Digital Image Correlation Measuring Shear Strain Distribution on Wood/Adhesive Interphase Modified by Sealants

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In this study, three different sealants (gelatinized starch (GS), gelatinized starch/wood flour mixture (GSWF), and soy-protein adhesive (SPA)) were used to seal the lathe checks in veneers before applying phenol formaldehyde adhesive. The shear strain distribution on the interphase of the lap joint specimens was measured by a digital image correlation technique. The results showed that the average shear strain along the bond line on the interphase was 1.94×10^{-3} when the specimen had lathe checks. Sealing treatment can thus reduce the average shear strain effectively. Soy-protein adhesive seemed to have the greatest ability to decrease the average shear strain along the bond line, from 1.94×10^{-3} to 0.94×10^{-3}. In contrast, gelatinized starch appeared to decrease the strain slightly to 1.61×10^{-3}. Average shear strain along the bond line of specimens treated with gelatinized starch/wood flour mixture was 1.00×10^{-3}, which was between the values of the other two sealants. Dry shear strength of samples treated by GS and SPA increased from 7.6 MPa to 9.65 MPa and 8.85 MPa, respectively. The mixture of GSWF decreased the strength to 6.32 MPa. Wet strength of treated samples were smaller than untreated ones.

Keywords: Lathe checks; Sealants; Digital image correlation (DIC); Interface; Strain distribution

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INTRODUCTION

With rising standards of living, people tend to use more wood products than ever. Compared to oriented strand board and fiber boards, veneer-based products pose more challenges because timber resources are limited. Therefore, the efficient utilization of logs is critically important. However, lathe checks seriously degrade the quality of veneer (Pałubicki *et al.* 2010), while adhesives penetrate excessively into wood substrates through the checks during manufacturing to result in a thin glue line and poor mechanical properties of the products. To ensure adequate bonding within these properties, higher amounts of adhesives are needed, leading to higher manufacturing costs. Sealing lathe checks is necessary to prevent the over-penetration of adhesives.

Research into the improvement of lathe checks may be divided into two approaches. The first involves understanding the mechanism of check propagation (Lawrence 1960; Koch 1965a,b) and using real-time monitoring to control the degree of checks (Cade and Choong 1969; Pałubicki *et al*. 2010). The second approach is to seal the checks. After densification, lathe checks present on veneers before densification were conglutinated by function of heat and steam, and surface roughness decreased (Fang *et al.* 2012). Fluorescence microscopy analysis showed that spreading soy adhesive on peeled

veneer surfaces before applying phenol formaldehyde (PF) adhesive can efficiently prevent the adhesive from over-penetrating the wood (Wang and Guan 2012).

To date, articles focusing on the effect of lathe checks on bond quality have mainly focused on the properties on a macro scale; *e.g.*, wood failure percentage and failure strength (Koch 1965a,b; Lawrence and Moir 1968; DeVallance *et al.* 2007). Few studies have explored the impact of checks on wood material properties on a micro level. In fact, mechanical characterization on a micro scale can give information about strain and stress concentration, which is of great significance to the materials. As one of the non-contact measurement techniques that characterizes strain distribution on material surfaces on a micro level, digital image correlation (DIC) has been used in wood materials for some time (Zink *et al.* 1995; Serrano and Enquist 2005; Muszyński *et al.* 2006; Jeong *et al.* 2009). In the present study, we used DIC to measure the shear strain distribution on the wood/adhesive interphase of both treated and untreated lap joint specimens, thereby evaluating the effects of these treatments. Three different sealants were employed: gelatinized starch (GS), gelatinized starch/wood flour mixture (GSWF), and soy-protein adhesive (SPA).

EXPERIMENTAL

Materials

Peeled veneers of poplar (*Populus euramericana* Cv.) with dimensions of 400 mm × 400 mm × 3 mm were obtained from South Wood Technology Ltd. (Lian Yungang, China). To avoid effects due to variations in density, the sapwood poplar peeled veneer specimens were selected from the same section of the same log, without any defect, and density was uniform.

The manufacturing process of phenol formaldehyde resin was as follows: phenol (analytically pure), water, and sodium hydroxide (NaOH analytically pure) were added to a reactor and stirred at 40 to 45 °C. The first part of formaldehyde (80% of the total amount) was added. The liquid in the reactor was warmed to 80 to 85 °C and reacted for 45 min. Subsequently, the water bath was heated to the boiling point for 10 min. The liquid was then cooled to 40 to 45 °C, and the remainder of the formaldehyde was added. The total mixture reacted for 80 min at 85 to 90 °C. Finally, the reaction mixture was cooled to room temperature. The formula and properties of the adhesive are found in Table 1.

