



Original Article

Strength and reliability of Oriented Strand Lumber made from heat-treated Parawood strands

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Received 14 March 2008; Accepted 4 August 2008

Abstract

This study was carried out to investigate engineering properties of one type of wood composites known as Oriented Strand Lumber (OSL). Heat-treated Parawood strands were used for producing OSL specimens (HOSL) and compared to a control one (nonheat-treated or NOSL). The structural application as beams was selected to determine the effect of sheared volume to longitudinal shear strength since shear failure is a critical mode of OSL. The reliability concept was then employed to analyze the data to ensure that OSL structural members can be used for construction safely and economically.

The results indicated that mean values of strength of HOSL subjected to axial loading, i.e., compression (39 MPa) and tension (36 MPa) parallel to the grain as well as bending in the flatwise (59 MPa) and edgewise (61 MPa) directions were significantly higher than those of NOSL. However, the differences between HOSL and NOSL subjected to normal loading, i.e., compression perpendicular to the grain (26 vs 25 MPa), shear parallel to the grain (4 vs 3 MPa) and internal bonding (0.48 vs 0.47 MPa) were non-significant. The results of shear strength studies showed that the shear strength of HOSL beams was higher than that of NOSL beams and regression analysis revealed that the shear strength depended on sheared volume. It showed that shear strength decreased with increasing sheared volume. The results of the reliability analysis indicated that the fitted distribution of the flexural rigidity (*EI*) could be represented well as normal. The coefficient of variation of the fitted *EI* distribution was found to be within the serviceability limit state required by the building codes. This implies that OSL beams can be used safely as an alternative structural material for wood construction. The safety factor and recommended allowable design stresses are also presented.

Key words: heat treatment, engineering properties, oriented strand lumber, Parawood, shear strength, reliability analysis

1. Introduction

1.1 Parawood residues

Pararubber trees (*Hevea brasiliensis* Muell. Arg.) are widely planted for the production of latex in Southeast Asia. The total area of plantations in Thailand is about two million hectares, located in the southern, eastern and north-

eastern regions. Trees are felled for replanting between the ages of 25 and 30 years, when the production of latex becomes uneconomical. The quantity of Parawood residues from plantations in Thailand is estimated annually to be approximately 14 million m³ (Suwanprecha, 2006). If these residues could be turned into usable raw materials for the production of wood composites, it would not only contribute to the efficient utilization of bioresources but it would also reduce the production cost of composite products. One type of highly engineered composites from wood, known as oriented strand lumber (OSL), was adopted in this study

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because of its high strength and potential for application.

1.2 OSL

Oriented strand lumber is a structural composite lumber product composed of wood strands oriented along the length of a member and bonded together utilizing heat, pressure and an exterior adhesive. OSL has been developed for structural applications such as beams, columns and chords for trusses. OSL is the newest product of structural composite lumber, and markets are under development. Strength properties make OSL a highly competitive alternative to traditional lumber and will become an important forest product in the future.

Several studies on OSL made from Parawood residues have been carried out at the Wood Science and Engineering Research Unit, Walailak University. Their findings are summarized next. Malanit (2005) investigated the optimum parameters for manufacturing OSL from Parawood residues and found that the use of isocyanate resin, 9% resin content, and a strand length of 140 mm were suitable for producing Parawood OSL. Choowang (2005) studied the basic properties and termite resistance of OSL made from heat-treated Parawood strands and found that heating treatments with a temperature between 130 and 190°C and for time intervals between 30 and 110 minutes improved the physical and mechanical properties of OSL. The toughness was found to decrease with increasing temperature and length of heat treatment duration, especially at 220°C, where the reduction is drastic. Yingprasert (2005) determined the effects of phenol formaldehyde and isocyanate hybrid adhesive on the properties of OSL from Parawood residues. A 75/25 ratio of phenol formaldehyde to isocyanate blend was found to be optimum with respect to the competing factors of strength and cost. Chirasatitsin *et al.* (2005) investigated the effects of strand length and orientation on Parawood OSL and found that for orientations parallel to the grain direction, strength increased with increasing strand length. This positive relationship between strand length and strength, however, was not observed for the direction normal to the grain. The relationship between the mechanical properties of OSL and strand length is well described by the modified Hankinson formula.

