estimating the magnitude of internal stress within industrial kiln-dried lumber. This technique, still a destructive method similar to the traditional prong one, should give a reliable and meaningful stress measurement and is easy to perform. Ongoing research focuses on determining σ_m outside the flexural response regime, which is not covered by this model especially with relatively narrow ($W < 90$ mm) or thick ($d > 30$ mm) lumber. Finite element analysis will be employed to study the complex stress behavior outside the flexural response regime.

Conclusion

The following conclusions can be drawn from this work.

1. A procedure and an apparatus for the assessment of internal stress within kiln-dried lumber have been presented. The restoring force measured on the half-split specimens appears to be a reliable quantitative measure of the magnitude of the internal stress.
2. The magnitude of the restoring force is dependent on the half-split length and thickness of the specimens. With increased half-split length, the restoring force sharply increases, reaches the maximum value and then gradually decreases. Higher restoring force is obtained in the thicker lumber.
3. The model based on an elastic cantilever beam theory has been successfully developed to directly deduce the maximum linearly averaged internal stress from the measured restoring force data within the flexural response regime. No information on the modulus of wood is required in the calculation. In the 30-mm-thick lumber, the flexural range is between the half-split lengths from 60 to 100 mm. This flexural range becomes smaller in the thicker lumber.
4. General agreement is found between the magnitudes of the maximum linearly averaged internal stress derived from the restoring force technique and the conventional McMillen slice technique, especially in the specimens having a relatively low and roughly linear stress profile.
5. The restoring force–internal stress chart has been proposed for a practical use in the lumber industry. A demonstration was carried out to follow stress relaxation during conditioning and during storage of industrial kiln-dried rubberwood lumber.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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