SERVICEABILITY MODELING OF FIRE-RETARDANT-TREATED PLYWOOD ROOF SHEATHING

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SUMMARY

In North America, fire-retardant-treated plywood is sometimes permitted by building codes as an alternative to noncombustible materials in structures where increased fire safety is required (Sweet 1993). In the mid-to-late 1980's, some commercial fire-retardant(FR) treatments failed to perform adequately when used as roof–sheathing plywood and roof-truss lumber. When it occurred, this problem required costly roof replacement. Because of the regional nature of building codes in North America, the problem occurred mainly in the castern and southeastern United States on nonresidential commercial and multifamily dwellings built without parapet walls between 1976-1989. The problem is especially acute in urban areas where high property values have increased the attraction of multifamily dewllings. In addition. some State Governments in the United States require mandatory 10-year homeowners warranties in which those State Governments often underwrite some insurance liability.

Since 1990, extensive research at FPL has defined the meehanism of the thermal degrade problem, but field methods were and are still needed to evaluate the condition of FR-treated plywood currently in-service and from which to estimate its residual service-life. This report provides an update on our continuing research and describes the results of a series of completed research projects. These projects/studied are part of a systematic program intended to determine the current condition of FR-treated plywood roof sheathing and to develop methods to predict its residual serviceability out over an additional 2-3 yeat period.

INTRODUCTION

In the United States and Canada, fire safety is engineered into light-framed wood structures through either passive or active means in the four major regional Muilding Codes(Basic Code, Uniform Code, Southern Code and Canadian Code). The deciding factors when choosing between active and passive fire safety systems would be dictated by regional Building Codes and recommended designs would depend on:

1) Type of occupancy (i.e., commercial, residential, hotel, etc)
2) Life-safety characteristics (i.e., height, size, and type of structure and emergency egress from structure), and
3) Time to fire-suppression activity (in some Code-1ocations).

Passive measures are most often used in single-family and limited multifamily residential light-framed wood construction. These passive measures would include wood-framed walls sheathed with various thicknesses of gypsum wa11board(9, 12, or 16mm thick) or other wood-based or composite products. They might also include fire-retardant treated lumber and plywood. The decision process of the designer for selecting an appropriate wall/gypsum/sheathing make-up would be dictated within each regional Building Code by their prescriptive requirements. Active measures would include detection, alarm, and/or sprinkler systems which might be required for commercial and/or multi-family residential, high-rise($\geq$ 4 floors) structures.

In roof systems fire-retardant- (FR) treated lumber roof trusses and FR-treated plywood roof sheathing are sometimes permitted as an alternative to noncombustible construction materials. While some commercial fire-retardant(FR) treatments have performed acceptably for more than 15 years, some other FR treatments have experienced in-service thermal degradation and have failed to perform adequately when used as roof - sheathing plywood and roof-truss lumber. Because of a series of major regional Building Code changes, this in-service thermal degradation problem occurred mailny in the eastern and southeastern United States on nonresidential commercial and multifamily dwellings built without parapet walls between 1976-1989. The problem resulted because the Codes mandated only FR-treated materials which meet American wood Preservers' Association Standards C-20: FR-treated lumber and C-27: FR-treated plywood (AWPA 1996). However, both AWPA C20 and C27 are Product Standards which set a series of minimum performance requirements and prior to 1989 these performance requirements were insufficient for use under the reoccurring high-temperature exposures experienced by roofing systems, due to solar radiation.

After 1989, the field problems or FR-treated wood diminished because new performance requirements were instituted into AWPA Standards C20 and C27 which included strict limitations on temperatures and durations of post-treatment kiln-drying and pre-qualification strength-property testing after extended high - temperature exposures under two newly developed ASTM Standards, ASTM D-5516 (ASTM 1995a) and D-5664 (ASTM 1995h).

Replacement costs for thermally degraded FR-treated plywood roof sheathing have been predicted to exceed $2 U.S. billion (NAHB 1990). The first stage of a research program at the Forest Products Laboratory (FPL) involved a Conference of all involved parties which attempted to define the problem (ASTM 1988). This set the stage for a systematic series of studies at FPL which identified chemical mechanisms and quantified potential strength loss. That work was summarized by Winandy et al. (1991a). 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). In a comprehensive study using FR-treated clearwood, we 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 threshold required to convert the FR formulation into its acidic form(LeVan et al, 1990). Continuing work in that study confirmed that thermal degrade was consistent across treatment and temperature regimes (Winandy 1995). Additional work using plywood found that the rate of strength degradation for untreated and FR-treated plywood increased as relative humidity increased: a test method was developed to evaluate commercial FR treatments (Winandy et al. 1991b). Eventually, tentative guidelines for engineering design were developed (Winandy 1990).

