Ultrasonic Inspection of Waterfront Timber Structures: An Economic Advantage to the Marine Facility Owner

Ultrasonic inspection is a viable alternative to traditional means of inspecting underwater wooden structures, which can be misleading and which can result in greater repair and maintenance costs.

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Maintenance of waterfront structures has always been limited by the quality of information available to the facility owner or engineer. Decisions on whether to replace, repair or redesign are balanced precariously on the current condition and predicted structure lifespan. Ultrasonic testing of timber piles represents an opportunity to accurately direct financial, physical and technical resources to an aging "fleet" of marine timber structures.

Wood, because of its inherent variations in quality and its unique susceptibility to biological agents, usually finds itself on a premature ride to the incinerator. This early retirement can be driven by the desire to use newer exotic materials but more often than not it is the result of the limitations of the inspection techniques available to produce accurate data on which the owner or engineer can make confident decisions.

Traditional inspection techniques to evaluate and assess the condition of aging timber structures include visual observations, tactile probing, hammer testing and mechanical coring. While these inspection methods can determine the physical dimensions of a timber member and provide estimates of the amount of internal deterioration, they do not adequately quantify the material's condition, strength or durability. Non-destructive ultrasonic testing devices can be used to characterize the internal condition of timber members.

In the hierarchy of marine structure costs, inspection is at the tip of an inverted cost pyramid. Where thousands of dollars are spent on inspection, tens of thousands will be spent on engineering and in turn hundreds of thousands of dollars on construction. Important economic decisions are based on inspection and it is vital to identify the key economic impacts of inspection on facility operations.

Background

Waterfront structures are subject to a variety of environmental conditions that lead to the deterioration of structural members and their unforeseen premature failure. Severe weather conditions, extreme loadings and biological agents can reduce the structural capacity and integrity of waterfront structures by reducing their thickness or overall dimension and their ability to sustain design loads. While steel and concrete structures suffer primarily from mechanical, chemical and electrolytic forces, timber is subject to mechanical and biological agents such as fungi, insects and marine borers.

Fungal Decay. Fungal decay in timber structures occurs where moisture, oxygen and moderate temperatures are present, which typically pertain to the portion of waterfront structures above the mean high water line. In this region, fungi develop and produce either dry or wet rot depending on the amount of moisture and ventilation encompassing the structure and the species of fungi present. As the fungi break down the wood for food, the timber loses its strength, thereby decreasing the mechanical properties of the structural element.

Insect Damage. The most common insects that can cause deterioration in waterfront structures above the mean high water line are the termite and carpenter ant. Termites feed on wet or dry wood in order to gather sugars and starches from the sapwood. Since the wood is a source of food for the termite, the extent to which it will deteriorate a timber element is unlimited. In contrast, carpenter ants burrow in moist decaying wood, not as a source of food, but rather to build nests for their colonies. The voids that are created by termites or ants can reduce the physical and mechanical properties of structural elements, leaving them subject to early failure.

Marine Borer Infestation. Marine borers have presented a problem for mankind ever since wood was first put into the ocean. Christopher Columbus and other great marine explorers of the fifteenth and sixteenth centuries were plagued by marine borers and were probably more concerned about developing leaks due to shipworm damage than sailing off the edge of the world.

To combat the threat of marine borers, ancient mariners would scorch the outside of their ships or sheath their ships' hulls with a thin layer of metal that would act as a protective skin. More modern methods of preventing marine borer attack on wood have concentrated on the use of chemicals. Toxic salts and creosote-based preservatives form effective barriers against marine borers when forced into wood under pressure. While these preservatives typically penetrate several centimeters into the wood, injuries that pierce the protective layer and/or areas of insufficient treatment allow marine borers access to the untreated portion of the wood.

In North America, there are three genera of marine borers that are of major importance. The crustacean *limnoria spp.* and the mollusks *bankia setacea* and *teredo navalis*. *Limnoria spp.* is commonly called a *sea louse* or *gribble*. *Teredo navalis* and *bankia setacea* are similar in appearance to each other and are often called *teredo* or *shipworm*. Today, marine borers' appetite for wood continues to destroy millions of dollars of timber in North America annually.

Standard Inspection Methods

Visual Inspection. By definition, visual inspections require an unobstructed view of the timber surface. This type of inspection is generally possible for superstructure elements such as pile caps, stringers and deck boards, with the exception of the interfaces between structural elements. In addition to being obstructed from view, these contact surfaces frequently accumulate moisture that results in accelerated deterioration.