1.3 Heat treatment

Heat treatment is a process first used for treating lumber to improve its durability and dimensional stability (Viitaniemi and Jamsa, 2002). However, a trade-off exists between these advantages and the material strength. Many papers reported that heat treatment of lumber at high temperatures (150 to 260°C) causes large decreases in tensile, bending, and impact strengths (up to 50%), but increases in the compressive strength parallel to the grain and the modulus of elasticity have been observed (Bengtsson *et al.*, 2002; Kubojima *et al.*, 2000; Boonstra *et al.*, 2007). More-

over, the shear strength of the bond lines of glued-laminated beams fabricated from heat-treated lumber also decreased in spite of the improvement of bond-line delamination (Sernek *et al.*, 2008). Regarding the application of heat treatment on wood-based panels, it has been reported that an oriented strand board (OSB) made from heat-treated strands shows a significant reduction in thickness swelling, but no improvement in internal-bond strength (Paul *et al.*, 2006). Investigations regarding the application of heat treatment to only wood strands have also been carried out. Goroyas and Hale (2002) applied a heat treatment of 200 to 260°C for 20 minutes to OSB strands under inert conditions and found that the modulus of rupture and the modulus of elasticity of the strands were reduced by 20 percent. Nevertheless, recent work on Parawood strands revealed that a 30-minute boiling pre-treatment of strands before a heat treatment of 190°C for 30 minutes under ambient conditions could increase the crystallinity and the tensile strength of the strands (Phetkaew, 2008).

The objectives of this research were to 1) fabricate heat-treated and nonheat-treated OSL, 2) determine the engineering properties of heat-treated and nonheat-treated OSL, 3) investigate the longitudinal shear strength of OSL beams, and 4) examine the reliability of OSL beams.

2. Materials and Methods

2.1 OSL processing

2.1.1 Strand generation

Strands were machined from Parawood branches of diameter less than 150 mm collected from Thasala District, Nakhon Si Thammarat Province. Branches were crosscut into 140 mm long sections and subsequently debarked for strand preparation. Stranding was carried out on a CAE 6/36 Laboratory Disc Flaker. Machine conditions were set as follows: a counter-knife angle of 60 degrees, a knife projection of 0.72 mm, and a scoring-knife distance of 140 mm. Using these conditions, the target size of a strand would be 0.70 mm thick, 22 mm wide, and 140 mm long. All strands were sorted by a Gilson screen.

2.1.2 Heat treatment

The selected strands were boiled in water for 30 minutes and subsequently subjected to heat treatment in an electric oven maintained at a temperature of 190°C for duration of 30 minutes (Phetkaew, 2008).

2.1.3 Billet fabrication

An inhouse-made rotary-type blender, with a diameter of 1,700 mm and a rotating speed of 8 rpm, was used for spreading Polymeric Methylene Diphenyl Diisocyanates (pMDI) adhesive onto strands. The adhesive content is 9%

by oven-dry strand weight. Oriented strand mats were formed using an inhouse-made strand orienting apparatus equipped with fins spaced at 10 mm. The free fall distance, which is the distance between the bottom of the fins and the top of the mats, was kept at 70 mm. Cold press and hot press machines were employed to assemble all billets. Cold pressing was conducted in only one step in order to compact the mat to proper thickness by using a 1 MPa working pressure for duration of 3 minutes. Hot pressing was performed in two steps as recommended by Wang and Winistorfer (2002). The mat was first pressed at 2.5 MPa and kept at this maximum pressure for 8 minutes. The pressure was then decreased to 1.25 MPa and held at this level for 10 minutes. The platen temperature was 160°C.

