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MODELING OF THE ELASTIC PROPERTIES OF LAMINATED STRAND LUMBER

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ABSTRACT

Laminated strand lumber as a structural composite lumber material has gained remarkable acceptance in light commercial and residential construction. A model was established to predict the elastic properties of the laminated strand lumber. The model assumes homogeneity in each panel layer to allow for multiple-layer panels to be simulated. The elastic constants of each panel layer were calculated by the modified elasticity energy principle in which the wood strands were regarded as the reinforced phase and the adhesive resin as the matrix. The panels with different structures were manufactured to verify the model. The predictions of the model match well with the measured results. The model may be helpful in design and manufacture of the laminated strand lumber.

KEYWORDS: Wood based composites, laminated strand board, elasticity energy principle; laminated theory, engineering constants.

INTRODUCTION

Laminated strand lumber (LSL) is a structural wood-based composite material consisting of oriented wood strands that are spray blended with adhesives and hot-compressed to form panels. The thickness of the wood strands for producing LSL is 0.5 to 2 mm and the length is shorter than 300 mm. Low density woods are the preferred raw material which permits property enhancement through densification. It can be produced from smaller diameter and low quality trees thereby reducing our dependence on old growth forests. Because LSL sometimes has stronger mechanical properties and less variability than solid lumber, it is an attractive alternative to solid sawn lumber and has gained a lot of research interest in many areas, including basic production technology, property improvement and product development (Moses et al. 2003, Denizli-Tankut et al. 2004, Josčák et al. 2006, Me et al. 2008, Ferraz et al. 2009, Ma and Yang 2011).)

Wood strands have their intrinsic mechanical and physical properties. When they constitute the composite material and are hot-compressed to produce the final panels, their properties are influenced by the resin, the heat, the pressure and the water. These factors not only influence the wood strands-resin (SR) system but also influence the final properties of the panels. Tensile properties of individual flakes in the different places of the mat were measured by Price (Price 1976). He found tensile modulus in the face layer increased by hot pressing, while those in the core layer decreased. However the flake-adhesive system affected by the hot pressing has not been considered. The Halpin and Tsai equation was used to predict the flake-adhesive system by Jong N. Lee et al. (Lee and Wu 2003). But more information should be known about the wood-adhesive system, because the wood-adhesive layers are viewed as the main building unit of the wood composite products. Laminated theory which consider a well-bond panel as a layer plate have been widely used to predict the elastic modulus and hygroexpansion of composite wood products (Clouston and Lam 2002, Moses et al. 2003, Wu et al. 2004, Painter et al. 2006, Benabou and Duchanois 2007, Chen et al. 2008, Sturzenbecher et al. 2010).

In this study, the LSL with a "U" shaped vertical density profile was regarded as a multi-layered system. Each layer was composed of wood strands as the reinforced phase and the adhesive resin as the matrix. Then the elasticity energy principle was used to predict the elastic constants of the layers. Based on the classic laminated theory, the rigidity of the thick LSL can be deduced from the different elastic properties of all the layers in the LSL.

The specific objectives of this research were (1) to establish a model based on the elasticity energy principle to predict the elastic constants of the SR system and verify it, (2) to develop a method to predict the elastic properties of the LSL.

MATERIAL AND METHODS

Raw materials

The veneers from poplar (*Populus italica*) bought from a mill in Jiangsu, P.R. China were used for the experiment. The veneers with nominal thickness 1.5 mm were air dried to a moisture content of 10 % and only veneers with no defects were chosen to study in the experiment. Then the veneers were cut into wood strands with 200 long and 10 mm wide for the manufacturing of LSL. The Phenol formaldehyde resin (PF) used in the experiment was produced in the laboratory with a solid content of 44 %.

Sample fabrication and testing methods

Specimen preparation

In order to get the relationship between the elastic constants of the wood strands with their density, different hot-pressing process parameters were designed to handle the veneers. The hot-pressing pressures were 2, 3 and 5 MPa, the temperature and time were 150°C and 5 min, respectively. After the hot pressing, the veneers were cut into different sample sizes for the measurements.

Thin LSL assumed its density was constant was manufactured to study the elastic constants. The thin LSL were regarded as the composite layers with a SR system which constituted the thick LSL with the multi-layered system. Based on the 8 % of the resin blending content in the thin LSL and the density of the wood and curing resin, 4 % was calculated as the volume fraction of the curing resin in the SR system. The resin blending was accomplished in the drum glue-mixing machine with air-spray head with pressure 0.3-0.5 MPa. The hot-pressing process parameters were the same as above and only three strands were laid in the thickness of the thin LSL. The dimension of the thin LSL fabricated here was 40×400 ×2.5 to 4.0 mm because of the different hot-pressing pressure.

