United States
Department of
Agriculture

Forest Service

Forest
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Laboratory

Research
Paper
FPL–RP–568

Predicting Bending Strength of Fire-Retardant-Treated Plywood From Screw-Withdrawal Tests

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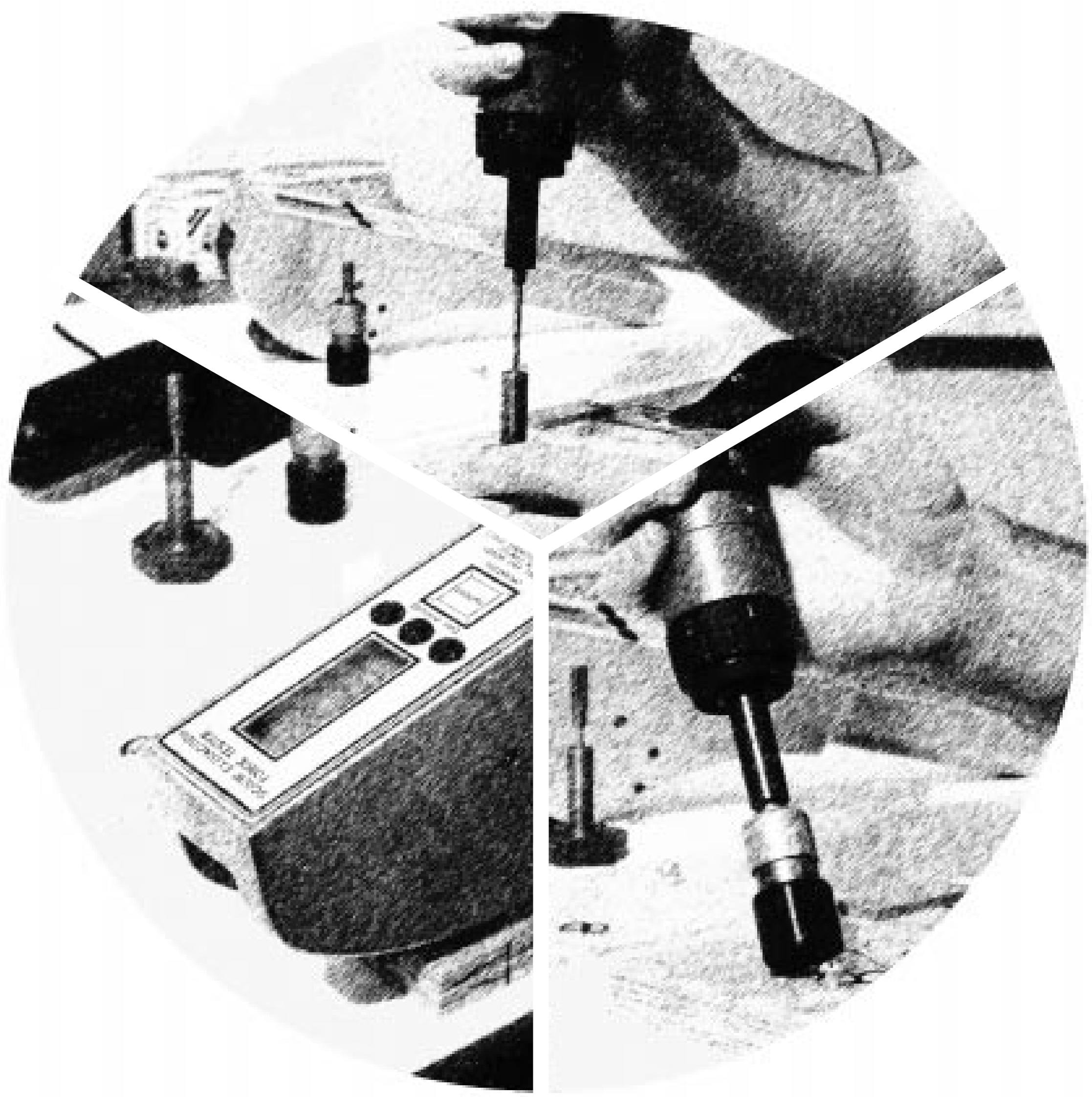

Abstract

This report describes the development of a test method and predictive model to estimate the residual bending strength of fire-retardant-treated plywood roof sheathing from measurement of screw-withdrawal force. The preferred test methodology is described in detail. Models were developed to predict loss in mean and lower prediction bounds for plywood bending strength as a function of a screw-withdrawal force. Our analysis of fire-retardant-treated plywood from three different studies, each with various fire-retardant-treatment, processing, plywood thickness, and exposure temperature groupings, clearly indicated that different fire-retardant-treatments and plywood thicknesses could not be grouped into a single "universal" model. Nevertheless, some grouping was possible; parameter estimates for several grouped fire-retardant formulations and plywood thicknesses are reported for mean trends and lower prediction boundaries. Although the models were shown to acceptably predict plywood bending strength, additional work is needed to expand these models to address the effects of plywood quality, wood temperature, and moisture content at time of test.

Keywords: Fire-retardant, treatment, plywood, roof sheathing, models, bending strength, screw-withdrawal force, field evaluation, in-place evaluation

February 1998

Winandy, Jerrold E.; Lebow, Patricia K.; Nelson, William. 1998. Predicting bending strength of fire-retardant-treated plywood from screw-withdrawal tests. Res. Pap. FPL–RP–568. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 20 p.

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Research Highlights

In North America, fire-retardant- (FR-) treated plywood is sometimes permitted as an alternative to noncombustible materials in structures that require a high level of fire safety. In the mid- to late 1980s, some commercial FR treatments failed to perform adequately when used as roof-sheathing plywood and roof-truss lumber. This problem was costly because these roofs needed to be replaced. Since then, extensive research has defined the mechanism of thermal degradation, but field methods are still needed to evaluate the condition of FR-treated plywood in service and to estimate residual service-life.

Our analysis of FR-treated plywood from three different studies, each with various FR-treatment, processing, plywood thickness, and exposure temperature groupings, clearly indicated that various FR treatments and plywood thicknesses could not be grouped into a single "universal" model. Groups that could be combined were evaluated together. The ensuing models had the form

$$\mathrm{R}_{\text{lower bound}} = \hat{y} - t_{n\text{-}2,1\text{-}\alpha} \cdot \mathrm{SE}_\mathrm{p}$$

where

$\hat{y}$	= predicted mean plywood strength, $\hat{b}_0 + \hat{b}_1\ (x)^{1/2}$
x	mean of multiple screw-withdrawal measurements, avg x_i
$\hat{b}_0 + \hat{b}_1$	fitted parameters (Table 7)
$\mathrm{SE_p}$	standard error of prediction, $\mathrm{SE} \cdot \{1 + 1/n + [(x^{1/2} - \bar{x})^2/\mathrm{SS}]\}^{1/2}$
SE	Eq. (3) model estimate of error (Table 8)
$t_{n\text{-}2,1\text{-}\alpha}$	t-test statistic
n	number of observations
$\bar{x}$	observed mean of square root screw-withdrawal measurements (Table 8)
SS	mean-adjusted sums of squares, $\sum(x_\mathrm{j}^{1/2} - \bar{x})^2$ (Table 8)

Parameter estimates are given for several tested FR formulations and plywood thicknesses for the curvilinear lower prediction boundary (Table 7). Parameter estimates for a less preferred, but simpler-to-use, linear lower prediction boundary can be calculated using data given in Table 8. Both lower prediction boundary model forms were found to predict residual plywood bending strength acceptably for several FR formulations and plywood thicknesses near the mean. However, the curvilinear form (Eq. (5)) is preferred because of its more comprehensive nature when predicting values in the extreme tails of the screw-withdrawal force distribution. Additional work is needed to expand these models to address the effects of plywood quality, wood temperature, and moisture content at time of test.

Predicting Bending Strength of Fire-Retardant-Treated Plywood From Screw-Withdrawal Tests

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Introduction

Building officials and inspection professionals are frustrated by the limited nondestructive evaluation (NDE) tools for assessing the residual strength of thermally degraded fire-retardant - (FR-) treated plywood. Definitive relationships between nondestructively measured properties and engineering design properties are needed before NDE techniques can be completely useful. There are two broad types of NDE methods, chemical and mechanical.

Chemical-based NDE, such as monitoring relationships between wood pH and strength (Lebow and Winandy, in press, b) or changes in carbohydrate chemistry and strength (LeVan and others 1990, Winandy 1995), is rapidly becoming better understood and more reliable. Nevertheless, chemical tests are often prohibitively expensive because of equipment needs, operator time, and lag time between field inspection–sample collection and test results. Work continues to focus on developing a less expensive chemical NDE test based on assessing the pH of treated wood.

Mechanical NDE often involves proof-loading-type tests (APA 1989a) or basic relationships such as those between stress wave speed and modulus of elasticity or between stress wave attenuation and strength (Ross and Pellerin 1994). The use of proof-loading is often complicated by cumbersome equipment; the use of stress wave analysis is impeded by inappropriate boundary conditions, which limit field application by complicating signal processing.

Another variant of mechanical tests is the relationship of screw withdrawal to strength (ASTM 1996a). Screw-withdrawal tests were initially found to be simple indicators of biological degradation (Fig. 1) (Talbot 1982; see Ross and others 1992 for details). Talbot's work was critical. Although others had used the relationship between resistance of a probe (in penetration) to residual strength properties, Talbot reasoned that a similar relationship existed between screw-withdrawal resistance and residual wood strength properties.

Screw-withdrawal tests have recently been used for other purposes. They have tentatively been shown to be simple indicators of FR-induced thermal degradation (APA 1989a (app. H), Cooper 1992, Cooper and Reilly 1991, Ross and others 1990). Early work at the Forest Products Laboratory (FPL) evaluated some basic relationships between screw-withdrawal force and bending strength of FR-treated plywood (Ross and others 1992) (Fig. 2). However, predictive models with confidence boundaries were not defined. Prior results had been encouraging, but they were not thorough or robust enough for developing models. Additional systematic data were needed. Thus, over the last few years an extensive data base for matched screw-withdrawal force and destructive bending strength data has been collected at FPL for various kinds of FR-treated and exposed plywood. These new and more comprehensive data are reported here, and the development of predictive relationships between screw-withdrawal force and residual bending strength for FR-treated plywood is discussed. When completely developed, such a series of models can be used to predict lower boundary estimates of the residual strength of FR-treated plywood roof sheathing once the user has decided upon an acceptable statistical level of confidence.

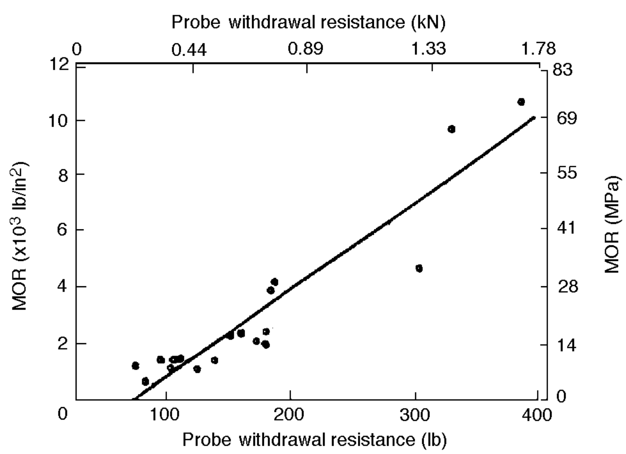

Figure 1—Relationship of residual strength (modulus of rupture) to probe withdrawal resistance—Talbot 1982.

