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DEVELOPMENT OF ELASTIC STRAIN AND MECHANO-SORPTIVE STRAIN DURING CONDITIONING OF *EUCALYPTUS CAMALDULENSIS* LUMBER IN BATCH KILN

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ABSTRACT

Final conditioning of 25mm thick dried *E. camaldulensis* lumber was carried out in small capacity batch drying kiln in laboratory, and the elastic (EL) strain and mechano-sorptive (MS) strain was analyzed by slicing method. Mean moisture content(MC) of boards increases 2.5-3.0%, while surface MC increases from 9.8% to 14.2% and center MC always keeps at 12.3% or so. Difference of each slice oven-dried length, through the thickness of the board decreases with the going on of conditioning. Compressive EL strain in the surface decreases significantly during the first 9h of conditioning, and tensile EL strain in the center doesn't change significantly with the going on of conditioning. Compressive EL strain of sub-surface is greater than that of surface during middle and final period of conditioning, so reverse stress gradient is formed. Casehardened surface is softened by moisture picking-up and then complementary shrinkage makes EL strain and MS strain decrease, but because of the effect of drying history, the change of MS strain lags behind that of MC.

Keywords: *E. camaldulensis*; Final conditioning; MC; Elastic strain; Mechano-sorptive strain

INTRODUCTION

Due to wood shrinkage below fiber saturation point (FSP), tensile stress will occur in the surface layer of the board during drying. This stress combined with the change in moisture causes mechano-sorptive creep. If the process is abruptly terminated when the target MC is reached, then there will be a considerable internal moisture and stress gradients, which will cause distortions in subsequent machining.

Steaming with high humidities at atmosphere pressure has been a successful way of relaxing residual stresses in lumber after drying. Stress relaxation is achieved within one to two hours, merely depending on board dimensions and initial stress distribution (Moren, 1994a, b). But steaming often causes overheat phenomena, especially with large, well-insulated kilns, so the desired wet-bulb depression cannot be obtained (Hart, 1990). Water sprays are very effective at reducing kiln overheat and when used in conjunction with steaming they improved moisture pick-up and stress relief, but the required duration may be up to three times the durations of steaming (Haslett et al., 2001).

Now, the procedures of conditioning are often experiential according to the methods reported by Mcmillen (1963), especially in China. So, many studies were carried out following these procedures during conditioning. Moren (1994a) reported the possibility of estimating the average

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moisture pickup from measuring or calculating core temperatures in the boards during conditioning, so the possibility of settling the average moisture pickup by means of controlling the core temperature could be used to predict the required duration of the conditioning process. For the same objective as reported by Moren (1994a), Sandland (2001) determined the casehardening level after the drying period from the relation between distortion gap and MC gradient.

The analysis of conditioning phase with a wood drying model reported by Salin (2001) shows that traditional conditioning with a constant climate cannot completely release the distortions, even at very long conditioning times. So, an optimizing procedure with a varying climate is developed by him and the residual stress can be relieved completely with this optimizing procedure.

Mechano-sorptive effect caused by moisture change during conditioning may be the main reason of stress relieving, especially when residual drying stress is far below the proportional point (Pang, 2000).

It is well acknowledged that the total strain during drying consists of shrinkage strain, EL strain, visco-elastic strain and MS strain. Shrinkage strain occurs when the MC of lumber falls below FSP, which is the essential property of wood and cannot be changed. Visco-elastic strain is the time/stress-dependent movement of wood in the absence of any change in moisture content. Compared with the service time in other environments such as in building and furniture, drying time is so short that the magnitude of visco-elastic strain is minimal and can be neglected, so this component is neglected in this research. On the basis of the above thoughts, only EL strain and MS strain in the total strain are studied in the experiment.

Eucalyptus is one of the main fast-grown species in south China and much research has been performed to control collapse and checking during drying while little in relieving residual drying stress. The objective of this study was to gain knowledge about the development of EL strain and MS strain during conditioning. This would be beneficial to illustrate the mechanism of casehardening relief during conditioning, and also beneficial to develop a proper schedule for Eucalyptus lumber drying.

MATERIALS AND METHODS

The boards came from 18-year-old plantation *E. camaldulensis* grown in Lufeng, Yunnan, South China. Average diameter at breast height (1.3m) was 44.5cm. The conditioning board dimension was 900x100x25mm, which was already dried to 11% MC.