For piles below the high water mark, it is often necessary to remove the marine growth (a costly procedure) before a visual inspection can be completed, and even then good water clarity is essential to properly examine the pile. Further complicating the visual inspection process is the inconsistent correlation between external evidence of insect or marine borer attack and the underlying damage. During its lifespan *bankia setacea* will increase in volume two billion times and the only evidence on the pile surface will be a 1-millimeter-diameter entrance hole. In terms of cross-section loss, the internal tunnel of an adult *bankia setacea* or *teredo navalis* could increase by as much as 225 times and 100 times, respectively, over the size of the entrance hole. These factors limit visual inspections to providing a good assessment of external damage and at best an opinion as to the internal condition. The accuracy of visual inspections has been described as being less than ±25 percent.[1]

Visual inspections are further complicated by variability in inspector training and experience. It is not uncommon for a timber element to be rated differently by two different inspectors or to be rated differently on two separate occasions by the same inspector. This subjective interpretation of results makes comparison of past and present inspection results impossible and creates a lack of confidence when performing maintenance and budget planning or loading calculations to determine the safe capacity of a structure.

Hammer Sounding. The tone emitted by a timber when struck by a hammer can, in some instances, indicate the level of decay. While the tone of a heavily damaged timber can be remarkably different from the tone in a sound timber, the subtle differences in pitch associated with lower levels of damage and the variability within any given piece of wood are in most cases not a reliable indicator of internal voids or the hardness of the material. This method of inspection relies entirely on the hearing ability and experience of the inspector and again results only in an opinion as to the condition of a timber. As in the case of visual inspections, hammer sounding also requires the surface of the timber to be clean and results often differ from one inspector to another. Underwater hammer sounding only compounds difficulty in inspection.

Coring & Drilling. Coring and drilling is a laborious method of inspection that produces results on a specific location of a timber member. The limited size and number of cores that can be taken (for economic and structural reasons) produces results that may or may not reflect the condition throughout the entire timber element. This inspection method has often been described as a "two-dimensional test looking for a three-dimensional problem."

Typically, insect tunnels run in any direction along a member, while marine borer tunnels normally extend along the grain. When cores are taken they may or may not intersect one or more of these tunnels. If there is only one tunnel in a timber and the core passes through it, the inspector will be misled into predicting the timber is in poor condition. Conversely, if there are several tunnels and the core misses the damage, then the inspector will wrongfully consider that the timber is undamaged. In addition, the core provides no evidence as to the length of the tunnel – the third dimension. The solution to these issues is to take more cores, which significantly increases inspection costs and can cause more damage than the deterioration they seek to identify. If core holes are not plugged with marine borer resistant materials, the risk of marine borer attack is increased.

Resistance-to-drill-penetration tests suffer from the same problems as coring and rely heavily on the inspector's experience to determine whether an element contains internal deterioration. The primary indicators of damage are the wood's resistance to drilling and the smell, look and feel of the extracted fibers — all of these indicators require a subjective opinion by the inspector.

Ultrasonic Testing

Ultrasonic instruments typically utilize stress wave testing techniques to measure the time of flight and/or the signal strength (amplitude) of the returning sound waves. The longer the transmission time and the weaker the returning pulse, the greater the deterioration. Through these quantitative measure-

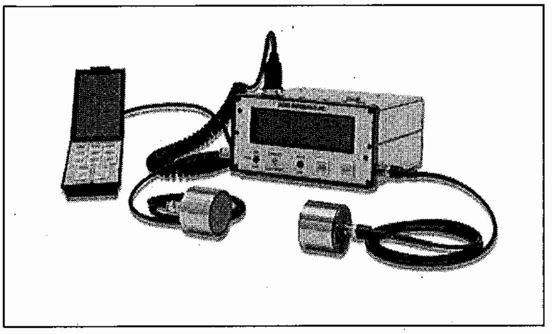

FIGURE 1. A typical ultrasonic testing meter.

ments the subjectivity normally associated with the inspector can be removed and an objective prediction as to the internal condition of a timber element can be made. While ultrasonic instruments have introduced numerical and repeatable results into the inspection process, there are many factors that influence the transmission of stress waves and ultimately the number that appears on the instrument. Inspectors must be familiar with these factors and take them into account when operating ultrasonic instruments. Ultrasonic instruments also provide the opportunity to scan sections of wood in three dimensions, providing an overall assessment of the timber condition and a greater level of understanding of the internal structural conditions of the timber members undergoing inspection.