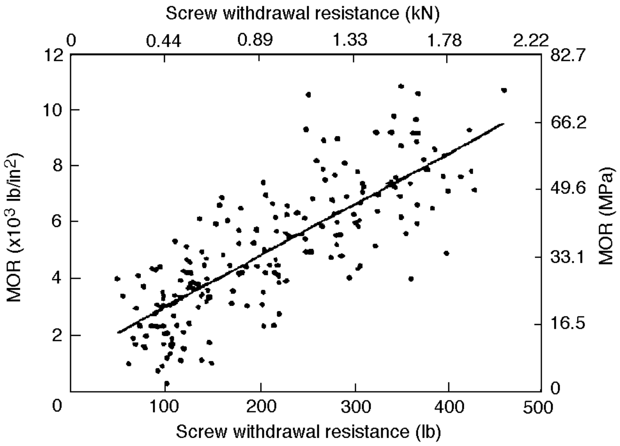

Figure 2—Relationship of bending strength (modulus of rupture) to screw withdrawal resistance—Ross and others 1992.

Background

In the United States, replacement costs for thermally degraded FR-treated plywood roof sheathing have been predicted to exceed $2 billion (NAHB 1990). The first stage of a research program at the FPL involved a systematic series of studies to identify chemical mechanisms and quantify strength loss (Winandy and others 1991b). Preliminary investigations had indicated that field problems resulted from thermal-induced acid degradation of wood carbohydrates by the acidic FR chemicals (LeVan and Winandy 1990). More comprehensive work confirmed the proposed acid-degradation mechanism and showed that the relative effects of many FR treatments could be classified by the type of FR chemical employed and the time–temperature combination required to convert the FR formulation into its acidic form (LeVan and others 1990, Winandy 1995). Additional work found that the rate of strength degradation for untreated and FR-treated plywood increased as relative humidity increased; consequently, a test method was developed to evaluate commercial FR treatments (Winandy and others 1991a). This test method led to consensus standards for plywood (ASTM 1996b) and lumber (ASTM 1996c). To elevate the resulting test data, several kinetics-based models for thermal degradation of FR-treated material have been presented (APA 1989b, Pasek and McIntyre 1990, Winandy and others 1991a, Woo 1981). Winandy and Lebow (1996) built on this work to develop a single-stage time–temperature model based on first-order kinetic theory for a series of generic FR treatments. They later verified that this model could accurately predict strength loss (Lebow and Winandy, in press, a). LeVan and others (1996) found that strength losses from cyclic thermal exposure were generally similar to those from steady-state temperature exposure when compared on a cumulative time-at-temperature basis.

Objectives

The objectives of the work reported here were

1. to develop a preferred screw-withdrawal test methodology,
2. to define basic relationships between nondestructively measured screw-withdrawal properties and an engineering property, such as bending strength, for FR-treated plywood roof sheathing, and
3. to use those models to predict lower boundaries for residual plywood bending strength in service after assuming various levels of confidence.

Methods and Materials

Based on screw-pull testing procedures developed in earlier work (appendix H, Rep. SPE–1007, APA 1989a; Ross and others 1990, 1992; Talbot 1982), we developed a simple screw-pull testing technique that involved inserting, then extracting, a No. 10 wood screw from various FR-treated and untreated plywood specimens that had been exposed for some time at various elevated temperatures (>54˚C (>130˚F)). Material from three FPL studies was used to define the relationship between screw-withdrawal resistance and remaining plywood bending strength. The data used in this report involved matched strength–screw pull data from three studies of larger scopes that individually evaluated the strength–thermal degrade relationship as their primary objective. The experimental variables of each study are shown in Table 1. These three studies involved

1. the effects of FR processing factors, retention, and buffers on thermal degrade, hereafter called the Factors Study (Winandy 1997),
2. the interrelationship between steady-state high-temperature laboratory exposure and variable (daily or seasonally) field exposure, hereafter called the Lab–Field Study (Winandy, in progress), and
3. the base data set used to verify the potential of new ASTM Standard D5516 (ASTM 1996b) to induce thermal degrade, hereafter called the FPL–501 Study (Winandy and others 1991a).

The experimental designs of the Factors Study (Winandy 1997) are shown in Tables 2 and 3; preliminary results of screw–pull tests from all laboratory-exposed specimens and 1- and 3-year field-exposed specimens of the on-going 5-year Lab–Field Study (Winandy, in progress) are shown in Tables 4 and 5. The primary objective of this Lab-Field Study was to relate laboratory degrade in strength from thermal degrade to real-world field degrade in matched specimens. However, after destructive testing of preliminary specimens to address the primary objective, these same

Table 1—Experimental protocols of studies used to develop predictive models for plywood bending strength from screw-withdrawal-force measurements[a]

Treatment[b]	Redrying[c] (°C)	Exposure Max. temp (°C)	Exposure Days (no.)	Sample size	FR composition (%) Mono-ammonium phosphate	FR composition (%) Phosphoric acid	FR composition (%) Borate/boric acid
Factors Study–12 mm[d]							
MAP	49/32	66	290	72	100	0	0
MAP	71/54	66	290	94	100	0	0
MAP/PA	71/54	66	290	92	90	10	0
MAP/TB	71/54	66	290	87	75	0	25
MAP	88/71	66	290	93	100	0	0
Untreated	None	66	290	84	None	None	None
Factors Study–16 mm[d]							
100/0/0	66/60	66	290	40	100	0	0
80/20/0	66/60	66	290	60	80	20	0
80/0/20	66/60	66	290	60	80	0	20
60/20/20	66/60	66	290	60	60	20	20
80/10/10	66/60	66	290	60	80	10	10
Water	66/60	66	290	18	None	None	None
Untreated	None	66	290	20	None	None	None
Lab–Field Study–16 mm[e]							
MAP	71/54	66	160	40	100	0	0
MAP	None[f]	66	160	40	100	0	0
MAP/PA	71/54	66	160	40	90	10	0
MAP/PA	None[f]	66	160	40	90	10	0
MAP/TB	71/54	66	160	40	75	0	25
MAP/TB	None[f]	66	160	40	75	0	25
Water	71/54	66	160	40	0	0	0
Water	None[f]	66	160	40	0	0	0
Untreated	None	66	160	40	None	None	None
FPL–501 Study–16 mm[g]							
MAP–77C	77/66	77	63	79	100	0	0
Untreated	77/66	77	63	118	None	None	None

[a]$T_F = T_C$ (1.8) + 32.
[b]MAP is monoammonium phosphate; PA, phosphoric acid; TB, Timbor (disodium octaborate tetrahydrate).
[c]Dry-bulb/wet-bulb temperature.
[d]Winandy 1997.
[e]Winandy, in progress.
[f]Not redried after treatment and exposed to extended high-temperature while wet.
[g]Winandy and others 1991b.

Table 2—Results of individual paired *t*-tests on data for 12-mm- (1/2-in.) thick plywood from Factors Study[a]

Treatment	Redrying temp (°C (°F))	Exposure	*t*-value for exposure at 66°C (150°F)/ 75% RH 0 days	60 days	160 days	290 days
MAP	54 (120)	Dry	0.077	—	0.365	0.529
MAP	71 (160)	Dry	0.716	0.865	0.888	0.207
MAP/TB	71 (160)	Dry	0.206	0.039	0.925	0.274
MAP/PA	71 (160)	Dry	0.974	0.682	0.455	0.932
MAP	88 (190)	Dry	0.076	0.168	0.490	0.210
MAP	71 (160)	Wet/dry	—	0.479	0.140	0.431
MAP	71 (160)	Wet/wet	—	0.338	0.806	0.066
Untreated	None	Dry	0.624	—	0.510	0.271
MAP	None	Wet/dry	—	0.828	0.145	0.999

[a]Data from Winandy 1997. For *t*-tests, H_0: $SWF_t - SWF_c = 0$. Differences are significant for *t*-values < 0.05.

Table 3—Results of individual paired *t*-tests on data for 16-mm- (5/8-in.-) thick plywood from Factors Study[a]

Treatment (MAP/PA/BA)	Redrying temp (°C (°F))	*t*-value at 66°C (150°F)/75% RH 0 days	160 days	290 days
100/00/00	66 (150)	0.735	—	0.698
80/20/00	66 (150)	0.177	0.625	0.362
80/00/20	66 (150)	0.661	0.867	0.032
60/20/20	66 (150)	0.175	0.032	0.552
80/10/10	66 (150)	0.072	0.014	0.128
Water	66 (150)	0.022	—	—
Untreated	None	0.912	—	—

[a]Data from Winandy 1997. For *t*-tests, H_0: $SWF_t - SWF_c = 0$. Differences are significant for *t*-values < 0.05.

Table 4—Results of individual paired *t*-tests on data for 16-mm- (5/8-in.-) thick plywood from laboratory part of Lab–Field Study[a]

Treatment	Redrying temp (°C (°F))	*t*-values for exposure at 66°C (150°F)/75% RH 0 days	60 days	180 days
Untreated	None	0.006	—	—
MAP	71 (160)	—	0.940	0.019
MAP	None	—	0.002	0.591
MAP/TB	71 (160)	—	0.062	0.125
MAP/TB	None	—	0.082	0.007
MAP/PA	71 (160)	—	0.179	0.889
MAP/PA	None	—	0.442	0.564
Water	71 (160)	—	0.029	0.007
Water	None	—	0.224	0.431

[a]Data from Winandy, in progress. For *t*-tests, H_0: $SWF_t - SWF_c = 0$. Differences are significant for *t*-values < 0.05.

Table 5—Results of individual paired *t*-tests on data for 16-mm- (5/8-in.-) thick plywood from field exposure of Lab–Field Study[a]

Treatment	Redrying temp (°C (°F))	Roof color	*t*-values for field exposure 12 months	36 months
MAP	71 (160)	Black	0.520	0.745
MAP	71 (160)	White	0.191	0.738
MAP	None	Black	0.878	0.882
MAP	None	White	0.789	0.551
MAP/TB	71 (160)	Black	0.627	0.400
MAP/TB	None	Black	0.831	0.149
MAP/PA	71 (160)	Black	0.116	0.342
MAP/PA	71 (160)	White	0.423	0.787
MAP/PA	None	Black	0.348	0.603
MAP/PA	None	White	0.083	0.899
Water	71 (160)	Black	0.739	0.003
Water	None	Black	0.720	0.280

[a]Data from Winandy, in progress. Specimens were exposed in simulated attic structures near Madison, WI, for various durations. For *t*-tests, H_0: $SWF_t - SWF_c = 0$. Differences are significant for *t*-values < 0.05.

specimens were also evaluated using our screw–pull test and used in the study reported here. The experimental design of the FPL–501 Study (Winandy and others 1991a) was a $2 \times 2 \times 7$ fractional factorial with 2 treatments (untreated and MAP-treated), 2 exposure temperatures (54°C (130°F) and 77°C (170°F)), and 7 durations of exposure (7, 14, 21, 28, 35, 49, and 63 days); not all combinations of treatment, temperature, and exposure duration were tested.

