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Protection of Wood Designs in Adverse Environments

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Abstract

Engineers and architects are becoming increasingly aware of the risks of poor wood design practices and the benefits of using wood properly. This paper addresses biological factors that influence the risk portion of the risk–benefit equation. It further suggests appropriate methods to prevent designed-in failure through the use and specification of wood preservatives accepted by the U.S. Environmental Protection Agency.

Introduction

Water is wood's worst enemy. Designers need to predict moisture interactions in wood and take positive steps to prevent wood–water contact. Mechanical barriers will often exclude moisture. However, mechanical barriers are sometimes impractical or unreliable. Thus, chemical preservative treatments present a needed alternative. If wood becomes wet and decays, serious structural problems can result. It is the responsibility of the designer to either exclude water from the system or provide a chemical means of decay and insect control.

This paper discusses organisms that attack wood, preservative treatments available, wood products with which preservatives are most often used, treating standards of the American Wood-Preservers' Association (AWPA), and the effects of AWPA-specified preservative treatments on mechanical properties.

Organisms that Degrade Wood

Wood, because of its polymeric nature, is extremely resistant to degradation by most biological agents. However, wood is also an excellent energy source. A number of organisms have evolved the capability to either degrade wood or to use the woody matrix for shelter. In general, these organisms have four basic requirements: free moisture, oxygen, adequate temperature, and food. The simplest methods for preventing biological deterioration are to keep the wood dry to limit free water or to keep the wood constantly wet to limit the oxygen supply. However, neither method is practical for bridge timbers or other exposed wood structures. Thus, an accepted practical method for preventing decay is to

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alter the food source, normally by applying toxic chemicals to wood or by depending upon natural toxins that decay-resistant wood species produce in their heartwood.

Wood deterioration can be attributed to three primary groups of organisms: fungi, insects, and marine borers. Some fungi discolor the wood, making it less esthetically pleasing, but has little practical impact on strength. Fungal stain is often an indicator of poor handling practices. Wood-degrading fungi can depolymerize and metabolize wood, causing significant strength loss. The wood-degrading fungi are grouped into three categories, brown rot, white rot, and soft rot, depending on the nature of wood attack. As the name implies, brown-rotted wood is brown in color. Brown-rot fungi primarily attack the carbohydrates. Their enzymes tend to affect the wood at some distance from the actual point of fungal growth. As a result, brown rot is especially difficult to detect in the early stages of attack, and the strength losses associated with it are dramatic. White-rot fungi leave the wood bleached white in appearance. White-rot fungi utilize all components of the wood at approximately the same rate and the strength losses associated with these fungi vary linearly with time. Despite their more gradual attack, white-rot fungi can still produce significant strength losses in a short time. Soft-rot fungi tend to attack the wood surface particularly where the wood is constantly kept wet. Examples include cooling towers, wood in wet soils, and submerged wood. Although soft-rot attack is often a slow process, the concentration of its attack on the outer wood surface can have dramatic effects on bending properties. Furthermore, soft-rot fungi often exhibit tolerance to many wood preservatives and sometime cause external attack of preservative-treated wood.

Insects can cause a variety of wood damage, ranging from discoloration of sapwood as a result of the growth of fungi carried by insects to complete degradation of wood. Six orders of insects are associated with wood damage, but only three are of significance: termites, beetles, and carpenter ants.

Termites are among the most common and damaging insects in wood degradation. Termites are social insects that live in highly ordered colonies whose numbers may exceed 10^6 per colony. The colonies are divided into three castes: workers, soldiers, and reproductives. In the United States, four groups of termites cause degradation of buildings. Subterranean termites are the most prevalent of the four groups and are found throughout most of the United States. They annually cause nearly 10^9 dollars in damage in the southeastern United States. Subterranean termites require soil contact and generally attack wood that has some moisture present. They can provide additional moisture to the wood by constructing earthen tubes up from the ground to wood not in ground contact. Formosan termites are similar to subterranean termites but have larger colonies and more aggressive feeding habits. Formosan termites are currently found along the Gulf Coast and in Hawaii, and they pose a major risk to wood in these areas. Dampwood termites are similar to subterranean termites, but their range is confined to the Pacific Northwest. These insects require very wet wood and can generally be controlled by removing the moisture source. Dampwood termites are sometimes transported in bundles of green lumber and can cause substantial damage as long as the wood remains wet. Drywood termites, found in the southwestern United States, pose the greatest termite-control challenge because they can attack dry wood (≥ 13 percent moisture content). These insects enter buildings through vents and can cause extensive damage with little evidence of their activity. Control of drywood termites normally requires fumigation of the building.

