Effects of various fire-retardants on plate shear and five-point flexural shear properties of plywood

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Abstract

The influence of four fire-retardant systems on the planar (rolling) shear properties of structural hardwood plywood is evaluated using two possible ASTM D2718 test methodologies: the plate-shear method and the five-point flexural shear method. Knowing the planar shear properties and the potential of the various fire-retardant systems to affect properties is critical in engineering design. The various fire-retardant systems were found to reduce plate shear properties for plywood more than flexural shear properties depending on the fire-retardant chemical and its chemical loading level. We also found the inherent variability of plate shear data was greater than it was for flexural shear data. We conclude that there exist practically important differences between the results derived in the two planar (rolling) shear test methods for fire-retardant treated plywood.

To ensure the acceptance of fire-retardant treated wood-based composites as engineering materials, their behavior over a range of loading regimes must be fully characterized and understood. Accurate information on the planar (rolling) shear characteristics of structural plywood panels is essential for the rigorous design of structural systems that use glued wood-based panels, such as box beams, folded plate roofs, and stressed skin panels. Each of these uses may also sometimes require enhanced fire-resistance. Thus, knowing the effects of the likely fire-retardant treatments on planar shear can also be critical. Planar shear also may govern the design at low span-depth ratios encountered in floors subjected to high concentrated loads, concrete forms at high pouring pressures, or bulk storage structures.

Soltis and Rammer (1994) recommended the five-point flexural shear test procedure as a standard test method to determine the shear strength of structural lumber. Bateman et al. (1990) found similar results when evaluating the planar shear stress of engineered wood composites using plate-shear specimens and five-point flexural shear specimens. Bradtmueller et al. (1997) reported that the five-point flexural shear test was an effective and efficient way of determining mechanical properties of structural composite lumber. Interlaminar shear fatigue behavior is one important property that needs to be understood for high-performance composites in which the matrix contribution to the load-carrying capability is significant (Cai et al. 1996). Kim and Drahan (1995) reported that five-point loading provides the advantage of a specimen having both high shear stresses and almost zero bending stresses over a substantial region of the specimen. This provides the possibility of using the five-point test configuration to measure interlaminar shear strength of unidirectional composites. In addition to the shear dominated stress distributions, the five-point flexural shear fixture has several advantages against other test methods, such as simple fabrication of the specimen and an economical testing jig.

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Bradtmueller et al. (1997) described a common problem for design of wood structures. They tend "... to be governed by some limiting deflection criteria. Such deflections are functions of both the mechanical properties and the geometry of the material in addition to the layout of the structure itself. Consider roof and floor sheathing, for example, where deflections are normally attributed to flexural stiffness only. In certain applications, however, a significant portion of the deflection of wood panels used for sheathing can be caused by shear deformation. Current design methods neglect shear deflections induced by lateral loading in roof and floor sheathing, which is justified for the following two reasons:

1) The support system (i.e., joists, rafters, or purlings) would have to be spaced fairly close together for shear to be a large percentage of the total deflection; consequently, the overall deflection of the sheathing would most likely be insignificant and either shear or bending strength would be the governing design criterion;
2) Typical methods of determining flexural stiffness do not separate out a shear component; thus subsequent use of flexural stiffness in deflection analysis partially compensates for shear deflection."

Hunt et al. (1993) investigated longitudinal shear strength of laminated veneer lumber via five-point flexural shear test and compared with the ASTM D143 (1983) shear block method and a short-beam test. They found that for laminated veneer lumber the five-point test yielded the most consistent results with the least variability of the three test methods. Bradtmueller et al. (1997) determined mechanical properties of OSB via five-point flexural shear test. Xu et al. (1998) investigated the rolling shear strength of Lauan and Douglas-fir plywoods using a flexural vibration test. They concluded that the rolling shear strength was related not only to the shear property of the core but the flexural stiffness of two faces when the deformation of out-of-plane plywood was not restrained.