An undamaged end-section of a 600-mm- (24-in.-) long by 75-, 100-, or 150-mm- (3-, 4-, or 6-in.-) wide by 12- or 16-mm- (1/2- or 5/8-in.-) thick plywood specimen was used for the screw-pull testing procedure. This specimen had been previously tested for maximum load by destructive tests. The face of the specimen subjected to tension stress in service was then destructively stressed in tension using ASTM D5516 (ASTM 1996b) bending test methodology. In each undamaged end-section from the plywood bending-test specimen, two or four pilot holes (as appropriate) were marked and drilled to a set depth (75% of screw depth), No. 10 wood screws were inserted to another set depth (either half- or full-thickness), and a handheld "load-cell" device was used to measure maximum screw withdrawal for each inserted screw. Specifically, a template was used to mark the location of screws. The screw sites were located on opposite ends and faces of the plywood specimen (Fig. 3A), exactly 25 mm (0.98 in.) from each end and side but on opposite faces. Pilot holes were drilled using a jig to ensure a perpendicular hole, and a 3.1-mm- (1/8-in.)-diameter drill bit (Figs. 3B and 4A) was placed in a battery-powered screwdriver (Fig. 3C). This jig was used to determine a precise hole depth and to ensure that the pilot hole was perpendicular to the specimen surface. A new 22-mm- (7/8-in.-) long No. 10 wood screw (Fig. 3D) was then inserted and driven using a different jig (Jig E, Figs. 3E and 4B) and a battery-powered screwdriver. Jig E ensured that the screw was driven in vertically. The jig was fitted with a clutch that prevented the screw from being driven completely through the opposite surface of the plywood, and it left the bottom surface of the screw head exactly 6.35 mm (1/4 in.) above the plywood surface. Each screw was extracted using a specially designed screw-extraction-force tool (Figs. 3F and 4C). The technicians attempted to apply the load at a uniform rate of

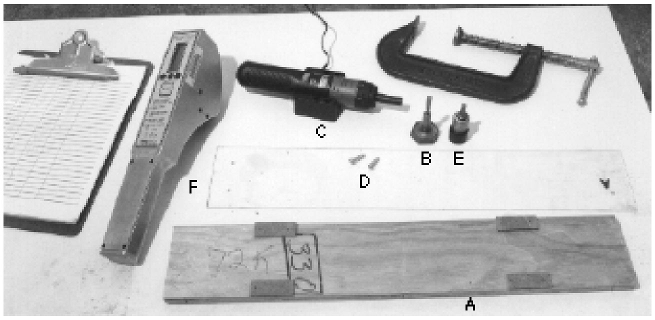

Figure 3—Specimen and equipment for screw-withdrawal test: (A) plywood specimen, (B) 3.1-mm- (1/8-in.-) diameter drill bit, (C) battery-powered screwdriver, (D) 22-mm- (7/8-in.-) long No. 10 wood screws, (E) jig, and (F) screw-extraction-force tool.

increase; total time from load initiation to failure was approximately 2 to 4 s.

The screw-extraction-force tool was designed and supplied by Sensor Development, Inc. (Lake Orion, MI), but other comparable devices are available. The load cell in the screw-extraction-force tool measured load to the nearest 44.5 N (10 lb). The load cell was factory calibrated; zero load could be re-verified by an internal resistor circuit. Factory documentation of the electrical resistance of the load cell at zero load was also provided. During testing, ongoing calibration procedures included checking of the digital "read-out zero" of the load cell prior to each screw-withdrawal test and periodic re-verification of "electrical zero" via the internal resistor.

Results

Our original plan called for using the basic relationships between screw-withdrawal force and residual bending strength in a similar manner as modulus of elasticity is used to predict bending strength in machine-stress-rated grading of lumber. We had hoped that a single "universal" relationship between decline in screw-withdrawal force and loss in strength over time could be identified. A preliminary analysis of the test data indicated that not all study–treatment–exposure groups could be grouped simultaneously for analysis. This clearly indicated that the test methodology was not independent across treatments, especially across various plywood thicknesses, as earlier studies had anticipated (Cooper 1992, Cooper and Reilly 1991, Ross and others 1990, 1992). Accordingly, the screw-withdrawal data were separated by plywood thickness and study (Table 1).

These multi-study data were then evaluated across comparable thickness–treatment–exposure groups using graphical and analytical methods. In the graphical analysis, plots were reviewed to explore the relationship between screw- withdrawal force and strength. In cases where sets of similarly treated groups exposed for different periods were available,

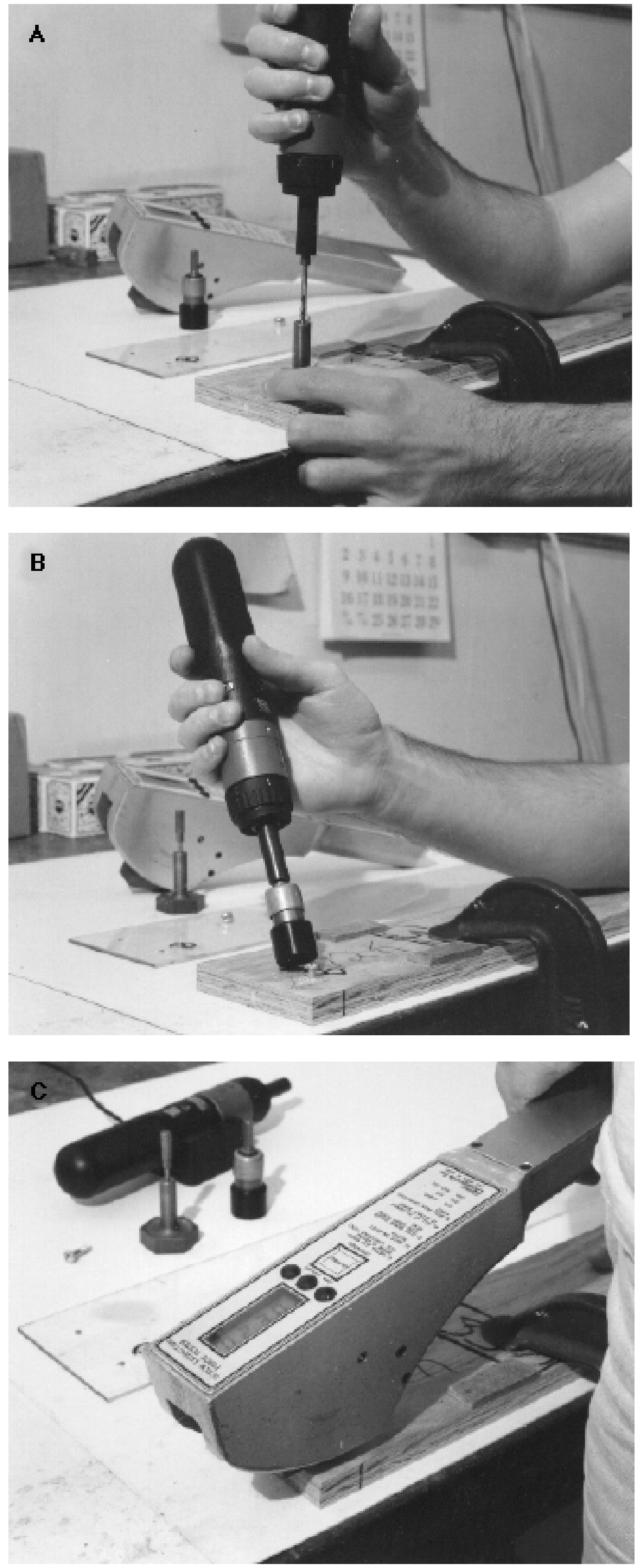

Figure 4—Screw-withdrawal test. Battery-powered screwdriver and jig are used to drill pilot hole (A) and insert screw (B); screw-extraction-force tool is used to withdraw screw while peak withdrawal force is monitored (C).

the analytical methods showed a general relationship between decline in screw-withdrawal force and loss in strength over time. Nevertheless, before comprehensive statistical analysis and model development could be more fully undertaken, several preliminary questions had to be answered:

1. What is the effect of specimen width?
2. Is there any underlying relationship between multiple screw-withdrawal measurements taken from each panel?
3. What is the effect of screw-insertion depth and which depth is best?
4. What is the distributional form of the data and should it be transformed to facilitate modeling?

Specimen Width

As described in Methods and Materials, a different specimen width (75, 100, or 150 mm (3, 4, or 6 in.)) had been used in each study. As expected, specimen width exerted no significant influence on screw withdrawal when other factors (such as FR treatment and plywood thickness) were held constant. Thus, specimen width was not further considered, or differentiated, during subsequent development of the models.

Multiple Measurements

Preliminary work (Winandy, in progress) had indicated no discernible or significant differences between mean estimates for two or four measurements of screw-withdrawal force per specimen. However, that same preliminary work had shown that estimates obtained by using only one test per specimen were often not as stable as estimates obtained from two measurements per specimen. Screw-withdrawal force estimates from a single-observation were often more than 25% greater or less than estimates from the average of two or more matched measurements. In view of this, we advise that at least two full-depth measurements should be used to estimate screw-withdrawal force per specimen.

Two screw-withdrawal force measurements were taken per specimen, one on the tension face (SWF_t) and the other on the compression face (SWF_c) of FR-treated plywood. (Note: tension and compression faces refer to plywood sides used in ASTM D5516 destructive bending test.) To examine whether the two measurements exhibited significant differences, pair-wise *t*-tests were used to analyze each treatment–redrying–exposure combination (homogeneous groupings) for the Factors Study (Winandy 1997) and Lab–Field Study (Winandy, in progress) (Tables 2 to 5). These two studies allowed comparison of two complementary scenarios. For the Factors Study, we expected no difference in screw-withdrawal force between tension (top) and compression (bottom) plywood faces because the high-temperature exposures on each face were similar. Likewise for the Lab–Field Study, we expected no difference between top and bottom plywood faces of the laboratory-exposed specimens. However, we anticipated a real difference for the matched field-exposed specimens because the cumulative thermal exposures on the top and bottom faces were not equal in this outdoor exposure (roof sheathing) (Winandy and Beaumont 1995). Also, when used as a "field evaluation" technique, screw-withdrawal measurements are taken from only the tension face (underside) of roof sheathing plywood.

Few significant ($\alpha < 0.05$ by Student's *t*-test) differences between top- and bottom-face screw-extraction measurements were found, especially in the critical field-exposed groups. Since significant differences were expected in 1 of 20 cases as a result of naturally occurring variability, those few significant differences that did occur appeared random—they showed no distinct pattern in any one treatment or exposure category or in any particular direction. When the tests were analyzed in respect to duration of exposure, a higher percentage of results were significantly different. But again these occurrences appeared random in that they were not apparently systematic across any treatment or exposure type. Thus, we considered the two observations on matched tension and compression faces as replicates (subsamples) and used the mean of the tension- and compression-face measurements as the "optimum" screw-withdrawal-force measurement for each specimen.

Screw Depth

We used 16-mm- (5/8-in.-) thick plywood material from the FPL–501 Study (Winandy and others 1991a) to evaluate the influence of screw insertion depth on the relationship of screw withdrawal force to bending strength. We compared the variability and reproducibility of half-depth (8-mm (5/16-in.)) screw insertion to the results of full-depth (16-mm (5/8-in.)) screw insertion on the same panel. The half-depth measurements appeared to be less stable; they exhibited lower measurements with an increased coefficient of variability. In many instances, load-cell resolution (±4.5 kg (±10 lb)) exceeded 25% of the measured value. For the full-depth measurements, load-cell resolution seldom exceeded 10% of the measured value. Thus, we selected the full-depth screw-withdrawal measurements as the preferred technique. Since screw-withdrawal load is a function of insertion depth (Forest Products Laboratory 1987), we did not evaluate the variability of half-depth screw-extraction for 12-mm- (1/2-in.-) thick plywood because it was reasonable to assume that screw-withdrawal force would be less than that for 16-mm- (5/8-in.) thick plywood, which had been shown to be unacceptable. Consequently, all models hereafter were fit using full-depth screw-withdrawal measurements.

Transformations

Initial analysis of the data showed that several of the multi-study groups (Table 1) could be better modeled by transforming the strength and/or the screw-withdrawal measurement. The traditional Box–Cox tests for transforming response and Box–Tidwell tests for transforming predictors did not consistently select the same transformations for all the groups or subsets of groups (Weisberg 1985). The Box–Cox procedure indicated fairly flat likelihood, which prompted us to compare models based on root mean squared error (RMSE) and graphical (visual) analysis. This graphical and RMSE analysis allowed us to narrow the alternative transformations to identity, square root, and logarithmic transformations for both the strength and screw-withdrawal measurements.

