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# EFFECTIVENESS OF SEVERAL NDE TECHNOLOGIES IN DETECTING MOISTURE POCKETS AND: ARTIFICIAL DEFECTS IN SAWN TIMBER AND GLULAM

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**ABSTRACT:** Several nondestructive evaluation (NDE) technologies were studied to determine their efficacy as scanning devices to detect internal moisture and artificial decay pockets. Large bridge-sized test specimens, including sawn timber and glued-laminated timber members, were fabricated with various internal defects. NDE Technologies evaluated in this research were ground penetrating radar (GPR), microwave scanning, ultrasonic pulse velocity, ultrasonic shear wave tomography, and impact echo methods. Each NDE technology was used to evaluate a set of seven test specimens over a 2-day period and then raw data scans were processed into two-dimensional, internal defect maps. Several parameters were, compared including the relative size, orientation, and moisture conditions of the internal defect. GPR was the most promising NDE technology and is currently being more rigorously evaluated within the laboratory. The study results will be useful in the further development of a reliable NDE scanning technique that can be utilized to inspect the primary structural components in historic covered timber bridges.

**KEYWORDS:** inspection, timber bridge, nondestructive, internal decay, moisture pockets

## 1 INTRODUCTION

Bridge engineers are assigned the difficult task of assessing the integrity and safe load-carrying capacity of highway bridges in the United States. This task becomes even more challenging in the case of historic covered timber bridges due to the multitude of members and connections involved. Most inspectors are not adequately trained for evaluating timber bridge structures and typically tend to be overly conservative in their assessments. When relying solely on visual inspection techniques, many signature indicators of internal decay and/or deterioration in timber bridge components are misinterpreted. Several advanced nondestructive tools are available in the marketplace to supplement visual inspection data, but most require complicated data interpretation, which limits their use within routine bridge inspections. In recent years, computer data processing algorithms are increasingly capable of assembling multiple linear data scans into 2D and 3D mapping of internal defects. This will undoubtedly help newer scanning-type nondestructive inspection tools achieve more widespread acceptance by bridge inspectors. The aim of this study is to evaluate several NDE inspection technologies for their effectiveness in detecting moisture pockets and/or decayed zones in large bridge-sized test specimens. The ability to penetrate through an asphalt layer and still achieve good object resolution will also be evaluated. The most promising NDE technology will then be selected for more rigorous evaluation within the laboratory setting. This study represents an initial step towards the further development of a user-friendly and more reliable NDE scanning device that can be utilized to inspect the primary structural components in historic covered bridge truss structures and for routine inspection of highway bridges.

## 2 BACKGROUND

Current timber bridge inspectors utilize a toolbox of NDE techniques to collectively quantify the internal integrity of structural timber components. These NDE techniques typically include moisture meters, stress–wave timers, and resistance micro-drilling devices [1, 2]. Moisture meters are useful for accurately measuring the moisture content at a single member location and pin penetration depth. Stress wave through-transmission measurements, collected with a perpdicular-to-grain orientation, are capable of detecting internal defects but their relative size within the member cross-section is not always evident. Resistance micro-drilling devices effectively measure the relative size of an internal defect via true scale relative density plots. However, these conventional NDE techniques often require repetitive testing, and access to both opposing member sides, in order to evaluate a single bridge member which can be a time-consuming

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endeavour. These factors have prevented current NDE tools from achieving wider acceptance by inspectors for routine timber bridge inspections.

NDE technologies are increasingly being studied for timber bridge inspection, as they can often rapidly scan bridge members using multiple linear datasets. Electromagnetic (EM) and mechanical wave methods were comparatively evaluated with various advantages and limitations [3].

Infrared thermography (IRT) can effectively be used for detecting areas of elevated moisture due to its temperature sensitive imaging capabilities. Passive IRT inspection relies on ambient temperature fluctuations while active inspection uses a heat source on the bridge members. IRT can be used for decay detection in timber bridge-sized members, but it cannot penetrate deeply into wood members in a reliable manner. Therefore, it has been primarily used for quantifying near-surfam wood characteristics such as moisture and chemical concentrations [4].

Microwave inspection of wood has been investigated for assessment of material density, moisture content and grain angle in automated lumber grading systems [5]. Since EM waves are sensitive to the presence of moisture, it has been suggested that microwave techniques have significant potential for detecting decay in historical timber structures

Ground penetrating radar (GPR) is another EM wave 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. A recent bridge inspection found that GPR was a reliable method for locating internal defects such as piping and rot in timber girders as large as 425mm diameter [6]. The GPR results in the study closely correlated to defect locations identified through forensic analyses of the wood girders.

