Assessment of Deterioration in Timbers with Time and Frequency Domain Analysis Techniques

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Abstract

The research reported here focuses on the use of time and frequency domain analysis techniques for assessing the internal condition of timbers. Several large timbers obtained from a historic public viewing tower were evaluated with acoustic-based nondestructive testing techniques. Waveforms were captured and analyzed using both time and frequency domain techniques. The slope of the phase with respect to frequency shows potential to be a metric that is more sensitive to the presence of internal decay than time of flight.

Keywords: timber, deterioration, acoustic signals, time domain, frequency domain, phase

Introduction

Wood is used extensively for both interior and exterior applications in the construction of a variety of structures. The deterioration of an in-service wood member may result from a variety of causes during the life of a structure. It is important, therefore, to periodically assess the condition of wood used in structures to determine the extent of deterioration so that degraded members may be replaced or repaired to avoid structural failure.

Assessment of the condition of wood in a structure can be conducted for a variety of reasons. Code compliance, historic preservation, or alternative uses of a structure are frequently cited reasons for conducting a condition assessment. A structural condition assessment consists of the following: (1) a systematic collection of data pertaining to the physical and mechanical properties of materials in use; (2) analysis and evaluation of the data collected; and (3) developing recommendations regarding portions of an existing structure that affect its current or proposed use. Such an assessment relies on an in-depth inspection of the wood members in the structure. During these inspections, a wide variety of techniques are used to assess the condition of the wood. Visual, resistance drilling (probing), and stress wave or ultra-sound-based techniques are all used either individually or collectively to inspect in-service wood.

These techniques are discussed in detail in *Wood and Timber Condition Assessment Manual, Second Edition* (White and Ross 2014).

A significant volume of research has been devoted to the use of sound waves for locating areas of deterioration in timber structures, and a practical set of guidelines for their use has been prepared by the USDA Forest Service, Forest Products Laboratory (FPL) (Ross et al. 1999). In summary, the transmission of sound in wood is affected significantly by the presence of deterioration. Consequently, ultrasound and stress-wave-based technologies have been developed and are widely used to inspect wood structures (Allison et al. 2008; Brashaw et al. 2005; Clausen et al. 2001; Emerson et al. 2002; Franca et al. 2015; Ross et al. 1999, 2006) and have been used for the assessment of culturally significant historic ships and artifacts (Ross et al. 1998, Wang et al. 2008, Dundar and Ross 2012).

A simple, inexpensive stress-wave timer is commonly used in inspections. Sensors are placed on opposite sides of a timber. The timber is then struck, generating a stress wave. The time it takes for the wave to travel between the sensors is measured by the timer and recorded. Transmission times for wood from several species are known and are used as a baseline. Transmission times significantly longer than baseline values indicate the presence of deteriorated wood.

Currently used stress-wave timing equipment uses simple electronic circuitry to process the waveforms, with simple time domain evaluation techniques. Information on the use of more advanced signal processing techniques, specifically those that use frequency domain analysis techniques, for evaluating wood exposed to in-service conditions is lacking. One laboratory study using frequency analysis was McGovern et al. (2011) in which the wave dispersion qualities of 1-in. (25-mm) loblolly pine cubes of varying decay were assessed. The objective of the research described here was to examine the use of both time and frequency domain stress wave techniques to evaluate several large timbers that were exposed to a variety of in-service conditions for more than 80 years.

Background on tower

FPL was contacted in late 2015 to assist engineers from the Wisconsin Department of Natural Resources (DNR) in evaluating the condition of timbers in a historic viewing tower located in Wisconsin's Peninsula State Park. Located in Door County, Eagle Tower (Fig. 1a) was a 75-ft (22.9-m) tall observation tower that sat atop a 180-ft (54.9-m) limestone bluff. From its top platform, one could see Peninsula State Park, surrounding islands in Lake Michigan, and Michigan's Upper Peninsula.

The tower structure was built in 1932. It replaced the original tower built on Eagle Bluff, which was constructed in 1914. This iconic tower stood as one of the most unique landmarks in Wisconsin. Peninsula State Park is visited by more than a million people every year.

The DNR periodically examined the structure using visual inspection techniques. Engineers looked for signs of distress, such as failed members and those showing evidence of attack by decay fungi or carpenter ants or nesting activity by local bird populations. After an extensive inspection, the DNR concluded that the main structural members were severely deteriorated and, consequently, closed the structure. The tower was dismantled September 19, 2016.

