

Assessing the Ability of Ground-Penetrating Radar to Detect Fungal Decay in Douglas-Fir Beams

C. Adam Senalik¹, James P. Wacker¹, Xiping Wang¹, and Frank Jalinoos²

¹United States Department of Agriculture, Forest Service, Forest Products Laboratory
One Gifford Pinchot Dr., Madison, WI 53726
(608) 231-9200, fax (608) 231-9592; e-mail christopherasenalik@fs.fed.us, jwacker@fs.fed.us,
xwang@fs.fed.us

²United States Department of Transportation, Federal Highway Administration, Office of Infrastructure R&D
Turner–Fairbank Highway Research Center
6300 Georgetown Pike, McLean, VA 22101
e-mail Frank.Jalinoos@dot.gov

ABSTRACT

This paper describes the testing plan and current progress for assessing the efficacy of using ground-penetrating radar (GPR) to detect fungal decay within Douglas-fir beams. Initially, the beams were assessed using a variety of physical, mechanical, and nondestructive evaluation (NDE) test methods including micro-resistance drilling, Janka hardness, ultrasonic transmission, and GPR. After initial baseline assessment, beams were inoculated with brown rot fungus, *Fomitopsis pinicola*, and exposed to above-ground conditions approximately 25 miles (40 km) north of Gulfport, Mississippi, USA. Beam specimens will be removed from the exposure site at six-month intervals and scanned using GPR to detect and assess interior rot. After GPR scanning, micro-resistance drilling and ultrasonic transmission testing will be performed. Finally, the beams will be cut into 2-in. segments for Janka hardness testing, which will give the most definitive information regarding the spread of the brown rot fungus throughout the beams. The GPR scans will be compared to the hardness testing, micro-resistance drilling, and ultrasonic testing results to evaluate the ability of GPR to detect interior rot within the beams.

KEYWORDS

Ground-penetrating radar, fungus, brown rot, Douglas-fir, sawn timber, glulam

INTRODUCTION

The 2014 Federal Highway Administration (FHWA) National Bridge Inventory includes more than 40,000 wood or timber bridges in the United States (USDOT NBI Library 2014). To ensure continued safe usage of these bridges, regular maintenance and inspection are necessary. Many wood inspection techniques are well-known and reliable, 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, making a comprehensive evaluation of the entire bridge structure a time-consuming undertaking. 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 to make 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. 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 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) diameter (Muller 2013). The GPR results in the study closely correlated to defects located using test drilling and post inspection cutting of the examined wood girders.

Rodriguez-Abad and others 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 the grain. No significant differences were noticed between propagation directions that were parallel to the radial axis and those parallel to the tangential axis (Rodriguez-Abad et al. 2011). Martínez-Sala and others presented similar findings and expanded the study to

examine the variation in parameters listed above with respect to 12 species commonly used for commercialized sawn timber in Spain. They found that, for all examined species, longitudinal versus transverse dielectric wood behavior was clearly identifiable (Martínez-Sala et al. 2013).

Riggio and others briefly overviewed 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 (Riggio et al. 2014). Maï and others showed that dielectric permittivity was affected by moisture content of the wood, fiber direction, and wood density (Maï et al. 2014). A subsequent study found that GPR provided the possibility of estimating the 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 and others 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 (Hans et al. 2015a,b). 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. In this project, the efficacy of using ground-penetrating radar (GPR) to detect fungal decay within Douglas-fir beams is examined.

RESEARCH STUDY

This study is conducted under a joint agreement between the Federal Highway Administration (FHWA), Turner-Fairbank Highway Research Center, and the United States Department of Agriculture, Forest Service, Forest Products Laboratory (FPL). The study is part of the Research, Technology, and Education portion of the National Historic Covered Bridge Preservation (NHCBP) program administered by the FHWA. The NHCBP program includes preservation, rehabilitation, and restoration of covered bridges that are listed or are eligible for listing on the National Register of Historic Places; research for better means of restoring and protecting these bridges; development of educational aids; and technology transfer to disseminate information on covered bridges in order to preserve the Nation's cultural heritage.

