Practice Points NUMBER 10

Nondestructive Evaluation: Wood

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Introduction

Preservationists look to methods of nondestructive evaluation (NDE) to answer questions about the condition, strength, and construction details of wood in historic buildings in the interest of saving historic fabric and reducing or eliminating damage to significant historic features or materials caused by investigative probes. Many times, a basic wood inspection can answer questions posed when a structure is being considered for renovation or adaptive reuse (see "Practice Points Number 3: Basics of Wood Inspection," which addresses visual inspection, probing, and moisture diagnostics). However, when information generated through a basic inspection is insufficient to make informed decisions, advanced investigative techniques should be considered.

Since answers to questions about condition, strength, and construction are often concealed in a historic structure, NDE methods are a means to assess hidden conditions and obtain vital information for decision makers. Although considerable research on the NDE of wood has been conducted, there are only limited numbers of NDE methods for assessing timber that are available for field use. These include:

- moisture-content measurements
- remote visual inspection
- resistance drilling
- infrared thermography
- visual grading
- stress-wave measurements
- digital radioscopy

NDE methods are tools to be used in conjunction with other assessment methods and experience to obtain information about wood that can be used to make decisions concerning appropriate treatments. Table 1 provides a summary of the various NDE methods discussed and the information that can be obtained through their use.

This Practice Point introduces the most commonly available NDE methods for in-situ assessment of wood members and construction. They should not be used without understanding the capabilities and limitations of each method. Some methods require more training or experience than others to properly interpret the data acquired. The use of NDE methods during a condition assessment can identify the current condition of the wood, but users must remember that the data obtained provide only a snapshot in time. If the structure is to be renovated, any ongoing problems (such as leaks) must be addressed.

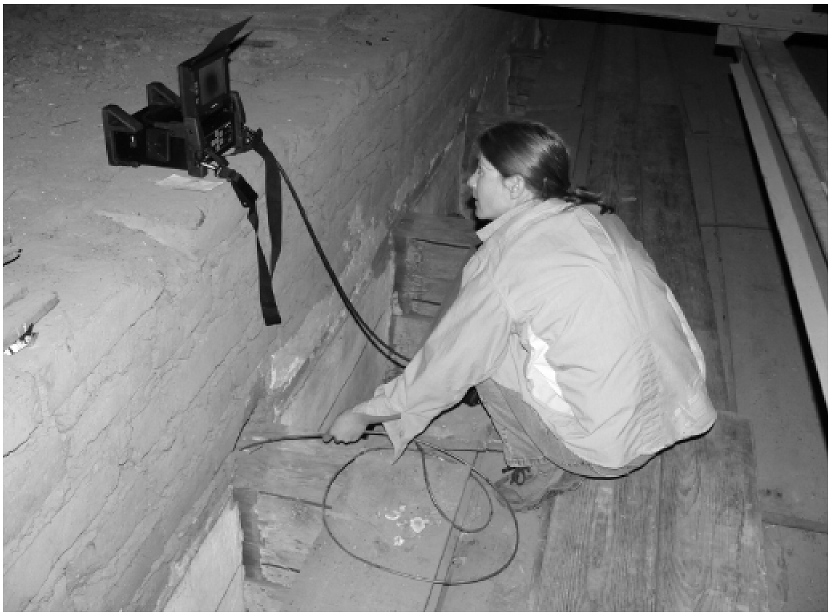

Fig. 1.
A videoscope being used to inspect the interior of timber embedded in adobe. All images by the author, unless otherwise noted.

