Using Kinetic Models to Predict Thermal Degradation of Fire-Retardant-Treated Plywood Roof Sheathing

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ABSTRACT

Between 1985-1995 a substantial number of multifamily housing units in the Eastern and Southern U.S. experienced problems with thermally degraded fire-retardant-treated (FRT) plywood roof sheathing. A series of studies conducted at the USDA Forest Service, Forest Products Laboratory (FPL), examined the materials, chemical mechanisms, and process implications and has developed both practical and theoretical solutions for controlling strength effects during treatment and processing and for minimizing strength loss in-service. In addition to a series of technical publications, FPL research contributed to the development of four new ASTM/ANSI performance-based qualification standards to address performance issues as well as two new American Wood Preservers' Association (AWPA) standards to address treatment processing and strength-effect limits. Currently, field serviceability issues that have been quantified are being combined with formerly developed kinetic degradation models to predict service-life of FRT constructions.

INTRODUCTION

The economic, engineering, and environmental efficiency of wood make it a desirable material for fiber and structural use. Impregnation of wood with certain types of chemicals can substantially extend its service life beyond untreated wood when exposed to degrading, destructive environments. This allows wood, treated with chemicals, to extend its utility into new markets. Such is the case, in North America, where fie-retardant-treated plywood is sometimes permitted as an alternative to noncombustible materials in structures that require increased fie safety. However, in the mid-to-late 1980s, some commercial fire-retardant (FR) treatments failed to perform as expected when used as roof sheathing plywood and roof truss lumber. Elevated roof temperatures caused by solar radiation in combination with FR chemicals and moisture prematurely activated some FRs, often causing the plywood to exhibit a darker brown color, become brittle, experience cross-grain checking, and crumble easily. This problem required costly roof replacement. Because of the regional nature of building codes in North America, the problem was most common in the eastern United States on nonresidential commercial and multifamily dwellings built without parapet walls between 1980-1995. To lessen the economic and environmental costs of replacing up to 75 million FR-treated plywood panels, serviceability assessment methods were needed to evaluate the condition of FR-treated plywood and to estimate residual service life.

Extensive research defined the mechanism of the problem as well as contributing factors throughout an intensive 10-year research program conducted at the Forest Products Laboratory. Initially we focused on the effects of FR treatments on mechanical properties of the treated wood and on identifying the mechanism of thermal degradation as described in detail by Winandy et al. (1). Focus then shifted to the development of a FR-treated plywood serviceability research program (2). This involved a simultaneous progression of studies, each specifically designed to address important voids in our technical knowledge at that time. When evaluating the current and future serviceability of any structural system, such as roof sheathing, two questions need to be addressed. First, what is the current level of performance of the system? Second, if the system currently meets some acceptable level of performance, what is the expected remaining service life? The service life model developed under this FR-treated plywood serviceability program addressed these two concerns. Defining further chemical mechanisms, exploring the influences of processing factors and service conditions, and assessing the current condition of FR-treated wood in service were considered the initial objectives. Research also focused on defining the environmental and exposure conditions imposed on FR-treated wood in service as a result of design and location that could potentially influence strength degrade. The final objective was finalizing the development of a reliable tool for predicting residual service life of FR-treated roof sheathing that incorporates product and environmental uncertainties.

Aspects of the research program have been adapted to the standardization process to try to prevent future performance problems. Experimental methodologies that assessed the effects of FR treatments on mechanical properties and their potential to undergo thermal degradation on extended exposure to elevated temperatures resulted in two new ASTM Standard Test Methods (ASTM D 5516 and D 5664) (3). Standard practices for deriving adjustment factors for FR-treated plywood (ASTM D 6305 (3)) and FR-treated lumber (ASTM D 6841 (3)) were also developed. To preclude future serviceability problems with the use of FR-treated wood in engineered wood systems, these new ASTM test methods and design practices have been incorporated as mandatory treatment and performance requirements in AWPA Standards (4). Equivalent requirements have also been incorporated into the new use category system of the AWPA (4).

