Smart Timber Bridges for In-Situ Evaluation

Xiaobin Le[a], Jim Kainz[b], M. L. Peterson[a], and Eric N. Landisc

[a]Colorado State University, Fort Collins, CO 80523
[b]Forest Products Laboratory, Madison, WI
[c]University of Maine, Orono, ME

1. INTRODUCTION

It has become well known that the roadway infrastructure in the United States has been deteriorating over the past 20 years. Recently, the Federal Highway Administration has listed nearly 50 percent of the countries bridges as either structural deficient or functionally obsolete. In this group, approximately 75 percent are located on rural or secondary roads and are in the small to medium span range. In order to prioritize the structures in most need of repair or replacement, inspection methods need to be introduced that will take into account all types of bridges including those constructed of concrete, steel and timber.

2. BACKGROUND AND MOTIVATION

Wood is probably the first material used by humans to construct a bridge. As a building material, wood is abundant, versatile, easily obtainable and renewable. Although in the 20th century concrete and steel have replaced wood as the major materials for bridge construction, wood is still widely used for short and medium span bridges. Wood is useful because it is economical, fast to construct and easy to maintain in a number of applications. Of the bridges in the United States with spans longer than 20 feet, approximately 12 percent of them, or 71200 bridges are made of timber. The USA Forest Service alone has approximately 7500 timber bridges in use and more are built each year. In addition, the railroads have more than 1500 miles of timber bridges and trestles in service. Timber bridges have also recently attracted the attention of internationaI organizations and foreign countries, including the United Nations, Canada, England, Japan and Australia1.

Sufficiently conservative bridge design and maintenance could ensure the reliability of these aging timber structures However since this level of conservatism in bridge design and maintenance is unsustainable in the current business climate, alternative strategies which ensure the operational safety must be identified. These operational strategies must center around a repair-for-cause approach to bridge maintenance. Structures can no longer he scheduled for a complete rebuild at a predetermined time, instead repair and replacement must be scheduled by a priority based decision making process. The bridges which are unsafe or have significant deterioration must be identified in a low cost and efficient manner based on a sound technological basis, modern inspection and evaluation. When repairs are made, critical components of the bridge which have deteriorated must be identified for replacement. This preliminary study begins to address both of these needs by considering methods for global evaluation of the structure and possible methods for local tests of the bridge components. The net result will be an approach to smart structure design which addresses some of the realities of civil engineering applications.

While the use of smart structures is rapidly becoming accepted in aerospace, applications to civil engineering structures presents a different set of circumstances. Most important the operational environment and the impracticality of high levels of preventative maintenance restricts application of many of the advanced technologies which are becoming available in aerospace applications. In addition to the need for durability for the sensing system cost issues must also be addressed before extensive use of smart structures can become a reality in civil engineering.

SPIE Vol. 3396 l 0277-786X/98/$10.00

3. GLOBAL - STRUCTURAL DYNAMICS

3.1 Low cost global monitoring for smart bridges

As described above, a need exists for improved methods of monitoring the entire bridge system with a single analysis tool. A number of approaches are possible which provide full field bridge evaluation. The traditional approach is proof loading and consideration of bridge loading non-linearities. While this is a costly approach it is still widely accepted and provides a gold standard of sorts for this type of work. Other promising approaches are provided by some applications of radar and various imaging modalities. Work has also been done by D. W. Prine and other investigators using a large number of acoustic emission sensors for in-place system evaluation[2]. While this approach is well suited to certain critical application the quantity of sensors required for general monitoring presents a significant challenge for general adoption of this technology[3].

The detection of damage in civil structures using shifts in natural frequency and other modal parameters obtained from dynamic excitation of the structure has been investigated by Hearn and Testa[4] as well as Lauzon and DeWolf5 among others. This has also motivated other investigations into more advanced methods of processing the data which are based on traditional modal analysis and system identification concepts. One such approach to global damage detection is use of modal assurance criterion or more advanced modal comparison techniques[6]. Damping measurement may also provide a promising alternative since material damping is also likely to provide an measure of the global system damage. The work which has relied on shifts in spectral peaks is attractive, however, because of the simplicity of the analysis required. If the testing can be performed using only the location of spectral peaks operational input loading can even be used to excite the bridge[7]. This type of operational excitation has also been demonstrated on timber railroad bridges[8]. Impulse excitation has also been used to characterize advanced timber structures with some success as well[9]. An analytical characterization method such as the modal assurance criteria should then be sufficient to determine the state of the structure. However, unless base line data is available for the structure the analysis will require that simple models be used to provide as built characteristics of the bridge. It is then necessary to understand the reliability with which the base line bridge characteristic can be known without a-priori characterization information.

Timber presents a particular challenges related to the base-line knowledge of the structure. Specifically, the density and the modulus of the material have significant variation. This variation is somewhat less significant for other commonly used construction materials, although concrete, another important bridge material, shows significant variability as well. To determine if material variation must be addressed in the evaluation of structures, a simple model is presented in the following section. This model is intended to evaluate the use of the first natural frequency for characterization of a bridge system The use of this technique for global system evaluation depends on the ability to predict the response of the structure using typical material properties for timber.

