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Section 2 Test Methodology and assessment.

Serviceability modeling—Predicting and extending the useful service life of FRT-plywood roof sheathing

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ABSTRACT

One of the most, if not the most, efficient methods of extending our existing forest resource is to prolong the service life of wood currently in-service by using those existing structures to meet our future needs (Hamilton and Winandy 1998). It is currently estimated that over 7 x 10^9 m^3 (3 trillion bd. ft) of wood is currently in service within the United States of America (PATH 1999). Research programs throughout North America are increasingly focusing on understanding and defining the salient issues of wood durability and by maintaining and extending the serviceability of these existing wood structures.

This report presents the findings and implications of a major 10-year research program carried on at the U.S. Forest Products Laboratory. This research program developed serviceability models for fire-retardant (FR)-treated plywood roof sheathing exposed to elevated in-service temperatures and experiencing thermal degrade. FR-treated plywood roof sheathing is often required by U.S. Building Codes in roof systems for multifamily dwellings having common property walls. This 10-year research program found many important facts. Qualitatively, the mechanism of thermal degrade in FR-treated plywood was acid-hydrolysis. The magnitude of strength loss could be cumulatively related to FR chemistry, thermal exposure during pre-treatment, treatment, and post-treatment processing and in-service exposure. The effects of FR chemistry could be mitigated by use of pH buffers. The strength effects were similar for many levels of plywood quality. Quantitatively, a kinetics-based approach could be used to predict strength loss based on its time-temperature history. This research program then developed models with which to assess current condition, predict future hazard based on past service life, and then predict residual serviceability of untreated and FR-treated plywood used as structural roof sheathing. Each of these findings is briefly described in this report.

There are many opportunities for extending the useful service life of wood by better maintenance, remedial treatment, or enhanced serviceability assessment to predict both residual strength and residual utility. Results of research programs such as this can be used to extend service-life by providing the engineer with a estimate of residual serviceability and thereby avoiding premature removal. Many of the concepts employed in the development of these FR-plywood serviceability models are directly applicable to the development of predictive durability models for wood as affected by decay. When such a durability-based service-life model is developed, that serviceability model will aid building code officials, regulators, contractors, and engineers in determining replacement time schedules for wood undergoing biological attack.

Keywords: Serviceability, Modeling, Durability, Fire-retardant, Treatment

INTRODUCTION

North American building codes often require FR-treated plywood roof sheathing for 1.2 m on either side of fire-rated common property walls in multifamily dwellings. Some commercial FR-treatments have failed in this use due to premature thermal degradation in as little as 2-8 years (Figure 1). Serviceability assessment methods were needed to evaluate the condition of FR-treated plywood currently in use and to estimate its residual service life. The objective of an intensive 10-year research program was to develop:

- methods to assess the current condition of FR-treated plywood roof sheathing,
- models to relate strength loss to treatment, duration of exposure, and exposure temperature and humidity, and
- models to predict residual serviceability.

Figure 1. Example of fully serviceable untreated plywood roof sheathing (top left of photo) adjacent to thermally degraded FR-treated plywood roof sheathing (center) used next to a gypsum-sheathed 60-minute-rated fire wall (lower right).

Five critical needs were identified to develop tools with which to assess current condition and to develop a predictive residual service-life model for FR-treated plywood roof sheathing. These five needs were:

(A) define the mechanisms of thermal degradation,
(B) define the relative importance of treatment, chemical, and processing factors,
(C) develop methods and models for condition assessment,
(D) define service and design factors and define the thermal loads, and
(E) develop models for predicting residual serviceability.

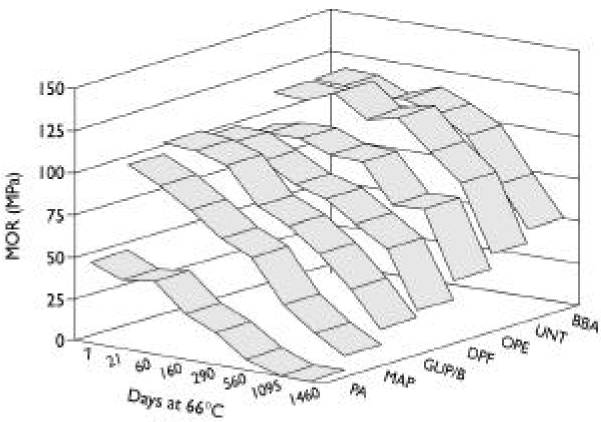
Our findings as they applied to each of these five research needs are now descibed.

