

Borate Treatment of CLT Panels Using Vacuum: A Proof of Concept

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Abstract

Cross-laminated timber (CLT) is an increasingly popular wood-based alternative for large building applications. CLT panels are typically not treated due in part to a perceived lack of efficient and effective methods for treating large panels and a lack of information on what effect treatment processes may have on the panels' mechanical properties. We propose that treating CLT panels with borate solution, applied under vacuum in flexible bags, could provide a practical and effective option for providing preservative protection for interior applications. Samples were cut from commercially produced CLT panels and treated with borate solution using vacuum. The samples were then evaluated for preservative retention, swelling, and degradation of mechanical properties. Initial treatments resulted in a wide range of preservative retentions and property effects among the products tested. In subsequent adjustments, the treatment parameters were changed to provide consistent and sufficient retention among the products. The vacuum treatment method effectively penetrated cracks in the lumber and the bond lines (adhesive joint between adjacent lamellae). Swelling and effects on mechanical properties were minimal in the adjusted samples. In addition to these samples that were treated in a rigid pressure vessel, a larger sample was successfully treated in a flexible plastic bag. Data from this study support the concept that vacuum treatment of CLT panels with borate can provide sufficient levels of preservative retention, can be adjusted to the material being treated, and has minimal effects on mechanical properties.

Cross-laminated timber (CLT) is emerging as an environmentally friendly alternative to concrete and steel in large buildings. CLT is among the mass timber family of products (with glulam, large timbers, etc.) that can provide flexibility in construction, allows for rapid construction, has good fire and seismic performance, and reduces holistic environmental impact. As with all building materials, CLT is subject to wetting during construction and when in service, which increases susceptibility to biological degradation. However, currently most CLT are not treated with preservatives and the strategy for durability is restricted to keeping the wood dry. CLT treatment options are needed to address the inevitable need for supplemental protection (Wang et al. 2018, Udele et al. 2021).

Research is underway on the efficacy of common wood preservatives when applied to CLT panels (Mankowski et al. 2018, 2020, 2022). However, the best way to apply such preservatives requires investigation. Traditional vacuum pressure treatment is not possible for panels that are too large to fit in currently available commercial wood-treatment cylinders. Dip-treating mass timber elements could result in limited penetration and retention levels because of the low surface-area-to-volume ratios (Adnan et al. 2021, Bagheri et al. 2022). It may be possible to pretreat the lamellae with preservatives (Lim et al. 2020), but this would require the redrying of the lumber and the generation of treated wood waste when the lamellae are planed before bonding. Failure to

plane the treated lamellae likely would reduce bond performance (Stirling and Morris 2017). One potential option is to treat by vacuum, a method that has been used successfully for millwork treatments with light organic solvent preservatives for decades and was demonstrated in millwork with borates (Jermer and Lloyd 2000). Vacuum bags are commonly used commercially to press laminations during gluing, and to impregnate fiberglass materials with resins. Such bags are readily available in custom sizes suitable for CLT panels, are reusable, and are relatively inexpensive. However, both the potential to penetrate CLT via vacuum

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treatment using a flexible plastic bag setup and the potential effects on the panels' mechanical properties are unknown.

Given that most CLT panels will be used in interior applications and mostly protected from wetting, borates are a good potential preservative. Borates are relatively safe, odorless, colorless, and inexpensive, all while protecting against a wide range of insects and fungi (Williams 1996, Lloyd 1997). Borates are also the only preservative available that is fully diffusible, providing increasing penetration with increasing moisture (Smith and Williams 1969, Schoeman et al. 1998, de Groot et al. 2000, Cabrera and Morrell 2009).

Initially, the objectives of this study were to determine if the postfabrication vacuum treatment of commercially produced CLT can achieve useful levels of borate preservative penetration and retention, and whether that treatment affects mechanical properties. Based on the initial results (Shahan et al. 2021), the subsequent objectives were to determine if treatment parameters could be adjusted to provide similar and acceptable treatments to the variety of panels considered and to see whether treatment could be conducted in a flexible plastic bag.

