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# Remote Detection of Termite Activity in Wooden Bridge Structures


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# Abstract

Wooden bridges, such as historic covered bridges or modern railroad and highway bridges, can become susceptible to subterranean termite feeding. This can result in weakened structural integrity of the wooden members of these bridges, and possibly even structural failure if damage is not discovered early and control measures are not implemented. The goal of this study was to evaluate the use of various remote detection methods, including acoustic emission sound waves, interruption of light transmission, radar and microwave transmission, moisture monitoring, and changes in gas concentrations in detecting termite activity. Successful methods for remote termite detection would reduce the number of annual site visits required to assess these structures and provide an early warning for potential damage, which could significantly reduce repair costs.



Keywords: historic covered bridges, biodeterioration, termite damage, remote sensing, acoustic emission, termite control, *Reticulitermes flavipes*


# Contents



This study is part of the Research, Technology, and Education portion of the National Historic Covered Bridge Preservation (NHCBP) Program administered by the Federal Highway Administration. 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.


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# Remote Detection of Termite Activity in Wooden Bridge Structures

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## Introduction

Wooden bridges, such as historic covered bridges and modern highway timber bridges, have a long history of use throughout the world. Time has shown that, as with bridges made of other materials, service life of wooden bridges is extended through proper construction, inspection, and maintenance (Ritter 1992; Ritter and Williamson 1995). The National Historic Covered Bridge Preservation (NHCBP) Program, which is sponsored by the Federal Highway Administration (FHWA), is focused on providing support for the preservation and restoration of these historic bridges, as these structures represent a unique cultural and technological heritage from that era (Yang and Clausen 2014). The serviceability of more modern timber bridges is also of major concern, as more than 24,000 of these structures are estimated to carry vehicle traffic within the United States (Wacker et al. 2013).

### Causes of Biodegradation

Countless variables can affect durability of wooden bridges in service. These include length of time in service, regional environmental conditions (such as mean annual temperature, humidity, precipitation), among other factors, which can substantially increase the risk of degradation and reduce treatment efficacy (Lebow et al. 2012). Multiple types and causes of degradation can occur simultaneously (such as excess moisture, decay fungi, wood-infesting beetles, termites) but require different remediation strategies (Moore 1979; Morrell et al. 1986, 1996; Lewis 1997; Yates and Grace 2000; Peterson et al. 2006; Ahmed and French 2008; Austin et al. 2008; Shupe et al. 2008). Therefore, identifying the source of biodegradation is important so that effective control or treatment measures can be applied.

### Problem Areas for Biodegradation in Wooden Bridges

As with any wooden structure, timber bridges are vulnerable to damage by a variety of wood-degrading organisms, which can result in significant damage. Much of this damage can relate back to an increase in moisture, which can actually increase vulnerability to decay fungi and termites. In timber bridges, areas most susceptible to biological deterioration includes wooden members in soil contact or those located in an area that is slow to dry (for example, stone or masonry used to construct abutments can wick and hold moisture) (Lebow et al. 2012). Other vulnerable areas are those located near the ends of the bridge, where wood may be continually subject to wetting from splashing, or along openings that allow for entry of wind-blown precipitation (Fig. 1) (Lebow et al. 2012). On covered bridges, one of the most common areas of deterioration is where the support members (bottom chord or bedding timbers) contact some form of an abutment (Fig. 2). Openings in the roof or cladding on these bridges can also be a common site for degradation. Therefore, preventative treatments should focus on these types of areas where moisture cannot be controlled, because excluding moisture is the best method for preventing biodegradation (Lebow et al. 2012).

Various methods or practices have been developed aimed at identifying and mitigating biodeterioration in wooden materials (Lebow and Anthony 2012; Lebow et al. 2012). In timber bridges, these practices can reduce the need for potentially costly supplemental repairs or replacement of damaged materials and may help prevent the possibility of complete structural failure. One common method for preventing biological attack is the use of timber that has been pressure-treated with wood preservative compounds (DeGroot and Felton 1998; Miltz 1991; DeGroot et al. 2000; Rhatigan et al. 2002). Pressure treatment with preservatives has allowed timber to be used for modern timber bridges without the need for protection from precipitation. However, in some situations, even pressure-treated wood materials can be vulnerable to biodegradation. In large timbers, continued exposure to wet and dry conditions can result in the development of drying checks, which expose non-treated wood in the center of the timber (Fig. 3) (Lebow et al. 2012).

### Termites

Much of the insect damage to wooden structures, including timber bridges, is the result of feeding by termites. Four families of termites occur in the United States:


**Figure 1. Members at ends of covered bridge are vulnerable to wetting from wind-blown rain because of the very small overhang.**

**Figure 2. Area in covered bridge members that often exhibit problems with moisture where they come in contact with an abutment or supports at the ends of the bridge.**

**Figure 3. Drying checks in bridge timber.**

Kalotermitidae (drywood termites), Rhinotermitidae (subterranean termites), Hodotermitidae (rotten or wet wood termites), and Termitidae (higher termites) (Peterson et al. 2006). Of these, the most economically important family is Rhinotermitidae, the subterranean termites, particularly species in the genera *Coptotermes* and *Reticulitermes* (Rust and Su 2012). In fact, an estimated 5 to 11 billion dollars are spent annually for prevention, replacement, and repair of subterranean-termite-damaged wood and wood products in the United States alone (Rust and Su 2012). For bridges in coastal areas, drywood termites can also be of concern. The rotten wood termites are not usually considered pests, although they do eat wood; species in this family feed on severely decayed, extremely wet wood that has already lost most of its structural capacity. Species of higher termites are generally not considered to be problematic, but in south Florida, a species in the genus *Nasutitermes* (an arboreal nesting, wood consuming, higher termite) is gaining a foothold, and thus may become a larger concern for bridge maintenance in the future (Scheffrahn 2013). In this report, the majority of the information presented concerns only subterranean termites because they represent the most significant risk to timber bridge structures.

## Subterranean Termite Identi ication and Detection

As their name suggests, subterranean termites require nearby contact with soil and spend the majority of their lifecycle underground, making termite detection difficult until damage is extensive. Signs of termite activity include visible, aboveground termite damage to structural members; mud or shelter tubes, which serve as a tunnel connecting the underground termite colony and the wooden building or structure above; and the emergence of winged reproductives (alates) in the spring or fall (Fig. 4).

Often, flights of termite alates are the first indication that a structure has an active termite infestation. The idea of using alate capture as a detection method, however, is not a solution for early detection of activity, because new colonies do not immediately produce alates (Barton 1934). Alates are a secondary concern for new colonies and generally occur only long after developing an actively feeding worker population. So by the time alates are noticed, damage may be more severe than if other detection methods are used. The other main flaw of using alates to determine termite activity in a bridge member is that they might have originated elsewhere. Alates of the eastern subterranean termite, *Reticulitermes flavipes* (Kollar), a common subterranean termite native to the eastern United States, have been shown to travel almost half a kilometer without wind assistance in laboratory studies (Shelton et al. 2006). Thus, alates detected on a bridge may have come from up to half a kilometer away and do not represent an active infestation of bridge members.

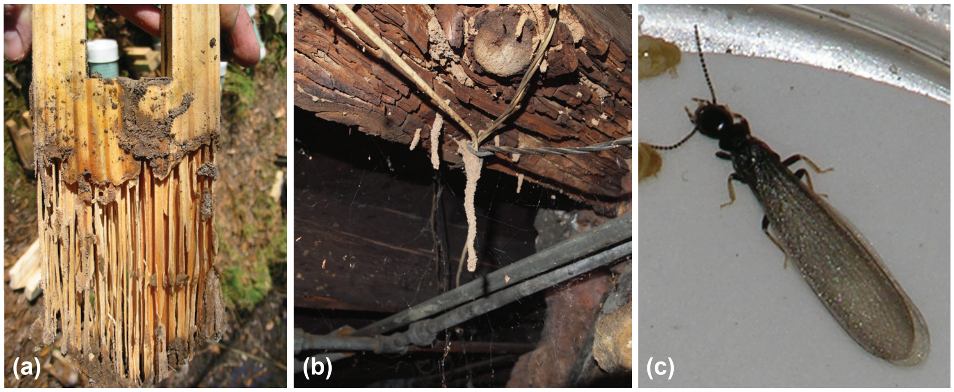


**Figure 4. (a) Termite damage to Southern Pine; (b) shelter/mud tubes; (c) alate.**

## Assessing the Need for Monitoring Biodegradation in Timber Bridges

As historic wooden and modern timber bridges grow older on our nation's highways, it has become increasingly important to consider how to maintain them in the long term. These bridges are often far from local management staff, making in-person inspections both expensive and time consuming. In addition, inaccessible areas within the bridge structure can impede traditional visual inspection methods. Thus, it is increasingly important to develop some means of monitoring structural integrity remotely to serve as an early warning sign of damage. Although this idea would serve as an efficient, cost-saving means of maintaining these structures, there is little research behind this type of monitoring. In this report, we discuss studies that have been performed by Forest Products Laboratory (FPL) researchers and others as means of remotely detecting wood degradation caused by these biological factors.

