

## **DETERMINING THE SOURCE OF CHANGING SHRINKAGE RATES DURING KILN DRYING\***

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### **ABSTRACT**

The conclusions drawn by researchers on the source of changing shrinkage rates are discussed. The objective of this study was to determine the source of changing shrinkage rates early in drying and whether shrinkage would make a useful parameter for an automated kiln control system. In this study, four loads of red oak and one of maple were kiln dried using established schedules. Shrinkage of the lumber was continuously recorded, and moisture content and released elastic strain were periodically recorded. The moisture content and strain data showed that the changing shrinkage rates early in drying boards were caused by reduced internal stress levels, not the occurrence of fiber saturation point or temperature as reported by some. Results of this study indicate it may be possible to develop an automated kiln system using shrinkage as the controlling parameter. This would reduce the drying time while avoiding additional drying defects.

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## INTRODUCTION

Many researchers have recorded board width shrinkage during drying. If the rate of moisture loss is kept constant early in drying and shrinkage is essentially a linear function of moisture content (Peck (1928)) the initial conclusion would be that shrinkage rate is a linear function of time. However, research has shown that this is not true (Erickson (1994), Rietz (1955) and Ross (1981)). As the author was collecting shrinkage data for an unpublished study on mechano-sorptive strain, stress development seemed to explain the non-linear shrinkage rate. A new study was then initiated to examine this possible explanation for nonlinear shrinkage rate. Determining the correct explanation for the nonlinear shrinkage rate is significant in that if it is caused by stress, the shrinkage rate might be a useful parameter for an automated kiln control system. The objectives of this study were to resolve the source of the observed non-linear shrinkage rates and if shrinkage can be used as a parameter for kiln control.

### Background

The traditional kiln drying control parameter for appearance grade lumber is average moisture content. Temperature is increased and relative humidity is decreased as the average moisture content decreases. As a consequence of this traditional method all present automated kiln control systems use moisture content directly or indirectly as the control parameter. However, the major concern during the early phase in the drying of appearance grade lumber is defects caused by high perpendicular-to-grain drying stresses. Therefore, the desired parameter to monitor the drying process should be stresses. McMillen (1963) showed that moisture content is not a good indicator of stress level and therefore is a poor parameter for kiln schedule control. This is why all the established schedules for appearance grade lumber were purposely developed to be excessively slow. Yet, without a good way to monitor stress levels, moisture content remains the only parameter to advance the kiln schedule.

Rietz (1950) also recognized the importance of stress level and developed a method that would alter the established schedule based on stress but still use moisture content as the monitoring parameter. He also recognized and noted that moisture content is a poor indicator of stress level and proposed the need for a "tension set detector".

Fracture strain is the strain at which a fracture is initiated. Bello (1972) developed moisture content based drying schedules to avoid fracture strain. Bello's work was based on the assumptions that: 1) drying stresses are generated by uneven shrinkage within the board caused by the moisture gradient developed during drying, 2) shrinkage is essentially a linear function of moisture content below fiber saturation point (FSP), and 3) shrinkage only occurs below FSP. He predicted the strain (shrinkage) developed by the moisture loss that would occur at a given kiln condition. This strain was then compared with fracture strain calculated

from a mechanical property model whose independent variables were temperature and moisture content. This method was called "shrinkage-strain-control method." Ross (1981) picked up this work and developed a knee gage to obtain surface strain measurements.

More recently, at least three groups of researchers have worked directly with shrinkage of lumber during drying. Their theories can be grouped into two categories to explain nonlinear shrinkage rate: 1) average moisture content being reduced to below fiber saturation and 2) elevated temperature.

Perre et al. (1994) measured surface shrinkage using a laser/peg system while monitoring moisture content. They concluded that the abrupt change in the shrinkage curve was caused by average moisture content being reduced to below FSP. While monitoring moisture content, Fortin, et al. (1994) used a semi-ring extensometer to measure shrinkage. They recorded that increased surface shrinkage rate occurred at 35% to 30% average moisture content, and was caused by the average moisture content being reduced to below FSP. Both studies by Perre, et. al. and Fortin, et al. were conducted on pine and neither measured internal stress levels.

The FSP cannot be used to describe average board moisture content. By definition, the FSP is the moisture content at which the cell wall is fully saturated and there is no free water in the cell lumens. As the board dries, it has a moisture gradient throughout the thickness, with the surface region being the driest and the center region being the wettest. The board also has moisture gradients developed by the differences in cell and pit diameters because of capillary forces (Olson and Chang (1990)). Therefore, the occurrence of FSP, as denoted by 30% average MC, cannot be the cause of shrinkage rate change because at that average MC the surface cells are below FSP and the center cells are above FSP. Only on one plane somewhere between the center and surface is the wood at FSP.

Erickson (1994) measured shrinkage, moisture content, elastic strain and mechano-sorptive strain for two drying schedules. One of the drying schedules was a typical step schedule for red oak and the other was a low temperature schedule with constantly diverging Dry-bulb and Wet-bulb temperatures. He concluded that the change in shrinkage rate was due to the increased temperature of the typical step schedule.

The objective of the overall study was to identify all the sources for non-linear shrinkage rates. The objective of this paper was to determine the source of non-linear shrinkage rate early in drying and if shrinkage can be used as a parameter for automated kiln control. This information would advance the progress of achieving a stress-based drying system instead of relying on the current moisture content-based schedule.

## METHODS AND MATERIALS

Using standard schedules, five loads of lumber were kiln dried, four red oak and one maple (using kiln schedule codes T4-D2 and T8-C3 respectively) (Boone et al. (1988)), with

a 6-hour fan reversal cycle. The MC was monitored using four kiln samples per load. Three loads of oak and one of maple were 1.2 m wide. The fifth load was oak and was 0.6 m wide. For sampling purposes, three boards 32 mm thick, 150 mm wide, and 4.3 m long were selected from each load. For ease of sampling and testing at selected time intervals, each board was pre-cut into 0.46 m long sample blocks and end-sealed with neoprene to reduce end drying. These sample blocks were inserted into the side of the load at center height with each sample block from a single board randomly placed along the length of the load and sampled successively.

