Assessing Ability of Ground-Penetrating Radar to Detect Internal Moisture and Fungal Decay in Douglas-Fir Beams

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Abstract

This report describes the testing plan and preliminary results in an ongoing project to assess the efficacy of using ground-penetrating radar (GPR) to detect internal moisture and fungal decay within Douglas-fir beams. Initially, the test beams were assessed using a variety of physical, mechanical, and nondestructive evaluation (NDE) test methods including micro-resistance drilling, Janka hardness, stress wave transmission, and GPR. After initial baseline assessment, test beams were inoculated with brown-rot fungus, *Fomitopsis pinicola*, and exposed to just above-ground conditions 22 miles (35.4 km) north of Gulfport, Mississippi, USA. Test beam specimens were inspected in the field at 6, 12, and 17 months of exposure using GPR, moisture measurements, and stress wave transmission. Select specimens were removed from the field during each site visit and returned to USDA Forest Service, Forest Products Laboratory, where the NDE tests were repeated. In addition, computer tomography (CT) scans were taken of a subset of the returned specimens. Finally, destructive Janka hardness testing provided insight into mechanical property change during exposure. The GPR scans were compared with the NDE, CT scans, and hardness results. It was found that the GPR scan was sensitive to the presence of internal moisture, which will be useful in locating areas of potential decay.

Keywords: ground-penetrating radar, fungus, brown-rot, Douglas-fir, sawn timber, glulam, weather exposure

Introduction

The 2014 Federal Highway Administration (FHWA) National Bridge Inventory indicates there are more than 40,000 wood or timber roadway bridges in the United States (USDOT 2014). To ensure continued safe usage of these bridges, regular maintenance and inspection is necessary. There are many well-known and reliable wood inspection techniques such as stress wave measurement, transverse vibration, and resistance drilling to name a few (Ross 2015). Many of the techniques require point by point inspection, which makes a comprehensive evaluation of the entire bridge structure a time-consuming undertaking as well as a safety risk because of limited access and passing traffic. Several techniques require specialized equipment that is too bulky to be moved into the field. As processing speed and computing power increases, so does the availability of advanced, field-ready tools that can process large amounts of data in sufficiently short times, which makes their use during routine inspections feasible.

Ground-penetrating radar (GPR) is a tool used for a variety of inspection purposes including concrete and masonry structures, paved and unpaved roads, ground imaging, archeological sites, and ice-covered areas to name a few examples. Currently available commercial GPR units are simple to use and provide near instantaneous and easily interpreted inspection data. Until recently, the use of GPR on wood and wood structures was a little-explored area.

Muller (2003) found that GPR was a reliable method for locating internal defects such as piping and rot in timber girders as large as 16.7 in. (425 mm) in diameter. The GPR results in that study closely correlated to the defects located using test microdrilling and post inspection cutting of the examined wood girders.

Rodriguez-Abad et al. (2011) examined 7.9- by 3-in. (200- by 75-mm) timbers of maritime pine (*Pinus pinaster* Ait.) and showed that signal amplitude, propagation velocity, and spectral composition varied significantly between propagation directions parallel to grain as opposed to those perpendicular to grain. No significant differences were noticed between propagation directions that were parallel to the radial axis and those parallel to the tangential axis. Martínez-Sala et al. (2013) presented similar findings and expanded the study to examine the variation in parameters previously listed with respect to 12 species commonly used for commercialized sawn timber in Spain. It was found that, for all examined species, longitudinal versus transverse dielectric wood behavior was clearly identifiable.

Riggio et al. (2014) gives brief overviews of several nondestructive wood inspection techniques including GPR. Advantages and disadvantages of GPR are listed, and a frequency range of 1.5 to 2.5 GHz is recommended for wood inspection. Maï et al. (2014) showed that dielectric permittivity was affected by moisture content of the wood, fiber direction, and wood density. A subsequent study found that GPR provided the possibility of estimating wood dielectric permittivity. As a result, GPR was assessed as a promising technique for moisture evaluation and early stage diagnosis of timber structures (Maï et al. 2015).

