WOOD BRIDGES—DECAY INSPECTION AND CONTROL

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Basic information relating to the cause of decay, to conditions conducive to its initiation and spread, and to means of preventing its occurrence is provided. Procedures for inspecting wood bridges for presence of decay are covered, including steps in preparing for inspection, visual signs of decay, and methods of detecting internal and external decay. Means of controlling existing decay or of preventing new infections are detailed.

KEY WORDS: Wood decay fungi ; decay resistance; wood preservatives ; in-place treatment ; decay detection ; fumigation ; moisture control.

WOOD BRIDGES—DECAY INSPECTION AND CONTROL

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PREFACE

Wood in use is almost inevitably exposed to decay fungi. Bridges, because of their wet locations, exposure to the elements, and design, are particularly susceptible to decay if not properly treated. We can ill afford the deterioration of bridges from any cause because of our dependence upon them for safe passage and because of their importance to commerce.

As of 1971, it is mandatory that all Federal-aid-system bridges be safety-inspected at least every 2 years. That mandate led to the preparation (by the authors of this handbook) of a manual on decay inspection for wood bridges. That manual was prepared for the use of the Engineering Staff of the Forest Service, U.S. Department of Agriculture.

While the manual was adequate for that purpose, it was subsequently felt that the information contained therein could benefit a wider audience, including engineers, wood products pathologists, and educators, as well as those involved in bridge inspection and maintenance work. In this handbook, hence, we have revised the original manual to accommodate the more diverse readership.

The authors wish to thank the Forest Service Engineering Staff, both in the Washington Office for their financial support, and in the field units for onsite assistance and for advice and discussions.

Mention of a chemical in this publication does not constitute a recommendation; only those chemicals registered by the U.S. Environmental Protection Agency may be recommended, and then only for uses as prescribed in the registration and in the manner and at the concentration prescribed. The list of registered chemicals varies from time to time; prospective users, therefore, should get current information on registration status from the Environmental Protection Agency, 401 M Street NW, Washington, D.C. 20024.

Numbers in parentheses refer to Literature Cited at the end of this report,

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SUMMARY

Considerations of wood decay, conditions, and causal organisms are presented for the engineer as basic information for the inspection and maintenance of wood bridges. Included are the requirements for fungus growth conditions conducive to decay, natural decay resistance of wood used in bridge construction, wood preservative treatments, and limitations of such treatments. Inspecting bridges for decay covers preparation for inspection, visual search for evidence of decay and conditions conducive to decay, equipment required, and the mechanics of detailed examinations. Maintenance and preventive maintenance measures for the control of decay are considered in regard to member replacement and structural modification. Moisture control and in-place-treatment methods are recommended with details for their application to prevent initiation of decay or to arrest decay before it causes significant structural damage.

WOOD BRIDGES—DECAY INSPECTION AND CONTROL

BRIDGES AND DECAY

Timber bridges, properly designed and adequately preservative-treated, fit well into the rural scene (fig. 1) and provide many years of service. These bridges are widely used in secondary road systems, in the National Forests, and in more than 1,500 miles of railroad structures (2). All use large quantities of wood, hence the proper design, treatment, and maintenance of these structures will aid in increasing the service life and safety of these structures and, consequently, result in conservation of both lives and timber resources.

The purpose of this handbook is to provide information on the characteristics and control of decay in wood bridges and wood bridge members to aid bridge inspectors and bridge maintenance crews. The information may also be of interest to bridge design engineers and to those concerned with bridge construction. The considerations apply to both new and older bridges.

The use of properly preservative-treated wood in bridge construction has significantly extended the service life of bridges, but decay

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Figure 1.—Timber bridges fit well into rural settings.

is still the primary cause for wood bridge replacements whether the service life of the structure has been abnormally short or long. For most wood bridges, a preventive maintenance program, including simple supplemental preservative treatments coordinated with the systematic inspections that are now mandatory,[1] can significantly extend bridge service life. Such a program is highly desirable, both from the standpoint of safety for the public and to help reduce bridge costs.

Minimizing the decay hazard in new bridges should be a responsibility of the design engineer and should be considered in his choice of materials, preservative treatments, design details, and to some degree in construction practices. The bridge contractor or builder should also take a similar responsibility in the handling, storage, and assembly of the various materials. During the service life of the structure, significant decay can be minimized by alert inspectors who can locate and provide information on developing decay infections or areas likely to become decay centers. With such information, maintenance crews can make the necessary supplemental in-place treatments to curb the development of decay that will otherwise make early repair or replacement necessary. To accomplish these aims some basic knowledge of the decay process and its limiting factors will be necessary.

The material is presented in three sections:

- Wood decay: Cause, characteristics, and occurrence.
- Inspecting wood bridges for decay.
- Decay and bridge maintenance.

WOOD DECAY: CAUSE, CHARACTERISTICS, AND OCCURRENCE

Inspectors must recognize potential problem areas where decay can occur in individual bridges. They must also confirm the presence and define the limits of any decay present in such areas. Variations in structural designs, materials used, bridge age, and various exposure factors make this a complex assignment. It is, therefore, desirable for the inspector to be acquainted with basic information about wood decay, its cause, and the factors that favor or limit its development. With such information as a guide, inspections can be tailored to individual bridges.

The Nature of Decay

Decay in wood is caused by living fungi, which are simple plants having the unique capacity to break down and utilize wood cell wall material as food. The fungus in an area of decaying wood is generally invisible but present as a growing network of microscopic threads (hyphae) that penetrate and ramify throughout the wood. Such areas are initially infected by the germination of fungus spores, which are functionally equivalent to the seed of higher plants. These spores, which are produced in great numbers, are microscopic; they are distributed so widely by wind, insects, and other means that they are commonly present on most exposed surfaces.

Many spores never germinate for lack of a sufficiently moist environment or as a result of prolonged exposure to direct sunlight. Others die shortly after germination for lack of water or food, or from the toxic components of wood preservatives.

Established infections of decay fungi in bridge members may result from the spores being carried by rain, snowmelt, or condensation from openly exposed surfaces into areas favorable for successful germination. Such areas include fastener holes, joint interfaces, or seasoning checks, all having the required moisture for a sustained period in decay-susceptible wood. Because environmental conditions in wood above ground may be unfavorable for fungus growth much of the time, a new surface infection generally does not quickly penetrate far into the wood from the germination site. However, under continuing favorable conditions, the fungus may penetrate aboveground wood bridge members sufficiently to become well established in a few weeks.

Once established, the fungus continues to grow as long as favorable conditions prevail.

[1] The National Bridge Inspection Standards, published in the Federal Register in April 1971, requires that all bridges on any of the Federal-aid systems be inspected at maximum intervals of 2 years.

Such growth is associated with changes in the character of the invaded wood. The wood cell walls may be perforated or thinned, or the walls of adjacent cells may be disassociated, with a consequent loss of structural strength. At the same time, the porosity of the infected wood increases. The greater porosity results in more water absorption during a given interval of rain or other wetting. As fungus growth progresses, an increasing number of growing hyphae occupy the margin of the expanding area of infection and this accelerates the rate of decay.

Conditions Required for Fungus Growth

Significant wood decay can only occur when four essential conditions prevail for fungus growth. Depriving the fungus of any one of these requirements will effectively curtail decay. These growth requirements are oxygen, favorable temperature, food, and water.

Sufficient oxygen.—A sufficient supply of oxygen must be available to fungi for their respiration. Comparatively small amounts of oxygen are necessary for vigorous growth and even less is required for dormant existence, but decay fungi cannot survive without some free oxygen. Unfortunately, this essential requirement by the fungi is generally not subject to practical, manipulative control in bridge members. The primary exception is piling placed in water so that it remains completely submerged at all times, severely limiting the amount of oxygen available in the wood.

Favorable temperature.—A favorable temperature range is a second requirement for fungus growth. At freezing temperatures, and below, fungi simply become dormant but remain alive and capable of a resumption of growth when prevailing temperatures rise above freezing. Growth rates gradually increase from near freezing to an optimum range at approximately 75° to 85° F, but growth drops off rapidly for most decay fungi as temperature rises above 90° F. Only temperatures well in excess of 100° F are lethal for most decay fungi. Such high temperatures do not occur naturally in bridge members other than at surface areas of dark wood exposed directly 'to summer sun. Rarely do these high surface temperatures penetrate appreciably into the wood. Thus, the temperature requirement also is not generally subject to control in bridge members to limit fungus growth. However, lethal high temperatures are an important factor in the elimination of living decay infections in new materials that are either kiln dried, steam seasoned, or preservative-treated by heat and pressure methods.

Adequate food.—An adequate supply of food is a third requirement for fungus growth. It is one of the essential needs of decay fungi that is subject to control and by which decay can be prevented. All sapwood, and heartwood with low natural decay resistance, can be used as a food source when other conditions are favorable. Heartwood from a naturally durable species, however, will be resistant in some degree to fungal attack. This resistance may be later lost as a result of weathering, leaching, or from other causes. An effective degree of decay prevention is possible through the process of poisoning the wood with appropriate wood-preserving chemicals. Natural decay resistance and preservative treatments will be discussed later in greater detail.

Available water.—Available water is the fourth requirement for initiation and spread of wood decay. Dry wood will not decay although the widely used misnomer "dry-rot" may imply that possibility. Moisture content of wood is one of the most significant factors regarding wood decay because a considerable amount of water is required for fungus growth and, in many instances, the moisture content of wood in service is subject to control.

Not only does the amount of water in wood directly control the possibility of fungus infection and growth, but it is significant to the decay process in less direct ways. Prolonged or repeated wettings contribute to leaching and a consequent loss of natural decay resistance. Further, during the seasoning of large timbers, the loss of water is accompanied by shrinkage that normally results in the development of seasoning checks. Such checks may expose untreated parts of preservative-treated timbers and may also form water-trapping pockets that can become infection sites for decay fungi. For these and other reasons it is important to understand basic wood-moisture relationships.

When wood is dried or seasoned from a wet condition, the drying cells give up any water

present in the cell cavities (free water) before the water absorbed in the cell walls (bound water) is removed. Conversely, as wood is wetted from a dry condition, the affected cell walls absorb water to their maximum capacity before water is accumulated in their respective cell cavities.

A number of related factors should be noted in regard to free and bound water:

- Wood containing a maximum capacity of water in the cell walls but no free water in the cell cavities is said to be at *fiber saturation,* i.e., at about 30 percent moisture content.
- Significant growth of the common decay fungi in wood depends on the presence of water in the cell cavities. Wood maintained at moisture contents below fiber saturation can be considered safely dry from decay hazard.
- After wood members have been dried or seasoned to a point below fiber saturation, prevailing humidities alone will not wet them enough to support decay. To attain moisture content levels above fiber saturation, such wood must be subjected to water contact.
- The shrinking and swelling of wood resulting respectively from drying and wetting occurs only in regard to water in the cell walls and thus in the moisture content range below fiber saturation (0 to 30 percent of the ovendry weight of the wood). The removal or addition of water in the cell cavities does not cause dimensional changes in wood.

The moisture content of large wood members is rarely uniform. In bridge structures exposed to natural weather cycles, variations in moisture content are likely to be broad. Fungus activity is directly affected only by the moisture content of the wood in the immediate vicinity of the infection. Thus a member may be well seasoned and generally dry, but be infected and severely decayed at a localized area such as a water trapping check, near a joint interface, or at some other point where the wood is continuously or repeatedly wetted at short intervals or where drying of the wood is inhibited after wetting. Soil-contacting members commonly show high moisture levels favorable for decay.

The primary source of hazardous wetting is rain, although snowmelt, condensation, and stream or ground water are also important sources. The decay potential for exposed wood is primarily correlated geographically with variations in average rainfall (16). This factor, plus temperature, or more specifically the number of days per year in which average temperatures are above freezing, permits an estimate of potential for decay on a regional basis. Thus the southern gulf coast area with abundant and frequent rainfall and a long growing season represents an area high in conditions conducive to decay. The Northwest Pacific Coast area is also in this category predominantly because of an unusually high yearly rainfall. Bridges in areas having low (less than 25 inches per year) rainfall, or abnormally short growing seasons, will have reduced potential for decay.

Fungi and Their Relative Importance

A very large number of fungus species have been found associated with wood. A considerable number of these species can cause decay, but only a small number are probably associated with decay in bridge timbers. While it is often necessary to be able to separate these wood decay fungi from the nonwood decayers, specific identification of the decay-causing organism is not necessary for the general purposes of bridge inspection and maintenance. In most cases, unless the fungus has developed its characteristic fruiting structure in which the reproductive spores are produced, it can only be identified by isolating and growing it on artificial media for detailed study. This process is time consuming, requires the services of a specialist, and in most cases the species determination would not change the inspector's appraisal of the decay present or the engineer's recommendations for corrective measures to be used in the maintenance procedures.

Some fungi, such as those causing mold and stain, use the wood cell contents rather than the cell wall material as food; hence, little or no wood strength is lost. However, the presence of active nondecay fungi will generally indicate conditions that are also appropriate for decay development. Further, the presence and continued growth of some mold and staining fungi may cause a slow detoxification of the natural

toxins or chemical preservatives and predispose the wood to earlier decay than would otherwise occur.

Another group of fungi, known as soft rots, are now recognized as being damaging to wood under certain conditions. These fungi, when present, generally attack and cause slow deterioration of surface wood that remains in an unusually wet condition. Normally such organisms cause little significant strength loss in wood bridge members.

The typical and long-recognized wood decay fungi fall into two broad classes, one group causing the brown rots and the other causing white rots. When significant decay occurs in bridges it will generally be caused by these organisms. Further, these fungi are associated predominantly with interior or hidden decay, particularly in preservative-treated members but also in untreated members, as intermittent surface drying frequently inhibits decay development on exposed wood surfaces.

The early stages of both brown- and white-rot infections are similar. Advanced or typical decay by the two groups can be differentiated, however, both on the basis of color and on the physical character of the decayed wood. Wood with advanced decay caused by the brown-rot fungi is brittle, usually brown in color, and typically shows distinct cross-grain checks that are similar in form to charcoal on the face of a heavily charred timber. In contrast the white-rot fungi produce decay that resembles normal wood in appearance; it may be whitish or light than in color and have a distinctly soft and punky texture, but the material is not commonly checked.