That is, we considered writing a model form for each treatment group of the form

$$g\,(\mathrm{MOR}) = f\,(\mathrm{SWF}) + \mathrm{error} \tag{1}$$

where either or both $g(x)$ and $f(x)$ are one of the following transformation functions:

identity $h\,(x) = x$
square root $h\,(x) = x^{1/2}$
logarithm $h\,(x) = \ln(x)$

In another attempt to identify potential common transformations, we used a nonparametric ranking procedure to compare RMSE of several variously transformed models (Table 6); RMSE can be defined as

$$\mathrm{RMSE} = \left[\sum (y - \hat{y})^2 / (n - p)\right]^{1/2} \tag{2}$$

where

y is observed strength value on original scale (MPa),
$\hat{y}$ estimated strength value (MPa) for a candidate model,
n number of observations used in developing the model, and
p number of parameters estimated for the model (two in all cases considered).

From this ranking procedure and review of the graphs, the general model form

$$\mathrm{MOR} = b_0 + b_1(\mathrm{SWF})^{1/2} + \mathrm{error} \tag{3}$$

was selected as most appropriate. Two notable exceptions in the ranking procedure are the 80/0/20 and the 80/10/10 treatment groups of the Factors Study–16 mm, which might be better modeled by

$$\mathrm{MOR}^{1/2} = b_0 + b_1\mathrm{SWF} + \mathrm{error} \tag{4}$$

However, after a thorough comparative examination of the graphs and residuals from both models (expressed as Eqs. (3) and (4)), it is our opinion that the previous model (Eq. (3)) can also adequately model these two treatment groups. The relationship between plywood bending strength and screw-withdrawal force for square-root transformation of the Factors Study data (Winandy 1997) is shown for 12-mm- (1/2- in.-) thick plywood in Figure 5 and for 16-mm- (5/8-in.-) thick plywood in Figures 6 and 7. The relationship between plywood bending strength and screw-withdrawal force for square-root transformation of the laboratory portion of the Lab–Field Study (Winandy, in progress) is shown for 16-mm- (5/8-in.-) thick plywood in Figures 8 and 9.

Modeling

Each treatment group listed in Table 6 was fit by the selected model (Eq. (3)), obtaining 26 separate regressions. Since the parameter estimates for several treatment subgroups appeared similar, the similar-appearing groups were separated out by thickness and similarly acting treatments; these groups were then evaluated for common parameter estimates of slope and y-intercept.

Factors Study

For the 12-mm- (1/2-in.-) thick material used in the study by Winandy (1997), we tested whether the regressions for each of the five treated groups were coincident; that is, whether they had the same y-intercept and slope. From the results of this test, the hypothesis of both common y-intercept and slope was rejected at $p = 0.0443$. However, the five treated groups did appear to have a common slope, which was tested and accepted at $p = 0.2182$. Visual analysis suggested that only the MAP/TB group had a different y-intercept; this group was consequently removed. The remaining four treated groups were tested for coincidence, accepted at $p = 0.7130$. Thus, for this 12-mm- (1/2-in.-) thick FR-treated material, three models were estimated: an untreated group, the MAP-treated group buffered with borate (MAP/TB), and the remaining treated groups (MAP alone, MAP/PA without TB). Model parameter estimates, standard errors, and coefficients of determination (r^2) are listed in Table 7.

Combined Factors and Lab–Field Studies

As would be expected from results of tests on the 12-mm- (1/2-in.-) thick Factor Study material, we found that the influence of buffering MAP-treated plywood with borate was significant for the 16-mm- (5/8-in.-) thick material.

Table 6—Root mean square error of various potential model forms of transformed *y* (MOR) to transformed *x* (mean screw-withdrawal force)

	y			$y^{1/2}$			log *y*		
Treatment, redrying, thickness[a]	*x*	$x^{1/2}$	log *x*	*x*	$x^{1/2}$	log *x*	*x*	$x^{1/2}$	log *x*
Factors Study									
MAP, KD 49°C, 12 mm	10.98	10.83	11.18	11.43	10.95	10.87	12.37	11.47	11.01
MAP, KD 71°C, 12 mm	10.91	10.70	10.84	11.43	10.89	10.71	12.87	11.61	10.93
MAP/TB, KD 71°C, 12 mm	10.56	10.55	10.74	10.68	10.56	10.65	10.95	10.69	10.67
MAP/PA, KD 71°C, 12 mm	9.10	8.88	9.10	9.58	9.05	8.91	10.82	9.71	9.05
MAP, KD 71°C, 12 mm	10.59	10.42	10.52	10.89	10.55	10.45	11.49	10.90	10.60
Untreated, 12 mm	11.79	11.80	11.80	11.81	11.81	11.82	11.85	11.85	11.85
MAP/PA/BA									
100/0/0, 16 mm	10.59	10.63	11.24	11.22	10.63	10.53	12.83	11.53	10.92
80/20/0, 16 mm	8.92	8.81	8.99	9.39	8.96	8.78	10.40	9.61	9.05
80/0/20, 16 mm	8.11	8.65	9.43	7.92	8.25	8.91	8.00	8.06	8.61
60/20/20, 16 mm	9.53	9.47	9.62	9.82	9.54	9.47	10.52	9.94	9.62
80/10/10, 16 mm	7.79	8.42	9.45	7.65	8.66	7.93	7.80	8.35	1211
Water, 16 mm	8.21	8.20	8.19	8.21	8.21	8.20	8.23	8.23	8.22
None, 16 mm	12.19	12.20	12.20	12.20	12.21	12.21	12.24	12.24	12.25
Lab–Field Study									
MAP, KD, 16 mm	11.55	11.55	11.55	11.58	11.58	11.58	11.67	11.66	11.66
MAP, no KD, 16 mm	10.04	9.98	9.93	10.13	10.05	9.99	10.28	10.19	10.11
MAP/TB, KD, 16 mm	10.09	10.07	10.05	10.13	10.10	10.08	10.22	10.18	10.15
MAP/TB, no KD, 16 mm	10.39	10.43	10.47	10.39	10.43	10.47	10.45	10.48	10.52
MAP/PA, KD, 16 mm	8.99	8.96	8.94	9.03	9.00	8.98	9.11	9.08	9.05
MAP/PA, no KD, 16 mm	8.01	7.97	7.94	8.05	8.01	7.97	8.13	8.08	8.04
Water, KD, 16 mm	13.07	13.01	12.94	13.14	13.07	13.01	13.26	13.19	13.13
Water, no KD, 16 mm	10.28	10.28	10.29	10.29	10.29	10.30	10.31	10.31	10.32
Untreated, 16 mm	8.56	8.60	8.63	8.54	8.58	8.62	8.54	8.57	8.61
FPL–501 Study (half-depth penetration)									
Untreated, 77°C, 16 mm	10.92	10.91	10.90	10.93	10.92	10.91	10.97	10.96	10.95
MAP, 77°C, 16 mm	9.43	9.42	9.44	9.47	9.44	9.45	9.55	9.51	9.50
FPL–501 Study (full-depth penetration)									
Untreated, 77°C, 16 mm	10.92	10.92	10.92	10.94	10.93	10.93	10.98	10.97	10.97
MAP, 77°C, 16 mm	9.76	9.73	9.72	9.80	9.76	9.75	9.89	9.85	9.82

[a]KD is kiln drying.

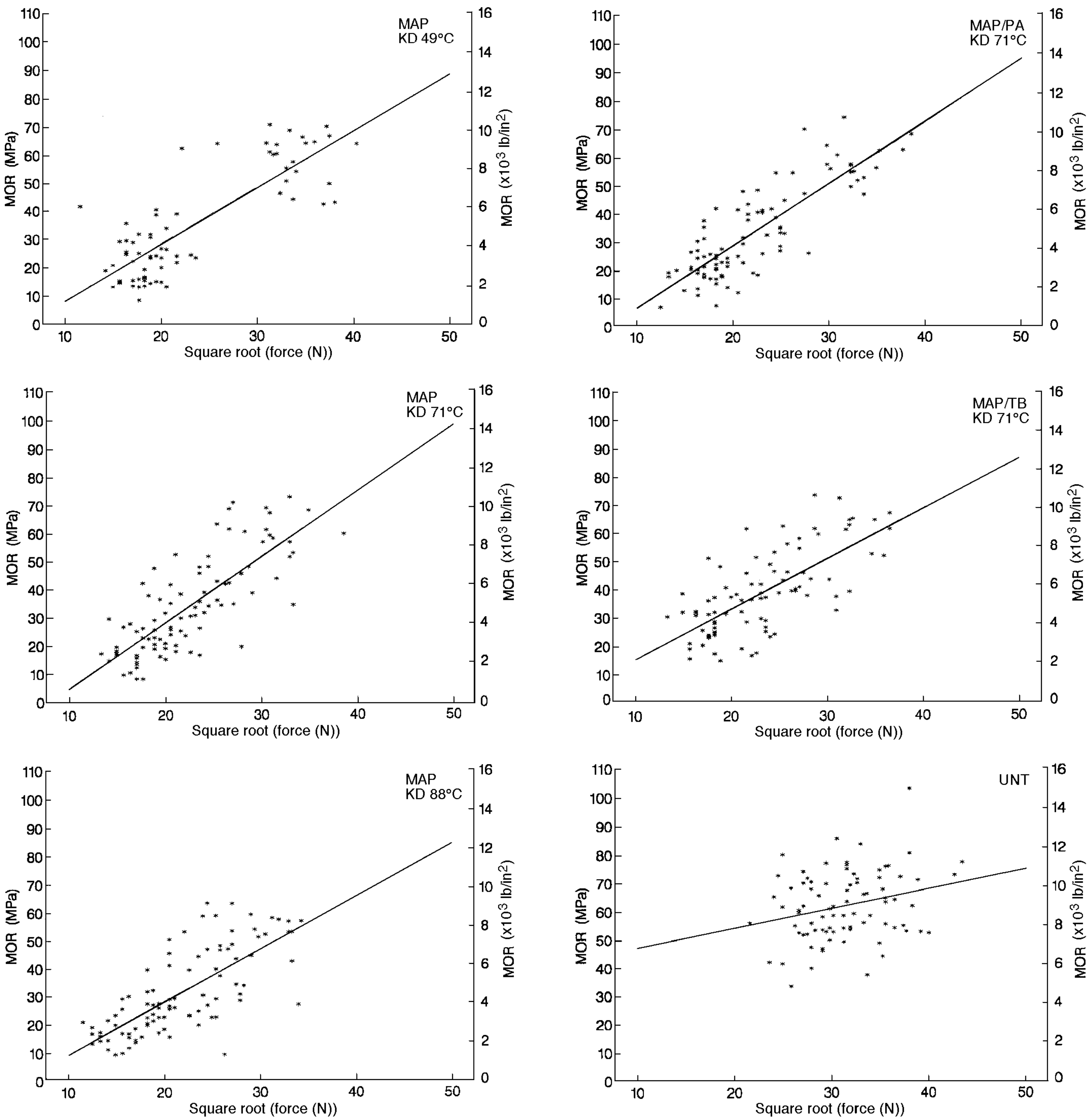

Figure 5—Relationship of screw-withdrawal force to bending strength for 12-mm- (1/2-in.-) thick plywood from Factors Study (Winandy 1997). MAP is monoammonium phosphate; PA, phosphoric acid; TB, Timbor; UNT, untreated. KD is dry-bulb kiln-drying temperature. Temperature: $T_F = T_C \cdot 1.8 + 32$; Force: 1 N = 0.225 lb.

