Evaluating Warp of 2 by 4s Sawn from Panels Produced through Green Gluing Dimension Lumber from Small Ponderosa Pine Logs

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Abstract

Overstocked small-diameter softwood timber in western US forests has created a serious forest health and fire hazard, and the costs of removing this material are high. One way to lower costs is to reduce loss because of warp on lumber sawn from these small logs. Using a green-gluing process, standard 38 by 89-mm (nominal 2 by 4-in.) pieces (2 by 4s) ripped from pressed panels of edge-glued (edge-glued-and-rip [EGAR]) boards sawn from small ponderosa pine (*Pinus ponderosa*) logs were evaluated for warp reduction. Material was bonded at high moisture content (MC) to simulate lumber freshly sawn from water-saturated logs and examine potential MC effects on wood–wood bonding. We selected a liquid, one-component, fast-curing, cold-setting polyurethane for green gluing wood. Results showed statistically significant reduction in bow ($P < 0.001$) and twist ($P < 0.001$) and no statistical difference in crook ($P = 0.321$) for EGAR boards compared with conventional 2 by 4s before planing. After planing and equilibrating, EGAR boards showed statistically significant increases in crook ($P < 0.001$) and bow ($P < 0.001$) but maintained a statistically significant reduction in twist ($P < 0.001$). Lumber quality decreased after planing and equilibrating to 12 percent MC. Because of high MC in flitches during the green-gluing process, bondline failures sometimes occurred, distorting the final results. High amount of bondline failure after planing and equalizing indicates this process is unfeasible as tested. Greater MC control during green gluing may reduce warp to allow more effective utilization of these small logs.

Significant interest has developed in green gluing wood to enhance physical properties and develop usable wood products from low-value material (Maun and Cooper 1999, Moody et al. 1999). Most of this past research has focused on green finger-jointing studs and glulam, and several commercial products have been developed, such as Greenweld and Soybond (Parker et al. 1991, Parker 1994, Kreibich et al. 1998, Lipke 2005). Green gluing allows processing of wood before drying, thereby taking advantage of its natural wet state and resulting in fewer defects and higher lumber quality (Pommier and Elbez 2006).

Polyurethanes (PURs) along with melamine urea formaldehyde and phenol resorcinol formaldehyde are used for green bonding wood (Pommier et al. 2005, Sterley 2005). PURs may be classified as moisture-cured because of their residual isocyanate group's ability to react with water to create wood–wood bonding (Properzi and Pizzi 2003). One concern in using PURs for gluing is the product may be subject to creep (deformation) and temperature-dependent creep, although some research indicates reformulation would alleviate these problems (Pommier et al. 2005, Richter et al. 2006). In addition, PURs developed 10 to 15 years ago have passed European testing, such as the single-burning-item method from EN 13823 (European Committee for Standardization [CEN] 1998) for heat resistance and the European version of American Society for Testing and Materials (ASTM) Standard 3535 (ASTM 1990) for deformation (creep). Newer PURs do not require testing in accordance with the latest version of EN 14080 (CEN 2009; R. Bredesen, Dynea, personal communication, January 2009). The most recent study by Karastergiou et al.

