AMBIENT EXCITATION FOR DETECTION OF DAMAGE IN TIMBER BRIDGES

J. A. Kainz, Xiaobin Le and M. L. Peterson
Colorado State University
Fort Collins, CO 80523

INTRODUCTION

As the needs for transportation systems change, the loading requirements and demands on the transportation infrastructure also change. This has resulted in increased number of bridges that are labeled structurally deficient or functionally obsolete since many of the bridges were built prior to present loading requirements [1]. Many of these bridges are open to vehicular and railroad traffic but only at posted loading limits or at reduced speed limits. In order to best use the existing bridge resource and/or schedule repair or replacement strategies, methods need to be developed to assess the actual condition of these transportation structures.

The railroad industry has been dealing with an increase in the number of bridges that do not fulfill present loading requirements. However, in contrast to the highway infrastructure where the vast majority of bridges are constructed of steel and concrete, the railroads possess a huge inventory of timber bridges. These railroad bridges are located on all types of routes; from highly traveled main transcontinental routes to seldom used short spur lines. In both of these cases the timber bridges are aging and becoming more of a demand on limited maintenance and repair budgets. The heavy traffic and competitive nature of railroads places further pressure on the timber railroad bridges. On the main lines, the cost of closing bridges for inspection is very high and should be avoided. In contrast spur lines may not generate sufficient revenue to justify extensive inspection and evaluation expenditures.

BACKGROUND

In the late 1800's, railroad expansion was booming. Many miles of rails were installed much of which required bridges. The majority of these bridges were constructed of timber using the existing technology of the time. These structures ranged from the large trestle structures over deep chasms to semi-continuous longitudinal beam structures. In addition to the large amount of timber used for railroad bridge construction, many of the bridge members have substantial cross-sections due to the large loads of trains.
The railroad guidelines for bridge design have not changed significantly since the turn of the century due to little change in the loading characteristics of the train. Most present day railroad bridges were constructed with a loading requirement of 30 tons per axle. However, the paradigm has changed in the railroad industry with the introduction of double stack container trains that have a loading requirement of 35.7 tons per axle. The increased loading adds an additional 19% load on a bridge that was designed for 30 tons per axle. In addition, due to economic constraints in the railroad industry, there is an anticipated need for an additional 10-20% increase in loading by the turn of the century. Many bridges that were designed for a 30 tons per axle load could have a future load of 41.7 tons per axle. In order to insure the safety and efficiency of rail traffic, the condition of bridges must be known and weakness in the railroad infrastructure must be identified and repaired and/or replaced with sound structures.

INSPECTION CONSTRAINTS ASSOCIATED WITH RAILROAD BRIDGES

The railroad infrastructure provides several unique challenges for an inspector. Due to the construction practices used in the railroad, the timber bridges in the railroad infrastructure vary in age from several years to a century old. This creates a two-fold problem of varying bridge design parameters and species strength variants over the past century (i.e., old growth forests have been shown to have higher strength than newer growth due to changes in growth cycles which affect the ratio of early wood to late wood rings in the tree).

In addition to the age variation on these timber bridges, many of these structures require a periodic rebuild in order to maintain structural integrity. At the present time, these rebuilds are based on a periodic visual inspection. Since a visual inspection only examines the surface of the structure, many internal defects or problems may be missed. Improved inspection methods are required to truly assess the performance of the structure.

Due to the number of timber bridges in the railroad infrastructure, it is impractical to perform a large scale, time expensive test on each timber bridge to determine its condition. In addition, many tests would require the bridge to be taken out of service, which is not practicable on high traffic routes. The required inspection system is low cost, reliable, and would allow the inspector to identify problem areas in the structure for replacement/repair or for a more extensive evaluation. The goal of this research is to identify a simple inspection system that fulfills these requirements.

AMBIENT EXCITATION

Significant advantages are associated with the use of ambient excitation to inspect railroad bridges in particular. Access and scheduling of use of railroads tracks is a significant barrier for any inspection technique for these applications. Even access to tracks by vehicles which can move onto and off of the tracks (rubber tire vehicles) is limited because of safety procedures. Ambient excitation is attractive since no scheduling beyond the time required to place instrumentation on the bridge is required. In addition the inspection technique would not be associated with any additional risk to the structure because the input signal would be simply whatever excitation force is generated in normal usage. However, two issues must be resolved for a viable inspection method -- is the amplitude of the excitation from normal usage sufficiently high to provide an acceptable
signal to noise ratio of normal transducers and is it possible to separate the useful information from the broadband excitation?