Generally, there will be a gradient of deterioration severity. At the advancing margin or newest part of the infection, there is little change in appearance or in strength properties of the wood. It progresses through more advanced stages of deterioration to the typical advanced decay, or actual void, representing the older parts of the infection. In the advanced or typical stages of decay the wood retains virtually no strength. Usually an inspector's appraisal of decay must be based on bored shavings or cores taken for that purpose. Recognizing decay in relatively early stages will be necessary. Locating decay will also be the most practical method of determining whether any fungi present include species that are destructive—asopposed to staining or other non-decaying fungi.

Conditions Conducive to Decay

The decay potential for wood members exposed in contact with the soil is generally more severe than for members exposed above ground (fig. 2). Soil-contacting parts of members such as posts, piling, abutments, and wing wall materials are exposed in some degree to nearly constant wetting. This results in wood moisture gradients that generally span or reach the optimum moisture content range for decay. The moisture level favorable for decay occurs below ground line in moderately dry soils but near or even at ground line in wetter sites. Soil

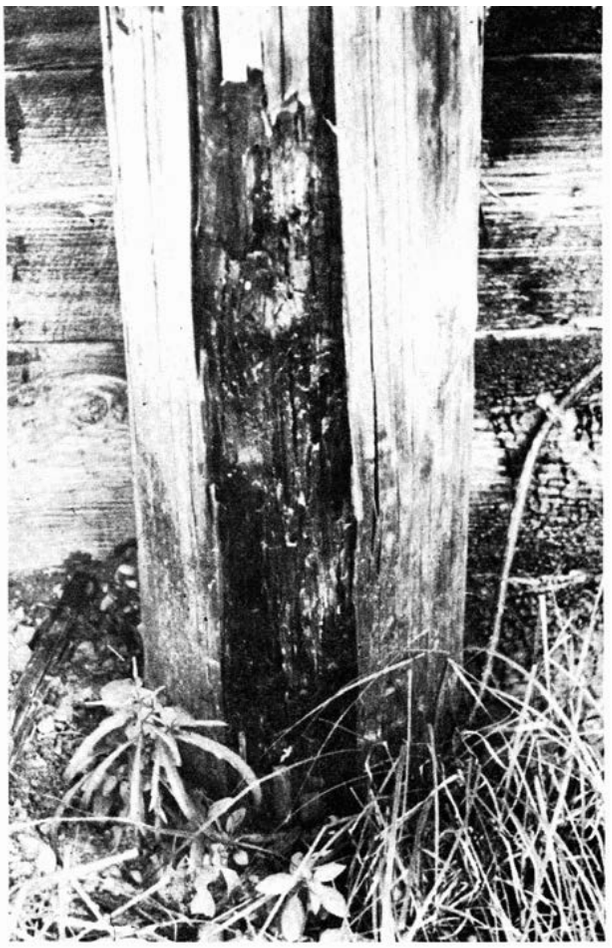

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Figure 2.-Decay in base of bridge piling. Potential for decay is high where wood is in contact with the ground.

commonly contains large numbers of fungus spores, and may contain wood such as construction scraps, small limbs, woody roots, or other plant debris in which decay fungi can live and from which vigorous vegetative fungus growth may spread to infect structural wood members.

In contrast, wood used above ground and isolated from soil contact is subject to conditions considerably less favorable to decay. This results in part from the less constant wetting and also from the more frequent and commonly prolonged periods when drying of the wood can occur. Further, the infection of above-ground wood depends almost solely on infection by fungus spores. Such spores are microscopic, single-celled structures that are relatively sensitive to environmental extremes and to toxins, in contrast to multicellular. vigorously growing vegetative fungus colonies in soil. Much lower concentrations of naturally occurring extractive toxins or wood preservatives will prevent spore infection than will prevent infection by established growing colonies of vegetative hyphae.

For members exposed above ground, positional aspect can be a factor having a direct effect on the incidence of decay. Large solid-sawn members are commonly subject to seasoning checks. When members are positioned horizontally as in decking, stringers, caps, and wheel guards, any checks on their upper surfaces and some on upper side surfaces become water traps if the members are exposed to rain or other forms of wetting. Vertically positioned bridge members with comparable checks commonly remain safely dry since most checks can

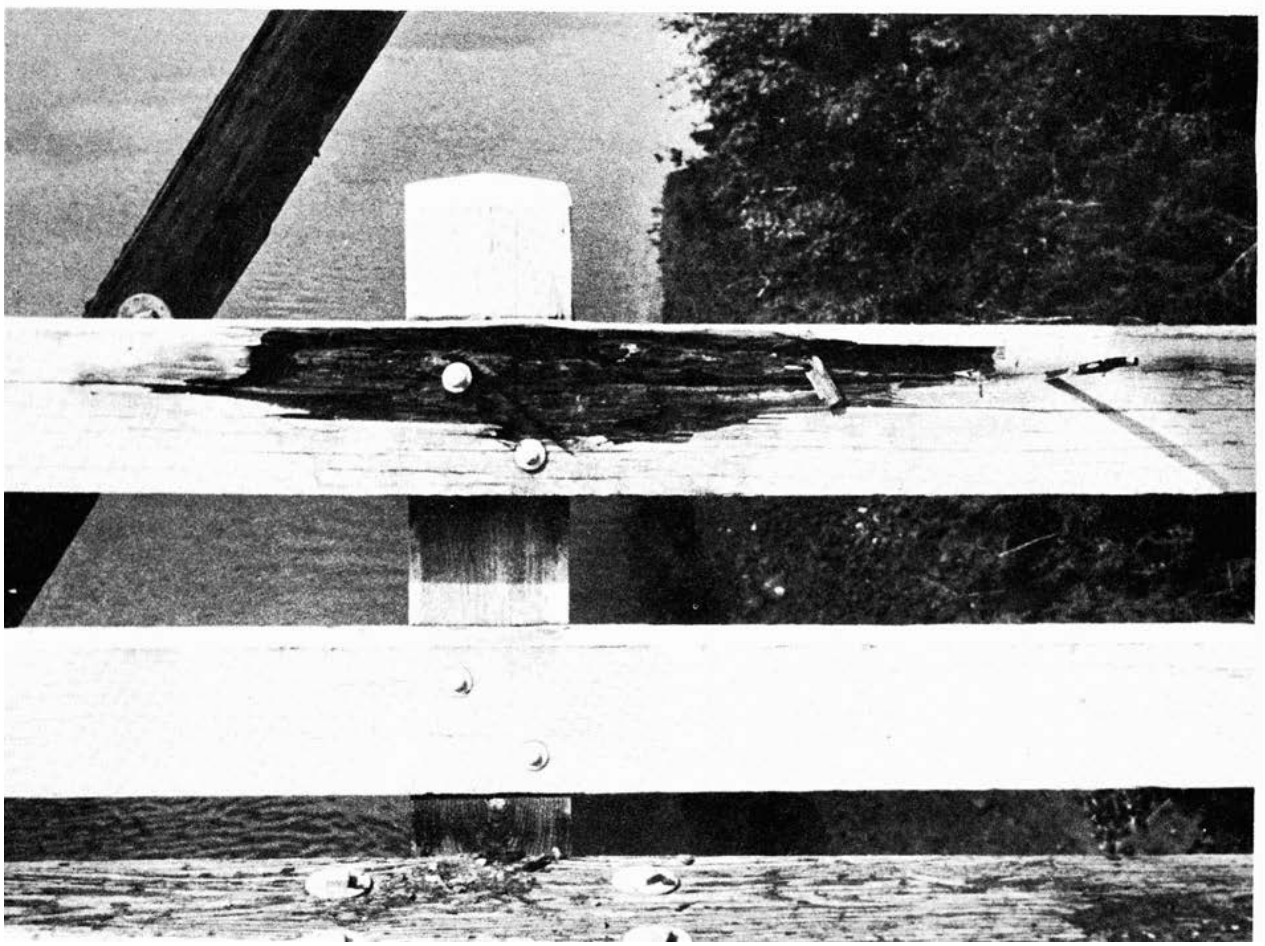

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Figure 3.—Advanced brown rot in guardrail member exposed by the removal of a thin, intact but sunken, layer of surface material. The decay unquestionably started in the bolt holes, and was also present in the guardrail post.

drain freely when subjected to wetting.

Another category of localized conditions conducive to decay in bridge members is represented by wood-penetrating fasteners or hardware (fig. 3). Water, carrying fungus spores, may move into bolt and nail holes to wet interior parts of wood members, and the drying rate of such areas is commonly restricted. Predrilling timbers prior to pressure preservative treatment, wherever possible, is one way of preventing hazardous conditions of this nature from arising.

The degree of penetration by water into wood members depends in part on the wood face exposed to wetting. For example, end-grain surfaces of wood absorb water much more rapidly than side-grain surfaces; permeability in the longitudinal direction is 50 to 100 times greater, other things being equal, than in the transverse direction (23). Hence, when water is introduced into a bolt or fastener hole, it moves along the grain away from the hole much further than across the grain and away from the hole.

Rate of liquid movement through wood is also affected by wood species and by whether sapwood or heartwood is involved. Relative permeability of the heartwood of some common woods has been delineated — ponderosa pine and red oak, for example, being listed with the most permeable groups and interior-growth Douglas-fir and white oak being listed with the least permeable group of woods (23). The sapwood is considerably more permeable than the heartwood. The heartwood resistance to water penetration, however, is not sufficient to prevent wetting suitable for initiation of decay where prolonged and continuous exposures to water or a high frequency of intermittent wetting is a feature of the member exposure.

Resistance: Natural and Induced

Natural Decay Resistance

The natural decay resistance of wood exposed under conditions favorable for decay is distinctly variable, and it can be an important factor in the service life of wood bridges. The heartwood of many tree species possesses a considerable degree of natural durability, while the sapwood of all commercial species is nondurable. The fungitoxic compounds that provide natural decay resistance are not present in the sapwood, being deposited with other compounds in the inner layer of living sapwood as it dies each year and is converted to heartwood (fig. 4). These compounds vary in quantity and composition in different species and are commonly referred to as *extractives.*

In evaluations of the comparative natural decay resistance of wood species, four categories of heartwood durability are recognized: highly resistant, resistant, moderately resistant, and nonresistant. The classification of a wood species in one of these categories is based on the average decay resistance of the heartwood of that species. Such an average may represent a very considerable range of variation both between trees of that species and also within individual trees.

Most existing wood bridges in this country have been constructed from either Douglas-fir or southern pine. Older bridges may contain such species as western redcedar, larch, various pines, and red and white oak, but recent and current construction is almost exclusively Douglas-fir or southern pine. Detailed information on the natural decay resistance of Douglas-fir is available (18) as is similar data for pines (3).

Except for western redcedar (fig. 4) and white oak, all the above-named species are classed as only moderately decay resistant. Such a level of resistance is not adequate to protect bridge members exposed to conditions favorable to decay. However, even a moderate level of natural decay resistance of heartwood is important to bridge service life in contrast to the nonresistant sapwood. For example, in above-ground exposures the heartwood of Douglas-fir or southern pine will usually last several times longer than the sapwood of these species.

From a practical viewpoint, two factors are significant regarding natural decay resistance: the degree of decay resistance inherent in the heartwood of the bridge member and the amounts of heartwood as opposed to sapwood present in the bridge material. There are distinct differences between Douglas-fir and southern pine in regard to the ratio of heartwood-sapwood present.

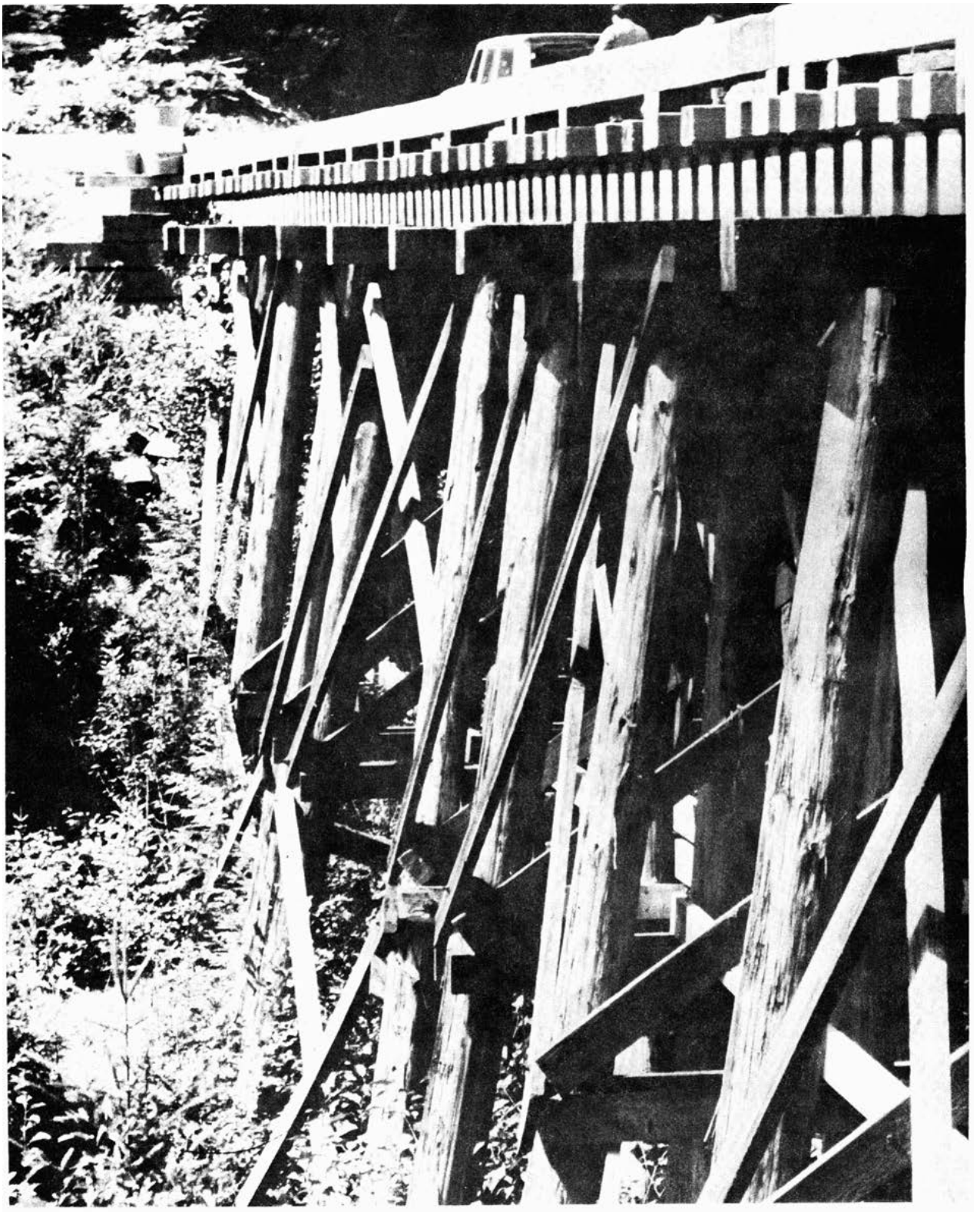

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Figure 4.- Bridge built in 1956 using untreated cedar as piling. Decay is present in the sapwood, but the decay-resistant heartwood remains structurally sound.