## Monitoring Systems for Remote Detection of Termites

A variety of methods used to detect termite activity remotely have been developed, including acoustic emission detection (AE) (LeMaster et al. 1997; Fujii et al. 1999; Fujii and Yanase 2001; Yanase et al. 2003a,b; Mankin and Benshemesh 2006; Osbrink and Cornelius 2013a,b; Green et al. 2015; González de la Rosa et al. 2015), gas analysis (Khalil et al. 1990), radar/microwave detection, LED sensors, moisture sensors, video scopes, and thermal imaging cameras (Lewis et al. 2010), to name a few. As part of this research project, several of the technologies that show promise for remote monitoring of bridges were evaluated.

Two identical stainless steel boxes (0.92 m wide by 1.5 m long by 0.61 m high) were fabricated and placed into a sub-basement where the ambient temperature ranged between 27 and 32 °C. Hinged lids framed with weather stripping were used to help maintain high humidity within the boxes. Sections of red and Southern Pine timbers 1.2 m in length were placed into each tank to represent bridge timbers. Subterranean termites (*Reticulitermes flavipes* (Kollar)) were captured in corrugated cardboard in Janesville, Wisconsin, and released with commercial sand and soil from the colony sites into both tanks. The number of termite workers in each tank was estimated using a mark–release–recapture method (Esenther 1980; Grace 1990; Thorne et al. 1996), as follows: A subset of workers was captured, fed filter paper stained with dye, counted, and then released back into the tank. After one week, another group of workers was captured and the number of marked termites was determined. This process was repeated two more times, allowing the number of worker in each tank to be estimated as 8,000–10,000. It should be noted that this method of estimating termite population relies on the unverified assumption that the marked termites become homogenously distributed within the termite population in the tanks (Thorne et al. 1996).

### Acoustic Emission

Acoustic emission devices have already been used successfully to detect activity of numerous insect species, and were used to detect termites as early as 1909 (Barton 1934; Mankin et al. 2011). When properly configured, AE devices can detect the small vibrations caused by termites as they snap or bend wood fibers while eating or moving (Mankin et al. 2011; González de la Rosa et al. 2015). AE devices have also been used to detect the stronger vibrations created when termite soldiers rapidly bang their mandibles (head banging) as a long-distress and warning signal (Fink et al. 2006; González de la Rosa et al. 2005; Howse 1965; Mankin et al. 2011). An advantage of AE detection, relative to some other technologies, is that termite activity does not need to be immediately adjacent to the sensor. Termites have been detected at distances of 2.2 m parallel to the wood grain and 80 mm across the grain. However, because AE devices are so sensitive, they also detect background noises, which may make it difficult to differentiate termite activity (Mankin et al. 2011; González de la Rosa et al. 2015).

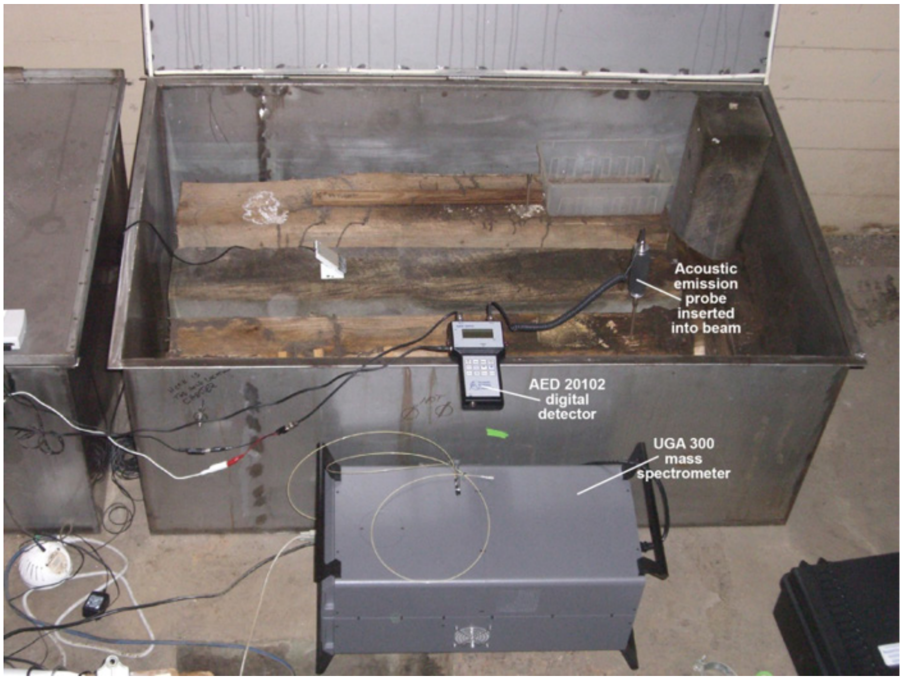


**Figure 5. Termite boxes for testing AE signals to establish an AE fingerprint of *R. flavipes* invading red pine and Southern Pine members.**

For approximately one year, continuous AE readings were monitored from multiple sensor locations within the two stainless steel termite boxes described. Methods to increase and refine the AE signal produced by the termites during wood consumption were explored. The best AE response resulted from the combined use of AED-2010L digital detection and piezoelectric probe-sensor Model SP-1L, which has a preamplifier built into the probe (Fig. 5), both supplied by Acoustic Emissions Consulting (AEC) (Fair Oaks, California). The low-frequency Model SP-1L probe provides an acoustic range of detection from 1 to 50 kHz. The AED-2010L allows the operator to hear the "pops" resulting from termites consuming the wood. The amplified AE signal output was captured using high-speed data acquisition for computer graphing and analysis. Four locations were monitored, and a direct correlation between radar detection of termites and AE was confirmed.

A record of "termite hits" over time is shown in Figure 6. A "hit" occurs when the amplitude of the AE signal rises above a set threshold defined in the AE device. The total number of hits per 4-s interval is recorded and can be displayed over time to show the level of termite activity, which varies due to factors such as number of termites and temperature. Other ways to analyze the vibration data are illustrated in Figure 7. On the left is the raw output from the vibration probe captured with a data acquisition system using the preamplified output of the AED-2010. This shows the spikes in vibration amplitude, which indicate termite activity and are captured as hits in the standard AED-2010 output. On the right in Figure 7 is a different kind of analysis, seeking to find patterns in the output by applying a Fourier transform to produce the power spectrum. A power spectrum allows visualization of the most common frequencies of vibration in the data sample (González de la Rosa et al. 2015). If a periodic signal exists, the power spectrum will show a large amplitude at the frequencies that characterize the periodic signal. However, no significant periodic components are evident in the termite signal shown in Figure 7.

Without a known pattern to the signal from termite feeding, we attempted to use the AED-2010L for counting hits to help characterize termite activity—essentially counting any signal above a threshold. The count should correspond to the number of large irregular spikes seen on the left in Figure 7. The count level depends on amplification and filtering applied to the raw vibration signal. With the AED-2010L set to gain of 4 and with the high-pass filter in place, one site produced an average of 10 to 50 hits every 4 s. Figure 8 shows hits over time at the other sensor locations, illustrating the variable but generally constant range of hits. The sharp drop in number of hits shown on the far right side of Figure 8 may have occurred because the termites temporarily ceased activity after being disturbed. This shows that the overall signal intensity from termites can be significantly stronger than a quiet background, and that AE can successfully detect termites in a controlled laboratory setting.

