Predicting Current Serviceability And Residual Service Life Of Plywood Roof Sheathing Using Kinetics-Based Models

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Summary: Research programs throughout North America are increasingly focusing on understanding and defining the salient issues of wood durability and maintaining and extending the serviceability of existing wood structures. This report presents the findings and implications of a 10-year research program, carried out at the USDA Forest Service, Forest Products Laboratory, to develop kinetics-based service-life models for untreated and fire-retardant- (FR) treated plywood roof sheathing exposed to elevated in-service temperatures. This program was initiated because some FR-treated sheathing products were experiencing significant thermal degrade and needed to be replaced. This 10-year research program systematically identified the cause of the degradation and has resulted in new acceptance and performance standards and revisions to U.S. building codes. The strength loss was cumulatively related to FR chemistry, thermal exposure during pretreatment, treatment, and post-treatment processing, and in-service exposure. Quantitatively, a kinetics-based approach could be used to predict strength loss of plywood based on its time–temperature exposure history. The research program then developed models to assess current condition, predict future hazard based on past service life, and predict residual serviceability of untreated and FR-treated plywood used as structural roof sheathing. Findings for each of these subjects are briefly described in this report. Results of research programs like this one can be used to extend the service life of wood by providing engineers with an estimate of residual serviceability and thereby avoiding premature removal. Many of the approaches in these kinetics-based service-life models for plywood roof sheathing are directly applicable to the development of predictive durability models for wood and wood composite roof and wall sheathing that has been exposed to moisture and has eventually decayed. When those models are developed, they will help building code officials, regulators, contractors, and engineers in determining replacement schedules for wood undergoing biological attack.

Keywords: Service life, serviceability, durability, fire retardant, treatment

1 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 to 8 years (Fig. 1). Serviceability assessment methods were needed to evaluate the condition of FR-treated plywood currently in use and to estimate its residual service life. An intensive 10-year research program (Winandy 2001) was undertaken to develop models to

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

Five critical needs were identified for assessing current condition and developing a predictive residual service-life model for FR-treated plywood roof sheathing (Winandy 2001):

define the mechanisms of thermal degradation,

define the relative importance of treatment, chemical, and processing factors,
develop methods and models for condition assessment,
define service and design factors and thermal loads, and
develop models for predicting residual serviceability.

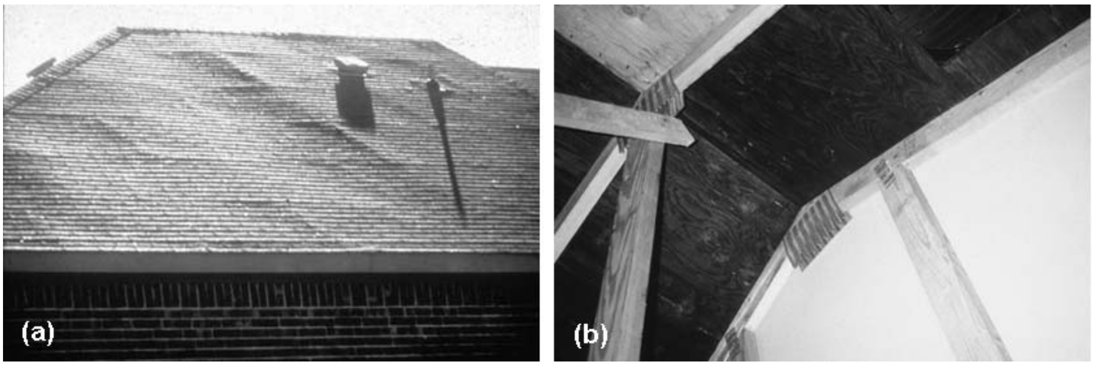

Figure 1. a) outside view of failed FR-treated plywood roof sheathing; and b) top left—inside view of fully serviceable untreated plywood roof sheathing; center—thermally degraded FR-treated plywood roof sheathing; and lower right—gypsum-sheathed 60-minute-rated fire wall.

2 MECHANISMS OF THERMAL DEGRADATION

Effects of FR treatments on strength properties 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.