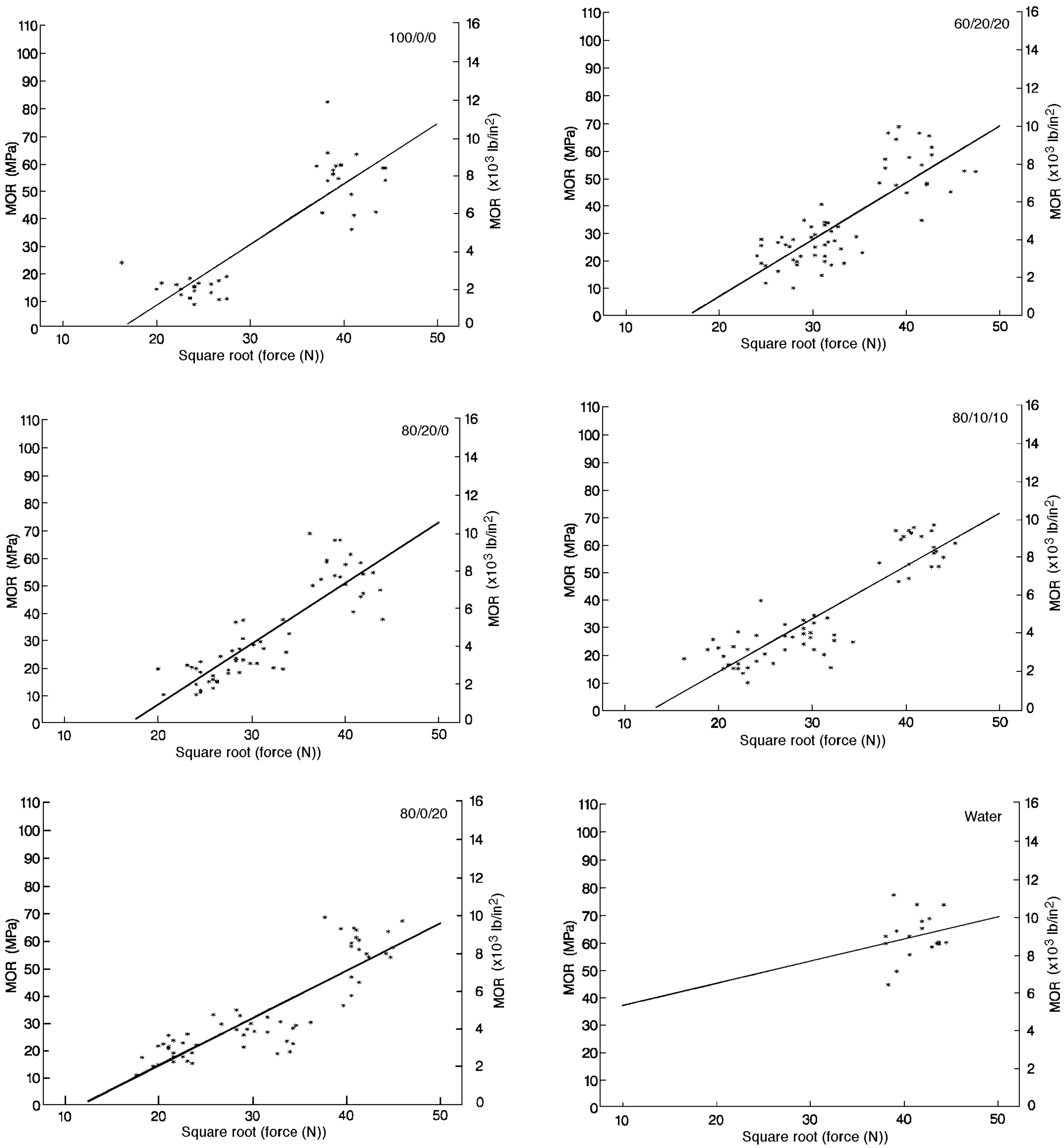

Figure 6—Relationship of screw-withdrawal force to bending strength for treated 16-mm- (5/8-in.-) thick plywood from Factors Study (Winandy 1997). Treatment is MAP/PA/BA.

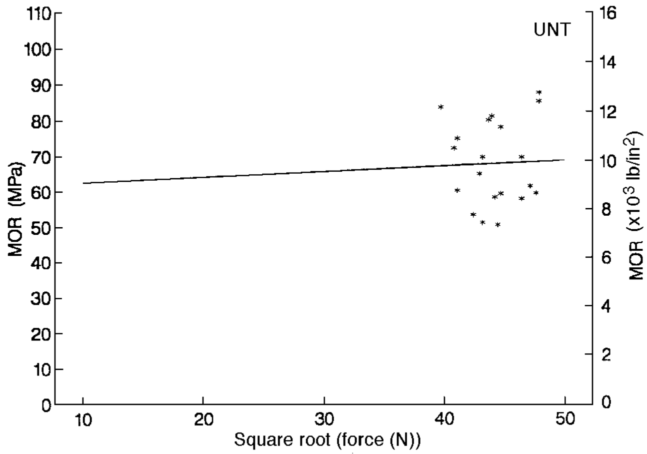

Figure 7—Relationship of screw-withdrawal force to bending strength for untreated 16-mm- (5/8-in.-) thick plywood from Factors Study (Winandy 1997).

For the Factors Study material, we found that all the chemically treated groups were not coincident ($p = 0.0268$) and did not have common slopes ($p = 0.1266$). On closer inspection, we found that the MAP- and MAP/PA-treated groups with less than 20% borate (all groups except the 80/0/20 group) were coincident (that is, common y-intercept and slope) at $p = 0.0609$. Further, if the 80/10/10 group were not considered, the remaining three groups (100/0/0, 80/20/0, and 60/20/20 groups) were coincident at $p = 0.6468$. Accordingly, the MAP-treated groups with less than 20% borate and those with any additional PA were modeled as a single group. The untreated, water treated, and combined borate-buffered (at least 20% borate) MAP-treated groups (including the 80/10/10 group, which could only be grouped with the 80/0/20 group ($p = 0.3789$)) were then modeled individually.

For material from the laboratory portion of the Lab–Field Study, we found that all the treatment groups were not coincident ($p < 0.0001$) but did have common slopes ($p = 0.9531$). This testing indicated that the chemically treated model parameter estimates were similar but not identical to those of the Factors Study. The water-treated groups and the untreated group were distinctly different from the chemically treated groups and so were modeled separately. The test of coincidence of the chemically treated Lab–Field groups was accepted with $p = 0.5350$ and the test of coincidence of the two Lab–Field water-treated groups was accepted with $p = 0.4838$.

For practical reasons, the 16-mm- (5/8-in.-) thick specimens of the Factors and Lab–Field studies were combined into similarly treated groups based on (1) similar performance and (2) presence or absence of supplemental borate in the FR formulation.

The following rationale was used for combining the individual Factors and Lab–Field groups by similar treatments:

1. Plywood for both studies was obtained from the same original batch of material, treated with similar FR treatments, and exposed in the same laboratory chamber.
2. Although there were a few statistically significant differences between some groups, we felt that it was not reasonable that similar material would react in a significantly different way. Some groups had few different thermal exposures, which resulted in different ranges of response (that is, strength loss) from thermal degrade. Thus, we compared different subsets of the population or populations. For an example, see Figure 10.
3. Graphical analysis of the data did not support exclusion; in fact, it seemed to indicate that data from the two studies were mutually inclusive when viewed as a whole. In Figure 10, note that although the tested mean trends are different, grouping of the two sets of material tends to fill in gaps resulting from differing thermal exposures.

Parameter estimates for mean trend models, standard errors, and r^2 values for the 16-mm- (5/8-in.) thick material from the combined Factors and Lab–Field studies are listed in Table 7.

Finally, material in the field portion of the Lab–Field Study was not modeled because it did not experience sufficient degrade after only 3 years of exposure; we hope to revisit this. These field data were retained to check their predictive ability using the models developed with the laboratory data.

FPL–501 Study

Untreated 16-mm- (5/8-in.-) thick plywood exposed at either 54˚C (130˚F) for 14 or 28 days or 77˚C (170˚F) for 7, 14, 21, 28, 35, 49, or 63 days (Winandy and others 1991a) did not show any distinct relationship between screw-withdrawal force and residual bending strength. However, the MAP-treated group exposed at the higher temperature (77˚C (170˚F)) exhibited a strong direct relationship between screw-withdrawal force and residual bending strength, while the MAP-treated group exposed at the lower temperature (54˚C (130˚F)) exhibited similar, but nonsignificant, behavior. The test of coincidence between the two MAP-treated groups exposed at two temperatures was rejected ($p < 0.0001$), yet the test of common slopes was not rejected ($p = 0.8440$). Parameter estimates for mean trend models, standard errors, and r^2 values of the MAP-treated groups exposed at 77˚C (170˚F) are listed in Table 7. Because these groups were significantly different and the original plywood materials of the FPL–501 Study were not matched to the Factors or Lab–Field Study materials, the MAP-treated material was not combined with materials from the other studies.

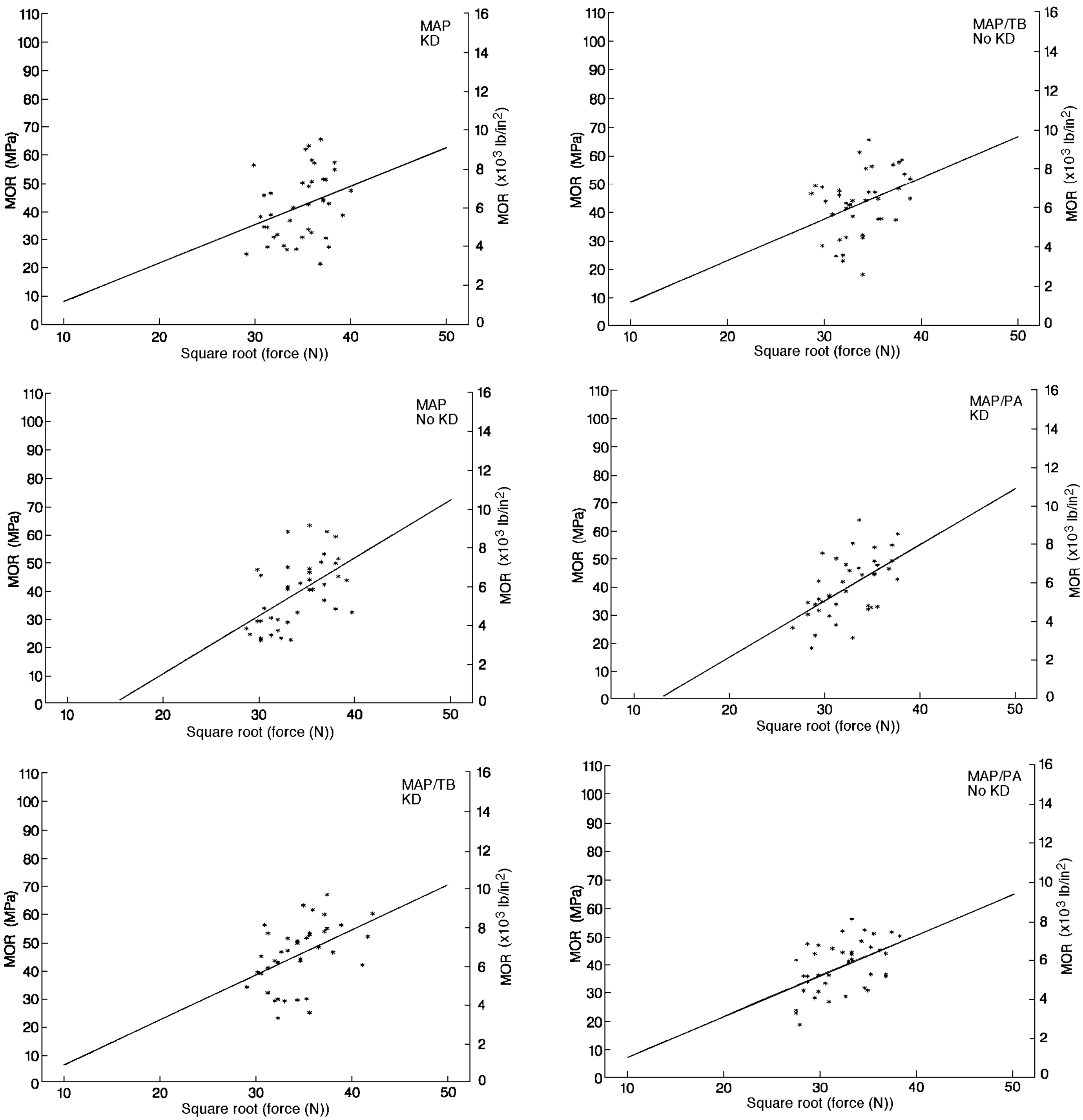

Figure 8—Strength of 16-mm- (5/8-in.-) thick treated plywood from Lab–Field Study (Winandy, in progress). Treatments were various combinations of MAP, TB, and PA, with or without kiln drying.