One of the concerns with AE termite detection is its susceptibility to interference from other sources of noise in the environment. To demonstrate this effect, the piezoelectric probe-sensor was plugged into the outer bark of a healthy tree in a quiet area of the laboratory

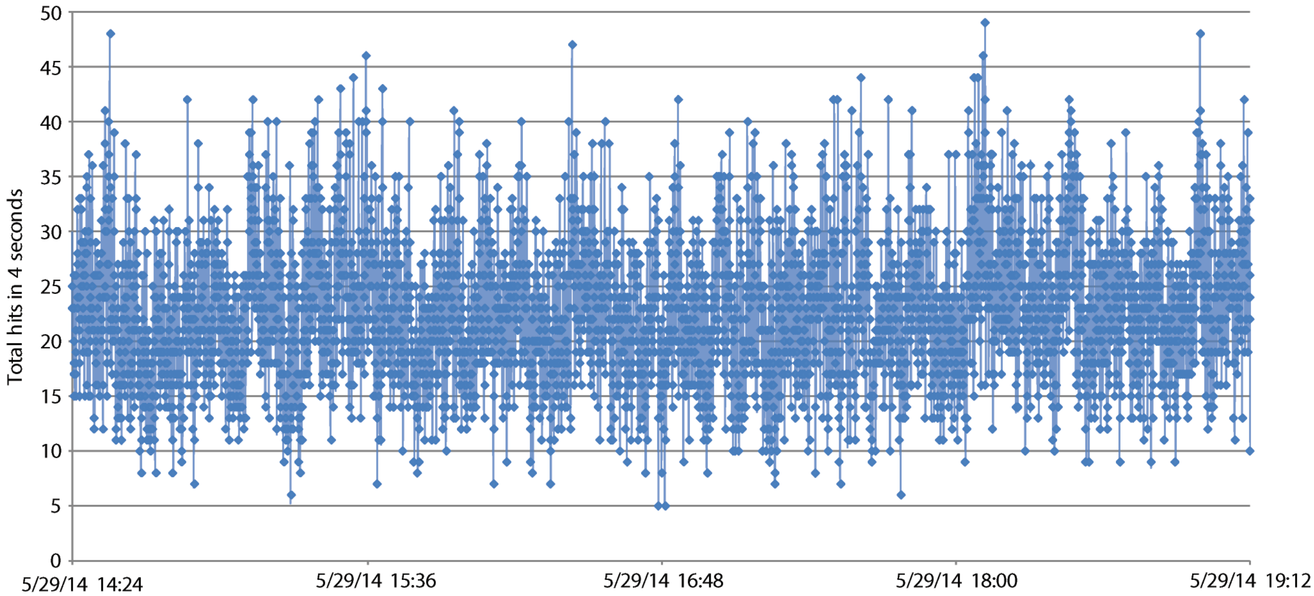


**Figure 6. Example of termite hits per 4-s interval detected at one of the locations within the boxes.**

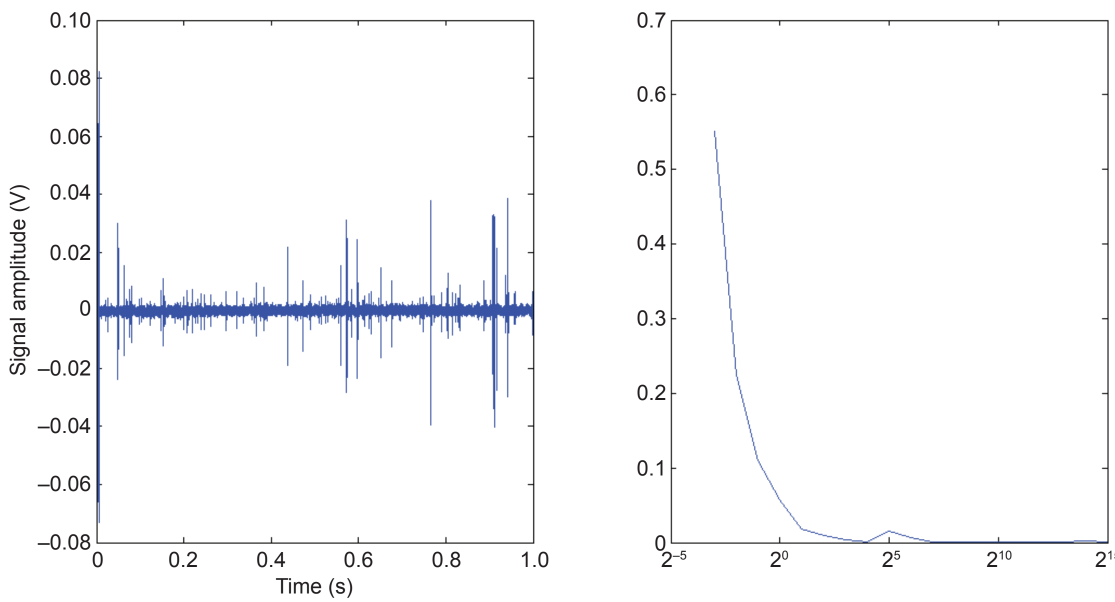


**Figure 7. Signal over time (left) and power spectrum (right).**

grounds. As in much of Wisconsin, there has never been an active termite colony near this location. Using AE, we could confirm the absence of termite activity in the tree or adjacent area, and the same settings (such as gain and filter) were used as for the termite tanks. The background noise was initially quiet, as shown on the left side of Figure 9, but an increase in hits 10 hits per 4 s was easily generated simply by tapping a rock near the tree. An even larger number of hits (30–60 per 4 s) as was created but scraping a stick on the bark of the tree. Although this simulated test does not replicate the background noises that may occur in a covered bridge, it does show how easily other activities in the environment can produce hits in the same range as that produced by termite feeding.

Because the normal feeding activities of termites produce a signal that may be difficult to separate from background noise, a second experiment was initiated in an attempt to focus on detection of the stronger vibrations ("head banging") (Howse 1965) produced by termite soldiers as an alarm signal. Figure 10 shows an experiment in which we used a small block of wood, which allowed for better control over the number and kind of termites that had access to the wood. The block and sensor probe were placed inside a laboratory incubator to maintain favorable