Fire-retardant-treated (FRT) plywood is used widely in many types of structures and building systems as structural components, such as roof sheathing and engineered box-beams. Winandy and River (1986) found that specimens treated with waterborne chemicals had significantly lower bondline shear strength than oil-borne-treated specimens. Most fire-retardant treatments for wood and plywood are waterborne systems. Many fire-retardants are known to cause strength reductions (Winandy 2001). These strength losses are usually attributed to a combination of interfering with adhesive-resin cure, resin penetration, and the potential for accelerated thermal decomposition of the wood material during high-temperature processing in panel manufacturing.

Bergin (1963), Raknes (1963), and Schaeffer et al. (1966) each studied the gluing of fire-retardant-treated wood. They investigated the effect on gluability of wood treated with ammonium-salt fire-retardants and with ammonium salts in combination with boric acid. Bergin (1963) and Raknes (1963) specifically reported that, on the basis of horizontal shear strength tests, gluebonds in fire-retardant treated wood were not as strong as glue bonds in matching untreated wood specimens glued under similar conditions.

Winandy et al. (1988) reported rolling shear properties for two species of plywood treated with several fire-retardant-treated (FRT) systems that are no longer marketed in North America. They found that rolling shear was negatively affected for Douglas-fir plywood by the fire-retardant (FR) treatments evaluated, but that it was not affected for Aspen plywood.

Table 1. — Typical composition of borax, boric acid, monoammonium phosphate and diammonium phosphate.

Chemical	Component	Amount
		(%)
Borax	B_2O_3	36.4
	Na_2O	16.4
	Purity	99.9
Boric acid	B_2O_3	56.2
	Purity	99.9
Monoammonium phosphate	P_2O_5	61.0
	N	12.0
	Purity	99.9
Diammonium phosphate	P_2O_5	53.0
	NH_3	25.0
	N	20.8
	Purity	99.9

To our knowledge, there is no information about effect of the current generation of fire-retardant chemicals on rolling shear property of FRT plywood. The objective of this study was to investigate the influence of fire-retardants on plate-shear strength and five-point flexural shear strength. In this study, a group of matched FRT-treated plywood specimens were tested using both the ASTM D2718 (2003) plate (rolling) shear method and the five-point flexural shear method. Our secondary objective was to identify if chemical treatments would validate the assumed equality between the two ASTM D2718 methodologies.

Material and methods

Plywood manufacture

Commercially manufactured rotary cut veneer of Akaba (*Tetraberlinia bifoliolata*) logs were used to make hardwood structural plywood under laboratory conditions. Akaba, naturally grown in West Africa, is used commercially in plywood manufacture in Europe. Air-dry density of Akaba wood averages 0.55 g/cm^3, and its wood is convenient for rotary peeling and plywood manufacturing. Each veneer sheet was 490 mm by 490 mm by 2.20 mm thick. Veneer specimens were kept in a conditioning chamber until they equilibrated at 7 percent moisture content (MC).

In the next step, the individual veneer specimens were placed in plexiglass boxes and laid horizontally 4 cm apart from each other in 3 percent or 6 percent aqueous solutions of borax ($Na_2B_4O_7 \cdot 10H_2O$) or boric acid (H_3BO_3), or in 3 percent or 11 percent aqueous solutions of monoammonium phosphate (MAP) ($NH_4H_2PO_4$) or diammonium phosphate (DAP) ($(NH_4)_2HPO_4$). The chemical compositions of borax, boric acid, MAP, and DAP are shown in **Table 1**. The temperature of the various treating solutions was 55 to 60°C during the 3-hour soak-treatment process. Individual veneers were weighed before and after the dip-treatment process and chemical retention was calculated. Ayrilmis (2006) found that plywood specimens treated with these four fire-retardants and at these loading levels achieved adequate fire-resistance based on defined ignition time and height of burning flame in DIN 4102–1 (1998).

Each treated veneer specimen was then reconditioned at 20°C and 65 percent relative humidity to 7 percent MC before plywood panels were manufactured. An exterior phenol-formaldehyde resin with 47 percent solid content was applied to the veneers at a rate of 200 g/cm^2. Those veneers were then laid-up into a plywood billet and hot pressed using a pressure of 1.2 N/mm^2 at a temperature of 130°C for 12 minutes in a computer controlled laboratory press. A total of thirty-six (36), 5-ply, 10- to11-mm-thick experimental panels, four for each treatment, were manufactured.