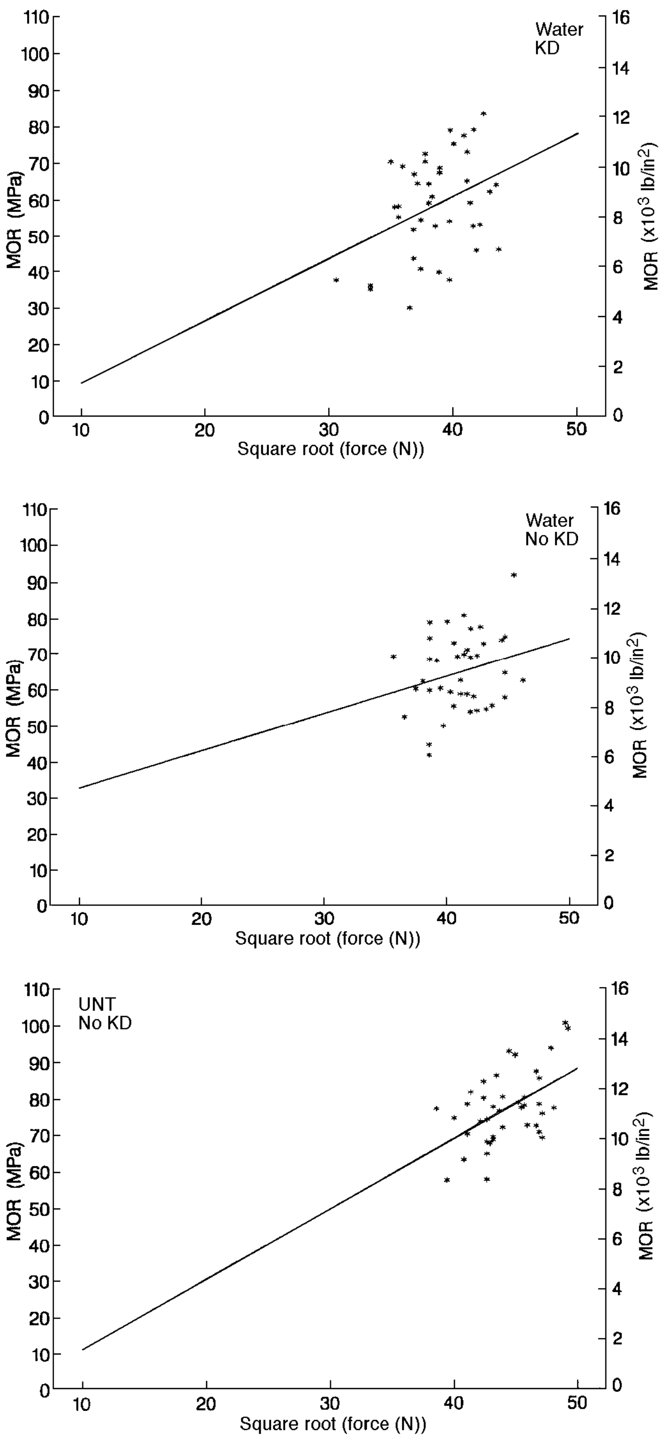

Figure 9—Strength of 16-mm- (5/8-in.-) thick water-treated or untreated plywood from Lab–Field Study (Winandy, in progress).

Table 7—Model parameter estimates, standard errors, and r^2 values

Treatment[a]	MOR = $\hat{b}_0 + \hat{b}_1(\mathrm{SWF})^{1/2}$		Standard error		r^2
	$\hat{b}_0$	$\hat{b}_1$	$\hat{b}_0$	$\hat{b}_1$	
Factors Study, 12 mm					
Untreated	40.15	0.70	9.0195	0.2842	0.07
FRT <20% borate	–13.59	2.09	1.9988	0.0856	0.63
FRT >20% borate	–2.53	1.78	4.7539	0.1978	0.49
Factors and Lab–Field Studies, 16 mm					
Untreated	11.86	1.41	24.3669	0.5503	0.10
Water	1.57	1.50	15.3992	0.3830	0.14
FRT <20% borate	–31.87	2.09	3.3126	0.0993	0.58
FRT >20% borate	–21.62	1.85	3.1636	0.0955	0.66
FPL–501, 16 mm					
MAP, 71°C	10.63	0.78	8.5626	0.2432	0.12

[a]FRT <20% borate refers to phosphate-based FR formulations with <20% borate (by weight relative to phosphate). This combined group includes 100/0/0, 80/20/0, and 60/20/20 groups from Factors Study; and MAP with and without KD, and 90% MAP/10% PA with and without KD from Lab–Field Study. FRT >20% borate refers to phosphate-based FR formulations with >20% borate(by weight relative to phosphate). This combined group includes 80/0/20 and 80/10/10 groups from Factors Study, and 75% MAP/25% TB with and without KD from Lab–Field Study.

Prediction Boundaries

Recall that our objective was to develop a method for predicting plywood bending strength (y^*) from a set of screw-withdrawal measurements so that the model could be used to estimate mean trends and construct appropriate prediction intervals based on model error. The mean trend models and their resulting prediction intervals (Table 7) could be used to establish a lower prediction boundary given the appropriate level of confidence in the lower prediction boundary. Table 8 contains the additional data necessary to construct lower prediction boundaries from the mean trend models described in Table 7.

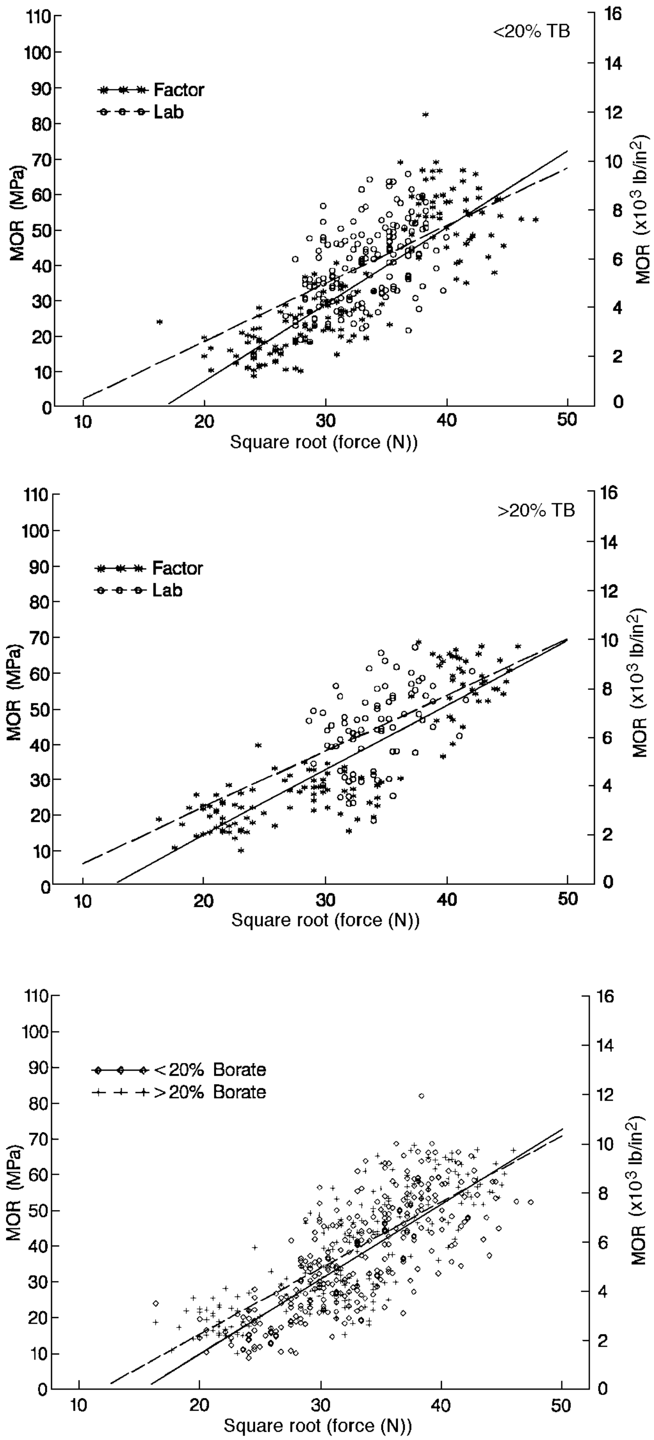

Figure 10—Example of how combined groups could have significantly different regressions but support the same general effect on bending strength of 16-mm- (5/8-in.-) thick plywood (Winandy , in progress; 1997).

Data from Lab–Field Study material treated with MAP/TB (<20% or >20% borate). Following the methods outlined by Weisberg (1985), the typical curvilinear form of a 100(1 – α) one-sided prediction interval for a single future observation of bending strength, based on the mean of at least two screw-withdrawal measurements ($x^* = \text{avg}(x_i)$), from some randomly selected single plywood specimen is

Table 8—Prediction estimates for models described in Table 7[a]

Treatment[b]	n	SE	$\bar{x}$	SS	SE_{press}
Factors Study, 12 mm					
Untreated	84	11.78	31.41	1722.35	11.96
FRT <20% borate	351	10.18	22.46	14132.05	10.21
FRT >20% borate	87	10.55	23.34	2846.22	10.66
Factors and Lab–Field Studies, 16 mm					
Untreated	60	10.86	44.21	389.52	11.08
Water	98	11.09	40.10	839.04	11.23
FRT <20% borate	320	9.83	32.89	9790.52	9.86
FRT >20% borate	200	9.42	32.38	9723.96	9.44
FPL–501 Study, 16 mm					
MAP, 71°C	79	9.73	4.92	1601.95	9.83

[a] $\bar{x}$ is observed mean of square root screw-withdrawal force; SS, mean-adjusted sums of squares $\Sigma\,[x_j^{1/2} - \bar{x}\,]^2$; SE_{press}, estimated prediction error.

[b]FRT <20% borate refers to phosphate-based FR formulations having less than 20% borate (by weight relative to phosphate). This combined grouping includes 100/0/0, 80/20/0, and 60/20/20 groups from Factors Study; and MAP with and without KD, and 90% MAP/10% PA with and without KD from Lab–Field Study. FRT >20% borate refers to phosphate-based FR formulations having more than 20% borate (by weight relative to phosphate). This combined grouping includes 80/0/20 and 80/10/10 groups from Factors Study, and 75% MAP/25% TB with and without KD from Lab–Field Study.

$$R_{\text{lower bound}} = \hat{y} - t_{n-2,1-\alpha} \cdot SE_p \tag{5}$$

where

$\hat{y}$ = is predicted mean plywood strength,

$$\hat{b}_0 + \hat{b}_1\ (x)^{1/2}, \tag{6}$$

x mean of multiple screw-withdrawal measurements, avg (x_i),

$\hat{b}_0 + \hat{b}_1$ fitted parameters (Table 7),

SE_p standard error of prediction,

$$SE \cdot \{1 + 1/n + [(x^{1/2} - \bar{x}\,)^2/SS]\}^{1/2}, \tag{7}$$

SE Eq. (3) model estimate of error (Table 8),

$t_{n-2,1-\alpha}$ t- statistic,

n number of observations,

$\bar{x}$ observed mean of square root screw-withdrawal measurements (Table 8), and

SS mean-adjusted sums of squares, $\Sigma(x_j^{1/2} - \bar{x}\,)^2$ (Table 8).