For timber pile sections located underwater, there are two conditions that allow sound to be used effectively in the evaluation of internal marine borer damage. The first is the saturation of the pile by water that takes place after it is installed in a marine or aquatic environment. As the water infiltrates the millions of tiny air pockets in the wood it reduces and eventually eliminates the distortion effects that air has on sound transmission. In addition, the water surrounding the pile acts as a couplant, allowing the pulses of sound waves to be transmitted efficiently to pile surface with little loss of signal strength. The second factor relates to the difference in speed of sound in wood versus that of water (approximately three times faster in wood). This difference allows ultrasound pulses to be transmitted into the pile being tested and the returning pulses received before the pulse that is traveling through the surrounding water interferes with the returning pulse that has traveled through the wood. More specifically, primary pulses of ultrasound are transmitted into a timber member and across the grain, setting up secondary pulses that travel along the grain. These secondary pulses in turn set up tertiary pulses that travel back across the grain and out into the surrounding water where they are received by the probe's transceiver. As marine borers tunnel into a timber pile, the water content of the pile increases, thus slowing and dampening the pulses of ultrasound. These changes to the returning ultrasonic pulses can be measured and then statistically correlated to the actual amount of cross-section remaining at a specific section of pile.

These factors were used as the basis to develop an ultrasonic instrument to test for internal marine borer damage in timber piles in the 1950s. These early instruments, and the ones that followed, were based on the use of donut-shaped magnetostrictive coils. They also provided accuracies of ±25 percent absolute error.[2] In the mid-1980s and 1990s, a variety of shaped ferrite cores were employed to produce ultrasonic systems that improved the reliability and accuracy of timber testing equipment to ±10 percent relative error at an 80 percent confidence interval.[3] In the late 1990s and 2000s, piezoelectric crystals replaced ferrite cores as the transmitters/transceivers, resulting in accuracies of ±10 percent at a 95 percent confidence interval.

Ultrasonic Testing Meters. Ultrasonic testing meters, such as the one shown in Figure 1, can be used to identify areas of insect deterioration and internal fungal rot that may otherwise go undetected in a visual, hammer sounding or coring inspection.

These instruments can be used quickly and effectively at various locations within a structure in order to assess the condition of timber pile caps, stringers and deck boards. The transducers are placed against the flat surfaces of these members and the transmission times can be recorded for the ultrasonic waves to pass through the material. Special devices can be used to augment the transducers and enable timber pile inspections.

Piezoelectric Resonators. Piezoelectric resonators are used underwater to evaluate internal damage in timber piles. The system shown in Figure 2 is a self-contained unit that the diver/inspector passes over the pile surface. A series of light-emitting diodes alert the inspector to suspect areas where a more detailed examination can then be made using the digital readout.

Typically, no cleaning of the pile surface is required; however, areas of dense calcareous or coral growths can impede the sound transmission into the pile.

Ultrasonic Testing Program

Timber waterfront structures are typically constructed of either southern yellow pine (east coast) or douglas fir (west coast), which are typically impregnated with pressure treatment preservatives to prevent deterioration and increase their life cycles. Ultrasonic tests performed on timber materials measure the time it takes for an ultrasonic pulse to travel a known distance and/or the reduction in amplitude of the returning pulse. These changes to the ultrasound pulses are then used to predict the timber's condition.

A limited testing program was established and performed for douglas fir and southern yellow pine members that included specimen samples that were examined under controlled laboratory conditions, as well as waterfront structures examined in situ in California and New Hampshire. The purpose of this limited testing program was to introduce to owners and managers of waterfront structures the ease of use and reliability of ultrasonic testing equipment in waterfront inspection programs. An introductory set of parameters were developed as the groundwork for future testing.

The specimen samples included two new 3.5- by 3.5-inch, No. 2 douglas fir members, and two new 3.5- by 5.5-inch southern yellow pine members. In-situ testing of members included timber deck boards and stringers of various sizes.

Control Specimen Test Results. The control specimens were selected in order to measure the typical pulse velocity in douglas fir and southern yellow pine members with various sized voids in order to simulate various stages of deterioration (see Figures 3 through 8 on the next three pages). Voids were introduced by drilling holes at the ends of the members at least 4 inches deep that ranged from 0.375-inch-diameter holes to slotted holes 4 by 1.25 inches wide. Where large voids were placed near the ends of a member, a smaller void was placed between 4 and 8 inches from the end to increase the number of tests.