A. Mechanisms of Thermal Degradation

Effects of FR treatments on strength properties were shown to depend on FR chemistry and thermal processing. FPL research confirmed that field problems with FR-treated plywood roof sheathing resulted from thermal-induced acid degradation.

Over 6000 specimens of density matched southern pine (16- x 35- x 250-mm) were systematically exposed at one of four temperatures: 25 °, 54 °, 66 °, and 82°C for exposures up to 4-years (LeVan et al 1990, Winandy 1995, Lebow and Winandy 1999). Data on the rates and magnitudes of thermal-induced strength loss at 27°, 54° , 66° , and 82°C were obtained for specimens treated with one of six FR-model chemicals or untreated. The influence of temperature and treatment pH was progressive, as shown by this example at 66°C in which each treatment (going from left-to-right on z-axis) has a progressively higher pH (Figure 2).

Figure 2 Strength loss over time of exposure to 66°C. Key to treatments: PA phosphoric acid, MAP monoammonium phosphate, GUP/B guanylurea phosphate/boric acid, DPF dicyandiamide-PA-formaldehyde, OPE organophosphonate ester, UNT untreated, and BBA borax/boric acid.



Kinetic-based models for predicting strength loss as a function of exposure temperature and duration of exposure were then developed from this data obtained at four temperatures. These kinetic models can be used predict thermal degradation at other temperatures (Lebow and Winandy 1999). A single-stage approach quantitatively based on time-temperature superposition was used to model reaction rates, such that:

$$Y_{ij} = b_j * \exp(-X * A * (H_i / H_o) * e^{(-Ea/RTij)}) \quad (1)$$

where

- i = Temperature of exposure,
- j = FR chemical,
- Y_{ij} = bending strength (MPa) at Temperature (T_i) for FR_j,
- X = time (days) at Temperature (T_i) for FR_j,
- b_{ij} = initial bending strength (MPa) at time ($X_i = 0$),
- H_i = relative humidity at test,
- H_o = normalized relative humidity (67% R.H. (per ASTM D5516),
- A = pre-exponential factor,
- E_a = activation energy,
- R = gas constant (J/°K*mole), and
- T_{ij} = temperature (°K) and for FR_j.

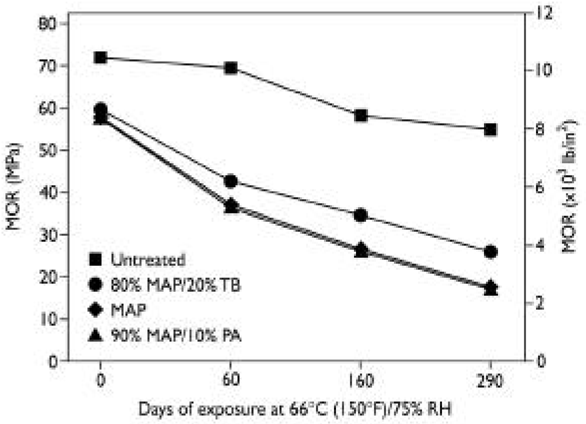
This kinetics-based model appeared to fit the combined data set (27°C, 54°C, 66°C and 82°C) as well or slightly better than alternative approaches (Lebow & Winandy 1999).

Working together with our academic and industrial cooperators, this program has resulted in three new ASTM Standard Test Methods: D5516 for evaluating FR-treated plywood, D5664 for evaluating FR-treated lumber, and D6305 for deriving engineering design adjustments for FR-treated plywood (ASTM 1999). All current AWPA FR-formulations have been evaluated under these methods and conditions (AWPA 1999).

B. Processing Factors

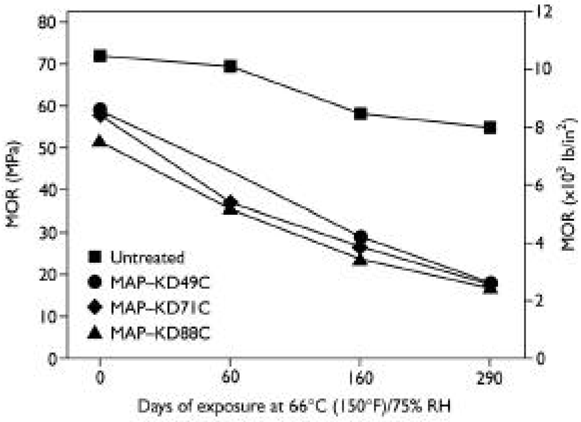
Our research has proved that the use of pH buffers in FR chemicals, such as borates, can partially mitigate the initial effect of the FR treatment on strength and then significantly enhance resistance to subsequent thermal degradation. For Modulus of Elasticity there appeared to be few real benefits derived from adding borate-based pH buffers to the FR-mixture on the subsequent thermal degrade of FR-treated plywood exposed to high-temperatures (Winandy 1997). However, after 290 days of exposure at 66°C there were significant ($p<0.05$) benefits derived with respect to limiting strength loss and loss in energy-related properties, such as work to maximum load, by the addition of borate to the FR-chemical mixture (Figure 3). Remedial treatments based on surface application of pH-buffered borate/glycol solutions were also developed to protect against additional in-service strength loss (Winandy & Schmidt 1995).