Plywood panels were conditioned at a temperature of 20°C and 65 percent relative humidity for 3 weeks before being shipped to USDA Forest Products Laboratory, Madison, Wisconsin for shear testing (ASTM D2718, 2003). We evaluated both shear test modes (plate-shear and 5-point flexure). The D2718 methods were followed except that in Method A (plate- shear), we employed a 100-mm-wide by 300-mm-long planar plate-shear fixture. This modification was within the size limitations allowed in the standard, which requires that the width and length of the plate-shear specimens be at least 4x and 12x the plywood thickness, respectively.

Shear testing

Test method A — Planar shear loaded by plates. — In this method, the test specimens having the form of a rectangular flat plate were bonded between flat-rectangular steel plates beveled that are loaded in compression at a uniform rate while a suitable LVDT-type gage measures slip between the plates due to longitudinal shear deformation through the thickness of the plywood specimen. Because plywood is a multilaminate system with each ply oriented perpendicular to the next, the shear strain is not uniform and this load configuration is often termed "rolling shear" because the off-axis wood cells in the alternating laminates tend to roll over rather than experience true shear. The thickness, width, and length of the plywood specimens were 10 mm by 100 mm by 290 mm, respectively. Specimens were tested at an average 14 percent MC. Shear strength is computed from maximum load as follows:

$$f_v = P_p/(L \cdot W) \qquad [1]$$

where f_v is the shear strength (N/mm^2), P_p is the maximum or proportional limit load (N), W is the specimen width (mm), and L is the specimen length (mm).

Effective modulus of rigidity for the specimens acting as a unit was determined from a plot load vs. slip as follows:

$$G = (P_p/\Delta)[t/(L \cdot W)] \qquad [2]$$

where G is the apparent modulus of rigidity for the entire specimen (N/mm^2), t is the specimen thickness (mm), and P_p/Δ is the slope of the force-deformation curve below proportional limit load (N/mm).

Modulus of rigidity determined from Test Method A is a composite estimate of rigidity throughout the entire thickness of the non-homogenous plywood specimen.

Test Method B — Planar shear induced by five-point flexural shear. — In this test, a symmetric two-span continuous beam is equally loaded at each midspan as depicted in **Figure 1**. This test method determines planar shear strength consistent with panel applications under transverse loading. The test specimens were rectangular in cross section. The thickness, width, and length of the specimens were 10 mm by 100 mm by 240 mm, respectively. Load was applied at a constant rate in order to reach ultimate load within a 4- to 6-minute time frame. Specimens were tested at 14 percent average MC.

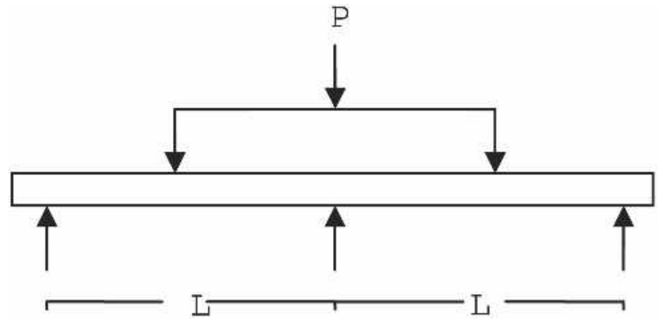

Figure 1. — Shear and moment diagrams for the five-point flexural shear (rolling) test.

When specimens failed in interlaminar shear, longitudinal five-point flexural shear strength was calculated as follows:

$$f_v = (33 \cdot P)/(64 \cdot b \cdot d) \qquad [3]$$

where f_v is the induced shear strength (N/mm^2) in five-point bending test, P is the ultimate test load (N), b is the specimen width (mm), and d is the specimen thickness (mm). Analysis of variance (ANOVA) and Duncan's multiple-comparison tests were conducted to compare and evaluate differences among the average properties of the treated specimens for each test method.