Moisture and moisture meters. Most ongoing problems with wood are related to moisture issues. Moisture meters are extremely useful for identifying the current moisture content of wood and can identify problem areas that are not easily seen with the unaided eye. The true moisture content of wood can be determined only by oven drying a sample removed from a structure. Fortunately, portable moisture meters allow investigators to take a reading of the approximate moisture content of wood without removing a sample from the structure. There are two primary types of portable moisture meters: one based on electrical capacitance and one based on electrical conductance. Additional information

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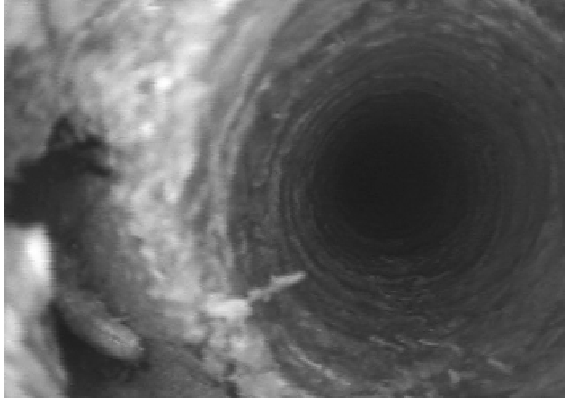

Fig. 2.
A videoscope image taken from a bore hole in a timber showing a live termite and internal termite damage on the left.

Fig. 3.
A resistance drill being used to quantify the extent of decay in a log.

on the significance of wood moisture content and the use of moisture meters can be found in “Practice Points Number 3: Basics of Wood Inspection.”

What is the Condition of the Wood?

The first questions that should be asked when renovations or alterations are considered for a historic structure with wooden elements are: What is the condition of the wood? Does it have any hidden decay? Is there evidence of current or past insect activity?

While most of the available NDE methods can be used to provide some information to answer these questions, there are two methods that stand out for their usefulness in assessing conditions: remote visual inspection and resistance drilling. Infrared thermography, stress-wave measurements, and digital radioscopy have also been used to determine wood condition, but with limited success. Methods of condition assessment are discussed below.

Remote visual inspection. Remote visual inspection allows for the imaging of wood that is inaccessible to basic visual inspection and beyond the capabilities of such other NDE methods as resistance drilling, digital radioscopy, and stress waves. It can be used to view conditions or construction within inaccessible areas, such as within beam pockets or within wall construction with embedded timbers. Remote visual inspection involves the use of either a flexible borescope or a videoscope — both of which have a very small camera mounted at the end of a long, flexible tube. A videoscope also has a monitor that displays the images transmitted from the camera (borescopes are not discussed here, but information about them can be found in Practice Points Number 9 on nondestructive evaluation of masonry). A portable videoscope camera and insertion tube may be as small as $^{1}/_{8}$-inch (3.8 mm) in diameter (Fig. 1). On some models, the camera tip articulates in up to four directions and can have a field of view as large as 120 degrees. The depth of field varies by camera; some models have interchangeable camera tips that allow for a depth of field from $^{5}/_{32}$ inch (4 mm) to infinity. Advanced models also have stereoscopic measurement tools for determining distances, lengths, and widths of viewed objects. Most videoscope models allow for capturing still images, and more advanced models can record video (Fig. 2).

Use of a videoscope may be nondestructive if it is inserted into existing gaps, cracks, holes, or crevices too small for access using other forms of inspection. An alternative methodology is to drill a small hole (just larger than the diameter of the insertion tube) into a wood member to determine the interior conditions of the wood; this approach necessitates some destruction of the historic fabric and therefore is quasi-nondestructive in nature. As such, remote visual inspection should be used only where it is warranted and when other methods are inadequate.

Resistance drilling. Resistance drilling provides information about the condition of the wood that may be hidden from visual inspection. The term “resistance drilling” has been used to describe any drilling technique intended to measure the ease of drill penetration into wood. Portable drills with standard bits have

Table 1. Factors that Can be Determined Using NDE

	METHODS						
FACTORS	Remote visual inspection	Resistance drilling	Infrared thermography	Stress waves	Visual grading	Digital radioscopy	Moisture measurements
Measure moisture content			Limited				Yes
Locate deterioration	Limited	Yes	Limited	Limited		Yes	
Quantify deterioration	Limited	Yes		Limited		Limited	
Assess strength				Limited	Estimate		
Determine modulus of elasticity				Estimate	Estimate		
Identify hidden construction details	Yes	Limited	Limited			Yes	
Locate and assess fasteners						Yes	