In the last 25 years, wood bridge materials have been obtained increasingly from smaller trees in young-growth timber stands; this situation contrasts to earlier supplies that came from larger trees in old-growth stands. As a result, recent supplies of lumber and timbers have contained increased percentages of decay-susceptible sapwood. This is particularly true of the southern pine materials, which, for a number of years, have been cut from logs in which 75 percent or more of the log volume is sapwood. In such material the decay resistance of the heartwood is hardly a factor to be considered; because of the absence of heartwood, preservative protection is a necessity.

Preservative Treatments

Numerous bridges and other structures of preservative-treated wood are in use and in good condition after 35 or more years of service, and these demonstrate the potential value of properly applied preservative treatments. Numerous citations of such service are impressive but may be misleading unless it is recognized that they represent the better case histories. More importantly for bridge designers, inspectors, and bridge maintenance personnel, wood bridge service life is most commonly terminated as a result of decay; such decay may occur early in some structures where insufficient protection or maintenance is provided.

A variety of wood preservative chemicals and several methods for their application have been available since the early 1900's. However, preservative-protected timbers in the older existing bridges have been treated almost exclusively by pressure applications of coal-tar creosote or pentachlorophenol in a heavy oil solvent. These two preservatives are considered comparable in effectiveness against decay when applied at equivalent toxic concentrations.

For some recently-built structures, inorganic salt preservatives applied in water solutions by pressure methods have been specified. Some examples of such preservatives include ammoniacal copper arsenate (ACA) and chromated copper arsenate (CCA) . Such treatments have the frequently sought characteristics of leaving the wood clean, non-oily, and paintable. For bridge members, the principal disadvantage of the waterborne salt treatment, in comparison to the more widely used creosote or penta-oil treatments, is the lack of water repellency that

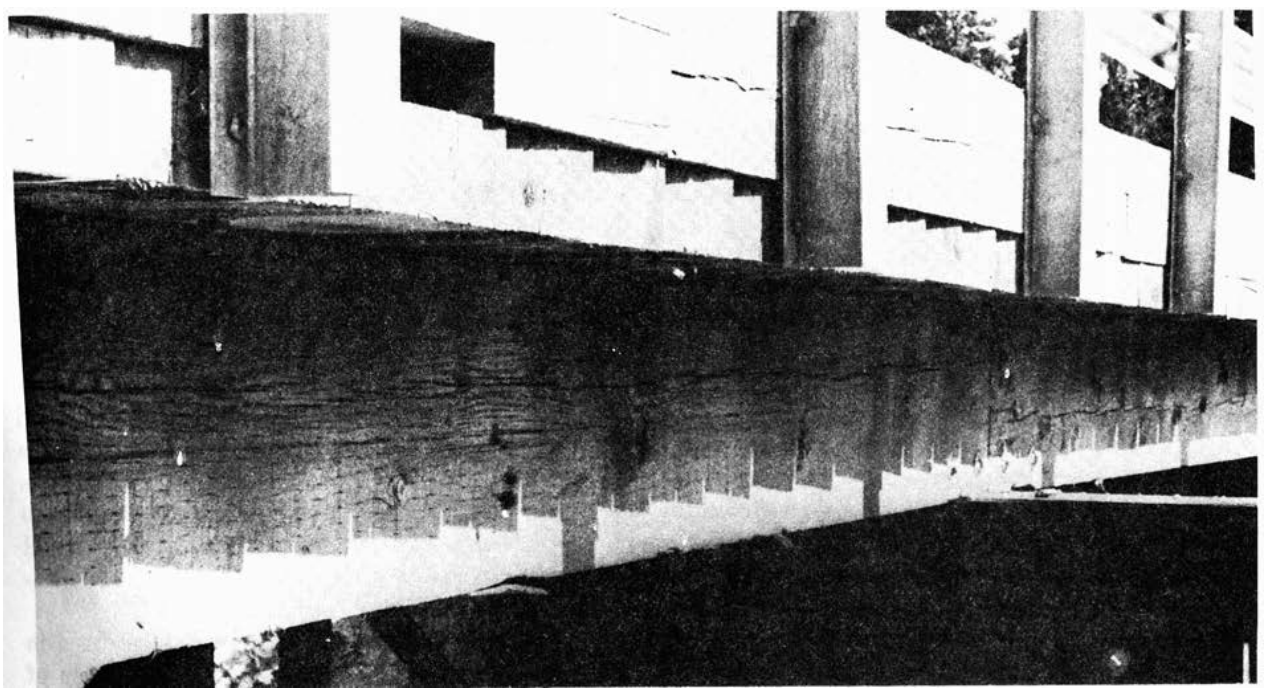

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Figure 5.—Severely checked timbers treated with salt preservative. Checking is deep enough to penetrate the incised and treated outer shell.

the oil treatments impart to treated wood surfaces. Checking is generally more severe with salt-treated than with oil-treated timbers (fig. 5).

For more specific information on preservative chemicals and suggested practices regarding their application, reference can be made to either the American Wood-Preservers' Association Standards (1) or the comparable Federal Specifications (25), or for more detailed, broad coverage of the field, Hunt and Garratt (11).

In the preservative treatment of material of sizes and thicknesses commonly used in bridge construction, it is generally impractical and usually impossible to obtain preservative penetration completely through the entire piece, except for very short members such as blocks or short truss elements. Instead, most members are protected by impregnating the outer wood to create a continuous toxic barrier to fungus invasion over the entire member surface. As long as this barrier is maintained without breaks in its continuity, fungi have little chance to invade the untreated interior wood. The depth of this preservative barrier (the penetration) and the quantity of preservative present in the treated wood (the retention) largely determine the effectiveness of preservative applications.

Until recently, the usual measure for bridge timber treatment specification and compliance was simply the retention of preservative in pounds per cubic foot of wood subjected to treatment. The common practice was to obtain this information for a given treating cylinder charge, based on the calculated volume of the wood and the quantity of preservative used. With such a procedure the specified amount of preservative might be applied to the array of timbers in a charge, but individual members could be heavily overtreated or decidedly undertreated. In most existing bridges the inspector should anticipate sizable variations in preservative retentions and penetrations.

In the last 20 years more precise measures have been developed and approved by the American Wood-Preservers' Association (AWPA). Although not used consistently, these measures have been available for the specification of treatments and for subsequent checks on specification compliance. This procedure is based on measurements of both the penetration and retention of the preservative in core samples of wood taken from appropriate depths of outer wood specified to be treated.

The treatability and the need for treatment of southern pine and Douglas-fir—the two principal species used for bridge building—can be compared.

The wood of Douglas-fir trees consists mainly of heartwood that is extremely difficult to treat. They have a relatively thin sapwood of which only small amounts are usually retained in the heavier, solid-sawn members. However, considerably more sapwood-edged members are present in the material cut from young-growth than from old-growth trees. Generally in the larger sawn timbers, sapwood is not present in sufficient amounts to increase overall treating efficiency.

By contrast, southern pine members used in decay hazardous exposures are at a disadvantage without preservative treatments because of the high percentage of decay-susceptible sapwood present. With proper preservative treatments, however, such material can be used advantageously; the sapwood can be treated more easily and effectively than the heartwood both in regard to the penetration and the retention of preservatives. The heartwood of southern pine is notably difficult to treat. The availability of large, solid-sawn southern pine timbers has become limited by young-growth tree size, but glued-laminated members of southern pine are substitutable.

The moderate level of decay resistance characteristic of Douglas-fir heartwood and southern pine heartwood (if present) will afford some decay protection in above-ground exposures where infection is limited to spore germination and where continuously sustained high levels of wood moisture content are less commonly a factor. However, much longer wood bridge service life is obtainable if the wood is treated adequately with appropriate wood preservatives. It has become standard practice to use preservative-treated wood for structural members, and this is now largely true for nonstructural members as well.

General use of preservative-treated wood in bridge construction may raise the question of why natural durability should be sought at all. It is simply that not all of the wood member is completely treated with preservative. Interior

parts untreated or inadequately treated can be threatened by fungus infection; in such situations, the natural decay resistance of the material is significant.

Preservative Treatment Limitations

Since the preservatives for bridge timbers and their methods of application have been more or less standardized by the general use of AWPA or Federal specifications, the bridge inspector should be less concerned with the specific preservatives used. Instead, he should be more concerned with the variations in treatment effectiveness to be encountered in different bridge members. Such variations are attributable to a number of factors that include: the inherent treatability of the materials; the preparation or conditioning methods used with materials before treatment; the bridge design details and the building practices used during bridge construction; and the service history and traffic loading use of the structure.

The treatability of Douglas-fir and southern pine has already been considered. Inspectors should also recognize that most Coast Douglas-fir and southern pine heartwood members will not have been adequately treated for use where decay potential is high with either creosote or penta in heavy oil unless the members were incised prior to treatment. Without incising, face grain penetration of these preservatives in some members is likely to be 1/4 inch or less and inadequate to protect such members in decay-hazardous exposures.

Even small surface seasoning checks or small fastener penetrations such as nails may afford avenues for fungi into the untreated interior wood. However, where wood has been incised prior to treatment, large checks must have formed before untreated interior wood is exposed (figs. 5 and 6).

Incising (fig. 6) is simply a process of establishing a systematic pattern of punctures in the face-grain surfaces of wood members. It permits positive and uniform preservative penetrations in moderately refractory wood species. Usually, with the pattern of incisions used, uniform treatment is obtained to the depth of the incising in treatable materials, but not in wood that is very difficult to treat (fig. 7). Normal incising depths for sawn bridge timbers have varied from 1/2 to 3/4 inch. Some use of treated Douglas-fir timbers without incising will also be encountered because effective incising equipment has not been available at all treating plants, and because the timber sizes specified may have exceeded the capacity of the available incising equipment, and for other reasons.

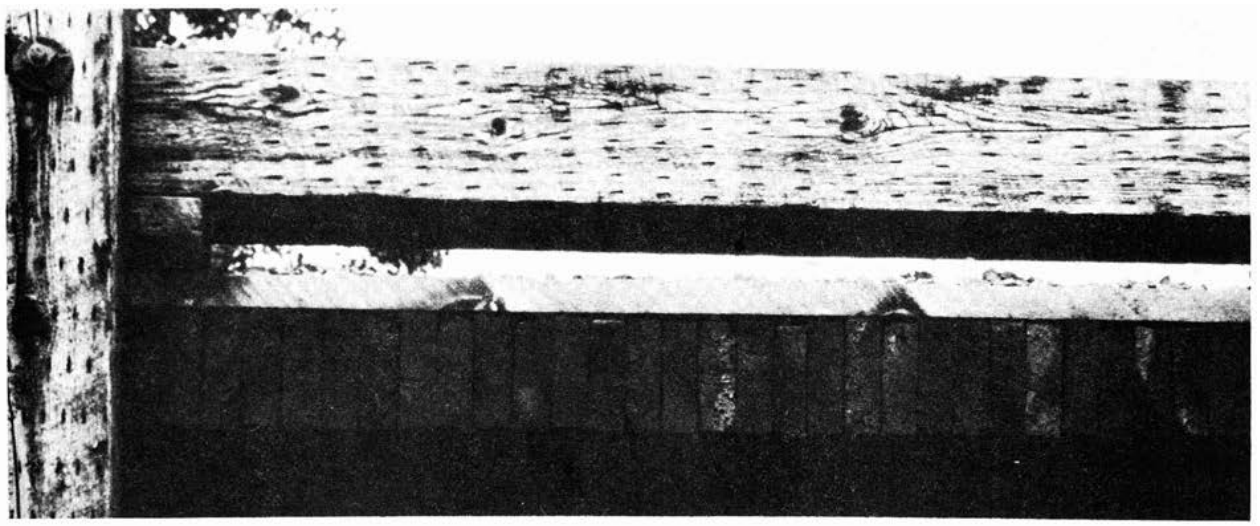

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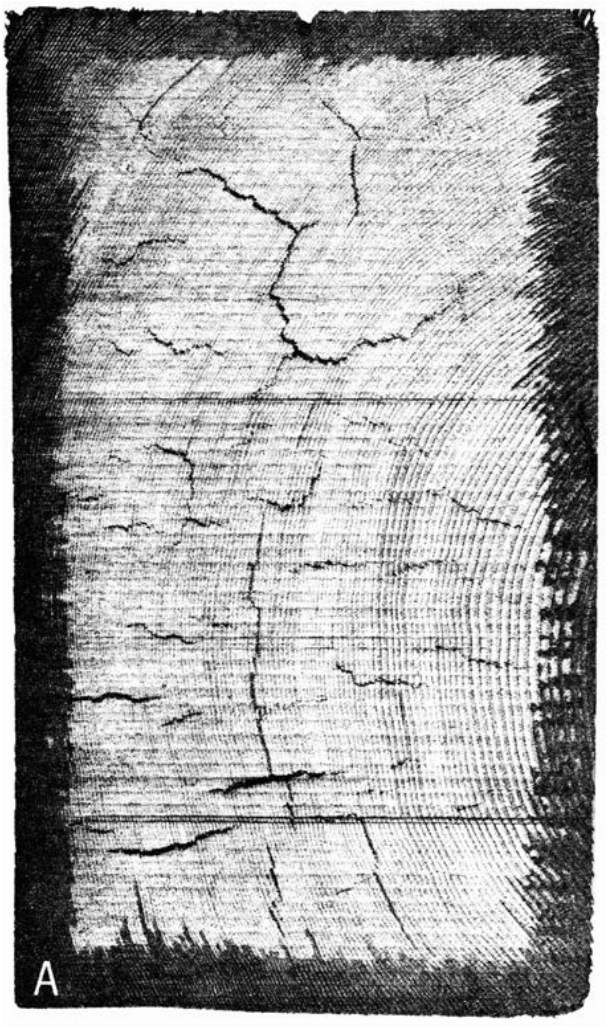
Figure 6.—Incised bridge members (wheel guard and handrail post) showing a commonly used pattern of incising tooth penetrations. Such evidence of incising in Douglas-fir and southern pine heartwood usually indicates that a better treatment has been obtained than would have been without incising. The seasoning checks in the foreground post and wheel guard commonly extend deeper into the wood than does preservative penetration, thus exposing untreated wood.