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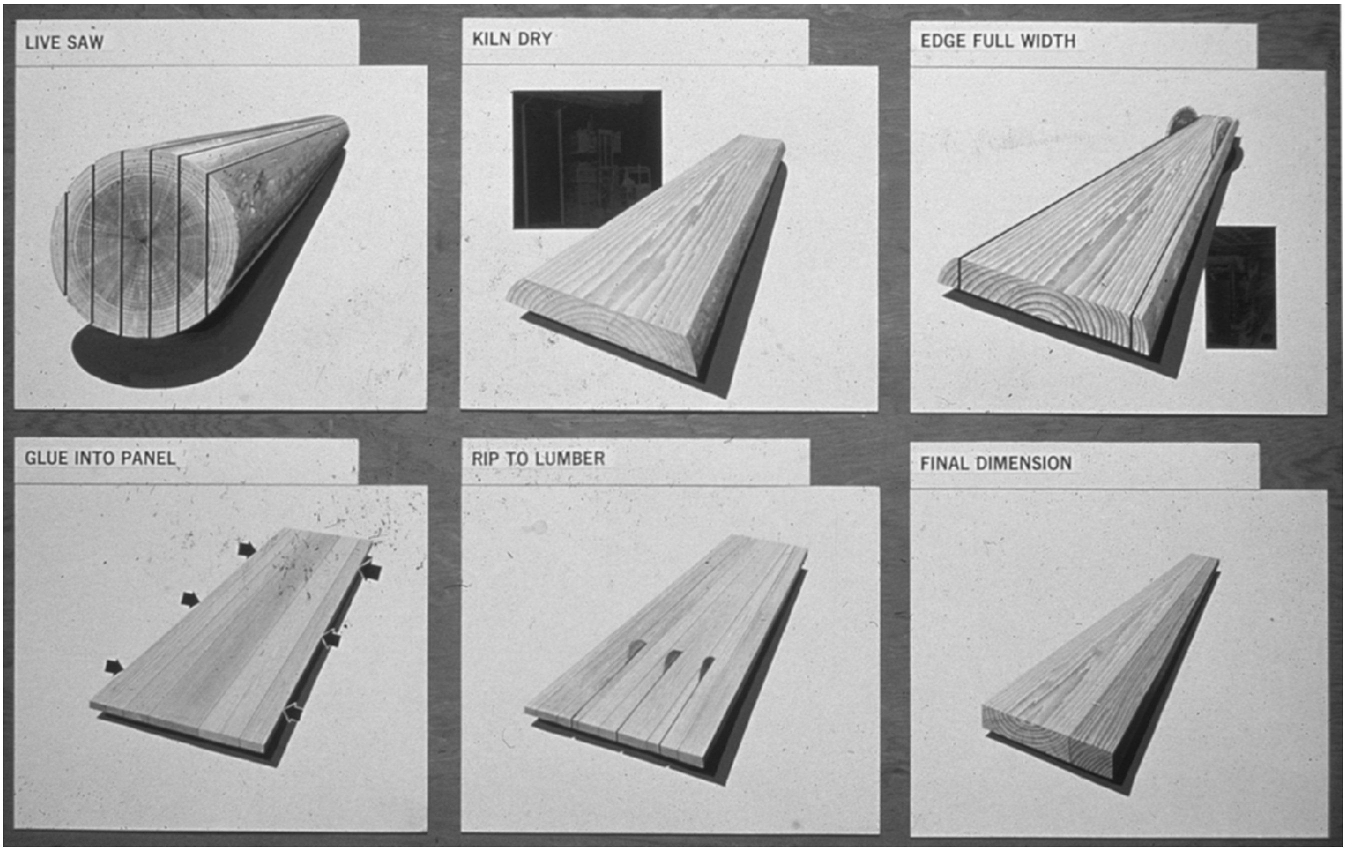

Figure 1.—Different stages of the original EGAR process.

(2008) showed the feasibility of green gluing oak at a high moisture content (MC) using a one-component PUR. The MC and its variability comprise the most critical parameter when green gluing wood with PURs. Material such as finger joints typically allows some air drying before processing (C. Frihart, USDA Forest Service, Forest Products Laboratory [FPL], personal communication, June 2005). Therefore, evaluating MC effects of gluing freshly sawn lumber from saturated logs (the material is at its highest MC) using a liquid, one-component, cold-setting, fast-cured PUR would be useful in simulating an industrial setting.

The edge-glued-and-rip (EGAR) process was developed in the 1970s at the FPL (Compton et al. 1977) using shortleaf pine (*Pinus echinata*) and evaluated economically by Harpole et al. (1979). Compton et al. (1977) summarized the process and the corresponding benefits by noting a significant increase in overall yield of 10 percent for lumber produced by the EGAR system over standard lumber.

The EGAR system is designed to use the full width of each flitch sawn from a log by live sawing logs to produce the highest lumber volume yield, drying round-edge flitches, ripping to the widest possible usable width, edge gluing into panels 91 to 122 cm (36 to 48 in.) wide, and ripping the panels to final dry widths for softwood dimension lumber (Fig. 1). A flitch is an unedged board, sawn to its thickness but not width (it contains wane). The panels are ripped to yield lumber that reflects the highest grade and strength potential within the panel. Placing knots away from the edges and containing them in wider lumber minimizes their effect (Compton et al. 1977, Barnekov et al. 1998). Narrow boards, such as the 2 by 4s in the present study, are not likely to minimize the effects of knot location. Another major benefit is log size does not restrict the width of lumber made.