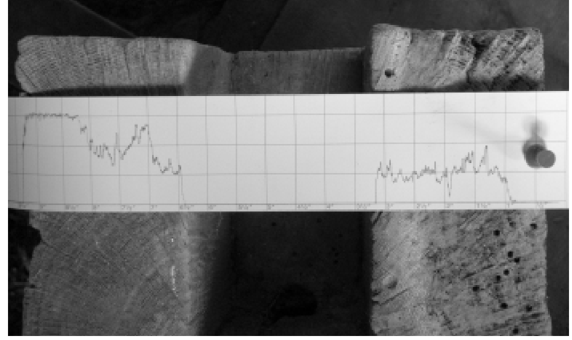

Fig. 4.
Resistance-drilling printout against a timber showing (a) insect damage on the right, (b) a void in the center due to construction details, and (c) solid wood that exhibits the effect of growth-ring orientation on the graph.

Fig. 5.
Setup for taking a digital radiograph of a mortise-and-tenon joint in a beam-column connection, with the x-ray source in the background and the imaging plate placed against the column.

been used not only to test the relative difficulty of drilling into wood (resistance) but also to observe the color and integrity of the wood chips extracted by the drill bit.

In the context of NDE, the term “resistance drilling” is a quasi-nondestructive assessment method using specialized equipment where a small-diameter needle (less than $\frac{1}{8}$-inch, or 3.8 mm in diameter) is pushed through a wood member at a constant rate of speed. The resistance drill records the relative density of the wood by measuring the amount of torque encountered by the motor as the needle advances (Fig. 3). A graph of the relative density is printed on a strip of paper simultaneously with the needle’s advancement (Fig. 4). Voids or areas of deterioration, which are usually due to insect attack or wood decay fungi, can be readily identified; they appear on the graph as flat-line zones or low-amplitude peaks relative to the overall graph. The orientation of the growth rings in the wood as the needle penetrates the wood can influence the graph, and, therefore, resistance drilling requires at least a minimal level of experience to properly interpret the graphs. This assessment method is best suited for determining internal problems in timbers or large members that do not show obvious signs of deterioration.

Due to the ability to measure areas of deterioration and the size of voids directly from the graph, this method is very reliable for quantifying the extent of internal voids due to decay or to wood-boring insects. Resistance drilling removes the subjectivity associated with the need to estimate the amount of resistance encountered when using a hand drill. The equipment is portable and compact enough to allow for investigation of most timbers. In some cases, access to the timber is limited, and drilling must be conducted between timbers or adjacent to the area of interest, such as beam pockets. The drillings can provide a profile of advanced internal decay that is not detectable by simple probing. Originally developed in Europe for inspecting the condition of trees, resistance drilling continues to be used in forestry and has also been used extensively in structure investigations.

Resistance drilling should be conducted in areas where deterioration is either visible or suspected. This includes, but is not limited to, masonry/timber interfaces, wood in contact with the ground, wood with moisture stains or visible decay, sill and top plates, attic timbers, and framing lumber around openings such as doors and windows.

Infrared thermography. All objects emit infrared radiation that can be detected in the form of heat. Infrared thermography (IRT) provides a visual depiction of nonvisible infrared electromagnetic energy. An infrared camera records an image that depicts the intensity of the thermal radiation emitted. IRT has been used successfully to detect structural flaws and failures, identify hidden construction details, and determine moisture presence and movement within masonry. On a limited basis, IRT can also be used to detect deterioration due to termite activity and areas of high moisture content in wood.

There are two types of infrared thermography: passive and active. Passive IRT images the natural infrared emissions from a structure, typically generated by solar radiation. Active IRT requires a heat source to artificially increase the amount of infrared emissions within a specific area or room. This latter type of imaging generally produces more detailed results; however, it should be noted that there are concerns regarding the high temperatures necessary for active IRT imaging and the potential to damage historic structures or finishes. Generally, the heat source should be behind the wall or portion of the structure that is being imaged.