In general, it is far simpler to prevent termite attack than to control existing infestations. The use of preservative-treated wood in areas near the ground appears to be the most practical method for preventing termite attack. This method, when used in combination with soil drenches of termiticides around the foundation of a building, should provide the highest degree of protection.

The next group of wood-inhabiting insects are beetles that normally cause damage in the larval stage. Beetles lay their eggs on or in the wood, and the eggs hatch into larvae. The larvae chew through the wood, digesting this material. Many beetles lay their eggs on the bark of freshly sawn trees, and the larvae continue their development in the finished wood product. Once they complete their development, the larvae pupate to become adults, exit the wood, and do not reinfest. Powderpost beetles, however, can attack wood without bark and at moisture contents less than 20 percent. The larvae of powderpost beetles tunnel throughout the wood leaving frass, extensive collections of fine, powdery droppings, which gave the beetle its name. Powderpost beetles can cause damage in museum pieces that are left unattended for long periods.

Beetle damage can be prevented by the use of preservative-treated wood. Preservative treatments that use elevated temperatures can sterilize the wood and eliminate beetle larvae that have already colonized the sample. However, treatments that do not use elevated temperatures will not.

The third group of wood-inhabiting insects are the carpenter ants. Carpenter ants differ from the other wood-inhabiting insects in that they use the wood only for shelter and do not digest the wood. Still, they can cause significant damage. Carpenter ants are social insects, much like the termites, and construct elaborate galleries inside large timbers or poles. Carpenter ants pose a hazard throughout the eastern United States and Canada. Their control also poses a challenge because their nests are difficult to locate and their colonies are quite mobile.

The final group of organisms that attack wood is the marine borers, which, as the name suggests, require some salinity to survive. Three types of marine borers attack wood in coastal regions of the United States, including Hawaii and Alaska: shipworms, pholads, and Limnorans. Shipworms are wormlike mollusks that tunnel inside the wood, growing to diameters of 1.25 to 2.5 cm and lengths of 0.3 to 1.5 m. As they tunnel, these organisms remove wood material, leaving the pile or timber unable to support compressive loads. Pholads are clamlike mollusks that bore just under the wood surface. The zone around their borings is weakened and eroded by wave action. Continued attack by pholads reduces the diameter of the wood to the point where it can not hold the load for which it was designed. Pholads pose a problem in tropical environments such as those found in Hawaii. Limnorans are mobile crustaceans that tunnel in the wood near the surface. These organisms also weaken the wood near the surface, leaving this material susceptible to scouring by wave action. Piling that experiences severe *Limnoria* attack eventually takes on an hour-glass shape near the tide line. Marine-borer attack can generally be prevented by the use of chemically treated wood or by the use of polyurethane barriers. Chemical treatments include creosote for preventing shipworm, pholad, and most Limnoria attack, Chromated copper arsenate (CCA) and ammoniacal copper zinc arsenate (ACZA) for preventing shipworm and *Limnoria tripunctata* attack, and dual treatment with both chemicals for severe tropical exposures.

Preservative Treatments

Where temperature, oxygen, and moisture cannot be entirely controlled, the only course currently available to the designer is to poison the wood food source. Preservatives are broad-spectrum toxins designed to poison the wood food source while maintaining levels of mammalian toxicity acceptable to the U.S. Environmental Protection Agency.

In North America, the most commonly used oilborne preservatives are creosote, pentachlorophenol, and copper naphthenate. Copper–8–quinolinolate is also used where direct contact with food may occur. The most commonly used waterborne arsenical preservatives are CCA and ACZA. The oilborne preservatives usually enhance dimensional stability because their oily solvents restrict the movement of water into the wood. The waterborne preservatives provide a clean, odor-free, paintable or stainable product. They also enhance user safety because the chemical components do not readily leach from the treated product into the surrounding environment. Waterborne preservatives achieve this optimized leach resistance through either of two mechanisms. In the ammoniacal systems, the metal salts-oxides precipitate as the ammonia evaporates, forming water-insoluble complexes within the wood cell lumens. Conversely, in chromium-based systems, the metal salts precipitate (in a hydrolytic process commonly termed fixation) as water-insoluble complexes form within the cellular structure or upon the cell lumens. In this process, the chromium is reduced from a hexavalent state to a trivalent state, and the wood material is oxidized. These fixation or precipitation processes give waterborne preservative-treated products their desirable properties: however, these processes can also reduce the strength of wood.