Hans et al. (2015a, 2015b) explored the use of GPR to determine the moisture content (MC) of frozen and thawed logs. In that study, it was found that a partial least square (PLS) regression between the signal amplitude and MC led to robust models that had greater accuracy when attempting to estimate MC from the GPR signal. A related study examined the use of propagation velocity (PV) to measure MC. Although the PLS method yielded a more accurate prediction of MC, the PV method covered a larger wood volume than the PLS method and was more easily transferable among GPR equipment with the same center frequency (Hans et al. 2015c).

A major concern with any wood inspection tool is its ability to detect internal decay. Internal decay is often found in areas of elevated internal moisture. In this project, the efficacy of using GPR to detect internal moisture and fungal decay within Douglas-fir beams is examined. This report is an update of Senalik et al. (2016) in which the research project was described but included no data from the test specimens.

Research study

The goal of these research efforts is to find fast, reliable nondestructive inspection technique(s) for covered timber bridges. Ideally, the technique(s) will require access to only one side of the inspected object, detect moisture pockets, detect voids, require minimal setup time, collect data quickly, provide instantaneous results in a manner easily interpreted at the inspection site, and penetrate through asphalt to underlying wood. Several techniques were initially evaluated by several industry representatives in a laboratory setting. All industry representatives tested the same specimens in a blind study. Techniques used were GPR, microwave, impact echo, ultrasound, and shear wave tomography. GPR was the inspection technique that best satisfied the criteria and therefore was selected for further in-depth investigation. The entire selection process is described in Wacker et al. (2016).

Objectives and field test setup

The objective of the research study was to assess the ability of GPR to detect internal decay and moisture in wood beams with cross-sectional sizes representative of those used in covered timber bridges. Douglas-fir specimens of varying degree of internal decay activity were created through fungal inoculation and are undergoing field exposure across a range of time from 6 to 48 months. At regular 6-month intervals throughout the decaying process, the specimens were examined using a variety of nondestructive techniques including GPR. At the conclusion of the study, bench marks for measuring efficacy of GPR for detecting internal pockets of fungal decay will be created through visual assessments, NDE evaluation, CT imaging, and hardness profile mapping of cut-away cross sections of the specimen interiors.

Material and methods

Douglas-fir specimens with internal decay were created from sawn timber and glulam beams with cross-sectional sizes representative of those used in covered timber bridges. Figure 1 shows the total number of specimens as well as the months of exposure. Four specimen cross-sectional sizes were selected for the study: 5.125- by 9-in. (130- by 229-mm) glulams, 5.125- by 7.5-in. (130- by 191-mm) glulams, 3.5- by 5.5-in. (89- by 140-mm) sawn timbers, and 3.5- by 7.25-in. (89- by 184-mm) sawn timbers. Six 11-ft (3.4-m) or longer beams of each cross-sectional size were selected and cut into four 32-in. (0.8-m) specimens for a total of 96 specimens (4 cross sections × 6 beams per cross section × 4 specimens per beam). There were three duplicates of each cross section for each time interval of testing. The cutting of each beam yielded remnants, which were used for initial cross-sectional hardness testing.