Materials and Methods

We obtained commercially produced CLT panels that were composed of a variety of species and layout types. The panels evaluated in this test included Douglas-fir (*Pseudotsuga menziesii*) from the United States, spruce (*Picea* spp.) from Austria, and radiata pine (*Pinus radiata*) from Chile. The Douglas-fir and radiata pine panels were each made from three lamellae, resulting in a total thickness of approximately 102 mm. The spruce panels were made from five lamellae with a total thickness of approximately 114 mm). The production process parameters, including the adhesives used, were not reported by the manufacturers.

Sample treatment

Samples with dimensions of 229 by ~102 (panel thickness) by 305 mm were cut from the panels. Each sample was completely edge-sealed, leaving only the panel faces exposed, using a neoprene coating (1300L, 3M, St. Paul, Minnesota). The initial weight and dimensions of the samples were recorded.

Because glycol is known to help borate diffusion over time, especially in dry wood (Turner 2008), samples were vacuum-treated with disodium octaborate tetrahydrate (DOT)/glycol solution (Bora-care, Nisus Corporation) in a small, rigid pressure or vacuum vessel using the following sequence (see Table 1 for specific parameters):

1. Initial vacuum was applied to the CLT samples in an empty vessel.

2. The treating solution, at ambient laboratory temperature, was introduced using the residual vacuum (the solution completely submerged the samples, which were weighted down to prevent floating).
3. Samples were allowed to soak in the solution under ambient pressure.
4. Vessel was emptied using gravity.
5. Final vacuum was applied to remove excess treating solution.

Posttreatment, the samples were wiped with paper towels and immediately weighed and measured to assess solution uptake and dimensional change. The treating solution was sampled and analyzed for borate content by titration (AWPA 2022b). Preservative retention was calculated as the product of solution uptake and preservative concentration. Swelling was calculated using the dimensional changes in each direction.

The samples were then conditioned to weight equilibrium at 20°C and 65 percent relative humidity (~12% moisture content) prior to mechanical testing. Some of these samples were cut in half along the 305-mm axis and sprayed with curcumin reagent to indicate the presence of borate above about 0.01 percent disodium octaborate tetrahydrate (SBX) inside the sample (Smith and Williams 1969). Control samples were subsequently tested as received, with no water-treated controls.

Initial treatments applied the same parameters to all the product types (Table 1). Subsequently, parameters were adjusted, and treatments repeated in order to find combinations that resulted in preservative retentions of approximately 1.0 kg/m³ SBX (inorganic boron measured as B₂O₃ per American Wood Protection Association (AWPA) Standard U1 [AWPA 2022b]) for each product type. This target was chosen because 1 kg/m³ is known to be effective for controlling wood-destroying beetles and decay fungi as determined under testing according to EN 599 (Lloyd 1997, DIN 2014). These adjusted treatment parameters are also listed in Table 1. Note that an ambient pressure dip treatment was sufficient for the radiata pine. All retentions were “gauge retention” based on the solution uptake and the solution concentration. No attempt was made to measure penetration or retention in an assay zone, given that initial trials indicated that penetration was mostly along bond lines and cracks and, as a laminated product, the more permeable sapwood sections are dispersed throughout the CLT panels.

Mechanical testing

Treated samples conditioned to a constant moisture content for each panel type were tested in rolling shear in accordance with EN 789 and EN 16351 (European Committee for Standardization [CEN] 2004 and 2021,

Table 1.—Treatment parameters.