Table 1. Formula and Properties of Phenol Formaldehyde (PF) Adhesive

Resin	F:P Ratio	NaOH (%)	Solid Content (%)	Viscosity (mPa·s)
PF Adhesive	1.5	8.8	46.3	136

The production of soy-protein adhesive proceeded as follows: defatted soy flour was added to water slowly and stirred for 15 min until no lumps were observed. Sodium hydroxide (concentration of 30%) was then placed in the suspension and stirred until it became sticky. The mass ratio of components was soy flour: sodium hydroxide: water = 100:15:400. To make the gelatinized starch, 20 g of wheat starch and 80 mL of water were added to a beaker that was placed in a water bath. The temperature was gradually

increased to 85 °C while the mixture was stirred continuously until a sticky substance appeared. This mixture was then ready for coating the veneer surface. The production process of gelatinized starch/wood flour mixture was almost the same as that of gelatinized starch, the only difference being that 10 g wood flour (passing through 100 mesh) and 10 g starch were initially added to 80 mL water.

Methods

Sealing treatment of lathe checks

Veneers with checks were covered by the above-mentioned sealants on their surface and laid aside for 30 min. Phenol formaldehyde adhesive was then spread on the sealed surfaces. As indicated in Fig. 1, two layers of veneers were laid parallel to their longitude direction with the checks on each side facing inwards.

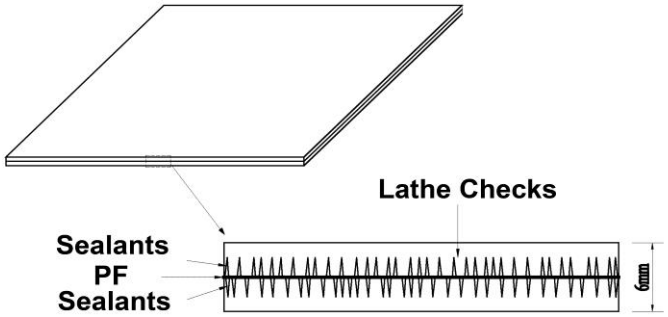

Fig. 1. Assembly pattern of samples with sealing treatment

The assembly was prepressed for 30 min before the hot-press. Double-sided application of sealants was 150 g/m^2 per side; single-side glue application of PF adhesive was 150 g/m^2. The parameters of hot-press were 140 °C, for 1 min/mm at 2.6 MPa. The boards were stored in a standard environment of 25 °C with 65% humidity for 7 days before they were cut into test specimens according to the dimensions in Fig. 2.