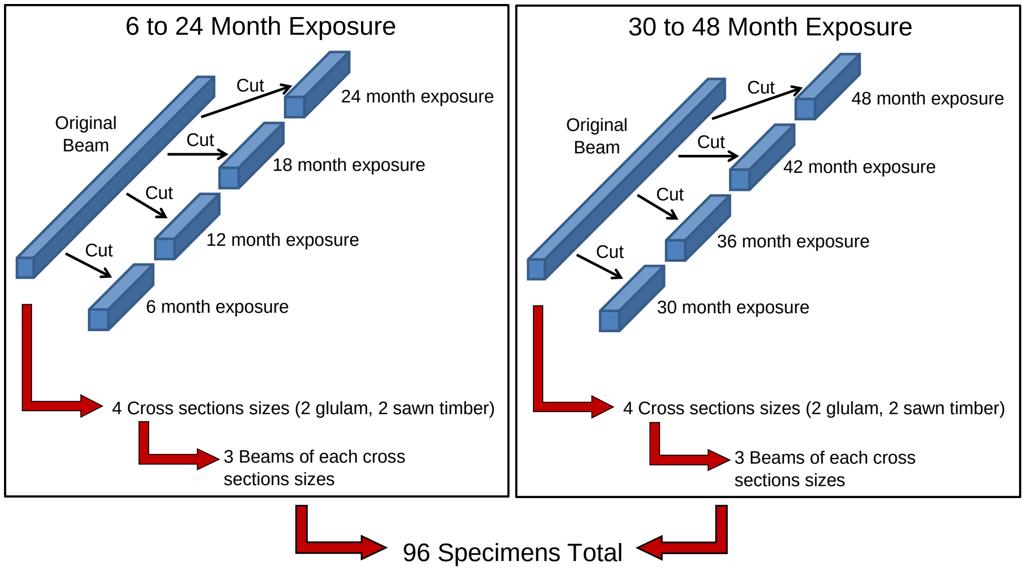
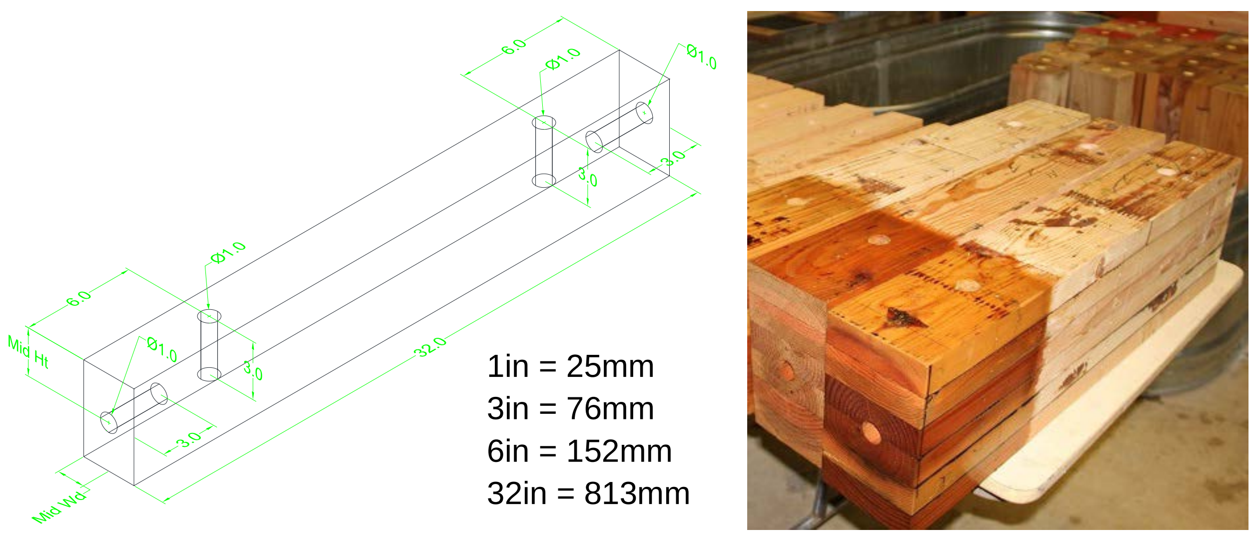


Figure 1. Number of specimens and months of exposure (12 specimens for each exposure subgroup).

Partial-depth circular holes were drilled into each specimen to serve as fungal growth cavities as shown in Figure 2a. The holes were nominally 1 in. (25 mm) diameter and 3 in. (76 mm) deep. The holes were located on the ends and top of each specimen. The hole on the end was centered at the midheight and midwidth of the specimen cross section and drilled parallel to the longitudinal axis. The holes on top were centered midwidth. Figure 2b shows holes drilled into six-laminate glulam specimens.



a. **b.**

Figure 2. Fungal cavity holes in specimens: (a) locations of the drilled holes (units shown are inches); (b) holes drilled in a six-laminate glulam.

Initial baseline data were collected on the specimens. The baseline data provided the control against which post-exposure data were compared. Data collected included mass, MC, stress wave transmission time, microresistance drilling, GPR scanning, and Janka hardness. MC was collected using a Delmhorst R-2000 electrical resistance moisture meter with two 3-in. (76-mm) insulated probes from Delmhorst

