Mem. Fac. Educ. Kumamoto Univ.
Nat. Sci., No.53. 97－102, 2004

Mechanical Properties of Laminated Veneer Lumber with Interlocked Grain

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(Received October 4, 2004)

To clarify the fundamental mechanical properties of cylindrical laminated veneer lumber (C-LVL), the 10-ply flat laminated veneer lumbers with interlocked grain were manufactured from two species of sugi (*Cryptomeria japonica* D. Don) and akamatsu (*Pinus densiflora* S. et Z.) by using a resorcinol-formaldehyde (RF) resin adhesive (Oshika Shinko Co. Ltd., Dianol D-33). Their elastic constants and strengths in different directions and planes against tension, compression and shearing were obtained by conducting the corresponding tests. Based on the theory of laminated composite, the effect of inclining angle of interlocked grain on stiffness of flat LVL could be easily investigated. In this regard, the other effects could be estimated from the comparison of experimental and calculated results. To summerize the results, the greater reduction of experimetal stiffness and strength in tensile and shearing was found in all directions and planes for both sugi and akamatsu flat LVL compared to the calculated results or those of solid sawn lumber. However, the reduction of compression strength in longitudinal direction was so slightly, even an observation of at least twice compression strengths in transversal directions were found than those of sugi and akamatsu solid sawn lumbers. These differences might be attributed to the discountinuity of veneer such as the existance of butt joint along fiber direction and the cracks perpendicular to grain caused by veneer cutting and stitching, etc. Besides inclining angle of grain, the other effects on tension seemed to be much severer than on compression. However, the important factor should be noted that cylindrical LVL has the structural characteristics in axial symmetrically, which might be potential helpful to c-LVL to be a competent structrural member of column.

Key words : LVL (laminated veneer lumber), cylindrical LVL, stiffness, strength, elastic constants.

1. Introduction

Laminated veneer lumber (LVL) reconstituted by the lamination adhesion has great advantages in uniformity of stiffness, strength and dimensional stability since the defects such as knots, cracks etc. are dispersed by the veneer cutting and laminating. In addition to the variability of curved LVL[1] in design, the use of LVL is getting more and more widely. Especially, as an ultimate new engineered wood for structural use, cylindrical laminated veneer lumber (C-LVL)[2] has been successfully developed and manufactured commercially by the authors' group. Different from the general laminated veneer lumber with a parallel grain, C-LVL has a special constitution with interlocked grain between the adjacent veneer layers as shown in Fig.1 due to its spiral winding manufacturing. The hollow C-LVL manufacture process can be summarized as follows. The rotary lathe peeled veneer in 2.4 mm thick will be cut into strips in 150 mm wide in fiber direction. The veneers strips will be once connected into a long, almost endless tape by sewing with polyester thread. Several layers of veneer tape will be then wound spirally around a steel mandrel from one end to another with winding directions of clockwise and counter clockwise for the adjacent

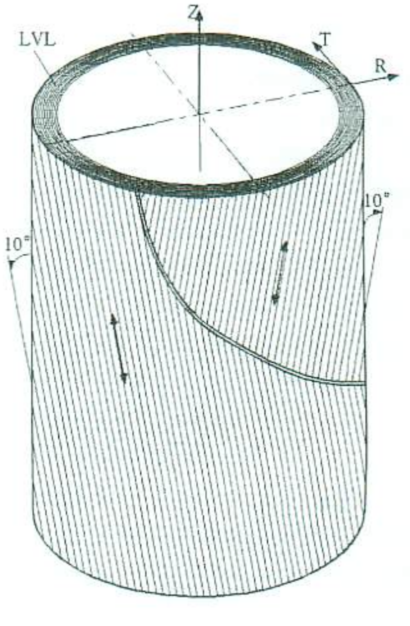

Fig. 1 Cylindrical LVL with interlocked grain.
Note: ⟷ : Direction of grain.

