목재공학18(3) : 17~25(原著)
Mogjae Gonghak. 18(3) : 17~25. 1990

Properties of 3-layered Laminated Veneer Lumber with Crack and Grain Angle from Stress Wave Tested Veneers*[1]

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응력파 실험에 의해 예측된 단판으로 제작한 할열과 목리를 지닌 3매 단판적층재의 특성*[1]

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摘　要

양표면은 무결점재를, 가운데 단판은 경사목리 및 목리방향의 할열을 가진 단판을 사용하여 제조한 3매 단판 적층재에 있어서 목리방향과 할열의 인장탄성계수 및 인장강도에 미치는 영향에 대하여 조사하였다. 또한, 비파괴 시험 방법인 응력파 실험에 의하여 각단판의 탄성계수를 측정하고, 이들 단판의 탄성계수로부터 단판적층재의 탄성계수를 예측하여 실측치와 비교하였다. 응력파에 의해 예측된 탄성계수는 인장실험으로부터 얻어진 결과와 거의 일치하였으며 인장탄성계수와 인장강도간에도 높은 상관관계를 나타내었다($r^2=0.681$). 인장강도에 있어서는 가운데 단판 할열의 영향은 나타나지 않았으나 목리의 경우 경사각이 증가함에 따라 인장강도가 감소하는 경향을 나타내었다.

1. INTRODUCTION

Perhaps one of the most useful characteristics of LVL is that it is comprised of several distinct layers of materials. Thus the manufacturer has the opportunity to control strength properties and their variability by the proper selection and placement of the materials comprising the individual layers. Basically the reduction in variability and increase in strength as compared to solid lumber is the minimizing of the influence of defects by selection and placement of individual veneer sheets. It also provides the LVL manufacturer with an opportunity to construct from material of known or estimated quality a product with the performance appropriate to its end use. The key to this concept would be the accurate assessment of the quality of each piece of veneer.

Although the term "nondestructive" testing covers all types of testing operations in which the specimen is not harmed by the test, stress waves has the potential for wide spread use in stress grading lumber. A more wide spread use of the technique for stress-grading wood pro-

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*1. 接受 1990年 3月 5日 Received March 5, 1990.

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ducts should result from a better understanding of the interaction of stress waves with wood. This study explored the question of what structural performance and predictability can be expected LVL members constructed from veneers segregated into stress wave predicted performance groups.

2. BACKGROUND

Jung(1979) tested the effect of grain and veneer width using 1/4 inch thick rotary peeled red oak veneers. He found that stress wave speed was not significantly affected by the width of veneer when free of defects. The velocities for grain angles of 5° and 10° were approximately 4% and 19% less than for grain at zero degree. The stress wave readings were relatively insensitive for grain angles less than 5° but at slightly larger angles the stress wave readings were significantly affected.

Bohlen(1974) examined the tensile strength of LVL(2×4×92in.) made from 1/4-inch thick, butt-jointed veneers. Strength reducing characteristics of natural origin, such as knots and severe slope of grain, were dispersed throughout the volume of wood by laminating randomly selected veneers. This yielded a product having a much smaller coefficient of variation(13.9%) than sawn lumber(37%). In general, the failure of 82% of all specimens initiated at a butt-joint and relatively low failing loads were obtained when there was grain deviation in a adjacent lamination, usually associated with a knot. Within the range of high strength specimens, only a few failures were associated with knots. Apparently, knots in themselves contributed little to weakness unless they were closely aligned throughout the cross section.

Leicester and Bunker(1969) studied the effect of lamination thickness on the tensile strength of butt-jointed specimens. For a butt joint in the center of three plies, their data indicated a tendency for increased tensile strength with reduced thickness(T). They expressed ultimate strength as a linear function of 1/T. The increase of stress with decrease in lamination thickness suggested the possibility that, by the use of sufficiently thin laminations, the effect of butt-joints would be no more severe than that of natural weaknesses in the laminations.

Peterson et al.(1981) found that MOE was the best predictor of tensile strength for all grades of glulam. Nearly 37% of the variation in tensile strength could be explained by MOE alone, compared with 28% for the predictor based on the knot measurement K/b. This suggested that MOE would be a better grading criterion than knot size when grading lumber for glulam tensile members for all grades.