Harpole et al. (1979) conducted an economic evaluation of the EGAR process and found that although a 12 to 13 percent increase in lumber recovery occurred, the process did not justify the additional investment. However, the EGAR process became more economical when roundwood prices increased relative to lumber prices.

In summary, the EGAR system offers several advantages for producing 51-mm-thick (2-in.-thick) softwood dimension lumber:

1. increase in volume yield when not restricted to ripping fixed-width boards;
2. capability and flexibility to produce 102-, 152-, 203-, 254-, and 305-mm-wide (4-, 6-, 8-, 10-, and 12-in.-wide) boards from (relatively expensive) small-diameter logs;
3. capability to rip boards from panels that minimize the effect of degrading knot locations, thus maximizing grade recovery;
4. ability to store panels and cut widths to order or to maximize the current width (i.e., price scene); and
5. variable and flexible board length using finger jointing (an advantage not considered in the original concept).

Although EGAR showed economic potential (Harpole et al. 1979), it was not implemented commercially. This previous work dealt with gluing kiln-dried material. Several new factors have emerged to prompt reexamination of EGAR. The possibility of gluing green (freshly cut) material

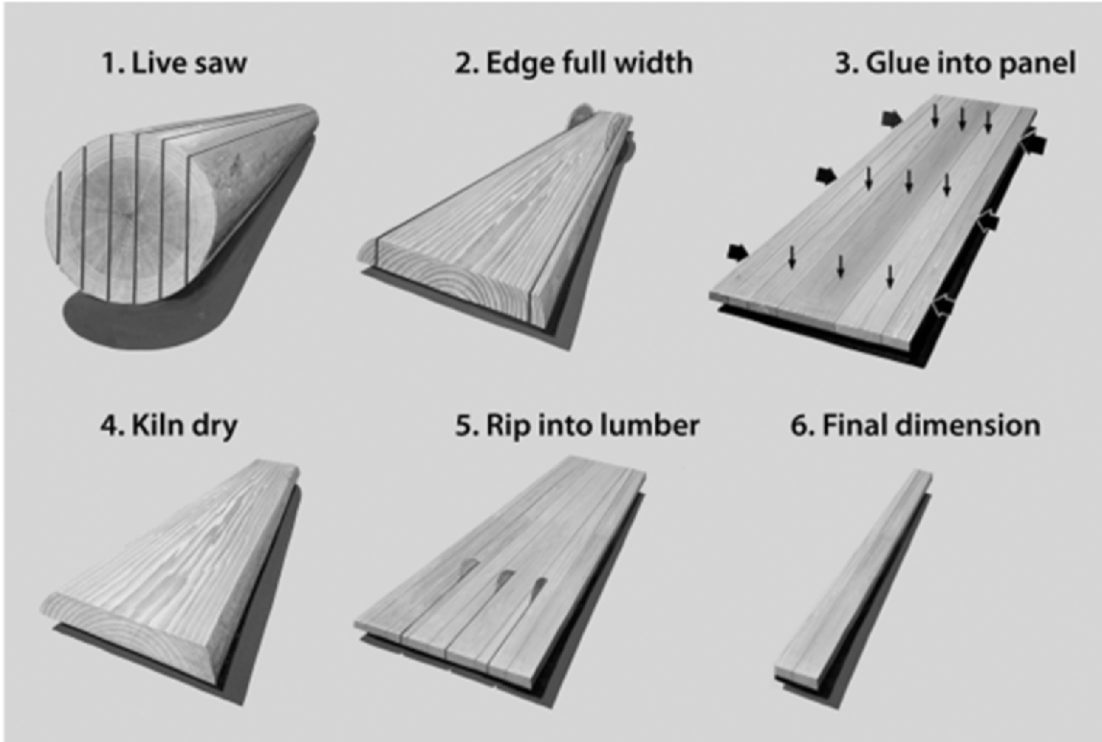

Figure 2.—Different stages of the modified green-gluing EGAR process.