IRT can determine areas of higher moisture content within a structure, since thermal conductivity increases as moisture content increases in the wood. However, moisture content cannot be quantified, and only areas of high moisture near the surface can be identified. IRT, therefore, can possibly identify, but not quantify, decay or insect activity associated with elevated levels of moisture within wood.

Stress-wave measurements. Stress-wave measurements focus on the speed of sound transmission through wood to identify areas of advanced internal deterioration. Based on one-dimensional wave theory, stress-wave technologies measure transmission time to establish stress-wave propagation speed. A longitudinal wave is generated by striking a wood member with a mechanical or ultrasonic impact tool, and the passing of the wave is measured by a piezoelectric sensor. Stress-wave transmission times are generally shortest when traveling with the grain (parallel to the long axis of the wood) and longest when traveling across the grain (perpendicular to the long axis of the wood). In general, stress waves tend to propagate quickly through dense, solid materials, while voids,

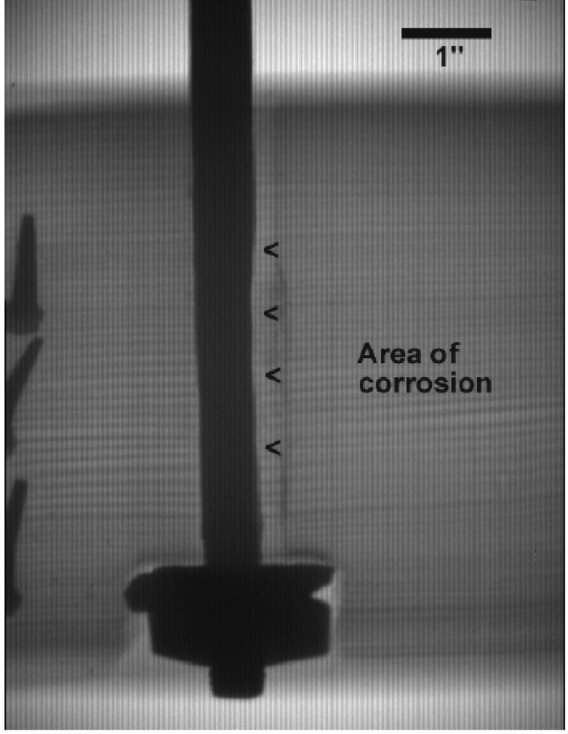

Fig. 6. *Radiograph showing surface corrosion of a wrought-iron rod embedded in a timber beam.*

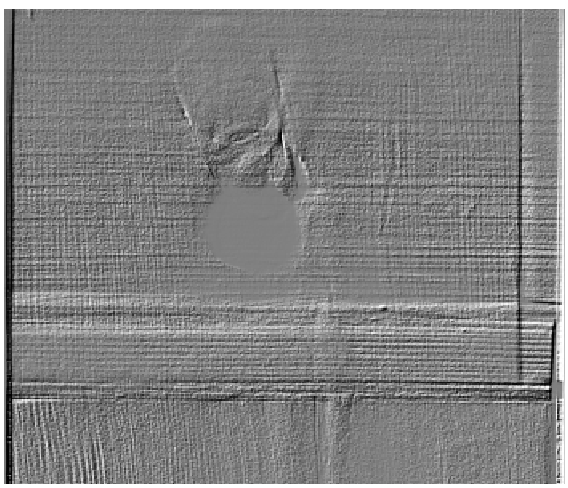

Fig. 7. *Radiograph illustrating post-processing image enhancement to better illustrate the overlapping wood grain of a mortise-and-tenon joint.*

cracks, or deterioration can attenuate and slow stress-wave propagation.

To determine stress-wave transmission time, an impact device fitted with an accelerometer sends a start signal to a timer at the moment of impact. A second accelerometer, held against the opposite side of the wood member, determines the front edge of the wave and sends a stop signal to the timer, which then displays the transmission time. Access to both sides of the wood member is required. Grain orientation affects the speed of the transmission, as will moisture contents below 30 percent. The lower the moisture content, the faster the transmission time (for moisture contents less than 30 percent). Moisture contents greater than 30 percent have little effect on transmission times. Stress-wave measurements are useful for conducting an initial screening of areas of timber that may warrant further investigation, and they can also be used for estimating the modulus of elasticity, described later in this paper.