Jung(1982) explored the question of the structural performance and predictibility to be expected from LVL members constructed from veneer segregated into performance groups predicted from stress wave timing measurements. He used specimen with six plies of 5 by 1/4 inch by 8 feet veneer. His results indicated both flatwise($r^2=0.823$) and edgewise($r^2=0.879$) bending stiffness can be predicted with reasonable accuracy, but the prediction of tensile stiffness($r^2=0.659$) was much poorer. The simple regression correlation between strength and MOE predicted from stress wave testing($r^2=0.185$) was slightly better correlated than that between strength and static

MOE(r^2=0.16). Statistical differences in the strength results for the different stiffness groups were not found. The reason for poor correlation between strength and stiffness was caused by the laminating process producing lumber of low variability.

3. EXPERIMENTAL METHOD

The material considered was 3-layer LVL with all layers 1/8 inch thick. The outer layers were chosen to be straight-grained, free from significant local defects and to have approximately the same mechanical properties. The central layer contained the experimental variables of slope of grain and crack length, the crack being parallel to the grain. To reduce the variability in specimen properties and to enhance the statistical replicability, matched strips of veneer were used for all specimens.

From a stack of 36×38 inch clear yellow poplar sheets of 1/8 in. thickness, a random procedure was used to select 25 sheets for face and back lamination and 10 for the central laminations with the grain direction. Center lines were drawn parallel and perpendicular to the grain on all the strips to enable the grain angle to be measured by a protractor. Each sheet was cut into 3 inch by 16 inch strips with the face grain oriented at the intended angle, the grain angle was remeasured and the boundaries of a strip a little bigger than 2 in. wide and 14 in. long was marked in pencil. Strips with the 90° grain angle were made slightly bigger than the others to provide an extra margin of safety in handling these fragile strips. After trimming the strips to the marked sizes, their dimensions and weights were determined and recorded.

3.1. Stress wave test

The modulus of elasticity(MOE) of each strip was determined using the impact stress wave equipment manufactured by Metrigard. The stress wave machine involves the use of a simple pendulum to provide a reproducible impact and the determination of the stress wave transit time between two accelerometers clamped near each end of the specimen. A compressional stress wave is induced in the end of specimen by the pendulum striking a steel plate clamped near the end of the specimen. The accelerometer near the impactor started a microsecond counter at the impact and the second accelerometer stopped the counter when the wave reached it. The counter thus gave the time for the impact stress wave to traverse the measured distance between the accelerometers.

The longitudinal stress wave speed, C, was obtained by dividing the distance between the accelerometers by the measured transit time($\triangle t$). The $\triangle t$ measured in microseconds was remarkably repeatable. Each specimen was impacted three times and the average of three readings of $\triangle t$ was used in calculating the modulus of elasticity of each lamina from following equation

$$E=\left(\frac{\text{gage length}}{\triangle t}\right)^2 \frac{\text{Weight}}{(386)(\text{volume})}$$

3.2. Selection of strips for LVL specimens

Based on the MOE as determined by the stress wave testing, 168 strips as straight-grained and defect-free as possible were selected for the surface layers. Each strip was ranked in ascending order of its MOE and 84 pairs were selected such that the MOE of both strips in each pair were as equal as possible. These pairs were than grouped into 7 replicate sets such that the pairs in each set were as similar in MOE as possible. The test variables were allocated to the pairs in each replication at random.

The strips for the inner layer of each grain angle were also ranked in ascending order of their MOE. An inner layer strip with the required grain angle was matched to a pair of outer strips in order of its rank number.

3.3. LVL specimen construction

Cracks were formed in the strips selected for the central layer by making a sawcut parallel to the grain with a jeweler's saw. A center line was first drawn of the strip parallel to the long side. A subsidiary line was then drawn parallel to the grain to intersect the first line at the center of the crack position. A small hole 3/32-inch was drilled at the intersection to allow insertion of a jeweler's saw blade which was used to make a cut of the required length in both directions from the hole. A small piece of plastic film was inserted in the crack to keep the glue from filling the crack. A press roller was used to spread the glue uniformly on the surface of the veneers. The adhesive was Franklin Titebond which has the characteristics of high durability and curing at room temperature. The strips were then stapled together to prevent sliding during pressing.

Several specimens separated by waxed yellow paper were placed side by side between wooden cauls in a glue reel machine. Pressure was applied by pneumatically driven clamps. All the specimens were kept in the machine around 24hr. The specimens were then sanded to the final dimension 14 inches in length and 2 inches in width.

