Investigation of Glueline Shear Strength of Pine Wood Bonded with PVAc by Response Surface Methodology

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The effects of process parameters (adhesive spread, press time, and applied pressure) on the response parameter (shear strength) of pine wood bonded with PVAc were studied. Response surface methodology was applied for design of experiments and for analysis of results. A mathematical model was developed to establish the relationship between the process parameters and response parameters. The results showed that the major factors were adhesive spread and applied pressure. The shear strength increased as the adhesive spread and applied pressure increased within certain ranges.

Keywords: Shear strength; Pine; Response surface methodology

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INTRODUCTION

Bonding technology is important for wood products. The shear strength is a crucial index to evaluate the quality of glued wood products. Different methods measuring the shear strength of wood joints are used to describe the performance of adhesive bonding. The factors that affect the shear strength are physical and chemical properties of the adhesive (such as surface free energy, penetration behavior), physical and structural properties of the cured adhesive (such as stiffness, creep characteristics), physical and structural properties of the wood substrate (such as mechanical properties of the wood cell walls, density, disintegrated wood cells within the weak boundary layer, wood anatomy, pore size, pith opening, *etc.*), process parameters (such as adhesive spread, press time, applied pressure), *etc*. (Follrich *et al.* 2007). In recent decades, some research has concentrated on these areas.

Kurt (2006) studied the effect of glueline thickness on the shear strength of wood-to-wood joints. The results indicated that glueline thicknesses exceeding 0.25 mm may produce inferior bonds. Silva *et al.* (2012) evaluated the effect of assembly pressure on the glue-shear strength of two tropical hardwoods. They concluded that denser wood species benefited from applying low pressure, while lighter wood requires higher pressure to produce stronger bonding. In one previous study, an end grain joint of spruce with different densities was investigated; the result showed that the bond strength increased as the density increased (Follrich *et al.* 2008). After this study, Follrich *et al.* (2008, 2010) conducted further research on the end joint with balsa wood. Balsa wood with a wide density range from 80 to 250 kg/m^3 was chosen to investigate the effects of density and porosity on the adhesive bond strength. The results showed that average wood failure percentage of tested samples rapidly decreased with increasing density, but bond strength slightly increased with increasing density. The surface quality also had an important effect on bond strength. The difference in bond strength between a sawn surface and a sanded surface was studied, and higher bond strength was found for sawn surfaces than for sanded ones (Bassett 1960; Follrich *et al.* 2010). Gindl *et al.* (2002) used UV-microscopy to study diffusion of melamine-urea-formaldehyde resin in cell walls of spruce wood. The results showed that UV-microscopy is a suitable method to study resin diffusion in wood cell walls. Konnerth *et al.* (2006) measured the strain distribution in timber finger joints. 2-D electronic speckle-pattern interferometry (ESPI) was used to observe the deformation of wood in the finger joint area during the mechanical experiment. But even though the results obtained in this study showed the overall distribution of strain very accurately, a further refinement of the measuring set-up was required. Follrich *et al.* (2010) studied the effect of different machining processes on surface roughness and on adhesive tensile strength of endgrain-bonded spruce wood specimens. The results showed that the tensile strength increased with increased surface roughness and adhesive spread quantities. In the present work, the effects of process parameters on glueline shear strength are investigated, and a mathematical model is established by response surface methodology (RSM) to predict the shear strength and find out the relationship between process parameters and the response parameter.

EXPERIMENTAL

Materials

The pine wood used in this study originated from a forest area in the north of Sweden (Scots pine, *Pinus sylvestris*). Based upon the standard for glued laminated timber – shear test of glue lines (EN392 1995), boards of Scots pine (*Pinus sylvestris* L.) were conditioned in a climate chamber with 20 °C/65% relative humidity (RH) until the equilibrium moisture content (EMC) was reached. The wood had a nominal density between 405 and 465 kg/m^3. Nominal density is oven dry mass divided by the volume at the time of testing. The boards were then cut to size, conforming to the standard mentioned above and planed to a thickness of 20 mm. The planed surfaces were used for gluing. Before conducting tests, the boards were mixed in order to avoid the influences caused by wood's inhomogeneity and all specimens were defect-free. The bonding processes were performed using polyvinyl acetate adhesive (ESSVE, Sweden). The properties of this adhesive is shown in Table 1.