Incising greatly improves preservative penetration and retention in most large heartwood members of Coast Douglas-fir, Therefore, incising, as part of the preservative specification, should not be waived for lack of incising equipment at a given treating plant.

A different type of incising equipment is required for incising round members such as piling and utility poles. New developments in such equipment now make possible incising depths of up to 3 inches. However, the development of this type of equipment is rather recent and not yet available at many treating facilities. Piling in most existing bridges has normally been incised only to a depth of $^1/_2$ or $^5/_8$ inch. The larger seasoning checks that develop commonly in the above-ground parts of piling generally exceed 1 inch in depth even though the process of incising tends to reduce maximum check size.

Another principal source of variation in treatment effectiveness relates to the forms of conditioning used to prepare materials prior to preservative application. Freshly cut green timbers with high moisture contents cannot be treated adequately with oilborne preservatives without removing some water from at least the parts of the wood to be impregnated. The old practice of air-seasoning stock prior to treatment provided for such drying and allowed the



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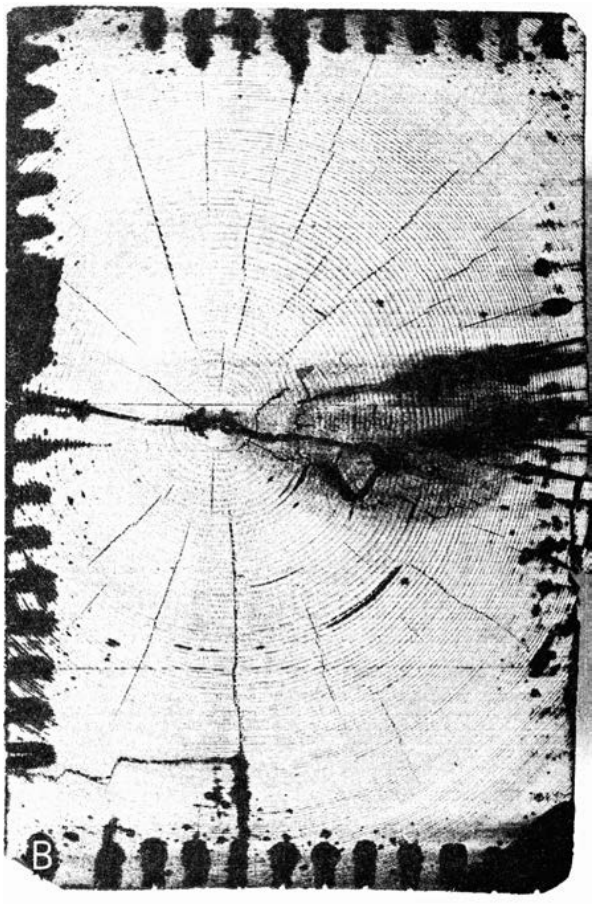

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Figure 7.—Cross sections of incised Douglas-fir bridge stringers : *A,* Coastal Douglas-fir takes treatment with reasonable uniformity to the depth of the incising; *B,* Rocky Mountain Douglas-fir shows the limited and nonuniform character of preservative penetration common with this highly refractory form of the species.

seasoning checks to develop before the preservative was applied. Thus the wood exposed by the natural check openings was treated. However, adequate air-seasoning of large timbers could take months or even years and require large inventories subject to decay and fire hazards.

Since about 1950, the practice of air-seasoning timbers before preservative treatment has been progressively replaced by other forms of conditioning. Increasingly, some form of rapidly conditioning freshly cut, green timber has been used, including four methods : steaming and vacuum treatments, boiling in oil under vacuum, vapor drying, and kiln drying. Bridge timbers have been conditioned most commonly by the first two methods. Steaming and vacuum conditioning is more commonly practiced with southern pine materials since higher temperatures can be used for the pines than for Douglas-fir without significant damage to strength properties. The more common practice used with Douglas-fir has become boiling in oil under vacuum (Boultonizing). In most cases, with either method, no more water is removed than is necessary to obtain the specified preservative penetration and retention. Normally only the outer inch of wood is appreciably dried in these processes.

Because these conditioning processes are applied in the pressure treating cylinders and are followed directly by preservative impregnation, there is little further chance for significant drying prior to installation. Treated bridge members are produced, therefore, and usually put into use relatively free of checks but with interior moisture contents in a range well above fiber saturation. Further drying of the treated members may be slow even in above-ground positions. The high moisture contents may remain for several years, depending in part on the placement and exposure of individual members in the structure. The continuity of the outer preservative barrier is therefore highly important because the interior, untreated wood is initially at a moisture level adequate to support decay fungi.

Drying is often accompanied by the development of seasoning checks that may expose untreated wood (figs. 5 and 6). Such checks will be larger and deeper in round members and in sawn, boxed-heart [2] members than in squared members that do not contain boxed-heart (fig. 8). In general, the size of checks that develop as wood seasons is correlated with the cross-sectional size of the member.

Preframing is another aspect of material preparation prior to preservative treatment that can affect treatment effectiveness. Some bridge design specifications call for members to have all possible preframing accomplished before treatment. This may include the required cutting to final shape, boring, and dapping.

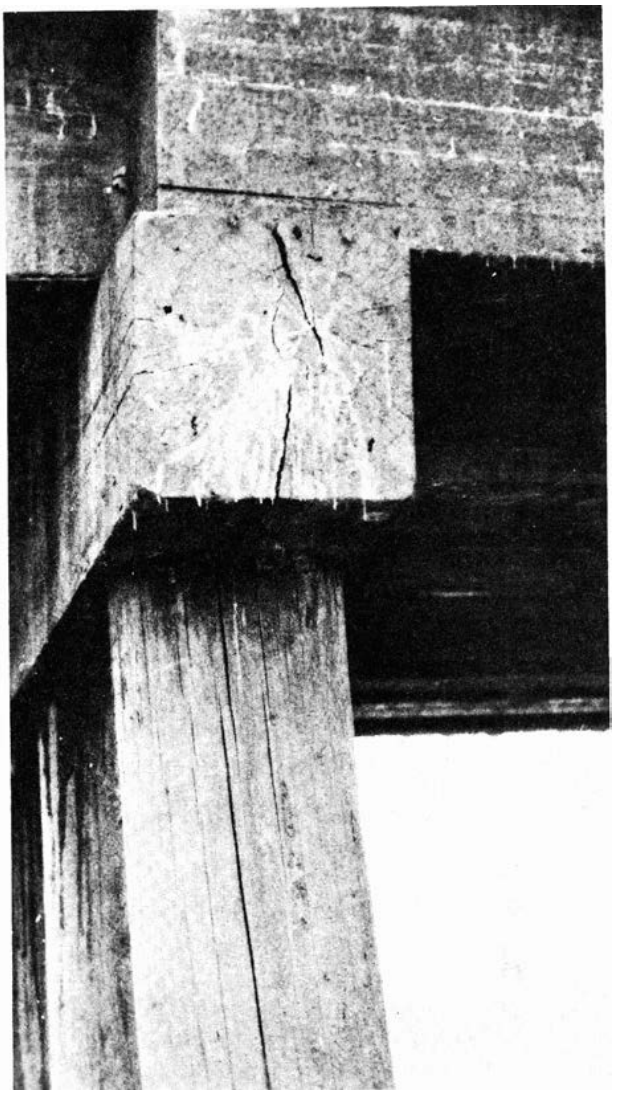

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Figure 8.-Deep checking associated with sawn, boxed-heart timbers and with round members (poles, piling). (cf. fig. 7)

'A member is said to have a boxed-heart if the pith of the wood stem is included in the cross section of the member.

With other designs, however, much hand framing is required at the construction site. Such framing commonly exposes untreated wood including some end-grain faces that are to form parts of joint interfaces or may expose untreated parts of members by holes bored for fasteners. Good building practice should ensure the preservative treatment of such exposed surfaces. On-site treatments can seldom provide the protection obtainable by pressure methods and such treating must, therefore, be done with care to obtain as thorough penetration as possible.

The effectiveness of preservative treatments can also be affected by the proper or improper handling and storage of the building material prior to and during construction. Significant damage to the protective potential of the treatment can result from rough handling or other factors that result in chipping, gouging, or other breaks through the preservative barrier.

Mechanical damage to treated bridge members may result from abnormal bridge use, and such damage can predispose the affected members to decay. Such damage may result from vehicular accidents, oversized loads, severe overloads, and from high-water damage. Also, the infrequent delamination of glued-laminated members that were preservative treated after fabrication can provide avenues for fungus attack.

INSPECTING WOOD BRIDGES FOR DECAY

Inspection Preparation and Considerations

The age, size, and design of individual bridges will dictate in part the inspection procedures and the equipment required to accomplish the job. Before going into the field, the inspector should formulate a general plan of procedure by referring to any available drawings, specifications, and data pertinent to the service history of the bridge. Any available records of previous inspections, damage, repair, member replacement, or structural modification should be noted with their respective dates.

Materials

Much of the equipment and tools required to inspect bridge members for decay will be those used for other aspects of bridge inspection. However, the following can serve as a checklist :

- Recordkeeping materials (waterproof notebook)
- Pad of $^1/_4$-inch graph paper (field sketches)
- Clipboard
- Camera and photo recordbook
- 10- and 100-foot tapes
- Probes and hammer
- Moisture meter, spare long-needle electrodes
- Thermometer for use in correcting electric moisture meter readings
- Increment borers
- Saw for cutting off dowels (plugs) flush with the surface
- Hardwood doweling (treated)
- Wood preservative and squirt can
- Electric drill and bits, and spare chuck key for electric drill
- Plug cutters and extractors
- Brace and $^3/_8$-inch bit
- Feeler gage or spatula to determine depth of checks or conditions of fasteners at joint interfaces
- Pocket knife
- Small shovel or trowel
- Ax and spade to investigate wood below ground level
- File and stone
- Canvas tool bag
- Keel, yellow or white and black
- Plastic tapes, red and yellow
- Assorted sizes and galvanized nails
- Aluminum foil, plastic bags, and glass or clear plastic vials
- Flashlight
- Binoculars
- Hardhat and nonslip shoes
- Safety belts, harness, and ropes
- Ladders and sling equipment.

The moisture meter is calibrated to read from 7 to 65 percent and is supplied with pin electrodes that can be driven to a maximum depth of $3^1/_4$ inches for moisture estimates (fig. 9).

The shank of the bit in the auger-type tool is threaded for use with different-length extensions made from drill rod stock. Either $^1/_2$- or $^3/_8$-inch bits are suggested. The plug cutter has been modified by threading for use with different-length extensions. The extractor with an end spur is made from $^1/_8$- or $^5/_{32}$-inch drill stock and used to break the plug free and withdraw it after it is drilled. Suggested plug cutter sizes cut plugs $^1/_4$- or $^3/_8$-inch in diameter (fig. 10).

A proper bridge inspection includes two major steps: First, the physical inspection of the structure, and second, the preparation of a permanent record of the findings. All decay should be reported in sufficient detail for an engineering appraisal of the defect and its effect on the member or structure. The record should also be prepared with a view to its future use. With the increased frequency of inspections now required for the majority of bridges used by the public, a more comprehensive appraisal of bridge conditions can be developed if sequential inspections can be correlated.

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Figure 9.—Moisture meter of the type recommended for bridge inspection work.

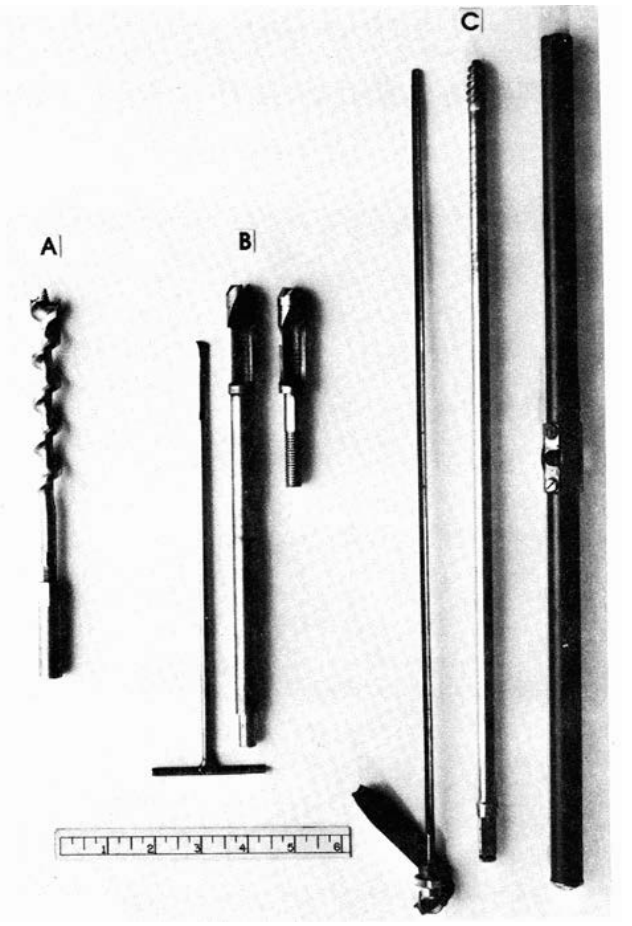

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Figure 10.—Boring and coring tools: *A,* Auger-type bit used for extracting bored shaving samples; *B,* plug cutter and plug extractor; *C,* increment borer consisting of three parts-extractor, hollow bit, and case that also serves as a handle for turning coring bit into and out of wood members.