Figure 3. Effect of pH buffers on rate of thermal degrade (Winandy 1997). MAP is monoammonium phosphate, PA is phosphoric acid, and TB is sodium tetraoctaborate.



Other work also found that the rate of strength loss was largely independent of plywood quality or grade (Lebow and Winandy 1998). Further, variation in redrying temperatures from 49°C to 88°C had little differential effect on the subsequent rate of thermal degradation when the treated plywood was exposed at 66°C for up to 290 days (Figure 4). This was related to the shorter kiln-residence times required at higher temperatures yielding similar states of entropy via differing, but thermodynamically comparable, temperature-duration histories.

Figure 4. Effects of kiln-drying after MAP-treatment at 49, 71, or 88°C on thermal degrade (Winandy 1997).

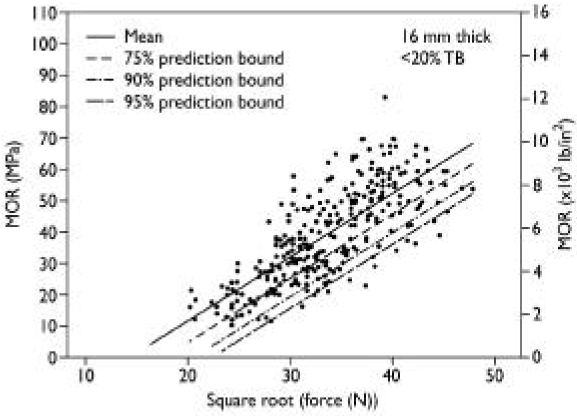


C. Condition Assessment

Before we could predict future strength loss, we had to know current condition. We found that screw-withdrawal tests (Figure 5) were reliable indicators of degradation (Winandy et al. 1998). This study defined constitutive relationships between nondestructively measured properties and the bending strength of FR-treated plywood (Figure 6). These constitutive relationships between screw withdrawal force and residual bending strength were then used in a similar manner as modulus of elasticity is used to predict bending strength in machine-stress-rated lumber grading. The final step to implementation will be for researchers and the engineering communities to work together to develop consensus precision estimates to enable third party interpretation of these constitutive relationships.

Figure 5. Screw-pull test using hand-held load cell.

Figure 6. Constitutive relationships for screw-pull tests (Winandy et al 1998).



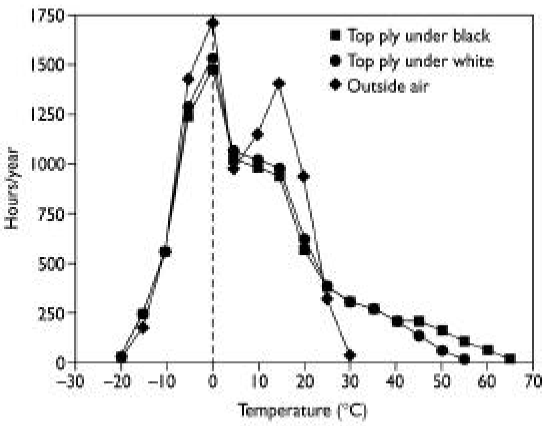
D. Serviceability Factors and Thermal Loads

Our first goal was to define relationships between field and laboratory exposures. Special roof temperature monitoring chambers were constructed in Madison, Wisconsin (latitude 43.4° North) and Starkville, Mississippi (latitude 33.5° North). These chambers monitored temperatures for the structural plywood and wood rafters in traditional North American wood-framed construction under asphalt-fiberglass shingles (Figure 7).

Figure 7. Field chambers for roof temperature studies in Wisconsin (Northern US) and Mississippi (Southern US).