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layers alternatively. A resorcinol-formaldehyde (RF) resin adhesive (Oshika Shinko Co. Ltd., Dianol D-33) will be applied between the layers. An elastic fastening belts will be wound around the outer surface of the C-LVL to exert pressure for ensuring the exact adhesion of laminated veneers. The hollow C-LVL will be removed from the mandrel after the resin adhesive cured completely.

As a dip angle is indispensable in spiral winding manufacturing, the orientation of fiber direction will be kept in an angle of plus or minus 10-degree inclining to the longitudinal Z-axis to minimize the reduction of stiffness and strength of C-LVL in Z-direction3). The layers laid down with the winding direction of the adjacent layers opposite to each other will result in an interlocked grain for the hollow cylinder wall. This structure is quite similar to the pattern in which wood secondary wall microfibrils are arranged. This so-called bio-mimetic structure of C-LVL could be expected to display a full scale of stiffness and strength of wood to create an ultimate engineered wood for structural applications.

This study attempts to clarify the fundamental mechanical properties of C-LVL which are the important factors relating to its applications. To investigate the stiffness and strength of C-LVL, 10-ply flat LVL with interlocked grain was produced from two species of sugi *(Cryptomeria japonica* D. Don) and akamatsu (*Pinus densiflora* S. et Z.). The mechanical properties of flat LVL including the elastic constants and strengths in different directions and plaens against tension, compression and shearing were determined by conducting the corresponding tests.

2. Experimental materials and Methods

2.1 Flat LVL manufacture

Sugi *(Cryptomeria japonica* D. Don) and akamatsu (*Pinus densiflora* S. et Z.) grown in Akita Prefecture were used for manufacturing the flat laminated veneer lumbers. Sugi and akamatsu logs were obtained from eighty and fifty-year-old trees, respectively. The diameters of both logs were approximately 350 mm. The kiln dried specific gravity of sugi and akamatsu were 0.37 and 0.45, respectively. Rotary lathe peeled veneers in 2.4 mm thick and 150 mm wide (in fiber direction) from the logs were dried to moisture content of 5%, then sewing with polyester thread into a long almost endless veneer tapes. 10-ply flat LVL was manufactured from sugi and akamatsu. The diagram of its constitutive characteristics is as shown in Fig.2. It is inevitably that butt joints and plus or minus 10-degree inclining angle of interlocked grain exist in the veneer layers. A resorcinol-formaldehyde (RF) resin adhesive (Oshika Shinko Co. Ltd., Dianol D-33) was applied between the veneer layers at a spread rate of 200 g/m^2 on each glue surface. The assembled laminated veneer was pressed at a pressure of 0.5 MPa for 24 hours, and then conditioned for ten days at ambient condition of about 20°C and 65% relative humidity to ensure sufficient curing of adhesive prior to testing.

3.2 Specimens preparation and testing

All test specimens were prepared from the conditioned flat laminated veneer lumbers. At least five specimens were taken for each test.

Fig. 3 shows the details of block shear test specimens of flat LVL in different shearing planes. These were prepared by gluing two pieces of 10-ply flat LVL in thickness. The load was applied through a self-aligning seat to ensure uniform lateral distribution of load. A loading tool was used to adjust the failure to occur along or adjacent to the glueline. Shear strengths in different planes were calculated by dividing the maximum load recorded during the test by the sheared area of specimen.