2.2 Engineering properties tests

The size of the fabricated billets was 400mm x 450 mm x 20mm with a target density of 0.70 g/cm³. The billets were machined into test specimens and placed in a walk-in conditioning room maintained at 65% RH and 20°C until constant weight was attained. Mechanical tests were conducted by using a universal testing machine (LLOYD 150 kN) equipped with a computerized data acquisition system following the procedures of ASTM D 5456-99a. The tests include static bending, in both flatwise and edgewise directions, tension parallel to the grain, and compression parallel to the grain in accordance with ASTM D 4761-96. Compression tests perpendicular to the grain and shear tests parallel to the grain are in accordance with ASTM D 143-94. Physical properties determinations consist of moisture content measurements, in accordance with ASTM D 4442-97, specific gravity measurements, in accordance with ASTM D 2395-97, along with water absorption, thickness swelling, and internal bonding measurements, in accordance with ASTM D 1037-99. Thirty replications of the specimens were tested for each treatment in both physical and mechanical properties.

2.3 Shear strength tests of OSL beams

This study was designed to examine the effects of depth, width, and shear span on the longitudinal shear strength of OSL beams by considering five groups. Load tests to failure were performed on 150 beam specimens involving 30 replicate beams in each group. Beam sizes and span lengths were chosen to provide a wide range of cross-sectional areas and shear span to depth ratios. Span lengths were selected to ensure shear failure rather than bending failure. All beams were tested in flexure under a concentrated mid-span load following the procedures in ASTM D 4761-96.

2.4 Reliability analysis

2.4.1 Basic concept of structural reliability

For time invariant reliability analyses, the structural

reliability, (p_s) may be defined as the probability that load effects (S) will not be exceeded by the structural resistance (R) within the whole service lifetime (Nowak and Collins, 2000; Ouypornprasert, 2001) as shown in Eq. (1).

$$p_s = P_r(R - S > 0) \quad (1)$$

In practice the complementary term of structural reliability, i.e. failure probability (p_f), is preferred.

$$p_f = P_r(R - S \leq 0) \quad (2)$$

In this case, the limit state function of a structural system, $g(X)$, may be defined as:

$$g(X) = R - S \quad (3)$$

where X is a vector random variable, $g(X) > 0$ defines a safe state of the structural system and $g(X) < 0$ defines a failure state.

In reality, both the load effects and the structural resistance are random in nature so that their effects can not be ignored. Therefore, the safety factor (FS) should be calculated from Eq. (4).

$$FS - 1 = \beta \sqrt{(FS)^2 (\Omega_R)^2 + (\Omega_s)^2} \quad (4)$$

where β is the safety index, Ω_R is the coefficient of variation (CV) of the structural resistance and Ω_s is the coefficient of variation of the load effects.

2.4.2 Transformed section of OSL beams

Since the modulus of elasticity of wood under tension (E_t) is relatively higher than compression (E_c), a timber beam subjected to bending could not be treated as a homogenous beam (Ngamcharoen *et al.*, 2007). In the case of OSL beams, the original cross section can be transformed to an equivalent cross section for one homogenous material in terms of the modular ratio ($n = E_t/E_c$) and the location of the neutral axis (k), as shown in Figure 1.

The location of kd can be obtained from the roots of an equation representing the summation of the first moment of the transformed sections with respect to the neutral axis. Therefore,

