Final Report 2002-34

Research

Inspection of Timber Bridges

Minnesota Local Road Research Board

Technical Report Documentation Page

1. Report No.	2.	3. Recipients Accession No.	
MN/RC – 2002-34			
4. Title and Subtitle INSPECTION OF TIMBER BRIDGES		5. Report Date September 2002	
		6.	
7. Author(s) Robert Seavey, PhD Timothy Larson, PhD		8. Performing Organization Report No.	
9. Performing Organization Name and Address Department of Wood and Paper Science University of Minnesota 2004 Folweel Avenue St. Paul, Minnesota 55108		10. Project/Task/Work Unit No.	
		11. Contract (C) or Grant (G) No. c) 71391 wo) 126	
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Office of Research Services 395 John Ireland Boulevard Mail Stop 330 St. Paul, Minnesota 55155		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes			
17. Document Analysis/Descriptors bridge creosote Douglas fir		18.Availability Statement No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 53	22. Price

16. Abstract (Limit: 200 words)

Approximately 35% of Minnesota's 1,373 bridges are reaching the end of their expected service life. Many of these timber bridges are located in rural, low traffic settings that do not justify the expense of replacement. Extending the life of these bridges will not only save communities money, but will ensure continuous bridge service.

This study reviewed both new and traditional techniques for inspecting decaying wood on timber bridges. Newer, nondestructive technologies examined include De-K Tector, stress wave timer, Sylvatest, PoleTest, pile length assessment, hammer sounding, shigometer, Resistograph, core and bore sampling, probing, moisture meters, and infrared thermography. These methods offer many advantages, but are still expensive and time consuming. Traditional inspection methods might be the best alternative in most situations. The researchers recommend inspecting older bridges every three years and newer bridges every five years, with more careful evaluation of areas that show wood decay.

The researchers conclude that the best way to pass on knowledge about timber bridge inspection is through hands-on seminars.

Inspection of Timber Bridges

Final Report

Prepared by

Robert Seavey, PhD
Timothy Larson, PhD

Department of Wood and Paper Science
University of Minnesota

September, 2002

Published by

Minnesota Department of Transportation
Office of Research Services
Mail Stop 330
395 John Ireland Boulevard
St. Paul, MN 55155

Acknowledgements

The financial support for this paper was provided by the Local Road Research Board. The authors would like to thank the assistance provided by Gene Isaakson, Sibley County Engineer, Ken Johnson, Wheeler Consolidated, Inc. and Hung Chen, University of Minnesota.

Executive Summary

The primary focus of this research is supplying quality, timely and cost-effective inspection information about timber bridges. Many timber bridges built in the 1950s and 1960s are approaching the end of their projected service life. Some of these bridges can be left as they are for the present time, some should be upgraded, and some will need to be replaced. Decisions about these alternatives are based on an inspection of the bridge.

The allocation of federal and state bridge funds is based on the condition of the existing bridge and the amount of traffic using the bridge. A number of states have implemented use of the PONTIS computer system to aid in bridge assessments. PONTIS provides a detailed evaluation of individual bridge elements (girders, bridge deck, pile caps, and so forth). However, to work effectively the PONTIS system requires uniform inspections and accurate information. Timber inspection poses a special problem because the material is so variable and because of the complexities associated with preservative treatments, moisture movement, and biological degradation.

A thorough review of traditional and newer, nondestructive methods for evaluating wood decay has been completed. At this time, the best alternative may still be traditional inspection procedures. The newest nondestructive technologies are still very costly and require a lot of time to inspect even a short distance of a bridge. Nondestructive evaluation might be appropriate for inspecting a small, but critical portion of a bridge. Areas of internal decay may be detected using a stress wave timer or a Resistograph drill. Nondestructive evaluation, however, is still largely ineffective for detecting incipient decay in timber bridges.

Infrared thermography (IR) has one advantage over other nondestructive procedures for early diagnosis of potential wood decay problems. IR allows inspection of bridge elements from

a distance. For some of the study specimens, infrared thermography was effective at determining the areas of high moisture content. Infrared thermography, however, has several major disadvantages: the equipment is expensive, a well-trained and experienced operator is needed, the time of day and the conditions need to be just right so that the wet wood will be at a different temperature than the surrounding wood, and finally, the wet wood zones may not have any wood decay or strength loss.

Another part of this project has been the development of a prototype expert system computer program. Timber bridge inspection is a good candidate for an expert system because the complexities of wood structure and because wood deterioration is a rather specialized area. The inspector in the field needs a general understanding of steel, concrete, and wood. The challenge in developing an expert system program is to develop an easy-to-follow presentation format while still providing sufficient depth and detail to be useful for bridge inspectors. An expert system is fundamentally a method of technology transfer. It is our conclusion that a series of hands-on timber inspection seminars is the most effective approach to implementing technology transfer of timber bridge inspection.

Table of Contents

List of Figures

1 Introduction

There are 1373 timber bridges listed on the Minnesota Department of Transportation (Mn/DOT) Bridge Inventory. Of these bridges, about 35% are over 40 years of age in the year 2002. Presuming that many of these bridges were designed for a 40–50 year service life, this would mean that about 480 bridges are now candidates for replacement in the coming years. Extending the service life of some of these bridges represents considerable savings for the state. While these savings may not seem significant relative to the total budget for highways and bridges, it must be noted that many of these bridges are in rural locations with low traffic demands. Diverting the money to repair or replace away from regular highway projects on well-traveled routes will certainly present significant problems.

It has been demonstrated that many timber structures have an actual life of well over a 100 years. While bridges constructed recently may have a life-span of 100 to 150 years, this was not the expectation when these bridges were designed and fabricated. It is good that these bridges have lasted so long. However, they still need to be inspected so that problems are detected and safety is insured. These structures have survived this long because they have been able to avoid moisture problems and subsequent biological degradation.

The primary mechanism for wood preservation in timber bridges has been creosote treatment. Wood will get wet in service, especially if it is in ground contact. A wood preservative treatment is critical. There are limitations to the effectiveness of wood preservative treatments because only the outer surface layer is treated and the core remains untreated and exposed to decay. After many years of service, the treated surface layers may be damaged and thus allow wood rot in the untreated core.

The vast majority of the timber bridges in Minnesota are assembled from creosote treated Douglas fir (K. Johnson, 1998). Selection of Douglas fir and creosote treatment has some advantages in that the heartwood is somewhat decay resistant, the wood is strong, and large dimension, high-grade timbers are available. A substantial limitation with creosote treatment is that even with incising, the treatment may only penetrate 2–3 inches into the wood. If wood is at a higher moisture content (MC>30%) when it is treated with preservative, there is a distinct possibility that drying checks will later develop on the surface. These drying checks will expose the untreated core to wood rot.

The greatest deterioration problem is fungal decay. Decay fungi have been categorized into three general groups: white rot (or those that first attack lignin components of wood), brown rot (those that preferentially attack cellulose and hemicellulose in the wood), and soft rot fungi, (those that operate at lower oxygen levels and slowly erode the surface of the wood).

There are four requirements wood decay. Oxygen is needed for the fungi that rapidly decay wood. In cases where wood has been kept in low oxygen conditions such as at lake bottoms, or buried below the water table, the wood has suffered only moderate degradation. The primary cause of this degradation has been anaerobic bacteria, which are very slow to degrade wood.

Moisture is another requirement for wood decay. Generally moisture contents above 30% (oven dry basis) are needed for significant wood decay. However, some wood decay will take place below 20%, especially if the decay has already been established.

Temperature is another important factor for wood decay. The temperatures between 10°(50°F) and 32° (90°F) are optimal for wood decay. As the temperatures rise above 32°

(90°F), fungal activity decrease as metabolic activity is inhibited. Concurrently, temperatures below 10° (50°F) will inhibit fungal activity and limit wood decay.

The final requirement for wood decay is a food source. The wood cellular structure of the bridge provides this source. Wood is comprised of cell walls, cell lumens, and pit openings that connect the cell lumens together. In this sense the wood is well suited for wood deterioration because the cell lumens and pit openings serve as long narrow routes for the hypha to grow into, while at the same time the cell lumen provides a food source.

Decay prevention is predicated on removing at least one of the requirements for wood decay. In climates like Minnesota, exterior wood decay is largely negligible from December through March because of cold winter temperatures. During this period the fungi become dormant. When temperatures increase again in the spring, the fungal metabolic activity will increase as well, and wood deterioration will take place.

Eliminating oxygen sources is obviously another successful way to limit fungal deterioration of wood structures. Logs, timbers and pilings that are kept well below the water surface or ground water level will not deteriorate even when left in these conditions for hundreds of years. Unfortunately, most wood structural members are exposed to oxygen and are therefore subject to wood decay.

Wood decay can be eliminated by first drying the wood and subsequently preventing it from getting wet. Interior storage and usage of wood has shown that there is little to no degradation of wood that has been dried. When wood is exposed to exterior conditions, it is much more difficult to prevent it from getting wet. There are a number of measures that can be used to significantly reduce moisture uptake in exterior conditions.