Instrument Company (Towaco, New Jersey, USA). Stress wave time was measured using the Fakopp Microsecond Timber from Fakopp Enterprises (Agfalva, Hungary). Microresistance drilling was performed on selected specimens using the PD 400 Resistograph from IML Wood Testing Systems (Moultonborough, New Hampshire, USA). Several GPR scans were taken of each specimen using a SIR 4000 GPR data acquisition system (Geophysical Survey Systems, Inc., Salem, New Hampshire, USA) with a 2.0-GHz palm antenna. The center frequency of the palm antenna was 2.0 GHz, but the frequencies emitted and received ranged between 500 MHz and 4 GHz. During post-collection data analysis, narrower frequency ranges were explored to determine what, if any, frequency range was particularly sensitive to the presence of brown-rot. The data acquisition system and antenna were purchased from Geophysical Survey Systems, Inc. A 2-in.- (51-mm) thick piece was cut from each beam remnant, and Janka hardness tests were performed using an Instron 5587 testing machine (Instron, Norwood, Massachusetts, USA). Measurements were taken across the cross section (parallel to grain) as shown in Figure 3; however, additional measurements were taken on the sides of each specimen (perpendicular to grain). It was assumed that beams were sufficiently consistent that the hardness profile obtained from the Janka tests of the remnant was representative of the hardness profiles of all specimens cut from that beam.

a.

b.

Figure 3. Janka hardness testing: (a) sawn timber remnant undergoing Janka hardness test; (b) hardness test impressions across glulam remnant cross section.

After initial data collection, one end of each specimen was placed in a water tank for 14 days. The water was sufficiently deep to cover the holes drilled near the ends of the specimens by no less than 2 in. (51 mm). At the end of the soaking period, the specimens were removed and wet sawdust previously inoculated with *Fomitopsis pinicola*, a brown-rot fungus capable of attacking Douglas-fir, was placed in each hole that had been below water level (Fig. 4). The soaking supplied water to the wood that the brown-rot would have used to establish itself and promote fungal growth. The holes were then sealed with cork stoppers. The specimens were then placed back into the soaking tanks with the opposite end below water level. After 14 days, the process was repeated with the holes on the opposite end of the specimen.

The inoculated specimens were shipped to the USDA Forest Service, Harrison Experimental Forest (HEF), approximately 22 miles (35.4 km) north of Gulfport, Mississippi, USA. The site was chosen as an ideal location to promote fungal growth because of its warm climate, high yearly rainfall, and high average relative humidity. Local temperature and precipitation data were recorded by a weather station at HEF. A field site was cleared down to soil level. Surrounding trees provided shade during most of the day other than midday when the sun was directly overhead; otherwise, sun–shade was not a controlled variable. Two layers of ultraviolet resistant, 8 mil black landscaping plastic were placed on the ground to prevent plant growth under the specimens. The specimens were raised off the ground approximately 7 in. (178 mm) using treated wood blocks to prevent external decay caused by ground contact. Once in place, each inoculated specimen was scanned with the GPR unit to provide a baseline against which post-exposure scans were compared. Black plastic covers were then placed over each specimen. The covers were approximately 18 in. (457 mm) long to protect the area of the beam between the two inoculated holes. The covers minimized rain contact with the middle portion of the beam, lowering the possibility that surface decay developed in that region and increasing the likelihood that when decay occurred within the center region, it grew internally from the fungal cavities rather than from the external surface. Small holes approximately 0.25 in. (6 mm) wide were drilled through each cork to allow moisture to enter the fungal cavities. The specimens were installed in the field on January 12th, 2016. Specimen placement as well as specimen scanning using the GPR tool is shown in Figure 5.

Figure 4. Inoculating specimens with *Fomitopsis pinicola*, brown-rot.

Figure 5. Specimens as positioned on site, and GPR scanning of specimens.

In 6-month intervals, USDA Forest Service, Forest Products Laboratory (FPL), researchers have returned to the test site for data collection. The return dates were July 2016 (6 months), January 2017 (12 months), and June 2017 (17 months). A limited pilot study conducted by FPL using Douglas-fir beams inoculated in a manner similar to those in this report showed that noticeable fungal growth could begin within 6 months in favorable conditions. Data collection included GPR scanning, MC readings, stress wave transmission time, and a visual assessment of the specimen condition. In addition, 12 predetermined specimens (three of each cross section) were retrieved during each site visit and returned to FPL. The retrieved specimens were reconditioned to 12% MC and then cut into 2-in. (51-mm) pieces along the length and perpendicular to the longitudinal axis. Janka hardness tests were performed across the cross section to obtain a hardness profile, which was compared with the original hardness profile for each beam as an indicator of the extent of fungal decay within each specimen (Green et al. 2006).