Approach

The diversity of bridge designs, bridge ages, and bridge site environments are only a few of the variables that make detailed recommendations for inspection procedures somewhat impractical. Some basic considerations will be covered, however, with the thought that the inspector will adapt these and other procedures to meet the needs of specific situations.

To ensure that all critical areas are covered, the inspection of moderate- and large-sized bridges should be undertaken systematically, working progressively from the lower substructure members to the superstructure or in reverse order. One advantage of starting below the bridge is the opportunity to observe load reactions in the decking and the supporting structural elements resulting from passing vehicles prior to actually inspecting them. Signs to watch for include abnormal deflections and looseness of joints or fasteners. Both conditions may be the result of decay. The presence of water forced from joint interfaces should also be noted. Any observed abnormalities should be noted for subsequent investigation as the systematic inspection progresses.

Evidence of Decay

Visual Evidence of Decay

It is good to begin an inspection with a visual search for evidence of decay and areas of possible decay. Location of areas to be investigated before the physical examination of members begins will make an orderly coverage possible, and will direct in part the progressive movement of slings, ladders, or other equipment used to obtain access to various members. The visual inspection will require a strong light as the details sought may be easily overlooked in poorly lit areas. Visible evidence of decay or probable decay will include three aspects: characteristic fungus fruiting structures; abnormal surface shrinkage or "sunken" faces; and insect activity.

Characteristic fungus fruiting structures.—Most fungi fruit in recessed or partially enclosed and shaded areas rather than in areas subject to direct sun exposure. Such poorly exposed, shaded surfaces are likely to be in the interior parts of bridges where reduced chances for drying and *higher humidities prevail, and conditions are favorable for the development of fruiting structures.

Fruiting bodies may take the form of shelf- or hoof-shaped projections, of flat leathery thickenings that protrude very little from the wood member surface, or they may be typical mushroom forms with or without stems (fig. 11).

When fresh, these fruiting bodies may range in color from near white to dark brown, but all usually darken with age. Soft fruiting bodies are short-lived since they are used commonly by insects and other animals for food. Other forms are perennial and these may be tough, woody, or corky, and may persist for periods of several years if left in place.

Some decay fungus species may produce fruiting bodies after relatively small amounts of decay have developed, while other species fruit only after extensive decay has occurred. Further, the decay associated with a given fruiting structure may be relatively near the surface of the infected member or it may be deep in the wood with its maximum development at some distance from the fruiting body. Any positive evidence of the presence of decay should be investigated by borings or the extraction of cores to define the limits of deteriorated wood.

Abnormal surface shrinkage.—Another visible clue to the presence of decay is the localized depressions or "sunken" faces of sawn or planed wood surfaces. Abnormal shrinkage over decay voids or pockets of advanced decay that occur or extend too close to the surface account for the sunken faces. Figure 3 shows advanced or typical brown-rotted wood exposed by the removal of a thin layer of intact wood from a sunken face in a guardrail member. Usually sounding or firm probing will confirm the presence of such decay, but coring or boring (to be described later) will be required to define the limits of the decayed area.

Insect activity.—Any evidence of carpenter ant or termite infestations should alert the inspector to the probable presence of decay. Both types of insects are attracted to decayed wood. Significant infestations of carpenter ants are most commonly noted by the accumulation of sawdust-like wood particles that result from their tunneling and excavating for nesting sites. The ants do not use the wood for food and the accumulations of wood particles remain comparatively coarse and not "powdered" by any digestive process. In contrast, termites utilize the wood as food and any accumulation of Wood residue will appear as finely powdered particles more or less packed in checks or cracks. Fortunately, termite infestations are seldom found in frequently used bridges and are rare or

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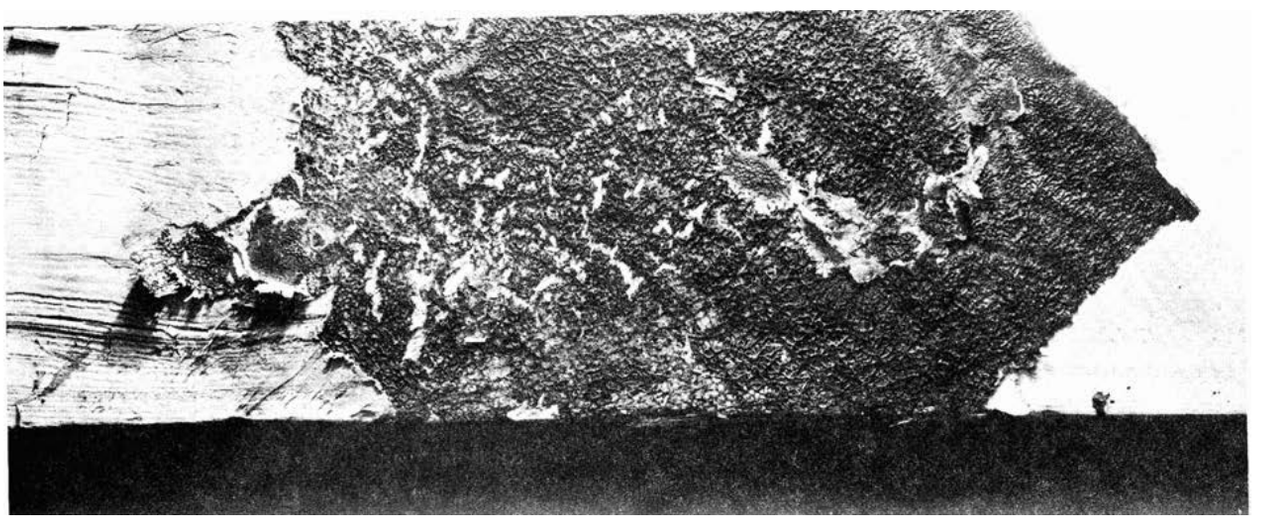

(Courtesy of Frank Porter Lumber Co., Chicago, Ill.)

Figure 11.—Examples of decay fruiting bodies: Upper, soft, fleshy, shelf-like forms; lower, resupinate form.

totally lacking in bridges throughout much of the country. Carpenter ants in bridge members can be eradicated by local applications of powdered or liquid insecticides in their tunnels or exit holes. Current information on effective insecticides permitted for this use should be obtained from the local county extension agent.

Visual Evidence of Conditions Conducive to Decay

Because of the very large number of similar structural areas in a bridge where decay-hazardous conditions may possibly develop, the inspector must be alert for any evidence that suggests an increased likelihood that hazardous conditions have developed in specific areas or member parts. Such evidence should be a factor in the selection of probing and boring or coring sites. For example, the inspector must consider where along the length of stringers to take borings or core samples when the upper surface of the full stringer length is repeatedly penetrated by deck nails. Visual evidence of decay-hazardous conditions includes watermarks of excessive wetting, rust stains, plants growing on the bridge, and joint interfaces.

Watermarks. — Because a high moisture content of wood is a required condition for decay, evidence of excessive wetting in localized parts of members can be a clue to possible decay-hazardous conditions. Commonly, the passage of water through decking and over substructural members leaves permanent watermarks. Such marks are usually the result of accumulations of soil, mud, or other materials washed down from the deck surface. Under open decking systems, such marks may be so numerous that chances of general wetting are indicated (fig. 12). However, under tight decking systems the principal water movement may be along less numerous and well-defined pathways and these indicate localized areas of possible

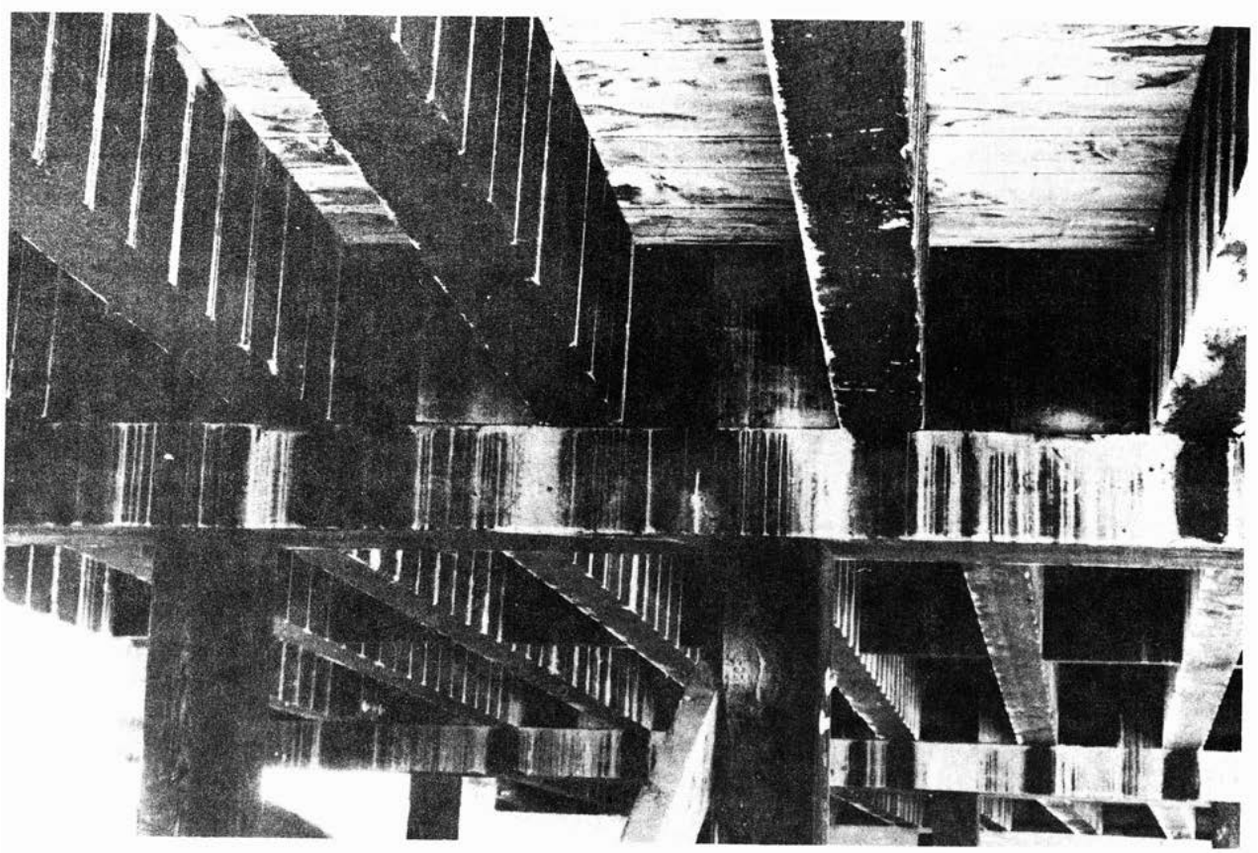

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Figure 12. — Profuse water markings on the stringers and caps indicate considerable water passage through the plank decking.

wetting. Water passing through asphalt-surfaced decks is frequently filtered free of soil particles and the resulting watermarks are less obvious but usually discernible.

Rust stains.—The presence of iron oxide or rust stain on the surface of wood members shows possible excessive wood wetting. This is most likely if the source of iron for such staining has been wood-penetrating fasteners or hardware such as bolts, drift pins, brace rods, or deck fasteners.

Plant growth.—Any appreciable growth of moss or other vegetation on wood surfaces or in checks or cracks is evidence of potentially hazardous wetting. Growth of vegetation rooted in soil accumulated at any point on the deck or other bridge members not normally in soil contact must also be taken as evidence of similar wetting. The amounts of moisture and elapsed time required for such growth indicate that a sustained period of wetting may have occurred in the adjacent wood.

Joint interfaces and water-trapping areas.—In the majority of cases, critical wetting will be found to have occurred where water has had access to end-grain surfaces. In preservative-treated members, such surfaces are more likely to be those resulting from on-site framing cuts or borings that are less thoroughly treated with heavy retentions of oily preservatives. Wood at joints is most vulnerable, as water may be held or trapped in the joint interface and continuously supplied by capillary movement to the end grain of associated fastener holes as it is absorbed into the wood.

Much emphasis has been placed on the importance of high moisture content as a factor evidencing conditions conducive to decay and possible decay sites. The inspector must also recognize that moisture conditions are subject to marked change over a period of time resulting from a number of factors ranging from structural modifications of the bridge to slight changes in the amounts of accumulated mud or debris that can alter water drainage pathways. Redecking, asphalt deck surfacing, or the seal-coating and repair of existing asphalt deck mats, may result in decided changes in the movement of water through the deck. Consequently, serious decay may be present in thoroughly air-dried material that has been previously wet.

Detecting Decay

After the initial survey for evidence of decay and conditions conducive to decay, more detailed examination of the questionable areas is in order. Several techniques are available to the inspector. As the inspection progresses, it will be necessary to check on the degree of wetting and possible decay that may be present at questionable areas. Where decay is confirmed positively, its extent usually must be defined.

The required accuracy in determining the position and limits of decay in bridge members must be judged by the inspector. In some cases, decay may be present in areas that are not likely to significantly affect the strength required of a given member. However, in other cases, any decay present may effectively reduce the load-bearing capacity of the member at points of maximum stress, so such areas must be appraised accurately. Figure 13 is a composite drawing showing some examples of locations where decay may occur. These examples also emphasize the association of decay with penetrating drift pins and nails. All of the decay indicated would be interior decay and not likely to be detected without boring or coring the infected areas.