Table 1. Properties of Polyvinyl Acetate Adhesive Used in this Study

Properties, unit	Value
Density, g/cm^3	1.1
Colour	White
PH	4-5
Viscosity, mPa-s	12000-15000
Solid content,%	45

The block shear tests were performed on a universal testing machine equipped with a 100-KN load cell (INSTRON 5500R, USA). During the tests, the loading was undertaken at a constant rate (load rate was 3 mm/min in this study) to make sure that the failure occurred after at least 20 s.

Methods

The adhesive was applied to one side of the samples with a brush. Samples were weighed before and after applying adhesive in order to determine the amount of glue applied. Adhesive was cured at a temperature of 20 °C. In total, 85 samples were produced, *i.e.* 5 samples for each combination of process parameters. After the bonding process, all samples were stored at 20 °C and 65% relative humidity until equilibrium moisture content was reached. A mean value for moisture content of 11.7% was found for the specimens.

RSM was applied using a Box-Behnken to arrange the testing in this study (Box and Behnken 1960). Version 8.0.6 of the Design-Expert Software (Stat-Ease Inc., USA) was used to set up the experimental plan and to analyze the experimental data. The specific process parameters and levels are shown in Table 2. In the RSM, the quadratic model, which was obtained using the fitted second-order polynomial regression analysis, can be written as follows (Eq. 1),

$$Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i,j}^{k} b_{ij} X_i X_j + \sum_{i=1}^{k} b_{ii} X_i^2 \tag{1}$$

where b_0 is the free term of the regression equation and the coefficients b_1, b_2, … b_k and b_{11}, b_{22}, . . . b_{kk} are the linear and the quadratic terms, respectively, while b_{12}, b_{13}, . . . $b_{k-1\ k}$ are the interaction terms (Li *et al.* 2014, 2015).

Table 2. Process Parameters and Corresponding Codes and Levels

Process parameters	Code	Levels		
		-1	0	1
Adhesive spread (g/m^2)	A	150	250	350
Press time (h)	B	1	2	3
Applied pressure (MPa)	C	0.4	0.8	1.2

RESULTS AND DISCUSSION

The results from all 17 tests are shown in Table 3. The numbering of results in Table 3, shown divided in the two leftmost columns, refers to the fact that experiments were conducted in the order denoted by “b” (randomized), and the results were inputted to the RSM software in the order shown in column a (standard).

Analysis of Variance

The significances of the fitted model for shear strength were evaluated by analysis of variance (ANOVA). The results of ANOVA are shown in Table 4. The result indicates that the model is considered to be statistically significant. In addition, the values of R^2 and adjusted R^2 were very close to 1. This means that the model achieved a high degree of fit and could provide a satisfying prediction for the experimental results.

Table 3. Experimentally Recorded Data

Standard order[a]	Real order[b]	Process parameters			Response parameter
		Adhesive spread (g/m^2)	Press time (h)	Applied pressure (MPa)	Shear strength* (MPa)
1	13	150	1	0.8	7.92
2	2	350	1	0.8	8.69
3	3	150	3	0.8	7.85
4	12	350	3	0.8	9.88
5	14	150	2	0.4	7.08
6	15	350	2	0.4	9.03
7	9	150	2	1.2	8.76
8	4	350	2	1.2	9.39
9	6	250	1	0.4	8.31
10	10	250	3	0.4	8.22
11	17	250	1	1.2	9.96
12	16	250	3	1.2	9.39
13	7	250	2	0.8	8.46
14	11	250	2	0.8	8.53
15	5	250	2	0.8	8.54
16	8	250	2	0.8	8.49
17	1	250	2	0.8	8.50
* Each standard order was mean value of 5 samples					

Table 4. ANOVA for the Fitted Model

	Sum of squares	Degrees of freedom	Mean square	F value	Prob.>F
Model	8.05	9	0.89	12.98	<0.05 (Sig.)
Pure Error	4.12×10^{-3}	4	1.03×10^{-3}		
Corrected Total	8.53	16			
R^2= 0.94			Adjusted R^2 = 0.87		

Model and Adequacy of Developed Model

The quadratic model of shear strength was established through nonlinear regression analysis. The final mathematical model is provided by Eq. 2, where *A* represents the adhesive spread, *B* represents press time, and *C* represents applied pressure in term of the coded levels.

$$\text{Shear strength} = 8.50+0.67A+0.058B+0.61C+0.31A*B-0.33A*C-0.12B*C-0.16A^2+0.24B^2 + 0.22C^2 \quad (2)$$

The adequacy of the developed model was tested by three confirmation experiments carried out with different process parameter combinations. The predicted values were calculated automatically using the mathematical model. The predicted values, actual values, and errors are listed in Table 5. The values of error were acceptable, which means that the model was effective in predicting the glueline shear strength of the pine when bonded with PVAc. Figure 1 shows the correlation between predicted values and actual values.