(rather than kiln dried) is of particular interest. New factors include the following.

1. A huge supply of small-diameter softwood timber in western US forests has created a serious forest health and fire hazard. Costs of removing this material are high, so any utilization improvements could help offset this high cost (Glickman and Babbitt 2000).
2. Not only is this supply of small-diameter timber costly to remove, lumber sawn from it is notoriously prone to degrade from warping during drying (Shelly et al. 1979).
3. New adhesive technology opens up the possibility of edge gluing green material and then kiln drying full-width panels. The expectation is that boards sawn from the dried panels will have less warp than boards already ripped to width before drying (Sterley et al. 2004, Ormstad 2005).

The main objective of the present study was to modify the original EGAR process to a green-gluing process to evaluate warp reduction potential of small ponderosa pine (*Pinus ponderosa*) timber. The EGAR process was modified to use the full width of each flitch sawn by live sawing logs; ripping to the widest possible usable width; edge-gluing the green lumber into pressed panels 122 to 132 cm (48 to 52 in.) wide using a liquid, one-component, fast-curing, cold-setting PUR adhesive (Prefere 6000; Dynea ASA, Lillestrøm, Norway); kiln drying the panels with top loading (9.6 kPa [200 lb/ft^2]) using a conventional kiln schedule; and ripping the panels into 2 by 4s (Fig. 2). Prerefe 6000 has been tested for heat resistance and has passed the single-burning-item method according to EN 13823 (CEN 1998).

Values of bow, crook, and twist for the EGAR 2 by 4s were compared with conventionally cant-sawn 2 by 4s from small-diameter ponderosa pine logs cut at the same site and time. In the present study, small logs were not likely to produce wider widths of conventionally produced boards. Therefore, the direct comparison was limited to 2 by 4s, although boards from the EGAR process can reach a width of 305 mm (12 in.). Ponderosa pine was chosen for evaluation because of the large volume of small-diameter timber available in western US forests and because of the tendency for lumber produced from this material to warp.

Materials and Methods

An exploratory test was conducted at the FPL to evaluate warp reduction using the EGAR process modified by edge gluing green boards into panels before drying. One 1.2 by 2.4-m (4 by 8-ft) panel was assembled from 12 green slash pine (*Pinus elliottii*) 2 by 4s using a resorcinol resin. Assembly was done with pipe clamps. The panel was kiln dried to 14 percent MC, the panel ripped into eleven 2 by 4s, and bow, crook, and twist measured on all boards.

The comparison to conventionally sawn material on warp reduction is shown in Table 1 for 2 by 4s ripped from this single panel produced using pipe clamps. With such a small sample size, we could not state that the reduction in warp had statistical significance, but it certainly suggests we explore green gluing in more detail.

Table 1.—Average warp values found using the pipe clamp method.

Process	Warp (in.)[a]		
	Bow	Crook	Twist
EGAR	5.1	4.1	4.8
Conventional	11.6	5.4	12.8

[a] 1 in. = 25.4 mm.

To evaluate warp on a larger scale, 2 by 4s ripped from kiln-dried panels produced from edge gluing green ponderosa pine dimensional lumber were manufactured according to the following details. Thirty ponderosa pine logs, ranging from 152 to 381 mm (6 to 15 in.) in diameter at breast height were obtained from an open-grown, 30- to 35-year-old stand near Idaho City, Idaho. After felling the trees and bucking the butt log of each tree to 2.6 m (8½ ft), logs were shipped to the FPL. To prevent deterioration (decay), the logs were stored outside during the winter (<0°C [<32°F]) and under a water spray during the rest of the year. The logs were sawn into one hundred 48-mm-thick (1⅞-in.-thick) flitches of the widest width possible, ranging from 70 to 292 mm (2¾ to 11½ in.), using a Wood Mizer Model LT 30 sawmill (Wood Mizer, Indianapolis, Indiana). Surface blue stain occurred during stacking and before moving flitches into cold storage. The flitches were stored to maintain freshness and prevent any further deterioration until ready for processing into panels. Before processing, press panel setup times and pressures needed to be estimated.