The process will be repeated until the final 12 specimens are retrieved after 48 months of exposure. The interval testing and the range of exposure times should increase the likelihood that data will be collected on specimens with internal decay ranging in severity from incipient, in which the wood is not perceptibly impaired, to advanced, in which the destruction is readily recognized (Ross 2010). At the conclusion of those 48 months, it is expected that the body of collected data will include GPR scans, NDE data, and hardness profiles for each of the four cross-section types from a period of 0 to 48 months in 6-month increments.

Results

To date, there were four site visits: at 0 months (when the specimens were initially placed), 6 months, 12 months, and 17 months. MC measurements taken on a random selection of the specimens at the site during each visit showed that MC was relatively consistent between specimens. Table 1 shows the average percentage MC during initial installation and during each subsequent site visit.

Table 1. Percentage moisture content at the end and center of the specimens by months of exposure

Location	0 months	6 months	12 months	17 months
End of specimen	~25	24.0	25.5	27.9
Center of specimen	11.3	19.1	19.4	18.1

A set of typical time domain and frequency domain plots collected by the GPR unit are shown in Figure 6. The specimen examined was C13. The plots were collected with the antenna on the top surface of the specimen (the surface with two drilled holes as shown in Figure 2a). To facilitate data clarity in Figure 6a, the time domain magnitude data shown are natural logs of the absolute values of the time domain data multiplied by the original sign for the individual data points. The process enhances the visibility of low magnitude peaks and valleys. Figure 6b has the frequency domain data subsequently described. Figure 6c is a side view of the specimen constructed from CT images. The CT images were collected on July 25, 2017. The bright object on the top surface of the specimen is the metal ID tag. In the CT image, pixel brightness is directly and linearly proportional to density. The four drilled fungal cavities illustrated in Figure 2 are clearly visible. The bright areas around the fungal cavities are moisture that has moved into the wood from the cavities. The CT image and time domain plots are aligned such that the vertical black dashed lines across the plots and CT image represent the same location within the specimen. The 0-month plot (top) shows a relatively small amount of variation along the length. There are distinct positive peaks and distinct negative valleys. The 6-month plot (second from top) has variation in the signal visible near the ends where the fungal cavities are present, although distinct peaks and valleys are still visible. In the 12-month plot, the time domain signals around both fungal cavities have shifted positively causing the loss of distinct negative valleys. The 17-month time domain plot shares many characteristics with the 12-

month plot. The fungal cavities have caused a loss of positive peaks on one end and a loss of negative valleys on the other. The fungal cavity at the 6-in. (15-cm) mark causes peaks that are mainly negative, whereas the cavity at 26 in. (66 cm) has peaks that are mainly positive. One complicating factor of the time domain plots is the high potential of internal features to clutter the image. Knots, voids, and moisture cavities are all reflectors that are visible to the GPR unit. Although the raw time domain data plots reveal the location of internal features, identifying what the feature represents can be a challenge.

In an effort to find a more consistent identifier for internal moisture and fungal decay, the time domain data were converted into the frequency domain. The associated frequency domain plots computed from the time domain signal data are shown in Figure 6b. The GPR antenna has a center frequency of 2 GHz. The red dashed line in Figure 6b shows the 2-GHz frequency band. The majority of the signal energy in the 0-month plot was at 2 GHz, as expected. All frequency domain plots were normalized to the maximum value present in the 0-month plot; therefore, a loss of magnitude in later months is visible as a shift from red to yellow, then to green, and finally to blue. As the moisture increased from field exposure, the magnitude of the 2-GHz signal decreased. There was a noticeable drop in the 2-GHz magnitude between the 0- and 6-month scans along with an associated increase in MC in the center of the specimens according to Table 1. Between the 6- and 12-month scan, there was another drop of 2-GHz magnitude and a shifting of the center frequency slightly lower, both of which were expected results of increased MC, but no increase in MC was recorded between those visits. During the 6-month visit, the 3-day inspection period had several passing showers. The passing showers probably increased the recorded MC results from the 6-month visit. At the 12- and 17-month visits, the magnitude of the signal along the 2-GHz signal was relatively consistent compared with the 0- and 6-month data; however, the regions of moisture caused the signal magnitude to noticeably decrease along the 2-GHz band. In addition, signal magnitude above 2 GHz decreased to a greater extent than signal magnitude below 2 GHz. This was expected because the electromagnetic wave speed through water is slower than through air or dry wood. The drop in magnitude associated with the fungal cavities was largely consistent for all specimens examined, indicating that MC was probably the source of the signal magnitude loss. Cross-sectional hardness profiles of the 6-month group have shown no indication of internal decay. Time of flight measurements taken during the 17-month visit, likewise, showed no indication of internal decay. The changes in the frequency magnitude are probably attributable to internal moisture. All CT scans of specimens retrieved from the field show the presence of moisture around the fungal cavities (Fig. 7).