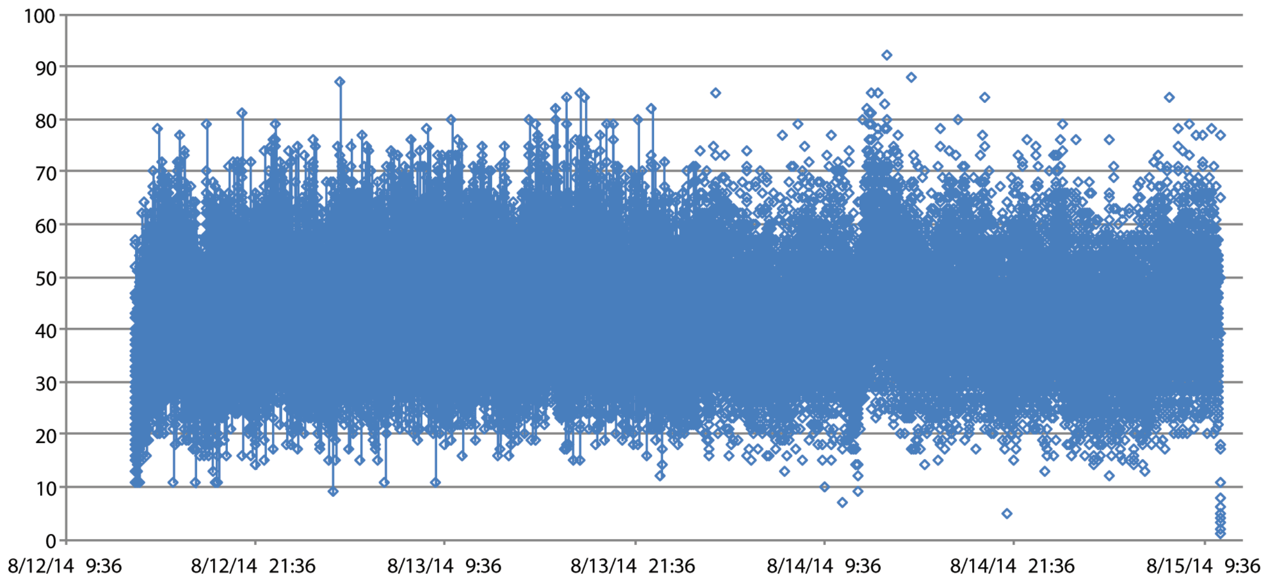


**Figure 8. Example showing an average of 42 hits per 4 s detected at another sensor location within a termite box.**

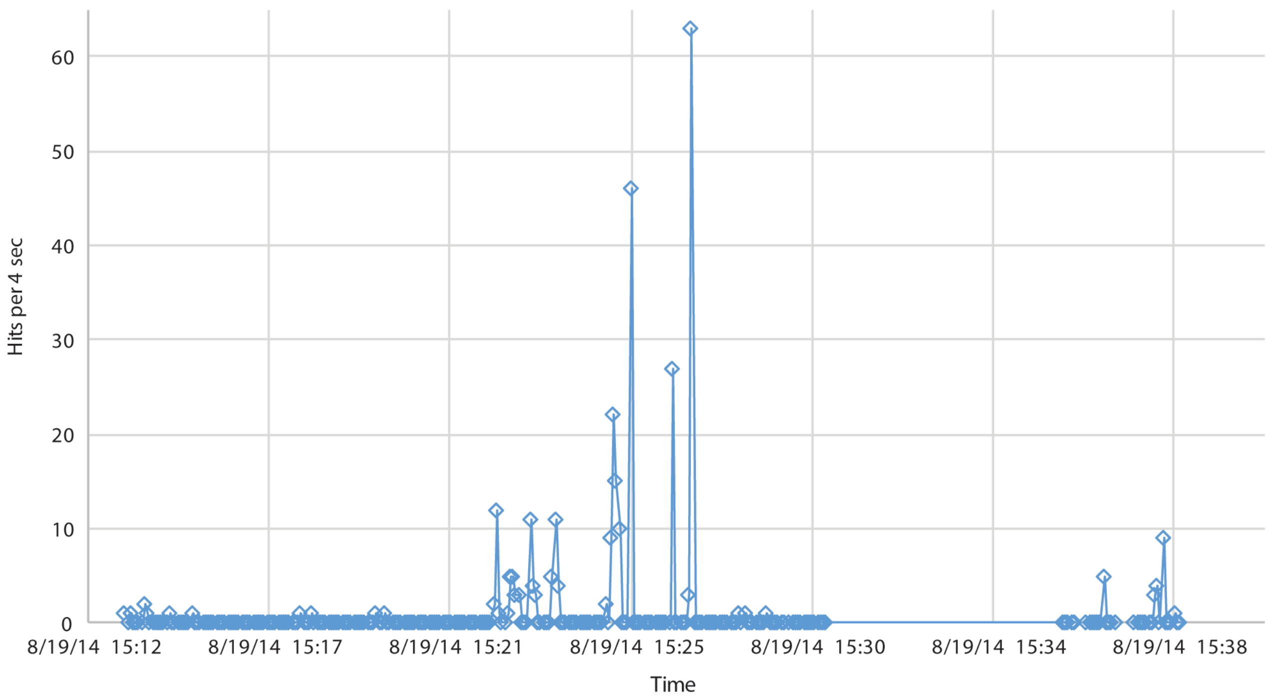


**Figure 9. Example of AE hits detected when sensor was installed in a tree on a quiet location within the laboratory grounds. Tapping a rock near the tree resulted in around 10 hits per 4 s; scraping the tree bark resulted in much greater hit intensity.**

temperature and humidity conditions while insulating the test from background noise. The test was inconclusive because, regardless of how many soldiers we added to the small block, or ants to try to excite or stimulate the soldiers to emit head-banging, no sudden, large, sharp increase in peak hits was observed in response to external stimuli. Cumulative counts from June 18 to June 24 showed a relatively steady number of counts over the period. We also measured average background counts of hits before and after turning off the incubator compressor motor. With the compressor on, there were 0.38 hits per 4 s; whereas with the compressor off, there were 0.49 hits per 4 s. This is unlikely to represent any significant difference, but it indicates that the compressor motor did not add any measurable number of hits.

Although detection of termites using AE was successful under laboratory conditions, the approach has some

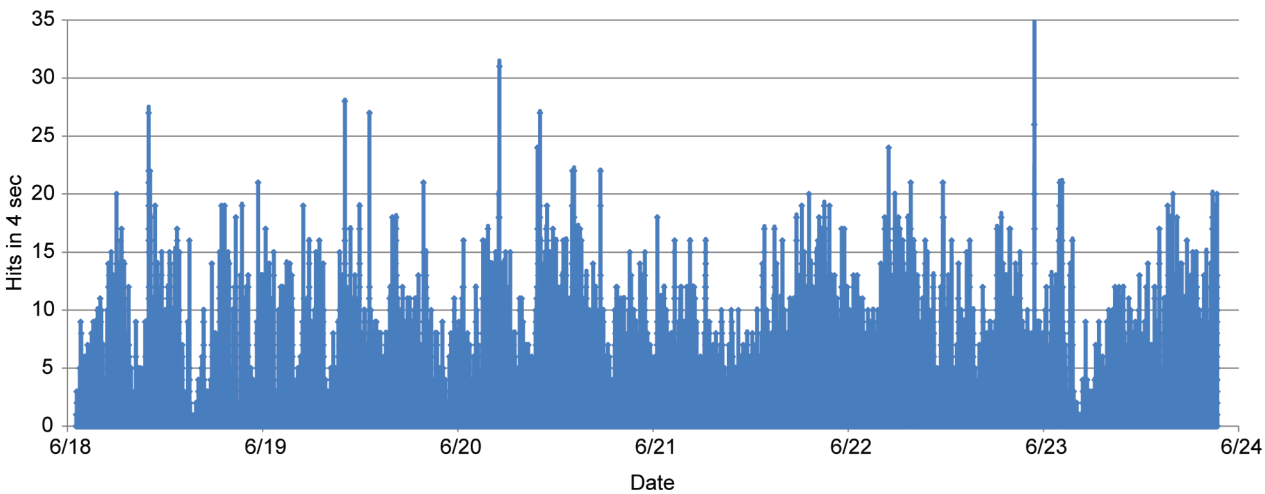


**Figure 10. Arrangement of probe in a small block of wood inside an incubator (top) and example of resulting hits detected (bottom) as part of an effort to characterize termite activity. The small block was used to allow better control of the number and castes of termites exposed to the wood.**

limitations for use in remote monitoring of bridges. One disadvantage is that the sensor evaluated would be costly if installed at multiple locations on a bridge. We also evaluated a less expensive 622B01 sensor from PCB Piezotronics (Depew, New York) but found that its sensitivity level did not allow detection of termite activity under our test conditions. We were not able to detect obvious head-banging behavior in our experiments and without head-banging, the AE signals were weak and difficult to distinguish from other acoustic noise in the environment. AE technology and data processing are also fairly complex and may not be ideally suited for the rigors of remote field monitoring.

Other researchers have also noted that although AE devices work well for termite detection in a laboratory setting, they may be somewhat less effective in field applications (González de la Rosa et al. 2015; Lewis et al. 2010; Zahid et al. 2012). As noted in this study, differentiation of termite activity from other sources of vibration can be difficult in uncontrolled settings. However, on-going research on signal processing and analysis appears to show promise in better differentiating termite activity (González de la Rosa et al. 2015; Mankin et al. 2011; Osbrink and Cornelius 2013a,b), and the use of AE technology for remote monitoring of bridges may warrant further evaluation as the technology evolves.

## Electrical and Light Sensors

Another approach to termite detection relies on termite feeding or mudding activity to interfere with tranmission of electricity or light. Technology that senses the breaking of an electrcial circuit is already in commerical use for monitoring of termite bait stations (Eger et al. 2011; Su 2002). The remote monitoring station contains cellulose or similar material with a conductive circuit that is intended to be fed upon by termites. In commercial use, the monitoring device with associated circuit is placed in the monitoring


**Figure 11. Termite mud/shelter tube deposition by termites on the plastic surface of sensor.**

**Figure 12. LED light sensor set to maintain 0 V as long as detector receives light.**

station housing that is planted in soil (Eger et al. 2011). Termite feeding in sensors can be readily detected because termites easily chew through the relatively thin circuit tracing while depositing mud and shelter tubes. Figure 11 shows an example of termite mud tube deposition that may occur inside a sensor. Previous studies indicate that even under a humid and warm climate, the sensor circuit may remain conductive for a long as six months or more in the absence of termite activity (Eger et al. 2011; Su 2002).

Current use of the electrical circuit approach appears to be confined to bait stations, and there is little evidence that it has been used on or within members of timber bridges. Soil around a bridge could potentially be monitored using bait stations equipped with this technology, but if termites are present in the area it is likely that the bait stations would be targeted regardless of whether the bridge was attacked. The cellulose or similar matrix imprinted with the electric circuit is also necessarily biodegradable, and thus may last less than a year even without termite feeding (Su 2002; Eger et al. 2011). There is also a risk of termites moving directly from the soil into a bridge timber without encountering a bait station. This risk would occur if even aboveground bait stations were fastened direclty to the exterior of a bridge timber. It is possible that this approach could be adapted to install sensors within brigde timbers, but additional research would be needed.