To estimate the optimum pressing time and side pressure for gluing panels, we conducted a preliminary test using small specimens from the same ponderosa pine material harvested in Idaho City. After gluing up four replicates of specimens for each condition, we determined the average shear parallel-to-grain values. The parallel-to-grain values were found according to ASTM D-905 (ASTM International 2003) and Okkonen and River (1989). Results for the shear parallel-to-grain values are shown in Table 2. Literature values found in the *Wood Handbook* (Green et al. 1999) for shear parallel to grain at 12 percent MC for ponderosa pine is 7.8 MPa (1,130 lb/in.^{2}). The main observation during pressing was the general trend of decreasing bond strength with increasing pressing pressure. This resulted primarily from adhesive squeeze out (the accumulation of adhesive on the wood surface during a pressing process, thus starving the bonding surface). Also noted were significant quantities of water expelled from the specimens when pressure was applied in excess of 345 kPa (50 lb/in.^{2}). The majority of the failures were in the bondline, with the exception of some earlywood failure in the 345- to 517-kPa (50- and 75-lb/in.^{2}) specimens. Little wood failure occurred in the samples, especially at the higher pressures. Spreading was limited in the small specimens because of foaming of the adhesive in contact with water. Based on these preliminary results and observations, we decided to use 345-kPa (50-lb/in.^{2}) side pressure and 60-minute press time for panel production. Panel production data are summarized in Table 3.

Once pressing time and pressure were found, panel production began. We removed the flitches from cold storage and edged the flitches to remove wane just before edge gluing. This edging also created a fresh surface for applying the adhesive that was expected to enhance the glue bond. The edged surface was inspected for the presence of blue stain. Heavy plastic sheets were used during the setup to allow easy entry and removal of the panels from the press and prevent inadvertent sticking of the panels to the mechanical screw press. Using a squeeze bottle and two rubber rollers (for quicker application to reduce assembly time), 32 g of adhesive was applied to one edged surface of the board, with the end result of just one glueline per bonding surface. The first panel used 10 boards (i.e., nine gluelines). For all panels, we alternated the pith direction of each board to help reduce potential warp. The uncured panel of boards of various widths was placed into the press, and side and top pressure were applied. Foaming action was expected to occur when using PUR glue because of the large amount of water present in the boards. After the panels were pressed for 60 minutes, the plastic was used to remove and then seal the panels for cold storage. Panels were placed in cold storage until all 10 panels were completed, and then all 10 panels were kiln dried simultaneously according to the kiln schedule shown in Table 4.

All 10 panels were loaded into an Irvington Moore research kiln (USNR [formerly Irvington Moore], Jacksonville, Florida) under the following conditions: The material was top loaded to 9.6 kPa (200 lb/ft^2) with concrete castings, average fan speed was maintained at 152 to 168 m/min (500 to 550 ft/min), and kiln samples were used to monitor daily moisture loss (Simpson 1991). Top loading helps reduce warp of ponderosa pine during kiln drying (Arganbright et al. 1978, Simpson and Green 2001).

After kiln drying, the panels were ripped into 95-mm-wide (3¾-in.-wide) boards and measured for crook, bow, twist, and MC (pin-type meter in two places per board). For each 2 by 4, we noted whether the board had a glueline. The nominal 2 by 4s were planed to 38 by 89 mm (1½ by 3½ in.), and the EGAR boards were stickered for equalizing in a 12 percent MC room with no restraint. After boards were

Table 2.—Glueline test results from preliminary EGAR test samples.[a]

Side pressure (lb/in.^{2})	Shear parallel to grain (lb/in.^{2}) at two pressing times	
	30 min	60 min
50	1,250	1,537
75	1,142	—
100	694	—
125	167	—
150	742	—

[a] 1 lb/in.^{2} = 6.89 kPa.

Table 3.—Panel production data.

Liquid one-component polyurethane adhesive	Prefere 6000 (Dynea ASA)
Average moisture content of boards	153% ± 34%
Pith direction of boards before assembly	Alternating
Glue spread rate	250 g/m^2 (roughly 32 g/board)
Average assembly time per panel	13.1 min
Applied top press pressure	172 kPa (25 lb/in.^{2})
Applied side press pressure	345 kPa (50 lb/in.^{2})
Pressing time	60 min

Table 4.—Kiln schedule used to dry ponderosa pine 2 by 4s.[a]

Step	Time (h)	Dry-bulb temperature (°F)[b]	Wet-bulb temperature (°F)[b]
1	0–24	160	140
2	24–42	165	140
3	42–88	170	140
4	88–140	170	160

[a] Equalized and conditioned as necessary.
[b] To convert degrees Fahrenheit to degrees Celsius, subtract 32, multiply by 5, and divide by 9.