## 3 TEST SPECIMENS

The test specimens used in this study were manufactured from the Douglas fir species. Prior to laboratory inspection, all test specimens were equilibrated to controlled conditions equivalent to a fifteen percent moisture content. Specimens were large sized to be representative of typical timber bridge members. Beam specimens were manufactured from sawn lumber and glued laminated timber components. A single deck specimen was manufactured from glued laminated timber panels. Internal defects were introduced by through-hole borings of varying diameters. Internal decay pockets were either air-filled or had moist sawdust packed into the bored holes. Plywood side plates concealed the location and size of bored-hole defects from all inspectors. In most cases, solid wood blocking was attached to the specimen ends in an effort to minimize boundary effects during scanning by electromagnetic wave-based techniques. Details on each set of test specimens are provided in the following sections.

### 3.1 Sawn Lumber Beams

Sawn lumber beam specimens were fabricated to a finished size of 140 x 337 x 914 mm. Specimen FPL-1 included a total of five uniformly spaced through-bored holes of increasing diameter, orientated parallel to the beam depth and aligned with the neutral axis (Figure 1). Specimen FPL-2 included a series of 5 through-bored holes which were orientated at oblique angles to the beam depth and width (Figure 2). Specimen FPL-3 included a total of five uniformly spaced through-bored holes of increasing diameter, orientated parallel to the beam width (Figure 3). The row of bored holes was offset from the neutral axis so defects could be inspected from both sides at either a shallow or a deep penetration depth.

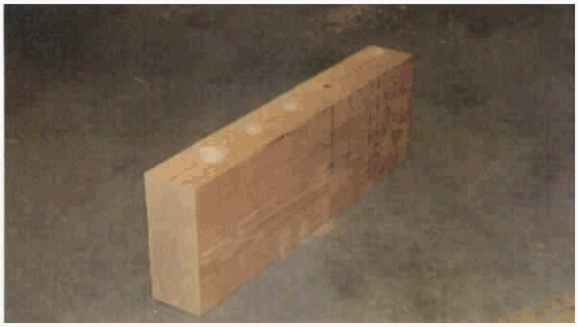

***Figure 1:*** *Specimen FPL-1 sawn lumber beam with defects through depth.*

***Figure 2:*** *Specimen FPL-2 sawn lumber beam with angled defects.*

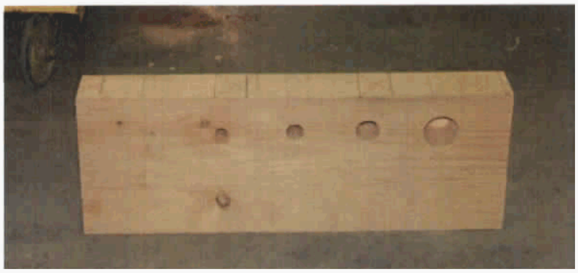

***Figure 3:*** *Specimen FPL-3 sawn lumber beam with defects through width and offset from beam neutral axis.*

## 3.2 Glulam Beam

Glued-laminated timber (glulam) beams were fabricated to a finished size of 273 x 343 x 914 mm. Specimen FPL-4 included a total of five uniformly spaced through-bored holes of increasing diameter that were orientated perpendicular to the glue lines but aligned with the neutral axis (Figure 4). Specimen FPL-5 included a series of 5 through-bored holes which were orientated at oblique angles to the beam depth and width (Figure 5). Specimen FPL-6 included a total of five uniformly spaced through-bored holes of increasing diameter and were orientated parallel to the glue lines (Figure 6). The row of through-bored holes was offset from the member neutral axis so that the defects could be inspected from both sides at either a shallow or a deep penetration depth.

***Figure 4:*** *Specimen FPL-4 glulam beam.*

***Figure 5:*** *Specimen FPL-5 glulam beam.*

*Figure 6: Specimen FPL-6 glulam beam.*

## 3.3 Asphalt Covered Glulam Deck

A single deck specimen was fabricated with a glulam panel measuring 610 x 191 x 914mm (Figure 7). It also had an asphalt overlay measuring 76mm deep installed following typical construction practice. A series of three uniformly spaced bore holes of increasing diameters were aligned along the mid-depth of the glulam deck. This specimen allowed for top-down inspection through the asphalt as would be required for a timber bridge deck, especially longitudinal “slab–type” systems.