One of the most effective ways is to use some type of roof to shed rainfall away from the structure. Another approach is to coat or impregnate the wood with a water-repellent product. An advantage of a creosote treatment is that it reduces water uptake by improving the water repellency. Paint films may also be effective, but when the integrity of the film breaks down, water can get through the cracks and into the wood. The use of flashing is another way to reduce moisture exposure. When flashing systems are properly designed, they eliminate most of the exposure to moisture while allowing air contact with the wood to facilitate the drying potential. Flashings that are properly designed and installed represent a vastly underutilized and misunderstood opportunity for wood preservation.

When wood is in contact with the ground, there are significant opportunities to reduce moisture damage by shedding water away from the structure. The soil or fill immediately around the structure should be well-drained and should be of a particle size such that water capillaries can not be form within the solid. Clay fill allows capillary action to keep the wood continuously wet. Another opportunity is to design the foundation and fill so that water is drained away from the structure. This is the same approach that has been used effectively to keep residential basements (concrete and wood) dry throughout the year. Channeling moisture away from the structure reduces the amount of water uptake over time, and facilitates drying potential so that any moisture that has been taken up can be easily dried.

Preservative treatments are properly considered as a last line of defense against wood decay. However, given the importance and the expense of timber structures, it is appropriate that the last line of defense be as strong as possible. An effective preservative treatment depends not only on the preservative itself, but also on the species treated and the manner of treatment. Species that are more permeable will be better treated with preservative chemicals and will have a longer service life. Creosote has a long record of very effective service against a wide number of wood deteriorating organisms. The problems with creosote are that it is not suited for direct human exposure and the smell is objectionable even in concentrations that may not be harmful. The preservative treatment process can overcome some of the species permeability limitations. Douglas fir is frequently used for timber bridges. While Douglas fir does not treat well, aspirated pits block preservative penetration, the use of incising, and pressure treatments have provided effective results with creosote preservative.

Three measures of preservative treatment have been used:

- Retention refers to the quantity of preservative that is taken up by a given volume of wood. It is frequently described in weight of preservative per volume of wood. In a high decay hazard situation, the retention of preservative should be as high as possible.
- Penetration refers to the depth of preservative treatment into the wood. This is especially important with large timbers, where the preservative is only likely to treat the surface perimeter of the wood. The untreated core is still untreated and, if exposed, could decay. Drying checks and postreatment drilling into these timbers can expose the wood in the core to decay. This situation has been noted with pile caps on timber bridges where the check at the top of the pile cap can trap moisture and provide an avenue for wood decay into the core.
- Uniformity is another important measure of preservative effectiveness. Some species allow sufficient preservative penetration and retention, but are nonuniform in their preserative uptake. Once again, those areas, that have taken up insufficient levels of preservative are vulnerable to wood decay.

The major concern with older timber bridges is the decision of what should be done with them. It is obvious, many of these bridges will need to be replaced. Unfortunately the expense of replacing these bridges is quite significant. At the same time their traffic usage may not make them worth the replacement expense. Other older timber bridges can be left in service or upgraded. These choices are difficult to make in many cases. It is difficult to prioritize decisions about where public funds will be spent.

The level of data management for the bridge inventory in Minnesota has been upgraded by the implementation of the PONTIS bridge management system. PONTIS is able to prioritize not only the bridge itself, but also the various elements within the bridge: stringers, pile caps, abutment, and so forth. Unfortunately, timber bridges pose a significant challenge because PONTIS can only be as effective as the information that is provided to it. The inspection and evaluation of timber bridges represents this sort of problem. Frequently timber products are not used properly because of a general ignorance about the service performance of this material. These problems have resulted in costly replacements and a general decline in the willingness to use timber structures. Similarly, the inspection of timber bridges is limited by the knowledge of the inspector and by the time that is needed to properly inspect a timber structure.

2 Nondestructive Evaluation of Timber

Adapted from Report provided for this project by Ron Anthony, Engineering Data Management

2.1. Overview

Structures built of timber represent a major portion of the nation's transportation infrastructure. Significant economic losses are encountered annually associated with deterioration and failures of structural members composed of timber products. A large portion of these losses result from our inability to detect initial degradation and distress, thus allowing the continuation of deterioration resulting in premature, costly replacement. Development of new and more effective nondestructive evaluation (NDE) methods, specifically designed for timber structures, is providing new detection tools for engineers and maintenance managers.

Among the major construction materials, wood represents the most complex behavior. Biodegradability, directional properties, inelastic behavior, inherent variability, fibrous composition, porosity, combustibility, hygroscopicity and inhomogeneity represent additional factors which need to be considered when developing NDE procedures for engineered structures built of wood and wood composites. The influences of many of these variables are much more severe under exterior conditions (e.g., a bridge or a power pole) than under interior (e.g., arches in an auditorium) conditions.

For many decades, NDE of timber structures was focused on visual identification of defects and determination of the presence of decay or insect-caused degradation. Quantification of the effect of these factors on the load-carrying capacity (strength) of structures is quite difficult and has not progressed significantly until recently.

Concepts of strength and quality are often used interchangeably. Quality is generally equated with the degree of decay present in a wood member. Strength is then indirectly predicted using the size of the decay pocket present. Few direct strength prediction methods are available. A distinction between quality and strength can be made when evaluating in-service timber as defined below:

Method	Primary Purpose
1. Quality Assessment	To assess treatment requirements to extend service life
2. Strength Evaluation	To determine load-carrying capacity

To a very large extent, decay detection still represents the major evaluation method used today to assess the structural soundness of timber structures. While it is true that extensive decay can cause structural failures, there are several other factors that are also responsible for structural failures.

The strength reduction of timber due to decay is generally evaluated by the ratio of the decayed cross section over the gross cross section without decay. A complex decay spread pattern is usually approximated by using as many as three incremented bore samples and assuming the existence of simplified patterns of geometry. Technology exists which can nondestructively detect the presence of decay.

One of the fundamental issues with the decay area approach is that it is unable to account for initial stages of decay degradation when the effect of decay cannot be considered as total strength loss. Even more critical is the fact that the true strength of the remaining so called "undecayed portion" of the cross section is not known. These limitations make the strength prediction of partially decayed structural timber more qualitative than quantitative.

Stress wave velocity (speed of sound) measurement is one of the quickest NDE methods used for evaluation of in-situ structural timbers. The measurement is relatively simple. Two sensors are located a fixed distance apart and a timer measures the time, usually in milliseconds, the sound wave takes to travel between these two points. Generally, the timer measures the travel time of a compression wave induced by an impactor. The application of the stress wave velocity to NDE is based on the observation that in lower quality and decayed timber the stress wave propagates at a slower speed. Thus, generally, a lower stress wave speed corresponds to weaker material. Limited success has been obtained with this method for in-situ applications since in inhomogeneous materials the stress wave travels faster in the higher quality than in the lower quality material. Nonetheless, this method provides for relatively quick quality assessment of timber.

While stress wave velocity measurements are used to assess timber quality, the reliability of this method to quantify residual strength is relatively low. This method must be supplemented by the decay area approach, as well as with other visual inspection, before a decision can be made on the residual strength of the structural members.

Unlike stress wave velocity measurements, application of stress wave analysis NDE methods to timber structures is relatively new. Stress wave analysis is based on the principle that in inhomogeneous materials, such as timber, not only do stress waves propagate at different speeds but also they attenuate differently at various frequencies.

Most theoretical treatments of stress wave or vibration analysis describe methods for directly determining material stiffness and damping. They also provide theoretical methods for detecting defects. While knowledge of size and location of defects is useful in evaluating a material, such knowledge is not always sufficient to predict its strength. Stress wave propagation in orthotropic solids, particularly wood, is extremely complex and this problem is further accentuated by the presence of inhomogeneities in the wood. Therefore, current implementation of stress wave techniques for NDE of timber are based on empirical relationships between strength and NDE parameters.

2.2. Nondestructive Testing Instruments

The following sections provide information on several NDE devices that are available for assessing the quality or strength of timbers used in bridges.

2.2.1. De-k Tector

De-k Tector is produced by Heath Consultants of Stoughton, Massachusetts. De-k Tector is a portable, battery-operated device designed to indicate the presence of decay and voids in wood. The system consists of an impactor for striking the surface of the wood and a transducer for detecting the relative level of energy that is transmitted through the wood. A measurement device amplifies the transducer signal and determines the frequency distribution of the transmitted sound.

Theory of Operation

De-k Tector consist of two bandpass filters for analyzing the measured signal. The frequency content, which passes through the filters, is used to determine the different response levels at high and low frequency ranges. A simple needle indicator displays the quality of wood based on the relationship between the two frequency ranges. When the high pass signal (higher frequencies) is greater than the low pass signal (lower frequencies), the indicator registers in a favorable zone, indicating a lack of internal voids. This response is due to the effect of defective wood inhibiting the transmission of higher frequencies normally present in sound wood.

Capabilities

De-k Tector is simple to use and requires virtually no setup time to inspect timber. This qualitative test allows for the user to quickly assess the potential for internal defects in timber. Unlike most NDE procedures, it does not require inserting sensors into the wood. It can be used as a screening method to determine which wood members require further inspection by boring or use of other NDE equipment.