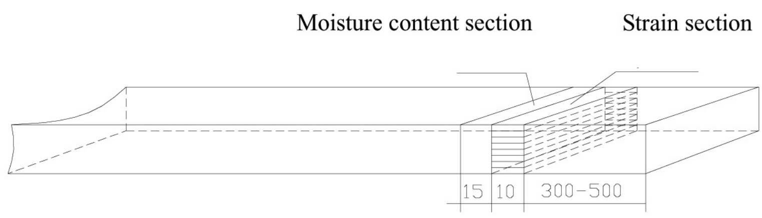

Fig.1 Schematic illustration of slice measuring (Unit: mm)

Conditioning was immediately done in batch kiln in Wood Drying Lab. of Nanjing Forestry University and lasted 24h with wet air at 62ºC and 14% EMC. Test samples for evaluating MS strain, EL strain and moisture content were taken at five conditioning times (0, 1, 3, 9 and 24 h) as illustrated by Fig. 1. At each sampling time, the freshly cut board were end-sealed with silicon before the boards were replaced in the stack.

$$\varepsilon_E = (L_2 - L_1) / L_1 \quad (1)$$

$$\varepsilon_{MS} = (L_4 - L_3) / L_0 \quad (2)$$

EL strain (ε_E) and MS strain (ε_{MS}) were calculated individually according to Formula 1 and Formula 2, where the parameters L_0, L_1, L_2, L_3 and L_4 were determined as follows:

a. Initial length of each slice L_0 was measured to the nearest 0.02mm before drying, which was the width of board before drying.

b. 10mm thick section was cut from sample board at each sampled time during conditioning. 8 same thin slices was acquired across section and labeled as slice 1 to slice 8 sequentially from bark to center. Each slice length was measured to 0.02mm before and after slicing, which is L_1 and L_2, respectively. Each slice was weighed to the nearest 0.01g immediately after slicing to calculate MC.

c. Each slice was dried in a stepwise sequence, e.g. room air-drying/low-temperature drying first at 30ºC, second and then at 60ºC, then finally at oven-drying at 103±2ºC. Each oven-dried slice was immediately weighed and its absolute length was measured to 0.02mm, which is $L_{3.}$

d. Before drying, the same thickness slices taken from the same board were firstly dried with the same stepwise sequence as illustrated in procedure c and then the length of each slices were measured, which is L_4.

Some hypotheses were assumed during the above procedures, which were as follows:

First, moisture distribution is even in each slice with no MC gradient because the slices are so thin only approximately 3mm. Second, during procedure, because the slicing and measuring is done as soon as possible, the slice length difference between before and after slicing can be regarded as EL strain. Third, no new MS creep was developed during slice drying as described in procedure c because the drying condition was very mild. Finally, in procedure d the shrinkage coefficient difference between L_4 slice and the slice sampled during conditioning is negligible because they were both taken from one straight-grain sample board.

RESULTS AND DISCUSSION

Change of Moisture Content during Conditioning

During conditioning, mean MC of sample board increased 2.5%-3.0%. Fig.2 shows that MC of surface slice 1 and slice 8 increases from 9.8% to 14.2% while that of center slice 4 and 5 doesn't change significantly. Difference between surface MC and media EMC can be regarded as the promoting power of surface adsorption. For the difference between moisture content of surface and EMC of media is great during the first 9 hours of conditioning, moisture gain was significant. With the remaining time of conditioning, the MC/EMC difference is minimal and the rate of moisture gain decreased, which results in the MC increase being small.