We also manufactured different structure thick LSL with dimension of 400×400×30 mm to verify the accuracy of the model. Different laid structures were 0°/90°/0°, 0°/30°/0°/-30°/0° and 30°/0°/-30° and the hot-pressing pressure, time, temperature and resin content were 3 MPa, 1.5 $min.mm^{-1}$, 150°C and 10 % respectively. The designed average density of the LSL was 0.8 $g.cm^{-3}$.

Testing procedures

The elastic constants of the different wood strands and thin LSL as the layers of the thick LSL were measured by the tensile test method. All the loadings were made in the universal mechanical testing machine. The strain in the specimen during loading was determined by the strain gauge. The longitudinal elastic modulus and Poisson's ratio were measured by the axial tensile test. The in-plane shear modulus was measured by the 45° partial axial tensile test. The sizes of the specimens are shown in Tab. 1 and the locations and orientations of the strain gauges are shown in Fig. 1.

Tab. 1: The sizes of the samples. The thicknesses of the samples t are the original thickness of the materials.

Sample orientation	L (mm)	(mm)		
0°	230	12.5	100	50
90°	170	25	50	50
θ°	170	25	50	50

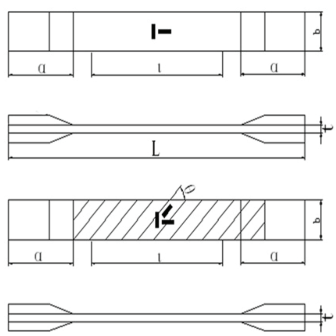

Fig. 1: Specimen shapes and the methods to fix strain gauges. The hatching represents the direction of the wood fiber.

The longitudinal elastic modulus ELand Poisson's ratio μLT are determined by the 0° specimen and calculated by

$$EL=PL/(\varepsilon Lbt) \quad (1)$$

$$\mu LT=-\varepsilon T/\varepsilon L \quad (2)$$

where: P - the force applied to the specimen,
ε - the strain measured by the strain gauge,

L and T - the longitudinal and transverse of the specimen.

The transverse elastic modulus ET and Poisson's ratio μTL are determined by the 90° specimen and calculated by

$$ET=PT/(\varepsilon Tbt) \quad (3)$$

$$\mu TL=-\varepsilon L/\varepsilon T \quad (4)$$

The shear modulus GLT are determined by the θ° specimens and calculated by

$$GLT=-P\theta sin2\theta 2bt[\varepsilon y-\varepsilon xsin2\theta+2\varepsilon 45°-\varepsilon x-\varepsilon ycos2\theta] \quad (5)$$

where: x and y - the length and width of the specimen.

Besides the elastic properties of the principal axis direction of the thin LSL were measured by the tensile method, the 15°, 30°, 45°, 60° and 75° thin LSL were also tested according to EN 310-1993 with three point bending method. The effective longitudinal and transverse modules of the thick LSL were also measured according to EN 310-1993.

Predicting model

Multi-layered structure of a thick LSL

A thick LSL with a "U" shaped vertical density profile (VDP) through its thickness may be regarded as a multi-layered system to simplify its structure. As the thick LSL is considered to be composed of many thin layers, it is reasonable to consider that each of the thin layers has a uniform density profile and exhibits homogeneous elastic properties. The homogenous thin layer is assumed to be an orthogonal anisotropic material composed of the wood strands as the reinforced phase and the adhesive resin as the matrix.

Elastic properties of each layer

Based on the previous research (Wang et al. 2012), the VDP can be obtained either the hot-pressing pressure is lower than 5 MPa or lager than 5 MPa. Each of layers in the thick LSL is so thin that we could consider the density of the wood strands in it is constant. Because the changes of the elastic constants of the wood strands may be attributed to the effect of the density, the elastic constants of the strands can be obtained by experiment method. The resin is isotropy. Then the effective elastic constants of the ith layer which is assumed to be a unidirectional SR system can be predicted according to the elasticity energy principle.

