5
Detecting decay in wood components

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5.1 Introduction

Wood deterioration is one of the most common damage mechanisms in timber bridges and other wood structures and often inflicts damage internally. This may occur without visible signs appearing on the surface until a member's load-bearing capacity has been largely destroyed. Determining an appropriate load rating for an existing timber structure and establishing rational rehabilitation. repair, or replacement decisions can be achieved only when an accurate assessment of its existing condition is made. Knowledge of the condition of the structure can lead to savings in repair and replacement costs by minimizing labor and materials and extending its life.

In wood structures, the degradation of a load-bearing (in-service) member may be caused by any one of several organisms that derive their nourishment or shelter from the wood substrate in which they live. For example, several types of fungi attack wood. The hyphae of these fungi secrete enzymes that depolymerize the chemical components of wood, thereby lowering the density, strength, and hardness of a member. This results in a significant reduction in load-carrying capacity, which in turn may result in the member's failure. Accurate detection of decay in wood structures is therefore critical to ensuring the safety of the public and extending the service life of the structures.

Recently, we prepared a comprehensive manual on the inspection of wood structural elements titled *Wood and Timber Condition Assessment Manual* (Ross *et al.* 2004). It was prepared at the request of the American Forest and Paper Association to assist field engineers and other inspection professionals. It is published by the Forest Products-Society and includes chapters on visual inspection techniques, ultrasound or stress wave based inspection tools, and probing type techniques. A chapter on post-fire inspection and assessment is included in addition to a sample inspection report and summaries from numerous inspections. Detailed descriptions of the various available tools, guidelines on their use, and interpretation of data obtained from them are included.

This chapter presents a summary of the Wood and Timber Condition Assessment Manual. It focuses on current inspection techniques for decay detection and provides guidelines on the use of various non-destructive evaluation (NDE) methods in locating and defining areas of deterioration in timber bridge components and other civil structures.

5.2 Conventional methods

Conventional methods for detecting deterioration in bridges are divided into two categories: those for exterior deterioration and those for interior deterioration. In both cases, specific techniques or tools are appropriate for certain types of damage, and their usefulness varies depending on the type of structure. Although a variety of inspection methods may be employed, in practice the inspector uses only a few tools. The methods or tools are often dictated by budget, previous experience, and the types of problem that are encountered.

5.2.1 Methods for determining exterior deterioration

Exterior deterioration is the easiest to detect because it is often readily accessible to the inspector. The ease of detection depends on the severity of damage and the method of inspection. Commonly used methods include visual inspection and probing. When areas of exterior deterioration are located by these methods, further investigation by other methods is required in order to confirm and define the extent of damage.

Visual inspection

Visual inspection is the simplest method for locating deterioration in timber structures. The inspector observes the structure for signs Of actual or potential deterioration, noting areas for further investigation. Visual inspection requires strong light and is suitable for detecting intermediate or advanced surface decay, water damage, mechanical damage, or failed members. Visual inspection cannot detect early stage decay, when remedial treatment is most effective. The following paragraphs describe signs of deterioration that should be noted during an investigation.

Fruiting bodies provide positive indication of fungal attack but do not indicate the amount or extent of decay. Some fungi produce fruiting bodies after small amounts of decay have occurred, whereas others develop only after decay is extensive. Fruiting bodies are not common on bridges, and they almost certainly indicate serious decay problems when they are present.

Sunken faces or localized surface depressions can indicate underlying decay. Decay voids or pockets may develop close to the surface of the member, leaving a thin, depressed layer of intact, or partially intact, wood at the surface. Staining or discoloration indicates that members have been subjected to water and potentially high moisture contents suitable for decay. Rust stains from connection hardware are also a good indication of wetting.

Insect activity is visually characterized by holes, frass, powder posting, or other signs previously discussed. The presence of insect activity may also indicate the presence of decay. Plant or moss growth in splits or cracks, or soil accumulation on the structure indicates that adjacent wood has been at relatively high moisture content suitable for decay for a sustained period of time.

Probing

Probing with a moderately pointed tool. such as an awl or knife, locates decay near the wood surface by revealing excessive softness or a lack of resistance to probe penetration. Although probing is a simple inspection method, experience is required to interpret results. Care must be taken to differentiate between decay and water-softened wood that may be sound but somewhat softer than dry wood. It is also sometimes difficult to assess damage in soft-textured woods such as western red cedar.