History of tower

The original tower on Eagle Bluff was constructed in 1914 at a cost of $1,061.92. The tower was 76 ft (23.2 m) tall, and it stood 225 ft (68.9 m) above Lake Michigan. It was constructed during the summer of 1914 to serve as a fire tower with the expectation it would become a tourist attraction. The ledger of Peninsula's first manager, A.E. Doolittle, lists payment to men for fire watch duty.

A construction crew cut logs and boards from timber in the park using tools and saws available at the time. To erect the tower, they first raised the center pole. Then they used the center pole to raise other support poles. Three trees composed each corner pole, with platforms between the separate trees. Horizontal landing support beams were added, followed by planks for decking at the three levels.

A telephone line connected the tower to the manager's residence and the local exchange so that fires could be quickly reported. Historical records indicate there was a large buildup of fire-prone material in the park. Peninsula's last significant fire was in 1921.

The original tower was dismantled. Eagle Tower was built in 1932. Foreman Sam Erickson and crew used horses, tractors, trucks, and other machinery. They wrapped cable around nearby trees to raise poles. A stump wrapped with rusty cable can still be seen a short distance from the tower, along the road leading towards Eagle Terrace (GPS coordinates N45.16275 W 87.19730). Untreated western redcedar poles were shipped from Washington State.

Eagle Tower was 75 ft (22.9 m) tall and stood 250 ft (76.2 m) above water level. Safety improvements were made in 1972, including slanting the top deck railings. Hardware and decking were replaced and stained in subsequent years.

a. **b.**

Figure 1. Eagle Tower prior to and after disassembly; (a) Eagle Tower just prior to disassembly; (b) sections cut from the four vertical supports of Eagle Tower.

Materials and methods

This study focused on six sections taken from the four western redcedar support legs of the tower as shown in Figure 1b. Timber inspection was performed on February 6th, 2017, at Peninsula State Park in Door County Wisconsin. The sections measured between 3 (0.9) and 6 ft (0.9 and 1.8 m) in length. The diameters of the sections measured between 12.5 and 16.5 in. (31.8 and 41.9 cm). The poles were given the identifiers B1, B2, B3, G1, G2, and G3. Two nondestructive testing tools were used in the inspections: a Fakopp Microsecond Timer from Fakopp Enterprise Bt. (Agfalva, Hungary) and Tree Check Sonic Wave Tree Decay Detector from Allison Tree, LLC (Verona, Wisconsin). Measurements were taken perpendicular to grain orientation, 6 in. (15.2 cm) from the end of the pole and then at 1-ft (30.5-cm) increments starting 1 ft (30.5 cm) from the end of the pole.

The Fakopp Microsecond Timer records the time of flight (ToF) of mechanical waves between two probes that are driven into the surface of the poles. The probes were installed on opposite sides of the pole at the locations described, and the ToF values of the waves were recorded and are shown in Tables 1 and 2. Tables with SI units are in the Appendix.

The Tree Check Sonic Wave Tree Decay Detector records the ToF between two accelerometers that are installed on awls that are driven into the surface of the poles. In addition, the waveform signal is recorded. The signal is recorded as 1,280 data points at a sampling rate of 20 kHz. Recording begins after a threshold voltage is surpassed; therefore, the recorded signal does not contain lead zeros. The probes were installed on opposite sides of the pole at the locations described above and the ToF values of the waves were recorded as shown in Table 1 for B group and Table 2 for G group. The waveforms were recorded for time and frequency analysis. A representative recorded waveform, the magnitude plot, and the phase plot are shown in Figure 2.

The recorded points were also given a designation based on a combination of the visible characteristics of the poles and ToF measurements. There were six designations: rot, transition, end of log, above hole, below hole, and good. A designation of rot indicated there was evidence of decay. Evidence of decay included visible indications of decay or a ToF above 400 µs/ft (1,300 µs/m). ToF measurements above 400 µs/ft (1,300 µs/m) are indicative of internal decay. A designation of transition was given to points between areas with the designation of rot and other areas. A test location adjacent to the end of the poles was given the designation of end of log. Previous experience of the authors (Senalik et al. 2010) with frequency analysis of signals collected near the end of beams and poles led to the creation of the end of log group because proximity to the end can create unique signal content unseen elsewhere in the log. At some locations, holes existed that had been part of the timber's use within the tower. For a pole section with a drilled hole, the original vertical orientation of the pole section was determined. The test location that was located above the hole was given the designation above hole, and the two test locations below the hole were given the designation below hole. In the absence of any visible signs of rot, decay indications from ToF, or drilled holes, a test location was designated as good. There was a caveat to the designation process. A rot designation preempted all others. For example, a test location at the end of a log with visible signs of rot would be designated rot rather than end of log.

