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Early Barn Repair in Central Vermont

Documentation and Assessment Methods for Timber Structures

OVER the past few decades new documentation and material assessment techniques and technologies have been introduced into the field of historic preservation, including computer-based photorectification, infrared thermography (IRT), stress-wave timing and resistance or microdrilling. While slow to catch on in private practice in large part due to initial cost, technological development has brought costs down to a point where their use appears to be gaining traction. These technologies and techniques offer those who work with historic timber-frame structures improved efficiency, increased retention of historic fabric and more informed assessments.

Photorectification Measured drawings are often among the first requirements when preservation, restoration or rehabilitation work is contemplated for historic timber structures. Such drawings assist in design, structural assessment, damage mapping, creation of construction drawings and academic research. The extent and accuracy of the measured drawings, however, vary widely. Until recently, accurate and highly detailed drawings such as those submitted to the Historic American Building Survey (HABS) were often considered too time consuming and expensive to undertake on a regular basis. With improved photorectification techniques and laser technology, such levels of documentation are becoming more cost efficient and are increasingly undertaken. While not warranted for all projects, this level of accuracy does allow a better understanding of a building's structural components and deficiencies, and also provides a solid base from which to conduct accurate condition assessments.

Photorectification uses optical means to remove both perspective and lens distortion from photographs, enabling measurements to be taken and line drawings to be produced directly from the image. Used for the creation of maps in World War II and employed by HABS for documentation as early as 1989, hardware and software advances have reduced the cost as well as the learning curve associated with this technique. Many older rectification techniques have been replaced by surveyors' total stations and AutoCAD-compatible software.

One recent set of projects conducted by the Department of Historic Preservation at the University of Mary Washington used photorectification to document and draw a series of Virginia barns in Warren, Stafford, Spotsylvania, Caroline and Orange counties. During the fall semesters of 2012 and 2013, students measured and drew a total of seven barns using a reflectorless total station which gathered *XYZ* coordinates for the structures being drawn. This device's laser is powerful enough to reflect directly off structures for distances up to 300m (984 ft.), thereby reducing preparation time and avoiding lift or scaffolding rentals to place reflectors.

The *XYZ* coordinates from the total station were exported directly into AutoCAD in the field using specialized software, allowing for real-time verification of measurements. Measurements for each barn were adequately taken by a team of four during a single day, with some barns requiring less time. The efficiency of such documentation arises from the fact that only key *XYZ* reference points on the building's elevations and projections need be obtained. The reference points are then used later to rectify (optically correct) digital images taken of the structure. This process compares favorably to traditional hand-measuring methods, which can often take weeks to complete depending on the size and complexity of the structure as well as the size and skill of the team assembled.

Once all necessary *XYZ* coordinates and field measurements are obtained, digital images of each elevation are imported into the AutoCAD file containing the field measurements. Using rectification software embedded within AutoCAD, the *XYZ* data points obtained in the field are aligned with their corresponding location on the digital image (Figs. 1 and 2). The digital image is then altered to remove any perspective distortion.

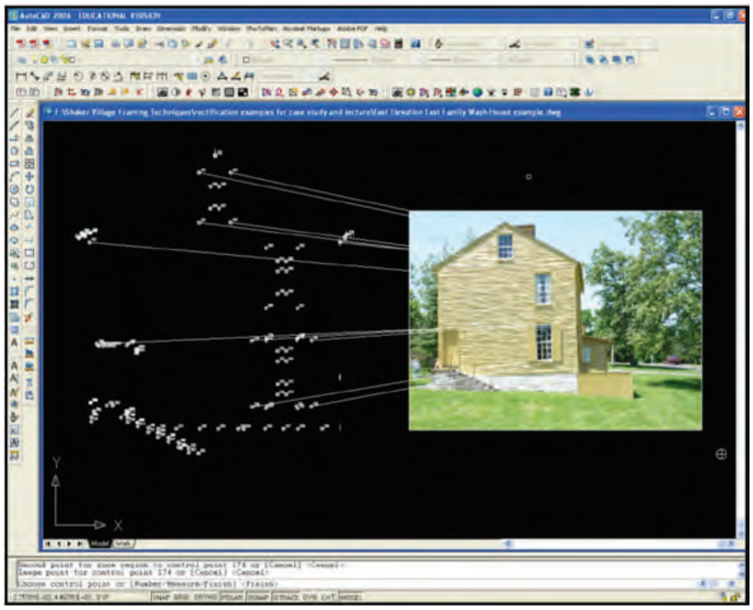
Lens distortion can be removed at the same time by using focal length settings previously calibrated by taking an image of a set of perpendicular grid lines at a known focal length. The digital image of the structure can then be altered to coincide with actual line trajectories.