Preservative treatment of wood represents one of the fastest growing segments of the forest products industry. Until about 20 years ago, creosote and pentachlorophenol were the major preservatives used in North America. Currently, waterborne arsenical preservatives command the major portion of the treated-wood market. Between 1978 and 1987, production of creosote- and pentachlorophenol-treated wood decreased 37 percent, while production of waterborne-treated wood rose 450 percent (USDA 1980, Micklewright 1989).

Treatment Standards

Both the American Wood-Preservers' Association (AWPA) and the American Society for Testing and Materials (ASTM) publish preservative standards (AWPA 1989, ASTM 1989). In addition, the AWPA Annual Book of Standards includes standards for treating and quality control in the treating process and inspection and purchase of treated wood. Thus, AWPA standards are often used. The AWPA standards are updated on an annual basis by the members who represent the common interests of treaters and users. To appreciate the number of treating concerns that must be addressed in specifying a treated product, the architect or engineer should carefully read two AWPA standards: M–1 on the purchase of treated wood and C–1 on the general principles of pressure treating. The following paragraphs briefly describe the more important AWPA standards. The AWPA standards can be divided into four general areas of interest: preservative (P), commodity (C), analytical (A), and miscellaneous (M). These standards often represent a series of maximum allowable treating limits that are intended to guide the treater rather than suggest best alternatives to the specifier. Therefore, carefully study the standards before attempting to use them.

Preservative Standards

The P–standards specify the composition and character of the preservative chemicals and their solvents that are approved for use. These standards include P–1/13 for coal–tar creosote; P–5 for waterborne preservatives such as CCA and ACZA; P–8 for oilborne preservatives such as pentachlorophenol, copper naphthenate, copper–8–quinolinolate, bis(tri-N-butyl tin) oxide; and P–9 for solvents of organic preservative systems.

Commodity Standards

The C–standards describe the technical limits of the processes used to pressure treat various commodity products. They include maximum limits for treatment pressures, temperatures, durations, and pre- and posttreatment conditioning factors. Also listed are recommended chemical retentions and penetrations. The most important of these standards is C–1 because it outlines the general requirements of treating wood by pressure processes. The other C–standards each refer to specific commodities and detail the various treating limits for that product, while referencing C–1 for general treatment principles. These other C–standards include C–2 for lumber and timbers, C–3 for piles, C–4 for poles, C–6 for crossties, C–9 for plywood, C–20 for fire retardant lumber, C–27 for fire retardant plywood, and C–28 for glulam.

Analytical Standards

The A–standards describe chemical assay or analytical methods that are used to insure that the preservative penetrates the wood to the desired depth and loading level. These standards include A–1 for creosote, A–2 for waterborne preservatives and fire retardants, A–3 for determining preservative penetration, and A-5 for oilborne preservatives.

Miscellaneous Standards

The M–standards describe the general methods of specifying a treated product. These standards include M–1 guidelines for specifying and purchasing treated wood, M–2 for inspection procedures, M–3 for in-plant quality control, M-4 for care, handling, and fabrication requirements, and M–5 for a glossary of terms common to the treating industry.

Practical Limits in Specifying Treated Products

In principle, all wood in a timber should be treated with a chemical for optimum protection. However, certain properties of some species limit the extent of treatability. For example, after treatment, thin members may be completely penetrated, but thick members will have an untreated core. In these instances, it becomes especially important to specify the product so that the outer shell of treated wood remains unbreached, allowing it to act as a barrier against fungal and insect attack. Acceptable penetration can be enhanced by deep incising to improve the uniformity of treatment, through pretreatment drying to insure that checks formed after treatment do not exceed the depth of preservative penetration, and preboring or cutting to length to reduce the need to field fabricate during installation. In round stock, a high degree of preservative penetration can be achieved in critical decay hazard zones by kerfing, radial drilling, or through-boring. Careful specification, which includes pre- and posttreatment processing, can have a dramatic effect on the quality and ultimate field performance of treated material.

Effects of Treatments on Properties

The strength of wood is affected by moisture content, temperature, and preservative treatments. The question is, When and to what degree is wood strength affected?