Species	Target solution concentration % SBX	Initial vacuum		Soak		Final vacuum	
		kPa	Min	kPa	Min	kPa	Min
Initial treatment							
All species	6	13	30	101	30	13	30
Adjusted treatment							
Spruce	6	13	30	101	5	13	30
Douglas-fir	11	13	30	101	60	13	30
Radiata pine	6	Dip treatment—no vacuum		101	1.5	Dip treatment—no vacuum	

respectively). Rolling shear was selected for evaluation in this study because it captures many aspects of the panel that could potentially be affected by the preservative treatment, including the wood and bond lines among multiple boards. Rolling shear is also an important property for the bending of CLT with short spans. In addition, the relatively small size of the sample needed to perform the tests allowed for more replicates with the same amount of material resulting in more statistically robust observations.

Each of the treated samples was cut in half to produce two mechanical testing samples with a nominal size of 95 by ~102 by 305 mm. An equal number of untreated controls cut from the same parent panels were also tested. Data from the two samples cut from each block were averaged in subsequent analysis and considered as a single replicate. The spruce samples were cut down from one side in thickness to ~102 mm with a bandsaw before testing (but after treatment) to provide correct dimensions for the test. As a result of an error in the testing process, seven of the optimized radiata pine sample were cut to 250 mm long; strength and stiffness calculations were based on the actual length when tested. Samples were placed in a specially designed and fabricated rolling shear testing rig in a uniaxial testing machine (Fig. 1). Applied load was measured with a load cell with a tolerance of less than 0.5 percent. Deformation of the panel was measured with two linear variable differential transformers (LVDTs) that were attached to opposite sides of the sample using aluminum brackets and hanger bolts. The measurements from the two LVDTs were averaged to obtain the shear deformation of the sample. Load was applied in displacement control at a rate of 2.54 mm/minute until a decisive rolling shear or glue bond failure occurred. For some

samples, the ends failed in compression prior to rolling shear failure. For these samples, thin steel plates were attached to the outer faces using adhesive and screws to better distribute the applied loads and the samples were retested. The screws were short and did not penetrate the bond line.

An example of the applied load versus shear deformation response for one of the Douglas-fir samples from the initial treatment is shown in Figure 2. The red circle indicates the maximum load obtained during testing, which was used to determine the rolling shear strength as follows:

$$f_r = \frac{F_{\max}}{lb} \quad (1)$$

where f_r is the rolling shear strength, F_{\max} is the maximum load obtained during testing, l is the length of the sample, and b is the width of the sample.

The red dashed line is a secant between 10 percent and 40 percent of F_{\max} . The slope of this line was used to determine the rolling shear stiffness as follows:

$$G_r = \frac{(F_2 - F_1) t}{(u_2 - u_1) lb} \quad (2)$$

where G_r is the rolling shear stiffness; $F_1 = 0.1 F_{\max}$; $F_2 = 0.4 F_{\max}$; u_1 and u_2 are the shear deformations at F_1 and F_2 , respectively; and t is the gage of the measurement (i.e., initial distance between hanger bolts supporting the LVDTs). Results from the two mechanical testing samples cut from the same treatment sample were averaged.

Vacuum bag treatment demonstration

One test treatment of a Douglas-fir (same stock as above) panel 762 mm by 470 mm by 102 mm thick was performed using a polyurethane bag (Vacuum Press Technologies, Brunswick, Maine; Fig. 3).

The non-edge-sealed sample was weighed and placed in the bag, a 30-minute vacuum was pulled (approx. 20 kPa), and the vacuum was used to draw in the solution (15.67% DOT) and 2.3 percent didecyl dimethyl ammonium chloride (DDAC); Boracare + Moldcare, Nisus Corporation, Rockford Tennessee). DDAC is used in combination with borate in this product because it mitigates mold fungi (Micales-Glaeser et al. 2004). As a powerful surfactant, the DDAC may also improve surface wetting by the treatment solution and thus aid penetration. This potential effect was not studied here. The panel was allowed to soak for 30 minutes (no vacuum), the solution was drained, and a final vacuum pulled for 30 minutes. After removal from the bag, the panel was reweighed and preservative retention calculated by weight gain with adjustment for solution concentration. After drying for a week under ambient conditions in the lab, the sample was cut open and the cut surfaces sprayed with borate indicator, as above.