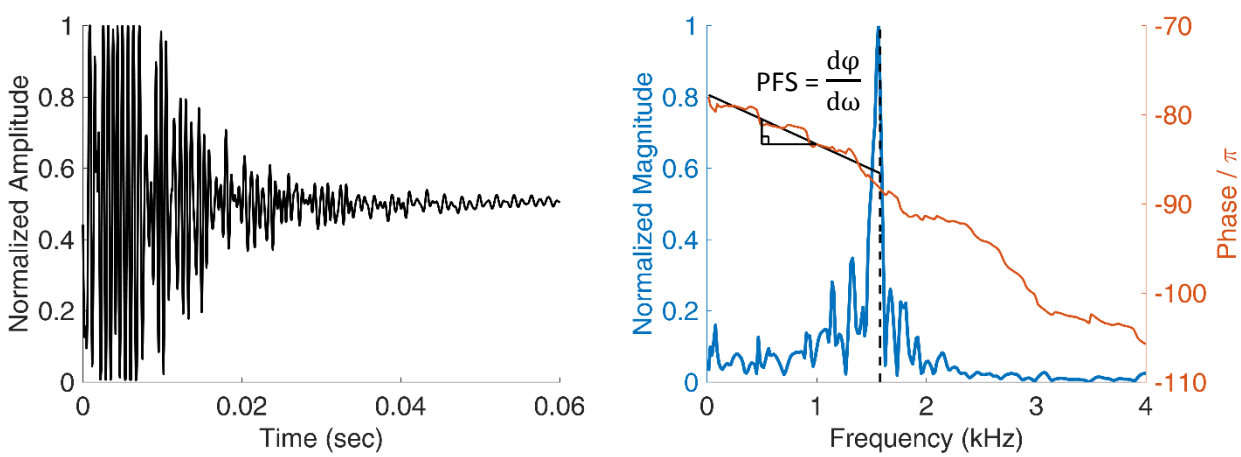
The frequency analysis occurred in two parts: magnitude and phase. The two plots are shown in Figure 2b. In a nondispersive material, all frequency components of a signal travel at the same rate; therefore, the signal received is similar in frequency content to the source signal. In a dispersive material, such as wood, the frequency content alters as it passes through the material. In a dispersive material, waves can have

frequency-dependent velocities; however, the bulk of the energy signal travels at a speed known as the group velocity. Group velocity for dispersive materials is given in the following equation (Sachse 1978):

$$V_g(\omega) = \frac{d_o}{\left(\frac{d\varphi}{d\omega} - t_o\right)}$$

where group velocity, V_g, is dependent on three unknowns: the distance between the source and receiver, d_o, the amount of time the wave is in the material (which is the ToF), t_o, and the slope of the line relating the frequency to phase, $d\varphi/d\omega$. For brevity, this term will be referred to in this report as the phase–frequency slope (PFS).

The ToF has been used as a metric for gauging internal decay of in-service wood for several decades, but PFS has not been examined for that purpose. Because wood becomes more dispersive as decay advances and PFS relies on more signal information than ToF, it was believed that PFS may provide a metric more sensitive to the presence of decay than ToF. To determine PFS, the upper and lower frequencies must be defined. The lower bound frequency was taken to be 1 Hz. The upper bound frequency was chosen such that 80% of the signal energy was below the upper bound frequency. The limit of 80% was chosen because it encompassed the majority of the signal energy, was normally within a relatively narrow range of frequencies between 1,500 and 2,000 Hz, and the range of frequencies that made up the final 20% of the signal energy varied widely between measurement locations and had a disproportionally large influence on the final slope values.



a. **b.**

Figure 2. Representative (a) time domain and (b) frequency domain plots. Thick blue line is the normalized magnitude. The thin orange line is phase angle. The vertical dashed line is at the frequency that 80% of the signal energy is below. The solid black line shows the phase–frequency slope (PFS).