The goal of the research study is to find fast, reliable nondestructive inspection techniques for covered timber bridges. Ideally, techniques will require access to only one side of the inspected object, detect moisture, 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 (Wacker et al. 2016). 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 selected for further in-depth investigation. The entire selection process is described in Wacker et al. (2016).

OBJECTIVES AND FIELD TEST SETUP

The goal of the research study is to assess the ability of GPR to detect internal decay in wood beams with cross-sectional sizes representative of those used in covered timber bridges. Douglas-fir specimens of various level of decay will be created through fungal inoculation and subsequent field exposure over a range of time from 6 to 48 months. At regular 6-month intervals throughout the decaying process, the specimens will be examined using a variety of nondestructive techniques including GPR. At conclusion of the study, sectioning of specimens, visual and photographic assessments, and hardness test mapping will serve as bench marks for measuring efficacy of GPR for detecting internal pockets of fungal decay. The minimal level of rot detectable by GPR and features within the GPR scans that are indicative of internal decay will be identified and reported.

MATERIAL AND METHODS

Specimens with internal decay will be 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 and months of exposure. Four specimen cross-sectional sizes were selected for the study: 5.125- by 9-in. (130- by 229-mm) glulam, 5.125- by 7.5-in. (130- by 191-mm) glulam, 3.5- by 5.5-in. (89- by 140-mm) sawn timber, and 3.5- by 7.25-in. (89-

by 184-mm) sawn timber. Six 11 ft (3.4 m) or longer beams of each cross-section size were selected and cut into four 32-in. (0.8-m) specimens for a total of 96 specimens (4 cross sections $\times$ 6 beams per cross section $\times$ 4 specimens per beam). There are three duplicate 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 described later in this section.

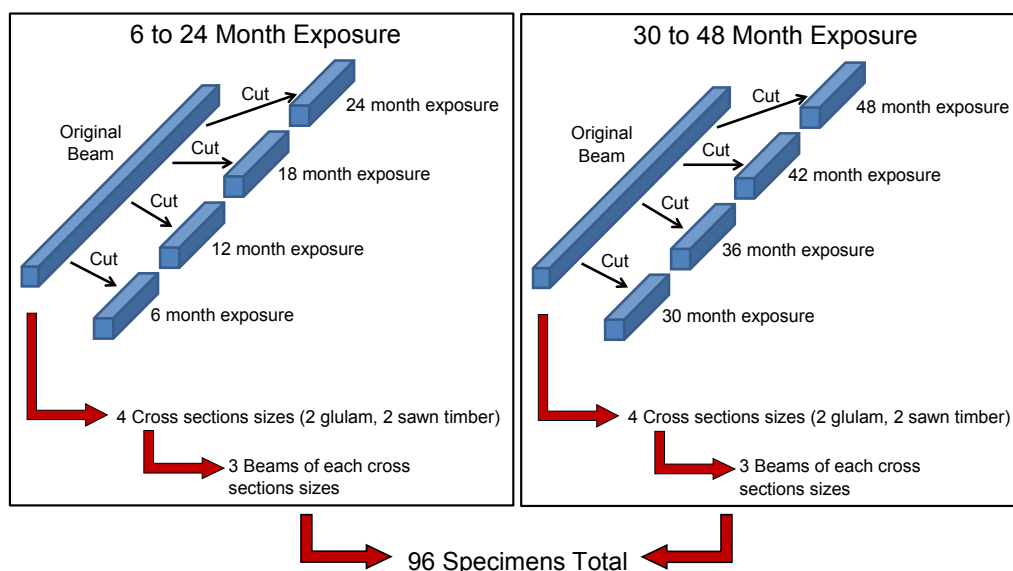
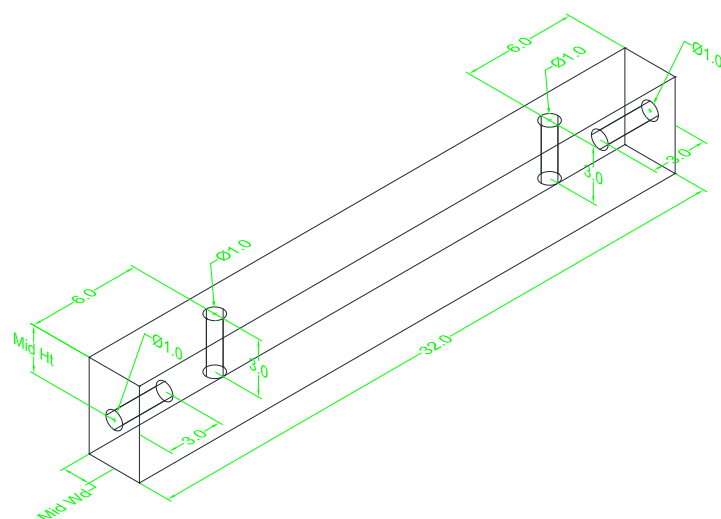