### Tests

Two tests were performed: 1) residual strain analysis and 2) shrinkage test using linear variable differential transformers (LVDTs). The residual strain analysis was to obtain residual strain and moisture content data. This test was first used by Peck (1928) and is typically referred to as the McMillen slice test. The sampling intervals were: 1) every 3 or 4 days, 2) immediately before each advancement of the kiln schedule and 3) 16 hours after each advancement of the kiln schedule. At this time, one sample block from each of the three sample boards was removed and two 25.4 mm long cross sections were cut off. The bare end of the block was recoated with neoprene and was replaced in the kiln. The first cross section was immediately weighed by a second person to obtain average moisture content. The width of the second cross-section (long dimension) was immediately measured using a digital indicator, then cut into 10 equally thick slices in the longitudinal-width plane. As each slice was cut on a bandsaw, the second person measured the width as it was held flat and weighed it on an electronic scale. Resolution of the data was to the nearest 0.025 mm and 0.01 g. Electronic data recording reduced any time delays. The slices were placed in a rack to maintain flatness and were oven dried along with the first cross-section. The oven dried weight and width were then measured.

### Strain Analysis

Using the dimensional data, released strain was calculated by dividing the pre-cut and post-cut slice length difference by the pre-cut slice length. The measured strains were converted to stresses (Ugolev (1955)) using the modulus of elasticity as a function of moisture content data collected by Fuller (1993). Then the stresses were adjusted to maintain stress equilibrium (Ugolev (1955)). The two corresponding slices for each layer were averaged and converted back to strain to obtain the reported strain values. Positive values imply that the slice was under compression, negative values imply that the slice was under tension.

### Shrinkage

Shrinkage was continuously recorded by an LVDT mounted on one block from each sample board to obtain the width shrinkage (Fig. 1). This block was positioned to be sampled last. The legs of the mounts penetrated 8 mm into the blocks and were fastened with 8.7-mm

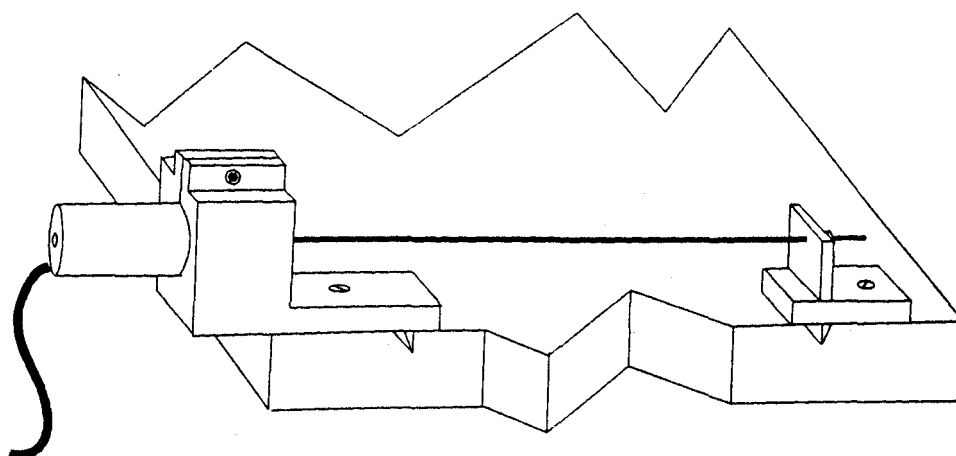


Figure 1. Shrinkage measuring device assembled on a board.

wood screws. Ross (1981) showed the importance of penetration depth of the mounts for shrinkage measurements; therefore values reported in this paper are not surface strain and may not be board shrinkage. They will simply be called shrinkage in this paper. The screw holes in the mounts were oversized, and the measurements reflected the distance between the legs of the mounts. Readings were electronically recorded every hour during drying. The sensitivity of the measurements was to the nearest 0.025 mm. Preliminary testing ensured that there was no drift of the output signal as a result of temperature or time. Cupping was minimized by the restraint of the stickers and lumber above and below the sample block to simulate typical boards in the load.

## RESULTS AND DISCUSSION

Equilibrium moisture content (EMC), average moisture content and shrinkage of Board 1 for the first load are displayed in Figure 2a, and released strain for Board 1 (McMillen slice test results) in Figure 2b. In Figure 2a, the stepped curve represents the EMC conditions of the kiln. The negatively sloped curve is the average moisture content of the first cross-section samples for the first board. The moisture content differences between the kiln samples, first cross-sections and average of the slices were less than 5% at any time. The two positively sloped curves represent the shrinkage for two sample boards in the first load. The third sample board was similar to the second and for clarity is not shown. The shrinkage values are based on green width. The vertical dashed lines provide a time reference between