As an overall result of this initial research program, a series of consensus Standards subsequently evolved from that test method for plywood (ASTM 1995a) and lumber (ASTM 1995b). These test methods provide a means to evalyuate the performance of new FR formulations prior to commercialization, thus avoiding costly in-service failures. These new Standard Test to assess performance for strength retention under elevated thermal exposures have recently been incorporated into AWPA Standards C-20: Lumber and C-27: Plywood which actually define the minimun performance requirements for fire-retardant treated lumber and plywood (AWPA 1996).

To elevate this resulting test data, several kineties-based models for predicting the extent of thermal degradation of FR-treated material have been presented (Woo 1981, APA, 1989a, Pasek and McIntyre 1990. and Winandy et al, 1991b), Winandy and Levow, P, K. (1996) built on that series of research publications to develop a single-stage Time-Temperature Model based on first-roder kinetic theory for a series of generic FR treatments. They recently verified that their single-stage kincties-based model could accurately predict strength loss (Lebow, P.K. and Winandy unpublished). Further work then 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 (LeVan et al 1996). This proved that accelerated steady-state laboratory exposure could be used to adequately screen and qualify new FR chemicals.

The FPL/NJ Serviceability Program

The next stage of research evolved to what is now called the FR-treated plywood serviceability program. We(NI code officials and FPL researchers) recognized that to evaluate the current condition and future serviceability of any structural system, such as roof sheathing, twe questions had to be addressed. First, what was the current lebel of performance of the system? Or in other words, did it currently meet existing design/performance requirements? Second, if the tested roof system currently met the code-specified level of performance, what is the expected remaining service-life? The service-life prediction model which is currently still under development under this FR-treated plywood serviceability program addresses these twe concerns.

To accurately address each of these twe critical concerns a simultaneous progression of studies were initiated in 1991. Each study was specifically designed to address important voids in our then-current technical knowledge. The research program required to develop the FR-treated plywood serviceability midel is reviewed in the next section on "Program Overview".

ln out opinion, the selected multiple-path approach has produced results which now loads us to predict success within the next year in developing a reliable tool for service-life prediction. Our plans call for FPL to carry through in publishing the results of each study cited in the next section. We will also supply to New Jersey Department of Community Affairs a service-life assessment model within the next 12-months.

PROGRAM OVERVIEW

To develop a predictive service-life model for FR-treated plywood roof sheathing, the following critical needs were identified (Winandy 1994)

1. Determine the key mechanical and/or chemical NDE parameters to predict strength, determine how these parameters should be measured, and empirically define their relationship to strength (Ross et al 1990, Ross et al 1992, S.T. Lebow and Winandy 1996, Winandy et al 1996).

2. Determine how relationships between treatment processing factors, mixtures of chemical components, and posttreatment temperature and moisture factors govern in–service performance: then relate these relationships to in-service thermal-indeced strength degradation rates (LeVan 1993, Sweet 1995, Winandy 1996, Winandy and Schmidt 1995).

3. Develop a kinetic-based midel to predict thermal induced strength loss in fire-retardant treated wood as a function of treatment and processing parameters and the temperature and duration of exposure to elevated temperature while in-service (Winandy unpublished, Winandy and Beaumont 1995).

4. Define relation ships between diurnal/seasonal field and accelerated laboratory exposures (Winandy unpublished, Winandy and Beaumont 1995).

5. Verify and refine the FPL Roof Temperature Model (Ten Wolde 1996).

6. Define the effects of roof sheathing plywood quality level and thickness in conjunction with in-service thermal degradation (S.T. Lebow and Winandy unpublished).

7. Select the best service-life model to predict future performance. This work is currently on going at FPL

The seven(7) FPL projects, two of which include extramural cooperative agreements, are either completed or now underway to achieve the overall program objective. Each project is now individually, but briefly reviewed in the next section. The reader is referred to the specific above references for more complete details on each individual project. Each report is included in the Appendixes.

INDIVIDUAL PROJECT OVERVIEWS

Study I. NDE Techniques for In-Place Evaluation of FR-Treated Plywood

Considerable concern is being voiced about the in-place strength of FR-treated plywood. In addition, building officials and inspection professionals are frustrated by the lack of nondestructive evaluation(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 usefully applied. Two board types of NDE methods exist, chemical and mechanical.

Chemical-based NDE, related to wood pH(a measure of a material's acidity) or changes in carbohydrate chemistry and strength is rapidly becomming better understood and more reliable (LeVan et al 1990; Winandy 1995), Still, chemical tests are often prohibitively expensive because of equipment needs, operator time, and lag-time between field inspection sample collection and test results.