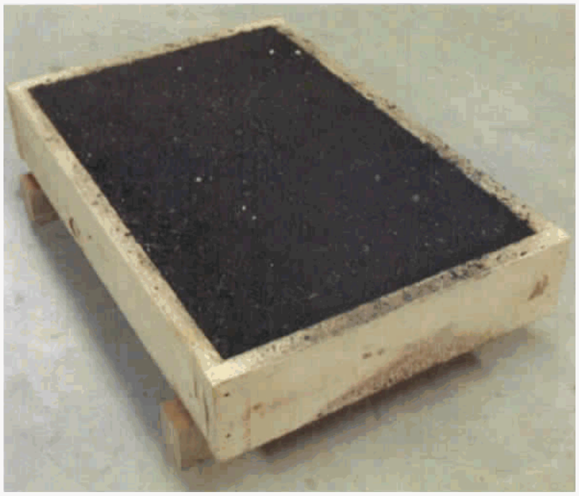

***Figure 7:*** *Specimen FPL-7 glulam deck panel with 76mm asphalt overlay. Side, forms are to conceal defect locations.*

# 4 INSPECTION METHODOLOGY

## 4.1 NDE Scanning Technologies Employed

Table 1 summarizes the NDE technologies employed in this research project to inspect several timber bridge-sized specimens. They included microwave scanners, ground penetrating radar, ultrasonic shear wave tomography, ultrasonic pulse velocity, and impact echo methods.

***Table 1:*** *NDE technologies used for inspecting test specimens.*

| NDE Technology | Frequency | Company |
|---|---|---|
| Microwave–A | 2.75 GHz | -- |
| Microwave-B | 10 GHz | Evisive |
| Ground penetrating radar-A | 2 GHz | GSSI |
| Ground penetrating radar-B | 2 GHz | IDS |
| Ultrasonic shear wave | 20-100 kHz | MIRA |
| Ultrasonic pulse velocity | 50 kHz | Olson |
| Impact echo scanner | 2-20 kHz | Olson |

## 4.2 Test Procedures

A series of inspection trials was independently conducted at the Forest Products Laboratory during the summer of 2014. Inspectors were NDE industry practitioners or academic researchers with no prior knowledge of the internal defect locations and there were no external indicators of deterioration on the specimens. Each investigation was scheduled separately and involved the use of one or more NDE technologies to evaluate all seven test specimens within a 2-day inspection timeframe (See Figures 8-12). All NDE investigations were conducted in identical environment conditions controlled at 21 degrees Celsius and 65 percent relative humidity. Approximately 24 hours prior to NDE evaluation work commenced, a few specimens had saw dust and moisture packed into the bored hole artificial defects. With exception of ultrasonic pulse velocity measurements, none of the other NDE technologies required any coupling agent during testing. After data scanning was completed, each investigator was asked to prepare a detailed inspection report and to post-process their datasets into two dimensional internal defect maps.

## 5 INSPECTION RESULTS

The results were evaluated based on the NDE technologies' ability to estimate the location, size, and orientation of the internal defects or moisture pockets in a given timber specimen. A variety of post-processing software methods were utilized by each inspector, after testing was completed, in order to provide an optimal two-dimensional mapping of the internal defect locations.