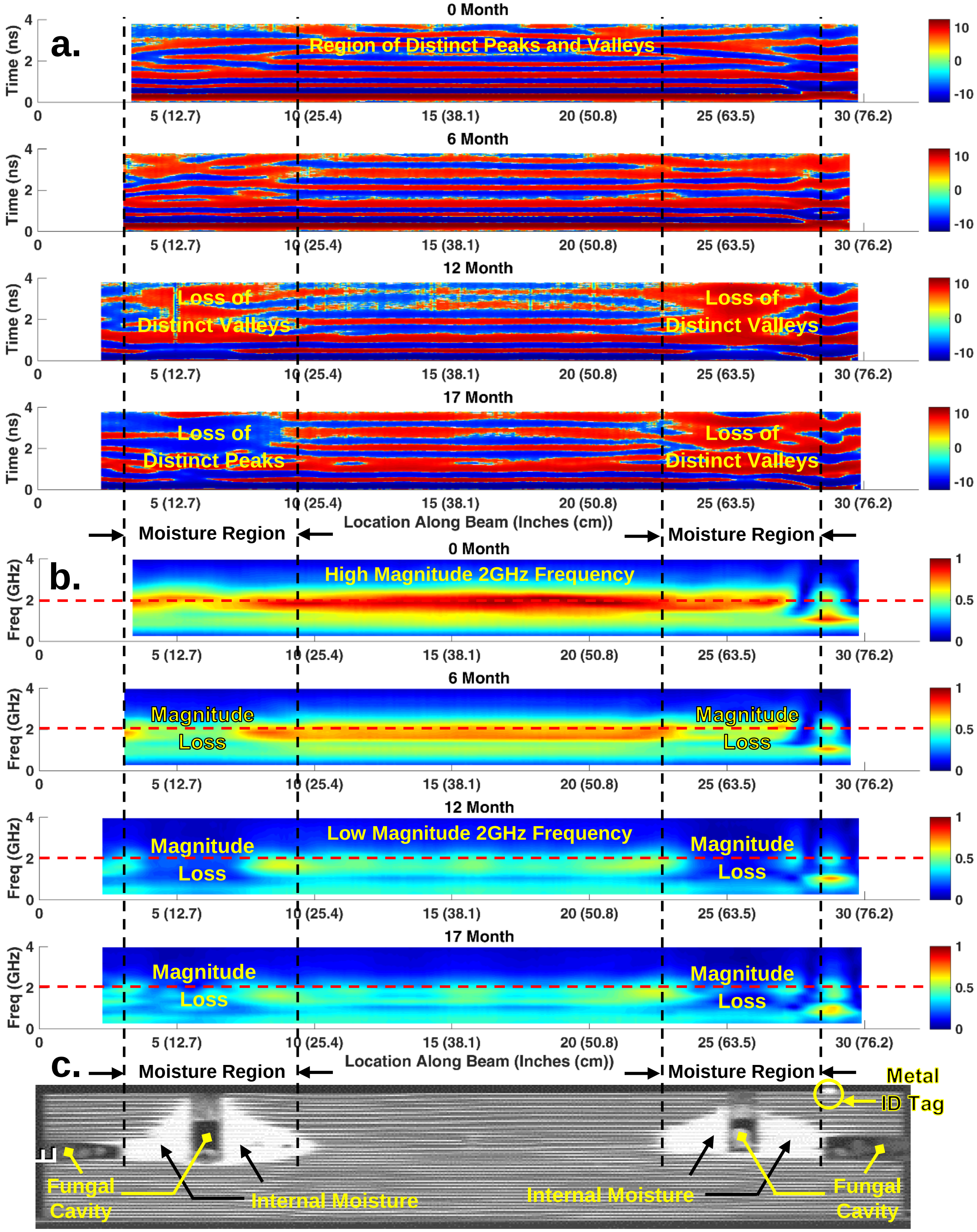


Figure 6. Through depth time and frequency domain plots at 0, 6, 12, and 17 months: (a) top four plots are time domain; (b) lower four plots are frequency domain (red dashed lines show the 2-GHz frequency band); (c) CT cross section of the specimen in which fungal cavities are visible and bright areas are internal moisture. Black dashed vertical lines show the boundary of moisture regions across all plots and images.