Statistical analysis

Mean values were compared across treatments using analysis of variance (ANOVA), with a Tukey's honest significant difference (HSD) test for multiple comparisons. For the mechanical tests, data for the two samples cut from the same block were averaged and considered as a single data point in the statistical analysis.

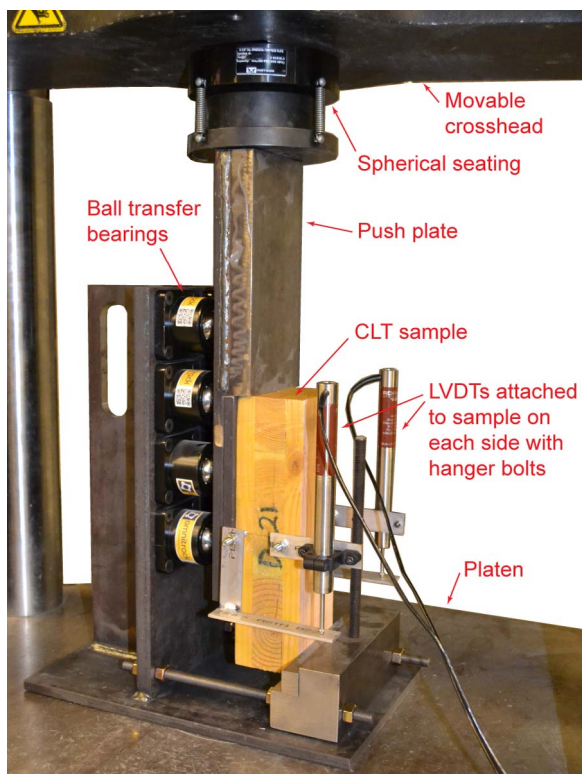


Figure 1.—Rolling shear testing rig.