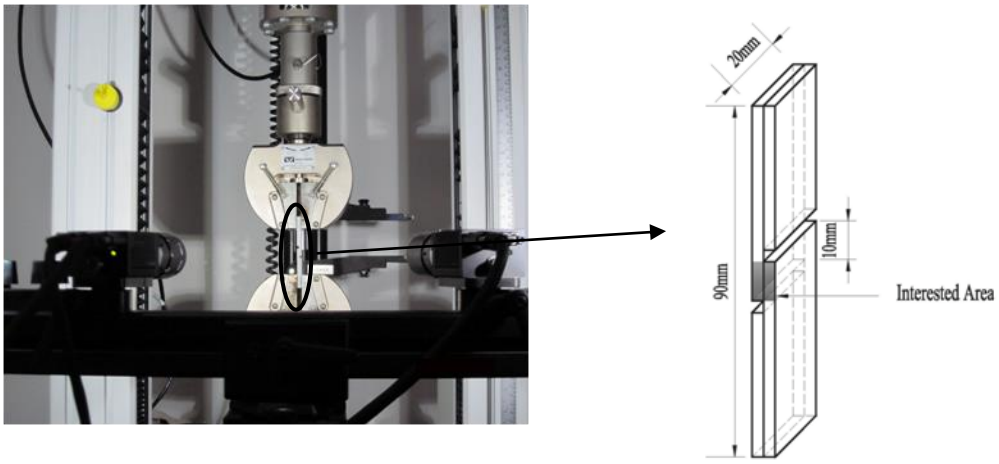

Fig. 2. Tensile shear test setup and dimensions of test specimens

Shear strain measurement by DIC

The test setup is shown in Fig. 2. The principle of DIC and the detailed test procedures were described in previous papers (Serrano and Enquist 2005; Jeong *et al*. 2009). The core of DIC is the monitoring of the in-plane displacements on a plane object by tracking the deformation of a random pattern in an image (Valla *et al*. 2011). Parameters applied in this experiment were a camera resolution of 2448 × 2048, subset 30, step 3, and 0.2 μm in the measured displacement accuracy. A random white-and-black spray pattern with a speckle diameter of 0.2 mm was used.

Some modifications were made in the present experiment: the samples were clamped with a free-clamping length of 60 mm. A Vic-2D 2010 measurement system (Correlated Solutions Inc.; USA) was set up in front of an Istron 3367 testing machine (Instron Cooperation, USA).

The universal testing machine was manipulated to load slowly and stop for 3 seconds to capture images of the areas of interest at an interval of 0.1 MPa shear stress. The stretch ended when the nominal shear stress reached 5.0 MPa; thus, the camera captured 50 images.

The system performed stepwise correlation analyses for all 50 images. However, only shear strains of 5.0 MPa were included in the analysis, with the underformed state used as a reference image. Post-processing of the strain was conducted using Vic-2D 2010 software, which can give the displacements of the surface and the corresponding strains ε_{xx}, ε_{yy}, and ε_{xy}. Grayscale maps were depicted with Origin8.0 software using the strain values from Vic-2D 2010.

Shear strength test

To investigate the influence of sealing treatments on the specimen's mechanical properties, shear tensile tests were performed. The samples were sawn to the dimensions required by DIN EN 302-1-2004 (150 mm × 20 mm × 10 mm). However, because the 5 mm-thick veneer is not generally produced by peeling method, a 3 mm-thick veneer was used instead, resulting in final dimensions of 150 mm × 20 mm × 6 mm. A shear strength test was conducted using the universal testing machine with a loading speed of 2.5 mm/min. The samples for dry state testing were subjected to procedure A1, which entailed a 7-day modulation in standard atmosphere. Meanwhile, the samples for wet state testing were subjected to procedure A4, which involved 6 h of soaking in boiling water, followed by 2 h of soaking in water at 20±5 ˚C. Ten replicates were prepared for each treatment.

RESULTS AND DISCUSSION

Shear Strain Distribution on Interphase

Figures 3 and 4 indicate that under a certain load, the shear strain in the areas of interest found in all samples showed the same trend. Along the bond line, the strain was noticeably concentrated at the ends of the overlap area, while it became gradually smaller towards the middle section of the overlap region. Along the vertical direction to the glue line, highly strained zones were observed very close to the bond line (< 1 mm); also, wood substrates had lower shear strain values.