Limitations

De-k Tector uses an impact directly on the wood surface and also places the receiving transducer directly on the wood surface. Therefore, surface roughness will affect the contact between the wood and either the impactor or the transducer. This condition can result in inconsistent readings. Further, the presence of internal checks or splits may produce questionable readings with the instrument which would indicate internal defects when the checks and splits may be naturally occurring and not necessarily impact the serviceability or strength of the timber.

2.2.2. Stress Wave Timer

The Stress Wave Timer is produced by Metriguard, Inc. of Pullman, Washington. It is a portable, battery-operated device for detecting decay in a variety of timber structures. The system consists of a special impacting hammer for introducing a stress wave into the wood, an accelerometer for sensing the arrival of the stress wave and an enclosed box which houses the electronics and display components. When the impacting hammer strikes the wood surface, or a lag screw embedded into the wood, a counter is triggered. The counter stops when the stress wave triggers the accelerometer placed away from the impact.

Theory of Operation

The operation of the Stress Wave Timer is based on the ability to measure the leading edge of an induced stress wave using accelerometers placed at any known distance apart. To detect internal decay, the impact would be delivered opposite the location of the "STOP" accelerometer. Internal amplifiers are used to adjust the gain of the measured signals to minimize the possibility of random triggering of the device due to extraneous noise. The electronics consists of a clock oscillator and gate circuit, which are used to define the "START" and "STOP" pulses. The time between the "START" and "STOP" triggers is displayed in microseconds. Although readings can be taken on several timbers to obtain qualitative results, the manufacturer provides tables of expected stress wave velocity values for various species of timber. From these species-average values, relative degradation can be inferred from field measurements.

Capabilities

The Stress Wave Timer has been used for several applications other than decay detection, including quality control during production of wood-based products, sorting or grading of timbers according to material properties and measuring directional properties in wood. For field use, the device is relatively simple to use, although care must be taken in the interpretation of the results. lt is perhaps best used when conducting a qualitative assessment of timber by measuring and comparing several readings on each piece of timber of concern. By establishing a grid for taking several readings on large timbers, piles or laminated beams, it is possible to determine where degradation has occurred.

Limitations

The Stress Wave Timer is somewhat sensitive to the level of impact, therefore, selection of the proper gain setting is important. Generally, efficiency and repeatability of readings improves with operator experience. Impacting directly on the wood surface or failing to securely mount the accelerometer to the wood may produce erratic results, which can be difficult to interpret. Attenuation of the frequencies in the stress waves is affected by material properties and wood moisture content. This will also affect the measured stress wave time. Further, due to the natural variability of stress wave velocity in wood, it is difficult to determine the presence of early stages of decay. Nonetheless, the Stress Wave Timer is useful for conducting a qualitative assessment of structural timbers relatively quickly.

2.2.3. Sylvatest

Sylvatest is produced by Sandes, S.A. in Switzerland. It was designed as an ultrasonic wave velocity device for grading Swiss timber. However, since it measures ultrasonic wave velocity, wood moisture content and temperature, it has application for inspection of timber in the field. Sylvatest consists of two piezoelectric transducers, one for transmitting at a frequency of 30 kilohertz and one for receiving the signal. The system includes a portable, battery-operated unit which houses the electronics for processing the ultrasonic wave velocity data. A separate carrying case houses all accessories needed for testing. Sylvatest can be used for rapid qualitative measurements for decay detection and, with calibration to appropriate species of timber, provide strength and stiffness information based on programmed correlations with destructive tests.

Theory of Operation

Measurement of timber quality is achieved with Sylvatest by measuring the speed of ultrasonic waves generated at 30 kilohertz. Wave speed is measured by inserting the tip of the transducers straight into the end-grain of the timber or at 45° angles on a surface of a member where the ends are not accessible. The transmitter sends 30 KHz pulses into the timber and the receiver triggers the electronics when the initial pulse is sensed. If desired, wood moisture content and temperature can be measured with Sylvatest to adjust the wave speed to reference conditions. The wave speed is displayed in microseconds.

Capabilities

Sylvatest can be used for verification of mechanical properties (using correlations with ultrasound velocity), quality control of wood products during manufacture and sorting of timber and wood products for grading. Its primary use in field applications is currently for qualitative assessment. Using the device in a manner similar to that described for the Stress Wave Timer, it is possible to compare ultrasound velocity readings within a member or between members to determine inconsistent material quality or relative ranking of member condition. It requires virtually no setup time other than creating a pilot hole for the transducers using a modified awl. When a pilot hole is used, readings at a given location are quite consistent and do not tend to be as operator-sensitive as other techniques.

Limitations

Sylvatest was developed for grading timber but has not yet been programmed for North American species for this purpose. Therefore, it should be used for qualitative, rather than quantitative, assessment of timber. The device was not designed for use on thinner timbers (thickness of less than 25.4cm (10 inches)) except parallel to the axis of the member. This makes it difficult to use Sylvatest to measure ultrasound velocity in many members typically used in bridge construction. However, the larger timbers in a bridge are generally those of primary concern during inspection and, therefore, Sylvatest has application for bridge inspection.

2.2.4. PoleTest™

PoleTest is produced by EDM, Inc. of Fort Collins, Colorado. PoleTest is a portable, battery-operated device designed for determination of bending strength of wood poles. The device is programmed for Douglas-fir, southern pine and western red cedar timber species and can be used on bridge piles in addition to poles. It is also possible to derive compression strength from a predicted bending strength value for round timbers.

Theory of Operation

PoleTest™ is based on the analysis of stress waves propagating through the cross section of round timber. Through empirical correlations with full-scale destructive bending tests, strength can be determined using PoleTest from the characteristics of a stress wave as it passes through the wood. A stress wave (sound wave) is induced by a simple pendulum device, which provides the consistent level of impact energy required for repeatability. The stress wave is sensed by two transducers placed on opposite sides of the timber and processed by an internal spectrum analyzer. A digital readout displays a predicted bending strength for each timber, measured in pounds per square inch.

Capabilities

PoleTest is the only testing device for timber that directly predicts bending strength. Although developed for use on utility poles, it can be used on other round timbers, such as piles, and can also be used to estimate compression strength, based on ratios of the bending-to-compression strengths for the species programmed into PoleTest.

Limitations

PoleTest is not a decay detection device; it is used to determine load-carrying capacity. The manufacturer recommends that it be used in conjunction with visual inspection techniques, such as boring or drilling. This will enable detection of the presence of decay as well as the strength of the timber. Although PoleTest is programmed for three species (Douglas-fir, southern pine and western red cedar) it has a selection called "OTHER" when timber species is unknown. This selection is to be used only on softwood species, and results in greater variation in the strength prediction.

2.2.5. Other NDE Devices

New developments for the inspection of timber should result in additional tools becoming available to bridge inspectors for timber. Two recent developments, which are yet unproven in the field in the U.S., are the Wood Decay Detector and the Resistograph Drill.

The Wood Decay Detector is based on ultrasonic wave velocity and is reported to measure and evaluate the existence and extent of internal decay in wood. Originally developed in Japan, this device requires a reference measurement of ultrasonic velocity through "good" wood. Then several diametric readings are taken at the location of interest. The device displays percent decay and, optionally, percent residual mechanical strength, or a "good" or "bad" indication. The Wood Decay Detector must be calibrated for North American species to estimate residual strength. At the time of this report, the calibration had not been done.

The Resistograph drill, manufactured by lnstrumenta Mechanik Labor GME3H in Germany, is a "quasi-nondestructive" inspection method for a wide range of wood products, including standing trees. The system includes a hand-held, battery operated drill with data storage capabilities and a printer. It can be used to detect internal defects, such as decay, splits and voids. It can also be used to measure relative density and growth rates of timber. The system is new in the U.S. market and holds considerable promise for inspecting timber structures. The Resistograph is limited by its inability to distinguish certain types of natural growth variation in wood from defects. Therefore, an operator may require training and experience to recognize such responses.

2.2.6. Pile Length Assessment

During the late 1980's, nationwide attention was directed toward bridge failures due to scour. Recognizing the need to uniformly evaluate bridge scour, the Federal Highway

Administration (FHWA) published a Technical Advisory on the scour of bridges. This Technical Advisory is used to address the effects of bridge scour in the design process and inspection of existing structures within the National Bridge Inspection Standards Program.

Knowledge of pile length is a vital component in calculating the scour resistance of a bridge. However, records of timber pile lengths may, in many cases, be nonexistent or incomplete due to the construction practices for timber piles. Piles are typically driven until they reach a predetermined resistance, and then trimmed at the end to provide a solid, level surface for substructure construction. Records that specify initial pile length, depth of driven pile or length of pile trim are often not available, especially in older structures. Thus, it is difficult to obtain timber pile length data for scour evaluations.

Past research by EDM, Inc. of Fort Collins, Colorado on timber poles and piles resulted in NDE techniques based on stress wave propagation that provides a basis to evaluate the length of timber piles. To adapt the NDE technique for pile length determination, modifications to existing impact methods and sensor attachments were necessary, coupled with testing on piles of known lengths. Field testing of the modified NDE technique which identified the accuracy, limitations and the means of applying the pile length determination technology was completed.