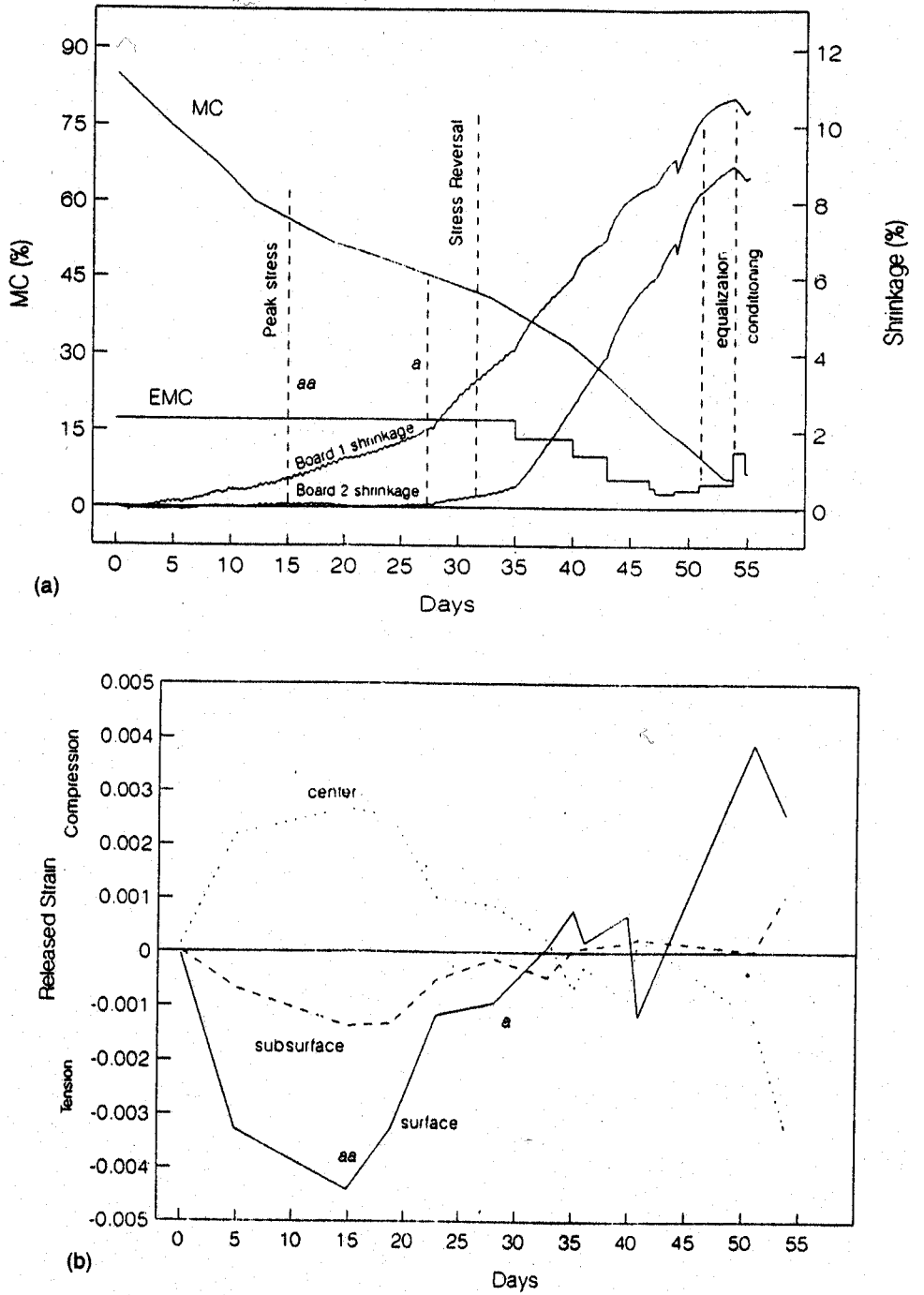


Figure 2 (a) Shrinkage for three boards, moisture content, and EMC of the dry kiln compared with drying time for the first oak load, (b) released strain for three layers through board 1 compared with drying time to show the cause of the shrinkage curve slope changes. Points a, and aa are described in the text.

curves. In Figure 2b, released strain is shown for three layers through Board 1: surface (slices containing the board surface), subsurface (the slices adjacent to the most outer slices) and center (two most inner slices). The two remaining intermediate layers are consistently between the subsurface and center and strongly favor the center layer. For clarity of the graph these two are omitted.

The precision of the measurements is supported by the shrinkage and swelling cycles caused by the desorption and adsorption cycles which follow the 6-hour fan reversal cycle. This shows up as irregularity in the first 35 days in Figure 2a. It is enlarged in Figure 3 for days 12 through 14 showing the 6-hour cycles. These results also show that the experiment closely simulates commercial drying with longer air flow paths and higher exit relative humidity values.

The specific objective of this study is to determine the source of shrinkage rate change early in drying. The other aspects will be the subject of future work.

#### Initial Change in Shrinkage Slope

The first visually discernible change in shrinkage rate for Board 1 (Fig. 2a, point *a*) occurred when the average moisture content was 45%, well above FSP, and just before the strain curves displayed stress reversal (Fig. 2b, point *a*). Shrinkage rate change and stress reversal occurred in the second load (Fig 4) when the average moisture content was greater than 50% and the core moisture content was 70%. These results show shrinkage occurs when average moisture content is above FSP and agree with previous findings. McMillen (1963) reported core shrinkage when the core was greater than 40% moisture content. Rice and Youngs (1990) reported shrinkage above FSP. Their explanation was that preferential drying, possibly around the rays, may have caused the shrinkage above FSP,

Other conflicting research interpreted the increased shrinkage rate as caused by an increase in the dry-bulb temperature (Erickson (1994)). However, according to the figures presented by him, the increase in temperature occurred up to 75 hours after the increased shrinkage rate started. His data did indicate that the shrinkage rate increased at the same time as stress reversal, indicated by released strain values, implying a direct cause-and-effect relationship.