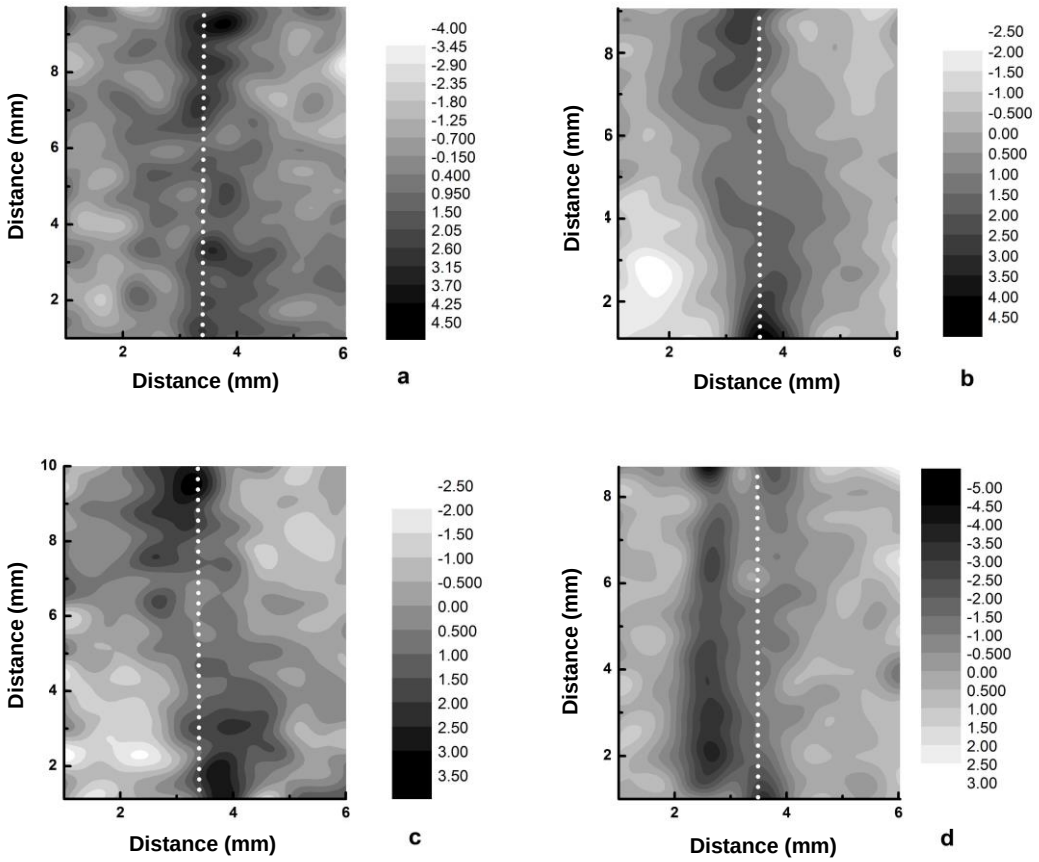

Fig. 3. Shear strain distribution at the interested areas of (a) unsealed samples, (b) samples sealed with gelatinized starch, (c) samples sealed with, gelatinized starch/wood flour mixture, and (d) samples sealed with soy-protein adhesive. The scale bars indicate strains multiplied by 10^{-3}; the white dotted lines denote the glue lines

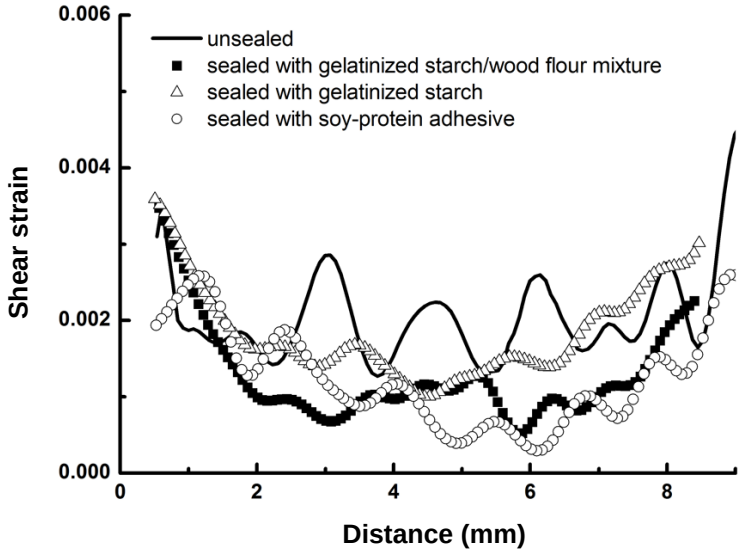

Fig. 4. Shear strain measured along the glue line of specimens with shear strength of 5.0 MPa

Table 2. Statistical Analysis of Strain Distribution along the Bond Line of Specimens

Sealants	Minimum ($\times10^{-3}$)	Maximum ($\times10^{-3}$)	Average ($\times10^{-3}$)	Standard deviation ($\times10^{-4}$)	Coefficient of variation (%)
None	1.27	2.86	1.94	4.33	22.3
Gelatinized starch (GS)	1.00	2.70	1.61	4.19	26.0
Gelatinized starch/ wood flour mixture (GSWF)	0.52	1.84	1.00	1.80	18.0
Soy-protein adhesive (SPA)	0.29	1.87	0.94	4.23	25.0

Overall, the average shear strain in unsealed specimens (Fig. 3a) in the areas of interest was larger than that of the sealed specimens (Figs. 3b, 3c, 3d). Since strain concentration is generated at the ends of the overlap area caused by external loading, strain values between 2 and 8 in the x direction along a bond line (Fig. 4) were used for statistical analysis. As indicated in Table 2, unsealed samples had a strain value between 1.27×10^{-3} and 2.86×10^{-3} in the overlap region; however, sealed samples had a strain value between 0.29×10^{-3} (SPA_{min}) and 2.70×10^{-3} (GS_{max}) in the same area. This may be because when lathe checks are present, PF can penetrate excessively into the veneer, leaving the bulk adhesive without enough resin to form a strong bridge with the substrate (Frihart 2005) and thus generating higher strain ranges in the overlap area under load. Once the checks were sealed (owing to the blocking of PF over-penetration), the adhesive layer thickness was guaranteed, and its mechanical strength was enhanced; therefore, the adhesive layer did not deform easily.