Figure 1. Number of specimens and months of exposure.

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) in diameter and 3 in. (76 mm) in depth. The holes were located on the ends and top of each specimen. The hole on the end was centered at mid-height and mid-width of the specimen cross section and drilled parallel to the longitudinal axis. The holes on top were centered mid-width and drilled through the depth of the specimen. 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) Image of the holes drilled in a six-laminate glulam.

Initial baseline data were then collected on the specimens. Data collected included mass, moisture content (MC), stress wave travel time, micro-resistance drilling, GPR scanning, and Janka hardness. MC was collected using Delmhorst R-2000 electrical resistance moisture meter with 3-in. (76-mm) insulated probes from Delmhorst Instrument Company. Stress wave time was measured using the Fakopp Microsecond Timber from Fakopp Enterprises. Micro-resistance drilling was performed on selected specimens using the PD 400 Resistograph from IML Wood Testing Systems. Several GPR scans were taken of each specimen using a SIR® 4000 GPR data acquisition system with a 2.0 GHz palm antenna. The center frequency of the palm antenna is 2.0 GHz, but the range of frequencies emitted and received range between 500 MHz and 4 GHz. During post-collection data analysis, narrower frequency ranges will be explored to determine what, if any, frequency range is particularly sensitive to the presence of brown rot. The data acquisition system and antenna were purchased from Geophysical Survey Systems, Inc. (GSSI). A 2-in.- (51-mm-) thick piece was cut from reach beam remnant and Janka hardness tests were performed using an Instron 5587. Measurements were taken across the cross section as shown in Figure 3. 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 the specimens cut from that beam.

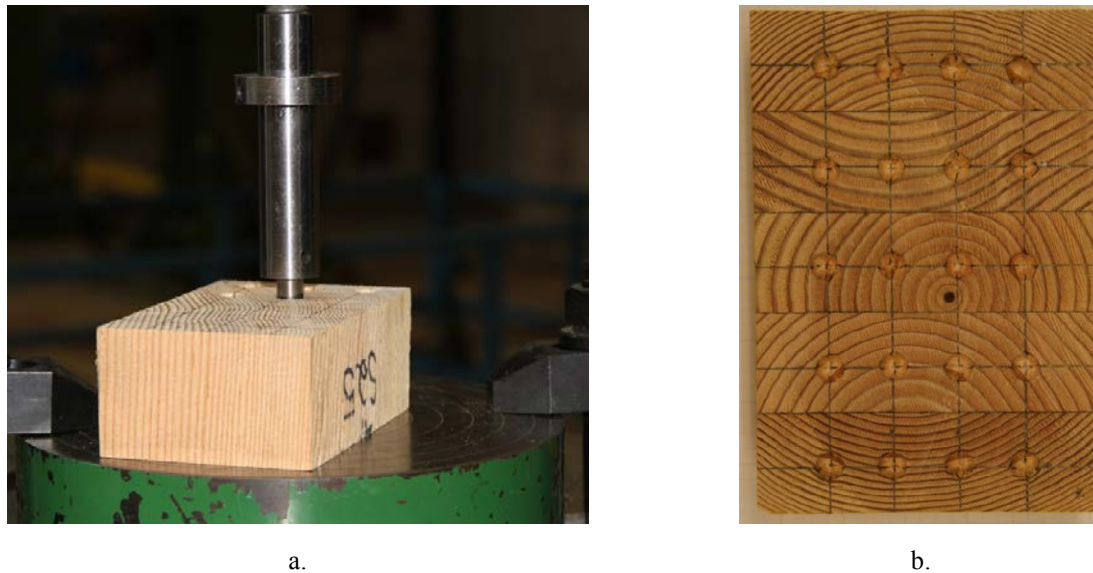


Figure 3. Janka hardness testing. a) Sawn timber remnant undergoing Janka hardness test. b) Hardness tests across glulam remnant cross section.