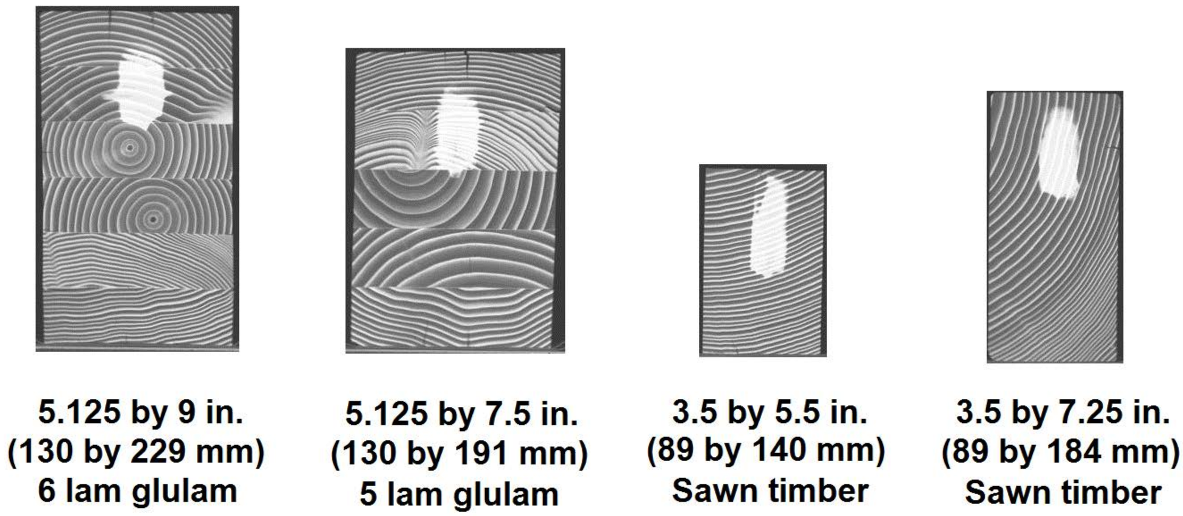


Figure 7. CT images of specimen cross sections after 17 months of field exposure showing internal moisture.

Summary

In this study, GPR was investigated for suitability for inspecting large timber bridge components. One focus of the study was the efficacy of using GPR to detect fungal decay and moisture pockets within Douglas-fir beams. A total of 96 specimens were created from two sizes of glulam beams and two sizes of sawn timber beams. The beams selected were of sizes typically used in covered timber bridge applications. Initially, the beams were assessed using a variety of physical, mechanical, and NDE test methods including, microresistance drilling, Janka hardness, stress wave transmission, and GPR. These data provided a baseline to which field-exposed specimens were compared. The specimens were inoculated with brown-rot fungus, *Fomitopsis pinicola*, and transported to HEF, 22 miles (35.4 km) north of Gulfport, Mississippi, USA. In January 2016, the specimens were placed outside at HEF to promote fungal growth. FPL researchers returned after 6, 12, and 17 months to evaluate the specimens using GPR scanning, stress wave, and visual assessment. During each visit, a subset of the specimens were retrieved from the field and returned to FPL. The returned specimens were subjected to visual assessments, NDE evaluation, CT imaging, and hardness profile mapping of specimen cross sections. At the time of this report (17+ months of field exposure), no testing method showed indications of internal decay in the specimens. Time domain and frequency domain data collected from the specimens using GPR showed a strong connection between signal magnitude and internal moisture pockets. Future work on this study will focus on developing a metric to positively identify internal moisture as well as assess the ability of GPR to detect internal fungal decay within the Douglas-fir specimens when it develops.

Acknowledgments

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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

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