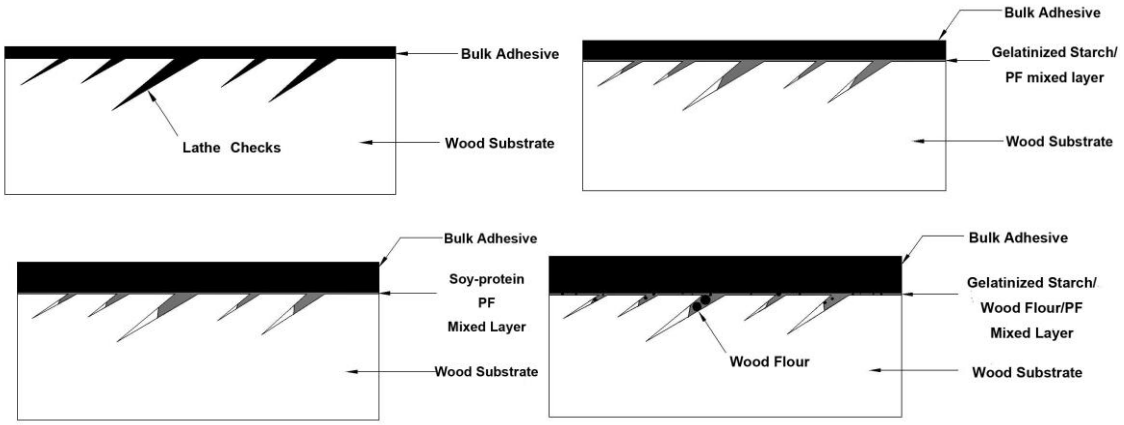

Fig. 5. Schematics of different sealing treatments on lathe checks

As shown in Fig. 4 and Table 2, the SPA seemed to have the greatest ability to reduce bond-line average shear strain from 1.94×10^{-3} to 0.94×10^{-3}. By contrast, GS appeared to decrease the average strain slightly to 1.61×10^{-3}. Comparing the shear strain of unsealed samples to GS sealed samples, no great difference of strain values was found at the ends of the overlap zone, whereas across the overlap region, the former had greater average shear strain than did the latter (Table 2). This phenomenon may have three

possible causes: (1) as shown in Fig. 5, with GS sealing the checks, the over-penetration of PF was partially relieved, and the mechanical property of the bulk adhesive was strengthened; (2) during the hot-press process, PF modifications with wheat starch favored para-para methylene bridge structures, which is effective in cross-linking hydroxymethyl phenol to form a rigid resin (Turunen *et al.* 2003); and (3) starch may also contribute to bonding strength by agglutination during hot-press (Veigel *et al*. 2011).

For samples that were sealed with SPA whose protein structure was degraded to tertiary or even lower structures with exposure of hydrophobic groups on the surface following sodium hydroxide denature (Frihart *et al*. 2010), the penetration of hydrophilic PF into the wood substrate is not favored because of the chemical polarity differences between PF and denatured soy-protein which provides the adhesive layer adequate thickness (Fig. 5). Furthermore, carbohydrate fraction and protein fraction containing many side-chain reactive amino acid groups (25 to 30%) are believed to have the ability to react with phenolic-type resin systems, forming thermoset networks with a suitable cross-linking agent (Wescott and Frihart 2004). Consequently, the average shear strain in the overlap area (Table 2) was smaller because the adhesive layer was enhanced.