3.2 Sensitivity of first natural frequency in timber

A simple analytical dynamic model will be used to explore the variation of material properties on the first natural frequency of a timber bridges. The measurement of the location of the first natural frequency of a bridge is, perhaps, the most attractive approach to the field evaluation of structures. However, a reasonable reliability of the expected values of frequency and a sufficient sensitivity to expected deterioration is necessary. The foliowing analysis addresses the first of these issues. **A** number of modeling assumptions which are used are consistent with previous work in the area of bridge dynamics. The primary assumptions made in the implementation of the analytical model are:

1. The bridge span is modeled as a simply supported continuous beam. The effect of the rotary inertia will be neglected.

2. The vehicle has been treated as the motion of a concentrated force at constant velocity. The concentrated force is analogous to the dynamic wheel load of the vehicle.

3. Damping in the timber bridge is assumed to have the form of vicious damping. The damping ratio in all modes of vibration will be assumed to be the same.

4. The bridge span is assumed to be at rest before the vehicle enters the bridge span.

According to thin beam theory, the Equation of motion for forced lateral vibration of a uniform thin timber bridge shown in Figure 1 is:

$$EI\frac{\partial^4 W(x,t)}{\partial x^4}+\rho A\frac{\partial^2 W(x,t)}{\partial x^2}=\delta(x-vt)F(t) \tag{1}$$

where, *E* is Young's modulus of the timber, and *I* is the moment of inertia of the bridge cross section about the *Y'* axis. The vertical dynamic displacement of the timber bridge is *W(x,t)* and *p* is the density of timber. The cross-sectional area of the timber bridge is *A*, and *v* is the moving speed of the vehicle, which is the moving speed of a concentrated force in this model. *F(t)* is the concentrated force, that is, the dynamic wheel load of the vehicle.

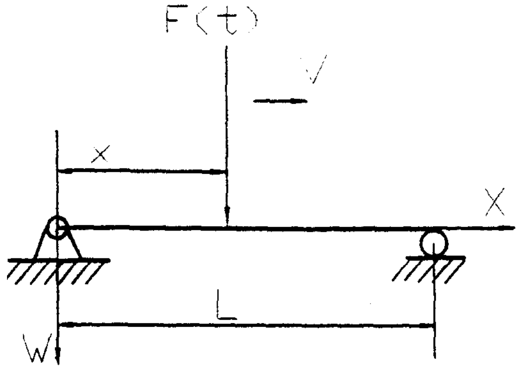

Figure 1: Configuration of simple model for timber bridge.

The boundary conditions shown in Figure 1 at *x=0* and *x=L* are

$$W(x,t)\big|_{x=0}=0 \tag{2}$$

$$\frac{d^2W}{dx^2}(x,t)\big|_{x=0}=0 \tag{3}$$

where *L* is the length of the umber bridge span. The natural frequencies of the timber bridge span are then

$$\omega_i=\left(\frac{i\pi}{L}\right)^2\sqrt{\frac{EI}{\rho A}}\quad (i=1,2,3,......) \tag{4}$$

where ω_i is the i^{th} natural frequeney of the span. When the normal functions of the thin beam are determined, let them satisfy the following condition.

$$\int_0^L \rho A\phi_i^2 dx=1 \tag{5}$$

So that the normal functions are:

$$\phi_i=\sqrt{\frac{2}{\rho AL}}\sin(\frac{i\pi}{L}x)\quad (i=1,2,3,......) \tag{6}$$

where ϕ_i is i^{th} normal function of thin beam. The response of the timber bridge span can be expresed by the sum of the normal modes.

$$W(x,t)=\sum_{i=1}^{\infty}\phi_i(x)q_i(t) \tag{7}$$

where, $q_i(t)$ is i^{th} normal mode vibration of the timber bridge span.

Based on the orthogonality of normal functions, substituting Equation 9 into Equation 1 and integrating from *0* to *L* with respect to *x*, yields

$$\ddot{q}_i(t)+2\xi\varpi_i\dot{q}(t)+\varpi^2 q_i(t)=\int_0^L\phi_i(x)\delta(x-vt)F(t)dx \quad (i=1,2,3,......) \tag{8}$$

$$=\phi_i(vt)F(t)$$

where ξ is the damping ratio, which is the same for all modes of vibration based on the assumptions. According to the assumptions, the initial conditions of the timber bridge span are:

$$W(x,0)=0 \tag{9}$$

$$\frac{dW}{dt}(x,0)=0 \tag{10}$$

When $t=0$ based on the above initial conditions, the initial conditions of the normal mode vibrations can be computed from the following Equations

$$q_{i0}(t=0)=\int_0^L \rho A\phi_i(x)W(x,0)dx=0 \tag{11}$$

$$q_{i0}(t=0)=\int_0^L \rho A\phi_i(x)\frac{dW(x,0)}{dt}dx=0 \tag{12}$$

where $q_i(t=0)$ and $q_{io}(t=0)$ are initial displacement and velocity of the i^{th} normal mode vibration respectively, According to Equation 8, 11 and 12, the normal mode vibrations are

$$q_i=\frac{1}{\sqrt{1-\xi^2}\omega_i}\int_0^L \phi_i(v\tau)F(\tau)e^{-\xi\omega_i(t-\tau)}\sin[\sqrt{1-\xi^2}\omega_i(t-\tau)]d\tau \tag{13}$$

Substituting Equation 4 and 13 into 7, the dynamic response of the timber bridge span is

$$\begin{aligned} W(x,t) &= \sum_{i=1}^{\infty}\phi_i(x)q_i(t) \\ &= \sum_{i=1}^{\infty}\sqrt{\frac{2}{AL\rho}}\sin\left(\frac{i\pi}{L}x\right)\left[\frac{1}{\sqrt{1-\xi^2}\omega_i}\int_0^L \phi_i(v\tau)F(\tau)e^{-\xi\omega_i(t-\tau)}\sin[\sqrt{1-\xi^2}\omega_i(t-\tau)]d\tau\right] \end{aligned} \tag{14}$$

From the preceding equation the displacements of the bridge may be obtained. This suggests a method of evaluation by which not only the sensitivity of the natural frequencies may be compared but the curvature or the displaced shape from superposition of modes. This more fully integrated characteristics of the bridge response may be more sensitive to the characteristics of interests than simply the first natural frequency. However, from the perspective of field testing the determination of the first natural frequency is clearly preferable and so will be explored further.