Results

Average retention values of the chemicals in plywoods are given in **Table 2**. Air-dry density values of the specimens ranged between 590 and 600 kg/m^3. Specimens treated with borax, boric acid, MAP, and DAP at all concentration levels showed no differences in density when compared to control specimens. Results for modulus of rigidity and planar shear strength in the plate-shear tests and five-point flexural shear strength from those tests are given in **Table 2**. Statistical analysis found some significant differences ($p < 0.05$) between some group means for the five-point flexural shear strength values. Significant differences between groups were determined individually for five-point flexural shear strength tests by Duncan's multiple-comparison tests (**Table 2**). The ANOVA found no significant difference between groups for plate-shear strength or Modulus of Rigidity (G) values.

Planar (rolling) shear strength loaded by plates

Plate-shear strength and effective modulus of rigidity results of all treated specimens were not significantly different as compared to untreated specimens according to results from the ANOVA. However, it is critical to note that the variability of plate-shear values ranged from 18 to 47 percent of each group's respective mean value (**Table 2**). The average plate-shear strength values of all treated specimens generally ranged from 21 to 47 percent lower than the average of the untreated specimens (**Table 3**). Specimens treated with low and high retention levels of borax showed less reduction in plate-shear strength (−21% to −24% of untreated controls) than the boric acid or MAP treated specimens (−34% to −42%). Generally, when retention of the specimens treated with borax or with DAP increased, the plate-shear strength decreased from 21 to 24 percent for borax and from 24 to 47

Table 2. — FRT-retention values as function of chemical concentration and average values of planar (rolling) shear in plywood loaded by plates or in a five-point flexural shear test.

Treatment chemical	Average retention in plywoods	Density	Moisture content	Planar shear induced by five-point flexure (//)[a] Shear strength[b]	Planar shear loaded by plates (//)[a] Effective modulus of rigidity	Planar shear loaded by plates (//)[a] Shear strength
	(kg/m^3)	(kg/m^3)	(%)	(N/mm^2)		
Untreated	--	590	14.1	4.8 A (0.50) [c]	392.3 (81.31)	3.8 (1.23)
Borax 3%	8.6	600	14.0	4.5 AB (0.36)	400.9 (32.32)	3.0 (1.08)
Borax 6%	14.5	600	14.0	3.9 BC (0.33)	392.0 (17.58)	2.9 (1.04)
Boric acid 3%	11.0	590	14.1	4.2 AB (0.26)	394.5 (83.21)	2.3 (0.42)
Boric acid 6%	19.4	600	14.3	3.4 C (0.73)	471.4 (125.24)	2.5 (0.77)
Monoammonium phosphate 3%	21.0	600	14.1	4.0 B (0.32)	321.7 (48.58)	2.2 (1.15)
Monoammonium phosphate 11%	37.6	600	14.0	3.9 BC (0.28)	290.7 (102.43)	2.5 (1.19)
Diammonium phosphate 3%	25.6	600	14.1	4.3 AB (0.14)	353.8 (78.77)	2.9 (1.23)
Diammonium phosphate 11%	41.8	600	14.1	4.3 AB (0.26)	519.2 (213.61)	2.0 (1.20)

[a]Parallel to the surface grain of the plywood specimen.
[b]Groups with same letters in column indicate that there is no statistical difference ($p < 0.05$) between the samples according to the Duncan's multiply range test.
[c]Values in parentheses are SDs.

Table 3. — Percent change in shear strength and modulus values of treatment groups as function of chemical retention.

Treatment chemical	Average retention in plywoods	Decreases (-) and increases of strength values of treatment groups: Planar shear induced by five-point flexure (//)[a] Shear strength	Planar shear loaded by plates (//)[a] Effective modulus of rigidity	Planar shear loaded by plates (//)[a] Shear strength
	(%)			
Borax	8.6	−6.25	2	−21
Borax	14.5	−18.8	−0.1	−23.7
Boric acid	11.0	−12.5	0.6	−39.5
Boric acid	19.4	−29.2	20	−34.2
Monoammonium phosphate	21.0	−16.7	−18	−42
Monoammonium phosphate	37.6	−18.8	−26	−34.2
Diammonium phosphate	25.6	−10.4	−10	−23.7
Diammonium phosphate	41.8	−10.4	32	−47.4

[a]Parallel to the surface grain of the plywood specimen.

percent for DAP. But, the plywood specimens treated with boric acid and MAP showed less of an effect on plate-shear strength when the retention increased.