The results in the present study and Erickson's data support the interpretation that the cause for the change in shrinkage rate is not the reduction of average moisture content below FSP nor the increase temperature, but drying stresses and is explained as follows: Initial drying develops stored energy in the form of elastic strain (tension in the surface, compression in the remaining material) as a result of surface shrinkage while non-elastic strain occurs. This shows up as the average shrinkage rate being less than tabulated free shrinkage (U.S. Forest Products Laboratory (1987)), .05% shrinkage/%MC and 28% shrinkage/%MC respectively. When the center of the board starts to shrink, the energy stored as elastic strain is released and shows up as the average shrinkage rate being greater than tabulated free shrinkage, (.44%

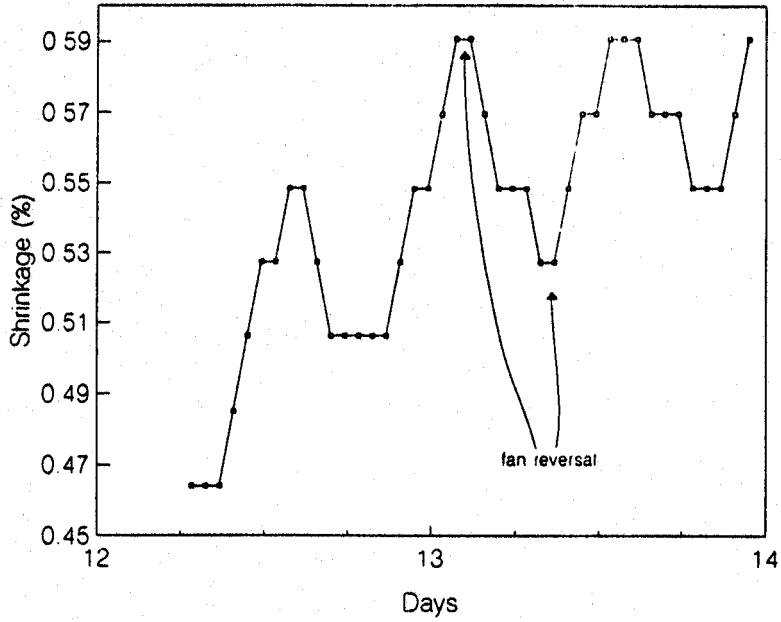


Figure 3. Shrinkage curve for Board 1 during days 12 to 14, displaying 6-hour fan reversal.

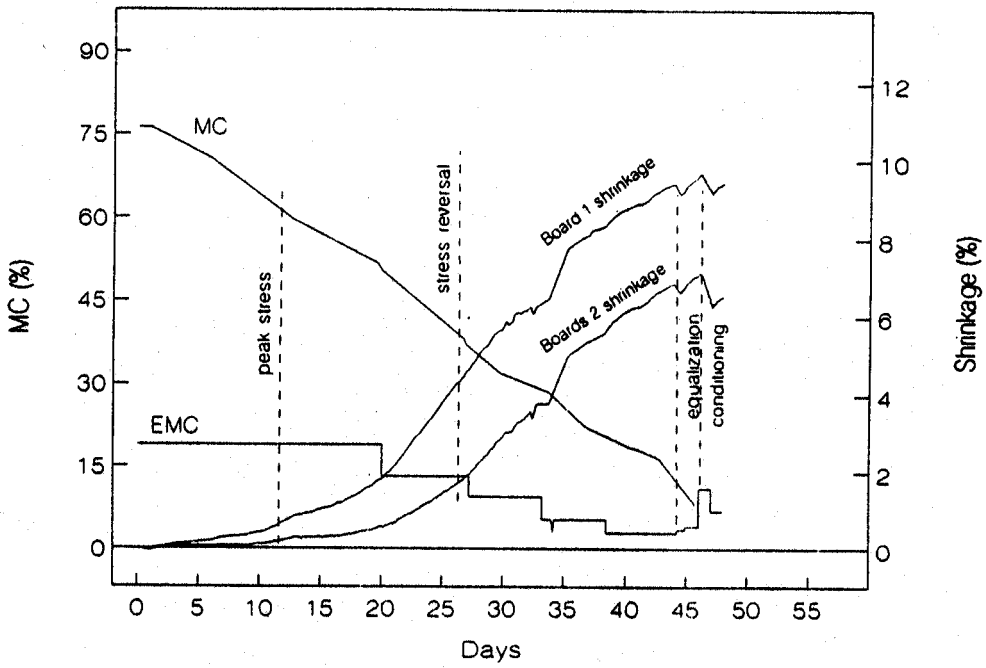


Figure 4. Shrinkage, moisture content and EMC of the kiln compared with drying time for the second oak load.

shrinkage/%MC). Average shrinkage rate is determined by dividing the amount of shrinkage by the moisture loss.

There are only limited possible explanations to account for this. Rice and Youngs (1990) reported that time dependent non-elastic strain is insignificantly involved in drying and does not account for the shrinkage. Temperature is not changing, therefore, it cannot be a temperature-dependent strain. The only known type of strain left is a moisture-dependent strain. Either the subsurface layers are shrinking and creating greater tension or the center is shrinking. Figure 2b shows the subsurface layers are decreasing in tension at the same time as the surface. Therefore, the strain is not caused by the subsurface shrinking which is below FSP. This means a moisture-related strain occurs during the loss of moisture of center material when the gross MC of the center is above FSP.

#### Statistical Determination

As noted, when the surface stresses are reduced, the shrinkage rate increases. The following statistical method was developed to quantitatively characterize the shrinkage curve for the basis of an automated (computerized real-time) kiln-control system. This monitoring would enable the detection of a rate change before the  $i$ th data point, the last collected data point. This method is called short/long term slope comparison (SLSC) method.

As drying progresses, the method compares a long-term slope with a short-term slope both of which share the  $i$ th point as their common end point (Fig.5). The long-term slope is the slope of a segment where the first end point is the initiation of drying (point 1) and the second end point is the  $i$ th point. The short-term slope is the slope of a segment where the first end point is the  $(i-j)$ th point and the second end point is the  $i$ th point. The length of  $j$  points is selected to satisfy a predetermined short term as dictated by the schedule and species which must be subject to further study. Criteria for deciding how large  $j$  is are: 1) For fast drying species,  $j$  needs to be shorter so that the statistical method can respond more quickly. 2)  $j$  must be long enough so that the statistic will not be over powered by the noise created by such variability as the fan reversals. 3)  $j$  must be short enough so that the short-term slope will be distinguishable from the long-term slope.  $j$  remains constant while  $i$ th and  $(i-j)$ th point progresses with the drying.