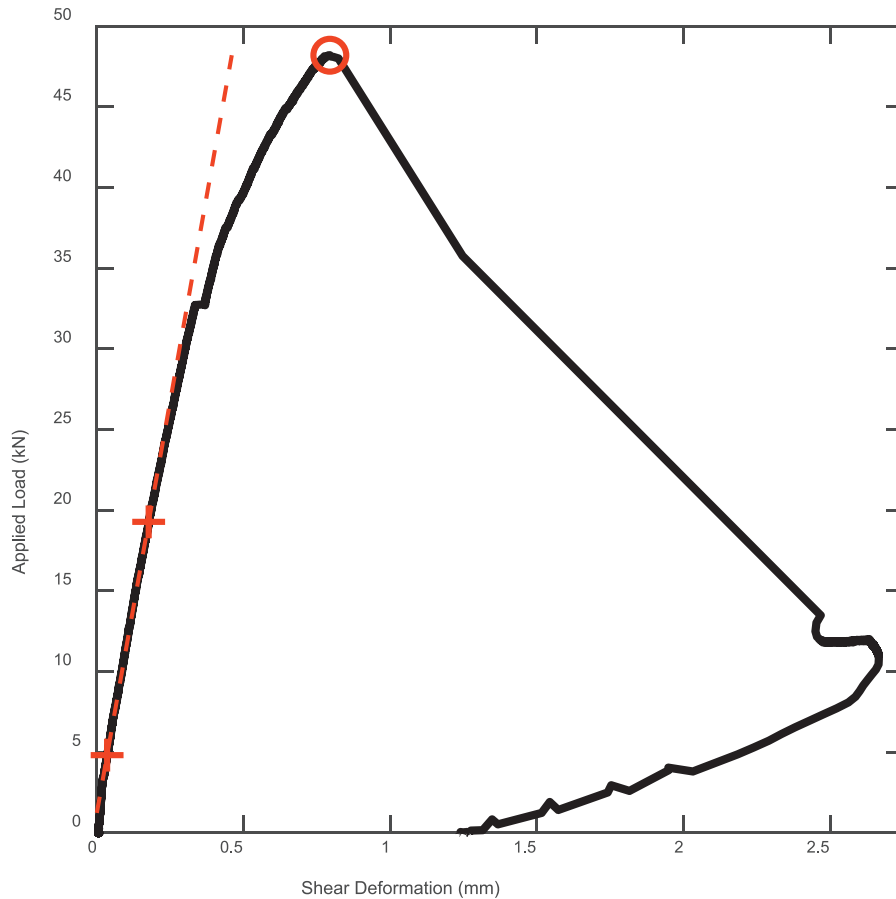


Figure 2.—Example load-deformation response from one Douglas-fir sample.

Results and Discussion

As expected, initial treatments provided highly variable retentions depending on the product type (Douglas-fir, spruce, or radiata pine; Table 2). The preservative solution appeared to preferentially penetrate along pre-existing

cracks in the wood and along the bond-lines, particularly in the panels made with refractory species (Douglas-fir and spruce; Fig. 4). The distributions of borate shown in Figure 4 are following treatment and without any diffusion storage or subsequent wetting. If these treated samples were

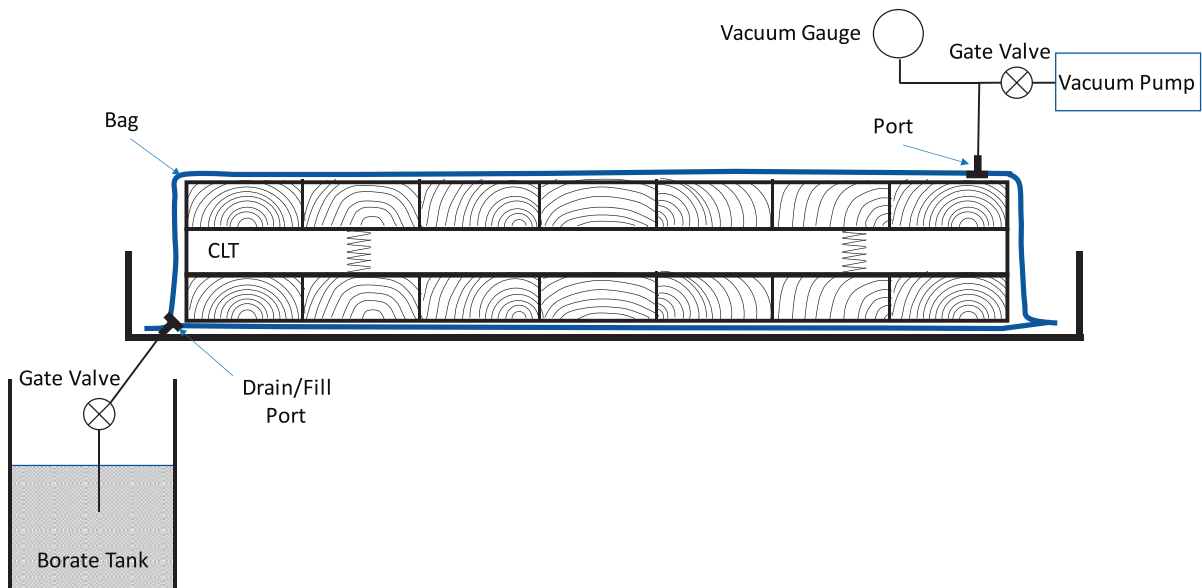


Figure 3.—Schematic of flexible bag setup for vacuum treatment of CLT panels.

Table 2.—Summary of preservative retention, swelling, and mechanical properties.