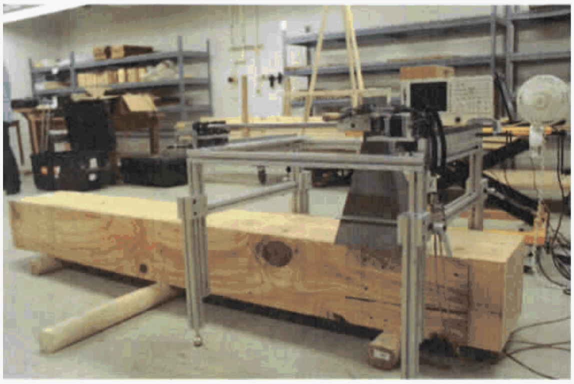

***Figure 8:*** *Inspecting specimen FPL-4 with a 2.75 GHz microwave antennae mounted on on automated test frame.*

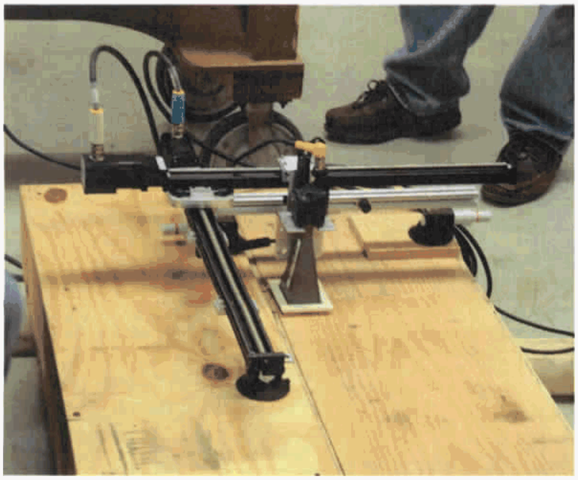

***Figure 9:*** *Inspecting specimen FPL-1 with a 10 GHz microwave antennae mounted on an automated test frame.*

Comparisons to the actual test specimen defect locations yielded the resolution and accuracy of each NDE technique. As mentioned previously, some specimens had wet sawdust compacted into the drilled holes prior to each of the NDE testing scenarios. This tested the ability of these techniques to detect internal moisture pockets.

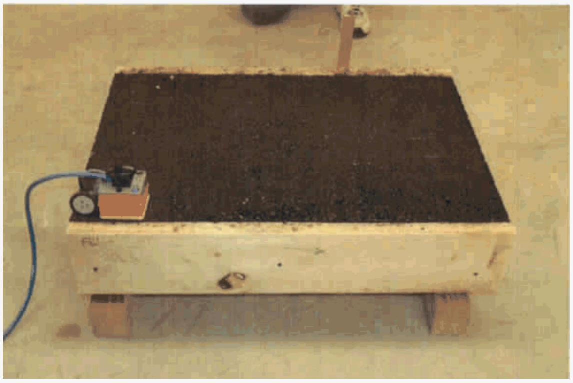

***Figure 10:*** *Inspecting specimen FPL-7 with a 2GHz handheld ground penetrating radar (GPR) antennae.*

***Figure 11:*** *Inspecting a specimen with ultrasonic shear wave tomography device.*

***Figure 12:*** *Inspecting specimen FPL-3 with handheld impact echo scanning device.*

## 5.1 Microwave-A

The resulting 2-D defect map resulting from the 2.75 GHz microwave device is presented in Figure 13. In this testing, specimens FPL-1 and FPL-2 were positioned end-end, with end blocks added and defect locations concealed by plywood side plates. The horizontally drilled holes in FPL-1 were filled with compacted wet sawdust, and were discernible for those bored hole diameters greater than 38mm. In addition, some of the angled drilled holes that were air-filled were discernible at diameters of 25mm.

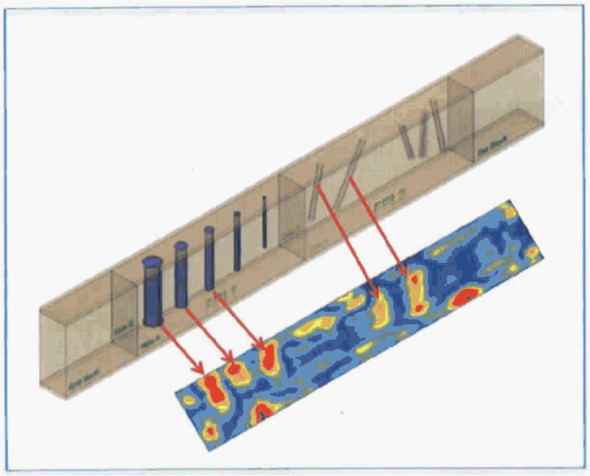

***Figure 13:*** *2–dimensional defect mapping of specimens FPL-1 and FPL-2 positioned end-to-end generated from the 2.75 GHz microwave device. (blue indicates moist sawdust filled holes)*

## 5.2 Microwave-B

The resulting defect imaging results from the 10 GHz microwave device is presented in Figure 14. In this testing, specimen FPL-4 included several bored holes with different diameters and were packed with wet sawdust prior to testing. However, these defects were not discernible by the microwave device even for the largest hole diameters.