Roof temperature data is now available for 8 years in Madison, Wisconsin (latitude 43.4° North) and 4 years in Starkville, Mississippi (latitude 33.5° North) (Winandy and Barnes 2000). The maximum temperatures recorded in our 4-year Mississippi study for black-shingled roofs in dry buildings were 78°, 63°, and 58°C for the top-ply veneer, bottom ply, and internal temperatures of nominal 2x8 (38- x 184-mm) rafters, respectively. The maximum temperatures recorded for the matched Wisconsin roof systems over an 8-year period were 75°, 59°, and 54°C, respectively. The maximum temperatures recorded in our 4-year Mississippi study for black-shingled roofs in heavily humidified buildings were the coolest at 74°, 58°, and 54°C for the top-ply veneer, bottom ply, and internal 2 x 8 rafter temperatures, respectively. Daily maximums and annualized temperature data for each wood component exhibited similar differences to that of the previously reported 3-year Madison data (Figure 8). These results clearly indicated that the temperatures of wood components used in wood roof systems were more dictated by the influx of radiant solar energy than by ambient outside air temperatures (Winandy and Barnes 2000).

Figure 8. Annualized roof temperature data for plywood roof sheathing in Madison Wisconsin (Winandy and Beaumont 1995).



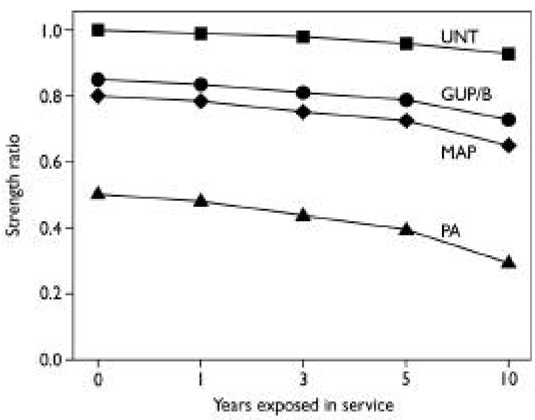
The second goal was to verify and refine the FPL temperature history model to predict in-service temperatures of wood roof-system components. The FPL Roof Temperature Model predicts roof temperatures for plywood roof sheathing based on geographical factors, site factors, orientation to sun, building construction, and historical weather data for that location (TenWolde 1997). That model has now been published and is used as the tool for predicting temperature histories for roof sheathing in untested locations and designs in our new residual serviceability models.

E. Predicting Residual Serviceability

The goal of this final project is to develop the best service-life model to evaluate residual service life of FR-treated roof sheathing plywood. A residual serviceability prediction model was recently developed to predict on-going strength loss from solar-induced thermal loads and to compare candidate FR-systems (Figure 9). We then used our models (*Eqn. 1*) to simulate a 10-year exposure in Madison, WI, USA using the annualized data shown in Figure 8. The predicted strength losses and field serviceability from these kinetic-based degrade models seems to parallel actual field performance. Our residual serviceability model predicted that the worst FR-model compound, which was a treatment of 56 kg/m^3 phosphoric acid (PA), could be expected to experience an additional 20% loss from its original in-service load capacity after the 10-year simulation. Untreated wood only experienced a predicted loss of 4% after the 10-year simulation. Other tested FR chemicals, such as 56 kg/m^3 of monoammonium phosphate (MAP) or a

70/30 mixture of guanylurea phosphate/boric acid (GUP/B), experienced intermediate levels of strength loss. Based on time-temperature superposition the loss in capacity in warmer, sunnier climates would be slightly greater. Information of this type is currently being introduced into U.S. design codes and standards.

Figure 9. Preliminary residual serviceability prediction model (Winandy 1998). Key to treatments: UNT untreated, GUP/B guanylurea phosphate/boric acid, MAP monoammonium phosphate, and PA phosphoric acid. Each has progressively lower pH.



The predicted strength losses and projected loss in field serviceability obtained by applying the kinetic degrade models discussed in *Section A. Mechanisms of Thermal Degrade* to measured roof temperature histories paralleled actual field performance. An extensive model development project is now underway to more fully define and refine the residual serviceability model for FR-treated roof sheathing exposed to elevated in-service temperatures.

SUMMARY

When completed, this residual serviceability model will aid building code officials, regulators, contractors, and engineers in determining replacement time schedules for wood undergoing acid-catalyzed thermal degradation. Many of the concepts employed in the development of these FR-plywood serviceability models are directly applicable to the development of predictive durability models for wood as affected by decay.

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