External Decay

Probing with a moderately pointed tool such as an awl or fine-bladed screwdriver is useful in detecting shell rot and other forms of decay that extend too close to the wood surface. Probing into end-grain faces or side-grain faces adjacent to joints may reveal the presence of decay by the excessive softness or lack of resistance to probe penetration. Care must be taken to differentiate between decay and water-softened wood that may be sound although somewhat softer than equivalent dry wood. Here again, experience is required, particularly if species other than pine and Douglas-fir are encountered—such as hard oak timbers or softer textured western redcedar.

Recently, a new instrument for nondestructively testing the shock resistance of wood has been developed in Denmark. This instrument, termed a pilodyn, was originally developed to assess surface decay in utility poles and is, at present, being used by several power companies

in Sweden and Denmark (10). It appears to be a promising tool for use in other structures also, such as bridges.

Internal Decay

While detecting external decay is fairly simple, detecting internal decay is more involved, requiring the use of various devices, some of which are quite sophisticated. A number of nondestructive techniques utilizing tools such as radiography, sonics, and various mechanical probing devices have been available for a number of years to detect internal decay in wood. These devices generally are useful for detection of advanced decay; less advanced stages of decay are often difficult to detect (4). However, in recent years a new device—the Shigometer—has been marketed which enables detection of early decay.

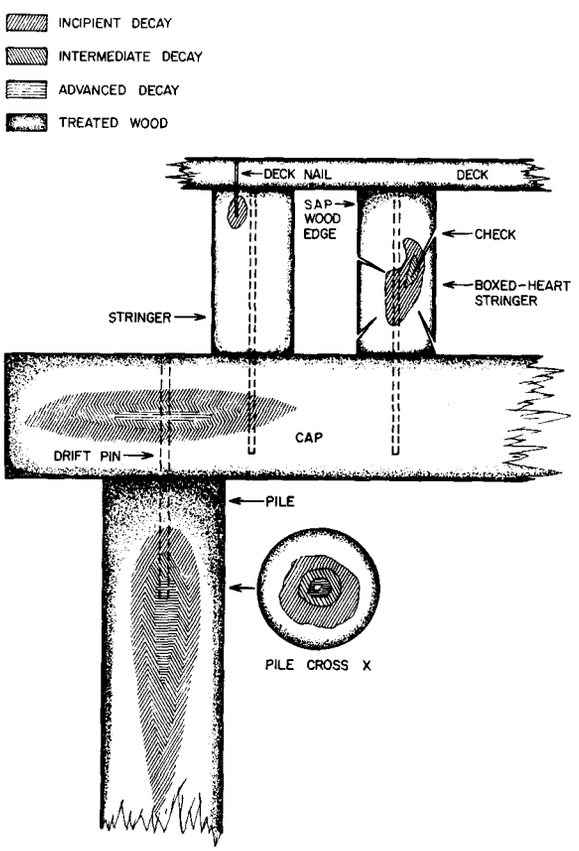

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Figure 13.—Schematicdiagram of portion of pile bent, stringers, and deck showing locations where decay may occur.

For inspecting bridges without the use of sophisticated aids, simple methods used for years by pole inspectors are available. These methods, which include "sounding," and extraction and inspection of cores or shavings, and probing, may be used singly or in combination.

Shigometer.—Amongthe sophisticated devices developed to aid in detection of decayed wood, the Shigometer appears to be of most use. It operates upon the principles that resistance to a pulsed current decreases as concentrations of cations increase in wood, and that cation concentrations increase in wood undergoing fungal staining and decay (22). The Shigometer has been tested on both trees and utility poles. The advantages of this device over others used for similar purposes are that it will allow an experienced operator to detect initial breakdown of wood which normally would go undetected, and that only a small diameter hole needs to be drilled in the wood undergoing test in order to use the instrument. Such early detection of wood breakdown will permit remedial measures to be taken while the wood in question is still structurally sound enough to not require replacement.

The Shigometer functions only when wood contains moisture at, or above, the fiber saturation point (21). This disadvantage may be overcome by wetting dry wood with deionized water prior to use of the device (20). Where wetting is required, it is necessary to drill three holes close to one another; two of the holes are wetted while the third is used for testing decay.

Sounding.—Soundingis done by sharply striking the wood member along its edges and listening to the quality of the sounds it makes. Dull or hollow sounds indicate decay. The method is crude, requires considerable experience, and can be considered truly diagnostic only where decay is relatively severe and, in large members, extends to areas near the surface tested. In such situations, the technique is useful but factors other than the presence or absence of decay may contribute to the variation in the sounds obtained. Consequently, strength-damaging decay may be present in some members and easily missed by sounding. Wood members suspected of containing internal decay, as a result of sounding, must usually be bored in order to verify the diagnosis.

Core and bore sampling.—Coring or boring are the most widely used techniques for detecting internal decay. These are alternative procedures, but each has certain advantages and disadvantages.

Skillfully extracted cores taken with sharp increment borers or plug cutters (fig. 10) provide intact samples of wood that can be more accurately appraised for most physical characteristics. Also the depth or positional aspect of the characteristics observed can be readily determined from intact cores. The principal disadvantage of extensive coring is the much longer time required to obtain the equivalent number of samples.

As samples of interior wood, bored shavings obtained with sharp auger bits may be adequate for experienced inspectors or where advanced decay only is involved, but bored shavings offer no advantages over cores other than the far greater rapidity of taking the samples. Bored shavings offer at best a multidivided sample of the wood. Spatial relations of the sampled wood characteristics are less easily determined. The auger bit shavings also have the disadvantage of being repeatedly split or broken so that the physical character of the wood is often more difficult to appraise.

Inspectors may find that auger bit sampling is best for general use until some evidence of decay is found. They may then prefer coring for defining the limits of the infection. Any samples to be retained for subsequent use will generally serve best if taken as cores. Increment borer cores can be easily protected and stored in large drinking straws with proper identification on the straw. Plug cutter cores require larger containers; aluminum foil and small glass or plastic tubes have been found useful.

The presence of some common timber defects and abnormalities must be anticipated and not confused with decay. For example, the presence of resin pockets, shake, abnormal grain, and knots materially affects the character of wood samples. Skill in appraising cores and shavings comes with considerable practice.

Core sampling through preservative-treated wood commonly carries tracings of the preservative oils along the sides of the cores, showing various degrees of discoloration. When needed, estimates of preservative penetration are best obtained by splitting fresh cores and immediately checking the split face for the extent of the preservative from the outer face of the sample.

In taking coring or boring samples, it is important to use sharp tools. Dull tools tend to crush or break wood fibers, which changes the appearance of cores. Dull tools may also cause excessive core or shaving breakage and produce wholly unsatisfactory samples. Inspectors should carry extra bits, plug cutters, and increment borers in their supply of equipment. Cutting edges are easily damaged beyond practical field maintenance by striking hidden fasteners.

In this discussion, the terms coring and boring will be used as seem most appropriate, but it should be understood that the alternative technique could be used in most cases.

The inspector may, from experience, recognize areas with conditions suitable for decay, but some investigation of the specific areas will be required to confirm the degree of decay potential and the possible presence of decay as the inspection proceeds. The recommended initial procedure is the use of a moisture meter to check the moisture content percentage of the questionable wood. Use of moisture meters and their limitations are discussed by James (12). If the moisture content is above 30 percent, conditions suitable for decay are indicated unless all the wood in that immediate area is preservative treated. If the inspection is conducted after an unusually long period of dry weather, somewhat lower levels of moisture (20 to 25 percent) should be taken as the lower limit of the range indicating possible hazardous conditions.

At least one boring should be made at either the point of highest moisture content detected or at a point of most probable decay occurrence, if this is evident. If a penetrating fastener is in the area being examined, then the wood adjacent and in grain-alinement with the fastener hole will be the most suspect.

Where possible, the boring should be made parallel to the fastener hole. This will reduce the chance of missing any decay present that may occur at variable depths from the wood

surface due to the penetration of the preservative present and the depth to which water may have penetrated.

If no decay is detected, but the boring indicates only shallow preservative penetration and if meter readings have shown a moisture content above 30 percent over a considerable area, a second boring may be desirable. If any decay is detected, additional borings will be necessary to define the decayed area.

Bore holes may become avenues for decay unless properly treated. After core or shavings extraction, a wood preservative should be squirted into the hole and the hole then plugged with a preservative-treated wood dowel.

Records of the decay and its positional limits should be made immediately to avoid loss of detail. The records should include:

- Both the longitudinal and transverse dimensions of the decayed wood should be given and the position in the member indicated. This can probably be recorded best with careful sketches.
- The probable source of water and its pathway to the decay site should be noted because the condition may be correctable.
- Any indication of member weakness or failure should be noted and should include such evidence as excessive deflection, crushing, buckling, cracking, collapse, abnormal looseness of joints, or member displacement at joints.

Chemical decay indicators.—While detection of advanced decay in cores may be accomplished with little training, detection of intermediate decay is often difficult even for the experienced inspector. Incipient decay can only be detected with the aid of a microscope or with application of culturing techniques.

To facilitate detection of decay in wood, various chemicals, particularly pH indicators, have been used with limited success. Alizarin red-S, for example, was useful in identification of a particular storage decay in green southern pine wood (14). A recent study (5) reveals that other chemicals may aid in detection of at least intermediate stages of brown-rot in pine. A similar study is under way with Douglas-fir wood.

Assessing Associated Strength Loss

There is relatively little information on strength loss correlated with either the amounts or stages of decay in bridge timbers. However, a number of researchers have developed information in tests comparing the loss of strength with the loss of weight resulting from decay in small wood samples. This work has been reviewed by Hartley (8) and Kennedy (13).

Those investigations show that strength loss resulting from decay by some brown-rot fungi can be as high as 50 to 70 percent in very early stages of infection before the weight of the sample has been reduced more than 3 percent. Normally it is difficult to detect the presence of early decay with certainty at stages that cause no more than 3 percent weight loss. The large and disproportionate effect of early decay on strength loss versus weight loss was also shown to be more common with brown-rot than with white-rot fungi.

To calculate the residual strength of partially decayed structural members, it is important that the visible portion of the decay infection be outlined by the inspector, in both its cross sectional and longitudinal extent. In defining the area of decay, allowance must be made for nonvisible, incipient decay that extends outwardly from the visibly decayed areas (fig. 13). Position of the decay and its extent will be critical in determining whether the member may be retained in service. The engineer can appraise the problem in relation to the type and intensity of stresses imposed on that portion of the member containing decay. The residual strength estimate should be based on the remaining uninfected material.

Considerable amounts of decay may not be service-limiting in some piling, abutments, and other members. However, in appraising the residual strength of members containing localized areas of decay, the engineer should be hesitant in assigning any strength value to the portion of wood showing definite evidence of decay. Several considerations support this recommendation:

Most decay infections in pine and Douglas-fir members will be the result of brown-rot rather than white-rot fungus infections. This factor is significant in light of the

large strength losses associated with the initial or incipient stages of some brown-rot fungi. Differentiating brown-rot from white-rot in their early stages is not possible in the field; hence, all such decay should be treated as though it were brown-rot.

Although a number of cores or Shigometer readings may have been taken to define the decayed area, some possibility will remain that the maximum dimensions of the area will not have been sampled. *Assigning no strength value to any decay detected results in a desirably conservative estimation of the residual strength in the member.*

The presence and extent of very early stages of infections cannot be determined in cores or bored shaving samples that do not contain more advanced decay.

A conservative estimate of residual strength is also appropriate because the decay fungus will generally continue to grow and spread until some remedial action is taken, and such action may be delayed.

DECAY AND BRIDGE MAINTENANCE

Maintenance Considerations

Decay as a factor in bridge maintenance may be divided into three arbitrary categories based on the severity, or potential severity, of decay development. The first category includes existing decay that has progressed until severe loss of structural strength makes repair mandatory or requires restricted use of the bridge.

In the second category, immediate repair is not required for continued normal service. Although the incipient, moderate, or advanced decay present may not be currently service-limiting, the bridge is likely to become more structurally damaged and load-limiting if corrective measures are not applied.

A third category that should be included in maintenance considerations is where decay has not started but where conditions conducive to decay are definitely present. The early development of damaging decay in individual hazardous areas can be predicted with little certainty, but in time decay will develop in such areas if the conditions favorable for fungus growth persist without correction.

Efforts to maintain bridge members in the second category may be termed *early remedial,* and the third, *preventive maintenance.* A strong case in favor of such maintenance as a coordinated part of the inspection procedure can be made on the basis of the following points:

The increased frequencies and intensity of inspections now made on most bridges will disclose more and earlier stages of decay than have been detected in the past.

Usually, during the inspection procedure, the inspector will have obtained access to and bored any questionable areas one or more times and determined the character and extent of any decay or hazardous conditions present.

Once the areas of high decay potential present in a particular bridge are located, corrective measures can sometimes be applied to alter conditions and preclude fungus infection of the wood. Moisture control would be an example of a corrective measure applied to wood subjected to frequent, decay-hazardous wetting.

In-place treatments should be considered for any established interior decay in critical structural members such as stringers, caps, and piling. Localized areas with conditions conducive to decay due to excessive moisture buildup in untreated parts of members should also be considered for in-place treatment.

Such treatments can usually be accomplished at moderate additional expense above regular inspection costs.

A program of preventive maintenance for wood bridges offers considerable promise of: extending service life, reducing the frequency and extent of costly repairs, improving bridge safety, and conserving wood resources. To date, preventive maintenance for decay problems in highway bridges has been largely neglected after the initial period of construction. To some extent railroad bridges have been given preventive maintenance.

Available Measures to Control Decay

The principal aim of maintenance as applied to decay problems should include both the control of established decay and the prevention of new infections. Factors to consider in the selection of available control or preventive measures will include the extent and severity of the decay or potential for decay, its location, and its likely effect on bridge or member serviceability. The remedial measures available and their potential effectiveness and limitations include replacement of members, adding of reinforcement, and fungi eradication.

Replacement or Reinforcement of Members

Member replacement may be indicated when its residual strength is found to be inadequate. Two aspects of replacement deserve decay potential considerations. If extended service is anticipated, the replacement member should be pressure-treated with an appropriate preservative, remembering that the original member had decayed when exposed to the existing conditions of that location. When the defective member is removed, all adjacent and contacting members should be checked for possible decay infections that could have spread from the defective unit. Such areas, if confirmed or questionable, should be treated in place before the new member is installed.