The boundary of the longitudinal elastic modulus of the composite with wood SR system EL can be calculated by

$$EfLEmEfLVm+EmVf\leq EL\leq 1-\mu fLT-4\mu fLT\beta+2\beta 21-\mu fLT-2\mu LTf2EfVf+1-\mu m-4\mu m\beta+2\beta 21-\mu m-2\mu m2EmVm \quad (6)$$

with $\beta=1-\mu m-2\mu m2\mu fEfVf+1-\mu f-2\mu f2\mu mEmVm1-\mu m-2\mu m2EfVf+1-\mu f-2\mu f2EmVm$

where: EfL and Em - the longitudinal elastic modulus of the wood strands and the elastic modulus of the adhesive resin,
μfLT and μm - the Poisson's ratio of the strands and the resin,
Vf - Vm - the volume fraction of the wood strands and the resin in the wood SR system,
β – a undetermined constant.

The boundary of ET can be calculated by replacing the longitudinal elastic modulus of strands EfL with the transverse elastic modulus EfT and μfLT with μfTL of the wood strands in the formula. The in-plane shear modulus GLT can be get by the following formula (7) with the same method.

GfLTGmGfLTVf+GmVm≤GLT≤GfLTVf+GmVm (7)

where: GfLT and Gm - the in-plane shear modulus of the wood strands and adhesive resin. The non-principal axis elastic modules Ex of thin LSL with different orientation were calculated by :

1Ex=cos4αEL+1GLT-2μLTELsin2αcos2α+sin4αET (8)

where: α - angle between the orientation of the wood strands and the length of the material, μLT - the Poisson's ratio of the SR system in the principal axis.

After we have calculated the boundary of the elastic constants of the SR system, the range of the non-principal axis elastic modules Ex can be get by substituting the lower and upper values into the formula (3).

Prediction of the effective elastic properties of LSL

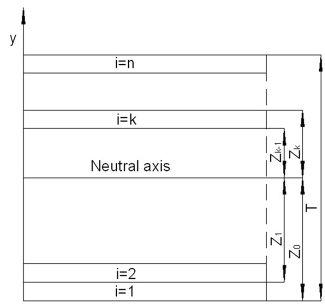

Fig. 2: The schematic multi-layer structure of a LSL. Where n is the total number of layers along the board thickness; T is the total lumber thickness, Z_k and Z_{k-1} are the distance from the upper and lower boundary of the kth layer to the neutral axis of the lumber.

After the effective elastic constants of the layers were determined, stiffness matrix (A), (B) and (D) of the thick LSL can be calculated by the classical laminated theory:

Aij=k=1nQijkZk-Zk-1 (9)

Bij=12k=1nQijkZk2-Zk-12 (10)

Dij=13k=1nQijkZk3-Zk-13 (11)

where: Aij - the in-plane stiffness coefficient,
Bij - the coupling stiffness coefficient,
Dij - the bending stiffness coefficient,
Qij - the stiffness coefficient of the kth layer (Fig. 2).

Make a=[A]-1,b=-[A]-1[B],c=[B][A]-1,d=D-BA-1[B], then the total flexibility matrix can be get: a*=a-bd-1[b]T, b*=[b][d]-1, c*=-[d]-1[c], d*=[d]-1 Then the equivalent elastic constants can be get by

Ex,eq=1a11*, Ey,eq=1a22*, Gxy,eq=1a66*, μxy,eq=-a12*a11* (12) where: Ex,eq and Ey,eq - the equivalent longitudinal and transverse elastic modulus of the thick LSL, Gxy,eq - the equivalent in-plane shear modulus, μxy,eq - the equivalent Poisson's ratio.

RESULTS AND DISCUSSION

The elastic constants of the wood strands

The density has great influence on the mechanical and physical properties of the wood and wood products have been accepted widely. Xu used a linear function to relate MOEL to the panel layer density (Xu 1999). In Ee Ding Wong's research, no matter it is a homo-profile fiberboard or conventional fiberboard, its MOE increase with the mean density of the fiberboard (Wong et al. 2000). Ee Ding Wong also found that MOE of the homo-profile particleboard correlate to the mean board density in a curvilinear trend (Wong et al. 1999). In the study, quadratic polynomial and linear models were chosen to describe the density of the hot-pressed wood strands and the elastic constants. The corresponding regression equations and figures are shown in Fig. 3. The regression equations can be used to calculate the elastic constants of the wood strands under different density.