<u>Basis of Pile Length Determination</u>

Stress waves, produced from an instrumented hammer impact, travel along the length of a pile and are reflected at boundaries until dissipation of the impact energy. The stress waves travel at a velocity that is dependent on the timber pile density, moisture content and material quality.

Pile length can be evaluated by measuring the reflection time required for the stress wave to travel down to the base of the pile and return. The reflection time is related to the resonant frequency of the pile. The measurement of resonant frequency and stress wave velocity enable the calculation of pile length. By inducing a stress wave in the pile with an instrumented hammer and measuring the resulting echoes with sensors attached to the pile, a computerized data acquisition system can collect and process the information to determine pile length.

Application of the Technique

The objective of this project was to reliably evaluate the length of timber piles. An NDE method now exists to evaluate the length of timber pilings. Field-rugged hammer impact methods and sensor attachments are simple to install and employ. The stress wave technique has been shown to reliably estimate pile lengths between 6.1m and 18.2m (20 and 60 feet) with an identified accuracy of + 15% of pile length.

It is recommended that trained technicians coordinate the data collection and review the NDE data (frequency records) of each pile at the time of testing. Comparisons should be made of pile length estimations within a single bent to minimize erroneous data. The technician should discuss with bridge maintenance personnel the local geotechnical conditions to further validate the pile length estimations. Given the current computerized data acquisition system and sensor configuration, approximately 20 piles per day can be evaluated with a trained technician and assistant.

Limitations of the Stress Wave Pile Length Estimation

Decay and fractures at the mudline from excessive bending loads were found to influence the harmonic content of the pile data. Damage that may occur during pile driving, such as severe bending of the pile, separation of annual growth rings near the surface and crushing of the tip were not evaluated. Thus, if such conditions are encountered, the length estimate may be altered.

The estimate of the wet velocity of the wood below the water or mud line is subjective. It has been reported that for sound timber, the wet velocity will be approximately 90% of the dry velocity. However, the developers of the technique are aware of wet velocities well below the commonly known dry velocity range of 10,400 to 18,300 ft/sec. for timber. Misjudging the wet velocity adds to the error of the pile length estimation.

Engineers and maintenance personnel who require the knowledge of pile length to evaluate the effects of scour on pile capacity will find the stress wave pile length estimation technique a unique opportunity to acquire information previously unavailable. Applied NDE technology can effectively provide the required information to make more sound engineering decisions.

2.3. In-place Nondestructive Evaluation Techniques

This section describes the basic theory behind NDE techniques and presents practices of various NDE techniques.

2.3.1. Hammer Sounding

This method of testing has been done for centuries and is still used today. The procedure is to hit a structural wood member with a hammer and determine from the quality of the sound if the component is sound. A dull or hollow sound indicates problems and the need for further investigation whereas a ringing, clear sound indicates the wood is good. The accuracy of “hammering” depends on judgment, experience and hearing. Decay has to be extensive and/or near the surface for this method to be effective.

2.3.2. Shigometer

This device operates by the principle that resistance to pulsed current decreases as the concentration of cations increases in wood. The cation concentration in wood goes up it is decayed by fungi. The wood being inspected has to have moisture content above 30% for this device to work. The shigometer allows the user to detect the initial breakdown of wood by fungi.

2.3.3. Core and Bore Sampling

Coring and boring are the most widely used methods for detecting internal decay. Coring entails the removal of a core of wood, which can then be examined for depth of preservative, and the presence and location of decay.

Borings, on the other hand, refer to the use of a drill and a bit to extract shavings from the interior of the wood, which are then examined for decay. This technique is faster than coring but the information collected is not as quantitative as coring.

Both of these evaluation techniques drill hoes in the structural members but have little impact on the strength of that timber. It is very important that coring and borings are done with sharp instruments.

2.3.4. Probing

Probing is a technique that is used to evaluate the surface of wood and its soundness. An awl or fine-bladed knife is used to probe the surface of the wood to detect shell rot or other decay that is close to the surface. Another instrument useful in measuring the soundness of wood surfaces is called a pilodyn, which has a spring-loaded probe that measures the shock resistance of wood. The depth of penetration of the probe into the wood is an indication of its soundness.

2.3.5. Moisture Meter

The electric resistance moisture meter is a valuable tool for evaluating structural member moisture content. One of the ingredients needed for decay is moisture. This moisture meter will give qualitative readings above 30%, which is the critical moisture content above which decay can take place. As moisture contents may vary seasonally, it is important that the appearance of water stains be used to identify potential sites of decay. Identifying areas of high moisture content and then removing or diverting the moisture source is critical in protecting a timber bridge from premature deterioration.

2.3.6. Infrared Thermography

Infrared (IR) thermography is another nondestructive technique for evaluating timber structures. IR thermography can be used, in the right circumstances to determine if wood has an excessive amount of moisture within it. The presence of moisture may lead to wood rot, which will degrade the strength of the wood. The limitation to IR thermography is that the equipment is expensive, the operator must be well-trained and the conditions must be just right for the temperature difference to occur. Anther limitation is that IR thermography provides only an inference about the moisture content of the wood, rather than a direct measure of either wood rot or residual strength.

2.3.7. Visual Inspection

It is important to remember that one of the most effective decay detection procedures is to visually inspect the area in question. A trained technician who is equipped with a flashlight and probe can accomplish much. Often the greatest challenge is having the time and being able to get to sections of the bridge where decay is most likely. Decay of wood pilings is most likely to occur immediately below the groundline. Pile caps are subject to deterioration if water from the bridge deck is able to seep into checks on the top face of the piling. Sometimes, however, pile caps may be inaccessible without a ladder or some sort of scaffolding.

Water stains are a valuable piece of information in identifying areas of high moisture content. It is also important to visually examine fastener connections as these joints may have undergone fatigue or because they are inherently areas of high moisture content. Piles and other parts of the bridge subject to moving water should be examined for mechanical damage because of water and debris or water vehicles.

3 Expert Systems Inspection Computer Program

For an accurate assessment of a timber bridge or the structural elements of the bridge, the inspectors must be equipped with the knowledge of wood pathology, wood technology, and timber engineering. The county inspectors who evaluate timber bridges, however, are trained in the general issues of bridge inspection, but are not trained to have a thorough understanding of the complexities of wood such as deterioration and preservation practices. In addition, the old inspection system has been replaced with PONTIS Bridge Inspection Program (BIPP) which requires rating the condition of the bridge elements in a very detailed manner. Providing the inspectors additional training in wood properties along with handy reference materials will help to improve the quality of information supplied to BIPP. The Expert Systems computer program is meant to address these concerns.

3.1. PONTIS Bridge Inspection Program

BIPP is a generalized program used for any kind of bridge. It contains a report form and a database for inspection records which can be retrieved and saved (Figure 3.1).

To complete the report, an inspector is required to rate bridge elements, in most situations from a condition 1 to a condition 4. BIPP does not offer an on-line description of the criteria of each condition, nor does it provide instructions on the methods to determine the condition of the bridge elements. For example, a column is rated from condition 1 to 4; these conditions are described by the inspection manual as sound condition, minor decay, significant decay, and major decay, respectively. The inspectors need to evaluate whether the deterioration is due to minor decay, significant decay or major decay. Furthermore, they need to determine what tools should be used to detect decay and what inspection procedures should be followed. BIPP does not offer this kind of detailed information. Each bridge element has a unique deterioration potential and therefore may need a different method or procedure for inspection and decay detection. Because the bridge inspector may have a limited amount of time and may have limited training in wood science, only the obvious features of the bridge are evaluated while hidden problems may go undetected. This is where Timber Bridge Inspection Assistant (TBIA) can benefit timber bridge inspection.