Table 5.—Warp limits for 8-ft-long 2 by 4s under Structural Light Framing grading rules (WWPA 2005).

Grade	Warp (in.)[a]		
	Crook	Bow	Twist
Select structural	0.250	0.50	0.375
No. 1	0.250	0.50	0.375
No. 2	0.375	0.75	0.500
No. 3	0.500	1.00	0.750
Economy	—	—	—

[a] 1 in. = 25.4 mm.

equalized to 12 percent MC, the EGAR boards were again measured for crook, bow, twist, and MC (pin-type meter in two places per board). These warp values were compared with values found in a previous study done on conventionally sawn ponderosa pine 2 by 4s from the same material source (X. Wang and W. T. Simpson, FPL, unpublished results, 2008). One difference noted was that the EGAR material had higher and greater variability in MC. The logs used for the EGAR process were stored under water spray, but logs for the conventionally sawn 2 by 4s were not. Warp was judged in two ways: by actual measurements and by whether warp limits in the Western Wood Products Association (WWPA) Structural Light Framing grading rules (WWPA 2005) were met or exceeded (Table 5). A statistical analysis (Wilcoxon signed-rank test) was completed for crook, bow, and twist between the two groups at two different times (before planing and after planing and equalizing to 12% MC).

Gluelines were inspected on the EGAR boards before planing and after planing and equilibrating. Before planing, the boards were inspected visually for splits at the glueline. After planing and equilibrating, the glueline of each board was inspected, and the level of glueline separation was noted based on the following criteria.

1. Minimal separation occurs at the end of the specimen.
2. Minimal separation occurs at the center portion of the specimen.
3. Moderate separation occurs at the end of the specimen.
4. Moderate separation occurs at the center portion of the specimen.
5. Major separation occurs at the end of the specimen.
6. Major separation occurs at the center portion of the specimen.

The three categories of separation (minimal, moderate, and major) were described as follows. A minimal separation is a separation of less than 1.27 mm (0.050 in.) over a span of less than 102 mm (4.0 in.). A moderate separation is when one or more of the following occur: a separation of less than 1.27 mm (0.050 in.) over a span of 102 to 203 mm (4.0 to 8.0 in.) or a separation of 1.27 to 3.18 mm (0.050 to 0.125 in.) over a span of less than 203 mm (8.0 in.). A major separation is when one or more of the following occur: a separation of 1.27 to 3.18 mm (0.050 to 0.125 in.) over a span of greater than 203 mm (8.0 in.) or a separation greater than 3.18 mm (0.125 in.) over any span of the bondline.

Physical inspection of each board was conducted for other potential lumber-degrading problems. Knot locations were noted if near the gluing surface. Planar damage was also noted, because a malfunctioning planar damaged several boards.

Table 6.—Average warp values for EGAR and conventional 2 by 4s (preplaning).

	Warp (in.)[a]			MC (%)
	Crook	Bow	Twist	
Conventional[b]	0.472	0.600	0.098	13.9
EGAR[c]	0.418	0.435	0.003	16.1
P value	0.321	<0.001	<0.001	

[a] 1 in. = 25.4 mm.
[b] $n = 260$.
[c] $n = 118$.

Results and Discussion

This modified EGAR process was designed to edge glue green dimensional lumber into panels and then rip the dried panels into desired widths to help reduce warp. The same kiln schedule shown in Table 4 was used for both the green panels and the conventionally sawn 2 by 4s. No blue stain was noted on the edged surface after removing the wane just before gluing. Of the 118 boards, 39 did not have a glueline, because some flitches were wider than 102 mm (4 in.) and the panels were ripped to maximize yield.

Average warp values are shown in Table 6 for the 2 by 4s ripped from the 10 EGAR panels before planing. Average warp values are shown in Table 7 for the 2 by 4s ripped from the 10 EGAR panels after planing and equilibrating to 12 percent MC.