Species	Treatment	N	SBX retention (kg/m ³) ^{a,b}	Thickness swelling (%) ^{a,b}	Rolling shear strength (MPa) ^{a,b}	Rolling shear stiffness (MPa) ^{a,b}
Douglas-fir	None	10	—	—	1.70 ± 0.11 A	195 ± 32 AB
	Initial	10	0.25 ± 0.04 A	0.40 ± 0.49 A	1.59 ± 0.13 A	154 ± 20 B
	Adjusted	10	1.04 ± 0.19 B	0.80 ± 0.61 B	1.68 ± 0.13 A	246 ± 64 A
Spruce	None	10	—	—	1.28 ± 0.11 AB	172 ± 23 A
	Initial	10	2.48 ± 1.04 A	0.93 ± 0.59 A	1.10 ± 0.07 B	131 ± 33 AB
	Adjusted	18 ^c	1.12 ± 0.19 B	1.63 ± 0.65 B	1.29 ± 0.08 A	124 ± 18 B
Radiata pine	None	10	—	—	2.06 ± 0.23A	294 ± 59A
	Initial	10	9.11 ± 2.09 A	2.77 ± 1.24 A	1.18 ± 0.38 B	149 ± 51 B
	Adjusted	6 ^d	1.80 ± 1.03 B	0.51 ± 0.95 B	2.68 ± 0.26 A	188 ± 53 AB

^a Mean values shown with 90 percent confidence intervals.

^b Values within a species and measurement group with a different capital letter are significantly different ($P < 0.05$, ANOVA with Tukey’s HSD test for multiple comparisons).

^c Extra samples of this treatment were tested accidentally.

^d Samples of this treatment were limited as a result of limited supply of CLT panels.

exposed to increased moisture, the yellow (unprotected) areas could be expected to turn red (protected) with time (Cabrera and Morrell 2009), as long as adequate overall retention was achieved.

There is currently no standard for preservative treatment of CLT after it has been fabricated; however, the New Zealand (where subterranean termites do not occur) Standard NZS3640 (New Zealand Standard 3602 2003) for lumber is approximately 1.0 kg/m³ SBX, as is the biological reference value (similar to a toxic threshold for various fungi; Lloyd 1997), suggesting that it might be suitable for CLT to prevent beetles, drywood termites, and fungi. Interestingly this retention may also mitigate subterranean termite activity over time (Jones 1991), although it does not prevent damage in small test specimens according to EN 599 (DIN 2014). The AWWA standard for lumber for interior applications (UC2 [AWPA 2022b]) requires much higher retentions (2.7 or 4.5 kg/m³ SBX), but this is intended to protect against subterranean termites (non-Formosan and Formosan, respectively), in addition to

decay and other insects. For this study, we targeted the lower biological reference value and the New Zealand Standard, based on the assumptions that CLT buildings are constructed above-grade and that separate subterranean termite control measures will be implemented according to building codes (e.g., soil termiticides). By this reasoning, the main threat to CLT will be nonsubterranean insects and fungi, for which 1.0 kg/m³ SBX will provide effective control.

With reference to the 1.0 kg/m³ target, the initial treatments undertreated the (mostly heartwood) Douglas-fir while overtreating the spruce and radiata pine samples. The adjusted treatments came close to achieving the target, across all the species. This potential for adjustment is noteworthy, given that Douglas-fir and spruce are refractory species, while radiata pine in this test was mostly highly permeable sapwood.

Dimensional changes in the length and width were negligible, as expected for a cross-laminated product in which the longitudinally oriented lamellae restrain swelling in that direction. Thickness swelling was measurable and mostly positively correlated to the amount of preservative retained (Table 2). The apparent increase in spruce swelling in the optimized samples (with lower retention) is counterintuitive and we believe may be an artifact of a different person making the measurements of those samples. Standard tolerances for thickness variation of CLT panels are 2 percent (FPIInnovations 2019); the average thickness swell of the samples receiving optimized treatments was below that level, suggesting that the thickness swelling observed here would be acceptable in practice. Delamination was not measured but appeared to be minimal across all samples.