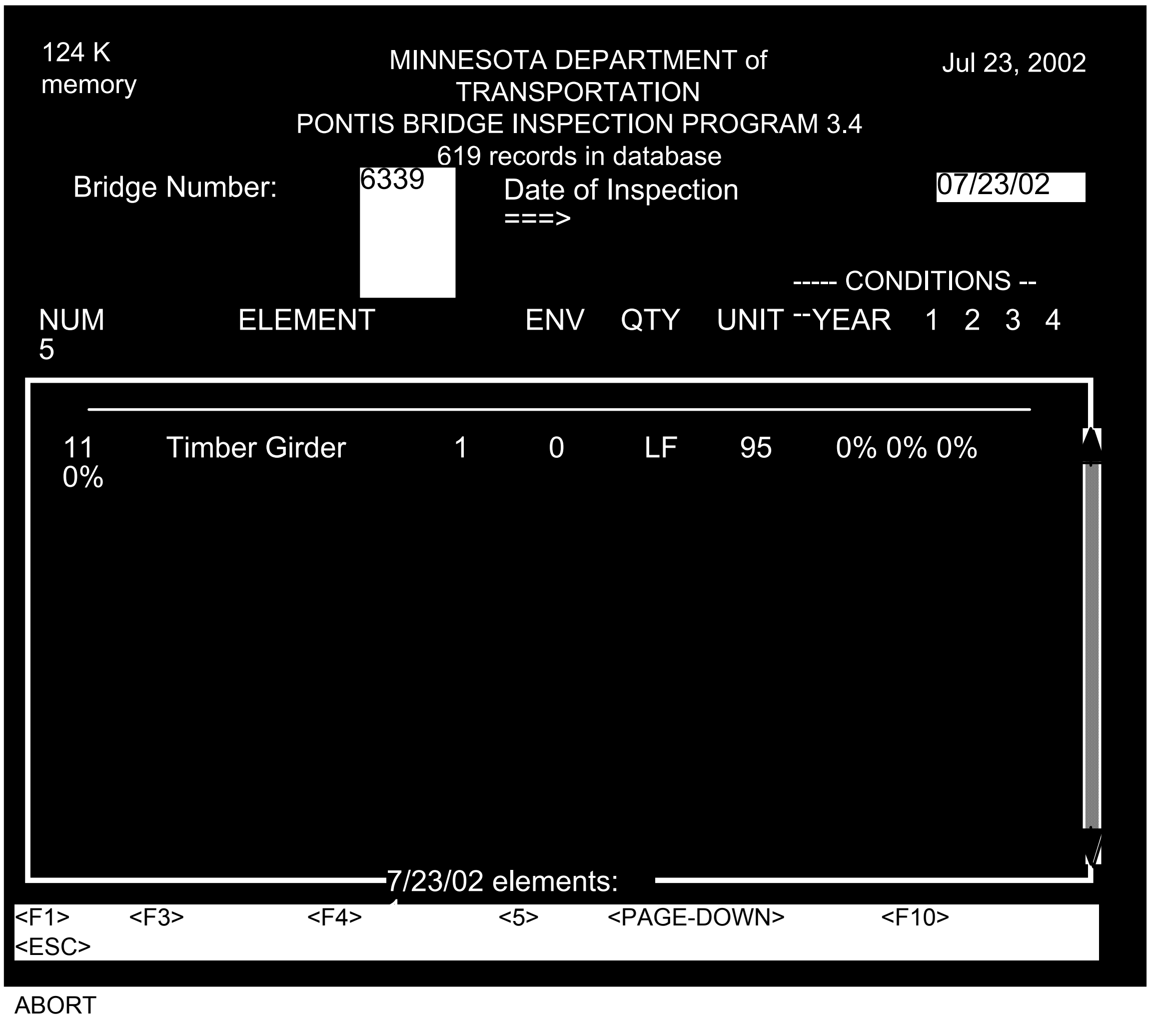


Figure 3.1 Representation of BIPP's report form, showing the knowledge needed for an inspector to complete a bridge report.

The objective of this portion of the project has been to develop an expert system computer program. TBIA would serve to supplement PONTIS to provide guidance, expertise, and references for the inspection of timber bridges. The expert systems program would (1) guide the inspector through a field inspection by answering numerical and multiple-choice questions, and requesting comments concerning the condition and use of a timber bridge; (2) provide on-line advice and expertise for inspection procedures, methods, and deterioration factors; and (3) provide a timber bridge inspection library for self-training purposes.

3.2. Program Development Participants

A team that consisted of a knowledge engineer, three experts, and several potential end users developed TBIA. The knowledge engineer, also a programmer, is a wood science and technology graduate student with some experience in expert system development, but no background timber bridge inspection. The three experts included Ken Johnson, Wheeler Consolidated, timber bridge design engineer, Robert Seavey a timber inspection consultant, and Tim Larson, assistant professor in wood-water relations and wood mechanics. Two county engineers and a MnDOT bridge engineer assisted as a mock user group.

Prior to beginning the design of TBIA, the knowledge engineer visited two timber bridges with the experts to experience and observe the entire inspection process. A sketch of the system design was then drafted and submitted to the experts to verify that the inspection process and the knowledge needed were fully understood. Once the design was agreed upon, the first version of the TBIA prototype was programmed and presented to the team for discussion. Numerous interactions of the expert system dealing with knowledge acquisition, programming, discussion, and modification followed.

3.3. Knowledge Acquisition

Background knowledge was obtained from interviews with experts and from documented publications. The experts were asked either to verbally respond to questions or to type their expertise directly into TBIA. To avoid misunderstanding, the questions asked to the experts were discussed and revised by the team. It was efficient to have experts directly input to the system because the knowledge engineer did not have to use time otherwise needed to obtain, understand, organize, and input the necessary expertise. This also gave the experts the flexibility to think and compose at desired times. The knowledge from the PONTIS bridge inspection manual was used primarily in the Guided Inspection to describe the condition criteria. The information from *Timber Bridges—Design, Construction, Inspection, and Maintenance* by Ritter (1990) was primarily used to compose the Library section of the program.

3.4. Software Tools and Hardware Requirements

An object oriented software development tool, Level 5 Object, was used for the development of the TBIA. It requires an IBM PC or 100% compatible with a minimum of a 286 processor, 4MB of random access memory, a mouse, and Microsoft Windows Version 3.0 or later. Among other features, Level 5 Object contains graphical user interface development editors, forms and display builders, database access, and interfaces to external programs.

3.5. Organization of TBIA

TBIA consists of three parts: Quick Inspection, Guided Inspection, and Timber Bridge Inspection Library. The general structure of the TBIA is shown in Figure 3.2. To avoid management problems for the Department of Transportation in handling bridge inspection report data, TBIA was designed so that its database is compatible with BIPP database.

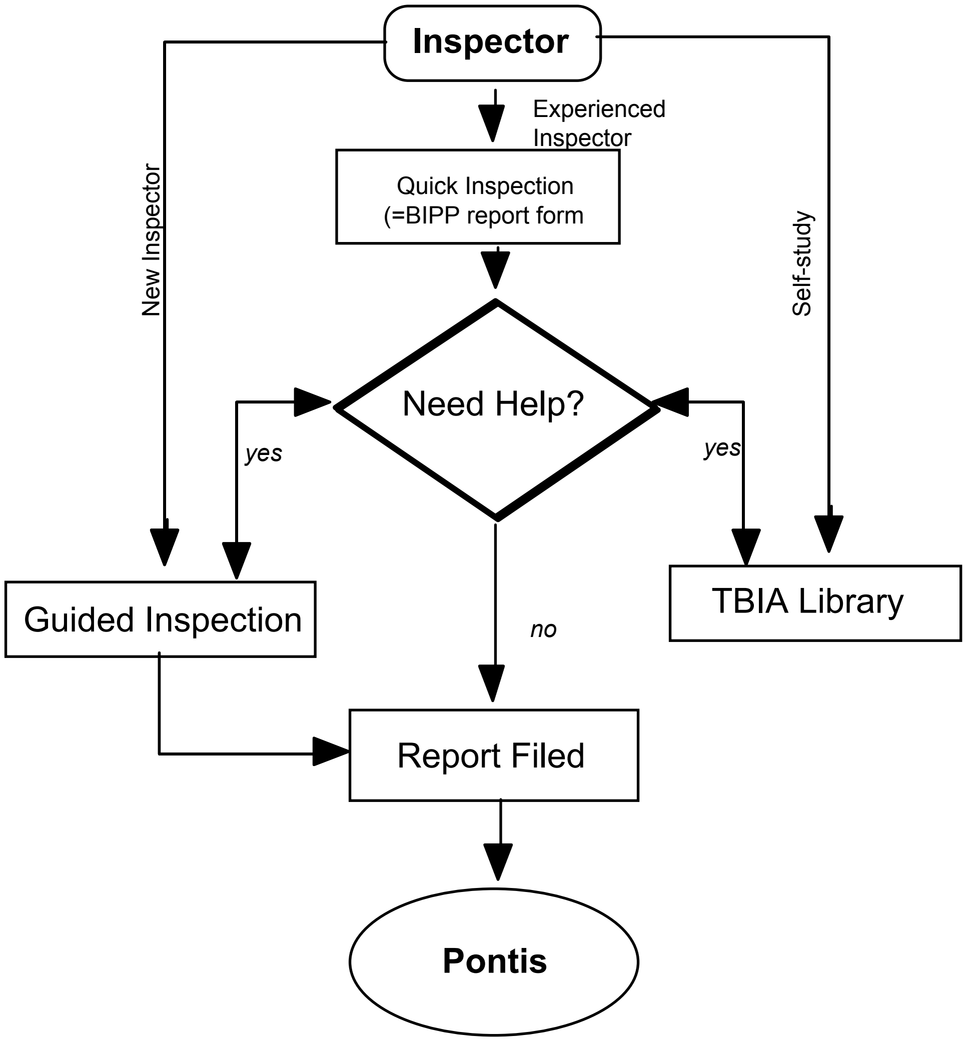
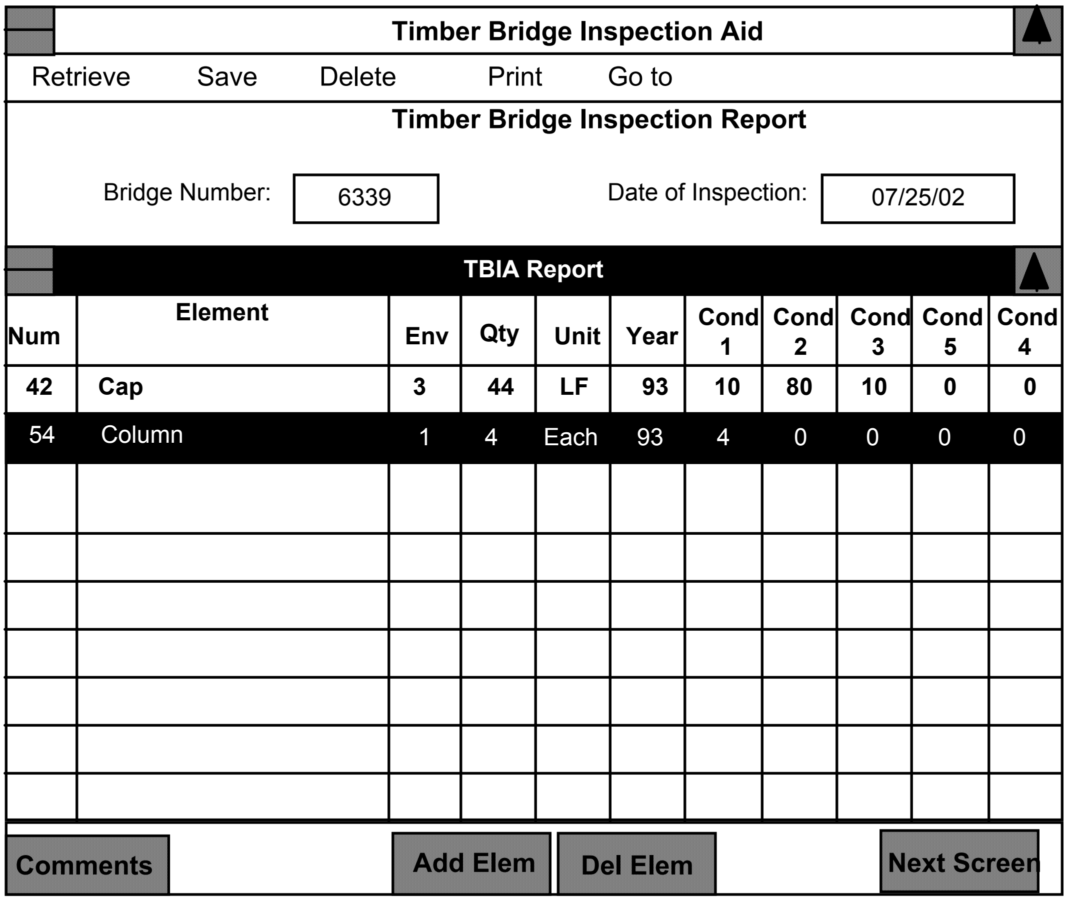