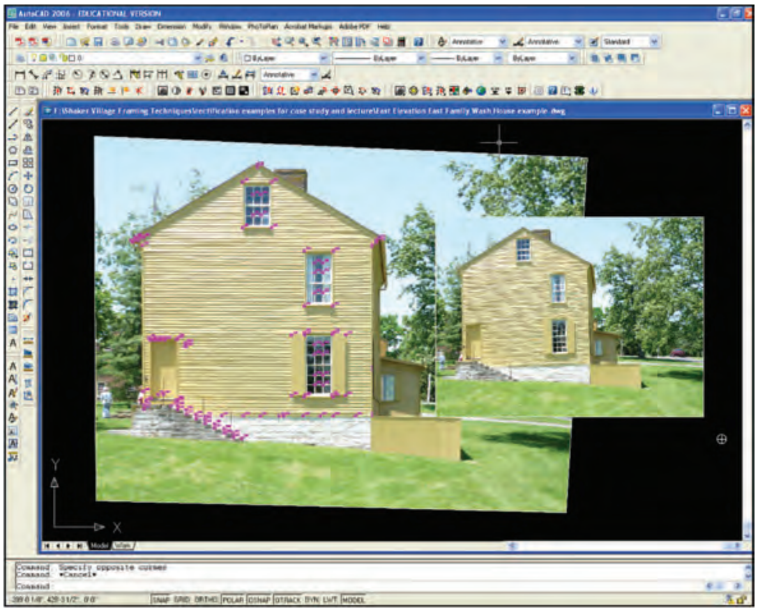
The final rectified image when scaled is often accurate to ¼ in. or better, with greater accuracy possible, and it can be traced easily to produce amazingly detailed line drawings. A rectified and scaled image is also beneficial in making certain building condition observations and assessments, something not always picked up by methods such as laser scanning or even possible to measure with more conventional techniques. Rectified images can be stored for creation of line drawings at a later time without having to worry about whether all measurements were taken in the field, thereby avoiding additional site visits.

Infrared thermography (IRT) Traditionally, the condition assessment of timber-framed structures has relied on a seasoned eye and a sharp tool. Even with the advent of new techniques and technologies, visual inspection and basic tools remain an integral first step to the evaluation of historic structures. Infrared thermography (IRT), a nondestructive assessment tool that measures temperature variations, is, however, quickly becoming a cost-effective complement. (FLIR Systems Inc., a prominent manufacturer of infrared cameras, has even developed an IRT "jacket" for iPhones, to be introduced later in 2014.) IRT can quickly identify areas of potential concern via temperature anomalies; distinctly colder temperature readings are often associated with the presence of moisture. Infrared images taken over time or as a video can also assist greatly in determining the location of moisture infiltration.

The technique can also be used to help identify the placement and relative size of concealed timber members by taking advantage of the different thermal transmission rates inherent within frame wall construction. Used in conjunction with photorectification techniques, such images can accurately convey the size, placement and even deflection associated with timber-framed structures, allowing for more accurate and less destructive evaluations (Figs. 3–5). The technology's short learning curve is another advantage, with only a basic understanding necessary for qualitative assessment and analysis.

Stress-wave timing Whereas observational data and IRT can identify the presence of moisture and symptoms of deterioration within timber-framed structures, further assessment is needed to confirm the extent of deterioration. Damage is often concealed within finished walls, making it difficult to quantify without destructive exploration. Such exploration is often time consuming, messy and expensive, and it can lead to the loss of additional material integrity, making it far from ideal.

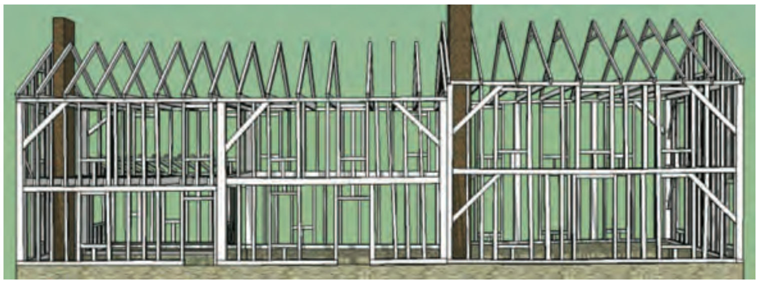




Illustrations Michael Spencer unless otherwise credited

1 Above, screenshot of *XYZ* data points gathered using total station, East Family Wash House at Shaker Village of Pleasant Hill, Kentucky, then referenced with corresponding locations on digital image of building, indicated by lines, imported into AutoCAD.