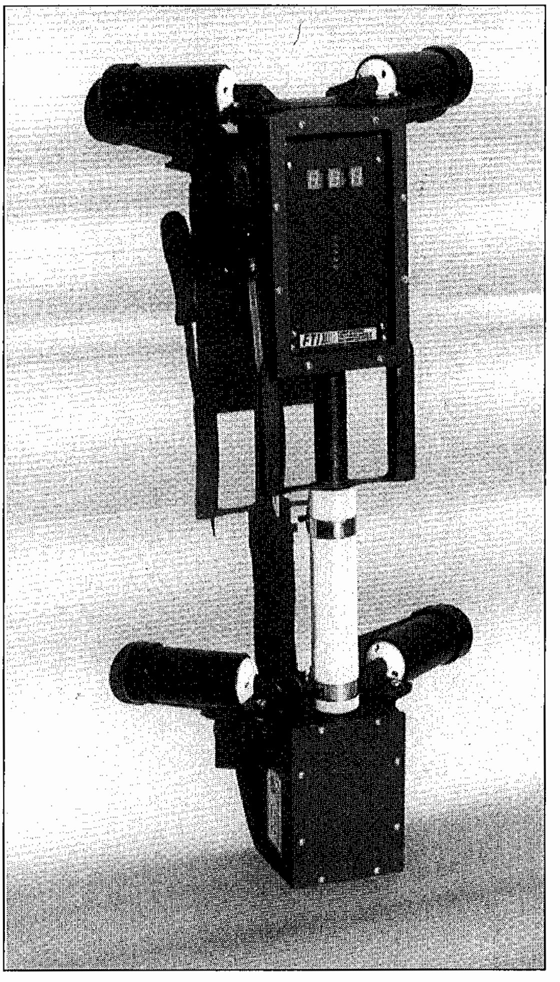

FIGURE 2. A typical piezoelectric resonator.

Three readings were independently obtained at each test location, and the readings were taken in both directions in order to account for grain directionality. The averages of the three readings are shown in Tables 1 through 4 (on pages 13 to 14), along with the corresponding velocity. Based on these results, a suggested condition rating scale is presented in Table 5 (on page 15).

FIGURE 3. Douglas fir sample specimens S5 and S6.

FIGURE 4. Douglas fir sample specimens S5 and S6 at Side A. Voids were created at the ends of the members to simulate internal deterioration. Circles indicate the locations for transducer placement.

FIGURE 5. Douglas fir sample specimens S5 and S6 at Side B. Similar voids and circles are shown.

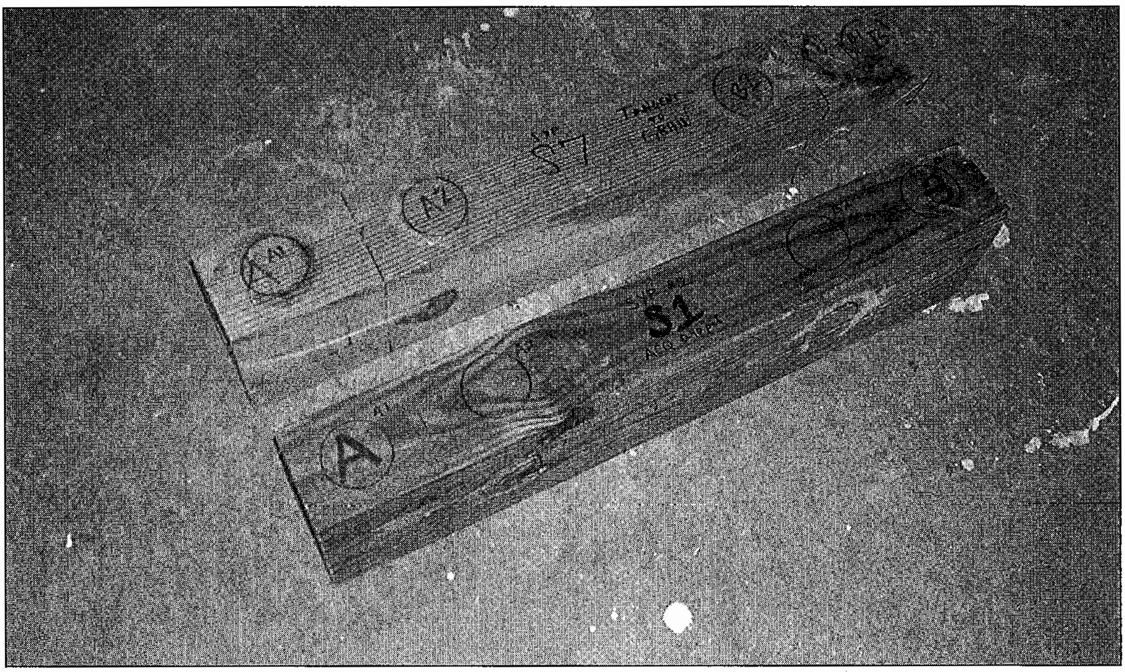

FIGURE 6. Southern yellow pine sample specimens S1 and S7.