To account for variability in the curves, an upper-bound long-term slope curve is calculated by adding the long-term slope curve's standard deviation to the long-term slope curve. A similar procedure is performed to the short-term slope curve by subtracting the short-term slope curve's standard deviation to obtain a lower-bound short-term slope curve. When the lower-bound short-term slope curve is greater than the upper-bound long-term slope curve, stress reversal occurs. This can be used as an indicator to show when the reduced stresses impart a significant change in the shrinkage slope. Figure 6 displays these data for the first 35 days for Board 1 and is representative of the other boards for stress reversal. Point  $a$  in Figure 6 is the same point as depicted by Point  $a$  in Figure 2a, representing the time when

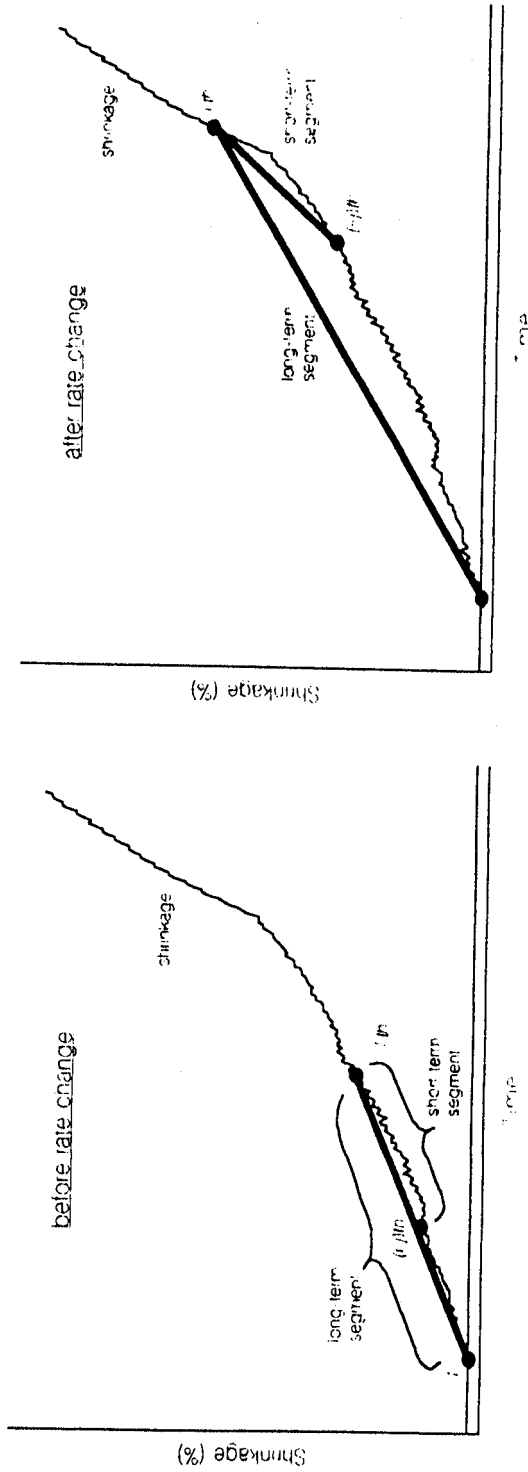


Figure 5. Displaying how the slopes of the short-term and long-term segments will indicate a shrinkage rate change.

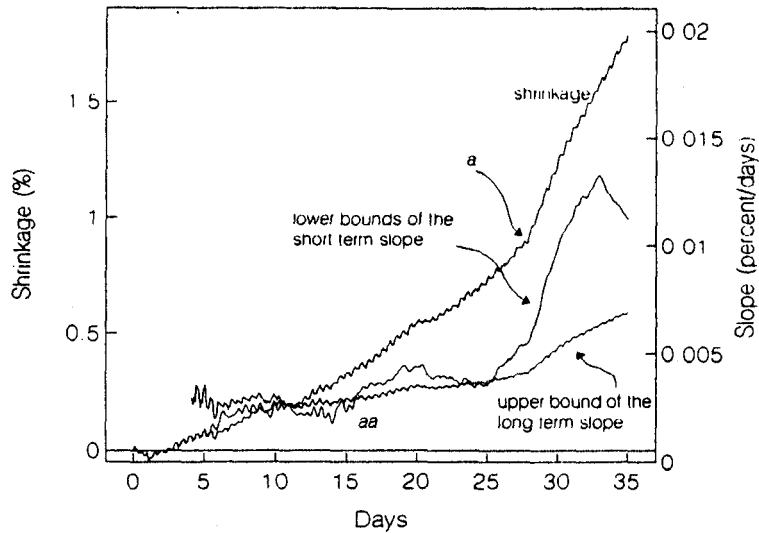


Figure 6. Changes in the shrinkage curve slopes depicted by shrinkage curve, upper bounds long-term slope curve, and lower bounds short-term slope curve for Board1 in the first oak load.

the stresses are about to reverse. Point *aa*, the time the short-term slope is greater than the long-term slope, will be discussed later. This also occurred the same day for Boards 2 and 3 (Fig 2a). In these boards, the lower-bounds short-term slope curve had a greater value than the upper-bounds long-term slope curve, indicating a change in stress level.