Figure 3.2. TBIA flowchart showing the interactive relations between the basic bridge report form and the added inspection support - Guided Inspection and Library.

Quick Inspection is a report form and a database, similar to BIPP (Figure 3.3.). The difference is that it is designed to allow interaction with the Guided Inspection and Library, allowing access to expertise and knowledge stored in those parts when needed. Quick Inspection is designed for inspectors who are already experienced with timber bridge inspection but may need to obtain some advice/education for some bridge elements. It would also be appropriate for recently built bridges, which do not need an in-depth inspection.



Timber Bridge Inspection Aid

Retrieve Save Delete Print Go to

Timber Bridge Inspection Report

Bridge Number: 6339 Date of Inspection: 07/25/02

TBIA Report

Num	Element	Env	Qty	Unit	Year	Cond 1	Cond 2	Cond 3	Cond 5	Cond 4
42	Cap	3	44	LF	93	10	80	10	0	0
54	Column	1	4	Each	93	4	0	0	0	0

Comments Add Elem Del Elem Next Screen

Figure 3.3. Quick Inspection showing the report form designed based on BIPP. The "Go to" on the menu bar is connected to the Guided Inspection and Library

Guided Inspection is designed with hierarchical structure. The timber bridge elements are divided into five categories: superstructure, deck, and area under the deck, substructure, and other.

The first level of the structure is a list of the categories with hypertext links. The second level is a list of the elements within the categories. Descriptions of the Environment ratings (1 to 4) for this category and a graphical description of the bridge elements and their locations are provided under a question mark button. The third level is a particular element display, where the descriptions of the condition ratings are listed. Expertise is provided under buttons labeled “Decay Agent,” “Detecting Method,” and “Inspection Procedure.” A comment window is accessible by a Comment button. Both environmental and condition ratings are listed in a multiple-choice format. The selection of a description will generate a numerical rating in the report. The inspector can subsequently edit the report generated following the completion of the Guided Inspection.

The Library is similar to an on-line textbook organized for easy and efficient access. Detailed knowledge about timber bridge inspection is organized under Agents, Methods, Procedure, Maintenance, and Cases. It is a handy tool for reference and self-training.

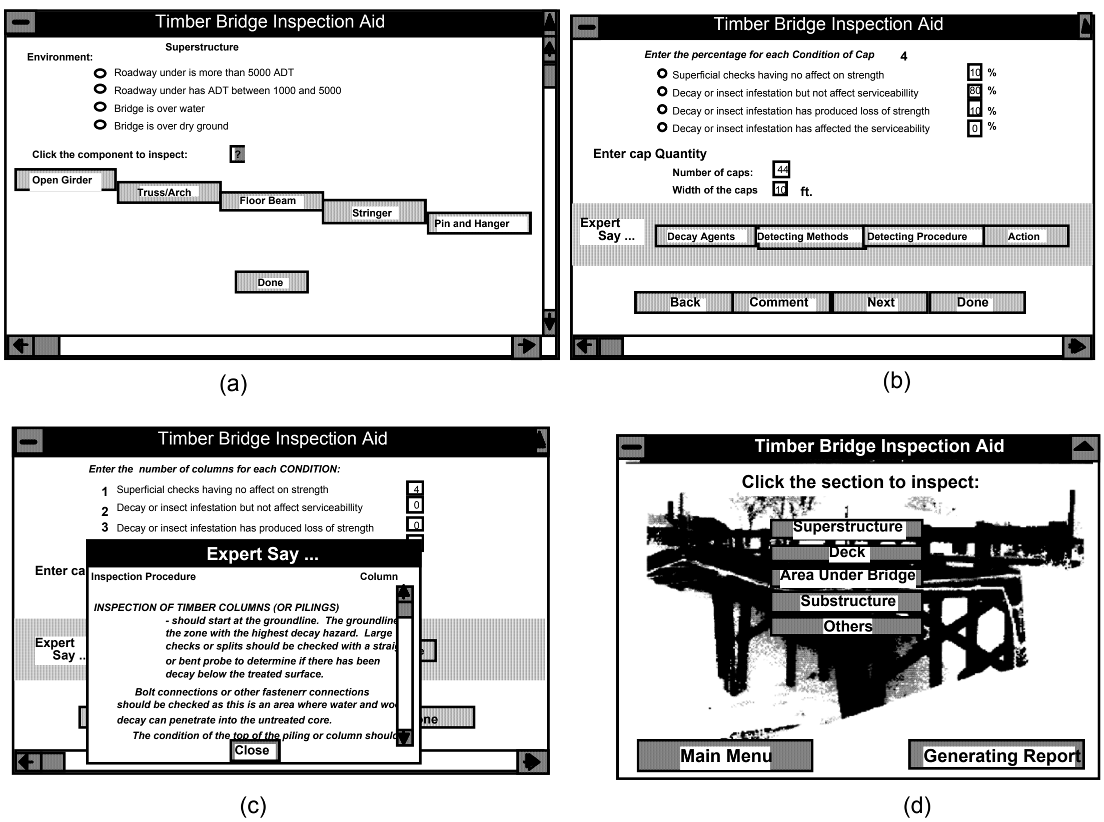


Figure 3.4. Guided Inspection showing the hierarchical structure of the system. a. First level, the categories of a timber bridge; b: Second level, the elements and environment rating descriptions; c: Third level, the descriptions of the condition rating and the expertise provided in the Expert Say Section; and d: example of expert's input.

3.6. Obstacles and Issues Related to Implementation

The first response from MnDOT and the counties was a concern about how TBIA would impact the present system (BIPP). MnDOT officials were concerned that TBIA would not be compatible with PONTIS. BIPP could create more management effort to deal with bridge inspection data because the results from the inspections would be stored in a different database than PONTIS. In response to these concerns, TBIA was then redesigned and modified to generate the same database as BIPP.