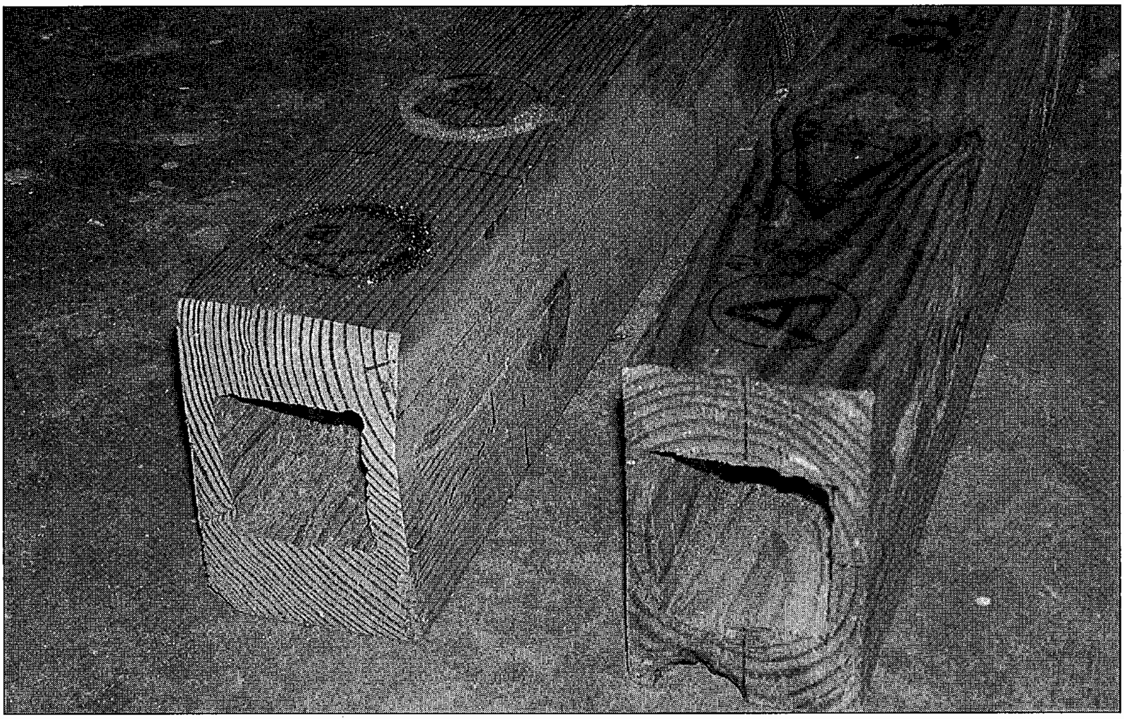

FIGURE 7. Southern yellow pine sample specimens S1 and S7 at Side A. Voids were created at the ends of the members to simulate internal deterioration. Circles indicate the locations for transducer placement.