2 Above right, screenshot of image rectified by Kubit software's PhoToPlan program. Prerectified image (right) adjacent to rectified image (left). Magenta points now align with corresponding locations on the digital image, thereby removing any perspective distortion.



3 At right, top, composite digital image of East Family Wash House rectified and combined using points obtained through a total station and use of both TachyCAD and PhoToPlan software.

4 At right, middle, infrared images taken of same elevation during assessment, likewise combined and rectified, yielding a single, accurate image highlighting concealed framing.

5 At right, bottom, accurate 3-D model (shown 2-D) of framing developed in SketchUp from composite infrared image.

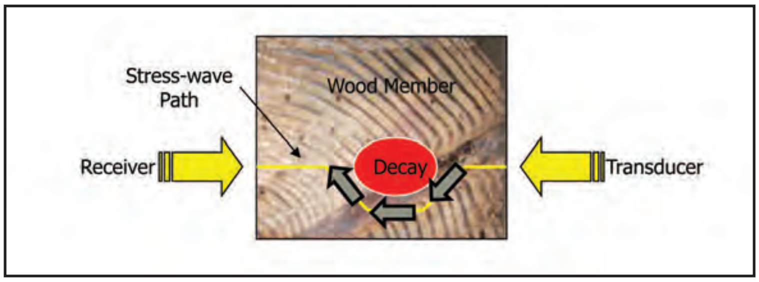
Stress-wave timing, a technique developed by the lumber industry for the evaluation of standing timber, is one minimally destructive technique that can help avoid problematic destructive evaluations. First applied to structures in the 1970s, the technique has seen increasing use within the field of historic preservation. Because of the early groundwork laid by researchers such as Roy Pellerin, Robert J. Ross and others at the USDA Forest Products Laboratory in Madison, Wisconsin, the applied concept of stress-wave timing is relatively easy to understand.

The technique works by connecting a timing device to a transducer and receiver placed directly opposite on parallel surfaces of the wood member under investigation (Fig. 6). Both transducer and receiver are firmly attached to the wood by spikes driven about ¼ in. deep and placed at about 45 degrees to the surface. The observer then strikes the transducer with a small hammer, starting the timer and inducing a stress wave that propagates through the wood member. The receiver senses the leading edge of the wave and stops the timer, providing an accurate measure of the time of flight of the stress wave. The stress wave can move quickly when wood is solid but slows when rotten material is encountered. Time

6 Microsecond timer used for stress-wave timing analysis. Transducer probe on right is struck with hammer, inducing stress wave to receiver probe. Device records wave flight time.

		Stress Wave Transmission Times (perpendicular to grain) @ 1'-0" Elevation on Posts		
	Moisture Content	Radial Direction (µs/ft.)	Tangential (µs/ft.)	Tangential (µs/ft.)
White oak sample	6%	236	240	240
Post 8	10.8%	318	328	256
Post 13	13.3%	234	418	216
Post 15	10.3%	**974**	**632**	**574**
Post 19	13.5%	426	285	219

Table 1 Adjusted stress-wave timing values of control white oak sample and four white oak posts analyzed at Bowman-Hite bank barn, Long Meadow, Warren County, Virginia. Transmission times, initially displayed by device as *µs* readings, have been converted to *µs*/ft. for easy comparison independent of member size. Compare readings for post 15 with control value as well as (sound) post 8. Posts 13 and 19 readings indicated possible deterioration but inspection using resistance drill confirmed them to be sound, with interior checks causing longer transmission times.



7 Stress wave passing along transverse plane of wood sample in mostly radial direction. Rotated 90 degrees clockwise in image and stress wave would be going in mostly tangential direction. Rot or decay slows stress wave, resulting in longer transmission times. Bend in wave represents diffraction in much-simplified form.

discrepancies between sound wood and rotten wood can be as high as 30 to 50 percent, with values over 50 percent often indicating severe decay.[1] Flight time of the stress wave is measured in microseconds (*µs*) and later converted to a flight time per foot.