In addition to probing with simple tools. some mechanical devices, such as the Pilodyn, can also be used to detect surface damage. The Pilodyn is a spring-loaded pin device that drives a hardened steel pin into the wood. The depth of pin penetration is used as a measure of the degree of decay. The Pilodyn is used extensively in Europe. where soft rot attack is more prevalent. It is also used to measure the specific gravity of wood for tree improvement programs. Where surface damage is suspected, the Pilodyn can produce an accurate assessment, provided corrections are incorporated for moisture content and the wood species tested.

5.2.2 Methods for detecting interior deterioration

Unlike exterior deterioration, interior deterioration is difficult to locate because there may be no visible signs of its presence. Numerous methods and tools have been developed to evaluate internal damage that range in complexity from sounding the surface with a hammer to sophisticated X-ray or radiographic evaluation. In addition. tools such as moisture meters are also used to help the inspector identify areas where conditions are suitable for development of internal decay.

Sounding

Sounding the wood surface by striking it with a hammer or other object is one of the most commonly used inspection methods for detecting interior deterioration. Based on the tonal quality of the ensuing sounds, a trained inspector can interpret dull or hollow sounds that may indicate the presence of large interior voids or decay. Although sounding is widely used, it is often difficult to interpret because factors other than decay can contribute to variations in sound quality. In addition, sounding provides only a partial picture of the extent of decay present and will not detect wood in the incipient or intermediate stages of decay. Nevertheless, sounding still has its place in inspection and can quickly identify seriously decayed structures. When suspected decay is encountered, it must be verified by other methods, such as boring and coring.

Drilling and coring

Drilling and coring are the most common methods for detecting internal deterioration in bridges. Both techniques are used to detect the presence of voids and to determine the thickness of the residual shell when voids are present. Drilling and coring are similar in many respects and will be discussed together.

Drilling is usually done with an electric power drill or hand-crank drill equipped with a 10–19 mm (3/8 to 3/4 inch) diameter bit. Power drilling is faster, but hand drilling allows the inspector a better feel and may be more beneficial in detecting pockets of deterioration. Generally, the inspector drills into the structure, noting zones where drilling becomes easier (torque releases) and observing the drill shavings for evidence of decay. The presence of common wood defects, such as knots, resin pockets, and abnormal grain, must be anticipated while drilling and must not be confused with decay. If decay is detected, the inspection hole can also be used to add remedial treatments to the wood.

Coring with increment borers also provides information on the presence of decay pockets and other voids. and coring produces a solid wood core that can be carefully examined for evidence of decay. Where appropriate, the core can also he used to obtain an accurate measure of the depth of preservative penetration and retention. Where structures are not yet showing signs of decay, cores can be cultured to detect the presence of decay fungi. The presence of such fungi usually indicates that the wood is in the early or incipient stage of decay and should be remedially treated. Culturing provides a simple method for assessing the potential decay hazard, and many laboratories provide routine culturing services. Because of the wide variety of fungi near the surface, culturing is not practical for assessing the hazard of external decay.

Drilling and coring are generally used to confirm suspected areas of decay identified by the use of moisture meters or other methods. When decay is detected, drilling and coring are also used to further define the decay's extent and limits. Inspectors may find drilling best for initial inspection until some evidence of decay is found. When decay is detected, coring may be preferred for defining the limits of the infection and extracting samples for further examination and analysis. It is important to use sharp tools for both drilling and coring, and the inspector should always carry extra bits or increment borers. Dull tools tend to crush or break wood fibers and cause excessive core or shaving breakage that may be confused with decay.

Shell-depth indicator

A tool that is useful when drilling or coring is the shell–depth indicator. This tool is a metal bar, notched at the end and inscribed in inches or centimetres, that is inserted into the inspection hole and pulled back along the hole sides. As it moves along the wood, the hook will catch on the edges of voids. In this way the inspector can note the depth of the solid shell, which can be used to estimate residual wood strength.

Shigometer

The Shigometer, a device that has been compared to the moisture meter, uses a pulsed current to measure changes in electrical conductivity associated with decay. A small hole is drilled into the wood, and a twisted wire probe connected to a meter is inserted into the hole. As the probe encounters zones of decreased resistance, the meter reading drops. Zones of large meter declines (50—75%of that indicated for sound wood) are then bored or drilled to determine the nature of the defect. The Shigometer has performed very well in detecting decay in living trees, but wood in service is normally too dry to permit the use of this instrument. Nevertheless, several studies show that the Shigometer is a reasonable method for detecting decay if it is used under proper conditions by trained operators who understand its operation and interpretation.