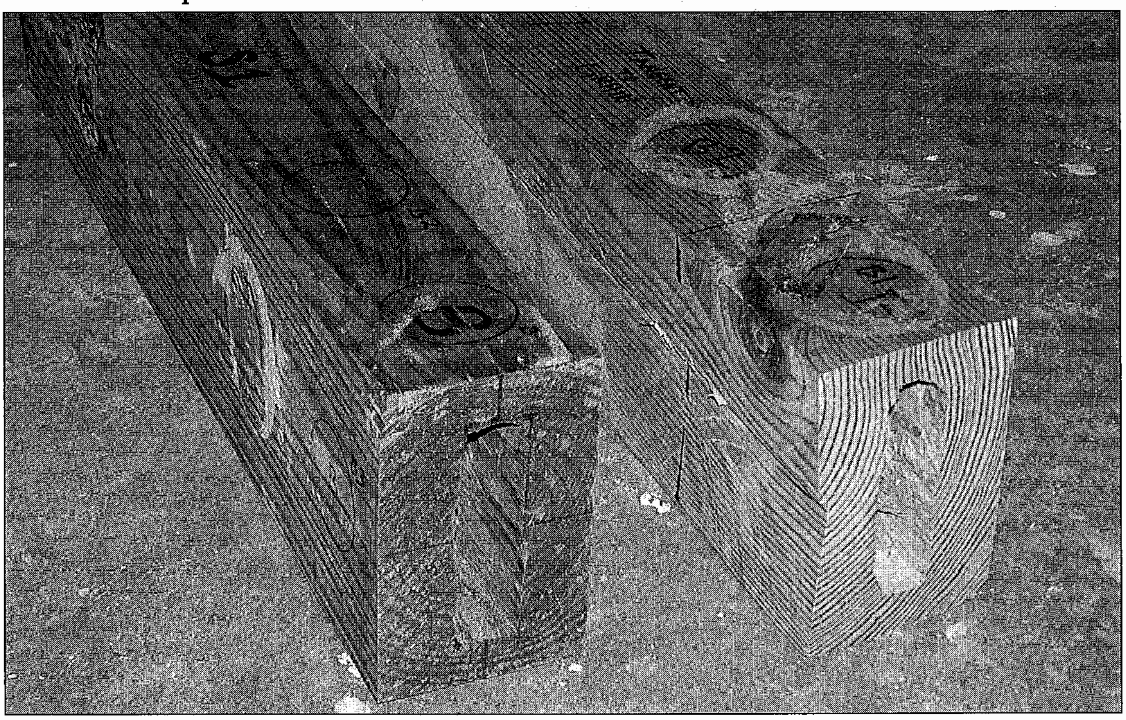

FIGURE 8. Southern yellow pine sample specimens S1 and S7 at Side B. Similar voids and circles are shown.

TABLE 1.
Ultrasonic Measurements on Douglas Fir: Tangent to Grain

Sample	End Location	Deterioration	Time Average (sec)	Sample Width (ft)	Pulse Velocity (ft/sec)	Suggested Rating*
S5	A1	Void: 2.25″ × 2.25″	85	0.292	3449	Serious
S5	A2	Void: 0.375″ diameter	54	0.292	5388	Fair
S5	B1	Void: 1″ diameter	56	0.292	5174	Fair
S5	B2	Solid	53	0.292	5479	Fair
S6	A1	Void: 1.25″ wide slot	57	0.292	5138	Fair
S6	A2	Solid	53	0.292	5486	Fair
S6	B1	Void: 2.75″ wide slot	73	0.292	4023	Poor
S6	B2	Solid	45	0.292	6439	Good

Note: *See Table 5 on page 15 for an explanation of the rating scale.

California Waterfront Structure (Douglas Fir) Test Results. At a waterfront structure in San Pedro, California, the timber deck boards and stringers were tested using an ultrasonic testing meter. It was noted that three different generations of deck boards were present, although the exact age of each generation was not known. These eras were labeled as: *vintage, seasoned* and *new*. Variation in stringer vintage could not be determined. Average ultrasonic measurements were obtained for these members and are listed in Table 6 (on page 15).

Testing of the timber piles was also performed at this site using a piezoelectric resonator. Results indicated that some piles contained severe voids and internal section loss due to marine borers. This information was

TABLE 2.
Ultrasonic Measurements on Douglas Fir: Normal to Grain

Sample	End Location	Deterioration	Time Average (sec)	Sample Width (ft)	Pulse Velocity (ft/sec)	Suggested Rating*
S5	A3	Void: 2.25″ × 2.25″	77	0.292	3803	Serious
S5	A4	Void: 0.375″ diameter	44	0.292	6609	Good
S5	B3	Void: 1″ diameter	46	0.292	6331	Fair
S5	B4	Solid	45	0.292	6496	Good
S6	A3	Void: 2.75″ wide slot	68	0.292	4312	Serious
S6	A4	Solid	45	0.292	6540	Good
S6	B3	Void: 1.25″ wide slot	53	0.292	5507	Fair
S6	B4	Solid	34	0.292	8672	Good

Note: *See Table 5 on page 15 for an explanation of the rating scale.

TABLE 3.
Ultrasonic Measurements on Southern Yellow Pine: Tangent to Grain

Sample	End Location	Deterioration	Time Average (sec)	Sample Width (ft)	Pulse Velocity (ft/sec)	Suggested Rating*
S7	A1	Void: 2.25″ × 2.25″	127	0.458	3618	Poor
S7	A2	Void: 0.375″ diameter	100	0.458	4603	Fair
S7	B1	Void: 1″ wide slot	114	0.458	4031	Poor
S7	B2	Solid	99	0.458	4609	Fair

Note: *See Table 5 for an explanation of the rating scale.

critical in the underwater inspection since the piles were jacketed with PVC wraps that could not be removed without considerable effort. For the sample piles, the wraps were removed and the timber pile conditions confirmed.