Another approach that has potential for use within both bait stations and bridge timbers relies on light sensors to detect the presnce of termite activity (Capella et al. 2011; Oliver-Villanueva and Abian-Perez 2013; Wright et al. 2009). Oliver-Villanueva and Abian-Perez (2013) describe a system using LED light emittance and reflection recapture to detect termites and potentially other wood boring insects. Sensors are installed in plastic sleeves that can be inserted into holes drilled in wood. Data from individual sensors are sent to a base station, which processes the data and transmits it via a cellular data connection. The authors note that the termites appear to be bothered by the light source and actively seek to block it with mudding activity. Capella et al. (2011) describe how an entire sytsem of these sensors can be arranged to monitor a historic wooden structure. A somewhat opposite approach is discussed by Wright et al. (2009) for use in bait stations. In this case a termite bait is used to block light transmission, and the sensor is triggered when termites consume the bait.

We briefly experimented with the LED sensors as part of this study. An LED detector was set up covering an outer hole in a cardboard tube and then exposed to a colony of *R. flavipes* in the laboratory (Fig. 12). As the termites invaded the cardboard tube, they characteristically mudded in the hole in the tube, blocking the light signal to the detector, which caused a 5.0-V increase in the signal to the detector (Fig. 13). This type of simple technology could also be used in an aboveground bait station to remotely detect the presence of a termite infestation, and possibly be installed within bridge timbers as described by Oliver-Villanueva and Abian-Perez (2013).

One disadvantage of both the electrical circuit and light tranmission sensors is that termite activity is detected only if termites directly interact with the sensor. In theory, termites could be active within a few millimeters of the this type of sensor withough being detected. Thus, closer sensor spacing might be required than for a technology such as AE detection.

## Radar and Microwave Detection

Radar devices use microwave technology to detect movement of termites (Lewis et al. 2010; Le Marshall and Tirkel 2011). At least one device, the multichannel Termatrac T3i handheld detector (Termatrac, Stapylton, Australia), is commercially available (Fig. 14). This device is a portable unit that is controlled by a cell phone or tablet computer. It also incorporates a thermal sensor with laser guide to detect potential termite risk areas via heat

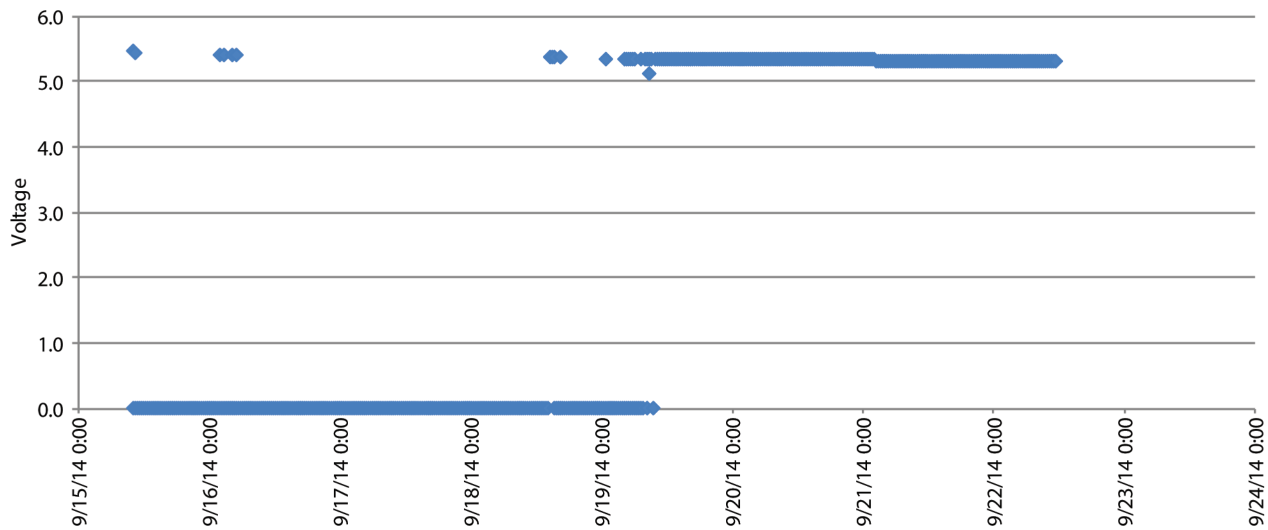


**Figure 13. Change in voltage (0 to 5.0 V) after mud tube deposition and light blockage on LED detector.**


**Figure 14. Termatrac T3i radar termite detector.**

differentials and a moisture sensor to identify moisture levels conducive to increased termite risk. Wireless connectivity with the computer enables data from the three technologies to be managed, analyzed, stored, and integrated into inspection reports. This study briefly evaluated the Termatrac T3i device and found that it was able to detect termites under laboratory conditions.

Other researchers have reported that radar is effective in detecting termites in laboratory studies but has been somewhat less effective in field inspections (Le Marshall and Tirkel 2011; Lewis et al. 2010; Zahid et al. 2012). Detection is limited to a relatively small area and depth within the wood, and readings can be affected by moisture, movement of the device, and vibration within the structure (Le Marshall and Tirkel 2011; Lewis et al. 2010). Research continues to develop radar detectors that scan a larger area and produce high-resolution imaging (Le Marshall and Tirkel 2011).

## Remote Moisture Monitoring

Wood moisture content is a critical factor in risk assessment of biological (decay and termite damage) and nonbiological degradation of wood used in historic timber and covered bridges (Lebow and Anthony 2012) and in many climates is the primary determinant of aboveground decay hazards. There has been substantial international interest in remote monitoring of timber bridge moisture contents to allow early detection of areas vulnerable to degradation. In one of the earlier efforts, Forest Products Laboratory researchers reported success in remotely monitoring moisture content in bridge timbers using OmniSense sensors (Wacker et al. 2007). More recently, researchers in Sweden report on monitoring of nine timber bridges with electrodes installed for resistance-based determination of wood moisture content. Data collected by data loggers was transmitted weekly via cell phone (Koch et al. 2017). A similar approach has been used to monitor four timber bridges in Switzerland (Franke et al. 2013). Research has also been initiated to apply this technology to covered bridges in the United States (Phares et al. 2010; Wacker and Phares 2010).

Although the focus to this point has been the use of moisture content monitoring to detect fungal decay, the technology is also applicable to termite detection. One difference is that fungal decay occurs only when the wood has previously become wet from an external source, whereas termites are able to transport moisture into the wood from adjacent soil (Gautam and Henderson 2014). This allows termite attack to become a concern in bridges that have otherwise been designed and maintained in ways that prevents moisture intrusion. Previous laboratory studies report that subterranean termites can increase the moisture content of dry wood by 20% to 40% MC after two weeks (Guatam and Henderson 2014) and increase the moisture content of cellulose to 46% after 3 weeks (Gallagher and Jones 2010).

**Figure 15. Two external, aboveground termite bait stations, each containing the OmniSense Remote wireless sensor (inset), which tracks RH and temperature 24 h per day as termites in the parent tank accept these bait stations into the colony domain and begin to consume the substrates. Data can be downloaded from the internet and graphed.**

In this study, moisture contents as high as 28% were noted in the vicinity of termite degradation. Because the moisture content of wood used above ground and protected from precipitation is typically below 15% and rarely exceeds 20% (Simpson 1998), the moisture increase caused by termite activity should be detectable.

Devices that allow remote moisture monitoring are commercially available. OmniSense sensors monitor temperature, humidity, and moisture content (also known as wood moisture equivalent, WME). These sensors integrate a wireless transceiver, temperature sensor, humidity sensor, and pin-type (resistance) moisture meter and operate from a lithium battery with a typical battery life of 15+ years. They can be permanently embedded onto structures for long-term building envelope performance monitoring or temporarily mounted for monitoring structural drying. Data is transferred via cellular service to the OmniSense server where it can be downloaded by the user.

Moisture sensors can also be incorporated into termite bait stations, and that approach was evaluated as part of this study. Two types of aboveground bait stations were installed on the top of the lid of a stainless steel tank and an access hole drilled thru each to connect with the termite colony below. Stations were baited with corrugated cardboard, microcrystalline cellulose, pine wood, and plywood blocks. A remote sensor was added to each bait station (Fig. 15) and set to collect approximately 700 data points per day. The server database checks each data point against user-settable alarm thresholds and permanently stores the data point and its context, including the sensor ID, network ID, and time of occurrence. The data captured by the wireless sensor is relayed to a base station that is connected to the internet. The sensor periodically “wakes up” and sends data to the base station, which then relays the data to internet cloud storage maintained by OmniSense so that it is available on their website (Sandberg et al. 2011).