MECHANISMS OF THERMAL DEGRADATION

The reduction in initial strength properties of wood products treated with fire retardants has long been recognized, as well as initial accelerated loss due to post-treatment redrying, where accelerated drying of products is achieved through exposure to short durations of elevated temperatures (5). Engineers compensated for this initial reduction in strength from FR treatment and redrying through modifications to allowable stress design values. What was not foreseen prior to the mid-1980s was that additional in-service degradation in strength might occur when some FR-treated products were exposed to elevated temperatures such as those induced by solar loads on roof systems.

FR-treated plywood roof sheathing field failures were hypothesized to result from thermal-induced acid degradation of wood carbohydrates by the acidic FR chemicals (5). Subsequent work confirmed the proposed acid-degradation mechanism (6, 7, 8). We further discovered the relative effects of many FR treatments could be classified by the type of FR chemical infused and the time–temperature combination required to convert the FR formulation into its acidic-functional form (9).

Across time, temperatures and humidity, untreated and FR-treated wood specimens experienced a relatively consistent reduction in material properties over time of exposure at high temperatures. Figure 1 shows the effect of accelerated, steady-state high-temperature exposure on bending strength, modulus of rupture (MOR), for up to 4 years at 66°C (150°F) at 75% relative humidity on bending strength of untreated wood or wood treated with several FR-model formulations. Each treatment, at 66°C, has a progressively higher pH (left to right on the treatment axis). Data were compiled from Winandy (7) and Lebow and Winandy (6), which both include summarizations and evaluations for accelerated destructive degradation tests with additional specimens exposed to 54°C (130°F) and 82°C (180°F) for extended periods of time. Although the time axis in this figure is not shown to scale, we can still discern that that the two FR-model formulations having the lowest pH—phosphoric acid (PA) and monoammonium phosphate (MAP)—caused a significant reduction in the initial bending strength of the treated wood as well as a relatively consistent reduction in bending strength relative to time of exposure at high temperature. Wood specimens treated with less acidic guanylurea phosphateboric acid (GUP/B), dicyandiamide–phosphoric acid–formaldehyde (DPF), and organophosphonate ester (OPE) appeared to experience measurable initial strength loss with longer period of resistance to measurable thermal degrade. Untreated wood and wood treated with slightly alkaline borax/boric acid (BBA) exhibited little to no measurable reduction in initial bending strength, and appeared to have longer periods (~60 days) of resistance to thermal degrade than the other treatments.

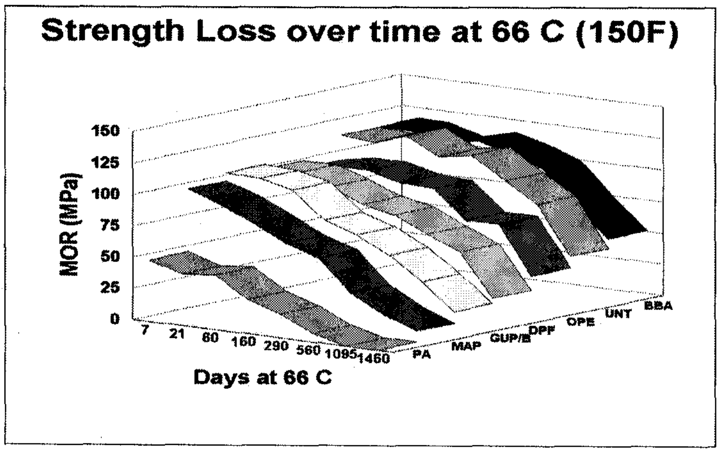


Figure 1. Average bending strength over steady-state exposure of up to 4 years at 66°C (150°F) for untreated (UNT) wood or phosphoric acid (PA)-, monoammonium phosphate (MAP)-, guanylurea phosphateboric acid (GUP/B)-, dicyandiamide- phosphoric acid-formaldehyde (DPF)-, organophosphonate ester (OPE), borax/boric acid (BBA)-treated wood (10).