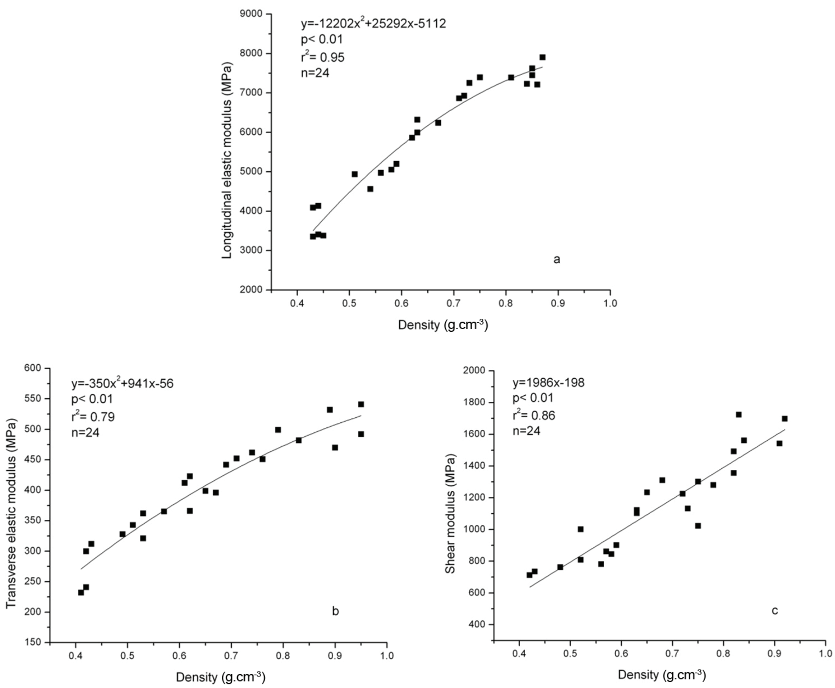

Fig. 3: Correlations between the longitudinal elastic modulus EfL a), transverse elastic modulus EfT b) and in-plane shear modulus GfLT c) and the density of the wood strands.

In order to ascertain the validity of the measured Poisson's ratio in our experiment, the restrictions imposed to the Poisson's ratio from the terms of the stiffness matrix are positive can be deduced as:

$$1-\mu LT\mu TL>0 \quad (13)$$

For all the measured Poisson's ratio, the condition was satisfied. Besides this, the ratios between the Poisson's coefficients and Young's modulus are:

$$\mu TL/ET=\mu LT/EL \quad (14)$$

The values calculated by the right and left of the equation were not exactly the same for all the measured samples. However, the relative differences did not exceed the limit of 10 %. So the measured values approximate satisfied the equation. And there was no significant difference between μLT and μTLof the wood strands in difference groups. So the average of μLT and μTL of all the samples were used in the model. μLT was 0.43 and μTL was 0.04.

The elastic constants of the lays

In the elasticity energy principle to predict the elastic properties of the unidirectional composites, the specific shape and distribution mode of the reinforced phase and the matrix are not involved. So this method has a common meaning. But when the (Ef/Em)>>1, the boundary values calculated by the method is very big and it is the situation that most common fiber-reinforced composites have. So the elasticity energy principle has no practical value in the common fiber-reinforced composites. However there is no such big difference between the elastic properties of the wood strands and resin adhesives. So the elasticity energy principle was used here to calculated the boundary of the elastic constants of the unidirectional composites with the wood SR system.

Tab. 2: The measured elastic constants and the predicted values of thin LSL under different hot-pressing pressure. The standard deviations of ten measured values are in parenthesis.

Hot-pressing pressure		E_L/GPa	E_T/GPa
2 MPa	Measured	7.84 (0.50)	0.55 (0.05)
	Predicted	6.97-7.09	0.51-1.12
3 MPa	Measured	8.77 (0.76)	0.69 (0.04)
	Predicted	8.26-8.35	0.61-1.25
5 MPa	Measured	9.54 (1.04)	0.72 (0.07)
	Predicted	10.78-10.88	0.80-1.42

The lower and upper predicted values of the longitudinal modulus and shear modulus calculated by the elasticity energy principle did not different a lot (Tab. 2). The boundary of the difference of longitudinal modulus calculated by (upper predicted value lower predicted value)/ measured value were 1 to 2 % and shear modulus were 3-8 %. But the boundary of predicted transverse modulus was big, because the elastic modulus of the adhesive is more than ten times bigger than the transverse modulus of the strands.