#### Peak Stress

Peak stress is the maximum tension stress the surface achieves early in drying, after which the stress level quickly reduces. If no surface checks are initiated up to this time, none will be initiated by a stress lower than the peak stress. Therefore, the severity of the kiln conditions can be increased to a degree that increases the stresses to a level just below peak stress. This would require an appropriate time delay after peak stress is detected to allow stresses to reduce by an amount slightly greater than the stress the kiln schedule advancement would create. With an early increased severity of kiln conditions, the drying time can be significantly reduced while avoiding surface checks. This is the same concept Rietz (1950) proposed when he proposed the need for a "tension set detector."

The passage of peak stress, a stress reduction, can be detected by the SLSC statistical method. This is accomplished by identifying when the lower-bounds short-term slope curve first exceeds the upper-bounds long-term slope curve, this indicates a statistically significant difference in slope. In the application of this statistical method peak stress, not stress reversal,

would be sought after. Point *a* would not occur because the kiln schedule will have already been advanced.

In the current study, the first change in slope occurred on about 15.6 days (Fig 6. point *aa*). Figure 2b (point *aa*) shows this is just after the point of peak stress, as indicated by the McMillen slice test, day 15. The exact occurrence of peak stress could not be determined by the McMillen slice test because the strain sampling was done at discrete times, every 3 or 4 days. Peak stress could occur shortly before or after the discrete testing time. However, it is desirable to advance the kiln schedule after peak stress has occurred, the exact desired delay can be programmed. In this run, the shrinkage data indicated the stress reduced on day 15 and the schedule could have been advanced while the moisture content schedule dictated a wait until day 35 to advance the schedule. Using the stress based method, advancements could have been approximately 20 days earlier than the moisture content based method. Now with a usable detection device, a stress-based schedule can be used instead of a moisture-content based schedule.

The change in slope associated with peak stress is also observable in Erickson's figures (1994). This provides independent data supporting the proposed explanation for the change in shrinkage rate.

A second statistical method, two-phase regression (Worsley (1983)) was used only to confirm the proposed statistical method (SLSC) and the results. As will be realized in the description, this is not an efficient process control method. The two-phase regression procedure calculates a separate regression for the points on each side of the *k*th point, giving two variance estimates,  $\hat{\sigma}_1^2$  and  $\hat{\sigma}_2^2$ , based on *k* and *n* - *k* points, respectively. The *n*th point is the same as the *i*th point in the SLSC method. These variances are compared with an overall regression fit, which gives a variance estimate of  $\hat{\sigma}^2$  based on *n* points, detecting the changes in the estimated variance values.  $L_2(k)$  quantifies the difference between the slopes of the two segments.

$$L_2(k) = -n \log_e \frac{k \hat{\sigma}_1^2 + (n-k) \hat{\sigma}_2^2}{n \hat{\sigma}^2}, \quad k = 2, 3, \dots, n-2 \quad (1)$$

The higher the value the greater the difference of the two estimated slopes. Each time a new *n*th point is recorded, every previous data point is successively considered as the *k*th point again. This is done until the maximum  $L_2(k)$  decreases, signifying that slope change has occurred. Figure 7 displays the results for 7 different days. After the 27th day the maximum value of  $L_2(k)$  decreased. The analysis on the 27th day indicated that a slope change occurred on the 14th day.

The two-phase regression method is in agreement with the SLSC method and provides additional support for it, yet the two-phase regression method proves to be much slower to indicate the change. The method requires many data points after the *k*th point. This delays the detection of slope change occurrence by a variable length of time as well as the

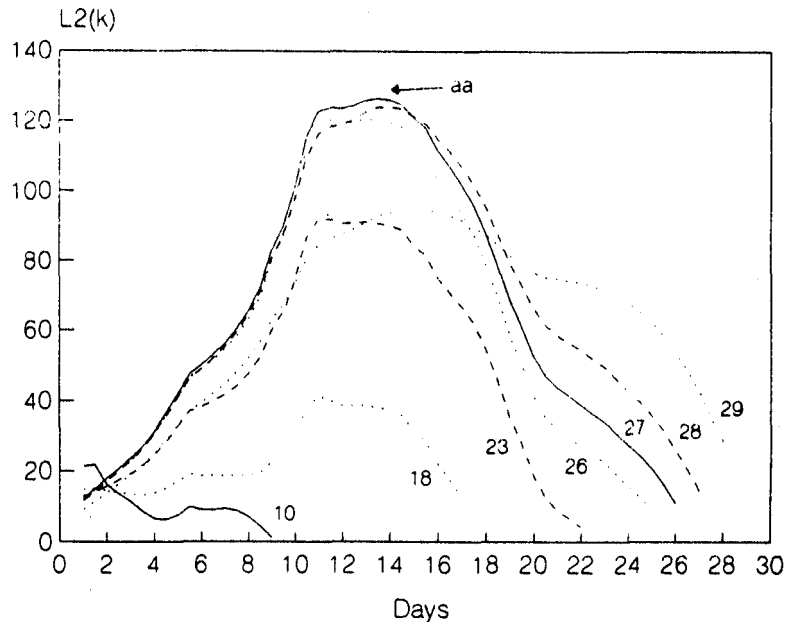


Figure 7. Worsley's (1983) two-phase regression results for 7 days. The results on day 27 had the maximum apex and depicts the point of change in shrinkage curve on day 15.6.

decision to advance the schedule, in this instance by 13 days. Therefore, the SLSC statistical method is more desirable for use in actual drying.

#### Influence of Surface Checks

The difference between the two shrinkage curves in Figure 2a is the initial apparent lack of shrinkage for the first 28 days in Board 2. This is due to development of surface checks in this board first observed on the third day, as shown in Figure 8. The explanation for this is that the board remained stationary because the core was not shrinking and restraining the mounts. The mid-section shrank inwards and the material from the check to the edge shrank outwards. As drying continued, the checks deepened and displayed a significant reduction in shrinkage. This was also detected by the SLSC statistical method. In Figure 9, the instantaneous slope flattens out and is indicated by the long term slope reduction and the short term slope remains less than the long term slope curve until stress reversal occurs. When the center of the board started to shrink the checks started to close and exhibited increased shrinkage rate (Fig. 2a), the same as for a non-surface checked board, Board 1. For uniform kiln drying without surface checks, material differing in species and initial moisture content, as well as material susceptible to defect, would be sorted out and dried separately using appropriate schedules.