The rolling shear test typically resulted in failure near one or both bond lines, usually crossing over the middle lamella (Fig. 5). Initial treatments that resulted in overtreatment led in some cases to dramatic reductions in mechanical properties (e.g., radiata pine rolling shear strength; Table 2). In contrast, the optimized treatments did not lower the strength values of any species tested. Reductions in rolling shear strength, associated with very high treatment (water-based treatment) retentions, may result from the wetted wood swelling, and the differential swelling across- and along-the grain causing stresses on the bond lines. Stiffness values were less consistent in response to treatment

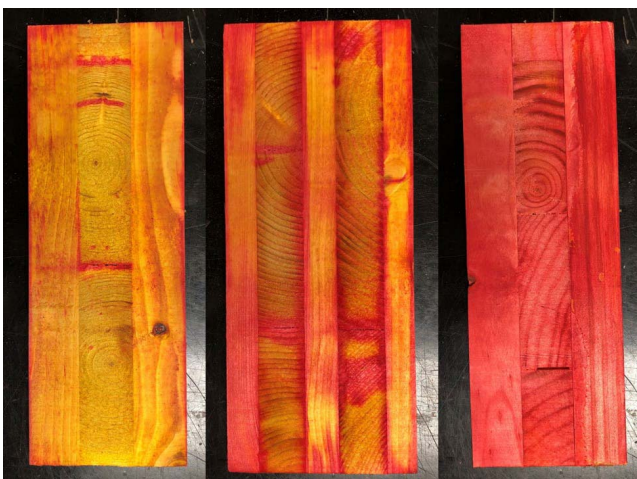


Figure 4.—Typical penetration of borate into treated CLT samples (initial treatment). Red color indicates the presence of boron above approximately 0.8 kg/m³ SBX (AWPA 2022a). L–R: Douglas-fir, spruce, and radiata pine. All samples were edge-sealed prior to treatment and cut open after treatment. The cut faces are shown.



Figure 5.—Typical failure patterns in rolling shear test. From left, radiata pine, Douglas-fir, and spruce. Each of these samples was treated but the controls did not look different in terms of failure pattern. The holes are where the linear variable differential transformers (LVDT) brackets were located.

retention levels and poorly correlated to strength values ($R^2 = 0.31$, simple linear regression). Guidance in EN 789 (CEN 2004) notes that the variability of rolling shear stiffness obtained from planar shear testing is high.

Overall, these results suggest that meaningful retention levels of borate treatment can be achieved using vacuum, that the process can be adjusted to the species being treated, and that the effects on the mechanical properties can be minimized.

Vacuum bag treatment demonstration

The vacuum bag trial was successful. It provided high retention (1.52 kg/m^3 SBX) and good penetration (as indicated by red color between interior lamellae and in internal checks; Fig. 6) in a panel made with a refractory species (Douglas-fir) in which the lamellae were edge-glued in addition to being face-glued. This result suggests that vacuum treatment of full-size panels in plastic bags is practically possible, even in less permeable panels. In our trial, some of the treatment liquid entered the vacuum port, which was close to the surface of the panel. Thus, relocating the vacuum port and/or installing a vacuum trap may be



Figure 6.—CLT panel that was treated in a vacuum bag. A corner section was cut and removed from the panel after treatment and the interior sprayed with boron indicator. Red color indicates the presence of boron.

necessary to prevent problems with treating solution entering the vacuum pump.

Purpose-built, rigid vacuum treatment tanks may be more practical in commercial settings, but flexible bags may provide useful test chambers for the development of treating processes with reasonably large samples.

Conclusions

An initial test of double-vacuum borate treatment of CLT samples achieved a wide range of solution uptakes. Subsequent adjustment of treatment parameters yielded samples with consistent levels of preservative retention, with minimal effect on dimensions or mechanical properties. These data suggest that vacuum treatment of CLT panels is practical and adjustable, while providing effective levels of protection against degradation and maintaining panel integrity.

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Conflict of Interest Statement

The authors have no competing interests to declare that are relevant to the content of this article.

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