Compression ratio of the wood veneers increased with the hot-pressing pressure. When the compression ratio increased to a certain degree, the elastic properties did not increase with it (Wang et al. 2012). So in this study, when the pressure reached 5 MPa, the measured values were all below the lower predicted value owing to the crushing of the strands. The model established here mainly aimed at the pressure below 5 MPa.

In the model, we only considered the wood strands and the resin adhesive while the permeating of the adhesive into the wood strands was ignored leading to the measured longitudinal modules were all bigger than the upper predicted values. In order to establish the elastic properties of the PF modified wood, Yue Kong (Yue 2008) could not find the reason why the elastic properties increased with the solid content of the PF used to modify the wood. So he brought in a factor k influenced the resin to the rule of mixture to correct it:

$$EL=EfLVf+kEmVm \quad (15)$$

where: k=4.7-4.2x, x - the solid content of the resin.

The solid content we used here is 44 %, so k is 2.87. Put k into the upper predicting model, we got the boundary in the pressure 2 and 3 MPa (6.97, 8.43) and (8.26, 9.68), respectively. From the modified predicted values, the measured values were in the range. So the modified model has the practical value.

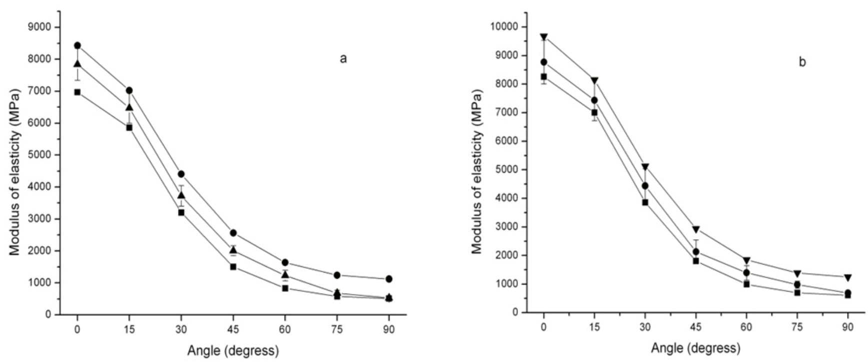

Fig. 4: Comparison of the model simulated effective MOE for the seven oriented angles of 2MPa a) and 3MPa b) pressed thin LSL.

In the manufacture of the thick LSL, the orientation of the strands in each layer may be different. We also verified the model when the stands had different orientations in the thin unidirectional composites (Fig. 4). All the predicted values were found to compare well with experimental results.

There were no significant differences between μLT and μTLof the thin LSL in difference groups. So the average of μLT 0.43 and μTL 0.03 were used in laminated theory to predict the elastic properties of the thick LSL.

Model validation

Tab. 3: Comparison of the predicted elastic properties of the thick LSL with the measured values. The standard deviations of ten measured values are in parenthesis.

	0°/90°/0°		0°/30°/0°/-30°/0°		30°/0°/-30°
	Measured	**Predicted**	**Measured**	**Predicted**	**Measured**
EL/GPa	5.7 (0.35)	4.9-6.1	6.3 (0.28)	5.9-7.2	5.9 (0.16)
ET/GPa	2.7 (0.17)	2.4-3.3	1.3 (0.16)	1.0-1.6	1.8 (0.21)

Laminated theories are widely used to predict the elastic modules and hygroexpansion coefficients of composites (Clouston and Lam 2002, Benabou and Duchanois 2007, Sturzenbecher et al. 2010). Its application in the composite wood products has gain more attention (Xu 1999, Moses et al. 2003, Wu et al. 2004, Painter et al. 2006, Chen et al. 2008). The measured values of the longitudinal elastic modulus and the transverse elastic modulus were all in the range of the predicted field (Tab. 3). So the model established here can be used to predict the elastic properties of LSL and optimize the production of LSL.

CONCLUSIONS

The elastic constants of the wood strands can be measured by the tensile method using the strain gauges. Both the longitude and transverse elastic modulus have a quadratic polynomial relationship with the density of the wood strands. A linear relationship exists between the in-plane shear modulus and the density. The modified elasticity energy principle can predict the elastic modulus range of the unidirectional wood SR system. Because the elastic properties between the wood strands and the resin do not as big as the common fiber-reinforced plastic, the range is not that big so we can accept it. Based on the modified elasticity energy principle and the laminated theory, the elastic properties of the LSL can be predicted which can be helpful in the design of the manufacturing of LSL.

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