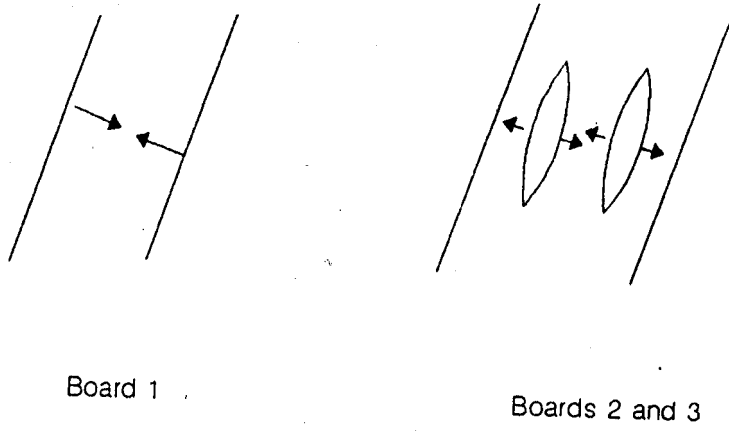


Figure 8. Board 1 shows normal shrinkage while Boards 2 and 3 illustrate how surface checking give the appearance that no shrinkage is occurring.

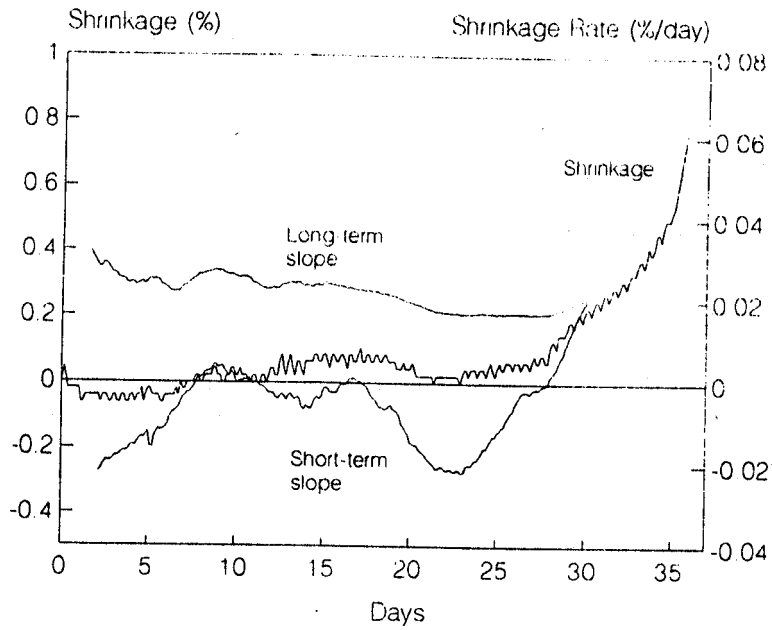


Figure 9. Changes in the shrinkage curve slopes depicted by shrinkage curve, upper bounds long-term slope curve, and lower bounds short-term slope curve for Board 2 in the first oak load.

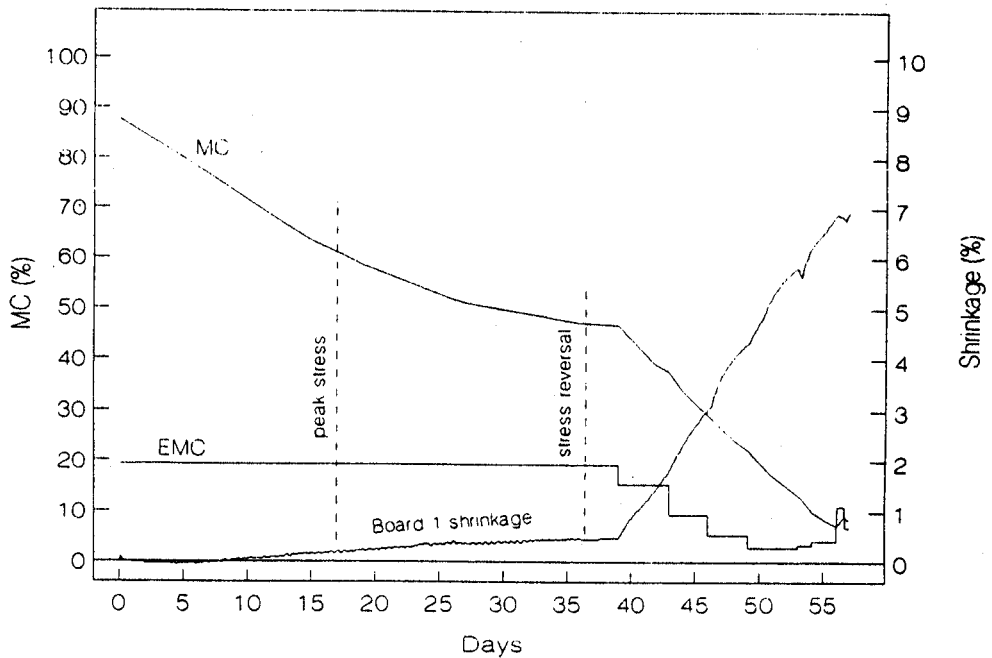


Figure 10. Shrinkage, moisture content and EMC of the kiln compared with drying time for the third oak load.