The anisotropic nature of wood is important to take into consideration when stress-wave timing, as wood-grain direction and growth-ring orientation can affect transmission times. Typically in historic structures the timber's grain orientation allows for stress-wave timing tests to be conducted across the grain in both the radial and tangential directions. Shortest transmission times are found when testing in the radial direction, while the longest times are along the tangential direction at 45 degrees to the growth rings[2] (Figs. 7 and 8). Temperature and moisture content of the wood under investigation can also play a role and require the application of adjustment factors.

Testing using stress-wave timing is a good way to begin mapping deterioration within certain historic timber-framed structures. Barns, for instance, provide good opportunities for stress-wave timing as the process requires that the wood member be exposed on at least two opposite sides.

A test case The Bowman-Hite bank barn, owned by the National Park Service at Long Meadow in Warren County, Virginia, was initially assessed by stress-wave timing performed in 2011–2013 by the University of Mary Washington. While symptoms such as surface rot, termites and water staining could be identified by visual inspection, much else remained hidden below the surface of the barn's structural members. Each post except the four corner posts (precluded from investigation because two opposite sides were not accessible) would be evaluated using the stress-wave timing device. Preparation for field-testing the 16 accessible posts first required the identification of the wood species (white oak), in order to take initial readings off site from sound examples to establish baseline data. Results from this testing in microseconds were converted to *µs*/ft. values and established that readings for sound white oak in the radial direction should be approximately 236 *µs*/ft. and approximately 240 *µs*/ft. in the tangential direction. Variables such as travel distance, temperature and moisture content would be recorded regularly during the investigation. In the Bowman-Hite case, since most symptoms of deterioration such as water staining appeared within 4 ft. above the floor, three readings would be taken at both 1-ft. and 4-ft. heights for each post.

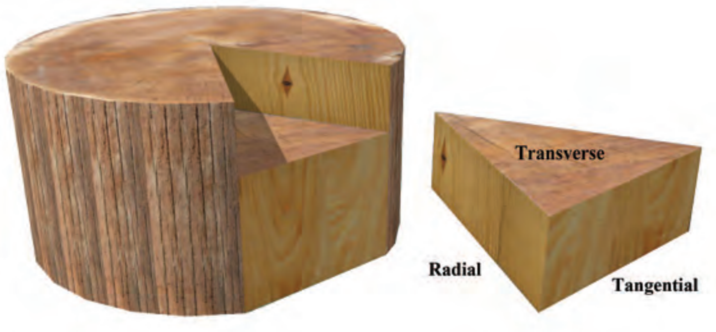
Unadjusted qualitative readings taken within a few hours identified seven posts with possible subsurface deterioration. Upon closer visual inspection, four of the seven posts were judged sound, with observable splits and checks having adversely affected the results of earlier testing. Three of the posts (13, 15 and 19) warranted further investigation as they displayed no such visible defects. After closer study using another minimally invasive technique, one post, 15, was confirmed to have a 57 percent loss of material integrity, supporting the stress-wave results. Posts 13 and 19 were later confirmed to be sound with unseen checks causing the longer stress-wave propagation times (Table 1).

Resistance drilling Resistance drilling is another minimally invasive method used to quantify deterioration in timber-framed structures. More recently developed than stress-wave timing, resistance drills have been used since the 1990s to investigate buildings. Though more time consuming than stress-wave timing, resistance drilling produces easily interpreted quantitative data that can be used to confirm stress-wave timing results. The tool is also effective in evaluating members where stress-wave timing cannot be used, for instance the four corner posts in the Bowman-Hite bank barn. In some instances, the process can be used to evaluate members concealed behind plaster or drywall as long as the location of the member has been determined by methods such as infrared thermography (IRT).

Easy to use, the resistance drill works like a traditional cordless drill with a housing containing the drill bit and a recording device situated on top (Fig. 9). When the trigger is pressed, the 3mm-dia. drill bit is sent through the piece of wood under investigation. As the bit moves through the wood, resistance it encounters is passed along to the calibrated stylus, which inscribes results in a 1:1 ratio on wax paper strips. Recent innovations also allow results to be captured digitally and downloaded to a computer to be analyzed. When sound wood is encountered, high resistance is conveyed on the wax paper strip, whereas when decay is encountered the resistance drops toward zero. Such results allow for the investigator to determine the degree of deterioration as well as its extent within a particular location in a wood member, making it a great tool for confirmation of suspected degradation.

Tests performed at the Bowman-Hite bank barn utilized two drillings for each of the three posts identified by stress-wave timing as having possible deterioration. The drilling locations repeated the stress-wave timing locations. Each drilling measured the resistance along the radial direction of the post. Results of the resistance drilling conducted confirmed that only post 15 was deteriorated (Fig. 10).