X-rays and tomography scanners

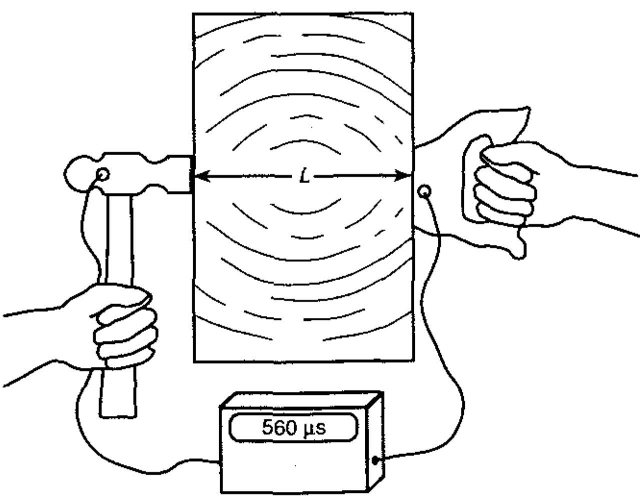
X-rays were once commonly used for detecting internal voids in wood. As the X-rays pass through the wood, the presence of knots or other defects alters the density of the resulting radiograph. X–ray technology has advanced considerably since the first field units were developed; however, the high cost of equipment, safety factors associated with the use of ionizing radiation, and the need for expert interpretation of results have largely eliminated its use in wood. Despite these problems, X-rays are particularly useful for detecting insect and marine borer infestations in wood.

5.3 Stress wave propagation method

Another method that has been successfully used for decay detection in wood structures is the inducement of a stress wave in a structural member and measurement of attenuation and time required for the stress wave to propagate through the member (Pellerin and Ross 2003). If decay is present in the member, the attenuation and propagation time of the stress wave passing through the member is increased. Propagation time in decayed wood may he as much as several times the propagation time in solid wood.

5.3.1 Concept and limitations

As an introduction to this stress wave concept for detecting decay in wood structural members, a schematic of the stress wave measurement in a rectangular timber is shown in Fig. 5.1. A stress wave is induced by striking the member with an impact device that is instrumented with an accelerometer that in turn emits a start signal to a timer. A second accelerometer, which is coupled to the timber, then responds to the leading edge of the propagating stress wave and sends a stop signal to the timer. The elapsed time for the stress wave to propagate between the accelerometers is displayed on

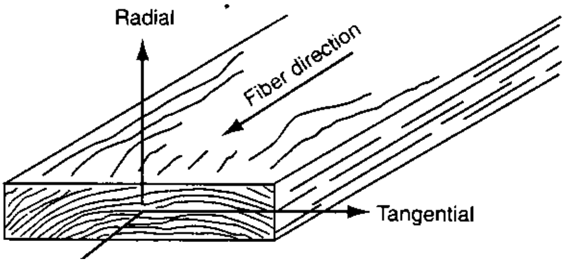


5.1 Schematic of stress wave measurement in a rectangular timber.

the timer. The underlying premise for this technique is that the speed, and hence the transmission time, at which a stress wave travels through a wood member is indicative of the member's condition.

The use of stress wave velocity to detect wood decay in timber bridges and other structures is limited only by access to the structural members under consideration. It is especially useful on large timbers or glulam timbers ≥89mm (≥3.5 inches) for which hammer sounding is not effective. Access to both sides of the member is required. Because timber is an organic substance, material properties and strength vary in accordance with the direction timber is hammered relative to the cell structure orientation. Hammering the end grain of a beam or post will cause a primarily longitudinal shock wave along the length of the cell structure in the timber. Hammering the side or top of the beam will cause a wave across or transverse to the timber cells. The timber cells are arranged in rings around the center of the tree. The velocity at which a stress wave propagates in wood, as well as other physical and mechanical properties, is a function of the angle at which the fibers of wood are aligned. For most structural members, fibers of the wood align more or less with the longitudinal axis of the member (Fig. 5.2).

Stress wave transmission times on a per length basis for various wood species are summarized in Table 5.1 (Ross *et al.* 2004). Stress wave transmission times are shortest along the grain (with the fiber) and longest across the grain (perpendicular to fiber). For Douglas fir and southern pine, stress wave transmission time parallel to the fiber is approximately 200 µs/m (60 µs/ft). Stress wave transmission time perpendicular to the fiber ranges from 850 to 1000 µs/m (259 to 305 µs/ft). When the stress wave propagation method is used to detect localized decay in timbers, measurements should be made in transverse paths (perpendicular to grain). Parallel-to-grain travel paths (longitudinal direction) can bypass regions of decay and therefore are not effective.