Although the kiln would not be controlled based on surface checked boards, it would be something to look out for and understand when these type of results occur.

Data for the remaining three loads are displayed in Figures 10-12 which supports the preceding discussion. Table 1 summarizes all the loads when stress reversal and peak stress occurred and what the moisture content was at each point. Sample boards in one oak load did not develop a distinct peak stress because surface checks circumvented the development of high stresses and created a plateau in the stress behavior. The maple schedule starts out more mild than necessary and advances the schedule quickly therefore peak stress developed after the first schedule change. In addition, because of the frequent schedule changes for maple, distinct stress reversal did not develop.

### CONCLUSIONS

In this study, the changes in shrinkage rates early in the kiln-drying schedule were shown to originate with changes in internal stress levels. These stress level changes correspond

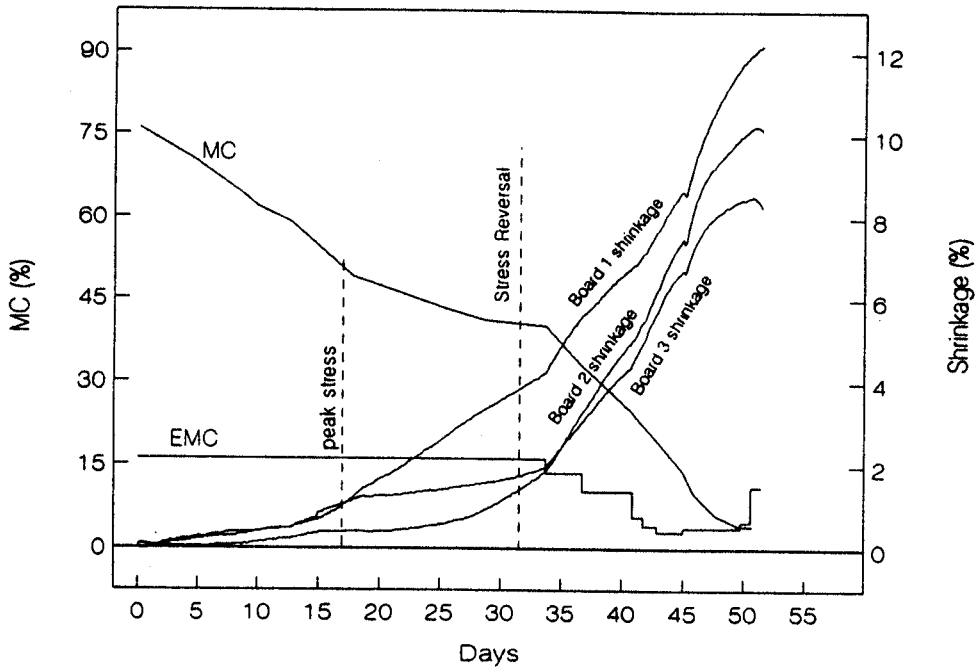


Figure 11. Shrinkage, moisture content and EMC of the kiln compared with drying time for the fourth oak load.

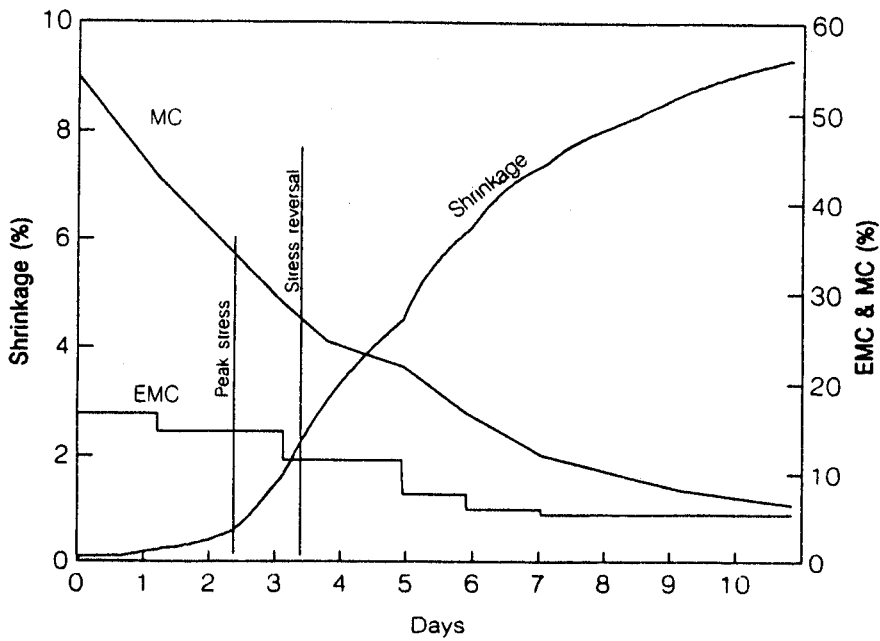


Figure 12. Shrinkage, moisture content and EMC of the kiln compared with drying time for the maple load.

TABLE 1. Summary of all the loads for when peak stress and stress reversal occurred with the corresponding moisture contents

Load	Peak Stress (days)	Moisture Content at Peak Stress (%) <sub>i</sub>	Stress Reversal (days)	Moisture Content at Stress Reversal (%)
Oak 1	15	56	27	45
Oak 2	12.7 <sup>2</sup>	60	26.5	36
Oak 3	17-25	61-53	37.5	41
Oak 4	17	52	32.7	40
Maple	2.5	33	3-4 <sup>3</sup>	29-24

with stress reduction and stress reversal. Thus, shrinkage rate changes are not caused by the occurrence of fiber saturation point, as measured by the average board moisture content, nor are they caused by an increase in temperature, as some previous research has concluded. With the source for the changes in shrinkage rate early in drying known, there is a real possibility of an automated kiln control system based on a parameter directly related to internal stress levels.

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