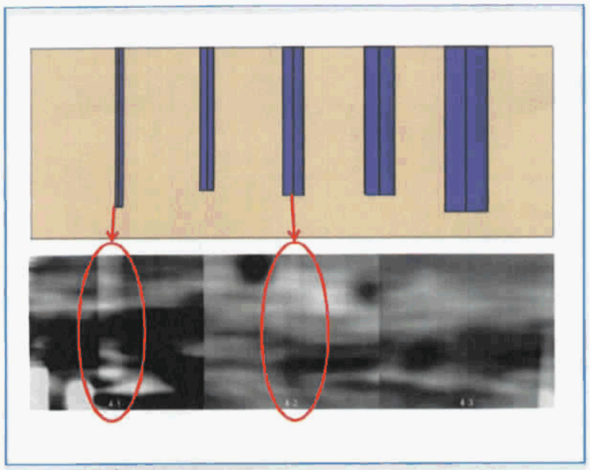

***Figure 14:*** *2-dimensional defect mapping of Specimens FPL–4 generated by the 10GHz microwave device.*

## 5.3 GPR-A

Figure 15 shows the results of testing scans for specimen FPL-6 using the 2 GHz ground penetrating radar (GPR-A) equipment. The specimen was constructed of glulam materials and the artificial defects (drilled holes of increasing diameter and depths) were orientated perpendicular to the scanning direction for best results. Scanning direction was oriented perpendicular to the glue lines in the beam but was still able to identify all holes.

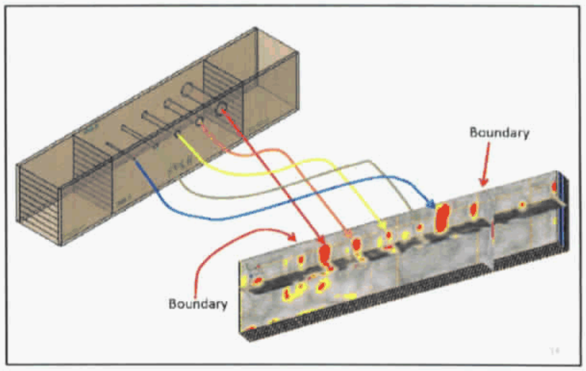


***Figure 15:*** *2-dimensional defect mapping of specimen FPL-6 generated from the 2.0 GHz GPR device.*

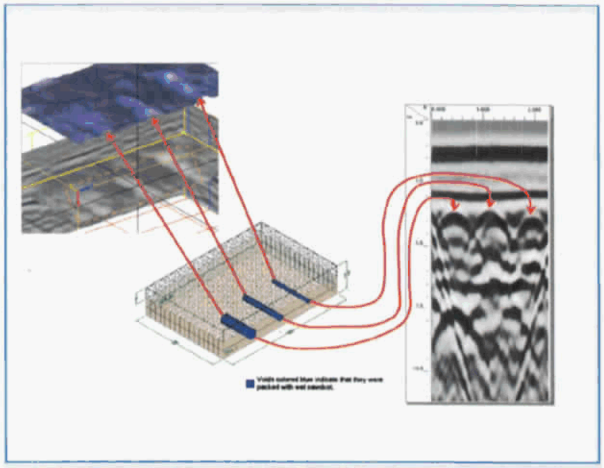

***Figure 16:*** *2-dimensional defect mapping of specimen FPL-7 generated from a 2.75 GHz microwave antennae.*

Figure 16 shows the results of testing scans for specimen FPL-7 using ground penetrating radar (GPR-A) equipment. The specimen was constructed of glulam materials and included an asphalt overlay. Testing was performed from asphalt side viewing through into the glulam panels. It is evident that all three moist sawdust filled holes were identified by this GPR device. Raw data scans are provided on the right side showing the characteristic peaks expected for round anomalies.

## 5.4 GPR-B

The resulting 2-D defect map resulting from the 2.0 GHz ground penetrating radar device is presented in Figure 17. In this testing, specimens FPL-1 and FPL-2 were positioned end-end, with end blocks added and defect locations concealed by plywood side plates. The horizontally drilled holes in FPL-1 were filled with compacted wet sawdust, and were detectable for nearly all bored hole diameters.