5.2 Three principal axes of wood with respect to grain direction and growth rings.

Table 5.1 Summary of research on stress wave transmission times for various species of non-degraded wood

Species	Moisture content (%-OD)[a]	Stress wave transmission time (µs/m (µs/ft))	
		Parallel to grain	Perpendicular to grain
Sugar maple	12	256–194 (78–59)	–
Yellow birch	11	230–180 (70–55)	–
White ash	12	252–197 (77–60)	–
Red oak	11	262–200 (80–61)	–
Birch	4–6	213–174 (65–53)	715–676 (218–206)
Yellow poplar	4–6	194–174 (59–53)	715–676 (218–206)
Black cherry	4–6	207–184 (63–56)	689–620 (210–189)
Red oak	4–6	226–177 (69–54)	646–571 (197–174)
Several	11	203–167 (62–51)	–
Red oak	12	302–226 (92–69)	–
Several	–	272–190 (83–58)	–
Sitka spruce	10	170 (52)	–
Southern pine	9	197 (60)	–
Douglas fir	10	203 (62)	–
Southern pine	10	197–194 (60–59)	–
Douglas fir	12	–	1092–623 (333–190)
Douglas fir	11	–	850–597 (259–182)
Douglas fir	–	–	1073 (327)
Southern pine	9	200–170 (61–52)	–
Live oak	12	–	613–1594 (187–486)
Northern red and white oak	Green	–	795 (242)

[a] OD is oven dry.
Source: Ross *et al.* (2004).

5.3.2 Effect of decay

The presence of decay greatly affects stress wave transmission time in wood. Table 5.2 summarizes stress wave transmission values obtained from field investigations of various wood members subjected to degradation from decay (Ross *et al.* 2004). Stress wave transmission times perpendicular to the grain are drastically reduced when the member is degraded. Transmission times for non-degraded Douglas fir are approximately 800 µs/m (244 µs/ft), whereas severely degraded members exhibit values as high as 3200 µs/m (975 µs/ft) or greater.

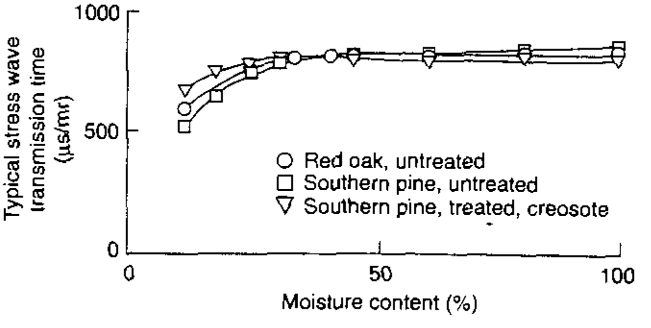
5.3.3 Effect of moisture content

Several studies have revealed that stress wave transmission times perpendicular to the grain of wood follow a relationship to moisture content (Fig. 5.3). At moisture contents less than approximately 30%, transmission

Table 5.2 Summary of research on use of stress waves for detecting decay in timber structures

Structure	Wood product	Test	Analysis
Bridge	Douglas fir glulam, creosote pressure treated	Stress wave transmission time perpendicular to grain, across laminations at 0.3 m (0.98 ft) intervals	Sound wood: 1279 µs/m (390 µs/ft) Moderate decay: 1827 µs/m (557 µs/ft) Severe decay: 2430 µs/m (741 µs/ft)
Football stadium	Solid sawn Douglas fir, creosote pressure treated	Stress wave transmission time perpendicular to grain, near connections	Sound wood: 853 µs/m (260 µs/ft) Incipient decay: –Center of members: 1276 µs/m (389 µs/ft) - 38 mm thick solid wood shell: 2129 µs/m (649 µs/ft) Severe decay: >3280 µs/m (1000 µs/ft)
School gymnasium	Douglas fir glulam arches	Velocity of stress wave transmission time perpendicular to grain, near end supports	Sound wood: 1073 µs/m (327 µs/ft) Decayed wood: 1574 µs/m (480 µs/ft)

Source: Ross *et al.* (2004).