Before planing, the EGAR boards showed statistically significant reduction in bow and twist and no statistical difference in crook when compared with conventional 2 by 4s. The MC for all 2 by 4s tested was 16.1 percent, with a range of 10.5 to 26.5 percent. The higher MC values tended to be found in the center boards that were ripped from the dried panels. After planing and equilibrating to 12 percent MC, the EGAR boards showed statistically significant increases in crook and bow but maintained the statistically significant reduction in twist when compared with conventional 2 by 4s. Also, no significant difference was found for crook, bow, and twist between boards including or not including a glueline. Boards without a glueline tended to be material cut from larger logs. Unexpectedly, all warp values for the EGAR boards increased when planed and equilibrated to 12 percent MC; this result was opposite that of the conventionally sawn 2 by 4s, which indicated warp reduction would occur. However, this increase in warp followed the resultant splitting rate found between the two MC conditions (16.1% and 12%).

Twelve of 118 preplaned EGAR boards showed splits at the glueline, for a split rate of 10.2 percent. Most of these splits showed up in the panels after kiln drying to 16.1 percent MC (Fig. 3). Panels show signs of adhesive squeeze-

Table 7.—Average warp values for EGAR and conventional 2 by 4s (after planing and equilibrating).

	Warp (in.)[a]			MC (%)
	Crook	Bow	Twist	
Conventional[b]	0.407	0.395	0.063	12.0
EGAR[c]	0.727	0.653	0.004	12.0
P value	<0.001	<0.001	<0.001	—

[a] 1 in. = 25.4 mm.
[b] $n = 260$.
[c] $n = 117$ for crook and bow and 116 for twist.

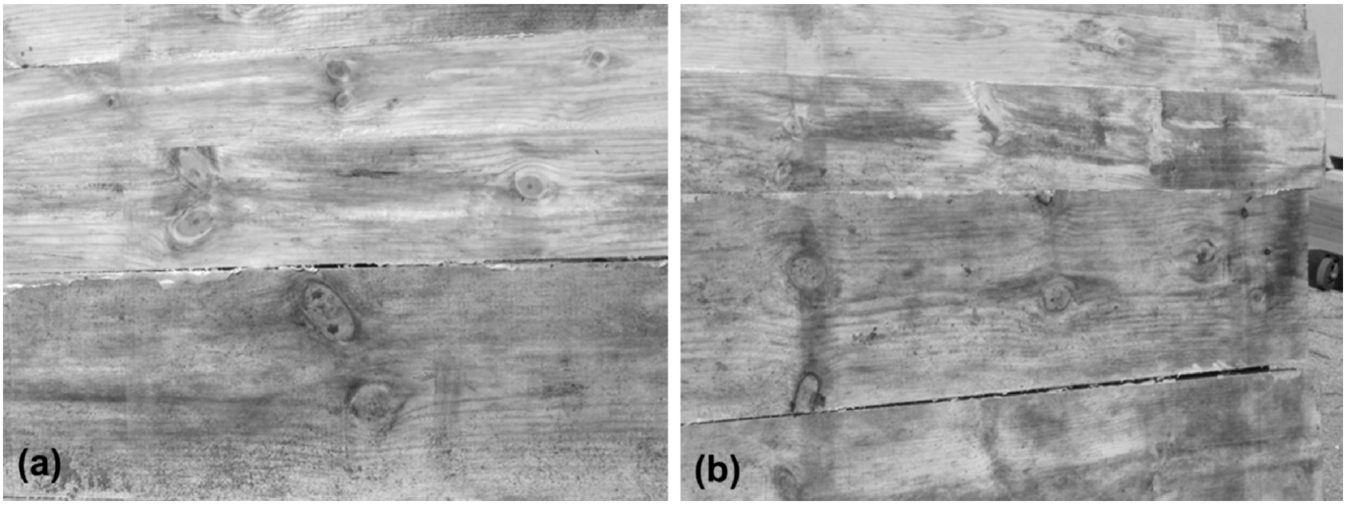

Figure 3.—Glueline failure in panels after kiln drying (major separation).

out. Greater amounts of squeeze-out tended to be found near bondline failures. The splits shown here were glue bondline failures, not wood failures, indicating a problem in the gluing process.