Our recent report shows that the pH of FR-treated plywood is significantly reduced by the FR formulation and the duration of high temperature exposure (S. T. Lebow and Winandy 1996). The pH of plywood treated with a number of FR formulations decreased greatly during the first 60 to 160 days of exposure at 66°C (150°F). Formulations containing phosphoric acid(P.A) and monoammonium phosphate (MAP) or MAP alone eventually reached similar pH levels when subjected to lengthy high temperature exposure, lending credence to the hypothesis that the effects of the two types of formulations are similar, if sufficient energy is supplied to cause conversion of the MAP to PA. The trends in pH reduction for all the FR-treated groups paralleled the trends of decreasing modulus of rupture(MOR) and work to maximum load(WML). For the FR-treated plywood, strength loss and pH decreases attributed to thermal degradation were closely correlated during the first 160 days of high temperature exposure. During the final days of exposure the pH tended to stabilize, while strength losses continued to decline. These findings suggest that the pH of FR-treated plywood is a good indicator of the potential for future strength loss if the plywood is evaluated early in its in-sevice exposure to high temperatures. There is also the potential that pH combined with other evaluation techniques might be effectively used to predict the current condition of plywood. Further work is continuing in this area under the direction of Dr. S. T. Lebow.

Mechanical NDE often involves proof-loading-type tests or concomitant relationships such as the relations between stress-wave speed and modulus of elasticity (MOE) or stress-wave-attenuation and strength. The use of mechanical NDE in the field is often complicated by cumbersome equipment or inappropriate boundary conditions, which limit application by complicating signal processing.

Another variant of mechanical tests are probe (screw) -withdrawal relationships to strength. Screw-withdrawal tests have been found to be simple indicators of plywood degradation (Ross et al, 1992), but constitutive relationships were not defined until recently. Quantitative models have now been developed to predict loss in mean strength valuse and lower prediction bounds for plywood bending strength as a function of a probe(i.e., screw)-withdrawal measurement (Winandy er al 1996). Both nonlinear and linear prediction boundary models were found to acceptably predict residual plywood bending strength for several FR-formulations and plywood thicknesses near the mean, butthe curvilinear form was preferred because of its more comprehensive nature when predicting values in the extreme tails of the screw- withdrawal force distribution. (Winandy et al 1996). These constitutive relationships between screw-withdrawal force and residual bending strength can now be used in a similar manner as modulus of elasticity is used to predict bending strength in machine-stress-rated lumber grading.

The next step is for researchers, building inspector/users, engineering communities, and code authorities to work together to develop consensus precision levels and required strength-retention thresholds which will enable third-party interpretation of the results of these, constitutive relationships and predictive models.

Study II. Effects of Chemical Treatment and Processing and Use Factors.

Earlier FPL results (Winandy et al 1991a) indicated that the level of degradation in mechanical properties and wood composition induced by steady-state laboratory exposure was less than that experienced in the field. Differences between field- and laboratory-induced property degradation rates appeared to be related to the severity of the processing factors employed in commercial treating and in preparing FR-treated material for field installation. Rhese factors included the retention, the mixtures of various FR chemical components used to form a commercial FR formulation, the temperatures employed in kiln-drying FR-treated material after treatment, or possibly the lack of posttreatment drying and/or wetting during construction. Each factor contributes to the differential performance of laboratory and field materials; however, the relative effect and interaction of each factor are unknown.

In Phase I, key experimental factors were identified using dynamic mechanical analysis of small plywood veneers about 1-mm-thick (LeVan 1993). From that work the key factors identified were FR retention and in-service moisture content. Additional Phase 1 work was also earned out to look at the effects of treatment processing variables on cellulose degree of polymerization and chemical composition. In that work Sweet(1996) showed that the cellulose degree of polymerization was not initially affected. Instead, decomposition of hemicellulose were key indicators of thermally induced decomposition. confirming earlier findings (LeVan et al 1990, Winandy 1995)

In Phase II. a comparison of full-size FR-treated plywood, redried agter treatment at various temperatures between 54°C (120°F) showed no significantly different effect on the magnitude or the rate of those materials subsequent susceptibility to in-service thermal degrade (Winandy 1996). This was probably related to the fact that the higher redrying temperatures extensively higher than 88°C (190°F) were not studied. These higher redrying temperatures might conservatively be expected to impart some additional cumulative effect towards accelerating in-service thermal degrade.