More than 6,000 specimens of density-matched southern pine (16 by 35 by 250 mm) were systematically exposed at one of four temperatures: 27°C, 54°C, 66°C, and 82°C for exposures up to 4 years (LeVan *et al.* 1990, Winandy 1995, Lebow & Winandy 1999). Data on the rates and magnitudes of thermal-induced strength loss at the four temperatures were obtained for specimens treated with one of six FR model chemicals and untreated specimens. The influence of temperature and treatment pH was progressive, as shown in Figure 2 in which each treatment, at 66°C, has a progressively higher pH (going from left to right on *z* axis). The influence of humidity at temperatures in the 50°C to 80°C range was found to be much less critical to modeling the rate of thermal degrade than the contribution of temperature (Winandy *et al.* 1991).

Kinetics-based models for predicting strength loss as a function of exposure temperature and duration of exposure were then developed from these data obtained at four temperatures. These kinetic models can be used to 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:

$$Y_{ij} = b_j * \exp(-X * A_j * (H_t / H_o) * e^{(-Eaj/RTij)}) \quad (1)$$

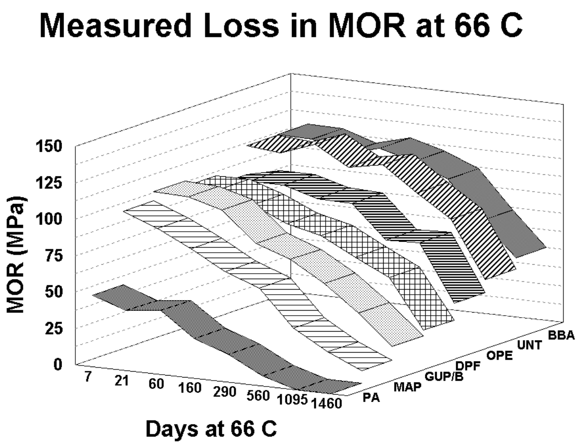

Figure 2. Experimentally measured bending strength loss with time of exposure to 66°C (Winandy 1995, Lebow & Winandy 1999) (PA phosphoric acid, MAP monoammonium phosphate, GUP/B guanylurea phosphate/boric acid, DPF dicyandiamide-PA-formaldehyde, OPE organophosphonate ester, UNT untreated, BBA borax/boric acid).

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_j	= initial bending strength (MPa) at time ($X_i = 0$),
H_t	= relative humidity at test,
H_o	= normalized relative humidity (67% RH per ASTM D5516),
A_j	= pre-exponential factor,
E_{aj}	= activation energy for FR_j,
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 (54°C, 66°C, and 82°C) as well or slightly better than alternative approaches (Lebow & Winandy 1999). However, this model should not yet be extrapolated beyond its intended temperature range (40°C–90°C) because it appears to overpredict strength loss at temperatures below 40°C (Winandy & Lebow, unpublished data).

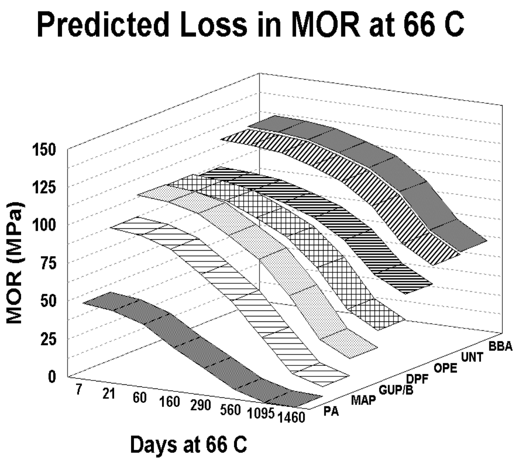

Figure 3. Predicted bending strength loss with time of exposure to 66°C (Lebow & Winandy 1999). (PA phosphoric acid, MAP monoammonium phosphate, GUP/B guanylurea phosphate/boric acid, DPF dicyandiamide-PA-formaldehyde, OPE organophosphonate ester, UNT untreated, BBA borax/boric acid).

With help from 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 2001). Also, all currently accepted AWPA FR formulations have now been evaluated under these methods (AWPA 2001).

3 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. 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).