The dynamic wheel load of a heavy commercial vehicle has a frequency spectrum in the range of about 1 to 30 Hz [10]. The vehicles exhibit two basic natural modes: body bounce with a frequency between 2 and 5 Hz, and wheel hop with a frequency between 10 and 15 Hz. Using the frequency spectrum [11 12] and considering the randomness of the roadway roughness 13, the vehicle dynamic wheel load shown in Figure 2 is used.

Because timber is a natural material the properties tend to be more variable than those man-made materials produced under controlled conditions. The timber is grown under a wide range of geographical and climatological conditions, which can be expected to vary more than, for example, steel, which is produced under controlled conditions. Timber properties are thus treated as random variables. In describing the statistical distribution form of the timber's properties, a number of distributions can be used to represent the variation. Three distributions, normal, log-normal, and *weibull* are most often used to represent the mechanical properties of timber. The normal distribution is typically used to describe the statistical distribution of timber properties[14]. From Equation 4 and 14, it is evident that the Young's modulus and density of the timber will affect the dynamic behavior of the timber bridge.

Measurement of only the first natural frequency would be convenience in field testing and any associated variation would be at least as great in higher modes. Variation in the first frequency is used to represent variation for all of the modes. Thus, only the fundamental mode of the timber bridge span will be considered for the calculations. The mechanical properties E and p of timber are random variables. Thus the first natural frequency and the dynamic response of the timber bridge span will also be random variables. According to the normal distribution parameters of Young's modulus and density, two serial independent random sample values of E and p can be produced. Then, the first natural frequency, i.e., fundamental frequency will be

$$\omega_{1j}=\left(\frac{\pi}{L}\right)^2\sqrt{\frac{E_jI}{\rho_jA}} \quad (j=1,2,3,.....m) \tag{15}$$

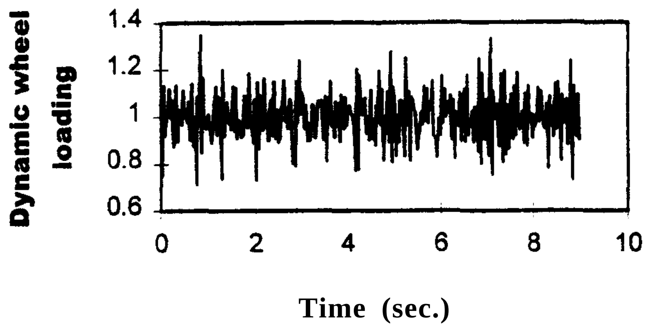

Figure 2: Simulated dynamic excitation of bridge.

where, *Ej* and *pj* are the j^{th} random sample values of random variable *E* and *p* respectively. ω_{1j} is the j^{th} random sample value of fundamental frequency. The dynamic response of the timber bridge span will be

$$W(x,t) = \sin\left(\frac{\pi}{L}x\right)\left[\frac{1}{\sqrt{1-\xi^2}\omega_{1j}}\int_0^L \phi_j(v\tau)F(\tau)e^{-\xi\omega_{1j}(t-\tau)}\sin[\sqrt{1-\xi^2}\omega_{1j}(t-\tau)]d\tau\right] \quad (16)$$

3.3 Results

Numerical result for a timber bridge, using the properties of Douglas fir, are used for example calculations. The design parameters used are based on Tomas [15] and the mechanical properties of Douglas fir are used from Bodig and Jayne[12]. Design and material properties are shown in Table 1.

Table 1 The parameters of the timber bridge

Material	Span	Distribution form of *E*		Distribution of ρ	
Douglas fir	40.1 (m)	Normal distribution		Normal distribution	
Cross section area (m^2)	Moment of cross section(m^4)	Average $\times 10^{10}$(N/m^2)	Deviation $\times 10^{10}$(N/m^2)	Average (kg/m^3)	Deviation (kg/m^3)
8.639679	2.25669	1.074871	0.216704	450	57
Damping ratio		0.025			

Calculated results for the fundamental natural frequency are shown in Table 2 and Figure 3. In Table 2, ω_1 is the fundamental natural frequency, and $f_{\omega 1}$ is the distribution frequency of ω_1.