3.4. Testing

The specimens were secured to the testing machine by steel wedge grips in the loading heads of the testing machine as shown in Figure 1. This arrangement minimized the chance of slippage because the grips tightened as the load increased. The upper grip was secured through a spherical seat to minimize bending effects. A Tinius Olsen extensometer

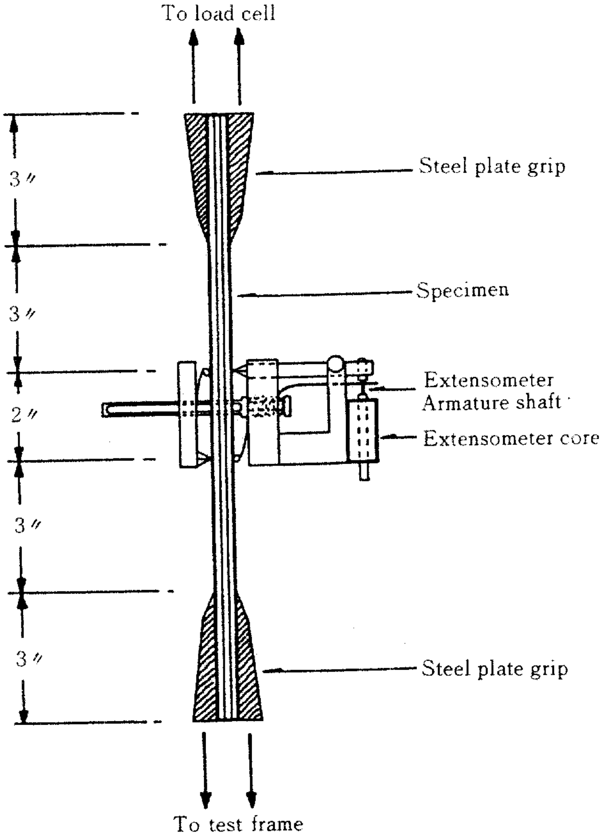


Fig. 1. Testing arrangement

was used to monitor the strain, the applied load being measured by the Tinius Olsen testing machine. The extensometer was positioned carefully over the crack and parallel to the specimen length with its knife edges 2 in. apart.

4. RESULTS AND DISCUSSION

Veneer stressed in tension 90° to the grain has very low strength, not only because the tensile strength of wood perpendicular to the grain is only a few percent of that parallel to the grain, but the lathe checks(cracks parallel to the grain produced in peeling the veneer) often extended halfway or more through the thickness. Consequently, artificial cracks in veneer stressed at 90° to the grain were expected to have negligible effect. Again, a statistical analysis verified that expectation and so all specimens with the center layer oriented at 90° to the specimen length were analyzed as a group.

4.1. Modulus of elasticity of LVL

The MOE's from the stress wave tests for the three veneers comprising each member were averaged to obtain an MOE for the member. Tables 1 and 2 list summary statis-

Table 1. Comparison of static test MOE and stress wave predicted MOE with different grain angles for crack-free specimen

Grain angle(°)	Test type	Sample size(no.)	MOE(10E+6 psi)				
			Mean	SD*	CV**(%)	Minimum	Maximum
0	Stress wave	14	1.412	0.066	4.674	1.310	1.560
	tension	14	1.612	0.120	7.444	1.380	1.860
10	Stress wave	7	1.285	0.084	6.536	1.161	1.401
	tension	7	1.404	0.110	7.835	1.283	1.618
20	Stress wave	7	1.158	0.070	6.045	1.042	1.251
	tension	7	1.325	0.182	13.736	1.139	1.637
30	Stress wave	7	1.058	0.064	6.049	0.966	1.152
	tension	7	1.173	0.142	12.106	0.947	1.353
60	Stress wave	7	0.990	0.054	5.455	0.909	1.064
	tension	7	1.137	0.090	7.916	1.027	1.292
90	Stress wave	7	0.976	0.052	5.327	0.903	1.045
	tension	7	1.052	0.073	6.939	0.984	1.181