$$(n-1) k^2 - 2nk + n = 0 \quad (5)$$

$$E_g I_g = \frac{1}{3} b E_c [(kd)^3 + \frac{E_t}{E_c} (d - kd)^3] \quad (6)$$

where $E_g I_g$ is the flexural rigidity of the cross section

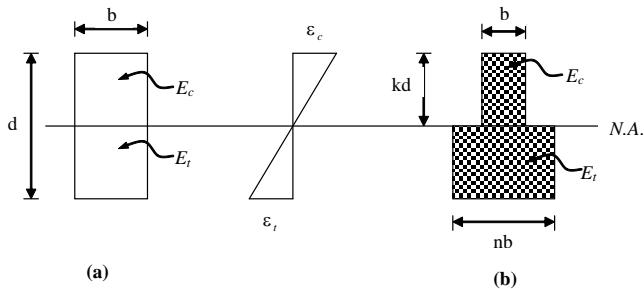


Figure 1. OSL beams: (a) Cross-section; (b) Transformed section

of OSL beams, E_c is the modulus of elasticity of OSL beams under compression and E_t is the modulus of elasticity of OSL beams under tension

2.4.3 Application of reliability to OSL beams

The statistics of engineering properties are summarized with confidence intervals of not less than 99% and might be represented in the form of the mean, standard deviation, coefficient of variation and the type of distribution. The best-fit continuous distributions are obtained by two Goodness-of-Fit Tests; i.e. the Chi-Square Test and the Kolmogorov-Smirnov Test (K-S Test). Each set of data was input in the form of a text file into Civil Engineering Statistical Test (CESTTEST) software. The software automatically selects fitted distributions.

3. Results and Discussion

3.1 Strand dimension

The obtained mean values of each size dimension of 200 dried strands, randomly taken from each bag, for the total of 60 bags were 0.76 mm thick, 22.11 mm wide, and 140 mm long. These mean values conform very well to the target.

3.2 OSL billets

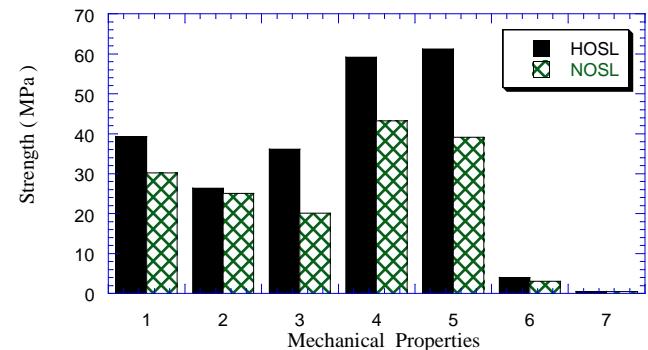
The size of the fabricated billets prepared for machining into test specimens is 20 mm thick, 400 mm wide, and 450 mm long. Surface texture of the billets is rough and the color of the HOSL billets is darker than the NOSL billets, as shown in Figure 2.



Figure 2. HOSL (right) and NOSL (left) billets

3.3 Engineering properties

The results of tests of the engineering properties are presented in Table 1-3. The data are accordingly plotted in frequency histograms, as shown in Figure 3.



Note: 1 = Compression // 5 = Edgewise bending
 2 = Compression ⊥ 6 = Shear //
 3 = Tension // 7 = Internal bonding
 4 = Flatwise bending

Figure 3. Strength of HOSL and NOSL for various mechanical properties tests

3.3.1 Compressive strength parallel to grain

The mean values of compressive strength and elastic modulus for HOSL versus NOSL are 39.28 MPa and 5483 MPa versus 30.19 MPa and 4470 MPa, respectively. The results indicate that both the compressive strength and elastic modulus of HOSL are significantly greater than those of NOSL. This might be due to growth of the crystalline region in the cell wall of wood, induced by heat treatment. From observation, the failure mechanism of the specimens occurs along the surface of the strands. This implies that compressive stress parallel to the grain is gradually increasing until it reaches the compressive strength. Then, the first crack between strands occurs and propagates rapidly with increasing loads. The failure is obviously caused by strand buckling and delamination.

3.3.2 Compressive strength perpendicular to grain

The mean values of compressive strength for HOSL and NOSL were 26.35 MPa and 25.08 MPa, respectively. The difference is obviously negligible. This is probably due to the fact that an increase in crystallinity does not contribute to the strength in the direction perpendicular to the plane of the strands.