The ability to generate sufficient signal amplitude with operational excitation has been previously demonstrated [2]. The separation of dynamic information from a broadband input signal has also been demonstrated for bridges built both of steel reinforced concrete and steel. Two approaches are commonly taken for separation of modal information from a received signal if the input signal is not known. The more common approach is the use of the wavelet transform. An example of the application of such a technique is the work by Bonato et. al. For evaluation of the Queensborough Bridge in Vancouver BC [3]. An alternative to wavelet decomposition is the use of cross-correlation. The use of the cross correlation has been demonstrated on a concrete and steel bridge by Farrar and James [4]. Neither of these techniques have been demonstrated for timber bridges. It is expected that significant differences in the material damping properties and the construction techniques used are likely to result in significant issues to be overcome in the use of the dynamic signal. In addition, large variation in material properties that are associated with natural materials such as timber will increase uncertainty in the expected dynamic characteristics of a timber bridge which meets the required performance criteria.

TWO TIMBER BRIDGES EVALUATED

The current results are based on the field evaluation of two different timber bridges. The first bridge is a timber railroad trestle which crosses the Poudre River north of Fort Collins, Colorado. The second bridge is, perhaps, more typical of timber railroad bridge applications. The second bridge only has three spans and crosses a dry creek bed. This bridge is east of Pueblo, Colorado and is on a spur line which serves government and
private customers. This bridge consists of longitudinal stringers placed across piers to form three spans. Both bridges are of an open (unballasted) deck design (figure 1). The Pueblo bridge had undergone renovation and strengthening prior to the testing where a helper stringer was added to stiffen the bridge.

Excitation source for the Poudre River bridge consisted of both the passage of a special test train and standard rail traffic over the period of time when testing was conducted. In the case of this bridge, speeds did not exceed 10 MPH (the posted limit of the track) because of operational limitations. The Pueblo bridge was on a spur which was less restrictive on allowable train speed. As a result multiple runs across the bridge were possible using increasing speeds up to approximately 30 MPH. However, in contrast to the Poudre River bridge, normal traffic on the Pueblo bridge is lighter in frequency and so data was only obtained for the special train provided for the testing. Figure 2 shows an example of a signal received from a vertically oriented accelerometer during the passage of normal traffic on the Poudre River bridge.

INTERPRETATION OF SIGNAL

Given that a signal of sufficient signal to noise ratio is usable from ambient excitation, it remains to interpret the signal. Considering the spectrum of the signal under ambient excitation is in general not useful. In particular the signal may not show the same input bandwidth depending on the traffic over the bridge. Spectral data for the signal shown in figure 2 is consistent with this difficulty. Therefore, we used two methods which are well established for other materials; the wavelet decomposition and the cross-correlation methods.

Paul Wavelet

A number of authors have used the Morlet wavelet for interpreting a signal from a broadband or random excitation [2]. The wavelet consists of a set of functions which has
compact support in both the time and the frequency domain. The wavelet then separates information from the broadband signal when the inner product of the wavelet and the unknown signal is taken. In the case of the Morlet wavelet, the basic form is that of a Gaussian modulation of a sinusoid. The basic wavelet, \( \psi(t) \), is then dilated and translated to produce a series of wavelets which select different frequency ranges of the signal that occur at different points in time. The resulting wavelet transformed data then consists of the inner product of the signal for the full range of dilation and translation operations.

\[
\Psi_{a,b}(t) = \frac{1}{\sqrt{a}} \psi\left( \frac{t-b}{a} \right)
\]

While a number of basic wavelet functions exist, the Morlet wavelet is desirable for a number of reasons. Most notably, the Morlet wavelet is complex valued. By plotting the modulus of the wavelet coefficients the underlying oscillations are removed from the data. This results in a visual description of the variation of the signal power with time and frequency much as in the case of a power spectrum representation represents the power variation with frequency. The Morlet wavelet shows one significant limitation however. The Morlet wavelet is only marginally admissible as a wavelet function because of the sum of the energy in the wavelet does not necessarily sum to zero. In other words,

\[
\int_{-\infty}^{\infty} |\psi(t)|^2 dt = 0
\]

is not true unless particular values of the adjustable parameters of the wavelet are used. This limits the ability to be more selective in either frequency or time depending on the situation. The advantages of the Morlet wavelet can be retained while eliminating the problem with marginal admissibility by using the Paul wavelet. The basic form of the Paul wavelet is:

\[
\Psi(t) = \Gamma(m+1) \frac{i^m}{(1-it)^{m+1}}
\]

The adjustable parameter, \( m \), for the Paul wavelet does not have the same restrictions as the corresponding parameter for the Morlet wavelet. As a result the wavelet can be freely adjusted to be more selective in either the time or the frequency domain.