Table 5. Confirmation Experiments

Process parameters			Values	Response parameters
Adhesive spread (g/m²)	Press time (h)	Pressure (MPa)		Shear strength (MPa)
250	2	0.4	Actual	7.8
			Predicted	8.1
			Error (%)	-4.0
350	3	0.4	Actual	9.1
			Predicted	9.7
			Error (%)	-6.6
250	1	0.8	Actual	8.9
			Predicted	8.7
			Error (%)	2.1

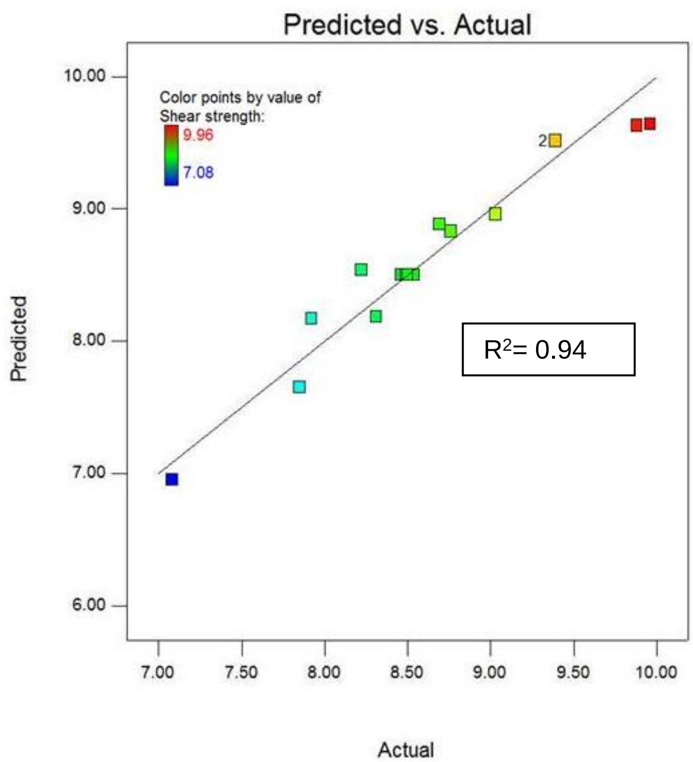

Fig. 1. Correlation graph for shear strength

Discussion

The effects of the process parameters on shear strength are shown in Fig. 2. The factors that significantly affect shear strength were adhesive spread and applied pressure. As shown in Fig. 2, the shear strength increased with increasing adhesive spread and applied pressure. When the adhesive spread is at a low level, most of the adhesive penetrates into wood which causes a starved glueline. With an increase in adhesive spread, part of the glue penetrates into the wood, and a uniform glueline will be formed in the press processing. It is essential to get a good gluing performance and high shear strength, but the shear strength will decrease when the adhesive spread is too large, because too much adhesive spread induces a thick glueline, which has a negative effect on shear strength (Hu 2013). This result agrees with previous research (Follrich *et al.*

2010). In this study, only normal and relatively low values were selected; therefore, no decreasing tendency can be seen in Fig. 2. These results are in good agreement with the results obtained in previous works (Kurt 2006; Hu 2013).

For the parameter of applied pressure, a relatively high pressure is essential to form a good glueline. Due to the high viscosity of PVAc, the penetration increases with an increase in applied pressure. This may be the main reason why the shear strength increased as the applied pressure increases. This effect of applied pressure on the bond quality is the same for LVL processing (Kurt and Cil 2012).

The shear strength from the mathematical models, as functions of the major process parameters, are shown in Fig. 3. From Fig. 3, it is easy to find the optimized process parameters to achieve highest shear strength. Based on goals and parameter ranges listed in Table 6, the optimized parameters for highest shear strength are 341g/m^2, 3 h and 1.2 MPa for adhesive spread, press time and applied pressure, respectively.