Finally, in the overlap area along the bond line, specimens sealed with GSWF had an average shear strain similar to that of SPA (Table 2). Although GS is not an effective blocker, it is possible that the multi-scale porosity structures of wood flour can absorb PF into its pores, thus impeding the flow of adhesive into wood substrates (Fig. 5). Therefore, the bulk adhesive has adequate resin to form a rigid layer that restrains its deformation under load. Figure 5(d) shows that the bondline was unsymmetric, and a dark strain area was apparent to the left of the nominal bondline (white dot); therefore, the shear strain of SPA should be higher than what was measured. Shear strain cannot be released in the bulk adhesive with a high modulus; it can be released only at the softer wood substrate, giving rise to simple failure at this location.

Shear Strength of Two-ply LVL

Compared to specimens in control group, sealing treatments had different influences on the shear strength of specimens (Fig. 6). In terms of dry strength, GS and SPA increased the strength from 7.6 MPa to 9.65 MPa and 8.85 MPa, respectively. But the GSWF decreased the strength to 6.32 MPa.

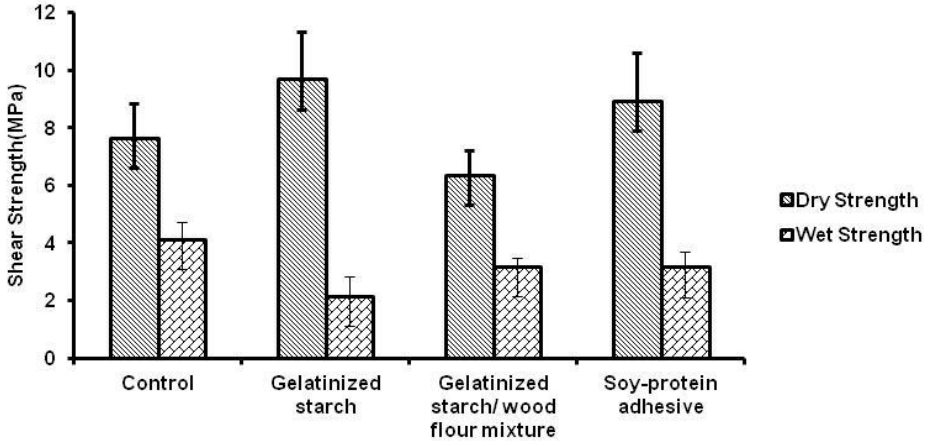

Fig. 6. Shear strength of specimens with various sealants

Wet strength had a trend that was distinctly different from that of dry strength: all sealing treatments decreased the strength. Among those, GSWF and SPA reduced the value from 4.1 MPa to 3.15 MPa and 3.12 MPa, while GS degraded the value to 2.1 MPa.

As illustrated in the strain distribution section, the increase of shear strain in GS-treated samples resulted from three reasons: 1) relieved over-penetration, 2) more cross-linked PF resin, and 3) starch agglutination during hot-pressing. SPA on the veneer surface blocked the over-penetration of PF resin and reacted with PF resin to form a rigid web structure. Thus it was able to increase the shear strength as well. In the case of GSWF, the reduced shear strength came from insufficient PF penetration as demonstrated by the strain distribution in Fig. 3d. Under such conditions, the mechanical weak area was transferred from the interface to relatively soft wood substrates.

The three sealants considered in this work are not water-resistant. Starch in the lathe checks absorbed water and became gelatinized again under procedure A4. Then it came out from the interphase and created voids that became stress concentration areas under load (Fig. 5). Despite the fact that the GSWF had the same problem, the addition of wood flour increased the toughness and fracture strength of the adhesive layer, which compensated for the degradation of strength due to starch loss (Ebewele and Koutsky 1986). Finally, SPA would further degrade to second or primary structures when exposed to the combination of heat and moisture. This resulted in a loose area inside the lathe check and the degradation in shear strength afterwards (Fig. 5). Due to the fact that SPA had already reacted with the PF resin, fewer voids were generated in the sealed area compared to GS. Therefore, the wet strength of SPA-treated samples were larger than GS-treated samples.

CONCLUSIONS

1. In this study, digital image correlation (DIC) measurements indicate that lap joint specimens made from peeled veneers with lathe checks tend to have large average shear strain along the bond line. Sealing treatment can be effective for reducing such strain, depending on the different sealants used. Gelatinized starch (GS) seemed to slightly decrease the average strain. A gelatinized starch-wood flour mixture (GSWF) and soy-protein adhesive (SPA) had almost the same ability to reduce the average strain along glue line.
2. GS and SPA increased the dry shear strength while the GSWF decreased it. In contrast, all sealing treatments decreased the wet shear strength.

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