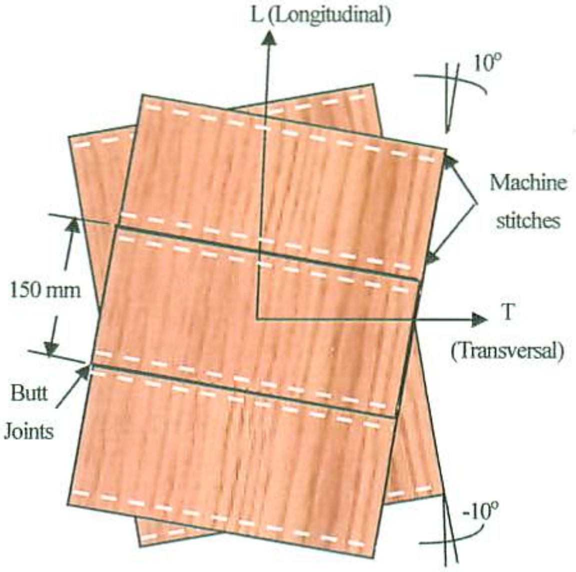
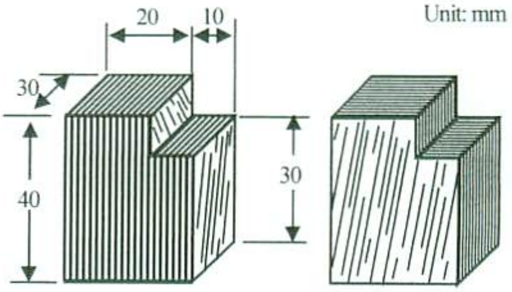


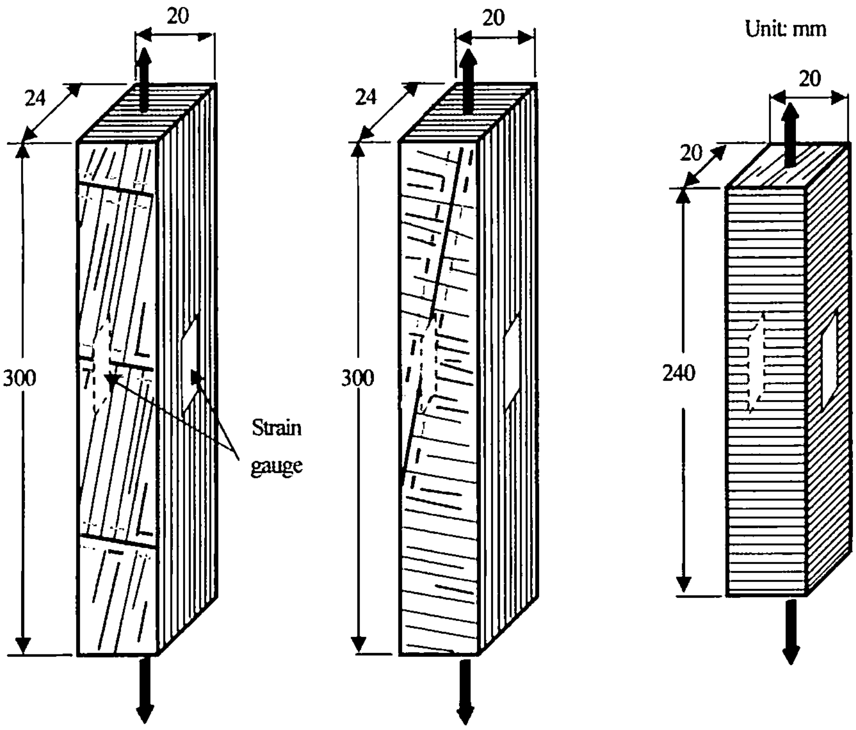
Fig. 2 Constitution of Flat LVL with interlocked grain
Notes: Thickness: 24mm (2.4 mm thick veneer, 10-ply)
Angle between grain and longitudinal axis:±10°



(a) LT-plane (b) LR-plane

Fig. 3 Specimens of block shear test

In general, waisted specimen of timber must be used for tensile test because of the very high longitudinal tensile stiffness and strength. For



(a) Longitudinal (b) Transversal (c) Through thickness

Fig. 4 Specimens for tensile test along different loading directions

simplicity, the tensile specimens used in this study were of full cross-section throughout their length as illustrated in Fig 4, and were of sufficient length to provide the test length clear of the grips of at least nine times the larger cross-sectional dimension. The dimensions of specimens for longitudinal and transversal tension are 300 mm long, 20 mm wide and 24 mm thick. However, the tensile specimen for the testing through thickness direction was composed by gluing 10 pieces of 20 mm x 20 mm 10-ply flat LVL into 240 mm thick in total. Four pieces of sawed kaede (*Acer* spp.) wood were used to reinforce the two ends of tensile specimen so as to avoid the occurrence of failure at grips during loading. Two pieces of 30 mm long strain gauges were attached to the midway of specimen length symmetrically. The modulus of elasticity (MOE) was calculated from the ratio of stress to strain under the assumed limit of proportionality at 10% and 30% of the ultimate load at failure. The value of the contraction strain (perpendicular to the loading direction) by the extension strain along the loading direction was taken as Poisson's ratio (μ). The tensile strengths in different directions were calculated from dividing the recorded ultimate load at failure by the cross sectional area of the specimens.