Table 2 The calculation results of fundamental natural frequency

Sample size	Distribution form of ω_1	Average of ω_1 (rad/sec.)	Deviation of ω_1 (rad/sec.)	Min. of possible ω_1	Max. of possible ω_1
10000	Normal	14.75	1.71	9.14	19.8

ω_1	9.14	9.36	9.57	9.79	10.0	10.2	10.4	10.7	10.9	11.1
$f_{\omega 1}$	40	36	24	0	26	34	74	73	88	64
ω_1	11.3	11.5	11.8	12.0	12.2	12.4	12.6	12.8	13.1	13.3
$f_{\omega 1}$	68	36	33	51	93	122	176	154	295	318
ω_1	13.5	13.7	13.9	14.1	14.4	14.6	14.8	15.0	15.2	15.4
$f_{\omega 1}$	343	369	364	437	494	577	619	666	608	591
ω_1	15.7	15.9	16.1	16.3	16.5	16.8	17.0	17.2	17.4	17.6
$f_{\omega 1}$	547	504	486	343	293	219	140	94	61	84
ω_1	17.8	18.1	18.3	18.5	18.7	18.9	19.1	19.4	19.6	19.8
$f_{\omega 1}$	45	56	61	51	21	42	24	17	18	19

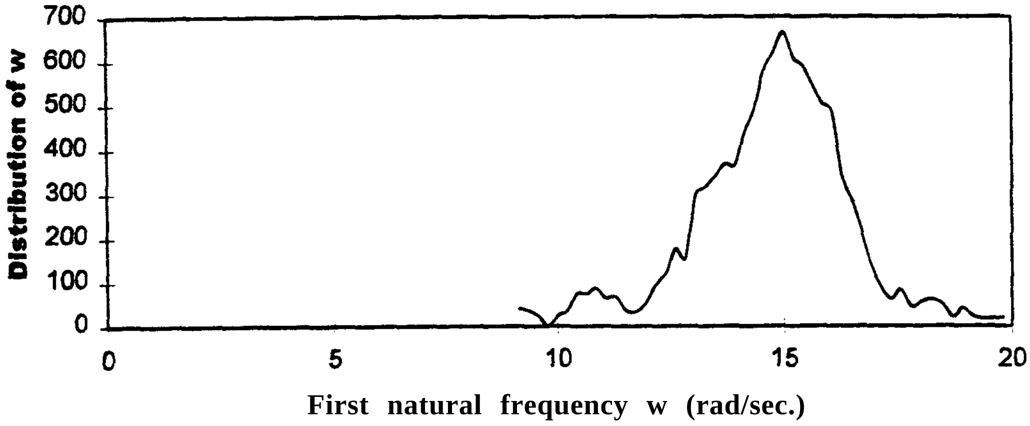

Figure 3: Distribution of first natural frequency resulting from material property variation.

It is evident from figure 3 and table 2 that a simple approach to dynamic monitoring of a timber bridge structure may not be effective. It is evident that a standard deviation of 1.71 rad./sec. for a fundamental natural frequency of 14.75 rad./sec. leads to significant uncertainty in the expected natural frequency of a timber bridge. This uncertainly exists based only on the variability in material properties for the bridge. Further uncertainty would be expected due to experimental conditions and uncertainties in the end conditions based on connection details and other factors.

These results suggests that a more sophisticated approach than a shift in the fundamental natural frequency must be taken to assess the conditions of timber bridges. Even if significant stiffness loss results form deterioration of bridge members, the uncertainty due to material properties may be sufficient to overwhelm these effects. While modal assurance criteria and other methods can be used to match the mode shapes in models, extensive modulus information would be required for the bridge before assessment could be performed using this sort of diagnostic method.

3.4 Future Directions

While the results shown for the uncertainly due to modulus and density variation are not promising, this limitation only applies to simplified approaches based on single or limited mode information. Extension of this work to more sophisticated approaches such as curvature based on superposition of modes or the matching of multiple modes remain the most promising approaches to global assessment of structures. What is also clear from these results is that a reasonable degree of confidence should be obtained based on modeling sensitivity or Monte-Carlo simulations prior to undertaking extensive field investigations. If, based on the modeling and pilot field data, the approach appears to be promising, then extensive field work may be undertaken at that time. In addition the need remains to develop methods which can be used to assess the localized damage in an area of concern in a timber bridge which has been identified from the global assessment method.

4. LOCAL - DISTRIBUTED AE WAVEGUIDE SENSORS

Once the global testing has identified areas of concern in a bridge, then those areas need to be assessed with an eye toward the development of an repair for cause strategy or, alternatively, a long term monitoring method. These ideas are already well developed in a number of aerospace applications and show great promise for the future. However, a different set of circumstances apply in civil engineering applications because of the size of the structures and the need to contain costs. In particular if, for example, acoustic emission (AE) sensors were distributed across a typical timber bridge, literally thousands of sensors would be required. The required density of the sensors results from the high attenuation of acoustic waves in timber and the need to determine the location of acoustic emission events to a reasonable degree. Data acquisition issues associated with this system would also be significant. In typical highway bridges the problem has been discussed considered and the concept of Mega-sensors or even Giga-sensors rapidly emerges. The data collection strategy then presents a technological as well as cost obstacle for the acceptance of embeddable sensor technology[16]. As a result two issues arise, the need to develop low costs distributed sensors and the need to improve data processing and monitoring methods.

4.1 Low cost distributed sensors

Acoustic emission monitoring is attractive for a number of reasons for the local monitoring system. Acoustic emissions (AE) can either provide a standalone method of evaluation or provide information to complement in-service dynamic testing. However it is important to understand how AE works and to consider some of the important issues associated with AE in timber. Many of these same issues arise in other potential local methods such as advanced ultrasonic processing or acousto-ultrasonic methods.

Acoustic emissions are the result of strain energy releases in a material. These energy releases are most commonly the result of changes in the material (such as cracking) due to external forces such as mechanical loading, temperature change, shrinkage, or in the case of wood moisture content change. The energy released during these changes propagate through the material as elastic waves.