Digital radioscopy. Structures have been examined with traditional x-ray technology using film and high-energy x-ray sources for quite some time; however, the use of x-rays was limited due to safety concerns and high costs. The use of digital radioscopy for structure investigation is a more recent technological development and presents many advantages over earlier techniques: the x-ray source is a cathode-type x-ray tube (i.e., it does not contain radioactive elements) and emits low-energy pulses of x-rays. The digital image is immediately available for viewing, so there is minimal processing time, which is a particularly important feature in building investigation where conditions are variable and future access may be difficult. Finally, the availability of relatively inexpensive mass-market post-processing software extends the power of digital radioscopy.

Wood conditions, including internal deterioration, due to decay fungi or insect activity, and hidden wood failures can be determined using digital radioscopy. It is possible, but somewhat difficult, to quantify decay or insect damage. Decayed wood can often be identified in a radiograph due to the lighter color(s) of the reduced cross section, a transition from an intact grain pattern to the lack of a visible grain pattern, or a generally mottled appearance.

Additionally, wood that has been attacked by insects will also show lighter areas in a radiograph, corresponding to a loss of material. The boundaries between undamaged and damaged wood are more abrupt than for decayed wood and tend to display a ragged or tunneled pattern. Colorization and additional image enhancement through post-processing manipulation can help to quantify the extent of damage or decay.

Generally, resistance drilling, in conjunction with visual inspection, is the recommended method for assessing wood condition.

How Strong is the Wood?

For wood in good condition, with no decay or insect damage, an estimate of strength can be made by determining the species of the wood and visually grading the wood members. This process of visual grading has been described in a publication available through the National Center for Preservation Technology and Training and is listed in the additional references section of this Practice Point. A summary of visual grading is described below.

Visual grading. For wood construction, structural engineers rely on design values referenced in the building code to determine an acceptable species, size, and grade for a particular load condition. The design values given in the building codes for solid wood products are established by the American Forest and Paper Association and American Wood Council and published as the National Design Specification for Wood Construction. The published design values are based on various test data and procedures published by ASTM International that demonstrate the engineering performance of the material.

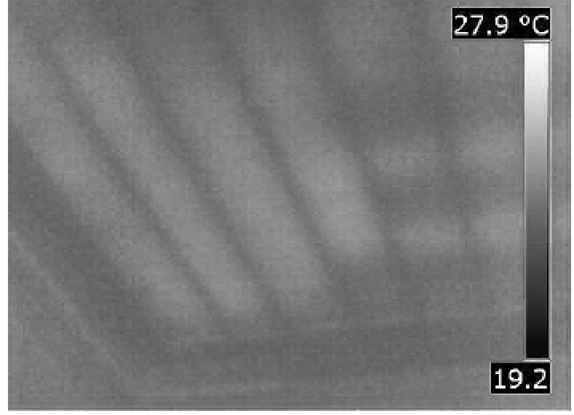

Fig. 8.
Plaster ceiling with unknown support framing. Courtesy of Jonathan Spodek.

Fig. 9.
Infrared thermograph of plaster ceiling showing wood support framing above the plaster. Courtesy of Jonathan Spodek.

Structures built before the establishment of building codes or design values for wood products — and that therefore lack grade stamps on individual wood members — present a quandary when determining what design values are appropriate. Frequently an assumed species and grade are assigned based on current standards and design values. However, the result of assuming a species and/or grade is often an overly conservative estimate of the design values and unnecessary replacement, repair, and retrofit decisions, along with associated unnecessary project costs and destruction of historic fabric. Visual grading of in-situ members allows for a more accurate assessment of wood strength and engineering performance.

The first step in visual grading is identifying the wood species. To determine the species of a wood element of interest, a small sample should be taken from an inconspicuous location. A representative number of samples should be taken from every framing member type (not from every member) to be graded. These samples can be analyzed for species identification by a number of wood consultants or laboratories for a fee, or they can be processed by the Center for Wood Anatomy at the U.S. Forest Products Laboratory in Madison, Wisconsin, at no charge.