Modulus of rigidity values of the plywood specimens treated with borax (3% and 6%), boric acid (3%), and DAP (3%) were virtually identical to that of the untreated specimens. The modulus of rigidity of the remaining treated specimens varied from the untreated control specimens from a 18 to 26 percent reduction for specimens treated with MAP (3% and 11%) to a 32 percent increase for specimens treated with 11 percent DAP.

Planar (rolling) shear strength induced in five-point flexure

All five-point flexural test specimens failed in shear and not in flexure. The results of the five-point flexural shear strength tests are summarized in **Table 2**. A significant difference was determined ($p < 0.05$) between the group averages from the five-point flexural shear test specimens for 8 groups (4 treatments and 2 retentions) of fire-retardants according to the ANOVA statistical analysis and as determined by Duncan's multiple range test.

All eight groups of treated specimens showed a noticeable reduction in five-point flexural shear strength when directly compared to untreated control specimens (**Table 3**). But also note how COV (determined as SD / mean) for this five-point flexural shear data are greatly reduced for 8 of 9 groups when compared to the COV of the planar shear data (**Table 2**, **Fig. 2**). Five-point flexural shear strength values of the specimens treated with 6 percent concentration of borax and boric acid and treated with both (i.e., 3% and 11%) concentrations of monoammonium phosphate (MAP) were significantly lower than matched untreated control values at the $p < 0.05$ level. The strength values of 3 percent concentration of borax, 3 percent boric acid, 3 and 11 percent DAP, and untreated control specimens are the same, while the strength values of the other treated specimens are significantly different to the untreated control specimens. Specimens treated with 6 percent concentration of boric acid had the lowest shear strength of any treated specimens with 3.4 N/mm^2. Increasing the retention for borax and boric acid treatments in plywood caused greater reduction in shear strength than did retention increases for MAP or DAP. Generally, as retention of the specimens borax and boric acid doubled, their average shear strengths were reduced from 8 to 18 percent and from 12 to 30 percent, respectively. However, when retention of the specimens treated with MAP and DAP was increased, very little if any decrease was noted in this strength property. We also noted that the shear strength of the specimens treated with DAP was generally higher than that of specimens treated with MAP.

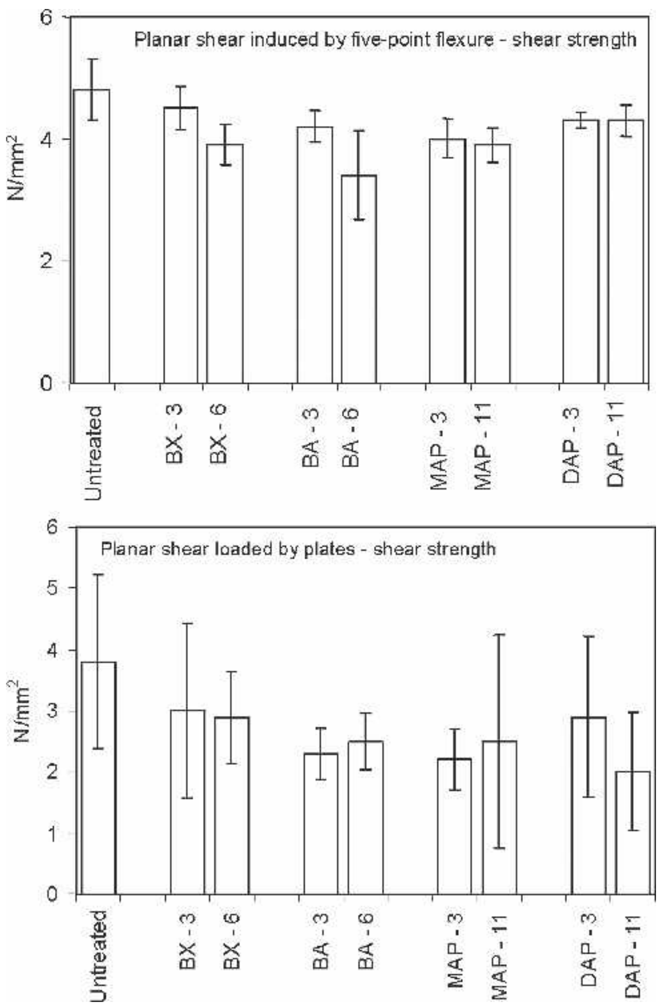

Figure 2.— Mean shear strength values and SD of plywood specimens.