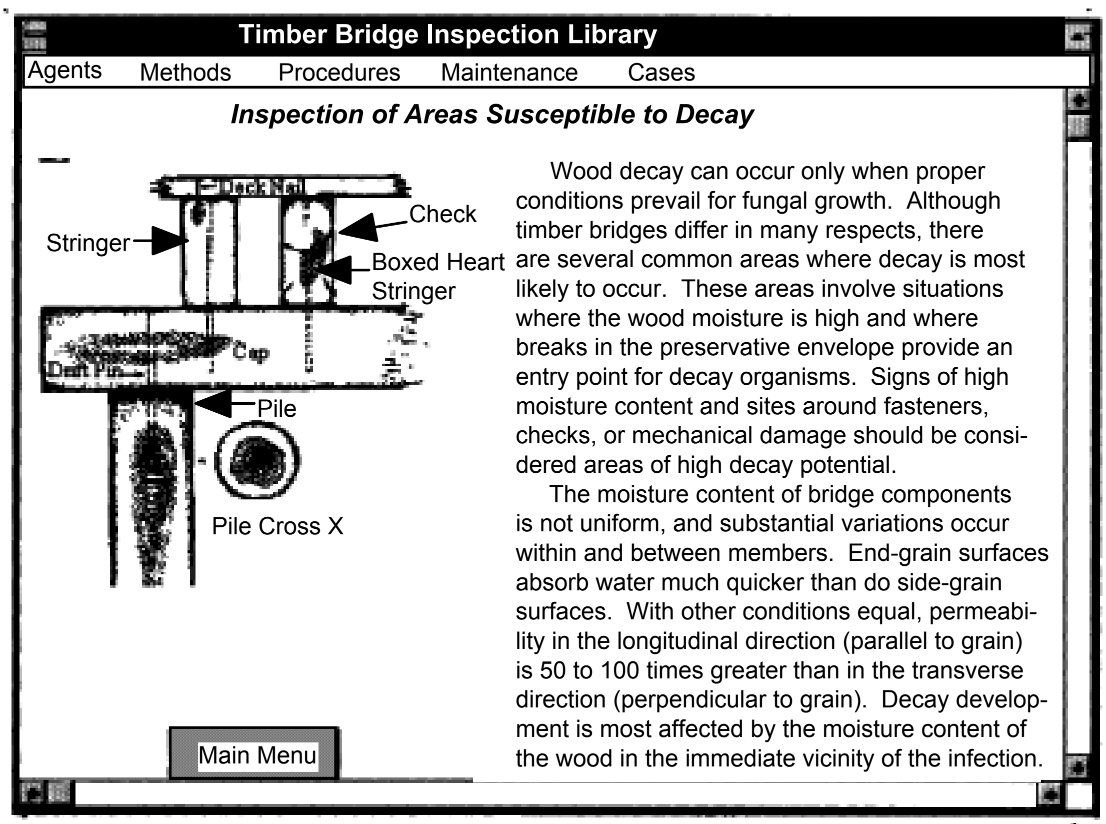


Figure 3.5. Library showing the design of the timber bridge inspection related knowledge.

The response from experts and end users to TBIA indicates that an expert system approach to facilitate timber bridge inspection is appropriate. TBIA brings expertise and training to the fingertips of the county timber bridge inspectors and also provides this expertise on site and concurrent with the inspection. Therefore improved inspection information would be expected. However, it is unfamiliar and therefore uncomfortable to most potential users. Further refining of the current version by providing more detailed expertise for each particular bridge element would be needed.

The expert-systems shell has been an appropriate tool for the development of TBIA. It is easier to use than a conventional programming technique and has the functions needed for TBIA development. The TBIA design relied heavily on the hypertext and hyperregion, especially in the Guided Inspection. TBIA attempts to be very user friendly, interacting with users via totally natural language and graphical demonstration. One of the limitations of Level 5 Object was its built-in database interface that was limited to dBIII and Focus. BIPP uses Paradox as its database, so an extra step is needed to convert between dBase and Paradox file formats.

The three experts were a good team for handling the complexity of wood and bridge domain. Many detailed questions were raised and answered during the group discussion. It is worth noting that the direct input of expertise to the expert system by the experts themselves is a very efficient way for knowledge acquisition and representation.

There are numerous human issues surrounding the development and implementation of an expert systems timber bridge inspection program. The human issues are very challenging, and this inspection system must fit smoothly into the existing procedures for inspecting and rating timber bridges in order to be accepted and used. The Expert Systems Computer inspection program may require more time and paperwork and may not find widespread usage.

Another important issue is whether the Expert Systems computer program will significantly improve the quality of information available from bridge inspections. A system of ratings and evaluations are already in place. A new system to aid the ratings would certainly require significant additional effort. Unless this system can prove that it will yield significantly better results, there will be limited acceptance.

Another problem is that the program is not well understood. Some may question the need for another program since the PONTIS program exists already. Many of the complaints about the transfer of ratings to the PONTIS system were used to object to this program. The major point that the authors of this program would like to raise is that TBIA was proposed and developed to produce better and more uniform bridge ratings, which could then be used by the PONTIS program. PONTIS is a much larger and more demanding project and does not address the detailed issues of timber inspection.

There were two points that should be raised about the technical limitations related to this project. TBIA requires a fast computer with substantial memory. The images require a high quality color screen. Some of the newer, more powerful laptops can perform pretty well. However, they are still very expensive. Another limitation is that the inspector needs to be using the computer at the bridge site. This may not be practical since bridge inspection involves climbing, crawling, probing, hammering and so forth. At this point, computers are not sufficiently versatile and durable to perform well under these conditions. Future developments may provide hardware that is better suited for these tasks.

Given the significant obstacles that face implementation, it is better to return to the fundamental objective of this project: providing superior information for the counties and MnDOT about the existing conditions and maintenance priorities for timber bridges. An on-line web site showing timber inspection procedures and issues would be a great help. This site could serve as a resource for inspectors as they encounter difficult inspection issues. Supplementary documentation about timber deterioration and preservation would also assist this process. Another suggestion would be hands-on workshops in the field with clusters of inspectors and inspection experts. As a final suggestion, it would be most helpful for counties to have a system for referring their particularly troublesome cases to experts who are trained in this area.

4 Remedial Treatments for Timber Bridges

Remedial measures to eliminate wood decay and to strengthen the structure offer an opportunity to lengthen the service life of many timber bridges. While some older structures will certainly need to be replaced, others will need to remain in service for the foreseeable future. This is especially true of timber bridges on low volume rural roads. The first step toward remedial measures is to identify the bridges that are good candidates. Bridges more than 25 years of age are likely candidates for remedial treatments. A thorough inspection would then be needed to identify the bridge components needing treatment. Particular attention would be directed to areas at the groundline, zones that might allow for moisture trapping and connector joint (zones where connectors or fasteners penetrate the wood).

The first step in remedial treatment for wood decay is to eliminate the source of moisture. This may be accomplished with a flashing design that will divert moisture away from the affected area. The two most important guidelines when designing a flashing system are to repel moisture and facilitate the drying potential of the wood. It is frequently better to space flashing away from the wood so that the surface is mostly protected from rain or runoff, but is also able to dry out when it becomes wet. A common problem is that flashing that is designed to protect a surface also serves to seal moisture into the wood by eliminating the drying potential.

In some cases water can not be diverted from the structure. Pilings that are exposed to seasonal flooding are a common example of this situation. In any case, a wood surface that shows evidence of wood decay should be treated with a surface-applied wood preservative. Products that are effective in these cases include many of the boron products, which have low mammalian toxicity, but are still effective against wood decay fungi.

Any surface applied preservative treatment will be limited in its effectiveness. The surface application will only penetrate a short distance into the core of the timber. Furthermore the preservative may well be susceptible to leaching. Sometimes the leaching can be used to benefit the treatment. In these cases preservatives may leach from the surface into the core of the timber. At other times, the leaching will remove the preservative from the timber surface. For these reasons, it is recommended that remedial preservative treatments be applied on a yearly basis so that the timber is continually protected.

Remedial preservative treatments may come as liquid, paste, or rods. In one case, where decay in pilings was identified, preservative paste containing boron was applied to the piling. Kraft paper wrap was then applied to maintain the paste on the wood surface.

Another issue that is important to understand for remedial treatments of timber bridges is the problems that develop from field cut preservative treated timber. Pressure treated creosote timbers will last many years in service. However, the preservative treatment is only along the surface shell of about 2.5-cm. thickness. Field maintenance of these bridges may involve cutting or drilling preservative treated wood. When cutting exposes untreated wood, field preservative treatments are needed. Most of these treatments are brush-on applications. There is limited preservative penetration and retention from this type of treatment. Frequently there may be no alternative to field cutting and brush-on preservative treatment. It is important to recognize the limits of this type of treatment and the need to frequently treat the area again.

There are two additional measures that can prolong the service life of a timber bridge and improve its performance. In cases where pilings had been damaged or buckled, a brace can be applied to support the piling. Pilings may be exposed to decay as well as physical damage from the stream. While wood has substantial strength parallel to the grain, a piling may be prone to buckling if it has been damaged. Applying a brace to the damaged area substantially reduces the potential for buckling. Once again, because of the over-design and the redundancy of the timber bridge, the concern posed by the damaged piling is primarily a service or maintenance issue. If a structural engineer were to determine that the bridge is unsafe, it would be unwise to use a brace as a remedy.

There is one final point to consider regarding remedial bridge treatments. The timber bridge as a functional unit includes not only the timber elements, but also the bituminous layer that covers it. One of the more perplexing problems for county engineers has been to maintain this bituminous surface with minimal cracks and failure zones. Lange (1997) has demonstrated that tightening the spreader beam under nail-laminated timber bridges substantially improves transverse load distribution. The study also found that using wedges to fill voids between bridge decks and spreader beam further improves load distribution. Both of these measures reduce interlaminar deflection and thereby provide a more stable surface for the bituminous surface to adhere to. Primarily, timber bridge inspections should relate to the general condition of the timber elements that comprise the bridge. However, in this instance it is advisable to also consider the appearance of the bituminous wear surface.