Once the species is identified, then wood-member characteristics, including width and thickness, knot size, knot location, and slope of grain, can be measured in the field and used to determine the appropriate grade. Knowing the grade allows for determining strength properties for design and structural analysis.

Stress-wave measurements. Stress-wave transmission times in wood and estimates of the density of the wood have been correlated to modulus of elasticity (stiffness). This value is useful when deflection of a structural member is important and for calculating loads that can cause column buckling. The estimate of the modulus of elasticity relies on the assumed wood density, which can vary between trees of the same species, as well as along the length of any individual tree. Typically, a species-specific average value is used. However, it should be noted that the actual specific gravity can vary considerably from piece to piece.

Strength estimates have also been determined from stress-wave measurements. However, these estimates rely on the correlation between the modulus of elasticity (which is estimated using the procedure described above) and a strength property, usually the modulus of rupture (bending). Since both correlations used in this approach can be quite variable (due to the range of density, moisture content, and strength that wood exhibits within a given species), the usefulness of this method to estimate strength is questionable for field applications. The use of strength-stiffness correlations is a reasonable statistical approach for grading new lumber involving perhaps thousands of pieces of lumber, but for individual pieces of lumber in an existing building, using visual grading rules provides a deterministic approach for providing an estimate of strength based on well-established procedures.

Visual grading is the recommended method for assessing the strength of wood members in situ.

How is It Constructed: Are There Hidden Construction Details?

Digital radioscopy. Digital radioscopy is used to document construction details, help develop a chronology of the construction of a historic structure, and/or identify fastener materials, types, and sizes (Fig. 5). Digital radioscopy can also identify alterations to a historic structure based on construction modifications that are not visible, as well as provide a means to evaluate interior wood condition.

Locating and determining the condition of metal fasteners embedded in wood is possible, in part, due to the different densities of wood and metal. The high contrast of density between the metal and surrounding wood allows for the identification of metal fasteners. Nail types, including hand-forged nails, cut nails, rosehead nails, and common wire nails, are all easily distinguished. Thread patterns for screws, bolts, and reinforcing rods can also be distinguished.

Of equal significance to the historian or architect, and perhaps of greater significance to the structural engineer, is the condition of the fasteners. Corrosion is often hidden within the timber and can lead to catastrophic failure. Digital radioscopy is able not only to detect embedded metal and fasteners but also to show the presence of corrosion of the metal (Fig. 6).

For wood connections, such as mortise-and-tenon joints, the interpretation of the radiographs is more challenging. Differences in the grain orientation of the mortise and tenon within a wood joint can be seen on a radiograph when it is possible to place the source and imager perpendicular to the face of the joint (Fig. 5). A cross-hatched pattern is typically visible where the two pieces of wood overlap as the tenon penetrates the mortise (Fig. 7).

Infrared thermography. Infrared thermography can be used to determine some wood construction details, such as wood framing-member locations, when the wood is covered with plaster (Figs. 8 and 9). Although this application of IRT is fairly recent and shows promise, further investigation is needed to better under-stand the capabilities and limitations when the wood is covered by a variety of materials.

Digital radioscopy is the recommended method for identifying hidden construction details.

Summary of Nondestructive Evaluation of Wood

Nondestructive evaluation methods, when used in conjunction with other assessment methods and experience, can provide valuable information about wood used in structures. The information gathered through NDE methods can yield better decisions concerning appropriate treatments during rehabilitation, restoration, and renovation projects. It should be noted that the data obtained from NDE methods represent a snapshot in time; therefore, any ongoing problems affecting the wood must be addressed prior to conducting preservation or restoration efforts. Use of NDE for wood assessment as summarized below:

- Moisture meters are extremely useful for identifying the current moisture content of wood and can identify problem areas that are not easily seen with the unaided eye.
- Resistance drilling is the recommended method for quantifying internal wood conditions.
- Visual grading is the recommended method for determining the strength of wood members in situ.
- Digital radioscopy is the recommended method for identifying hidden construction details.

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