The expectation of the results was that the rot group would have the highest PFS and ToF and the transition group would have the second highest PFS and ToF. After those groups, expectations were not clear. Experience indicated that the group with the next highest amount of decay was likely to be the below hole group, or the area immediately below drilled bolt holes. Water intruding into the pole around the bolt hole would probably pool in the hole and create an environment conducive for decay. The next group would probably be the above hole group but only if enough water entered the drilled hole to wet

both above and below the bolt. The good group would probably have the lowest PFS and ToF. No expectation could confidently be made regarding the end of log group. Because the pole sections were cut from larger poles, the top and bottom cross-sectional surfaces were not exposed to the elements during the 80-year service. The pole sections were placed on their sides so water was not allowed to pool on the newly cut top cross sections or come in contact with the newly cut bottom cross sections.

Results

The data collected in Tables 1 and 2 are shown in Figure 3. Individual data points are shown as small symbols. The large symbol is the average for the group. As expected, the rot group had both the highest average ToF and PFS. The second highest average PFS was the below hole B group; however, the average ToF was comparable with the good G group. The transition group had the third highest average PFS and the second highest average ToF. The end of log, above hole, and good groups had closely overlapping ToF and PFS values.

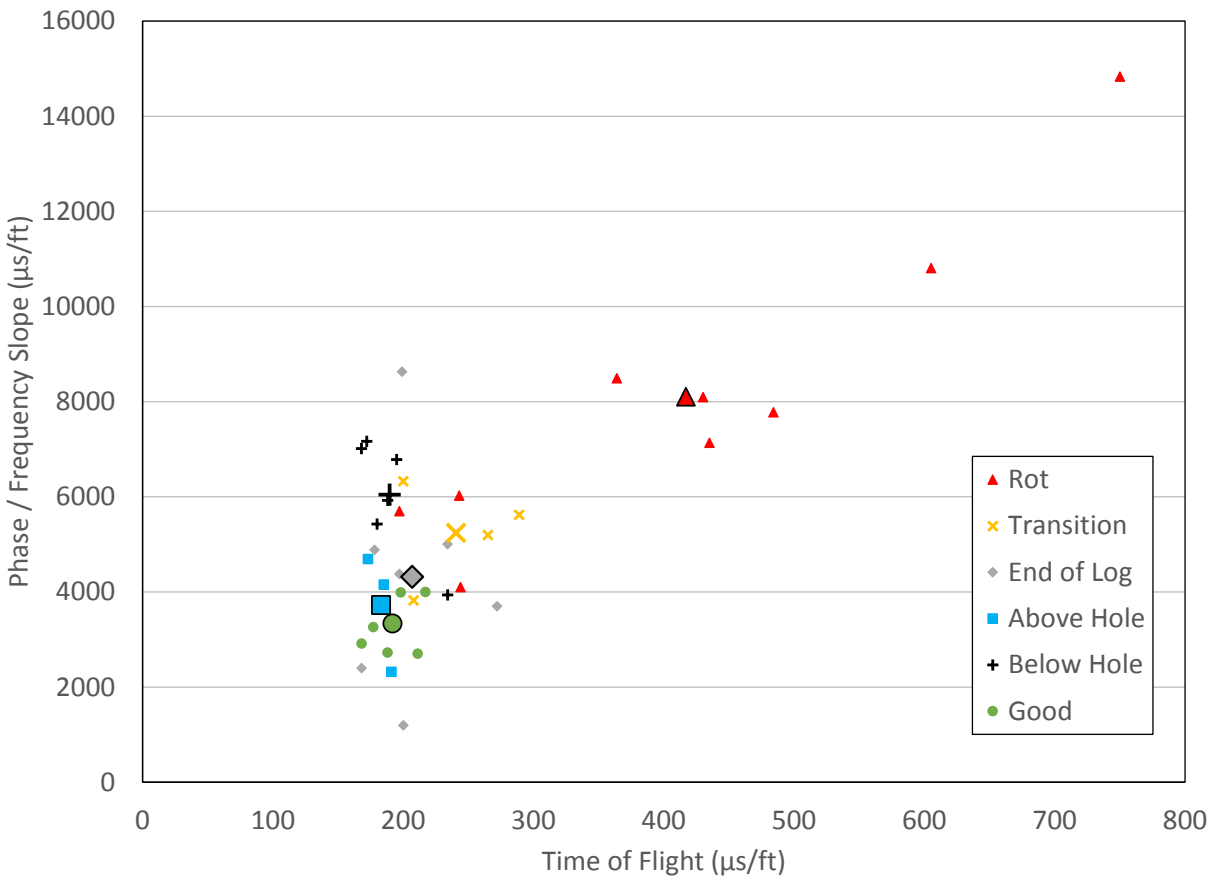


Figure 3. Time of flight versus phase–frequency slope. The small symbols represent the data points within each designation group. The large symbols represent the average value for the group.