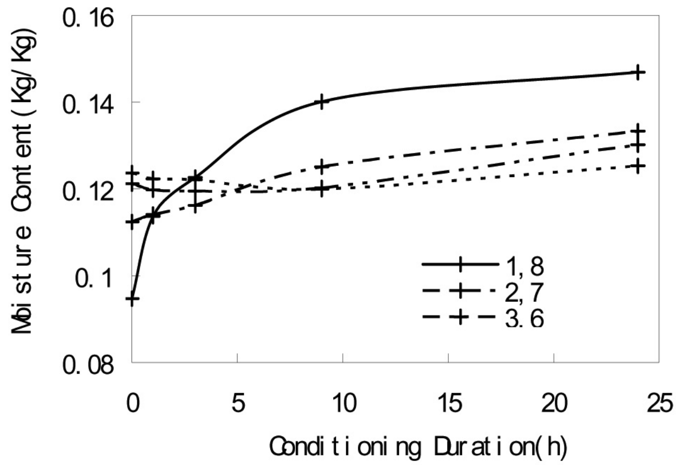

Fig.2 MC curve of sample board during conditioning

Change of core moisture content is dominated by moisture diffusion in the board. Though moisture was gained in surface, the surface MC was yet lower than that of center in the first several hours of conditioning, so the center moisture diffused to outer layers, driven by the moisture content gradient. With more moisture gained in surface, the surface moisture content would be higher than the center moisture content, so the moisture in surface moved to the center driven by the reverse moisture content gradient. Above all, the change of core MC before and after conditioning was insignificant, though it oscillating during middle period of conditioning.

MC development in the hyper-center slice 3 and 6 was analogous to that in surface slice 1 and 8. During the first hour of conditioning, MC of subsurface 2 and 7 increase with moisture diffusing from inner layers to subsurface, and then increase by the combined effect of moisture diffusing from center to subsurface and moisture picking-up in surface. When the reversed MC gradient formed at the 6th hour of conditioning, the MC increase of subsurface was entirely caused by moisture picking-up in surface.

Change of slice oven-dried length during conditioning

Effect of MC gradient on drying stress was assessed in conventional drying stress theory. Virtually, shrinkage difference between neighboring slice, which is caused by MC difference but also by shrinkage coefficient difference, is the direct reason of drying stress. Differential shrinkage across board, but not MC gradient, was used to reflect drying stress by Stohr(1998), and surface shrinkage was used to control drying process by Fuller(1999). The basic theory in their research is that differential shrinkage is the original of stress developing. With the decreasing of log radius, shrinkage coefficient difference makes more contribution to stress developing closer to the pith.

It was observed from Fig.3 that oven-dried length difference between neighboring slices as conditioning progressed was dependent on position: of surface slices (1 and 8) decreased while that of center slices (4 and 5) increase. This is related to residual plastic set because there is compressive set in center and tensile set in surface. During conditioning, casehardening in the surface is reduced was softened and shrinkage was also, because of moisture picking-up in surface, while swelling happened in center. After 24h conditioning, the difference of oven-dried length among slices were not minimized to zero because the shrinkage coefficient increases sequentially from slice 1 to slice 8.

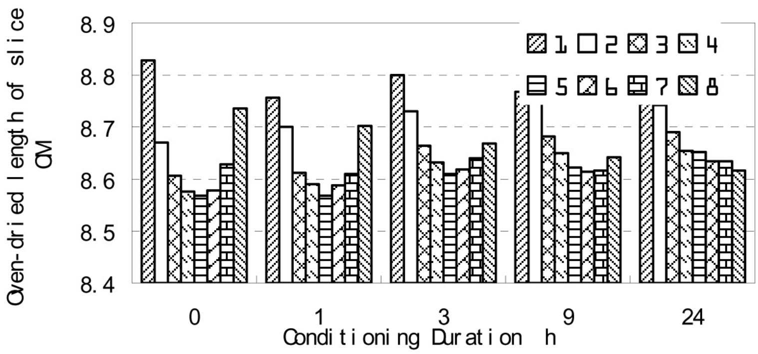

Fig.3 Oven-dried length profile of sample board during conditioning

Change of EL strain during Conditioning

It was observed from Fig.4 that compressive ES in surface passed a transient increase and then decreased from 0.449% to 0.133% rapidly during conditioning. When conditioning started, surface was wetted rapidly and swollen, but the neighboring subsurface (2-7) was not wetted and did not swell, so the compressive EL strain in surface increased. Mcmillen (1963) had reported wetting and softening of surface resulted in complementary shrinkage, which caused the compressive stress increase in surface. With the continuous wetting, the surface was softened and the complementary shrinkage happened in surface, which resulted in the decrease of compressive EL strain. With conditioning continuing, moisture gain in surface became slow and subsequently the effect of softening decrease and the complementary shrinkage decreased, so the decrease rate of compressive ES became slow. The above results were the same as Fuller's reports in 1995 (Fuller, 1995a,b).