5.3 Relationship between transverse stress wave transmission time and moisture content.

Table 5.3 Stress wave transmission time adjustment factors for temperature at various moisture contents for Douglas fir

Moisture content (%)	Adjustment factors			
	−18°C (0°F)	3°C (38°F)	27°C (80°F)	49°C (120°F)
1.8	0.94	0.95	0.97	0.98
3.9	0.95	0.96	0.98	0.99
7.2	0.96	0.98	1.00	1.01
12.8	0.97	0.99	1.00	1.01
16.5	0.99	1.01	1.03	1.05
23.7	1.05	1.07	1.09	1.14
27.2	1.07	1.10	1.12	1.17

time decreases with decreasing moisture content. Corrections for various moisture content values are summarized in Table 5.3. At moisture content values greater than approximately 30%, little or no change in transmission time occurs. Consequently, there is no need to adjust the measured values for wood that is tested in a wet condition.

5.3.4 Effect of preservative treatment

Treatment with waterborne salts has almost no effect on stress wave transmission time. Treatment with oil-borne preservatives increases transmission time by about 40% over that of untreated wood. Round poles are usually penetrated to about 37–61 mm (1.5–2.5 inches), except at their ends, where the treatment fully penetrates the wood. Table 5.4 was calculated to show expected travel time for round poles treated with oil-borne preservatives. Although these data illustrate the effect oil-borne treatments have on transmission time, these values should not be used to estimate the level of penetration.

5.3.5 Measurement of stress wave transmission time

Several techniques can be used to measure stress wave transmission time in wood structural members. The most common technique utilizes simple time-of-flight measurement systems. With these systems, a mechanical or ultrasonic impact is used to impart a wave into the member. Piezoelectric sensors are placed at two points on the member and are used to detect passing of the wave, The time required for the wave to travel between

Table 5.4 Stress wave transmission times for round poles treated with oil borne preservatives

Pole diameter	Stress wave transmission time (µs) for various levels of penetration		
(mm)	37 mm	61 mm	Full penetration
294	222	240	300
343	254	271	350
392	286	305	400
441	321	338	450
490	350	370	500
539	386	403	550
588	422	436	600

sensors is then measured. The commercial equipment options available for stress wave measurements are shown in Table 5.5. Field use of equipment should be conducted in accordance with the instructions provided by equipment manufacturers.

5.3.6 Field considerations

Before venturing into the field, it is useful to estimate stress wave transmission time for the size of the members to be inspected. Preceding sections provided information on various factors that affect transmission time in wood. This information can be reflected in a baseline transmission time of 1300 µs/m (400 µs/ft). Transmission time, on a per length basis, less than this value would indicate sound material. Conversely, transmission time greater than this value would indicate potentially degraded material. Using this value, one can estimate the transmission time for a member by knowing its thickness (path length) and the following formula:

$$T_{\text{baseline}}\,(\mu\text{s}) = 1300 \times \text{WTD}$$

where T_{baseline} is baseline transmission time (µs), and WTD is wave transmission distance (path length) (m). By knowing this number for various thicknesses, field work can proceed rapidly.

The baseline values provided here serve as a starting point in the inspection. It is important to conduct the test at several points at various distances from the suspect area. In a sound member, little deviation is observed in transmission times. If a significant difference in values is observed, the member should be considered suspect.

In the field, extra batteries, cables, and sensors are helpful. Testing should

Table 5.5 Commercial equipment for measuring stress wave transmission time in wood structural members

Name	Manufacturer	Method of wave seneration	Contact information
Metriguard Model 239A Stress Wave Timer	Metriguard, Inc.	Impact	Metriguard, Inc. PO Box 399, Pullman, WA 99163, USA www.metriguard.com
FAKOPP Microsecond Meter	FAKOPP Enterprise	Impact	FAKOPP Enterprise H-9423 Agfalva, Fenyo Str. 26, Hungary www.fakopp.com
Electronic Hammer	IML, Inc.	Impact	IML, Inc. 1275 Shiloh Road, Suite 2780, Kennesaw, GA 30144, USA www.imlusa.com
Sylvatest Duo	Concept Bois Technologie	Ultrasonic pulse generator	Concept Bois Technologie Jordils Park Ch. Des Jordils 40, CH-1025 Saint-Sulpice, Switzerland www.cbs-cbt.com
James´V´ Meter	James Instruments Inc.	Ultrasonic pulse generator	James Instruments Inc. 3727 North Kedzie Ave., Chicago, IL 60618, USA www.ndtjames.com

be conducted in areas of the member that are highly susceptible to degrading, especially in the vicinity of connections and bearing points.