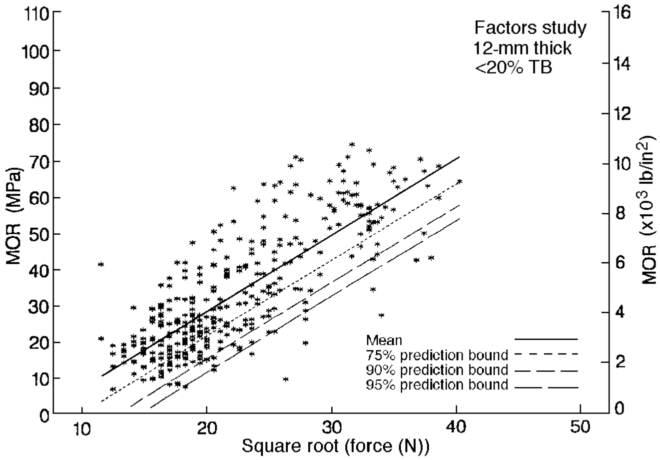

Figure 11—Mean trends and lower prediction bounds for relationship of screw-withdrawal force to bending strength for 12-mm- (1/2-in.-) thick plywood treated with MAP/<20% borate (Winandy 1997).

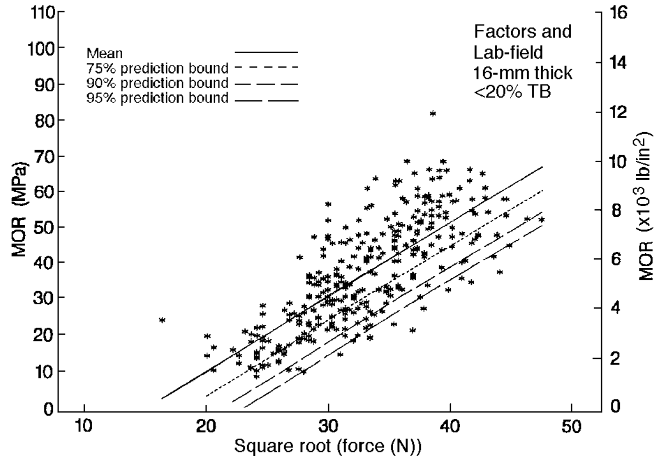

Figure 13—Mean trends and lower prediction bounds for relationship of screw-withdrawal force to bending strength for 16-mm- (5/8-in.-) thick plywood treated with MAP/<20% borate (Winandy, in progress; Winandy 1997).

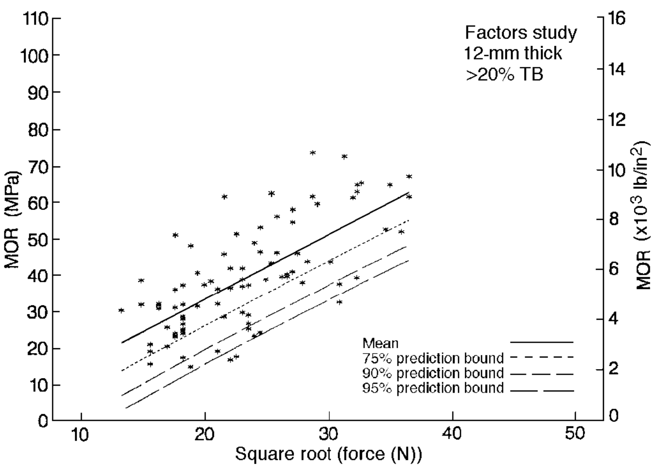

Figure 12—Mean trends and lower prediction bounds for relationship of screw-withdrawal force to bending strength for 12-mm- (1/2-in.-) thick plywood treated with MAP/>20% borate (Winandy 1997).

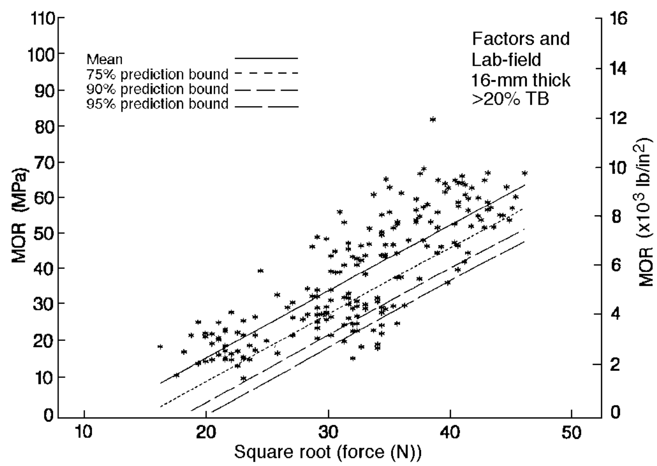

Figure 14—Mean trends and lower prediction bounds for relationship of screw-withdrawal force to bending strength for 16-mm- (5/8-in.-) thick plywood treated with MAP/>20% borate (Lab–Field Study) and 80/10/10 and 80/0/20 groups of Factors Study (Winandy, in progress; Winandy 1997).

The lower prediction bounds for the models described in Tables 7 and 8 and defined in Equation (5) are shown in Figures 11 to 18. Figures 11 and 12 show lower prediction bounds for treated (MAP plus <20% or >20% borate) 12-mm- (1/2-in.-) thick plywood from the Factors Study. Lower prediction bounds for combined data from the Factors and Lab–Field Studies for 16-mm- (5/8-in.-) thick plywood that had been treated predominantly with MAP plus <20% or >20% borate are shown in Figures 13 and 14, respectively. Figure 15 shows lower prediction bounds for untreated plywood in the Factors Study, and Figures 16 and 17 show lower prediction bounds for combined data for untreated and water-treated materials, respectively. Finally, Figure 18 shows lower prediction bounds for data from Winandy and others (1991a) for 16-mm- (5/8-in.-) thick MAP-treated plywood exposed for 7, 14, 21, 28, 35, 49, or 63 days at 77˚C (170˚F).

Note that when the curvilinear form (Eq. (5)) was used, the predicted lower bound appears curvilinear rather than simply parallel with the mean y trend because the variability in the slope of the predicted lower bound is magnified as the data move from the center of the curve towards its outer ranges. The additional variability reflected in Equation (7) results from the fact that the future observation will be different than its expected value.

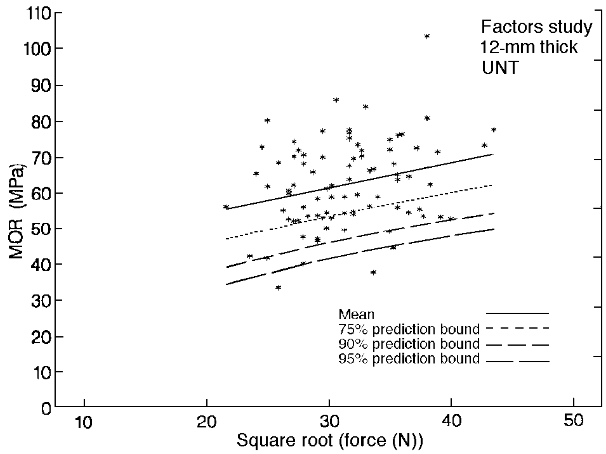

Figure 15—Mean trends and lower prediction bounds for relationship of screw-withdrawal force to bending strength for untreated 12-mm- (1/2-in.-) thick plywood (Winandy 1997).

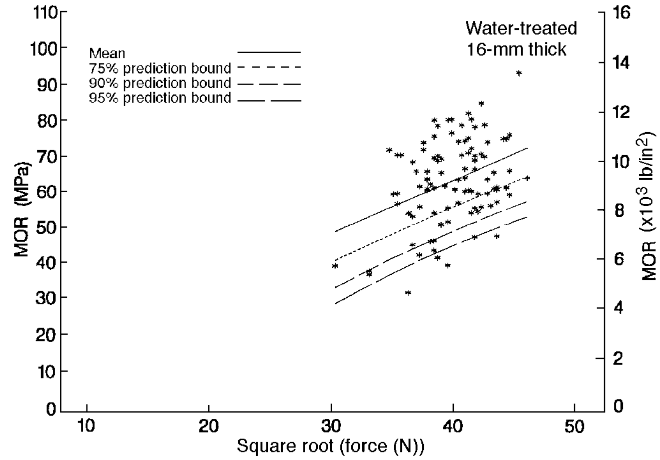

Figure 17—Mean trends and lower prediction bounds for relationship of screw-withdrawal force to bending strength for water-treated 16-mm- (5/8-in.-) thick plywood in both Lab–Field and Factors studies (Winandy, in progress; Winandy 1997).

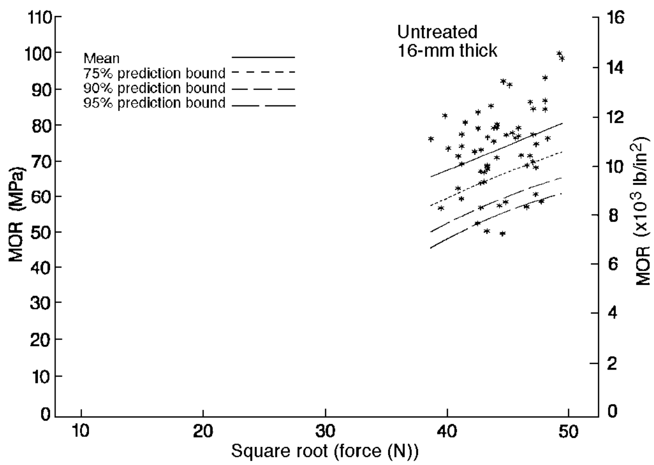

Figure 16—Mean trends and lower prediction bounds for relationship of screw-withdrawal force to bending strength for untreated 16-mm- (5/8-in.-) thick plywood in both Lab–Field and Factors studies (Winandy, in progress; Winandy 1997).

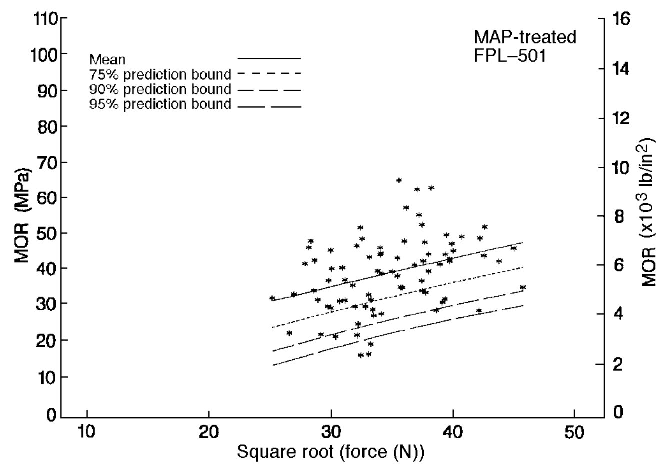

Figure 18—Mean trends and lower prediction bounds for relationship of screw-withdrawal force to bending strength for MAP-treated plywood exposed at 77˚C (170˚F) in FPL–501 Study (Winandy 1991a).

A linear form of a 100(1 – α) one-sided prediction boundary for a future strength observation based on the mean of at least two screw-withdrawal measurements ($x^* = \text{avg}(x_i)$) from some randomly selected single plywood specimen is

$$R_{\text{lower bound}} = \hat{y} - t_{n\text{-}2,1\text{-}\alpha} \cdot SE_{\text{press}} \quad (8)$$

where SE_{press} is estimated prediction error (from Table 8). The predicted residual sum of squares estimate of prediction error (SE_{press}) is the square root of the average predicted squared error, where the predicted squared error for each observed strength value is the difference between itself and the value predicted from a model fit without it squared (Weisberg 1985).