Discussion

When comparing the results from the plate-shear tests to those from five-point flexural shear tests, the reported mean shear strength of the specimens loaded in planar shear by plates was generally found to be lower than comparable five-point flexure shear strengths (**Fig. 2**). But also note that the respective variability of plywood in the planar shear data is about three-times greater than that for the five-point flexural shear data. Recall that for untreated laminated veneer lumber this phenomenon of reduced variability in the five-point flexural shear test data was previously noted by Hunt et al. (1993). Finally, note that when considering five-point flexural shear, the apparent FR-retention effect increases as FR-retention increases, whereas in planar shear this same apparent effect is less consistent in that it is sometimes higher and sometimes lower. When comparing chemically treated plywood to untreated plywood using the two shear-test configurations in ASTM D-2718, the results and our observations lead us to the opinion that the five-point flexural shear test is the preferable test method in that its results appear to be more consistent and less variable than those from the plate-shear test method.

Our results clearly show that adding borates to furnish to be bonded with phenol-formaldehyde (PF) resin affects PF curing (**Table 3**). We believe that the flexural and plate shear strength losses noted in our results are probably jointly related to two issues. One is that the FR may be causing chemical and/or mechanical changes in the wood cell wall structure and chemistry (Winandy 2001). The second is that some treatment chemicals may inhibit curing of resins by altering the requisite pH of the resin during curing (Winandy and River 1986). The use of borates in wood composite panels may cause several problems. A critical problem seems to be related to its effect on the functional methylol groups (CH_2OH) of the PF resin molecules and their interaction with borate ions (Sean et al.1999). Laks et al. (1988) also reported embrittlement of the wood furnish caused by crystal formation within the wood cell walls or crosslinking between cellulose or hemicellulose molecules by borate ion. This type of effect is known to occur in cases where a high loading of a water-soluble salt is present in the wood or if the treatment is acidic.

In our study, specimens treated with DAP and borax generally showed better shear strength than those of specimens treated with MAP and boric acid for Method A and B. Because some treatment chemicals are known to adversely affect wood-PF (phenol-formaldehyde) bonds by affecting pH and resin viscosity (Boggio and Gertjejansen 1982), we believe that the shear-strength reductions in plywood specimens were caused by a combination of accelerated resin cure and thermal decomposition. Acids in wood, especially when accelerated by acidic FR-treatments, could further hydrolyze the branched hemicellulose and the longer cellulose chains. Cellulose is often thought to be primarily responsible for the strength of the wood fiber; therefore reducing the length of the cellulose molecules (DP) would cause a reduction in macro-strength properties. This theory of hydrolytic cellulose depolymerization was originally proposed by Ifju (1964) and modified to also include hemicelluloses by Sweet and Winandy (1999).

Conclusions

All four tested fire-retardant systems and both fire-retardant retention levels were generally found to reduce plate shear and five-point flexural shear properties when compared to matched untreated plywood specimens. Depending on the test method employed, this treatment effect was shown to vary from 6 to 47 percent and depended on the fire-retardant chemical and its chemical loading level. Few practical effects on modulus of rigidity were noted. However, critical differences where noted when comparing the accuracy and precision of the two test methods when used to compare the shear strengths of FR-treated to untreated plywood. We found that the five-point flexural test provided less variable and more consistent data for evaluating treatment effects on shear strength. Thus, because this reduced variability results in increased statistical power in experimental analysis, we conclude that the five-point flexural shear test is the more appropriate test method for assessing treatment effects on shear strength than is the plate shear method.

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