3.3.3 Tensile strength parallel to grain

The mean values of tensile strength for HOSL and NOSL were 36.09 MPa and 20.16 MPa, respectively. Both tensile strength and elastic modulus values for HOSL were

Table 1. Test results of engineering properties of heat-treated oriented strand lumber (HOSL)

Engineering Properties	Strength		Elastic Modulus		EMC		SG	
	Mean (MPa)	CV (%)	Mean (MPa)	CV (%)	Mean (%)	CV (%)	Mean	CV (%)
Compression //	39.28	10.82	5483	9.19	8.47	2.20	0.71	6.72
Compression \perp	26.35	15.71	471	12.13	8.42	3.40	0.71	8.26
Tension //	36.09	10.80	7538	12.80	8.28	3.46	0.71	8.46
Flatwise Bending	59.12	10.53	12499	15.06	8.24	2.75	0.72	10.42
Edgewise Bending	61.23	11.93	12927	12.49	8.26	3.15	0.72	9.51
Shear //	4.05	12.78	117	13.65	8.63	2.45	0.70	8.41
Internal Bonding	0.48	11.71	426	13.71	8.57	3.42	0.70	7.99

Note: // = Parallel to grain

EMC = Equilibrium moisture content

 \perp = Perpendicular to grain

SG = Specific gravity

CV = Coefficient of variation

Table 2. Test results of engineering properties of nonheat-treated oriented strand lumber (NOSL)

Engineering Properties	Strength		Elastic Modulus		EMC		SG	
	Mean (MPa)	CV (%)	Mean (MPa)	CV (%)	Mean (%)	CV (%)	Mean	CV (%)
Compression //	30.19	10.42	4470	8.27	8.86	3.21	0.68	7.73
Compression \perp	25.08	12.72	390	11.83	8.81	4.56	0.69	9.21
Tension //	20.16	10.85	6254	11.76	8.78	3.68	0.69	8.65
Flatwise Bending	43.21	11.57	10732	14.65	8.72	4.25	0.69	11.19
Edgewise Bending	39.11	10.91	8816	11.78	8.89	4.12	0.68	10.06
Shear //	3.12	15.12	108	12.84	9.02	3.58	0.67	8.12
Internal Bonding	0.47	12.64	417	14.21	8.98	4.79	0.68	8.17

Note: // = Parallel to grain

EMC = Equilibrium moisture content

 \perp = Perpendicular to grain

SG = Specific gravity

CV = Coefficient of variation

Table 3. Water absorption and thickness swelling of oriented strand lumber (OSL)

Description	WA (%)	TS (%)	EMC (%)	SG
Heat-treated OSL	28.56	23.28	8.51	0.70
Nonheat-treated OSL	30.12	25.33	8.88	0.67

Note: WA = Water absorption

TS = Thickness swelling

EMC = Equilibrium moisture content

SG = Specific gravity

higher than those of NOSL due to an increasing crystallinity in the cell of the wood. The failure mode was brittle.

3.3.4 Bending strength

Static bending tests were conducted in edgewise and flatwise directions. The purpose of edgewise-static bending tests was to determine the bending strength for use in wall member design. For floor and beam member design, the

flatwise-static bending test was required. The mean values of the modulus of rupture (MOR) and the modulus of elasticity (MOE) in the flatwise-static bending tests were 59.12 MPa and 12499 MPa, respectively, for HOSL, and 43.21 MPa and 10732 MPa, respectively, for NOSL. In the edgewise-static bending tests, the mean values for MOR and MOE were 61.23 MPa and 12927 MPa, respectively, for HOSL, and 39.11 MPa and 8816 MPa, respectively, for NOSL. Both the MOR and MOE of HOSL are higher than those of NOSL

due to increased crystallinity in the cell of wood. The failure mode of HOSL was rather brittle, while the failure mode for NOSL was ductile.