In the past, acoustic emissions could only be measured when other external noises in the 20 Hz to 20 kHz range could be isolated. As a result of the advances in sensor and computer technology, the frequency range currently used for AE testing is between 50 kHz and 1 MHz (broadband AE). The use of broadband AE sensing eliminates many of the testing problems

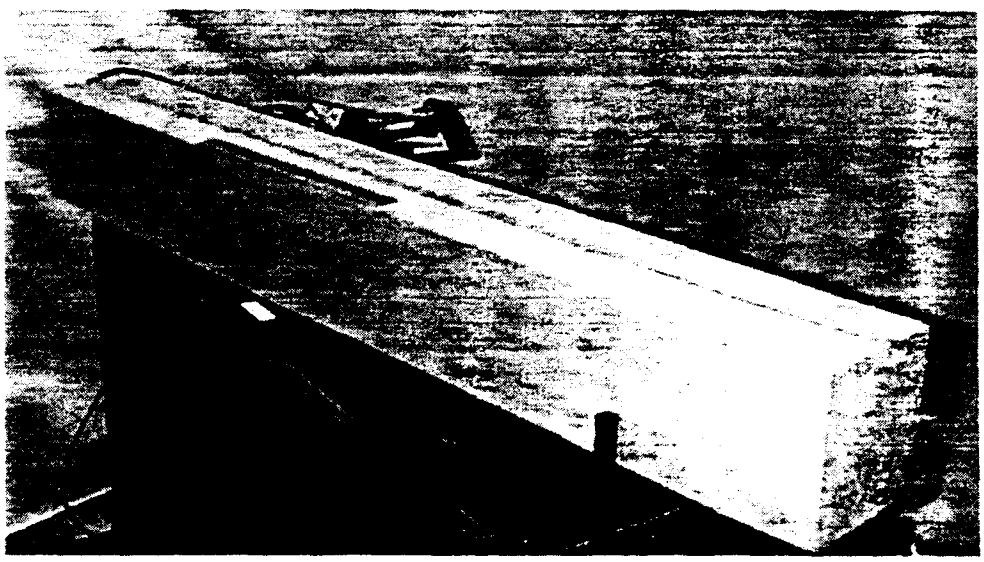

Figure 4: Configuration of wave guide sensing of AE events in timber

which previously presented a barrier to adoption. Tests have been performed on many materials to determine the performance of sensors and analysis on individual members. Results have indicated that the location of cracks can be indicated on these members.

When a structure is monitored, a sensor array is mounted on critical individual members in several locations and the structure is either loaded through normal daily or proof loading. The loads stress the structure and the resulting AE waveform can provide indications of location of a propagating crack, if applicable, or the condition of the members of the structure. AE technology works well for the monitoring of full scale structures provided a sufficiently large sensor array is used to record all areas of the structure under loading.

Acoustic emission testing has been applied extensively to damage evaluation of small structures and materials at a laboratory scale. However, because of the relatively small amplitude of the AE sources, coupled with material and geometric attenuation effects, its use as a full scale structural monitoring technique has been limited. AE monitoring of large scale structures has been limited to good acoustic conductors (in particular steel) [17, 18, 19]. But even in these cases, the monitoring was not truly "global" in that AE techniques were used to examine specific areas of interest such as fatigue crack growth [16, 17]. Maji's work is directed towards truly global monitoring, but it is still in the development stage [18]. In all of these efforts however the limitation noted above on the need for many sensors and large scale processing are very evident.

One very promising approach to the development of a distributed AE sensor for civil engineering has been presented by R. Chen and colleagues20. The reduction of the number of channels of data acquisition and the number of piezoelectric sensors is critical to the creation of a distributed AE sensing system for full scale structural monitoring. Chen has proposed the use of waveguides to collect the received signal for acquisition at a remote location. This approach is promising not only because of the reduction in the number of sensors required, but also because of the elimination of the need to collect data across wires. Instead, a solid waveguide can be used to collect the required data. Transduction and data acquisition can then be done in a remote location where the sensors are protected from damage and the elements.

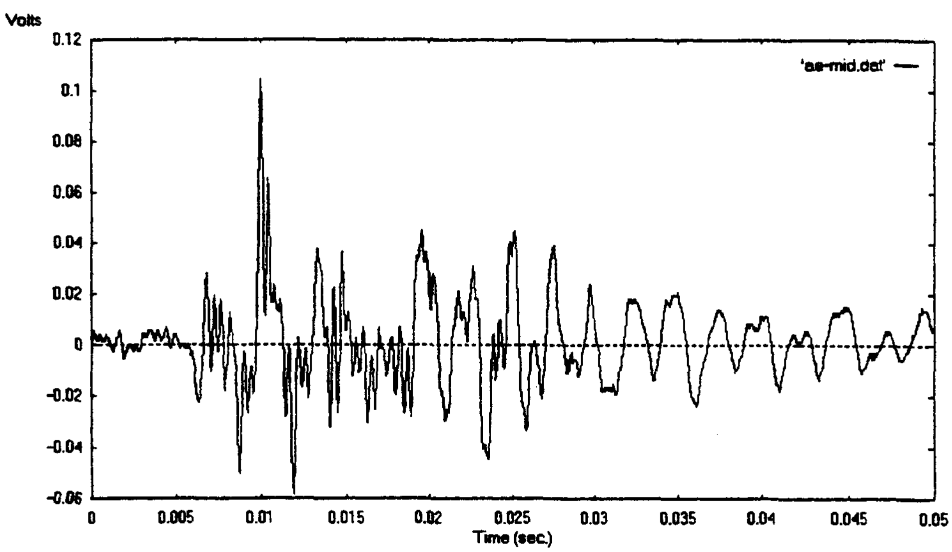

Figure 5: AE Signal from source located at the midpoint of test beam.