The specimens for compressive test had the same cross sectional areas as that of the tensile specimen as shown in Fig. 4, while the lengths in all cases were 240 mm constantly. Different from the tensile test, the ultimate load at failure during compression test is generally difficult to identify. The yield point was determined at where the value changed extremely in the stress strain curve. Then the compressive strength could be obtained by dividing the load at that point by the cross sectional area of the specimen.

3. Results and Discussions

Fig. 5 shows an example of stress-strain curve of tensile test along the longitudinal direction of flat LVL from Akamatsu. It could be recognized that tensile stress is almost proportional to tensile strain before the occurrence of failure. Thus the modulus of elasticity could be determined based on this linear stress-strain relation within the elastic range.

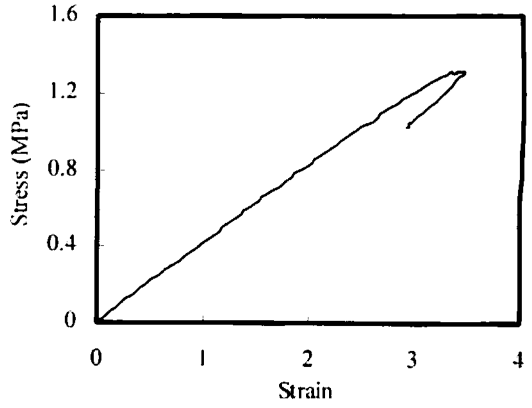


Fig. 5 An example of stress-strain curve of tensile test along the longitudinal direction of flat LVL

Tables 1 shows the experimental results of flat LVL specimens from sugi (*Cryptomeria japonica* D. Don) and akamatsu (*Pinus densiflora* S. et Z.) including modulus of elasticity (MOE), Poisson's ratio in different directions and planes. The table illustrates the high degree of anisotropy and difference in tensile and compressive stiffness present in flat LVL. Comparison of E_L with either E_R or E_T will indicate a degree of anisotropy, which was still as high as 36:1 for sugi LVL. Note should be taken that usually the value of MOE in tensile and compressive modes of lumber is approximatedly equal[4], thus there is only one category for MOE of wood species as shown in Table 2 which cites the mechanical proporties of sugi and akamatsu solid lumbers according to the literature[5]. Based on the theory of laminated composite matirial, which takes the inclining angle of interlocked grain into account, the modulus of elasticity of flat LVL with interlocked grain (E_{LIT}) could be calculated by transforming the elastic constants of veneer to the fiber angle (θ) of 10-degree as shown in the following famula[3]:

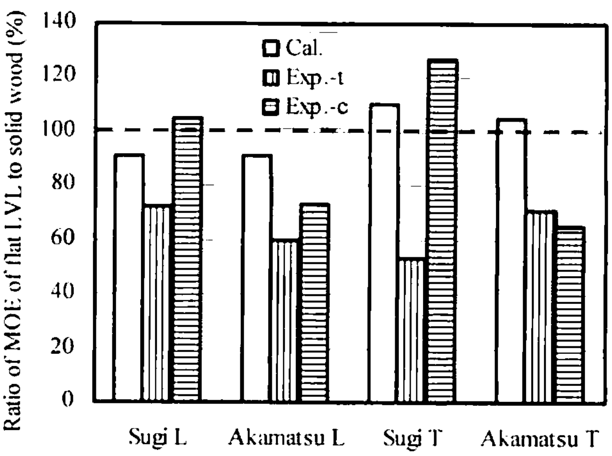


Fig. 6 Comparison of MOE between LVL and solid wood
Notes: L and T in x-axial label mean in longitudinal and transversal directions of flat LVL; In the legend, Cal. and Exp. mean the calculated and experimental results, the subscript letters t and c denote in tension and compression