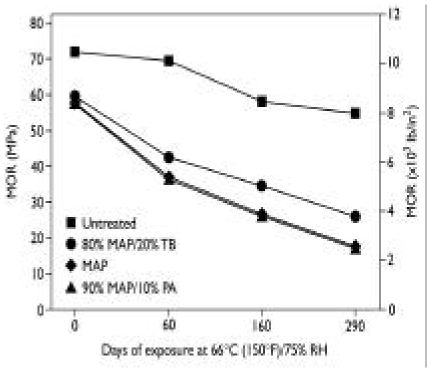

Figure 4. Effect of pH buffers on rate of thermal degrade (Winandy 1997) (MAP, monoammonium phosphate; PA, phosphoric acid; TB, sodium tetraoctaborate).

Other work also found that the rate of strength loss was largely independent of plywood quality or grade (Lebow & Winandy 1998). Also, 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. This was related to the shorter kiln residence times required at higher temperatures which yielded similar states of entropy via differing, but thermodynamically comparable, temperature–duration histories.

4 CONDITION ASSESSMENT

Before future strength loss could be predicted, current condition had to be assessed. We found that screw withdrawal tests (Fig. 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 (Fig. 6). These constitutive relationships between screw withdrawal force and residual bending strength were then used in a manner similar to how modulus of elasticity is used to predict bending strength in machine-stress-rated lumber grading. The final step toward implementation will be for researchers and the engineering community 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.

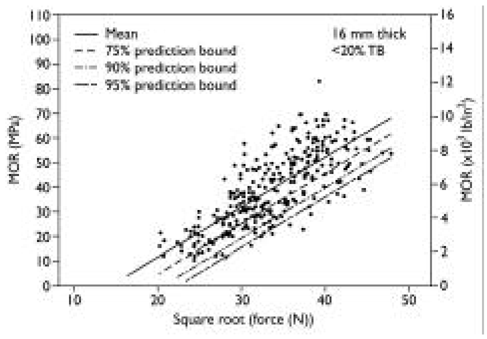

Figure 6. Constitutive relationships for screw-pull tests (Winandy *et al.* 1998).

5 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) (Winandy & Beaumont 1995, Winandy *et al.* 2000). These chambers monitored temperatures for the structural plywood and wood rafters used in traditional North American wood-framed construction under asphalt–fiberglass shingles (Fig. 7).

Figure 7. Field chambers for monitoring roof temperatures in Wisconsin on left (northern U.S., 43.4°N) and Mississippi on right (southern U.S., 33.5°N).

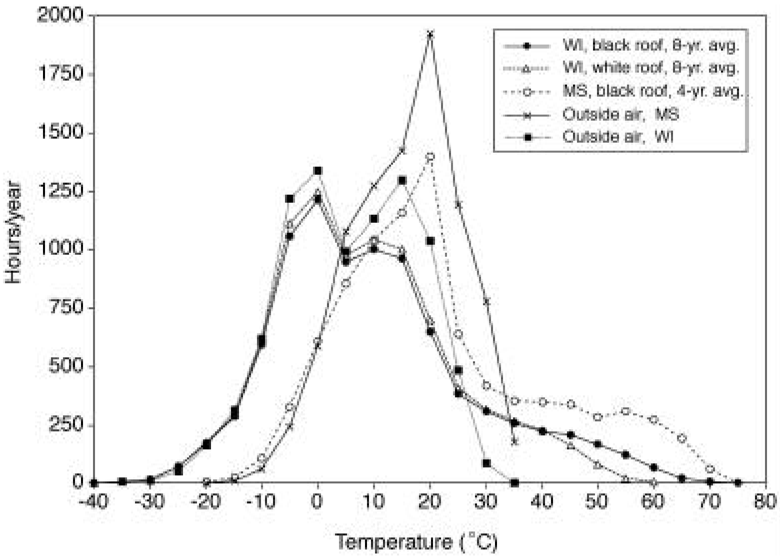

Figure 8. Annualized roof temperature data for plywood roof sheathing in Madison, Wisconsin (Winandy *et al.* 2000)