3.3.5 Shear strength parallel to grain

The mean values of shear strength for HOSL and NOSL were 4.05 MPa and 3.12 MPa, respectively. The comparison between HOSL and NOSL showed that the shear strength and elastic modulus of HOSL are higher than those of NOSL. The failure modes were ductile in nature. In the case of the shear through thickness, the properties that resist shear stress can be classified into two categories. The first category is the shear strength of the wood strands and the second category is the strength of the adhesive bonding.

3.3.6 Internal bonding

Internal bonding is the property evaluated for composite products in order to measure bonding strength between the adhesive and the wood. The mean values of bonding strength for HOSL and NOSL are 0.48 MPa and 0.47 MPa, respectively. Results indicated that there is no effect of heat treatment on the internal bonding of OSL which agrees with the findings on Scots pine strands (Paul *et al.*, 2006). These results may be due to normal tension applied directly to the hydrogen bonds of crystalline regions. The weak hydrogen bonds of amount of crystalline regions increased by heat treatment therefore do not contribute to the bonding strength.

3.3.7 Statistical analysis

In order to reduce error, the test results were classified

into two groups according to the mode of loading on test specimens (Table 4). The first group was axial loading, i.e., compression parallel to the grain, tension parallel to the grain, flatwise bending, and edgewise bending. The second group was normal loading, i.e., compression perpendicular to the grain, shear parallel to the grain, and internal bonding. Strength and elastic modulus values of the two groups were separately analyzed by paired-t tests. The results indicated that the difference between mean values of strength and elastic modulus of HOSL and NOSL of axial loading group were highly significant at the 1 % level, whereas the statistical tests on normal loading group could not find the difference between HOSL and NOSL. The improvement of the strength properties of the axial loading group is likely due to the boiling pre-treatment of the strands, since the 100°C saturated moisture in the strands provides energy for enhancing the crystallization of the amorphous cellulose. The increased volume of crystalline regions consequently helps improve the strength of the heat-treated strands since the strong covalent bonds of the cellulose chains are directly responsible for the resistance of axial loading.

3.4 Shear strength

The investigation of the effects of depth, width, and shear span on longitudinal shear strength of HOSL and NOSL beams yielded the results as tabulated in Table 5 and depicted in Figure 4.

The results in Table 5 reveal that the mean shear strength value of HOSL beams is higher than that of NOSL beams by about 30%. Observations of the results reveal a high percentage of failure in shear mode for each group, except Group 5. The observed behavior of shear failure suggested that when shear stress reached the shear strength

Table 4. Paired-t test analysis of the mean values of strength and elastic modulus of HOSL and NOSL according to loading modes

Loading Modes	Engineering Properties	Mean Strength (MPa)		t Value	LS	Mean MOE (MPa)		t Value	LS
		HOSL	NOSL			HOSL	NOSL		
Axial	Comp. //	39.28	30.19	5.511	**	5483	4470	6.562	**
	Tension //	36.09	20.16	14.825	**	7538	6254	10.907	**
	Flatwise Bending	59.12	43.21	5.174	**	12499	10732	4.207	**
	Edgewise Bending	61.23	39.11	9.267	**	12927	8816	8.532	**
Normal	Comp. \perp	26.35	25.08	1.092	ns	471	390	1.586	ns
	Shear //	4.05	3.12	1.622	ns	117	108	1.134	ns
	Internal Bonding	0.48	0.47	0.515	ns	426	417	0.617	ns