After planing and equilibrating the EGAR boards, a detailed visual inspection of the glueline was conducted that showed a high number of bondline failures. Glueline separations were found in 19 (minimal separation), 17 (moderate separation), and 15 (maximum separation) boards at either the end, the center, or both. Minimal, moderate, and maximum glueline separation rates of 16.1, 14.4, and 12.7 percent, respectively, were calculated. These results showed that the planing and equilibrating process caused higher glueline separations, with an overall glueline separation rate of 43.2 percent. This value was four times the preplaning overall separation rate of 10.2 percent and showed splitting significantly increased after planing and equilibrating to 12 percent MC.

During planing of the rough 2 by 4s, a malfunctioning planar damaged 20 boards. Fifteen of these 20 boards had a glueline, and all but 1 of the 15 had bondline failures of some degree. Therefore, planar-damaged boards tended to split more on average and also showed an increase in warp because of splitting compared with 2 by 4s that were not damaged by the planar. Knot locations near the bondline when the planar was malfunctioning also tended to increase bondline failures.

The results were also analyzed in terms of what boards failed to meet the maximum warp allowed for the Structural Light Framing grades shown in Table 5 for two conditions: (1) after drying and before planing and (2) after planing and equilibrating. Results showed the following grade distribution for after drying and before planing: 24 percent No. 1 or Better, 28 percent No. 2, 17 percent No. 3, and 31 percent Economy. Results also showed the following grade distribution for after planing and equilibrating: 8.5 percent No. 1 or Better, 14 percent No. 2, 7.5 percent No. 3, and 69 percent Economy. Warping of the lumber significantly increased after planing and equilibrating to 12 percent MC.

Conclusions

The initial high MC (153%) and large variability of MC in the wet and dried panels may be the causes of loss of lumber quality occurring after planing and equilibrating to 12 percent MC. This decrease was not expected, because ponderosa pine dries well and is moderately low in shrinkage. The quality of lumber decrease resulted from an increase in warping and the large number of splits in the ripped 2 by 4s caused by bondline failures. The high amount of bondline failure after planing and equalizing indicates this process is not feasible as tested.

Several factors played a role in this degradation. First, the high initial MC levels caused bondline failures in the glueline for some panels, distorting the final results. In the present study, squeeze-out occurred because the dimensional lumber was too wet for good bonding (it contained too much free water). This excessive water forced out the adhesive, thus preventing adhesive penetration into the wood cells when side pressure was applied during panel production. Large amounts of squeeze-out may result in a split in the glueline caused by a poor glue bond because of insufficient adhesive (River and Okkonen 1991). Second, the 345-kPa (50-lb/in.^{2}) side pressure used during panel production for the high initial MC may have contributed to excessive squeeze-out (starved glueline). The occurrence of squeeze-out is typically not a problem for dry edge-glued material, because the dryness of the material does not prevent adhesive penetration. Third, this initial condition of a high initial MC also likely was intensified by the variability of MC in panels during the drying process.

The large range of MC variability found in the kiln-dried panels indicated that panels must be equalized longer; less variability would minimize bondline separation failures that cause splitting. These separation problems tended to increase as the 2 by 4s equalized to 12 percent MC, because some 2 by 4s may have had significant MC differences across the glueline. This conclusion is supported because the edged flitches used for gluing had large ranges of MC ($\pm$34%). Finally, the rough mechanical agitation during the planing process by a malfunctioning planar probably caused greater bondline failure than expected, further distorting the results.

Moisture content was too high and too variable for the individual boards, both for green gluing and after ripping panels into EGAR boards. We identified several ways to lower the MC and reduce the variability in initial MC to prevent squeeze-out and adverse MC profiles:

- Perform several preliminary tests on small specimens to find the optimum MC for green gluing to produce greatest bond strength for a particular adhesive.
- Conduct calibration runs to determine the MC relationship between the edge and center parts of the panels during the kiln-drying process.
- Kiln dry the panels to roughly 15 percent instead of 16 percent MC, and equalize the entire panel longer to reduce MC variability to less than 2 percent if practical.
- Track individual logs, MC, and gluelines for each board within a panel to identify potential bonding issues.

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