Oilborne Preservatives

Creosote, pentachlorophenol, and copper naphthenate treatments have little effect on wood mechanical properties. However, to enhance penetration of these viscous oilborne solutions into the wood, the treated products or preservative solutions are heated during the treating process. Thermal processes can significantly reduce wood strength and must be controlled to minimize strength loss. In AWPA standards, the steaming and heating in preservative temperature–duration limits are designed to minimize the effects of creosote, pentachlorophenol, or copper naphthenate treatments on wood mechanical properties. If AWPA standards are strictly adhered to, the effects of oilborne preservatives on strength are negligible.

Waterborne Preservatives

The effects of waterborne preservative (WBP) treatment on wood strength appear to be directly related to several factors: species, WBP chemical or type, retention, posttreatment drying temperature, initial kiln-drying temperature, and incising (if required). This complexity makes it difficult to answer the seemingly simple question of exactly how WBP treatment affects mechanical properties. A review of each factor will illustrate their interaction.

Species—The results of several studies suggest that most species are affected by WBP to approximately the same degree (Winandy et al. 1985, Winandy et al. 1989, Resch & Parker 1982). Thus, if a chemical reduces bending strength of pine by 10 percent, it will reduce bending strength of Douglas-fir similarly.

Preservative Chemical–As WBPs undergo fixation or precipitation, these reaction processes affect strength. Accordingly, the relative impact of a WBP is directly related to its chemistry and the severity of its fixation or precipitation reaction. Generally, ammoniacal preservatives are considered to have less effect on strength than are the hydrolytic WBPs (CCA and other chromium-based WBP). The degree of strength effects associated with each of the three common CCA formulations used in North America appear to be directly related to their respective chromium contents (Bendtsen et al. 1983). The relative strength effects then seem to be as follows:

ACA (least effect) < CCA–B < CCA–C < CCA–A (most effect)

Preservative Retention–At the most commonly used preservative retentions of 4.0 to 9.6 kg/m^3 (0.25 to 0.60 lb/ft^3), the relative effects of WBP on wood strength are very similar when dried after treatment at comparable temperatures. However, the higher retentions required for marine use, 40 kg/m^3 (2.50 lb/ft^3), significantly reduce bending strength and reduce compression strength when treated wood is redried at 60°C (140°F).

Redrying Temperature–Regardless of the grade–size–species combination being considered, it is generally conceded that CCA treatments have little practical effect on strength when lumber is air dried after treatment (Winandy and Boone 1988, Winandy 1989). On the other hand, the negative strength effects from CCA treatments when lumber is kiln dried after treatment can be significant. In instances where redrying temperatures exceed 88°C (190°F), losses in bending strength become significant. At redrying temperatures below 71°C (160°F) (and possibly as high as 88°C (190°F) depending on grade), the reductions in strength and stiffness from WBP treatments apparently are not severe enough to warrant concern. Accordingly, AWPA standards currently limit redrying temperature to 88°C (190°F) for WBP-treated material.

Strength reductions appear to be more severe for higher lumber grades. Although redrying at 88°C (190°F) significantly decreased bending strength in No. 1 and Better Southern Pine nominal 2- by 6-in.(nominal 51- by 152-mm) lumber (Barnes & Mitchell 1984), it had little effect on the bending strength of No. 2 Southern Pine (Winandy & Boone 1988). However, all studies have shown significant strength loss when temperatures above 88°C (190°F) are used (Barnes & Winandy 1989).

Under comparable conditions, WBP treatments cause less strength reduction in larger sizes than in smaller sizes. This is probably related to the surface-to-volume ratio of each end product. Recent reviews have concluded that at comparable preservative retentions, poles and piles are generally reduced in strength less than 2 by 4 or 2 by 6 lumber, which in turn, is reduced in strength less than small (2.5 cm) clear specimens (Barnes & Winandy 1986, Winandy 1988).

Initial Kiln-Drying Temperature – while treating and redrying methods have come under considerable scrutiny in recent years, the implications of the effect of initial kiln drying on subsequent treatment and redrying have been neglected. Initial kiln drying of Southern Pine lumber at high temperatures 100°C to 116°C (212°F to 240°F) apparently has little effect on its structural properties (Gerhards & McMillen 1976, Koch 1985). However, recent work has shown that initial high-temperature kiln drying does increase the susceptibility of treated and redried material to further strength loss (Barnes et al. 1990, Winandy et al. [In preparation]).