From February 7 to 13, 2015, OmniSense detectors showed various changes in RH in the two aboveground (AG) termite stations (Fig. 16). The round clear 2-L plastic AG station (black line, sensor 180) and the rectangular gray AG station (gray line, sensor E9) differ in that the latter had been invaded by termites for only less than 1 week. Figures 17 to 20 illustrate the dramatic changes in humidity and WME detectable in the presence of invading termites in the aboveground bait stations. WME is the same as wood moisture content of the wood bridging the two pins of the OmniSense sensor. These graphs illustrate the principal differences in sensor readings that can be recorded depending on whether or not the aboveground bait stations are being invaded by *R. flavipes*. It is important to compare lower control or room values with those higher values for RH and WME after the stations contain termites. The large changes make it relatively straightforward to detect termites.

Remote sensors are capable of sending data directly from covered bridge timbers to any computer using a cellular data link. All sensors (Fig. 21) are wireless and are powered by a long-life lithium battery, which typically provides 15+ years of service. Users can configure custom alarm thresholds for all sensor data and receive real-time alarm messages by email or text message.

A limitation of commercially available resistance-based wood moisture sensors is that the two electrodes are typically less than 50 mm apart. As a result moisture content is monitored in a relatively small area when compared to the volume of a large bridge timber. Numerous sensors could be installed, but this increases cost and makes data collection more complex. Another alternative is modification of the electrode spacing, because research indicates that distance

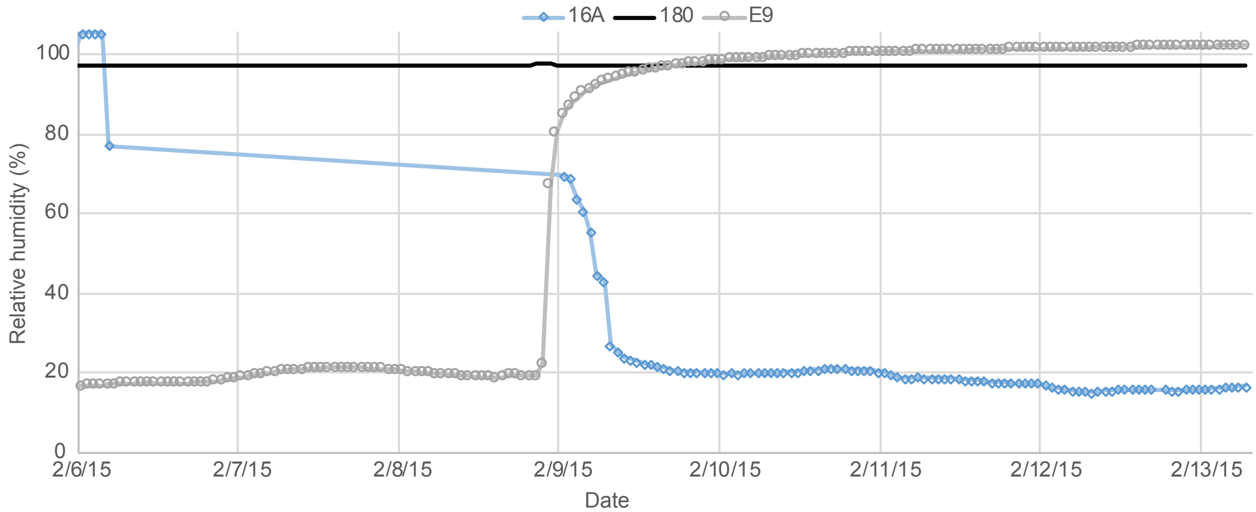


**Figure 16. Changes in relative humidity in the two external aboveground bait stations (as shown in Fig. 15). The blue line (16A) illustrates the low humidity exterior to the stainless tanks on February 13, 2015. The solid black line is sensor 180 in the clear biochamber, and the gray line is sensor E9 in the gray plastic aboveground Exterra (Ensystex, Fayetteville, North Carolina) station, both showing RH near 100%.**

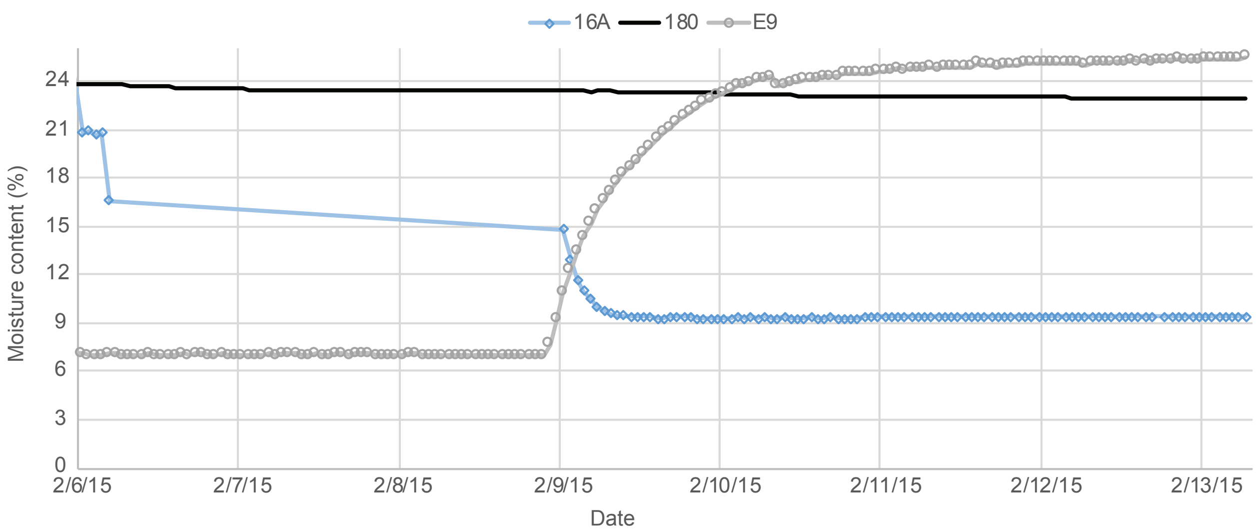


**Figure 17. WME of the plywood insert on the OmniSense remote sensors, which shows 24% to 25% on the infested aboveground stations and less than 10% on the control room sensor (16A).**

between electrodes has little effect on electrical resistance readings (Forsen and Tarvainen 2000; Zelinka et al. 2015). The problem remains, however, that a moisture pocket will be detected only if it extends far enough to contact both electrodes. Even a small area of drier wood surrounding one of the electrodes will increase resistance and prevent moisture detection. Thus, as the electrode spacing increases, the length of the moisture pocket must also increase to create a path of lower resistance. The lengths of electrodes in commercial wood moisture sensors are also relatively short in comparison to the depth of a large timber, and accordingly previous researchers have experimented with increasing the electrode length to increase the area of wood contact. This approach has shown promise for monitoring moisture content in both solid and glued-laminated bridge timbers, although recalibration may be needed for very long probes (Bjorngrim et al. 2017; Li et al. 2018).

An alternative approach is to install moisture sensors in aboveground baits stations, as was evaluated in this study. The bait stations can be fastened to the bridge structure in areas where termites are likely to attempt to gain access to a bridge. However, it remains possible that termites could enter bridge timbers without encountering a bait station. Aboveground bait stations may also accumulate moisture through condensation, potentially limiting their use for detecting increases in relative humidity or wood moisture content.