Table 1. Time of flight (ToF), phase–frequency slope (PFS), and designation groups for poles B1, B2, and B3

Loc. (ft)	Fakopp ToF (μs/ft)			Tree Check ToF (μs/ft)			Tree Check PFS (μs/ft)			Designation group[a]		
	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3
0.5	244	372	4,101	484	778	7,775	200	325	1,198	R	R	E
1	197	296	5,695	364	428	8,493	188	320	2,728	R	R	G
2	208	317	3,822	289	500	5,623	184	297	3,748	T	T	G
3	217	316	3,999	272	395	3,702	211	340	2,703	G	E	G
3.5	—	—	—	—	—	—	265	392	5,199	—	—	T
4	200	290	6,325	—	—	—	430	538	8,095	T	—	R
4.5	—	—	—	—	—	—	605	844	10,805	—	—	R
5	435	535	7,137	—	—	—	750	929	14,835	R	—	R

[a]Designation groups: R = rot, T = transition, E = end of log, A = above hole, B = below hole, G = good.

Table 2. Time of flight (ToF), phase–frequency slope (PFS), and designation groups for poles G1, G2, and G3

Loc. (ft)	Fakopp ToF (μs/ft)			Tree Check ToF (μs/ft)			Tree Check PFS (μs/ft)			Designation group[a]		
	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3
0.5	168	265	2,401	197	304	4,379	178	290	4,886	E	E	E
1	168	276	2,918	191	306	2,322	177	283	3,260	G	A	G
2	195	302	6,784	188	293	5,927	168	271	7,013	B	B	B
3	180	287	5,429	234	345	3,940	172	284	7,168	B	B	B
4	—	—	—	—	—	—	—	—	—	A	G	A
5	185	282	4,159	198	296	3,990	173	281	4,691	R	E	E

[a]Designation groups: R = rot, T = transition, E = end of log, A = above hole, B = below hole, G = good.

Concluding comments

Six pole sections from the disassembled Eagle Tower in Peninsula State Park in Door County, Wisconsin, were studied using advanced frequency analysis techniques that examined the magnitude and phase within the frequency domain. During inspection, data were separated based on a combination of visible characteristics and ToF values at the measurement location. The six groups were rot, transition, end of log, above hole, below hole, and good. Expected results were obtained for each group except for the below hole group. Although it was considered likely that rot was present below the drilled holes because of the intrusion of water during the service life, it is unknown as to why the ToF measurement would similar to the good group. A more in-depth inspection has been deemed necessary to evaluate the use of PFS as a nondestructive inspection method. Permission has been obtained to retrieve the six pole sections inspected in this project and transport them to FPL in Madison, Wisconsin, for further study, including the use of microresistance drilling. If the test locations of the below hole group are shown to possess decay, then the PFS method appears to be more sensitive to the presence of internal decay than the currently accepted method of using ToF.

Appendix

Figure 3 and Tables 1 and 2 are reproduced here in SI units as Figure A1 and Tables A1 and A2, respectively. Two data points are not shown on Figure A1 that are shown in Figure 3; the two data points that have the highest ToF and PFS values were excluded in Figure A1. The two excluded points were clearly indicated as rot by ToF, PFS, and visual inspection. As such, they were omitted in favor of producing a figure in which the other data points could be more clearly viewed.