$$E_{LVL}=\left(b_{11}-\frac{b_{13}^2}{b_{33}}\right)^{-1}$$

$$b_{11}=\frac{cos^4\theta}{E_L}-\frac{2\mu_{xy}cos^2\theta\, sin^2\theta}{E_L}+\frac{sin^4\theta}{E_T}+\frac{cos^2\theta\, sin^2\theta}{G_{LT}}$$

$$b_{13}=\left\{\left(\frac{2}{E_L}+\frac{2\mu_{LT}}{E_L}-\frac{1}{G_{LT}}\right)cos^2\theta+\left(-\frac{2\mu_{LT}}{E_L}-\frac{2}{E_T}+\frac{1}{G_{LT}}\right)sin^2\theta\right\}cos\theta\, sin\theta \tag{3.1}$$

$$b_{33}=\frac{1}{G_{LT}}\left(cos^2\theta-sin^2\theta\right)+4\left(\frac{1}{E_L}+\frac{2\mu_{LT}}{E_L}+\frac{1}{E_T}\right)cos^2\theta\, sin^2\theta$$

Table 1 Elastic constants of sugi and akamatsuflat LVL

Species	Sugi *Cryptomeria japonica* D. Don			Akamatsu *Pinus densiflora* S. et Z.		
MOE (GPa)	E_L	E_T	E_R	E_L	E_T	E_R
Tensile	5.40 (0.66)	0.158 (0.016)	0.257 (0.063)	7.14 (1.46)	1.50 (0.04)	0.93 (0.092)
Compressive	7.84	0.381	0.215	8.75	0.42	-
Poisson's ratio	μ_{LT} 0.78	μ_{LR} 0.28	μ_{RT} 0.24	μ_{LT} 0.56	μ_{LR} 0.28	μ_{RT} 0.45

Note: Figures in parenthesis are values of standard deviations

Table 2 Mechanical proporties of sugi and akamatsu solid sawn lumbers[4]

Sugi *Cryptomeria japonica* D. Don	MOE (GPa)	E_L 7.5		E_T 0.3	E_R 0.6		G_{LT} 0.35	G_{RT} 0.015			G_{LR} 0.65
	Poisson's ratio		μ_{LT} 0.6			μ_{RT} 0.90				μ_{LR} 0.40	
	MOR (MPa)	L_t 56	L_c 23	T_t 2.5	T_c 0.7	R_t 7	R_c 1.4	S_{LT} 7.5	S_{RT} 0.23		S_{LR} 6.5
Akamatsu *Pinus densiflora* S. et Z.	MOE (GPa)	E_L 12		E_T 0.65	E_R 1.25		G_{LT} 0.55	G_{RT} 0.045			G_{LR} 1
	Poisson's ratio		μ_{LT} 0.6			μ_{RT} 0.65				μ_{LR} 0.4	
	MOR (MPa)	L_t 130	L_c 28	T_t 4	T_c 1.8	R_t 9.5	R_c 2.5	S_{LT} 11	S_{RT} -		S_{LR} 10.5

Even though this approach by substituting the elastic constants of solid sawn lumber for those of veneer would derive an E_{LTL} without difference in tension and compression, the results obtained would be useful for estimating the other effects on stiffness of flat LVL separated from that of the inclining angle of interlocked grain.

To investigate the differences in MOE values among solid sawn lumber, the calculated and experimental results of sugi and akamatsu flat LVL in longitudinal (L) and trensversal directions (T), MOE ratios of flat LVL to solid wood are as shown in Fig. 6.