Incising – Incising significantly increases the penetration of preservatives, which results in increased decay resistance. However, most incising patterns reduce strength. It is generally agreed that the strength loss associated with incising is beneficial because the increase in treatability provides substantial improvements in biological performance. For example, an incised 2 by 4 may be reduced in strength by 10 to 20 percent when compared to an unincised 2 by 4. But, if these 2 by 4's are exposed to a severe decay hazard, the incised product will substantially outperform the unincised product. Incising should always be required for non-sapwood-containing material, regardless of species. However, although strength-effects data are limited, enough are available to lead us to support a 10-percent reduction in allowable design stresses for incised and treated materials less than 5 in. (12.7 cm) in least dimension. Incising is required by the AWPA standards for treatment of thin sapwood species. Whenever required by the AWPA standard, incising should never be waived.

Fire Retardant Treatments

For some types of multifamily residential and nonresidential construction, building codes require treatment with fire retardant (FR) chemicals. Although these treatments effectively retard flame spread and combustion, they also reduce wood strength. These strength reductions could be magnified when the lumber or plywood is improperly treated and kiln dried after treatment.

Fire retardant treatments use waterborne chemicals that yield a wood product with moisture contents of 50 to 100 percent. Drying after treatment is required (AWPA 1989) to dimensionally stabilize the material, inhibit chemical blooming, minimize in-service fastener corrosion, and reduce shipping weight. However, kiln drying after treatment can reduce the strength and stiffness of FR-treated wood unless relatively mild drying conditions are employed (Gerhards 1970, Winandy et al. 1988). Accordingly, AWPA specifications for FR-treated wood dictate that redrying temperatures shall not exceed 71°C (160°F) until the mean treated-wood moisture content falls below 25 percent. This requirement recognizes that elevated temperatures interact with the excess moisture in freshly treated wood to accelerate thermal–chemical degradation.

The effects of FR treatments and subsequent redrying on wood strength can be categorized by the type of FR and redrying temperature employed. In a comprehensive review of the FR-treatment literature, Gerhards (1970) concluded that the effects on modulus of rupture, modulus of elasticity, and especially work to maximum load are significant when FR-treated wood was kiln dried after treatment. The reductions in engineering design stresses generally range from 10 to 20 percent depending on the property and the FR chemical being considered. Because each FR formulation is proprietary, recommended adjustment factors to allowable design stresses should be obtained directly from the treater or treatment formulator.

Concluding Remarks

Water is wood's worst enemy. Whenever wood is at moisture contents greater than 20 to 30 percent, it becomes susceptible to attack by fungi and insects. This risk of deterioration places added responsibility on engineers and architects to design wood structures so that moisture is excluded. In many instances, water cannot be excluded and the wood must be chemically protected from decay.

Preservative chemicals are broad-spectrum toxins designed to poison the wood food source used by wood-destroying organisms. The major preservatives used in North America are creosote, pentachlorophenol, and waterborne arsenicals. Creosote and pentachlorophenol in heavy oil are often used in bridge timbers, ties, poles, and piles. Pentachlorophenol in light oils is the preferred preservative for glulam timbers. The waterborne preservatives are popular for lumber, marine piles, and plywood. Fire retardant (FR) chemicals are used for lumber and plywood.

Preservative treatments are usually performed under the American Wood-Preservers' Association (AWPA) Standards, a series of voluntary standards that describe treating chemicals,. processing, quality control, and inspection. The P–standards specify composition of the various preservatives. The C–standards detail maximum treatment process levels and requirements for the various commodities that are preservative or fire retardant treated. The A–standards describe analytical methods for the chemicals used. The M–standards describe miscellaneous standards for inspection, quality control, and purchase of treated products.

Preservative and FR treatments generally reduce the mechanical properties of wood. This effect is exaggerated when the wood is dried after treatment at high temperatures. Both preservative and FR treatments employ an upper redrying temperature limit. When the AWPA standards are strictly adhered to, no reduction in allowable design stresses is required for preservative-treated wood. Incising reduces wood strength and stiffness; yet the increased field performance of incised and treated material supports its use. For incised and treated materials less than 5 in. (12.7 cm) in least dimension, a 10-percent reduction in allowable design stresses may be appropriate. For FR-treated materials, strength is reduced and allowable design stresses require adjustment. Recommended design property adjustment factors should be obtained directly from the treater.

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