Among the other mechanical properties, degradation of modulus of elasticity (MOE) was relatively less affected than bending strength. However, the effects of treatment and temperature were just as apparent after an extended period of time. By contrast, the effects of treatment and temperature on work to maximum load (WML) were more immediate and severe than the effects on bending strength and MOE. Since WML is a measure of energy to failure, it is a good indicator of embrittlement. Further details can be found in Winandy (10).

Other work has found that strength loss from cyclic thermal exposure was generally similar to that from steady-state temperature exposure when compared on a cumulative time-at-temperature basis (11).

To evaluate the data derived from the test method, several kinetics-based models for thermal degradation of FR-treated material were developed (12, 13, 14). We then built on that work to develop a single-stage kinetics-based model (6, 15) to predict the magnitude of thermal degradation for the series of FR-model treatments listed in Figure 1. The work demonstrated that a single-stage model could predict strength loss in FR-treated wood across a wide range of temperatures and exposure conditions. Extrapolation of the initial models of (15) resulted in accurate estimates of isothermal strength loss for fire retardant treatments where increased degradation occurred (6). Extrapolation for untreated wood and BBA treated wood resulted in conservative estimates of strength degradation; hence model parameter estimates were updated to reflect the long-term isothermal strength loss (6). In general, extrapolation beyond any tested conditions must be done with care. The nonlinear model used to characterize each treatment's time-temperature effect on strength (MOR expressed in MPa) degradation was given by

$$\begin{aligned} &MOR = \beta \cdot \exp\{-A \cdot (H / H_o) \cdot t \cdot e^{-E_a/(RT)}\} + \varepsilon \\ &\varepsilon \sim N(0, \sigma^2) \end{aligned} \qquad (1)$$

where the experimental variables are t for the time of exposure (days), T for the exposure temperature (°K), H for the exposure humidity (%). The physical parameters estimated for each treatment are *ß*, the initial bending strength at time zero, A, the pre-exponential factor, and E_a, the activation energy. Physical constants are R, the gas constant, and H_o, the normalized relative humidity, 67%, per ASTM D5516 (3).

SERVICEABILITY RESEARCH PROGRAM

The methodologies and metrologies of service life prediction have received increased emphases within the last five years, especially in the areas of paints and coatings (16, 17). Of particular interest is the general modeling framework outlined by Meeker, et al. (18), for developing a product service life prediction model and estimating service life distributions. Although our program for developing serviceability models for plywood sheathing began over a decade ago, it has basically followed their outline for identifying, characterizing, and quantifying the influence of processing effects, characterizing environmental thermal loads, and increasing our understanding of critical serviceability/durability factors. In addition, our framework includes the development of physical or chemical non-destructive methods to assess current 'in-service' condition and understanding their relationships to FR-treated sheathing failure mechanisms. This is a necessary component since our primary model development is based on accelerated destructive degradation tests whereby the strength can only be measured destructively; however a reliable method of estimating current 'in-service' strength non-destructively is considered important for sheathing specific predictions.

Deterministic prototypes of the final residual service life modeling program have been evaluated for feasibility, but need further development and evaluation to correctly characterize variables and their uncertainties. To the extent possible, the various research components of this program were performed concurrently. Following is a brief summarization of many of these projects; further details can be found in Winandy (10).

Processing Factors

As common with most products, manufacturing process factors were known to effect sheathing life, especially the chemical components that constituted an applied FR-treatment. It was not clear, however, the extent of those relationships or to what degree other processing factors may influence strength properties. Differences in property degradation rates between laboratory and field specimens initially appeared to be related to the severity of the processing factors employed in commercial treating and drying (2). Besides the influence of the mixture of various FR chemical components used in a commercial FR formulation, the temperatures employed in kiln drying FR-treated material after treatment, and the presence or absence of post-treatment drying and/or wetting during storage or construction were also suspected as contributors to strength degradation (9). Overall, we found that many product-manufacturing and treatment-processing factors contribute to the differential performance of laboratory and field materials.