The results showed that phosphate-treated plywood exposed to a lower cumulative thermal exposure or having lower phosphate-retentions experienced less thermal degradation than material having higher retentions or higher cumulative thermal loadings. These results support a hypothesis that the combined effects of phosphate-retention and cumulative thermal exposure(i.e., thermal load history from redrying after treatment and subsequent exposures to elevated in-service temperatures) are both additive and cumulative.

Finally, the addition of borate buffers to phosphate-based FR-treatment chemicals at a phosphate-to-borate ratio between 3-to-1 or 4-to-l seemed to significantly mitigate subsequent thermal degrade when FR treated plywood was exposed to elevated in-service temperature. From a qualitative basis, it did mot matter whether borate was added by addition of disodium octaborate tetrahydrate or boric acid. Subsequent work showed that in-service application of borate/gylcol solutions could inhibit further thermal degrade and might serve as remedial treatments (Winandy and Schmidt 1995).

Study 3. Correlation of Laboratory/Field Strenght- Temperature Effects

Previous FPL results had indicated that thermal-induced acid dehydration of wood carbohydrates caused thermal-induced in-setvice degradation of FR-treated roof sheathing. However, while the level of degradathon in mechanical properties and wood composition induced by steady-state high-temperature laboratory exposures was correlated to, it appeared to be less than, the magnitude of the degradation sometimes experienced in the field. Thus, differences between field- and laboratory-induced property degradation rates must be established for similarly processed FR-treated materials to extrapolate laboratory results to field serviceability.

In the summer of 1991 five field test chambers were built for outdoor field-exposure. These five field chambers, each holding 96 specimens have been in use for nearly 5 year at our Valley View outdoor test site about 8 miles southwest of Madison, Wisconsin, (latitude = 43.4 North). The cumulative number of hours at each temperature level for white- and black-roofed chambers from October 1991 through September 1994 (3-yeats) were recently reported Valley View roof temperature report (Winandy and Meaumont 1995). Because the summer of 1992 and 1993 in Madison were much cooler than normal, five additional field chamber were constructed in the spring of 1994 under an extramural cooperative project with the Mississippi Forest Products Laboratory near Starkville, Mississioop (latitude = 33.5 North). The addidional funding for this cooperative project was obtained through a USDA Competitive Grant received October 1993. These new Mississippi chambers will provide for direct comparisons between northern and southern U.S. climates. In both Wisconsin and Missossoppi, matched specimens exposed in steady-state laboratory-exposure chambers (65°C) and diurnal field-exposure chambers will provide a basis to determine the relationship between laboratory strength-temperature effects and field (real world) strength-temperature effects. An empirical comparative relationship will be developed based on the correlation between matched laboratory and field data. This relationship will then be further modified based on historical weather data from other locations to predict field performance in those locations based on the FPL Roof Temperature midel (TenWolde 1996). All laboratory exposures, 36-month field exposures in Madison, and 12-month field exposures at Mississippi are now complete. A preliminary lab-field correlation model based on 36-month Missippi field exposure data and 60-month Nadison data will be non-destructively evaluated for material in the Starkville, MS and Valley View, WI exposure chambers, respectively in early October 1996. If that October 1996 data still shows no significant degrade, the 36-month ,Mississippi field exposures and the 60-month Madison field exposures will be allowed to continue until measurable field-induecd thermal degrade has occurred. Thereafter, that data will then require approximately 6 months to equilibrate, test, and combine with current 12- and 36-month data. Hence, the apparent lack of progress on the earlier promised Lab-Field correlations publication (Winandy unpublished).

Study IV. Development and Verification of FPL Roof Temperature Model

A mathematical model has been developed and verified which predicts attic temperatures, relative humidities, and roof sheathing moisture contents (Tenwolde 1996). The paper describes the model and its capabilities, and presents a comparison of model simulation results to measured data to provide a limited validation of the model. The following conclusions were drawn from that comparison;

The model was capable of providing reasonably accurate estimates for temperatures of the roof sheathing and the attic air with the difference usually within 5°F. However, heat storage effects, which were not accounted for in the model, often cause a time-shift (delay) of one to two hours in attic air temperatures.

The model was capable of accurately predicting the frequency of occurrence of high roof sheathing temperatures (above 120°F) during summer, but its accuracy depends on an appropriate choice of solar absorptivity and omissivity of the roof shingles. However, data on emissivity and solar absorptivity are usually not available for specific shingles.

We were unable to determine the model's accuracy of attic air RH predictions because of the suspect quality of measured RH data.
The model appeared to be capable of predicting average moisture conditions in the sheathing with reasonable accuracy, generally within 1% MC, when moisture contents were not excessively high or low, Moisture behavior at high and low moisture contents and humidty conditions was not tested.