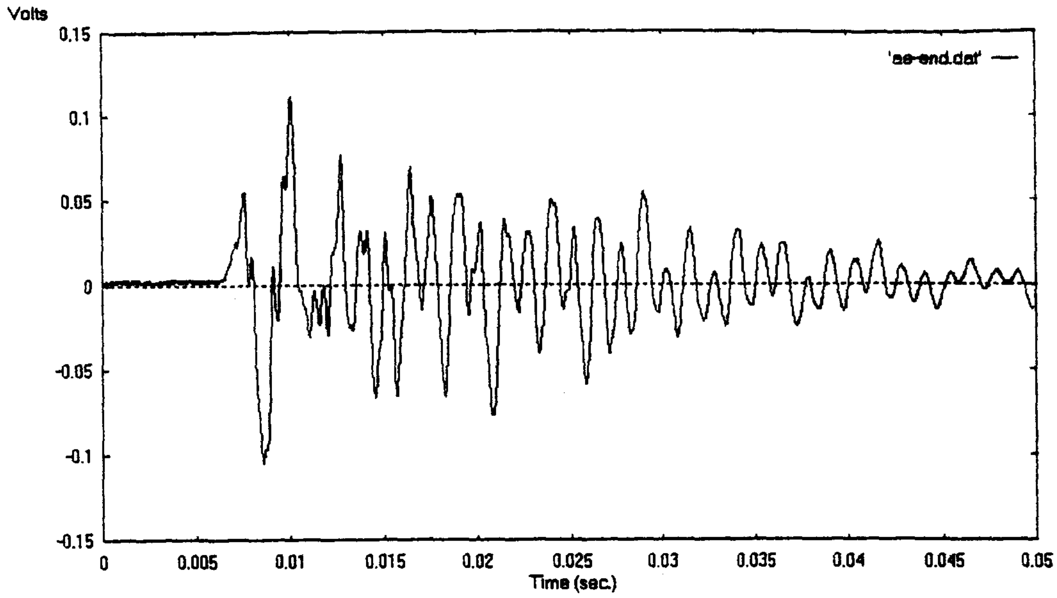

Figure 6: Signal from source located at the far end of timber beam from AE sensor.

4.2 Application to Timber

Timber as a material presents a new set of variables to the AE equation. Timber is natural occurring anisotropic material that has natural defects as a result of the growing process. Additionally, the mechanical properties as well as the dimensional stability of timber is affected by the change in moisture content Finally, timber has an orthotropic structure that has different mechanical properties in three directions; longitudinal, radial and tangential[21].

As described above, AE detection has been successful in monitoring bridges constructed of other materials such as steel and concrete. However, this technology has not been applied to wood bridges and has rarely been applied to wood at all. The few studies that have been completed have focused on methods of determining the failure process of wood during mechanical loading and drying [22, 23, 24]. The results of these studies have shown that AE detection can be used to predict potential distress areas in timber.

On a larger scale, the high attenuation rate in timber at high frequencies (50 kHz- 1 MHz) limits the possible spacing between sensors in a traditional AE array. In addition, the orthotropic behavior of wood affects the propagation of waves. Waves travel almost 5 times faster in the longitudinal direction versus the radial and tangential. These will limit the range of each sensor making it more critical to identify problem areas prior to AE installation.

Acoustic emission applications to wood has pretty much exclusively been limited to laboratory investigations focused at the material or component level. Successes in correlating AE activity with damage characterization lead some to consider it a viable technology for monitoring of wood or wood composite structures. The AE response of wood is fairly well-established [25,26] however little significant work has been done at the large scale structural level. Previous results that show particular promise for the technology as a structural monitoring tool include correlations between event count up to a certain point and the strength of the wood [27], and the relationship between AE measurements and the failure mechanisms of wood samples [28]. These results could potentially form a basis for a long term monitoring program, where strength and damage could be assessed for in-service structures.

The problem with AE monitoring of large wood structures is of course its poor **sound** conducting properties. This is further complicated by its anisotropy which makes quantitative analysis of AE waveforms more difficult. Advances in waveguide technology combined with new methods of data analysis will be necessary before AE monitoring of wood structures will be practical for large structures.