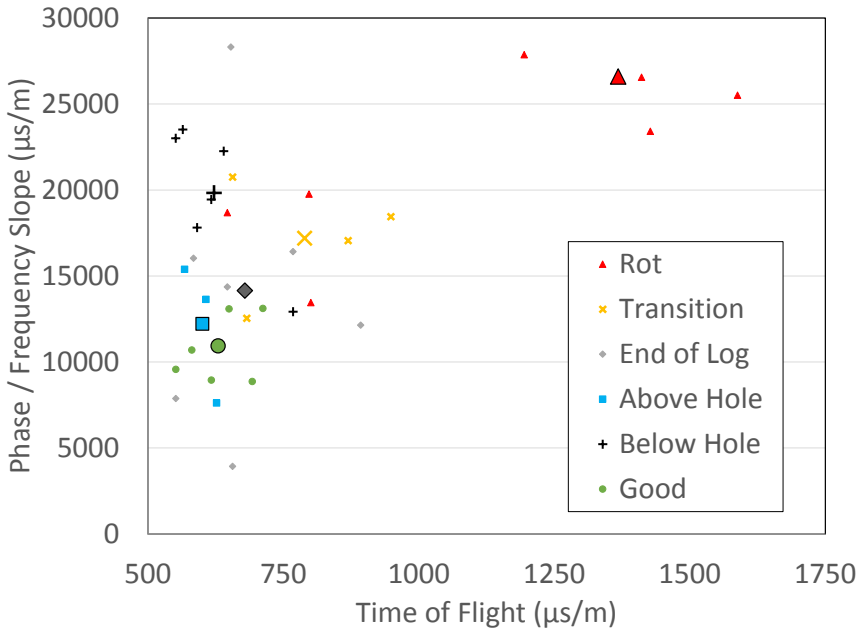


Figure A1. Time of flight versus phase–frequency slope. The small symbols represent the data points within each designation group. The large symbols represent the average value for the group.

Table A1. Time of flight (ToF), phase–frequency slope (PFS), and designation groups for poles B1, B2, and B3

Loc. (m)	Fakopp ToF (µs/m)			Tree Check ToF (µs/m)			Tree Check PFS (µs/m)			Designation group[a]		
	B1	B2	B3	B1	B2	B3	B1	B2	B3	B1	B2	B3
0.15	801	1,220	13,455	1,588	2,552	25,509	656	1,066	3,930	R	R	E
0.30	646	971	18,684	1,194	1,404	27,864	617	1,050	8,950	R	R	G
0.61	682	1,040	12,539	948	1,640	18,448	604	974	12,297	T	T	G
0.91	712	1,037	13,120	892	1,296	12,146	692	1,115	8,868	G	E	G
1.07	—	—	—	—	—	—	869	1,286	17,057	—	—	T
1.22	656	951	20,751	—	—	—	1,411	1,765	26,558	T	—	R
1.37	—	—	—	—	—	—	1,985	2,769	35,449	—	—	R
1.52	1,427	1,755	23,415	—	—	—	2,461	3,048	48,671	R	—	R

[a]Designation groups: R = rot, T = transition, E = end of log, A = above hole, B = below hole, G = good.

Table A2. Time of flight (ToF), phase–frequency slope (PFS), and designation groups for Poles G1, G2, and G3

Loc. (ft)	Fakopp ToF (μs/m)			Tree Check ToF (μs/m)			Tree Check PFS (μs/m)			Designation group[a]		
	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3
0.15	551	869	7,877	646	997	14,367	584	951	16,030	E	E	E
0.30	551	906	9,573	627	1,004	7,618	581	928	10,696	G	A	G
0.61	640	991	22,257	617	961	19,446	551	889	23,009	B	B	B
0.91	591	942	17,812	768	1,132	12,927	564	932	23,517	B	B	B
1.22	607	925	13,645	650	971	13,091	568	922	15,390	A	G	A
1.52	797	1,188	19,767	768	1,115	16,417	653	889	28,314	R	E	E

[a]Designation groups: R = rot, T = transition, E = end of log, A = above hole, B = below hole, G = good.

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Abstract

The 20h International Nondestructive Testing and Evaluation of Wood Symposium was hosted by the USDA Forest Service Forest Products Laboratory in Madison, Wisconsin, USA, on September 12–15, 2017. This Symposium was a forum for those involved in nondestructive testing and evaluation (NDT/NDE) of wood and brought together many NDT/NDE users, suppliers, international researchers, representatives from various government agencies, and other groups to share research results, products, and technology for evaluating a wide range of wood products, including standing trees, logs, lumber, and wood structures. Networking among participants encouraged international collaborative efforts and fostered the implementation of NDT/NDE technologies around the world. The technical content of the 20th Symposium is captured in these proceedings.

Keywords: International Nondestructive Testing and Evaluation of Wood Symposium, nondestructive testing, nondestructive evaluation, wood, wood products

September 2017

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