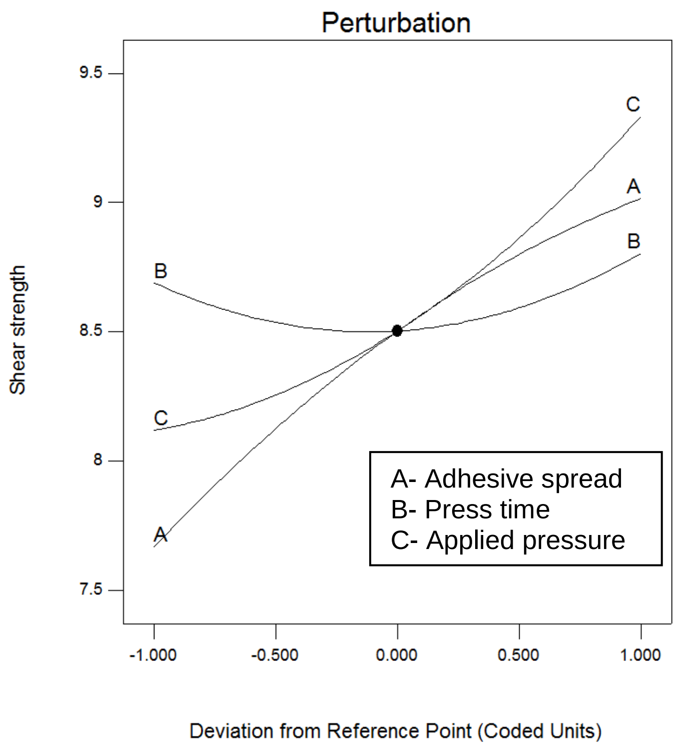

Fig. 2. Perturbation plots showing the effect of each process parameter on the shear strength

Table 6. Goals and Parameter Ranges for Optimization of Shear Strength

Condition	Goal	Lower limit	Upper limit
Adhesive spread (g/m^2)	Is in range	150	350
Press time (h)	Is in range	1	3
Applied pressure (MPa)	Is in range	0.4	1.2
Shear strength (MPa)	Maximize	7.08	9.96

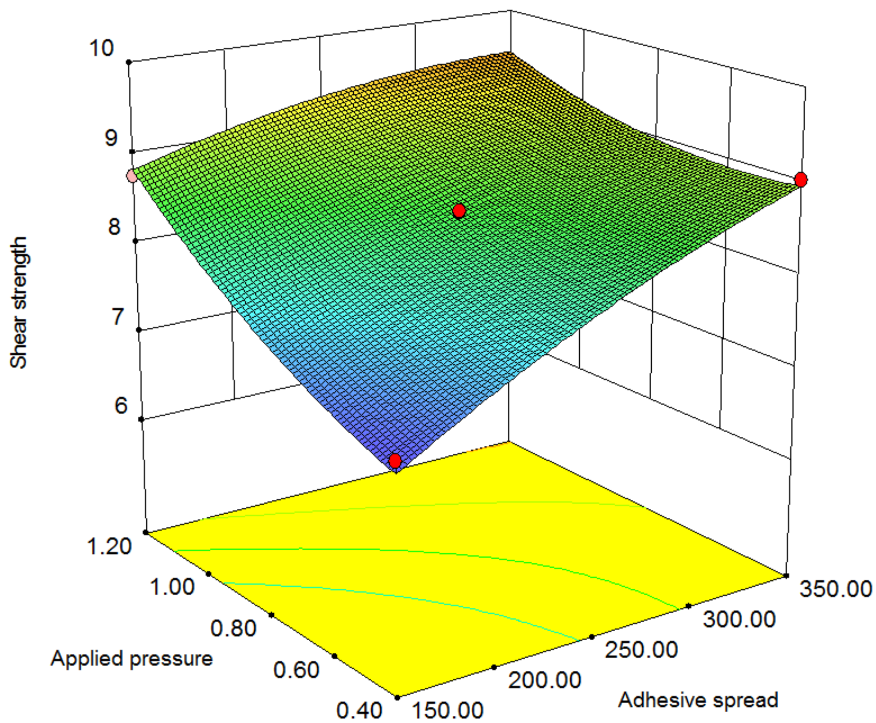

Fig. 3. Responses for shear strength as function of major process parameters

CONCLUSIONS

1. The response parameter of shear strength was affected by adhesive spread and applied pressure. Press time had insignificant effects on shear strength.
2. The shear strength of pine lumber bonded with PVAc increased with increasing adhesive spread and applied pressure.
3. The adequacy of the developed model was quite good. These mathematical models can provide an effective prediction for experimental data.

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