In some instances it may be more practical to remove and replace only the defective part 'of a member. In such cases the above recommendations apply. Additionally, it is important to remove an adequate length of the defective material to ensure the elimination of the infection. The undetectable extensions of the infecting fungi may reach 6 to 12 inches in the grain direction beyond the apparent limits of the decay. A safe rule in removing decayed parts of members is to include the visible decay plus an additional 2 feet of the adjacent wood in the grain direction. The newly exposed, cutoff face of the old member also should be preservative-treated in place.

Sister members or reinforcing elements may be added in establishing a load-carrying capacity to substitute for decay-weakened units. This would be logical where actual replacement is impractical due to the difficulty of working a new replacement into the position of the old member. Where feasible, the old member or its defective part should be removed as a guard against further spread of the decay to any contacting members. When it is necessary to retain the member or its decayed part, preservative treatments should be applied to eliminate the infection or to prevent its extension. The choice of removal versus treatment must be judged on the basis of the location of the infection and the chances of its spread by the vegetative growth of the established fungus.

Fungus Eradication

Eradication of decay fungi from infected wood has been successfully attempted in Douglas-fir utility poles using sodium methyl dithiocarbamate (vapam), trichloronitromethane (chloropicrin), and other fumigants (6, 7). Largely as a result of this work, both vapam and chloropicrin have been registered for use as internal decay arrestors in large timbers, These fumigants virtually eliminate decay fungi, within the treated area of the wood, within 1 year. To remain effective, retreatment is necessary every 6 to 10 years, depending upon the fumigant used (6). Additional studies are underway to determine efficacy of these fumigants against specific decay fungi placed in wood at varying distances from the point of application of the fumigant. Current information on pesticides permitted for use on bridge members should be obtained from the local county extension agents before any treatment is attempted.

Remedial treatment of large decaying timbers with internally applied, nonvolatile, liquid preservatives can be effective if done properly. Such applications can make use of the holes bored by the bridge inspector in determining the presence and extent of any decay found. However, because liquid diffusion through wood is limited and is primarily in the grain direction, additonal holes should be systematically placed and staggered across the member through the decay and beyond the area of infection. These extra holes ensure an adequate spread of the preservative into areas of early or incipient infection where the wood porosity has not been increased appreciably by the invading decay fungus.

Such treatment applications may be tedious and time-consuming, but they are better than no treatment and progression of the decay leading to the eventual replacement of the bridge. Certainly, other alternatives should be considered such as moisture control or other types of treatment.

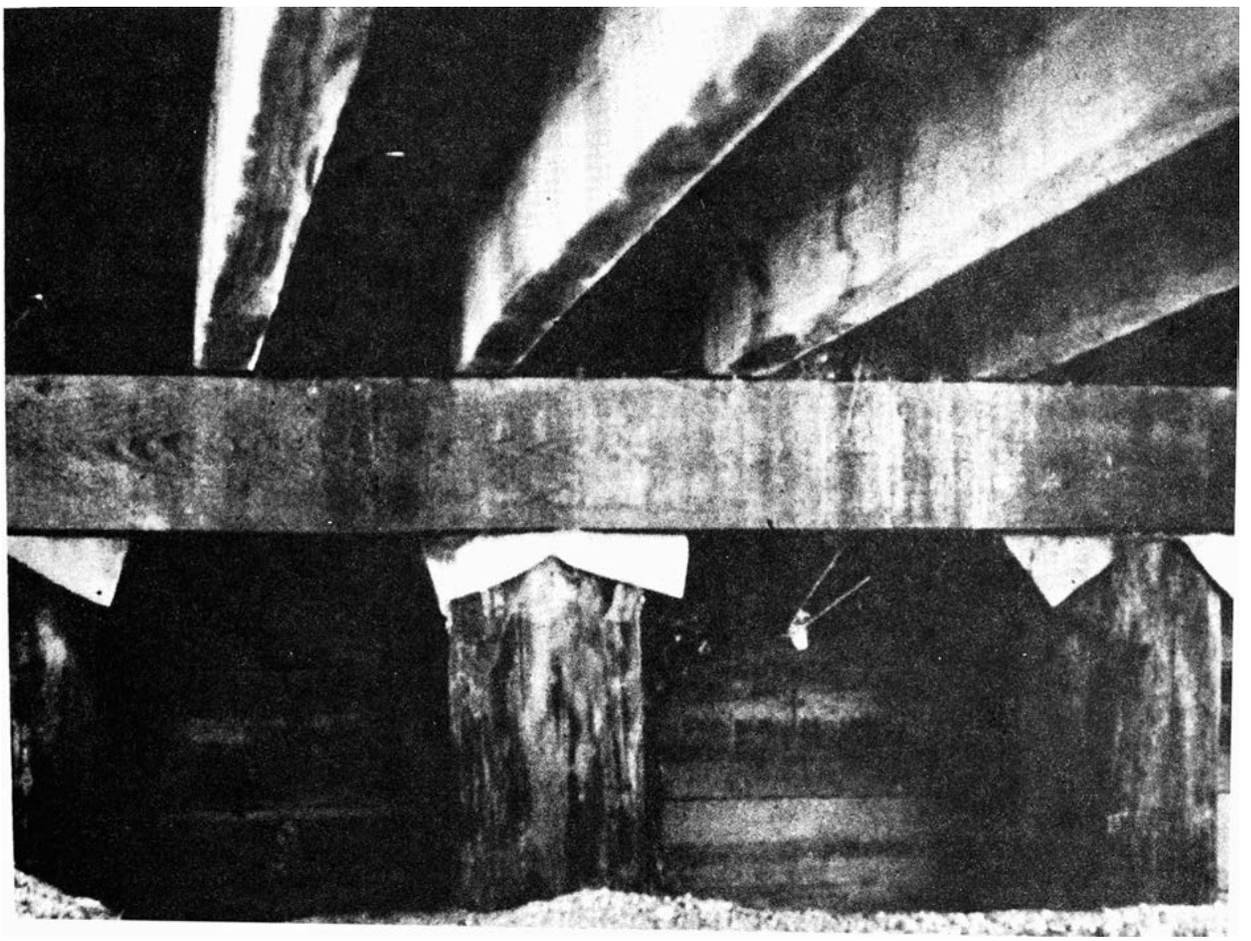
Pressure injection of pentachlorophenol or one of the waterborne preservative formulations into treatment holes may be commercially available as a service for control of internal decay in timbers. Holes $^3/_8$ of an inch in diameter and 11 to 12 inches deep are bored in a pattern around the decayed area. An injection nozzle is placed into each hole and the preservative is pumped into the hole to refusal. This service has been used extensively for railroad bridges.

Available Measures for Prevention and Control

Measures to both prevent infection by decay fungi and arrest an active infection in wood include control of moisture and in-place treatments.

Control of Moisture

Moisture control can be used as an effective and practical maintenance technique to obtain extended service from many existing bridges. This protective measure undoubtedly accounts in large part for the exceptionally long service obtained from many of the old covered bridges. In most of the more recent wood bridge designs, preservative treatments have been largely relied on as an alternative for decay control and little use has been made of the older principle.



M 145 280-14

Figure 14.—Metal inserts between pile top and supported cap. Such covers have questionable protective value.

Structure.—Some attempts at moisture control, such as the use of roll roofing material or sheet metal as water-diverting covers or caps within the bridge structure, have not resulted in the improvement sought, and in some cases have contributed to increased wetting. For example, roll roofing used as stringer covers under decking or as piling top covers under caps may initially reduce wetting; however, as the material ages and is used repeatedly, it becomes permeable to water. In either new or old condition such material will inhibit the drying of any covered wood that was initially wet or that becomes wet.

Another example of faulty piling-top shielding is the use of sheet metal inserts between the pile top and cap in timber bents (fig. 14). The metal is usually installed over the pile before the cap is placed in position. The drift pin depresses the sheet metal slightly as it is driven through the cap and into the piling, and also creates a less than watertight hole in the metal. This results in a funneling of capillary water in the metal-to-cap interface to the piling wood around the drift pin hole. Nails through the metal into the pile top function similarly.

During subsequent maintenance little can be done to modify this type of moisture problem in the wetted pile tops of older bridges. If the bridge is relatively new and the pile top is not too wet, applications of preservatives may be helpful or mastic sealants at the joint interface edges may divert water from entering the joint. Generally, the use of tight covering sheet metal or impervious membranes on individual members is questionable for new construction or for maintenance.

The use of bituminous or asphaltic mastics as sealants or bedding compounds appears to be more effective for such functions. As tightly adhering coatings, they do eliminate troublesome capillary spaces common with membranes and sheet metal covers. They may be applied appropriately as end-grain coatings, joint fillers or seals, and as check-filling compounds, but only if the wood is no more than moderately wet or if avenues other than those sealed are available for drying. Care must be exercised in making such repairs. Also, the repairs must be maintained to ensure a watertight coating or the problem may be compounded by formation of water entrapment areas under the coatings (fig. 15).

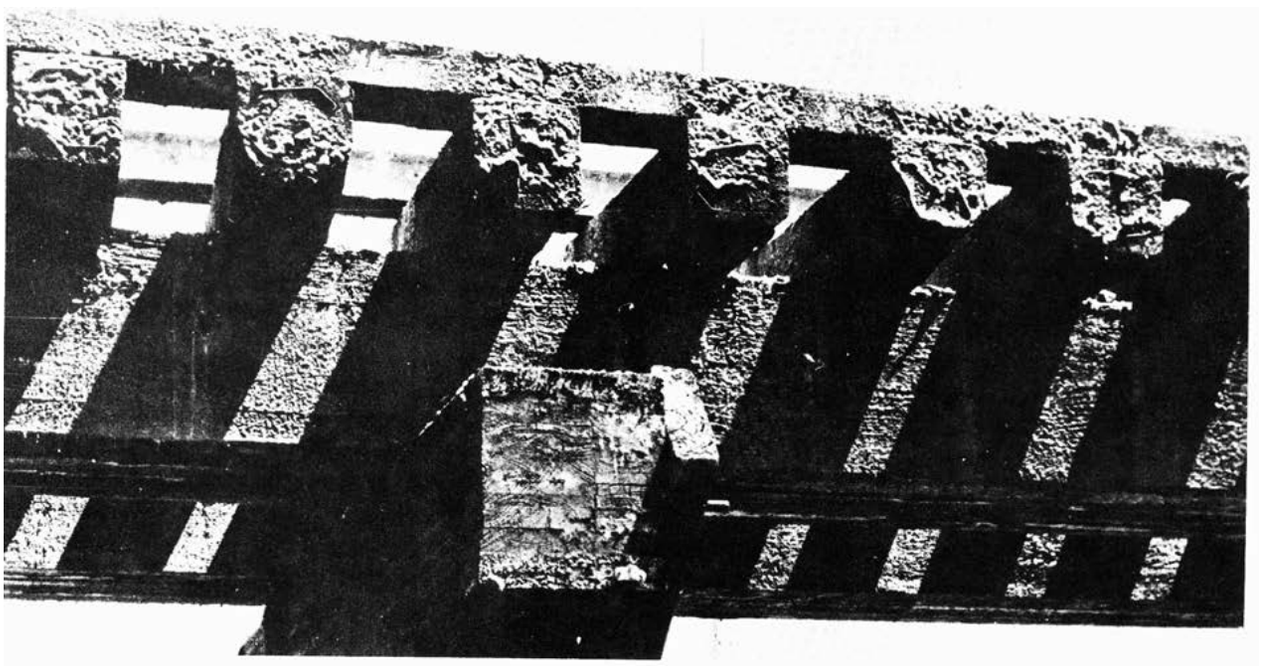


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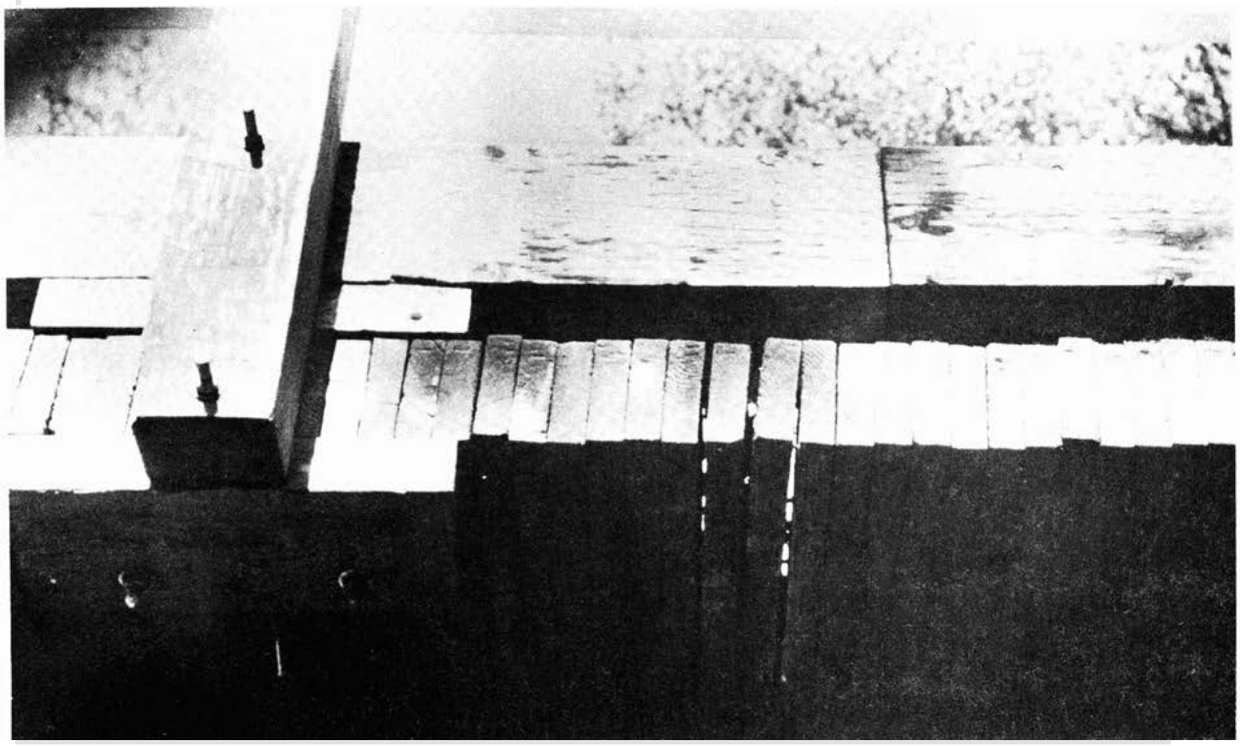
Figure 15.—Bridge timbers end coated with asphaltic mastic. Coatings no longer provide protection against wetting and subsequent infection, but form water-entrapment areas instead, leading to increased end wetting.