* Standard deviation

**Coefficient of variation

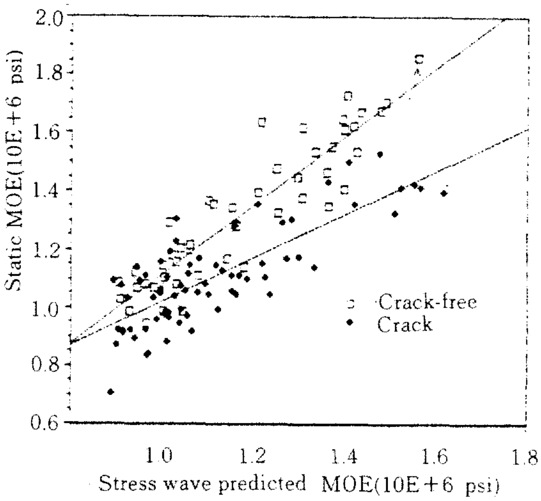


Fig. 2. Distribution of static MOE with stress wave predicted MOE.

tics for MOE from the stress wave and static tension tests for crack-free and cracked specimens, respectively.

Table 1 shows that the static MOE is somewhat higher than the stress wave predicted MOE for crack-free specimens. The variability of the stress wave MOE was consistently less than that of the static MOE. This table also shows a higher coefficient variation(CV), for 20° and 30° angles than at other angles, but that could be merely a sampling effect.

The MOEs from the static tests on cracked specimen were on average less than the stress

Table 2. Comparison of MOE from static test and stress wave predicted MOE with different crack angles.

Crack		Test	Sample	MOE(10E+6 psi)				
angle(°)	size(in.)	type	size(no.)	Mean	SD*	CV**(%)	Minimum	Maximum
10	3.0	Stress wave	7	1.525	0.064	4.200	1.422	1.618
		tension	7	1.410	0.065	4.610	1.325	1.533
20	3.0	Stress wave	7	1.304	0.071	5.445	1.211	1.408
		tension	7	1.277	0.166	12.999	1.046	1.502
30	3.0	Stress wave	7	1.216	0.051	4.194	1.154	1.285
		tension	7	1.132	0.087	7.686	1.046	1.303
30	3.0	Stress wave	5	1.070	0.055	5.140	1.008	1.155
		tension	5	1.099	0.071	6.460	0.989	1.170
60	3.0	Stress wave	6	0.996	0.052	5.221	0.911	1.059
		tension	6	1.145	0.082	7.162	1.072	1.303
90	***	Stress wave	39	1.009	0.076	7.532	0.892	1.161
		tension	39	1.006	0.116	11.531	0.705	1.178

* Standard deviation

** Coefficient of variation

*** Includes all the crack sizes and types wave values(Table 2). Figure 2 shows the plot of MOE from static test versus stress wave predicted MOE. Note the difference in static MOE between cracked and crack-free specimens for large stress wave predicted MOE.

Static MOE parallel to the grain averaged 1,612,000 psi and ranged from 1,380,000 to 1,860,000 psi. The corresponding stress wave values averaged 1,412,000 psi and ranged from 1,310,000 to 1,560,000 psi.

Table 3 shows the simple regression($Y=A+BX$) between static MOE and stress wave predicted MOE. Correlating the static MOE's as a function of predicted MOEs from stress wave test, it was found that the data generally lay above the ideal relationship of the stress wave predicted MOEs. Table 3 also shows regression correlations coefficients between the stress wave predicted MOE and static MOE for all specimens with and without cracks. Static MOE has a high correlation with a MOE predicted from stress wave test at crack-free specimen. However, the cracked specimens show a poorer relationship($r^2=$o.646) between the static MOE and stress wave predicted MOE than that of crack-free specimen($r^2=0.842$).

Table 3. Regression equations for the relationship between static MOE and stress wave predicted MOE* for all grain angles.

Sample	Sample size	Regression equation : Static E=A+B(stress wave E)		
		A	B	r^2
Overall	120	0.038	1.014	0.673
Crack-free	49	-0.074	1.186	0.842
Crack	71	0.265	0.753	0.646

* E values in 10^6 psi

In view of the close correlations the nondestructive stress wave test could be used for predicting tensile MOE.

4.2. Maximum stress in LVL

The maximum strength values are given in tables 4 and 5 for specimens with and without cracks, respectively. The average maximum strength decreased in general as the core grain angle increased, but there was no significant effect for grain angles greater than 30°. Cracks had no significant effects on stress just as they had no significant effect on MOE. The coefficient of variation of the cracked material was lower than that of the crack-free specimens for the smaller grain angles, but the differences were not significant.