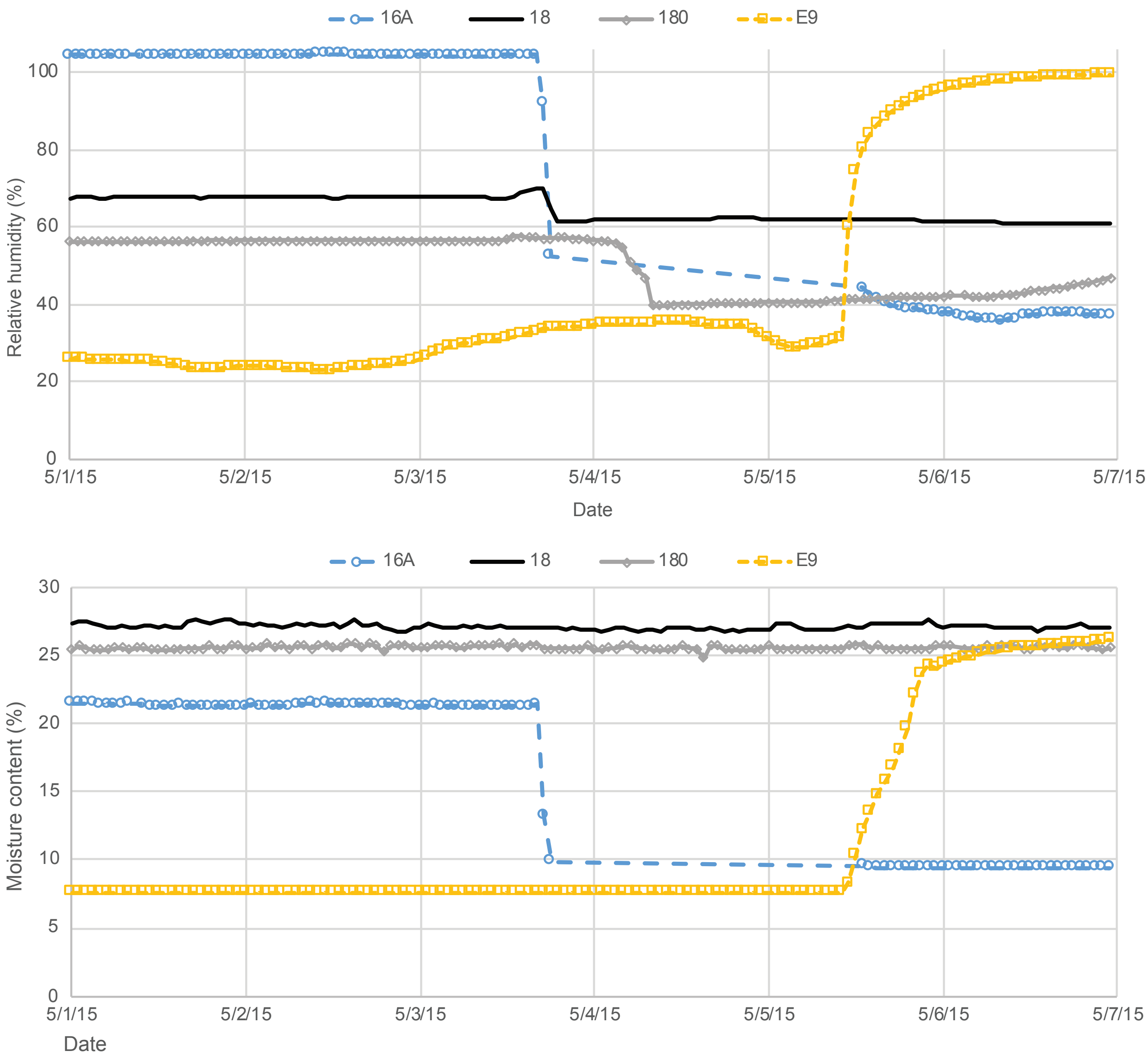


**Figure 18. Results from sensor E9 on 5/16/15 showing 100% RH (top) and a corresponding WME of only 25% (bottom). RH increases above 40% do not result in further increases in WME.**

## Gas Emission Detection

A number of studies have shown that termite colonies can produce measurable changes in gas composition in or around their nests. French et al. (1997) made in situ measurements of gas composition in and around Australian termite mounds, and Wheeler et al. (1996) and Cao et al. (2010) measured how small numbers of termites, including *R. flavipes*, changed the atmosphere of small sealed containers. Anderson and Ultsch (1987) measured $CO_2$ and $O_2$ in samples drawn directly from active *R. flavipes* tunnels. These studies show termite production of methane ($CH_4$) and hydrogen ($H_2$) as well as other compounds; however, gases produced and their ratios may depend upon a number of variables.

To determine the feasibility of detecting gases produced by termites as an infestation detection method on wooden bridges, several measurements of the atmosphere inside the termite tanks were made using a quadrapole mass spectrometer (UGA300, Stanford Research Systems, Sunnyvale, California, USA). This mass spectrometer was configured to measure the concentrations of nitrogen ($N_2$), oxygen ($O_2$), argon (Ar), carbon dioxide ($CO_2$), methane ($CH_4$) and hydrogen ($H_2$).

The mass spectrometer was used to sample the atmosphere in the tank in two ways. In one method, the sample tube was attached to a fitting on the side of the tank so that gas was sampled from the void space of the tank, above the infested timbers. This was done with the lid having remained closed

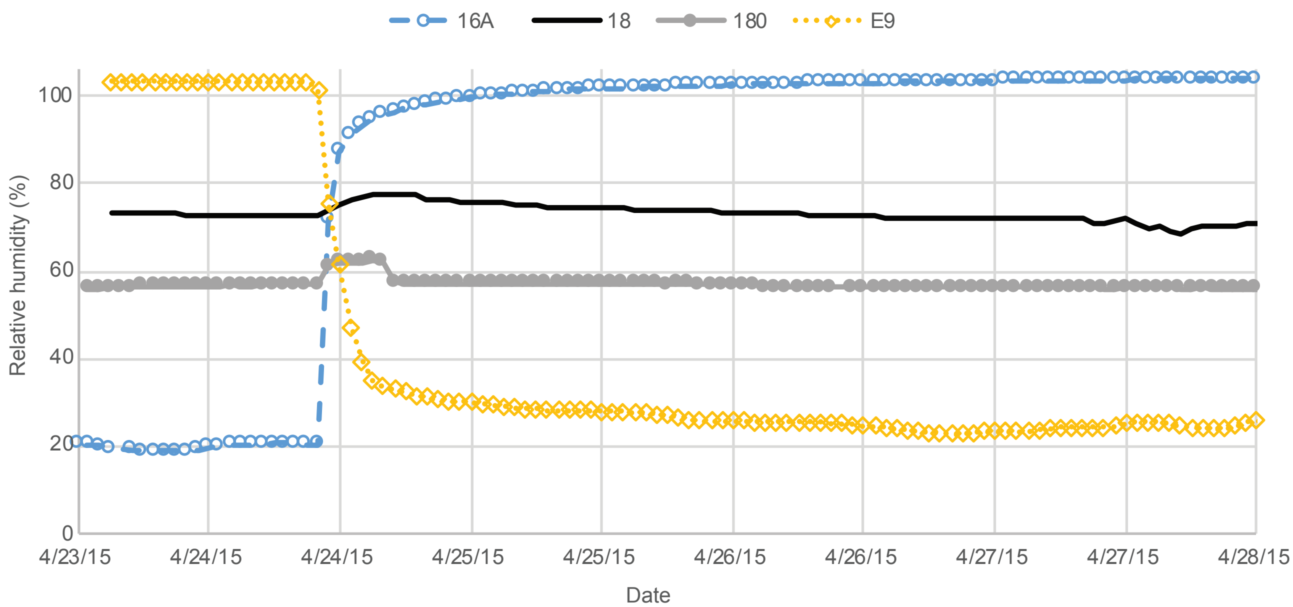


**Figure 19. Relative humidity (%) for the three aboveground bait stations.**

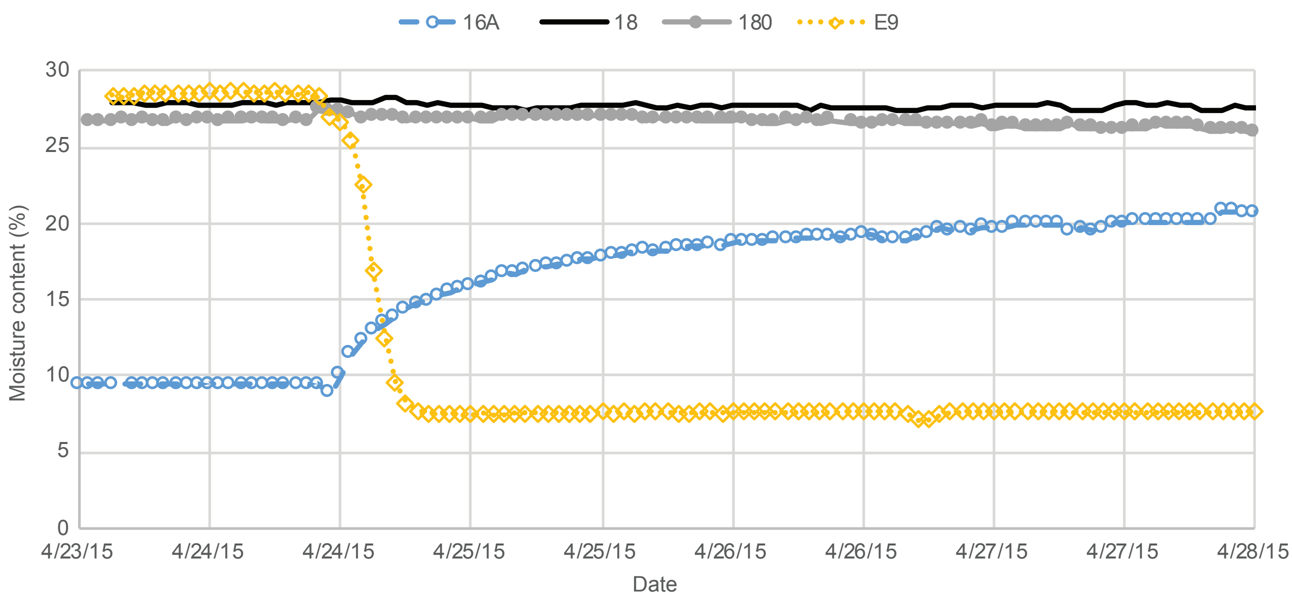


**Figure 20. WME (%) of wood block attached to each sensor. Moisture content of wood block in room air is <10% (yellow line). The highest RH levels do not always result in the highest WMC levels.**