The Paul wavelet was used to analyze the data from the accelerometers with the parameter, \( m \), adjusted to allow selectivity in frequency. This was necessary because the modal density was found to be reasonably high and the excitation events had significant separation in time. Using the Morlet wavelet the modes were less clearly separated in frequency. The disadvantage to the wavelet decomposition is that the technique produces a large quantity of data which must be interpreted. For example, the scalogram in Figure 3 is relatively simple because the number of modes is small and the signal is limited in time. However, even in this case some sort of automatic algorithm is required to select the natural frequencies from the surface plot and to obtain the damping from the half power bandwidth. This represents a significant undertaking in itself and suggests that other alternatives may be attractive for the separation of data from an unknown excitation source.
Cross-Correlation

The use of cross-correlation is an alternative to wavelet decomposition in cases where the input signal is unknown. This approach has been used successfully for ambient excitation of automobile bridges.

Signals acquired from the passing of two different trains are used, $x_1(t)$ and $x_2(t)$. The cross-correlation of the two train crossing events is the inverse Fourier transform of the multiplication of the spectrum of the two signals or:

$$X_{\text{Corr}}(t) = F^{-1}[X_1(\omega)X_2(\omega)]$$  \hspace{1cm} (4)

where $X_1(\omega)$ and $X_2(\omega)$ are the Fourier transforms of signals one and two respectively and $F^{-1}$ is the inverse Fourier transform of the quantity inside the brackets. The resulting signal can be shown to produce equivalent to the impulse excitation input function [3]. A typical problem with this technique is the need for careful windowing. Traffic excitation on a bridge is typically a near continuous excitation. However, train traffic is more discrete in time and so problems with windowing are reduced. More problematic is the low signal to noise of the resulting signal and the assumption that the input signal is white noise. The input signal from train traffic has clear frequency characteristics and thus does not meet the second criteria effectively. In addition the signal to noise of the resulting signal is poor. However, a reasonable comparison to the manually selected natural frequencies from the wavelet decomposition was obtained. Additional improvement in the signal to noise by combining cross-correlation with wavelet decomposition may make it possible to combine the features of both techniques. Additional development of this technique can also make use of ensemble averages for each of the input functions which should provide a more
reasonable excitation signal. The cross-correlated signal can be interpreted using any of a number of time domain system identification techniques which are well established.

FINITE ELEMENT MODEL COMPARISON

Finite element results presented in this work are based on a simple linear elastic isotropic beam element model. While these results do not completely describe the material, they provide a preliminary example of future methods that could be used to compare and contrast the results obtained through wavelet and cross-correlation decomposition. In the isotropic model, average material properties for Douglas Fir in the longitudinal direction are used. The supports are assumed to be infinitely stiff although the stiffness added by steel rails are included. A more reasonable model of the structure would include the effects of material anisotropy for the timber beams and would include some consideration of material property variation in the timber beams. However, this preliminary model suggests the modal density that would be expected and gives an idea of the mode shapes for the lower modes of the bridge. By looking at the mode shapes (as shown in Figure 4) and comparing the natural frequencies to the experimental values future experimental design can be improved upon. In addition an investigation into the sensitivity of the natural frequencies to deterioration of individual beams can be performed.

Table 1 shows the first five modes of the finite element results and the two consistent modes which appeared in the experimental data. The mode shape found in the finite element model was consistent with the type of deformation for which the accelerometer in the experiment would be expected to be sensitive. The other modes were out of the plane of the accelerometer axis with one exception. That mode was not detected using either of the methods of analysis of the data discussed. It is not clear at this time whether the model or the experiment is at fault. The model is obviously quite simple and the experiment has limitations as well.
Table 1: Comparison of natural frequencies from experiment and finite element model.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Finite Element Results</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>47</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>89</td>
<td></td>
</tr>
</tbody>
</table>

CONCLUSIONS

It is unlikely that the measured parameters can be used to quantitatively detect damage in the structures without baseline information for a particular bridge. Due to material variation alone, the natural frequency for a timber bridge can vary by as much as 90% of nominal [5]. In addition to the material property variation, variation in the structural damping due to fit of connectors and other factors is also likely to be significant and may not be a good predictor of the condition of the structure. In general, the uncertainty which exists between the model and the as-built bridge are likely to overwhelm the changes caused by structural deterioration. Other options exist which would be more demanding from an instrumentation standpoint but which are likely to result in a more reliable results. In particular, a better description of the mode shape using either laser based instrumentation or a large number of accelerometers would make it possible to detect changes in curvature of the beams during dynamic excitation. In the absence of baseline data this is likely to be the only practical method of detecting deterioration in the bridges.

In spite of the difficulty of obtaining quantitative results, simple structural identification from ambient excitation may make it possible to obtain qualitative results to describe the status of the structure. Gross damage which may not be evident from visual inspection may be evident from significantly reduced natural frequencies of the structure. In addition deterioration over time may be evident from decreases in the natural frequencies. In all, the global system identification techniques are early in their development for application to timber structures. Implementation continues to present significant challenges in all infrastructure applications even for application areas that are more developed than for timber.

REFERENCES

2 M.L. Peterson and R.M. Gutkowski, to appear in NDT&E International