Note: // = Parallel to grain

HOSL = Heat-treated oriented strand lumber

MOE = Modulus of elasticity

* = Significant

ns = Non-significant

\perp = Perpendicular to grain

NOSL = Nonheat-treated oriented strand lumber

LS = Level of significance

** = Highly significant

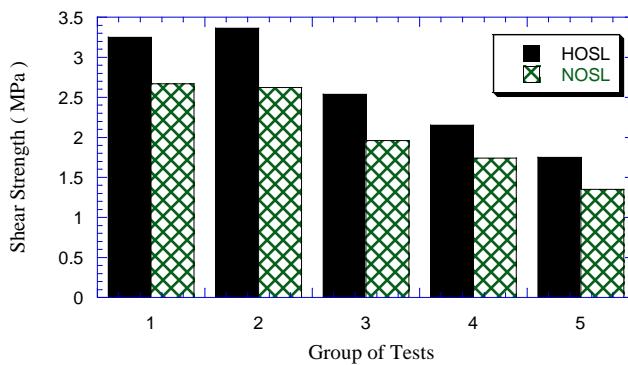


Figure 4. Shear strength of heat-treated and nonheat-treated OSL beams

in the longitudinal direction, cracks generally occurred at mid-depth of beam and at mid-span. The cracks then propagated gradually from mid span to the end of the beam, near the supports. It could be inferred that the mode of failure of both HOSL and NOSL beams frequently fell in shear mode in spite of the high shear span to depth ratio. It is therefore noted that the failure mode of OSL beams deserves special consideration because its mode of failure is different from solid-wood beams. The significant effects of beam depth, beam width, and shear span on shear strength suggest that sheared volume might also affect shear strength, a phenomenon also known to occur in Spruce glulam beams (Keenan *et al.*, 1985). Therefore, a scatter diagram of shear strength versus sheared volume for OSL beams is plotted in Figure 5. Regression analysis of the data yielded the following best-fit linear expression:

$$\tau_{\max} = 5.5728 - 1.8313 \log(V_s) \quad (7)$$

where τ_{\max} is the horizontal shear strength (MPa) and V_s is the sheared volume (width x depth x shear span), cm^3 .

The intercept and the regression coefficient (slope) are significant at the 1% level and the coefficient of determination (R^2) was 0.59. This expression conforms well to the

findings by Keenan *et al.* (1985) on Spruce glulam beams.

3.5 Reliability analysis

The shear strength of group 4 for heat-treated OSL was arbitrarily selected to illustrate the reliability analysis for OSL beams, since the results of shear failure of this group were higher than bending failure. The E_t and E_c of heat-treated OSL beams could be characterized by normal distribution with mean values (from Table 1) of 7538 MPa and 5483 MPa, respectively. The corresponding coefficients of variation are 0.128 and 0.091. The variables of beam length, beam width, and beam depth were assumed to be deterministic. The appropriate section of OSL beam is needed to ensure that the probability of mid-span deflections does not exceed the serviceability limit of acceptable failure probability of 10^{-4} . Based on the uncertainties of E_t and E_c , the randomness of k may be characterized by a normal distribution. Using a numerical method to solve Eq. 5, the mean value of $k = 0.539$ was calculated. Substituting EI into Eq. 6, the limit state function can be rewritten in the following form.

$$g(x) = \frac{1}{3} b E_c \left[(kd)^3 + \frac{E_t}{E_c} (d - kd)^3 \right] - \frac{75}{16} w L^3 \quad (8)$$

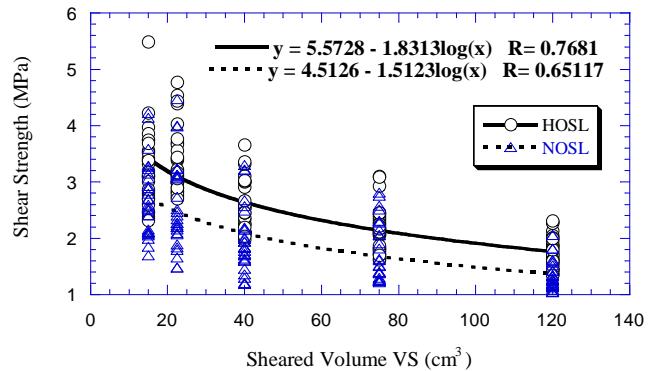


Figure 5. Scatter diagrams of shear strength versus sheared volume for HOSL and NOSL beams