As with any empirically fit model, a word of warning is required since the model parameters are a function of the data and the inherent characteristics of that data. Thus, the user should be warned that the ensuing prediction boundaries from either the curvilinear or linear models (Eq. (5) or (8), respectively) are based on a future observation from the population on which the model was originally based. Furthermore, the user needs to keep in mind that the data governed which form of model we used. Accordingly, unanticipated departures in the physical characteristics of future materials from this base population may mean that the resultant statistics are not the same as those given here. Therefore, the utility of these models may be decreased.

Discussion

A thorough review of the models and their predicted mean trends and lower predicted boundaries (Table 7, Figs. 11 to 18) revealed three important results:

1. Screw-withdrawal force was directly related to bending strength of FR-treated plywood.
2. For a given screw-withdrawal measurement, expected MOR was systematically shifted higher or lower based on FR treatment.
3. Addition of borate buffered the rate of thermal degrade when borate concentrations were generally more than 20% of the total salts concentration in inorganic-phosphate-based FR formulations.

Screw-withdrawal force clearly has a direct relationship to the bending strength of FR-treated plywood. Although at first glance this relationship appears to be consistent and uniform, such a universal relationship was not always found in comparisons across different FR-treatments or plywood thickness levels. Instead, we found that these relationships were uniform and systematic only when analyzed within similarly buffered FR treatments and plywood thickness groupings. Two primary grouping criteria were thus developed and are used for the remainder of this discussion:

1. Grouping of phosphate-based FR formulations with less than 20% borate (by weight relative to total salts concentration). For 16-mm- (5/8-in.-) thick plywood, this combined grouping included the 100/0/0, 80/20/0, and 60/20/20 groups from the Factors Study and the MAP and MAP/PA (with and without kiln drying) groups from the Lab–Field Study.
2. Grouping of phosphate-based FR formulations with generally more than 20% borate (by weight relative total salts concentration). For 16-mm- (5/8-in.-) thick plywood, this combined grouping included the 80/0/20 and 80/10/10 groups from the Factors Study and the MAP/TB (with and without KD) groups from the Lab–Field Study.

In the Factors and Lab–Field studies, the intercept parameters between subsets of some FR-treated groups were found to be different and the slope parameters were more similar. This infers that for a given screw-withdrawal measurement, the expected MOR will be systematically shifted higher or lower based on the FR treatment. Similarity in slopes can be seen by comparing the slopes (b_1) of comparable treatments for each thickness of plywood. Compare slopes for FR treatment with <20% borate (b_1 in Figs. 11 and 13) and with >20% borate (b_1 in Figs. 12 and 14). This similarity is also apparent in a comparison of the predicted slope parameters of the grouped Factors and Lab–Field data in Table 7.

Note that the data are ranked in a logical manner consistent with the ranks of thermal degrade data reported in previous studies (LeVan and others 1990, Winandy 1995, 1997). Also note how untreated plywood had the smallest response for the relationship between screw-withdrawal force and strength, and water-treated material had a slightly stronger response. Phosphate-treated material buffered with sufficient borate exhibited a still stronger response and that without sufficient borate buffers exhibited the strongest response. Finally, note the similarity in slopes between the 12-mm- (1/2-in.-) and 16-mm- (5/8-in.-) thick plywood. Although the intercepts are distinctly different, the slopes are remarkably similar for phosphate-treated material with or without borate buffers (Table 7).

The addition of borate buffered (lessened) the rate of thermal degrade when borate concentration was more than 20% of phosphate concentration in inorganic-phosphate-based FR formulations. This result can be seen in a comparison of the slopes (b_1) in Figures 11 and 12 to those in Figures 13 and 14. Although the b_1 of FR formulations amended with >20% borate (Table 7) were not "significantly" different from that of phosphate-only formulations or formulations with <20% borate for any thickness group, the consistency in the magnitude of these b_1 differences suggests a level of practical significance. This result of borate buffering agrees with recent findings that borate buffers the magnitude of thermal degrade of phosphorus-based FR-treated wood (Winandy 1997, Winandy and Schmidt 1995).

When FR-treated plywood is evaluated in the field, the presence of borate may be quickly established using spray-on colorimetric methods such as Method 1 of AWPA Standard A–3 (AWPA 1997), and the presence of phosphorus can be identified using Method 9 of that standard. Although there are quantitative laboratory methods for estimating borate and phosphorus levels, the field methods are merely qualitative. If the user of the models presented here is unable to ascertain whether borate is a significant portion of the original FR formulation, he or she is advised to use the model parameters for FR formulations that consist predominantly of inorganic phosphate and are amended with <20% borate.

Model Validation

To test the applicability of the predictive models and boundaries to other populations, we used the field portion of the Lab–Field Study that was not used in the development of model parameters. Examples of the application of the developed models (Eqs. (5) to (7), Tables 7 and 8) for this field sample can be seen by comparing the predicted mean trends and lower prediction bounds for a single future observation to data from the 1-year field exposure of 16-mm- (5/8-in.-) thick material treated with MAP and <20% borate (Fig. 19) or >20% borate (Fig. 20) (Winandy, in progress). While the

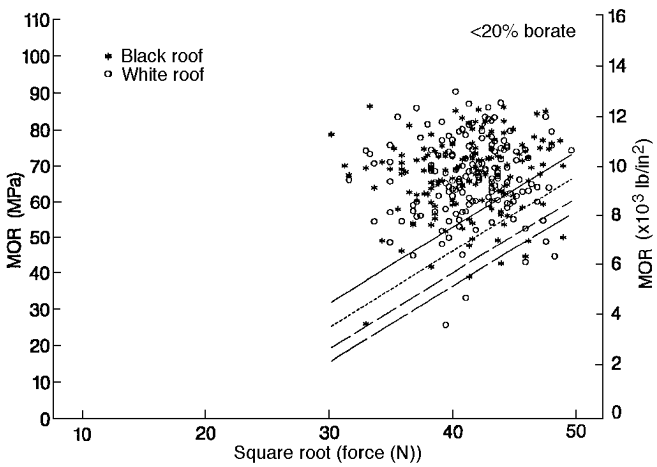

Figure 19—Example of applicability of models as shown by predicted mean trends and lower prediction bounds compared to real data from material treated with MAP and <20% borate. Real data was obtained from treated 16-mm- (5/8-in.-) thick material exposed in the field for 1 year; these data were not used to develop the model parameters (Winandy in progress).

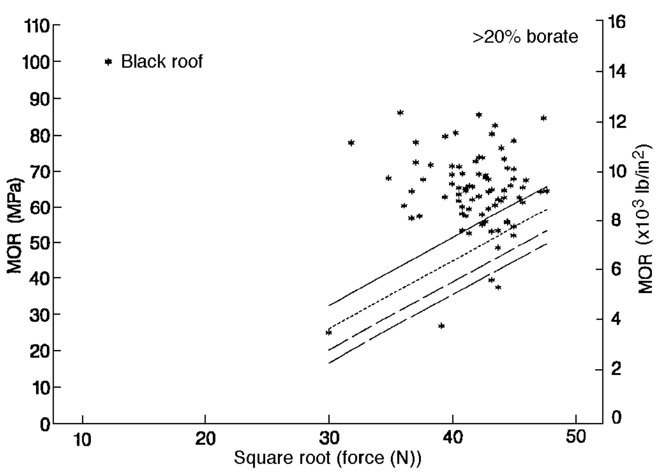

Figure 20—Example of applicability of models as shown by predicted mean trends and lower prediction bounds compared to real data from material treated with MAP and >20% borate. Real data were obtained from treated 16-mm- (5/8-in.-) thick material exposed in the field for 1 year; these data were not used to develop the model parameters (Winandy, in progress).

predicted mean trends and lower prediction bounds are in fact reliable, note that the mean trend is especially conservative. We believe that because the field exposure was limited to only one particularly cool year in Madison, Wisconsin, thermal loading (that is, exposure) was insufficient to produce a measurable response between strength and screw-withdrawal force. This lower-than-expected thermal loading during the summers of 1992 and 1993 was thoroughly discussed in a previous report (Winandy and Beaumont 1995).

Other Considerations

In accordance with our objectives, the prediction bounds constructed and reported in this paper were based on the prediction of a single future value. Similar prediction intervals could also be constructed on the basis of the prediction of a finite number of future values. Prediction intervals can be constructed from the information given in Tables 7 and 8. However, if the number of future predictions is large or unknown, then the use of tolerance intervals is the preferred methodology. The basic difference between prediction intervals and tolerance intervals is the mechanism by which they account for variability. As the number of future predictions increases, the usefulness of prediction boundaries becomes unacceptable (Miller 1981, Neter and others 1990).

It is important to select an appropriate confidence level. Selection of a high confidence level may tend to underestimate residual bending strength and thereby reject a higher number of test specimens than may be considered appropriate. Conversely, selection of too low a confidence level may tend to overestimate residual bending strength and thereby increase the chance of accepting a higher number of test specimens than may be considered appropriate. Users are advised to thoroughly consider the full implication of these decisions.

The models developed in this work can accurately predict residual plywood bending strength within user-specified levels of confidence from a measurement of screw-withdrawal force. Two problems still exist. First, while these models have been shown to work acceptably for special laboratory plywood constructed from all N-grade veneers, additional work is needed. Specifically, work is needed on the effects of plywood quality (such as manufacturing/processing methods, drying, species, veneer quality, voids), plywood temperature when it differs from room temperature at time of test, and deviation in plywood moisture content away from 10%–12% at time of test. Finally, using the concepts provided in this and earlier reports, researchers, engineering communities, and code authorities must work together to develop by consensus precision estimates and confidence levels that will enable third-party interpretation of these basic relationships in a manner similar to the methods used for machine-stress rating of lumber.

Examples

Using the screw-extraction-force instrument, suppose a user obtains a reading of 900 N (202 lbf) from a 12-mm- (1/2-in.-) thick, FR-treated (<20% borate) plywood specimen. The predicted bending strength would be obtained by substituting the regression estimates from Table 7 into Equation (3), yielding

$$\begin{aligned} \text{MOR} &= -13.59 + 2.09(900)^{1/2} \\ &= 49.1 \text{ MPa} \quad (7{,}123 \text{ lbf/in}^2) \end{aligned} \tag{3}$$

The predicted lower bound on that unknown strength, with a degree of confidence specified by $1 - \alpha$ (where $\alpha = 0.05$), as given by Equation (5) with estimates for Table 8, yields

$$\begin{aligned} R_{\text{lower bound}} &= 49.1 - 1.6492(10.25) \\ &= 32.2 \text{ MPa} \quad (4{,}671 \text{ lbf/in}^2) \end{aligned} \tag{5}$$

Conclusions

Individual models were developed for similarly performing groups of fire-retardant (FR) treatments and plywood thicknesses to predict average loss in strength and lower prediction bounds for plywood bending strength as a function of a screw-withdrawal measurement. Our analysis of FR-treated plywood from three different studies, each with various FR-treatment, processing, plywood thickness, and exposure temperature groupings, clearly indicated that various FR treatments and thicknesses of plywood could not all be grouped into a single “universal” model. The groups that could be combined were studied. The ensuing models had the general form

$$R_{\text{lower bound}} = \hat{y} - t_{n-2,1-\alpha} \cdot \text{SE}_{\text{p}}$$

The parameter estimates for several grouped FR formulations and plywood thicknesses are reported for a curvilinear lower prediction bound. Data are also provided for calculating the parameter estimates for a less preferable, but simpler-to-use, linear lower prediction bound. Both lower prediction boundary model forms were found to acceptably predict residual plywood bending strength for several FR formulations and plywood thicknesses near the mean. The curvilinear form (Eq. (5)) is preferred because of its more comprehensive nature when predicting values in the extreme tails of the screw-withdrawal-force distribution.

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