Initially, key experimental factors were identified using dynamic mechanical analysis of small plywood veneers about 1 mm thick (19). The key factors that influenced thermal degradation were FR retention and in-service moisture content. The results of that study were used in the larger second phase of this project to define experimental factors using specimens cut from full-thickness ½-inch (12-mm), 5/8-inch (16-mm), and ¾-inch thick plywood sheets (8, 20-22). The length of the period of resistance to thermal degrade was directly related to the initial effect of the FR treatment on strength and appeared to be related to the pH of the treating solution or wood (20). We later proved that control of the treating solution pH by the use of pH buffers, such as borates, could mitigate the initial effect of the FR on strength and then enhance resistance to subsequent thermal degradation (8).

That same study showed that changing 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 (8). Further, the study showed that the effects of thermal exposure during both redrying and in-service solar loading were cumulative on a time-at-temperature basis (8). In other work we found that remedial borate treatments were useful in preventing additional thermal degrade (21). Finally, the influence of plywood quality on thermal degrade of various grades of FR-treated plywood was also studied and shown to be, to a great extent, independent of plywood quality or grade (22).

Condition Assessment

Predicting future strength loss for a particular piece of plywood would be enhanced by an estimate of its current condition. To develop usable nondestructive evaluation (NDE) techniques, we needed to understand and determine the NDE property's relationships with strength. Considerable concern existed about the in-place strength of FR-treated plywood. In addition, building officials and inspection professionals were frustrated by the lack of NDE tools available for assessing the residual strength of these materials. Definitive relationships between nondestructively measured properties and engineering design properties were needed before NDE techniques could be completely useful.

For wood sheathing there are two broad types of NDE methods: chemical and mechanical. Chemical-based NDE utilizes the relationship between changes in wood strength from thermal degradation and changes in wood pH, carbohydrate structure, or wood chemistry (20, 23, 24). This technique is rapidly becoming better understood and more reliable. LeVan et al. (9) clearly showed that early strength loss during the thermal degrade process was related to changes in hemicellulose composition rather than cellulose or lignin. Sweet and Winandy (23) found that degradation of hemicelluloses was more strongly related to incipient strength loss than was cellulose degree of polymerization. They proposed a qualitative model in which early strength loss was initially a function of degradation in hemicellulosic sidechain components like arabinan and galactan. Later strength loss involved dissolution of main-chain hemicellulosic components, like xylans and glucomannans, and finally, degradation of cellulose and lignin. These authors proposed that additional work might find this relationship quantitative (23). Quantitative models have been developed to predict residual strength from changes in chemical composition (24). However, chemical tests are often prohibitively expensive because of equipment needs and operator time. There is also considerable lag time between field inspection for sample collection and test results.

Mechanical NDE typically involves the measurement of a property considered to have a concomitant relationship with the property of interest, such as probe (screw) withdrawal relationships to strength. Screw withdrawal tests were initially conceived by Ross, et al. (25), and have been found to be simple and reliable indicators of degradation. Winandy et al. (26) defined constitutive relationships between nondestructively measured properties and the bending strength of FR-treated plywood, which were then used in a similar manner as MOE is used to predict bending strength in machine-stress-rated lumber grading.

Serviceability Factors and Thermal Loads

Roof sheathing is placed along the interface between outdoor and indoor environments, and as such can be influenced by both internal and external factors. Two goals were established as part of the research program to understand and characterize the influence of those factors. First defining the relationships between field and laboratory exposures was a critical step because of differing exposure environments. The second goal included the verification and refinement of the FPL roof temperature history model so that it could be incorporated in serviceability predictions.

Test chambers were built for both laboratory and outdoor field exposure in Madison, WI (latitude = 43.4° N.) in 1991 and in Starkville, MS (latitude=33.5°N) in 1994. The results of the 8 years of the roof temperature data collection have been reported (27, 28). Roof system temperatures (Table 1) and annualized thermal histories were reported for interior attic air, exterior air, inner and outer veneers of plywood sheathing, and internal rafter temperatures for both black- and white-roofed structures.