As a matter of fact, the experimental stiffness of sugi and akamatsu flat LVL showed quite difference in tension and compression along either longitudinal or transversal direction within the elastic range. The experimental tensile MOE of flat LVL in all directions seemed to be lower than those of solid wood and calculated value, and the largest reduction recorded by sugi along the transversal direction was about 50%. The drop of experimental tensile MOE from the calculated value proved that the other effects including the butt joints and defects of veneer, such as cracks, stitching checks, etc. except inclining grain, were so significant. On the other hand, with the exception of akamatsu in transversal direction, the compressive MOE of flat LVL was greater than that of tensile one. Especially compressive MOE of sugi had such a great improvement which exceeded the calculated value even was as high as 105% and 127% of the solid wood in longitudinal and transversal directions, respectively. That could be speculated that the defects are much more sensitive to tensile loading than to compressive one. All effects on MOE of flat LVL through thickness direction also seemed to be significant, as the reductions of the experimental values recorded by flat LVL were 43% and 23% those of sugi and akamatsu solid sown lumbers, respectively.

Expect of μ_{LT} for sugi LVL, the Poisson's ratios were lower than the matching data of the solid wood. It could also be attributed to the discontinuity of veneer caused by veneer cutting and stitching processes.

The tensile compressive and shearing modulus of rupture (MOR) of sugi and akamatsu flat LVL in different directions and planes are tabulated in Table 3. Almost all of the mechanical properties of flat LVL from akamatsu were greater than the matching data from sugi, which could be convinced the contribution from the higher density of akamatsu.

Table 3 Strengths of sugi and akamatsu flat LVL

Strengths (MPa)	Sugi *Cryptomeria japonica* D. Don			Akamatsu *Pinus densiflora* S. et Z.		
Items	σ_L	σ_T	σ_R	σ_L	σ_T	σ_R
Tensile	13.1 (1.96)	0.652 (0.062)	0.631 (0.183)	19.7 (2.1)	1.50 (0.29)	0.933 (0.13)
Compressive	21.6 (5.25)	3.14 (0.09)	1.91 (0.08)	25.7 (5.18)	7.08 (0.29)	3.81 (0.34)
Shearing	τ_{LT}	τ_{LR}	τ_{RT}	τ_{LT}	τ_{LR}	τ_{RT}
	4.25 (0.31)	4.28 (0.63)	-	6.39 (0.68)	7.81 (0.73)	-

Note: Figures in parenthesis are values of standard deviations

Except of compressive MOR along transversal direction, the experimental results of MOR of Flat LVL were lower than those of solid sawn lumbers, irrespective of species and shearing planes. The MOR reduction of akamatsu LVL was more significant than that of sugi LVL. However, all values of compressive MOR were greater than those of tensile ones irrespective of species and directions, especially the transversal compressive MOR of flat LVL were higher than the matching data of both sugi and akamatsu solid sawn lumbers. It is undubitable that the effects of flat LVL constitution and the existence of lathe cutting cracks, stitching checks, butt joints and other defects in veneeer layers. The observations prevailed that the effects of defects on tension and shearing would be much severer than on compression, as the discontinuity of veneer in layers would reduce the capability in bearing the loading of tension and shear extremely.

However, with regard to the axial symmetrical structure of cylindrical LVL, an more possitive impact on longitudinal and circumferential stiffness and strength could be expected, and the cylindrical LVL would be anticipated the needs of potential structural applications.

4. Conclusion

This paper reports some mechanical properties of sugi and akamatsu flat laminated veneer lumber (LVL) with interlocked grain for investigating the fundamental factors of cylindrical LVL. Based on the experimental results obtained, it was certainly an improvement on transversal compressive stiffness and strangth of both sugi and akamatsu flat LVL with comparison to their solid wood, while the reductions in other components of stiffness and strength seemed to occur in flat LVL. These could be attributed to the constitutive characteristics of flat LVL including decline angle of interlocked grain, butt joints, cracks, stitching checks in veneer layers and so on. As a matter of fact, cylindrical LVL has a different constitutive structure from flat LVL, which is in axial symmetricallly. It may result in a more possitive impact on longitudinal and circumferential stiffness and strength of cylindrical LVL for it to be anticipated the needs of potential structural applications.

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