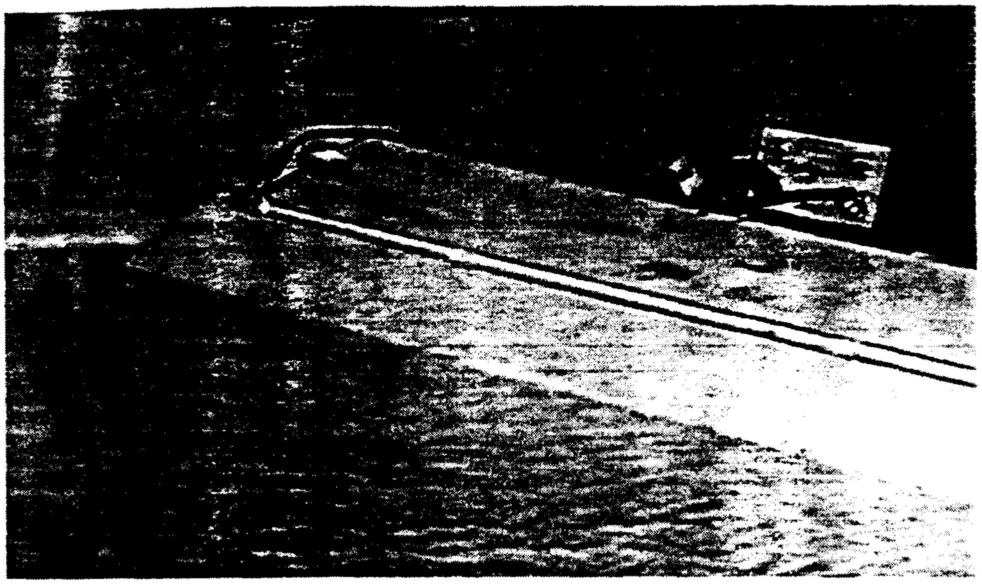

Figure 7: Close up view of waveguide and AE sensor.

Pilot work has been carried out which suggests the potential for distributed AE sensor technology in timber. The approach is directly related to that proposed by Chen and his co-workers [19]. Figure 4 and 7 show a general view and a close up view respectively of the configuration used to obtain the pilot data. A 5 mm diameter fused quartz waveguide was acoustically coupled to a four foot long section of 6 x 6 inch sitka spruce. The coupling between the waveguide and the beam occurred at intervals of approximately 8 inches. The couplant was a clear silicon adhesive. The signals show in figures 5 and 6 were obtained from breaking a 1/16 inch thick hardwood dowel against the surface of the sample at approximately half the depth of the beam. This source was an obvious extension of the pencil break reference commonly used in AE testing. Signals were acquired using a broadband AE transducer (Digital Wave) coupled to the end of the fused quartz rod. Corresponding signals from the sample without the waveguide are not shown because no signal of sufficient strength propagated to the sensor to be detected.

What is evident from figure 5 and 6 is the complexity of the received signal. This is to be expected since the waveguide is of a sufficiently large diameter to propagate more than one mode and those modes will be dispersive. However the dispersion am be used to localize the source of the signal if the input signal is known to some degree of accuracy. Source location is possible precisely because the dispersion carries with it information regarding the distance which the signal has propagated in the solid waveguide. A suitable inversion algorithm would be required in addition to knowledge of the spectral characteristics of the source.

The implications of this approach are quite significant. It become possible to effectively monitor a large number of points on a structure with a single AE sensor. While an inversion algorithm could be quite complex, embedded controllers routinely have available processing power which would have only been available in mini-computers only a decade ago. Distributed processing can occur while at the same time as transmission of the signal to a host system which would monitor the structure. This type of localized information can thus be provided for relatively large scale areas which would then be available based on successful but low cost global monitoring methods. Such a system would reduce the demand on the global system by making it possible to cost effectively monitor a larger area of the structure than has been previously thought to be possible. This same approach could also be used to develop entirely new sensing technologies for local monitoring such as ultrasonic attenuation measurements based on a single source. The use of a large number of sensors in the form of a distributed sensor may make it possible to eliminate the coupling problem which has consistently plagued such measurements.

5. SUMMARY

An overview of several issues regarding local and global monitoring of a structure have been presented. These methods in some ways fall short of commonly accepted smart structure technologies. However, unlike many of the other smart technologies, these local and global monitoring techniques are suitable to the cost and environmental realities of civil structures. By deploying these technologies in a cautious manner, it would be possible to reduce the maintenance costs in many key areas. In particular these technologies would be well suited to the monitoring of bridges which are critical for safety and currently present an area of concern.

The global monitoring method which was considered was simply the detection of shifts in the limit natural frequency of a timber bridge. While attractive from the perspective of simplicity, this work suggests that such a simplistic approach is not likely to be possible because of variation in material properties of timber. The use of more sophisticated system identification concepts or more complete modal analysis may still be sufficient to allow relatively straightforward global monitoring to be performed.

Pilot results for a distributed AE sensor were also presented. This approach seems very promising and provides a means for monitoring a large area of the structure at reasonable cost. By increasing the area of a structure that can be monitored by a relatively small number of sensors, the precision with which the global method must detect areas of concern is reduced. A total bridge management system can then be implemented which depends on current visual assessment technologies and global monitoring to assess structures for areas of concern. Those areas of concern can then be monitored and the health of the structure may be assessed so that a repair-for-cause strategy may be implemented

6. REFERENCES

[1] Ritter M. A., *Timber bridges: Design, Construction, Inspection and Maintenance,* United States Department of Agriculture, Forest Service, August 1992, EM 7700-B, Washington, DC, 1992.

[2] Prine, D.W., Acoustic emission and strain gage monitoring of CALTRANS structure B-22-26 R/L, I-80 Sacramento River (Bryte Bend), Sacramento, California, ITI Technical Report, Northwestern University, BIRL Industrial Research Laboratory Evanston, IL, 1995.

[3] Livingston, Richard A., “Embeddable-sensor monitoring strategies for the infrastructure, Proc. SPIE Vol. 2947, p. 246-258, Nondestructive Evaluation of Utilities and Pipelines, Martin Prager; Richard M. Tilley; Eds. 1996.

[4] Hearn, G., and Testa, R.B., “Modal Analysis for Damage Detection in Structures”. *Journal of Structural Engineering,* ASCE, 177(10),3042-3063., 1991.