5 Conclusions

1. There is an opportunity for improvements in inspection. More time spent on the inspection would help and more careful evaluation of the areas of wood decay is needed. If wood deterioration problems are not detected for several years, it is really too late for most cost-effective remedial treatment by the time the problem is finally observed. This is not the type of inspection that would be done every year for every bridge in the county; a more appropriate cycle would be something like every third year for older bridges and every five years for new bridges.
2. Sophisticated technologies for nondestructive evaluation of timber can yield a great deal of information about interior wood decay. However, the drawbacks to this type of inspection are considerable. The equipment is very costly and the procedures take a great deal of time to inspect a fairly small area. Some of the most sophisticated technologies are not very portable and may not work at all on a structural member that is buried in the ground. Furthermore, the training requirements for this equipment are often considerable and not justified unless the equipment is to be used for many inspections.
3. IR thermography has little application for timber bridge inspection except for some subtle evaluations related to moisture content levels within the wood. A highly trained operator is needed for this type of evaluation.
4. The expert systems program offers some real opportunities for counties to improve the quality of information collected and to bring timber inspection expertise directly to the site where the inspection is taking place. There is certainly an opportunity to improve the knowledge and reference materials for timber bridge inspection. This sort of training can come in the form of training workshops, technical notes and even the expert systems

computer program which has training documentation located in the Library module. The advantages of the expert systems program are only apparent after using the program and particularly after using the program for a timber bridge inspection. Only recently have computers become sufficiently portable and affordable so that these opportunities may be considered. However, the program needs input from user groups to improve the user-friendliness of the program. This would help the program become better accepted.

5. Remedial treatments may be used to block wood decay and to support damaged structural elements. These procedures offer excellent opportunities for lengthening the service life of timber bridges. The limitation of remedial treatments is that the problems are often diagnosed after the damage has progressed beyond repair.

References

Anthony, Ronald W. and Jozsef Bodig. 1990. Applications of Stress Wave-Based Nondestructive Evaluation to Wood. Proceedings of *Nondestructive Evaluation of Civil Structures and Materials*.

Anthony, Ronald W. 1992. Structural Timber Assessment Using Nondestructive Evaluation. Procedings of the *Conference on Nondestructive Evaluation of Civil Structures and Materials*, University of Colorado, Boulder, Colorado.

Beall, Frank C. and W. Wayne Wilcox. 1986. *Relationship of Acoustic Emission to Mass Loss from Decay Radial Compressive Testing.* Unpublished Research Note. Tacoma, WA: Weyerhaeuser Company.

Chudnoff, M., W.E. Eslyn, and D. B. McKeever. 1984. Decay in Mine Timbers: Part III, Species-independent Stress Grading. *Forest Products Journal. 34*(3): 43–50.

Clark, Joe W. and Wallace E. Eslyn. 1979. *Decay in Wood Bridges: Inspection and Preventive & Remedial Maintenance.* U.S.D.A. Forest Service Forest Products Laboratory. Agricultural Handbook No. 557.

Dunker, Kenneth P. and Basile G. Rabbat. 1990. Highway Bridge Tyep and Performance Patterns. *Journal of Performance of Constructed Facilities* Vol. 4, No. 3.

Dunlop, J.I. 1981. Testing of Poles by Using Acoustic Pulse Method*. Wood Science and Technology.* 15: 301–310.

Electric Power Research Institute. 1988. *Pole Analyzer Convinces Utility that Line Can Last 10 or More Years*, EPRI First Use, RP 1352. Palo Alto, Californina.

Elsyn, Wallace E. and Joe W. Clark. 1979. *Wood Bridges—Decay Inspection and Control.* U.S.D.A. Forest Service, Agricultural Handbook No. 557.

Halabe, Udaya B., Hota V.S. GangaRao, Samer Petro and V. Rao Hota. 1994. Nondestructive Evaluation of Wooden Bridges Using Ultrasonic Technique. Proceedings "*Life Cycle Improvement of Infrastructure Through NDE*," New Orleans, LA, March 12–25, The American Society for Nondestructive Testing.

Halabe, Udaya B. and Clement E. Solomon. 1993. Nondestructive Evaluation of Wood Using Dry-coupled Transducers*. Review of Progress in Quantitative Nondestructive Evaluation*. Vol 12B.

Halabe, Udaya B., Hota GangaRao and V. Rao Hota. 1993. Nondestructive Evaluation of Wood Using Time and Frequency Domain Analysis*. Proceedings of Review of Progress in Quantitative Nondestructive Evaluation.* Vol. 13.

Halbe, Udaya B., Hota GangaRao and V. Rao Hota. 1994. Nondestructive Evaluation of Wood Using Ultrasonic Frequency Domain Analysis. *Procedings of Review of Progress in Quantitative Nondestructive Evaluation.* Vol. 14.

Holye R. J. and R. F. Pellerin. 1978. Stress Wave Inspection of Wood Structure. In; *Proceedings, 4th Nondestructive Testing of Wood Symposium*; 1978 August 28–30; Vancouver, WA. Pullman, WA: Washington State University: 33–45.

Johnson, K. 1990. *Timber bridge design, engineering and construction manual.* 4th ed. Wheeler Consolidated, St. Louis Park, MN.

Klinkhachorn, Powsiri, Udaya B. Halbe, Hota GangaRao, Nagender Vedula and V. Rao Hota. 1994. Ultrasonic Field Monitoring Device for Nondestructive Evaluation of Timber Bridges. *Technical Session of the Annual Meeting of the Forest Products Society*, Portland, Maine.

Lemaster, R. L. and D. A. Dornfeld. 1987. Preliminary Investigation of Feasibility of Using Acousto-Ultrsonics to Measure Defects in Lumber. *Journal of Acoustic Emission,* Volume 6, 3: 157–168.

Miller, B. D., F. L. Taylor and K. A. Popeck. 1965. A Sonic Method for Detecting Decay in Wood Poles. *Proceedings AWPA*. 61: 109–115.

Moulin B., M.M. Boulet, and M.A. Meyer. 1992. Toward user-centered approaches for the design of knowledge-based systems. *Expert Systems for Information Management.* Vol.5, no.2, 95–123.

Muchmore, Frank W. 1983. *Timber Bridge Maintenance Rehabilitation and Replacement.* U.S.D.A. Forest Service USGPO: 693–015/41

Nowak, Andrzej. *Reliability Analysis of Wood Bridges.* Department of Civil Engineering, University of Michigan, 2370 G.G. Brown Building, Ann Arbor, Michigan 48109.

Patton-Mallory, M. and R.C. DeGroot. 1989. Acousto-ultrasonics for Evaluating Decayed Wood Products. In: *Proceedings, 2nd Pacific Timber Engineering Conference*; 1989 August 28–29; Auckland, New Zealand.

PONTIS Bridge Inspection Manual. 1994. Minnesota Department of Transportation, Office of Bridges and Structures, Bridge Management Unit.

Ritter, M. A., 1990. *Timber Bridges—Design, Construction, Inspection, and Maintenance.* United States Department of Agriculture, Forest Service, June 1990.

Ross, Robert J. and Roy Pellerin, 1991. Nondestructive Testing for Assessing Wood Members in Structures. *U.S.D.A. Forest Service General Technical Report* FPL-GTR-70.

Rutherford. P.S. 1987. *Nondestructive Stress Wave Measurement of Incipient Decay in Douglas-fir.* Pullman, WA: Washington State University. M.S. thesis.

Stewart, A. H., T. L. Brunette, and J. R. Goodman. 1986. Use of Nondestructive Testing in Rehabilitation of Wood Cooling Towers. In: Gopu, Vijay K. A., ed. *Evaluation and Upgrading of Wood Structures: Case Studies: Proceedings of the American Society of Civil Engineers Structures Congress;* 1986 September 15 – 18; New Orleans, LA. New York, NY: American Society of Civil Engineers.

Turban, E. and M. Tan. 1993. Methods for knowledge acquisition from multiple experts: an assessment. *Journal of Applied Expert Systems.* Vol. 1, no. 2, pp 101–119.

U.S.D.A. 1979. *Increment Cores: How to Collect, Handle and Use Them.* U.S.D.A. Forest Service, Forest Products Laboratory General Technical Report FPL 25.

Volny, Norbert J. 1991. Timber Bridge Inspection Methods. *Wood Design Focus,* Winter 13–15.

Wang, S. C.; O. Suchsland, and J. H. Hart. 1980. Dynamic Test for Evaluating Decay in Wood. *Forest Products Journal. 30*(7): 35–37.

Wilcox, W. Wayne. 1988. *Detection of Early Stages of Wood Decay with Ultrasonic Pulse Velocity. Forest Products Journal 38*(5): 68–73.

Wilcox, W. Wayne. 1978. Review of Literature on the Effects of Early Decay on Wood Strength. *Wood Fiber.* Vol. 9 (4): 252–257.

Wilson, J.L., S.J. Wagaman, 1994. Bridge Evaluation Using a Hybrid Information System. *Structures Congress XII*, Volume 2. Ed. N.C. Baker and B.J. Goodno. American Society of Civil Engineers, New York. pp.1131–1136.