New Hampshire Waterfront Structure (Southern Yellow Pine) Test Results. At a waterfront structure in Newington, New Hampshire, similar tests were performed on timber deck members and stringers using an ultrasonic testing meter. Average ultrasonic measurements were obtained for these members and are listed in Table 7 (on page 16).

Summary of Test Results. Timber elements that were tested using ultrasonic equipment were also examined using conventional mechanical inspection methods such as hammer sounding and coring and drilling. The testing program yielded consistent results between the mechanical test methods and the ultrasonic values used along with the suggested condition rating system. Timber superstructure elements that were either aged or located in high-moisture areas exhibited lower ultrasonic velocities than members that were newer and located in well ventilated areas. Wrapped piles that were evaluated using the

TABLE 4.
Ultrasonic Measurements on Southern Yellow Pine: Normal to Grain

Sample	End Location	Deterioration	Time Average (sec)	Sample Width (ft)	Pulse Velocity (ft/sec)	Suggested Rating*
S1	A1	Void: 2.5″ × 2.5″	164	0.448	2725	Serious
S1	A2	Void: 0.375″ diameter	71	0.448	6270	Fair
S1	A3	Void: 2.5″ × 2.5″	144	0.281	1954	Serious
S1	A4	Solid: 0.375″ diameter	42	0.281	6691	Good
S1	B1	Void: 1″ wide slot	119	0.448	3774	Serious
S1	B2	Solid	75	0.448	5956	Fair
S1	B3	Void: 4″ wide slot	72	0.281	3934	Serious
S1	B4	Solid	45	0.281	6311	Good

Note: *See Table 5 for an explanation of the rating scale.

TABLE 5.
Suggested Condition Ratings for Douglas Fir & Southern Yellow Pine

Direction	Velocity Range (ft/sec)	Suggested Condition Rating
Tangent	5500 < V	Good: Material Does Not Contain Significant Deterioration
Tangent	4500 < V < 5500	Fair: Material Contains Some Deterioration
Tangent	3500 < V < 4500	Poor: Material Contains Substantial Deterioration
Tangent	V < 3500	Serious: Material Contains Excessive Damage
Normal	6500 < V	Good: Material Does Not Contain Significant Deterioration
Normal	5500 < V < 6500	Fair: Material Contains Some Deterioration
Normal	4500 < V < 5500	Poor: Material Contains Substantial Deterioration
Normal	V < 4500	Serious: Material Contains Excessive Damage

piezoelectric resonator were examined when the wraps were removed for further visual and mechanical inspections in order to confirm the results.

A comparison between the results for douglas fir and southern yellow pine indicates that a basic condition rating system can be developed and employed for evaluating both material types using ultrasonic testing. While the two materials exhibit different physical and mechanical properties, it is possible to identify deterioration in these members using a generic condition rating system and non-destructive testing techniques. The use of ultrasonic test-

TABLE 6.
Ultrasonic Measurements on a California Waterfront Structure
(Douglas Fir: Normal to Grain)

Element Sample	Time Average (sec)	Sample Width (ft)	Pulse Velocity (ft/sec)	Suggested Rating*
Deck Boards (Vintage)	58.0	0.271	4670	Poor
Deck Boards (Seasoned)	47.1	0.271	5750	Fair
Deck Boards (New)	37.6	0.271	7203	Good
Stringer No. 1	158.0	0.354	2242	Serious
Stringer No. 2	720.0	0.304	420	Serious
Stringer No. 3	74.3	0.304	4066	Serious
Stringer No. 4	44.8	0.304	6743	Good
Stringer No. 5	101.4	0.333	3287	Serious
Stringer No. 6	66.8	0.333	4990	Poor
Stringer No. 7	54.5	0.333	6116	Fair

Note: *See Table 5 for an explanation of the rating scale.

TABLE 7.
Ultrasonic Measurements on a New Hampshire Waterfront Structure (Southern Yellow Pine: Normal to Grain)

Element Sample	Time Average (sec)	Sample Width (ft)	Pulse Velocity (ft/sec)	Suggested Rating*
Deck Timber (NH1)	124.8	0.781	6262	Fair
Deck Timber (NH2)	164.5	0.781	4749	Poor
Deck Timber (NH3)	179.2	0.781	4360	Poor

Note: *See Table 5 on page 15 for an explanation of the rating scale.

ing provided a quick and reliable inspection methodology for both materials.