		Thermocouple Location		
		Top-Ply Veneer (°C)	Bottom-Ply Veneer (°C)	Inside Rafter (2 by 8-in=38 by 184-mm) (°C)
Wisconsin (8-yrs exposure)	Black-shingled, Dry, Unvented	75	59	54
	White-shingled, Dry, Unvented	64	53	49
Mississippi (4-yrs exposure)	Black-shingled, Dry, Unvented	78	63	58
	Black-shingled, Humidified, Unvented	74	58	54

Research on serviceability factors and thermal loads included further development and verification of the FPL Roof Temperature and Moisture Model, which is a physics-based model to predict roof temperatures and moisture contents in plywood roof sheathing based on historical weather data from any location (29). The FPL Roof Temperature Model has been adapted for FR-treated plywood and verified with moisture and temperature data, which were collected under an extramural cooperative project with the University of Illinois. The annual roof-temperature profiles used in ASTM Standards D 6305 and D 6841 (3) for various localities across the United States were generated using this model. In the serviceability models discussed in the following section of this paper, the FPL Roof Temperature Model provides the basis for adapting in-service temperature and climate factors from locations with known conditions to other untested locations.

Predicting Residual Serviceability

This final project was to develop a service life model to evaluate the residual service life of FR-treated roof sheathing plywood. Predicting the residual service life of sheathing requires a service life model that incorporates information from many of the previously outlined studies and also provides a fundamental framework for adding site- and exposure-condition factors. The model generates a condition assessment (see Condition Assessment section) by using a nondestructive assessment of residual strength based on a screw withdrawal test. This condition assessment is then adjusted to reflect predicted material degradation rates derived from kinetic thermal degradation models (see Mechanisms of Thermal Degradation section) and adjusted for predicted field exposure using structure-specific thermal performance models (see Serviceability Factors section) to estimate the remaining service life of FR-treated plywood roof sheathing. Such a model is now being studied comprehensively and further developed. A first attempt at such a residual serviceability model was recently reported (30, 31). It should be noted that this model has not been substantiated with field data, and efforts are currently underway to evaluate its suitability for actual field data.

A one-year temperature exceedence history (27) was initially used for projecting possible strength degradation over a 10-year exposure (6). Results indicated that untreated wood could lose 4% of its initial strength, while wood treated with the worst FR-model treatment (phosphoric acid at 58 kg/m^3) could be expected to experience an initial 57% strength reduction compared to untreated and unexposed, followed by an additional 11% (raw) loss in original in-service strength after the 10-year simulation. Wood treated with other FR-model chemicals, such as 56 kg/m^3 of monoammonium phosphate (MAP) or a 70%/30% mixture of guanylurea phosphateboric acid (GUPB), would experience intermediate levels of strength loss. Based on time–temperature superposition, the loss in capacity in warmer, sunnier climates would be somewhat greater. Portions of this information have been introduced into U.S. design codes and standards. Twenty-year projections based on extended temperature histories (28) for Wisconsin and for Mississippi were developed (31) as illustrated in Figure 2. Wisconsin in-service projections for the worst treatment (PA) were not as severe as previously reported (6) because there were substantially fewer hours at the lower temperatures (40°C-55°C).