After initial data collection, one end of each specimen was placed in a water tank for a period of 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), as shown in Figure 4. At the end of that period, specimens were removed and a mixture of wet sawdust and *Fomitopsis pinicola*, a brown rot fungus capable of attacking Douglas-fir, was placed in each hole that had been below water level, as shown in Figure 5. The soaking supplied water to the wood that the brown rot would use to establish itself and promote fungal growth. The holes were then sealed with cork stoppers, and the specimens were placed back into the soaking tanks with the opposite end below water level. After a period of 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 25 miles (40 km) north of Gulfport, Mississippi, USA. The site was chosen as an ideal location to promote fungal growth due to its warm climate, high yearly rainfall, and high average relative humidity. Local temperature and precipitation data are recorded by a weather station at the HEF. A field site was cleared down to soil level. Surrounding trees providing shade during most of the day other than midday when the sun is directly overhead; otherwise, sun and shade are not controlled variables. Two layers of UV-resistant, 8-mil (0.2-mm-thick) black landscaping plastic was 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 future scans will be 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 specimens were placed outside on January 12, 2016, as shown in Figure 6. The covers will minimize rain contact with the middle portion of the beam and lower the possibility that surface decay will develop in that region. Small holes approximately 0.25 in. (6 mm) in diameter were drilled through each cork to allow moisture to enter the fungal cavities.



Figure 4. Pre-soaking specimen prior to inoculation. a) Specimen placement in the soaking tanks. b) Water level at least 2 in. (51 mm) above drilled holes.



Figure 5. Inoculating specimens with *Fomitopsis pinicola*, brown rot.

At 6-month intervals, FPL researchers will return to the test site for data collection. A limited pilot study 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 will include, but is not specifically limited to, GPR scanning, stress wave, and a visual assessment of the specimen condition. Micro-resistance drilling will be used when warranted. In addition, 12 pre-determined specimens (three of each cross section) will be retrieved from the test site and returned to the Forest Products Laboratory. The retrieved specimens will be 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 will be performed across the cross section to obtain a hardness profile. The collected hardness profiles will be

compared to the original hardness profile for each beam to evaluate the extent of fungal decay within each specimen (Green et al. 2006).

Every 6 month, the process will be repeated until the final 12 specimens are retrieved after 48 months. 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.



Figure 6. Specimens as positioned on site.

SUMMARY

In this study, GPR is being investigated for suitability for inspecting large timber components. One focus of the study will be the efficacy of using GPR to detect fungal decay within Douglas-fir beams. A total of 96 specimens were created from two sizes of glulam beams and two sizes of sawn timber beam. The beams selected were of sizes typically used in covered timber bridges construction. Initially, the beams were assessed using a variety of physical, mechanical, and NDE test methods including micro-resistance drilling, Janka hardness, ultrasonic transmission, and GPR. These data will provide a baseline to which decayed specimens will be compared. The specimens were inoculated with brown rot fungus, *Fomitopsis pinicola*, and transported to the Harrison Experimental Forest (HEF), 25 miles (40km) north of Gulfport, Mississippi, USA. On January 12, 2016, the specimens were placed outside at HEF to promote fungal growth. Every 6 months, a group of FPL researchers will travel to HEF to evaluate the specimens using GPR scanning, stress wave, visual assessment, and select micro-resistance drilling. During each visit, a subset of the specimens will be retrieved from the field and returned to FPL for sectioning, visual and photographic assessments, along with hardness test mapping. The sectional data along with the field inspection data will form a body of data that will be used to assess the ability of GPR to detect pockets of fungal decay within the Douglas-fir specimens. The minimal level of rot detectable by GPR and features within the GPR scans that are indicative of internal decay will be identified and reported.

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