[5] Lauzon, R.G. and DeWolf , J.T., Nondestructive Evaluation with Vibration Analysis, *in Nondestructive Testing Methods for Civil Infrastructure* Edited by Hota V.S. GangRao, ASCE, 1993.

[6] Pandey, AK. and Biswas, M., “Damage Diagnosis of Truss Structure by Estimation of Flexibility Change”, *Intl. Journal of Anal. and Exp. Modal Analysis.* 10(2), 104-117, 1995.

[7] Aktan, A.E., Farhey, D.N., Helmicki, A.J., Brown, D.L., Hunt, V.J., Lee K.L., Levi, A, “Structural Identification for Condition Assessment: Experimental Arts”, *ASCE Journal of Structural Engineering,* Vol. 123, No. 12, pp 1674-1684, 1997.

[8] Peterson, M.L. and Gutkowski, R.M., Evaluation of the Structural Integrity of Timber Bridge Structures, to appear in *NDT&E International*

[9] Landis, E. N. and H. J. Dagher, “NDE and Performance Monitoring of FRP-Wood Hybrid Structures”, in *Proceedings of the ASCE Structures Congress XV,* Portland, OR, ASCE, pp. 1504-1507, 1997.

[10] Tilly, G.P., Dynamic *Behavior of Concrete Structures,* Elsevier Science Publishers, New York, 1986.

[11] Mitschke, M., *Study* of *Vehicle Vibrations,* Deutsche Kraftfahrtforschung und Strassenverkehrstechnik, Heft 175, 1962.

[12] Page, J., *Dynamic wheel load measurements on motorway bridges,* Department of the Environment, TRRL Report LR 722, Crowthorne, Transport and Road Research Laboratory, 1976.

[13] Aramraks, T., Highway Bridge Vibration Studies - Interim Report, Rep. No. JHRP-72-2, Joint Highway Research Project, Purdue University, West Lafayette, Indiana, 1975.

[14] Bodig, J. and Jayne, B.A., *Mechanics of Wood and Wood Composites,* Krieger Publishing Company, Malbar Florida, 1993.

[15] Horyna, Tomas, Ventura, Carlos E., and Foschi, Ricardo O., Modal Characteristics of Timber Bridges Under Traffic Loading, *IMAC Proceedings of the 14th International Modal Analysis Conference,* Dearborn MI., 1996.

[16] Livingston, R.A., “Embeddable-sensor monitoring strategies for the infrastructure”, in *Proc. SPEI Non-destructive evaluation of Utilities and Pipelines,* Ed Martin Prageer and Richard Tilley, Vol 2947, P.246-258, 1996.

[17] Prine, D.W., "Application of Acoustic, Strain, and Optical Sensors to NDE of Steel Highway Bridges," Technical Report TR12, Infrastructure Technology Institute, Northwestern University, Evanston, 1994.
[18] Ghorbanpoor, A. and A. Rentmeester, "NDE of Steel Bridges by Acoustic Emission," in *Proceedings of the Structures Congress '93,* Irvine, CA, ASCE, pp. 1008-1013, 1993.
[19] Maji, A.K. and T. Kratochvil, "Acoustic Emission Monitoring of Steel Bridges," in *Proceedings of the Structures Congress* X11, Atlanta, ASCE, pp. 1322-1327, 1996.
[20] Chen, H.L. Roger, He, Yidong and Superfesky, Michael, "Acoustic Surface Waveguides for Acoustic Emission Monitoring of Fiber Reinforced Plastic Structures, Material Evaluation, Vol. 52, No. 9, p. 1112-l116, 1994.
[21] Forest Products Laboratory. *Wood Handbook: Wood as an engineering material.* Agric. Handb. 72. Washington, DC: U.S. Department of Agriculture; rev. 1987. p. 466, 1987.
[22] Patton-Mallory, Marcia. Use of acoustic emission in evaluating failure processes of wood products. In: Itani, R.I., ed. Proceedings of the 1988 Internationa1 Conference on Timber Engineering. 1988 September 19-22; Seattle, WA. Madison, WI: Forest Products Research Society; Vol. 1: 596-600, 1988.
[23] Beall, Frank. "Relationship of acoustic emission to internal bond strength of wood-based composite panel materials". *Journal of Acoustic Emission.* 4(1):19-29, 1985.
[24] Kawamoto, Sumire. Attenuation of acoustic emission waves during the drying of wood. In: *Ninth International Symposium on Nondestructive Testing of Wood.* September 22-24, 1993;. Madison, WI: Forest Products Society; 23-29., 1994.
[25] M. P. Ansell, "Acoustic Emission as a Technique for Monitoring Fracture Processes in Wood," in *Structural Uses of Wood in Adverse Environments,* R. W. Meyer and R. M. Kellogg, Eds., Van Nostrand Reinhold, 1982.
[26] M. Patton-Mallory, "Acoustic Emission Testing of Wood Products," *USDA Forest Service Engineering Field Notes,* V. 19, 1987.
[27] K. Sato, T. Okano, I. Asano and M. Fushitani, "Application of AE to Mechanical Testing of Wood," in *Proceedings of the 2nd International Conference on Acoustic Emission,* Lake Tahoe, pp. 240-243., 1985.
[28] A. Vautrin and B. Harris, "Acoustic Emission Characterization of Flexural Loading Damage in Wood," *Journal of Materials Science,* V. 22, pp. 3707-3717, 1987.