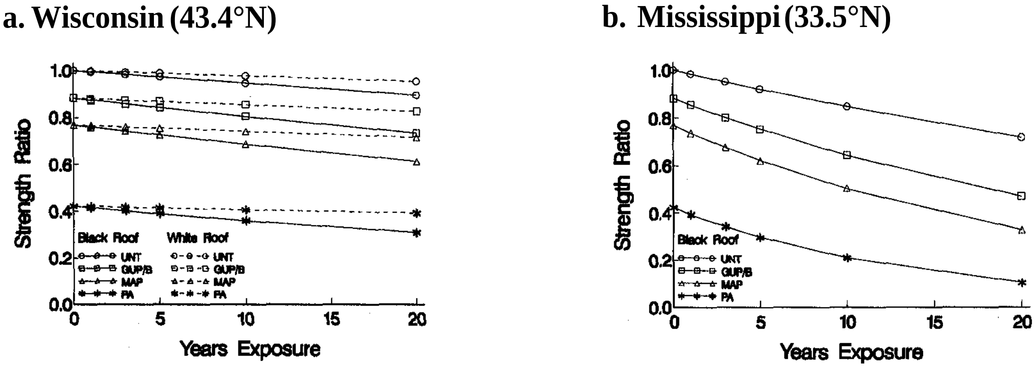
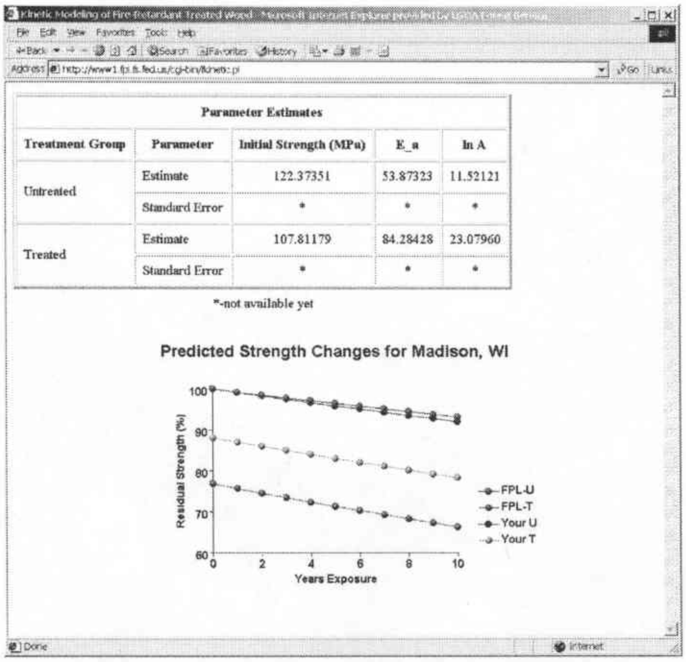


Figure 2. Predicted plywood strength after 20 years of in-service exposure using a preliminary residual serviceability model (31). Each treatment has progressively lower pH.

To further enable developers of fire-retardant treated plywood to estimate kinetic parameters for their product and help determine service life, an internet based implementation of our modeling approach has been deployed at wwwl.fp1.fs.fed.us. After uploading the appropriate data, our server calculates kinetic model parameter estimates using nonlinear regression routines (DNLS1E from the SLATEC package) from the National Institute of Standard's Guide to Available Mathematical Software (GAMS) website (32). Figure 3 illustrates the typical downloaded output from the program that would be displayed in the user's computer browser window. JAVA applets from Visual Engineering, Inc. (33) that graph residual service life are downloaded to the user's computer.



Parameter Estimates				
Treatment Group	Parameter	Initial Strength (MPa)	E_a	ln A
Untreated	Estimate	122.37351	53.87323	11.52121
	Standard Error	*	*	*
Treated	Estimate	107.81179	84.28428	23.07960
	Standard Error	*	*	*

*-not available yet

Predicted Strength Changes for Madison, WI

Figure 3. Web based program for estimating kinetic parameter estimates.

SUMMARY

The Forest Products Laboratory has research projects that are focusing on technologies aimed at extending the service life of wood used as structural systems by providing a more accurate condition assessment for residual serviceability analysis. Programs such as these will eventually increase the utility and durability of wood-based structures, increase the reliability and long-term efficiency of such structures, and decrease environmental impacts by making existing products last longer, thereby decreasing the need for replacement products. This paper focused on summarizing efforts at the FPL that characterized and quantified the effects of fire-retardant (FR) treatments on wood properties and described a serviceability framework to kinetically model and predict the residual service life of thermally degraded FR-treated plywood. First, assessments of the current residual condition or strength of FR-treated material is necessary. Then, future thermal loading based on past temperature history for material in that use and in that locality is predicted. Finally, the rate of future degradation of the material properties is estimated based on kinetic models parameter estimates from accelerated temperature exposure experiments and through the use of our internet-based modeling package.

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