5.4 Cases studies

5.4.1 Timber bridges

A report by Hoyle and Rutherford (1987) describes the evaluation of wood bridges for the Washington State Department of Transportation using speed-of-sound transmission as an index of deterioration. The previously described stress wave propagation method was used. Of 12 bridges evaluated, only one revealed signs of decay. Similarly, Aggour *et at.* (1986) used ultrasonic techniques to evaluate the residual compression strength of timber bridge piles. A good correlation was found between stress wave transmission time and the residual compressive strength.

5.4.2 USS Constitution

The USS *Constitution,* known as ‘Old Ironsides,’ is the oldest floating, commissioned ship in the world and still a part of the US Navy. Launched on 21 October 1797, the ship was recently in dry dock. At the time of dry dock, an intensive condition assessment of the ship’s timbers was conducted. Stress-wave-based techniques were utilized to assess many of the ship’s timbers (Ross *et al.* 1998). All deck beams (four decks of approximately 32 beams each), various knees, the stern post, the stem keelson, and keel were examined. Baseline stress wave transmission times for sound live oak wood (the species used in original construction of the ship) were calculated for the thickness of various members. Inspection of these members after they were removed from the ship revealed that the severity of degradation corresponded to increases in transmission times.

5.4.3 TRESTLE

Another structure evaluated with stress wave propagation method was TRESTLE, located at Kirkland Air Force Base, New Mexico. Constructed between July 1976 and February 1979, TRESTLE is one of the largest known glue-laminated structures in the world. It was built as a test stand for aircraft that weigh 250000 kg (550000 lb). It has a 15 x 120 m^2 (50 × 394 ft^2) access ramp and a 61 x 61 m^2 (200 × 200 ft^2) test platform, and the top surface is 36 m (118 ft) above the ground. In the early 1980s, the US Air Force wanted to test aircraft that were considerably heavier than had previously been tested, so they requested a structural evaluation of TRESTLE. One evaluation method relied upon stress wave propagation measurements. Measurements were taken both longitudinally and transversely to the length of the laminated beam. Neal (1985) and Browne and Kuchar (1985) reported that a total of 484 glulam members, representing approximately 5% of the structural members, were evaluated. They concluded that the structural framework of TRESTLE had not measurably degraded, but the exposed deck system was significantly degraded.

5.5 Future research and development

Several non-destructive inspection methods discussed here, such as sounding, resistance drilling, and stress wave propagation, offer great potential as means of locating internal decay in wood structures. However, the sensitivity of these methods to the detection and quantification of incipient decay is relatively low. Future research should be directed to improve the precision and sensitivity of existing NDE methods and also develop new technologies that are capable of detecting wood decay at the earliest possible stage when remedial treatments are most effective. Recently, several European universities have developed computer-aided tomography scanners for wood poles. The scanners move up or down a pole and provide an image of internal wood conditions. Prototypes of these devices are in the early stages of development, and further refinements are necessary to speed up the process of data evaluation.

Current inspection methods for wood structures are limited to evaluating each structural member individually, which is a labor-intensive, time-consuming process. A more efficient strategy would be to evaluate structure systems or subsystems in terms of their overall performance and serviceability. From this perspective, examining the dynamic response of a structural system might provide an alternative way to gain insight to the ongoing performance of the system. Deterioration caused by any organism or any type of physical damage to the structure reduces the strength and stiffness of the materials and thus could affect the dynamic behavior of the system. Research is currently being conducted at USDA Forest Products Laboratory and other research institutions to investigate the effectiveness of global dynamic testing methods for identifying deteriorated wood structures (Ross *et al.* 2002).

5.6 Conclusions

This chapter has reviewed current inspection techniques for decay detection and provided guidelines on the use of various NDE methods in locating and defining areas of decay within wood structural members. Visual inspection and probing techniques are commonly used for locating exterior deterioration of wood members. When suspect decay areas are located by these methods, further investigation by coring or drilling is suggested to confirm and define the extent of damage. Internal decay of wood structural members can be detected by a variety of means. Among the most effective and cost-efficient techniques for field applications are coring, resistance drilling, and stress wave propagation method. But the sensitivity of these methods to detection and quantification of early stage of decay is limited. New technologies are yet to be developed for more efficiently identifying deteriorated wood structures and detecting incipient decay in individual structural members before significant strength loss occurs.

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