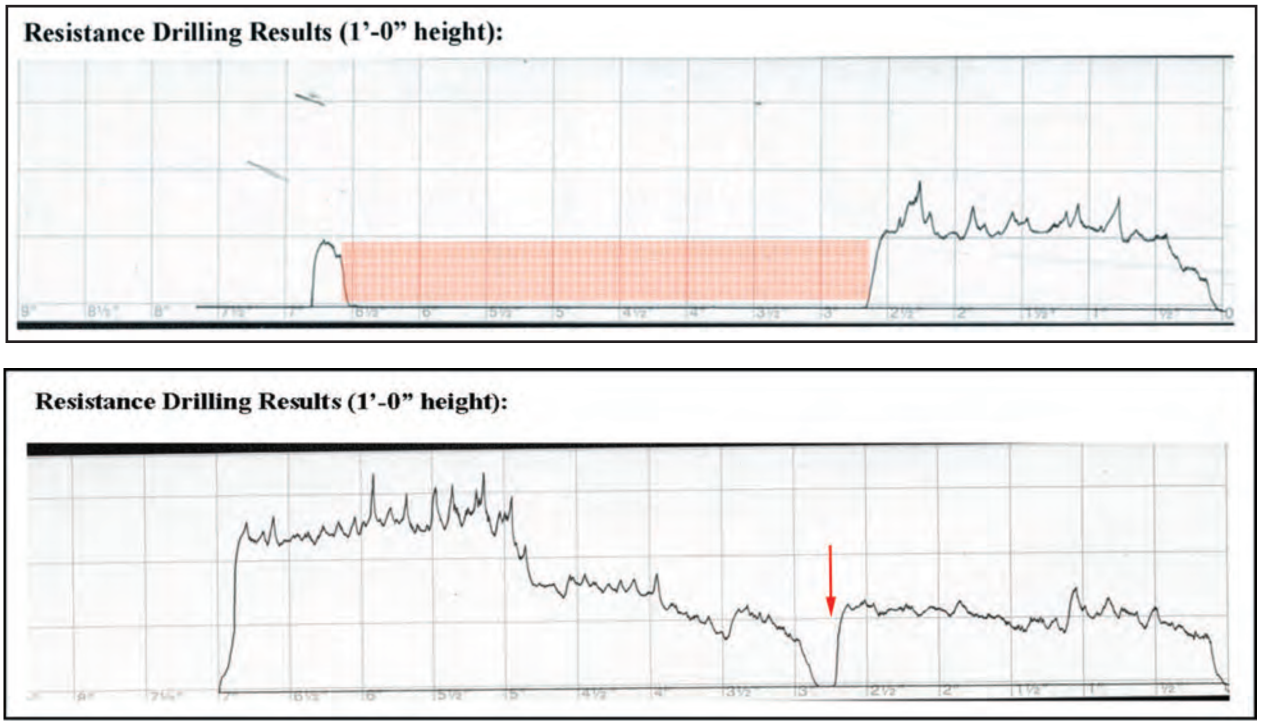
[1]Ross et al., *Wood and Timber Condition Assessment Manual*, p. 17.
[2]Ibid., pp. 15–16.



8 Three planes to specify path of stress-wave through timber.

9 IML Resistograph being used by author to assess a joist at Union Church (ca. 1819) in Falmouth, Virginia.

Logan Metesh



10 Resistance drill readings from Bowman-Hite post 15 (top) and post 19 (above) with each square equal to ½ in. Shaded red area on post 15 readout denotes extent and location of rot starting just ¼ in. under surface of post. Peaks in sound portion of wood (right side) denote denser latewood. Red arrow in post 19 reading indicates high stress-wave results despite majority of its wood being sound.

Results for posts 13 and 19 indicated invisible checks and splits had caused the higher stress-wave timing results.

While cost of equipment is still relatively high (upwards of $20,000 for the specialized hardware and $5000 for the specialized software omitting AutoCAD), and the accuracy generated may be considered overkill by some, their contribution to the preservation of historic timber-framed structures cannot be ignored. The efficient generation of accurate, actionable data—made possible by techniques such as photorectification, infrared thermography, stress-wave timing and resistance drilling—can assist in the retention of historic fabric and thus reduce the cost of replacement materials and labor in preservation, restoration and rehabilitation efforts. While much work is still necessary to fine-tune these techniques for use with historic timber-framed structures and in conjunction with the needs of the artisan, technological advances will continue to decrease cost, making the use of the tools ever more practical. —Michael Spencer

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