Table 6 shows a simple regression($MTS=B \cdot MOE$) between the tensile strength and the MOE determined by static and stress wave tests. There was a high correlation between strength and MOE for all specimens combined. The static MOE correlated relatively well to the strength($r^2=0.669$). A slightly higher correlation was obtained between stress wave determined MOE and tensile strength for all specimens($r^2=0.681$).

Figure 3 shows the maximum strength as a function of grain angle of the middle lamination. Strength had a reasonably good correlation with grain angle for an exponential regression function($Y=AX^B$). The crack-free specimens had a better correlation than the cracked specimens. Also this figure shows that there is no discernible crack effect on maximum stresses for small grain angle. Crack-free specimen had a slightly higher strength than that of cracked specimen(Tables 4 and 5).

Table 4. Effect of grain angle on the maximum tensile stress for crack-free specimens.

Grain type	Sample size	Maximum stress(psi)			Range of stress(psi)	
		Mean	SD*	CV**(%)	Maximum	Minimum
0	14	11949	1580	13.22	15930	11051
10	7	11717	651	5.56	12706	10999
20	7	9691	820	8.46	11142	8676
30	7	8519	594	6.97	9600	7833
60	7	8863	869	9.80	9600	7240
90	7	8242	979	11.88	9533	6787

* Standard deviation

**Coefficient of variation

Table 5. Effect of crack size and grain angle on maximum tensile stress.

Grain angle(°)	Crack size(in)	Sample size	Maximum stress(psi)			Range of stress(psi)	
			Mean	SD*	CV**(%)	Maximum	Minimum
10	3.00	5	11626	319	2.74	12033	11200
20	3.00	5	9867	397	4.02	10367	9433
30	3.00	6	9461	432	4.56	10167	9033
30	0.50	5	8679	636	7.32	9067	7560
60	0.50	6	8412	784	9.32	9433	7140
90	***	39	8207	1158	14.10	10267	6233

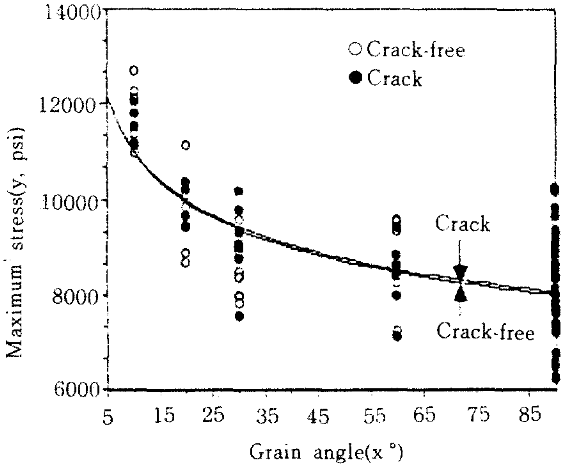
* Standard deviation

Coefficient of variation * Includes all the crack sizes and types

Table 6. Regression equations for tensile strength as a function of static MOE and stress wave predicted MOE*

Sample group	Test method	Sample size	Regression equation Strength=B×(MOE)	
			B(10^3)	r^2
Overall	Stress wave	120	7.695	0.681
	tension	120	6.176	0.669
Crack-free	Stress wave	49	8.670	0.733
	tension	49	6.441	0.676
Crack	Stress wave	71	6.389	0.654
	tension	71	6.355	0.568

* E values in 10^6 psi units



$y = 15397x^{-0.146} (r^2 = 0.560)$(crack-free)

$y = 15290x^{-0.142} (r^2 = 0.443)$(crack)

Fig 3. Stress distribution as a function of grain angle of middle layer.

5. CONCLUSION

1. The MOE of LVL can be predicted with reasonable accuracy by averaging the MOE's of the individual veneers estimated from the stress wave velocity.
2. Static test MOE correlated well with the average MOE determined from the stress wave test($r^2=0.673$).
3. The cracked specimen shows a poorer relationship between static MOE and stress wave predicted MOE than that of crack-free specimen.
4. Good correlations were obtained between MOE and ultimate strength($r^2=0.681$).
5. There was no difference between the cracked and crack-free specimen for ultimate strength.
6. Maximum stress decreased as a grain angle in the core layer increased for both cracked and crack-free specimen.

Further studies are necessary to investigate the effect of ply width and thickness.

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