Hourly moisture behavior was not represented as well by the model as daily or seasonal behavior, especially when considering the north-facing sheathing However, the performance of the model may be improved ny adding a factor for moisture storage to the model. This factor would represent cyclical moisture sorption in the attic floor, insulation, structural memnbers. and other hydroscopic materials in the attic.

The "FPL Roof Temperature Model" was in-part verified using roof sheathing moisture and temperature data, which was collected under an extramural cooperative project with the University of lllinois (Rose 1992, Rose 1994), The FPL Roof Temperature Model will be provide a basis for predicting exposures at other locations such as New Jersey. Predicted thermal exposure performance data for several hypothetical types of roof systems in New York City has been obtained through use of the FPL Roof Temperature Model and is included as Appendix Y.

Study V. Interaction of Plywood Quality on FR-Effects

Research to clarify the role of solution formulation, treatment and re-drying practices, and exposure ‘conditions on degradation of fire-retardant trated plywood has primarily been conducted with a special "N-grade" of plywood that is nearly defect-free to minimize variability. To allow adaptation of this data base to commercial grades of plywood, our study sought to determine if plywood grade or thickness influences the manner in which fire-retardant treatment and subsequent high temperature exposure affects of FRT were evaluated on 1/2" and 3/4" Southern Pine plywood using 3 commercial grades (A-C Exterior, C-C Exterior, C-D Exposure) and plywood constructed from nearly defect free "N-grade" veneers. Samples in each grade and thickness were treated with monoammonium phosphate (MAP) and then subjected to high temperature exposure (150°F and 75% RH) for periods of either 30, 60, or 90 days. The modulus of rupture (MOR), work to maximum load (WML) and modulus of elasticity (MOE) of these treated specimens was then compared to that of similarly exposed but untreated controls.

Fire retardant treatment and subsequent high temperature exposure caused a reduction in mechanical properties, and especially WML, for all grades and treatment groups. However, statistical analysis revealed that there was not significant interaction between plywood grade or treatment, meaning that all grades were similarly affected by the exposure. There was also no significant difference in the manner that the treatment affected the two different thicknesses of plywood, After 90 days of high temperature exposure the residual values (on a percentage loss-basis) of MOR, MOE and WML for the two thicknesses were almost identical. These findings are very encouraging because they suggest that the results of our previous research based on N-grade plywood are readily applicable to commercial plywood grades and thicknesses.

Study VI. Model for Evaluating Service-Life of FR-Treated Plywood

The objective of this final study of the FR-treated plywood serviceability program is to develop a predictive service-life model. Predicting the service life of FR-treated plywood sheathing requires a service-life model that incorporates information from each of the just reviewed studies (Studies I-V). This serviceability model will allow code officials/regulators, contractors, and engineers to determine replacement time schedules for any FR-treated plywood undergoing acid-catalyzed thermal degradation. The serviceability model will use a nondestructive assessment of residual strength (Study I), adjusted for predicted field exposure using the thermal-performance models (Studies III and IV) and predicted material degradation rates derived from kinetic thermal-degradation model (Studies II and V), to estimate the remaining service-life of FR-treated plywood roof sheathing. Based on the results of recent research (Winandy and Lebow 1996, Lebow, P.K. and Winandy 1996). reliability theory (Thoft-Christensen and Baker 1982), and the stochastic (thermal) load approach of Murphy er al (1987) to assess rate of thermal-induced thermal degradation for FR-treated plywood roof sheathing.

CONCLUDING REMARKS

This report has outlined the overall approcah for developing a predictive service-life model through the fire-retardant–treated plywood serviceability program. It has also reviewed the progress to date and outlined the timetable of the remaining work in progress. When combined, each study will contribute to the final methodology that will assess the current residual strength of FR-treated material, predict the future temperature history of the material, and finally estimate the rate of furure degradation of the material proper-ties based on the predicted elevated temperature exposures.

We currently anticipate having an preliminary Residual Serviceability Model available by the end of March 1997. That model will them further evolve over an additional 6- to 12-month period as it is updated to include final data from the just reported on-going studies.

ACKNOWLEDGMENT

The authors would like to acknowdege the indispensable contributions of the staff of the Engineering Mechanics Laboratory at the Forest Products Laboratory(FPL). We also acknowledge the finabcial assistance of the State of New Jersey, Department of Community Affairs.

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제 3 회

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PROCEEDINGS OF THE THIRD
WOOD BUILDING/ARCHITECTURE TECHNICAL SEMINAR

1996년 11월 14일 (목요일)
NOVEMBER 14, 1996 (WED)

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