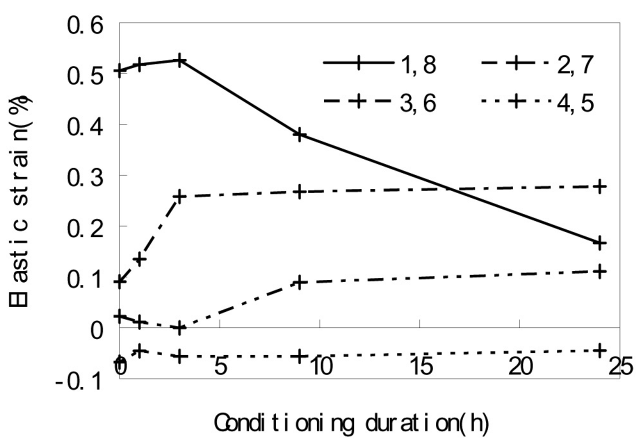

Fig.4 Elastic strain curve of sample board during conditioning

During the middle and final period of conditioning, subsurface EL strain is greater than that of surface because of the complementary shrinkage of surface. Wetting in surface caused the MC increase in subsurface and this led to the increase of compressive EL strain in the first 3h of conditioning.

Developing of EL strain in subsurface (2-7) was analogous to that in surface, while hyper-center (3-6) was analogous to center (4-5).

It was a pity that the zero sum of internal stress across section was not validated in this research because of the effects of settlements and methods, though the zero sum of internal stress is a common knowledge. But development of EL strain in each layer during conditioning could be illustrated sufficiently above.

Change of MS Strain during Conditioning

MS strain occurs as a consequence of moisture content change when the wood is under stress. During drying, this behavior is beneficial because it can relieve drying stress. However, this is not desirable when the lumber is in service, for this causes the dried lumber to deform after re-sawing and equalizing of the moisture content. So the minimization of MS strain can be used to evaluate the effect of conditioning.

According to Armstrong and Kingston's report in 1960, MS creep during conditioning belongs to Case 2: Increasing the moisture content to a value above the previous lowest moisture content decreases the MS strain. During conditioning, with moisture vapor entering wood, vaporization latent heat and differential wetting heat are generated at the lumber surface, so the surface temperature will arise rapidly (Hart, 1994; Pang, 2000). Heat and moisture will make the casehardened surface soften, so the MS strain is reduced.

Fig.5 shows MS Strain of each layer during conditioning decrease significantly. Compressive MS strain in subsurface (2-7), hyper-center (3-6) and center (4-5) shifted from 0.848%, 0.863 1.326 to 0.355%, 0.343% and 0.452% individually, while tensile MS strain in surface shifted from 2.031% to 0.329%. Fig.5 also shows the decrease was significant during initial and middle period of conditioning while it was minimal during the final stage of conditioning. So if the conditioning lasts, the decrease of MS strain will be insignificant and even cause reverse casehardening.

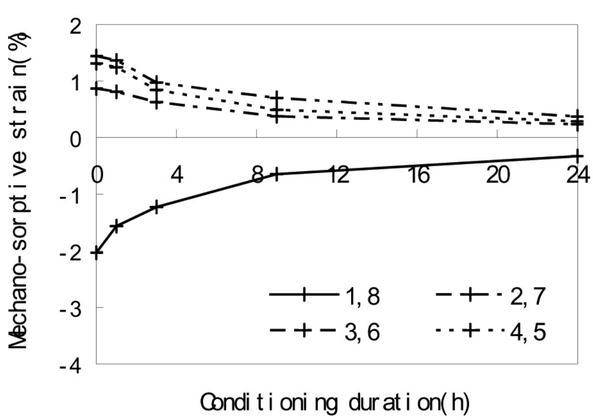

Fig.5 Mechano-sorptive strain curve of sample board during conditioning

From Fig.2 and Fig.5, it was concluded that the change of MS strain lagged behind that of MC, especially during the middle period of conditioning, which proves that MS creep is affected not only by instantaneous drying stress but also by drying history.

CONCLUSION

Moisture content data obtained by slicing the board show that mean MC of surface slice increased about 5% after being conditioned for 24h in temperature 62ºC, EMC 14% wet air, while the mean MC of board increased from 11% to 13.5% and center MC doesn't change significantly.

With the picking-up of moisture during conditioning, surface stress was found to attain a maximum value and then to decrease rapidly. This was accomplished through mechano-sorptive recovery, which was not only observed by slicing method, but also proved by the minimization of oven-dried length difference between neighboring layers during conditioning. Minimization of MS creep caused by surface wetting slightly lagged behind that of MC, so MS creep was affected not only by drying stress, but also by drying history.

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