M 128 168

Figure 16.—Nailed-laminated deck exhibiting excessive separation of the laminates. The separation permits considerable passage of water to the below-deck bridge support timbers.

Where applicable, the mastics have the advantage of lower material and installation costs than metal or membranes. Also, any mechanically damaged or weathered and defective coatings that are exposed and accessible can be repaired simply by adding more coating material. However, such materials will probably be more appropriately applied as preventive maintenance measures rather than as solutions to existing decay problems.

Deck surface.—A more effective and practical approach to moisture control for most wood bridge designs is to restrict or prevent water passage through the deck. Establishing a deck or deck surface that is impervious to moisture penetration will afford protection for critical structural members equivalent to or better than that obtained in covered bridge designs. There are some practical limitations that should be considered in regard to the effectiveness of decay prevention by such a measure. For example, measures that prevent further wetting of wood members will be effective in preventing infection or stopping fungus degrade only if such areas can dry to nonhazardous levels in a reasonably short period. The time required for drying will depend on the extent of wetting already present, the average atmospheric conditions, and the drying chances of specific members relative to the location of the contained water and avenues for its escape.

The time available for drying will be determined largely by the stage of decay present and the time remaining before it will become structurally damaging. With most bridge designs the overall benefit of reduced general wetting will justify this approach. Where necessary, other methods of decay control may be used as required for specific localized areas.

On all-wood bridges, some decks are sufficiently tight to permit little water passage until they have loosened as a result of shrinkage associated with drying or heavy use. Such decks have tight planks spiked flat on closely spaced, solid-sawn stringers or comparably supported, nailed-laminated decks with deck members positioned on edge. Most of these decks become water permeable in time, but are sufficiently

stable to support a durable, water-resistant surfacing such as an asphalt mat. Such mats have been used in the past primarily as alternatives for mechanical deck protection in the place of wood or steel tread runs, which are often difficult to maintain and require periodic replacements. Asphalt mats without seal coating and with only poor maintenance divert much of the deck surface water away from the decking, stringers, and other substructure members. With proper maintenance, including asphalt crack filling and surface sealing, the mats can provide a high degree of protection from water penetration and consequent decay hazards in the underlying wood members.

The nailed-laminated decks, frequently supported on only three or four glued-laminated stringers, commonly show varying degrees of looseness (fig. 16) after 6 to 10 years of service; in moderate- or high-rainfall areas, the decks allow sizable amounts of water to pass through.

The redecking of one such Forest Service bridge in 1969 made possible an extensive examination of the moisture, decay, and other physical aspects of the 12-year-old structure. Generally, high moisture conditions were observed in both the nailed-laminated decking and the upper stringer lamination, as was a high incidence of decay in decking. This clearly demonstrates the hazard of excessive moisture penetration, especially at nail holes, into and through such decks. Shrinkage associated with the in-place seasoning of green-treated decking, heavy traffic loadings, and numerous failures of the through- and toenail-deck fasteners largely account for the excessive looseness observed in the deck. The Douglas-fir decking was pressure-preservative treated but without incising, and decay was present commonly at through-nailing points and contributed further to the unstable deck condition. The conditions found suggest the probable need for corrective maintenance measures on similar bridges.

Converting the deck from a water-permeable to an efficient water-shedding structure is a maintenance procedure well suited for bridges of this design and others where the basic problem is similar. Many such bridges are supported on concrete abutments so that preventing water passage into and through the deck affords decay protection for virtually all of the structural wood members.

For such bridges having sound and adequately stable decks, the addition of a 3-inch asphalt mat over the entire deck surface will afford considerable protection, if the mat is well maintained. Where the decking is decayed or its movement under the heavier normal loads indicates excessive looseness, redecking may be necessary before an asphalt surfacing can be maintained. At least some maintenance of the asphalt mats at regular intervals should be anticipated to keep them seal-coated for water repellency. Also, shrinkage cracks that develop as the mats age should be filled with hot coal tar or an appropriate mastic.

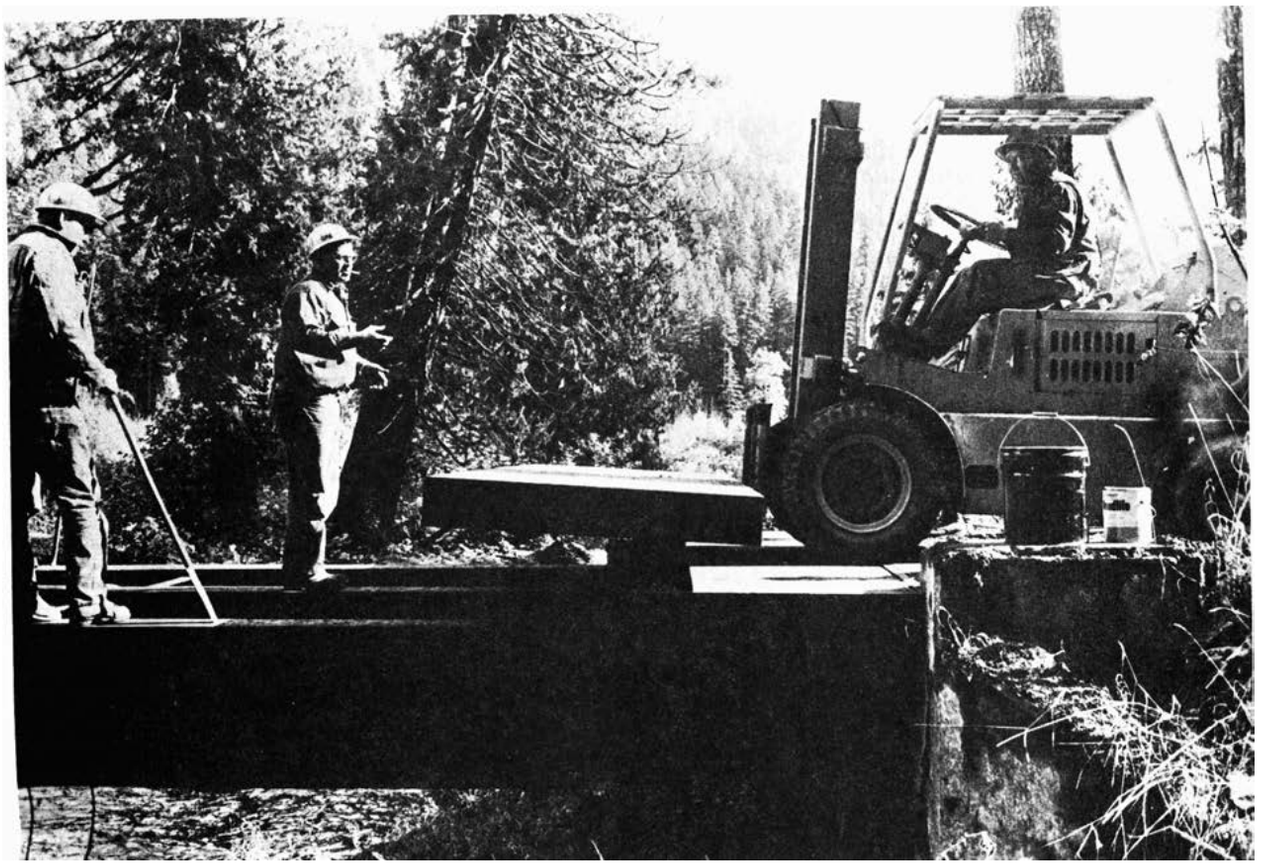
If redecking is required, glued-laminated deck slabs (fig. 17) offer several advantages to reduce decay hazards in both the decking and the supporting stringers. Such slabs afford excellent support for asphalt mats (2, 15). Further, glued-laminated deck slabs are produced at a moisture content of about 12 percent and will be subject to little shrinkage in service.

In-Place Treatments

Supplemental or in-place treatments on existing highway bridges have been little used in the past, partly because of the cost of locating members in early stages of decay. Commonly, decay has not been detected until after it has become severe, visible, or apparent from member weakening or failure in some degree. A significant factor is the lack of accessibility of many structural members in larger bridges. With the increased frequency and thoroughness of inspection, conditions conducive to decay and decay in its earlier stages will be detected more commonly. Permitting decay or conditions favorable to cause decay to remain without corrective action is unreasonable.

In-place preservative treatments available for maintenance of wood bridge members consist of applications of various liquid or heavier grease-type preservative compounds. Only limited use of such applications has been made on existing heavy timber structures other than the supplemental ground-line treatments for piling. Consequently, few data exist on the treatment of large members directly comparable to those in bridge structures on which to base in-place treating recommendations.

Conventional preservatives are available for in-place treatment. Some limited experiences in



M 138 108

Figure 17.—Glued-laminated deck slabs being installed as deck replacements on a 12-year-old bridge. Such decks have excellent stability and offer ample support for watershedding asphalt mats in contrast to nailed-laminated decks over widely spaced, glued-laminated stringers.

their use on bridge members are represented by on-site treatments during construction of untreated surfaces exposed by construction framing. Observations indicate that their effectiveness depends largely on thoroughness of application. However, no published records of penetrations or other pertinent data are available from their use on existing bridges or comparable heavy structures.

Because pesticides can be injurious to fish and other wildlife, if not handled or applied properly, care in in-place treating of bridge timbers should be exercised to ensure that no toxic materials be permitted to spill or drip into waters beneath bridges.

Liquid preservative applications.—Considerable evidence shows the potential effectiveness of such treatments as determined with experimental joints constructed of nominal 1-, 2-, and 6-inch material of both Douglas-fir and southern pine. Early comparative tests by Verrall (22) of different preservative chemicals applied in liquid form showed the generally superior effectiveness of the pentachlorophenol solutions. Most subsequent trials of light preservative applications have been made with pentachlorophenol. Recently, however, fluorchrome-arsenic-phenol (FCAP) has been found to more effectively protect simulated decking than pentachlorophenol when both were flooded onto the top surfaces of test units (9).

Work by Scheffer and Clark (17) has shown the extent of preservative penetration obtainable with these methods in experimental units, and the effectiveness of such treatments was appraised by laboratory bioassays. The companion field exposures are still in test, but they show very few failures in treated units after 12 years of aboveground exposures in Mississippi.

The marked effectiveness of nonpressure, 3-minute preservative dip treatments has been demonstrated in both laboratory tests and 10- to 15-year field exposures of experimental units (19, 24). Such short dips provide only slightly more preservative penetration than thorough surface flooding (spray or brush treatment), particularly where assembled joint interfaces are available to retain a small supply of the preservative in capillary spaces.

The low cost and ease of surface applications (particularly by spray-flooding) and their effectiveness as toxic barriers to new infections in aboveground members make such treatments useful in preventive maintenance. They can be reapplied systematically at intervals of a few years to supplement or reinforce existing marginal treatments such as those usually given onsite framing surfaces. These applications can also be used to extend preservative protection to the untreated parts of wood exposed at developing checks, infrequent delaminations, or mechanically damaged surfaces, if applied soon enough (before infection occurs) and systematically. Such treatments are particularly applicable to in-place members fabricated from nonpressure-treated material.

The shallow penetrations of surface-applied liquid preservatives limit their effectiveness for the control of established internal decay. Other methods are better suited for the treatment or elimination of such infections.

Water-repellent additives in light-oil preservative solutions are generally beneficial in reducing the moisture absorption of the treated wood subjected only to intermittent wetting. Solutions containing water repellents can be used safely on wet wood as drying of the wood is not seriously impaired. The thin film of repellent material that forms at the surface of treated wood is permeable to moisture vapor. The water-repellent film is permeable to water, if exposure is continuous and prolonged.

Wet wood absorbs less preservative than dry wood during brush- or spray-flooding treatments. This factor will frequently be significant, as the areas most in need of supplemental preservative are areas subject to wetting. In the experimental tests, improved treatments of wet wood were obtained by using the preservatives at double the customary 5-percent concentration.

Grease- or emulsion-type preservatives.— These investigations have involved surface applications of the liquid preservative primarily but include some tests of greaselike pentachlorophenol compounds. Commonly, the liquids were applied by a single brush- or spray-flooding of the test surfaces or joint interfaces. The grease-type preservatives were coated on the wood surfaces or extruded beads were applied to joint interface edges.

These preservatives are less easily applied, but may find special uses. The principal advantage to be obtained with such preservatives is that larger quantities of the toxic chemical can be locally applied in heavy coatings or extrusions of the semisolid carrier that adheres well even on vertical surfaces. Adsorption of the preservative over an extended period of time from such a coating or local application will afford deeper preservative penetrations than by single surface applications of liquid treatments. Penta-grease or emulsion treatments can be used advantageously also during member replacement or other structural modifications.

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Apply pesticides so that they do not endanger humans, livestock, crops, beneficial insects, fish, and wildlife. Do not apply pesticides when there is danger of drift, when honey bees or other pollinating insects are visiting plants, or in ways that may contaminate water or leave illegal residues.

Avoid prolonged inhalation of pesticide sprays or dusts; wear protective clothing and equipment if specified on the container.

If your hands become contaminated with a pesticide, do not eat or drink until you have washed. In case a pesticide is swallowed or gets in the eyes, follow the first aid treatment given on the label, and get prompt medical attention. If a pesticide is spilled on your skin or clothing, remove clothing immediately and wash skin thoroughly.

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