Roof temperature data are now available for 8 years in Madison, Wisconsin and 4 years in Starkville, Mississippi (Fig. 8) (Winandy *et al.* 2000). The maximum temperatures recorded in our 4-year Mississippi study for black-shingled roofs in dry buildings were 78°C, 63°C, and 58°C for the top-ply veneer, bottom-ply veneer, and inside nominal 2- by 8-in. (standard 38- by 184-mm) rafters, respectively. The maximum temperatures recorded for the matched Wisconsin roof systems during the 8 years were 75°C, 59°C, and 54°C, respectively. The maximum temperatures recorded in our 4-year Mississippi study for black-shingled roofs in heavily humidified buildings were cooler than in matched dry buildings at 74°C, 58°C, and 54°C for the top-ply veneer, bottom-ply veneer, and internal 2 by 8 rafter temperatures, respectively. Differences in daily maximums and annualized temperature data for each wood component were similar to those of the previously reported 3-year Madison data (Winandy & Beaumont 1995). These results clearly indicated that the temperatures of wood components used in wood roof systems were more influenced by the influx of radiant solar energy than by ambient outside air temperatures (Winandy *et al.* 2000).

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 (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 for designs in our new residual serviceability models.

6 PREDICTING RESIDUAL SERVICEABILITY

The goal of this final project is to develop the best 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 (Fig. 9). We used our models (Eq. 1) to simulate up to a 20-year exposure using the 8-year annualized data for both Wisconsin and Mississippi (Fig. 8). Our residual serviceability model predicted that plywood treated with 56 kg/m^3 phosphoric acid (PA) could be expected to experience an 11.3% loss from its original in-service load capacity after the 20-year simulation under a black roof in Wisconsin. Predicted strength loss for untreated wood was only 10.6% after the 20-year simulation under a black roof in Wisconsin. In Mississippi, which has many more warm days per year than does Wisconsin, those losses after 20 years were 31.8% for PA and 28.2% for untreated plywood under a black roof. Plywood treated with other 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. Information of this type is currently being discussed in U.S. design codes and standards.

a. Wisconsin (43.4°N) **b. Mississippi (33.5°N)**

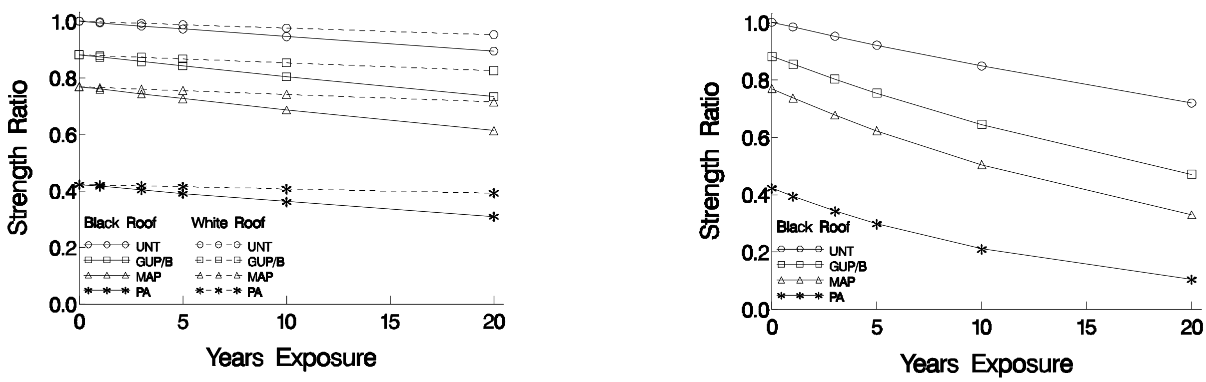

Figure 9. Predicted plywood strength after 20 years of in-service exposure using a preliminary residual serviceability prediction model. Each treatment has progressively lower pH (in the order of GUP/B, MAP, PA) (J.F. Murphy, P.K. Lebow, J.E. Winandy, Development of residual service-life models for plywood roof sheathing (unpublished)) (UNT untreated, GUP/B guanylurea phosphate/boric acid, MAP monoammonium phosphate, PA phosphoric acid).

The predicted strength losses and projected loss in field serviceability obtained by applying the kinetic degrade models discussed in the section 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.

7 SUMMARY

A kinetics-based service-life model can provide a valuable tool for building code officials, regulators, contractors, and engineers in determining replacement time schedules for wood and wood composites undergoing acid-catalyzed thermal degradation. Many of the concepts employed in the development of residual serviceability models for plywood roof sheathing are conceptually applicable to the development of predictive durability models for wood as affected by moisture and eventually by decay.

8 ACKNOWLEDGMENTS

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