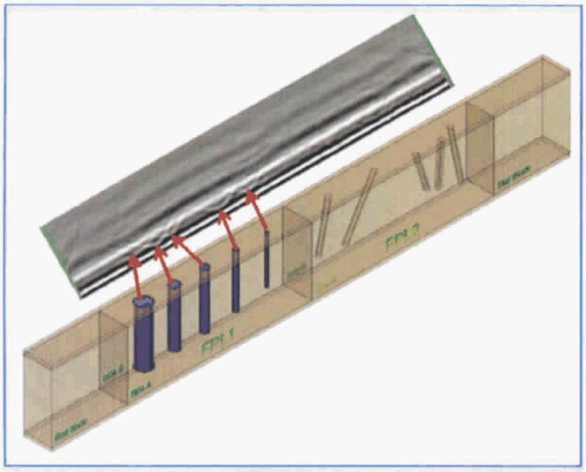

*Figure 17: Two-dimensional defect mapping of specimens FPL-1 and FPL-2 positioned end-to-end generated by the 2.0 GHz GPR device.*

### 55 Mechanical Wave Based Techniques

For the other mechanical wave-based techniques (ultrasonic pulse velocity, impact-echo scanner, and the ultrasonic shear wave tomography unit) the test results indicated they were not effective at detecting the air-filled or wet sawdust-filled defects within the test specimens. The energy required for the mechanical waves to penetrate into the larger sized wood specimens may not have been sufficient in these cases.

## 6 DISCUSSION OF RESULTS

The microwave and GPR inspection results indicated that these NDE technologies possess the ability to detect the moisture packets and internal defects, hut with different degrees of effectiveness.

The lower frequency (2.75 GHz) microwave device performed well in detecting moisture and defect voids in most specimens. It is a single sided technique, so access to only one side of the test specimen is required, and sensor coupling requirements are eliminated. On the negative side, while all of the demonstrations were automated, the process as a whole was slow in each case. The higher frequency (10 GHz) microwave signals were attenuated by the wood decreasing penetration depth. The ability of both microwave devices to see through asphalt to a wood deck below was limited. The higher frequency (10 GHz) microwave inspection device suffered from high attenuation making them less useful as inspection tools for wood bridge inspections.

GPR testing results revealed many positive features. Data collection was fast and continuous. Some of these GPR units are capable of being mounted on hand carts and used to inspect bridge decks at a walking speed. Some GPR units can be mounted onto vehicles to inspect at even higher speeds. Access to only one side of the target member is needed. The units are commercially available from a variety of vendors. No coupling agent is needed. Moisture pockets and internal defect voids were detectable at depths up to approximately 204mm. On the negative side, the attenuation of the radar through wood was significant. At depths greater than approximately 204mm, voids can become more difficult to detect. Also, the Federal Communications Commission has recently limited both the power and frequency range of GPR units sold in the USA.

Of the devices tested, GPR was capable of identifying internal moisture more reliably compared to the microwave devices. The microwave devices did not demonstrate the ability to detect voids that were at oblique angles to the antenna; GPR was capable of detecting voids at oblique angles, though its detection was limited. GPR was capable of scanning through the asphalt to see defects in underlying glulam deck with a greater accuracy than the microwave systems. Based upon these results, the next phase of this project will focus upon GPR with a 2.0 GHz antennae as the primary inspection tool.

## 7 FUTURE WORK

Other related studies are ongoing or planned as part of this overall research effort. A laboratory study is underway that is focused on study the 2.0 GHz GPR antennae device to determine more about its behaviour under varying conditions of temperature, moisture, and the presence of chemical preservatives. The effects of multiple metal fasteners embedded in a deck system is also being investigated in the laboratory. Another field study has been initiated with nearly 100 lumber and glulam specimens that have been inoculated with brown rot and assembled at an outdoor exposure site along the Mississippi gulf coast [7]. These will be closely monitored with the 2.0 GHz GPR device in the field to determine if any signs of incipient decay can be detected. Additionally, salvaged timber bridge members are being obtained from the desert of southern California. These unique bridges have been in-service for more than 80 years and will be inspected with a GPR device during the forensic analyses phase.

## 8 SUMMARY & CONCLUSIONS

Several NDE techniques were employed in this study to determine the most effective technique for inspecting for internal decay and internal moisture pockets for bridge-sized wood specimens. Inspectors were NDE industry practitioners or academic researchers with no prior knowledge of the internal defects and no external indicators of deterioration on the specimens. The ground penetrating radar unit identified the internal condition of the specimens with the best accuracy and warrants further investigation in the laboratory. Various parameters such as temperature fluctuations, moisture content effects, preservative treatments, and presence of metal fasteners are currently being investigated using the 2.0 GHz GPR antennae. The expected result of this research is the development of a reliable NDE scanning technique to rapidly inspect the primary structural components in historic covered timber bridges and other wood bridge structures.

## 9 ACKNOWLEDGEMENTS

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