Underwater Pile Inspection Data Review

During the period from 1997 to 2006, 38,065 piles were ultrasonically and/or visually inspected. The age of these piles ranged from new to 60 years, with the majority of the piles ranging from 30 to 45 years in age. The data were broken into four categories. Table 8 provides a summary of the damage noted in these inspections.

The cross-section loss of 40 percent was selected as the point at which piles would typically be replaced. As soon as that 40 percent threshold was reached there would be no need to inspect the remaining pile section since it would require replacement. Based on this criterion, the results indicate that on any given structure:

- 49 percent of the piles have sustained some level of damage;
- 33 percent of the piles have sustained marine borer damage;
- 4 percent of the piles can be accurately inspected visually; and,
- 29 percent of the piles cannot be accurately inspected visually.

As the level of visible damage decreases from 40 percent section loss, the accuracy of a visual inspection becomes worse. As a result, piles showing evidence of marine borer attack (29 percent of any given structure) could be replaced prematurely or identified as sound when in fact the pile needed maintenance or replacement.

Economic Advantages of Ultrasonic Testing

Over the past five decades, ultrasonic testing has demonstrated that it is a valuable procedure in determining the condition of timber

TABLE 8.
Distribution of Damage in Timber Piles Inspected From 1997 to 2006

Undamaged Piles	More Than 40 Percent Marine Borer Damage	40 Percent Marine Borer Damage	Other Damage*	Total
19,562	1,483	10,914	6,106	38,065
51%	4%	29%	16%	100%

Note: *Damage caused by mechanical forces, insects and/or fungi.

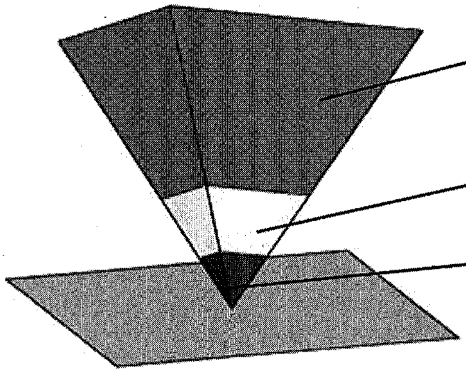

FIGURE 9. The pyramid of total project cost.

structures. By introducing ultrasonic testing to waterfront inspections there is less chance for "hidden" deterioration to be revealed during repairs. This increased accuracy adds confidence to repair operations and avoids the unexpected costs of this hidden damage.

The additional amount of funding required to implement ultrasonic testing in a waterfront facility inspection is a small fraction of the cost when compared to the expenses that are incurred when changes to design and construction are needed as a result of inaccurate inspection data (see Figure 9).

For the owner or manager of a waterfront facility, it is imperative that the information obtained from a structural inspection is accurate and cost effective in characterizing the overall condition of the structure and its individual components. Important economic decisions are based on inspection data. Case studies indicate that the additional effort spent during the inspection to employ ultrasonic testing can lead to a cost savings during design, construction and maintenance.

Case Study. In a recent wharf inspection project, 189 timber piles were inspected visually above and below water. The results showed that 36 piles had 50 percent or greater cross-section loss due to marine borers and would have to be scheduled for replacement. Twenty-five of these piles were located in the interior of the structure and their replacement would be costly because of the overlying prestressed concrete deck. Estimated cost of repairs per pile ranged from $3,000 to $8,000, with the final repair bill estimated to be $75,000 to $200,000.

Due to the difficulty and cost associated with replacing the 25 interior piles, a second opinion was sought from a different contractor. This second contractor performed an

TABLE 9.
A Comparison of Design & Construction Costs Against Inspection Method

	Number of Piles Inspected	Cost of Inspection	Cost of Design & Construction
Visual	25	$1,750	$75k to $200k
Ultrasonic	25	$2,200	$12k to $32k
Difference		$450	$63k to $168k

ultrasonic inspection of the 25 interior piles. The results showed:

- four piles had 75 percent or greater cross-section loss;
- four piles had 35 to 15 percent cross-section loss; and,
- 17 piles had 10 percent or less cross-section loss.

The cost to design and replace the damaged piles found under the ultrasonic inspection would be $12,000 to $32,000. The second opinion resulted in a savings of design and construction costs of $63,000 to $168,000 (see Table 9).

While the cost to perform an ultrasonic inspection is marginally more than a visual inspection, the cost savings in design, construction and maintenance can be substantial.

Conclusions

A limited testing program, historical data and case study demonstrate that ultrasonic testing equipment has useful application in waterfront inspections. Ultrasonic testing devices can be used successfully to enhance facility inspections and provide owners and managers with accurate data that will save money.

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