Table 5. Test results of shear strength of heat-treated and nonheat-treated OSL beams

Group	Depth (mm)	Width (mm)	Span (mm)	Shear Span (mm)	Sheared Volume (cm³)	Replication	Longitudinal Shear Strength		Shear Failure	
							HOSL (MPa)		NOSL (MPa)	
							Mean	% CV	Mean	% CV
1	20	10	150	75	15	30	3.25	10.15	2.67	12.66
2	20	15	150	75	22	30	3.36	15.02	2.62	14.25
3	20	20	200	100	40	30	2.54	12.19	1.96	11.46
4	20	30	250	125	75	30	2.15	11.84	1.74	13.84
5	20	40	300	150	120	30	1.75	11.16	1.35	10.56

Note: HOSL = Heat-treated oriented strand lumber

NOSL = Nonheat-treated oriented strand lumber

Table 6. Allowable design stresses for HOSL

Property	Comp.// (MPa)	Comp. \perp (MPa)	Tension // (MPa)	F.Bending (MPa)	E.Bending (MPa)	Shear // (MPa)
Strength	19	13	18	29	30	2
Elastic Modulus	2,741	235	3,769	6,249	6,463	58

Note : F = Flatwise; E = Edgewise

Then, the structural resistance can be represented as:

$$R = \frac{1}{3} bE_c \left[(kd)^3 + \frac{E_t}{E_c} (d - kd)^3 \right] \quad (9)$$

The structural reliability of OSL beams can be examined by means of the limit of Ω_R . A Monte Carlo simulation technique based on Eq. 9 could characterize the randomness of structural resistance. Based on statistical data and 1024 (2^{10}) simulations, the fitted distribution of curves could be obtained from CESTTEST software. For a confidence interval of 99%, the normal distribution could be accepted by Chi-Square and K-S Tests.

The randomness of the structural resistance could be characterized by $\mu_R = 6.36765 \times 10^7$ MPa and $\Omega_R = 0.078$. The fitted distribution of structural resistance was normal, and the limit of Ω_R was 0.269 ($p_f = 10^{-4}$). Substituting $\beta = 3.72$, $\Omega_R = 0.078$ and $\Omega_R = 0.20$ into Eq. 4, the safety factor (FS) was found to be 2. Since Ω_R of the structural system was less than the limit, the heat-treated OSL beams with 20 mm depth can therefore be used economically and safely with FS of 2. The allowable design stresses used in dry conditions are recommended, as shown in Table 6.

4. Conclusions

This research was undertaken to investigate the engineering properties of heat-treated and nonheat-treated Parawood-oriented strand lumber. The investigation of the effect of shear volume on shear strength of the beam was also carried out. Finally, structural members were evaluated by reliability analysis in order to verify that they can be used safely and economically. The conclusions of this study are outlined as follows:

- The results of all mechanical tests indicated that the differences of mean values of strength and elastic modulus between HOSL and NOSL subjected to axial loading group (compression parallel to grain, tension parallel to grain, flatwise bending, and edgewise bending) were highly significant. On the other hand, the differences of the mean values for HOSL and NOSL subjected to normal loading group (compression perpendicular to grain, shear parallel to grain, and internal bonding) were not detected. It can be concluded that an increasing crystallinity enhances strength only in the axial loading mode.

- The shear strength (τ_{\max}) of OSL beams depends on the sheared volume (V_s) and the corresponding regression can be expressed as

$$\tau_{\max} = 5.5728 - 1.8313 \log (V_s)$$

- For all five groups of different span-depth ratios, the shear strength values of HOSL are higher than those of NOSL.

- Reliability analysis shows that the cross-section of OSL beams produced from heat-treated strands can be used safely and economically with a safety factor equal to 2 and corresponding allowable design stresses are herewith recommended.

Acknowledgements

The authors are grateful to the Wood Science and Engineering Research Unit, Walailak University, for providing facilities of sample preparations, OSL manufactures and specimens testing.

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