**Figure 21. OmniSense Cellular gateway (left) and WME block with wireless antenna (right).**

**Table 1—Commonly used termite control methods**

| Control method | Examples of active ingredient(s) | Termites targeted | Type of control |
|---|---|---|---|
| Aboveground bait stations | Insect growth regulators (e.g., hexaflumuron, noviflumuron) | Subterranean termites Dry-wood termites | Monitoring/remediation |
| Below-ground bait stations | Same as in aboveground bait stations | Subterranean termites | Monitoring/remediation |
| Liquid barrier treatment/ trenching | Fiproles, nicotinoids, pyrethroids, anthranilic diamides | Subterranean termites | Preventative/remediation |
| Drill and treat with natural product extracts | Essential oils (e.g., orange oil) | Dry-wood termites | Remediation |
| Wood preservatives[a] | Borates (e.g., boric acid powder or brushed-on disodium octaborate tetrahydrate products),alkaline copper quaternary (ACQ) | Subterranean termites Dry-wood termites | Preventative |
| Fumigation | Sulfuryl fluoride | Dry-wood termites | Remediation |

[a]See "In-Place Wood Preservative Treatments" section.

for a number of days. In the second method the sample probe was inserted directly into a termite tunnel in the timber, with the lid of the tank open.

Both methods achieved similar results. It was found that the concentration of $CO_2$ and $O_2$ changed significantly; however, no production of $CH_4$ or $H_2$ was detected. Concentrations of $CO_2$ as high as 6.5% and concentrations of $O_2$ as low as 11.9% were measured inside the tanks. However, because $CO_2$ increases with corresponding $O_2$ decreases and changes could be attributed to biological activity other than termites, such as wood decay, it was determined that measuring $O_2$ and $CO_2$ levels would not be useful for detecting termite activity.

The study by Cao et al. (2010) showed that under controlled conditions *R. flavipes* produce $H_2$ at a maximum rate of 3.07 µmol/h/g body weight and $CH_4$ at a rate of approximately 4 times that. Additionally, $H_2$ and $CH_4$ both have densities lower than air and diffuse easily in air mixtures. The low production rate of these gases combined with their physical properties make it very unlikely that a detectable level of either $H_2$ or $CH_4$ could build up in or near an open wooden structure such as a bridge, unlike in a relatively well contained termite mound as was sampled by French et al. (1997). The results from this study agree with this hypothesis.

## Control Options for Termite Infestations after Detection

Once termite activity is detected and confirmed visually, an appropriate treatment method should be selected. Application of these treatments should be done by trained and licensed pest control operators (PCOs) using approved termiticides. There are a number of variables involved in treatment selection, such as proximity to water, which is a major consideration for treatment of timber bridges. Alternatively, there are also a few preventative measures that can be used in areas with known termite risk (Table 1).

Bait stations and liquid barrier treatments are likely to be the most practical methods of treatment for timber bridges. Bait stations are one of the most commonly used methods for termite monitoring and treatment to date. This includes both in-ground and aboveground stations. There are distinct advantages to using bait stations for termite detection because termiticidal bait product can be added directly to the stations once termite activity begins. In theory, this procedure gets termites to begin consuming the termiticide baits sooner because they are already feeding on the control baits during the detection period. However, due to the slow-acting nature of the insect growth regulators used for bait toxicants, control of the termites can take months to accomplish (Grace et al. 1996; Osbrink et al. 2011). Liquid barrier treatments could be applied to the soil where bridge members make ground contact. Liquid termiticides may also be applied directly to infested bridge members in an attempt to reduce feeding while other methods are employed. However, in both cases of liquid termiticide application, regulations on use near water could prohibit this type of treatment.

## In-Place Wood Preservative Treatments

Another approach to protecting bridges from termite attack is preservative treatment of the wood itself. Wood used to construct covered bridges typically was not treated with preservatives, and thus much of the structure is potentially vulnerable to termite attack. More modern timber bridges are constructed with pressure-treated wood, but the preservative often does not penetrate to the center of large timbers or piles. In some cases, field-applied preservative treatments may provide additional protection for both covered and modern timber bridges (Lebow et al. 2012).

A major limitation of in-place treatments is that they cannot be forced deeply into the wood under pressure, as is done in the pressure-treatment processes (Lebow et al. 2012). Surface-applied liquid treatments should not be expected to penetrate more than a few millimeters across the grain of the wood, although those containing boron can diffuse more deeply under certain moisture conditions. Liquid surface treatments are most efficiently used to flood surface opening such as checks, exposed end-grain, and bolt holes. They may move several centimeters parallel to the grain of the wood if the member is allowed to soak in the solution. Surface treatments with diffusible components will be washed away by precipitation if used in exposed members. In general, surface-applied liquid treatments will not effectively protect the interior of large piles or timbers.

Paste surface treatments can provide a greater reservoir of active ingredients than liquids. When used in conjunction with a wrap or similar surface barrier, these treatments can result in several centimeters of diffusion across the grain into moist wood over time. They are typically used for the ground-line area of posts or piles that are not usually exposed to standing water but can also be applied to end-grain of connections or pile tops.

Internal in-place treatments are often a better choice for the large timbers and piles used in bridge construction. They are applied to holes drilled into the wood, and come in the form of liquids, pastes, rods or tubes. They can be applied to smaller members in some situations. Diffusible internal treatments (typically borates) move through moisture in the wood. They are relatively easy to handle but do not move as great a distance as fumigants and do not move in dry wood. Diffusible treatments may be best suited for focusing on specific problem areas, such as near exposed end-grain, connections, or fasteners. In contrast, fumigant internal treatments move as a gas through the wood. They have the potential to move several feet along the grain of the wood but have greater handling and application concerns.

Wood preservatives and liquid termiticides are defined as pesticides under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and are regulated by the U.S. Environmental Protection Agency (EPA). EPA regulations provide a minimum set of requirements, and each state may have additional requirements. The EPA is most concerned with Restricted Use Pesticides (RUPs). Two of the fumigants (chloropicrin and methylisothiocyanate) fall into this category. EPA regulations require that RUP applicators be certified as competent to apply RUPs in accordance with national standards. Certification programs are conducted by states, territories, and tribes in accordance with these national standards. Certified applicators are classified as either private or commercial, with separate standards for each. All states require commercial applicators to be recertified, generally every three to five years. Some states also require recertification or other training for private applicators.

States vary in their regulations about application of non-restricted use pesticides. Most states require that commercial applicators become licensed to apply these pesticides. Because bridges are public property, many states require government employees to become trained and licensed to apply non-restricted use pesticides.

## Summary and Conclusions

Although the acoustic emission (AE) system readily detected termite activity, we concluded that this technology, although satisfactory for on-site, hand-held inspections, was unnecessarily cumbersome, complex, and expensive for remote detection of termites. We also concluded that the AE system is less than ideal because of its very high sensitivity and potential for false AE readings from wind, weather, and traffic.

For these reasons, it was decided that wireless sensors could be placed within above ground bait stations to measure other parameters that indicate termite infestation nearby. Aboveground bait stations, which quickly rise from 19% to 100% RH after colonization by *R. flavipes*, can readily be installed on wooden members and serve as an early warning system for termite activity. Wood moisture content also gave good separation of readings from room conditions and more than doubled after termite invasion of the bait stations. We conclude that commercial moisture/RH sensors are available that can be used in combination with bait stations for early remote detection of termites in wooden bridge members. Subterranean termites can be readily treated using commercial termiticides, and damaged wood can be replaced or treated with in-place preservative treatments to preclude further biodeterioration of the bridges.

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