Use of accelerometer to monitor pile vibration or displacement on timber bridges

Alvira Illana Navarro

Ali Karrech
Department of Civil, Environmental and Mining Engineering
The University of Western Australia

Bruce Hall & Wayne Spencer
CEED Client: Main Roads Western Australia

Abstract

This project investigates the instrumentation of timber bridges to facilitate inspection. With the increasing number of piles that are suspected to be displacing vertically, the need to accurately measure vibration in there structures has arisen. The proporsed approach is based on the hypothesis that the structural health of the bridge is linked to the change in natural frequencies. A change in the natural frequency can be attributed to the change in the pile stiffness or its degradation. This vibration-based method is to determine if the accelerometer could indeed aid in monitoring and identifying if the piles are displacing vertically or simply vibrating, which can save time and resources on repeatedly investigating the suspected pile., This non-intrusive solution can decrease the likelihood of replacing a good pile.

1. Introduction

Timber bridges have been in use in Western Australia for over a hundred years. Timber is a material desirable for bridge construction, due to its high strength capacity, lightweight and energy absorption (Ritter, 1990). Given that timber is a biodegradable material, constant monitoring in bridges is necessary (Altunişik et al., 2020; Björngrim et al., 2016).

Lately, it has been reported by bridge inspectors that there has been excessive movements in timber piles under traffic loads. The piles were reported to be "pumping," displacing vertically as heavy vehicles pass over the bridge. The movement observed in the timber piles has been assumed to be linked to the deterioration along the timber piles. Commonly observed and assumed possible deterioration (as seen on Figure 1) that has caused the pumping are to be observed on the experimental set-up of this project.

The current approach used by Main Roads WA to assess pile movements is deemed subjective. Therefore, the risk of misinterpreting a pile as pumping is high, which can cause the increased likelihood of replacing good piles.

It has been determined that the pressence of damage or deterioration due to age of the structure can cause changes in the natural frequencies of the structure (Salawu, 1997). Older timber piles that have already been deteriorating posing a risk on the overall strength of the bridge (Andrawes & Caiza, 2012). Damage on structures can manifest itself as a stiffness reduction and changes in intrinsic characteristics, such as natural frequencies (He & Zhu, 2011).

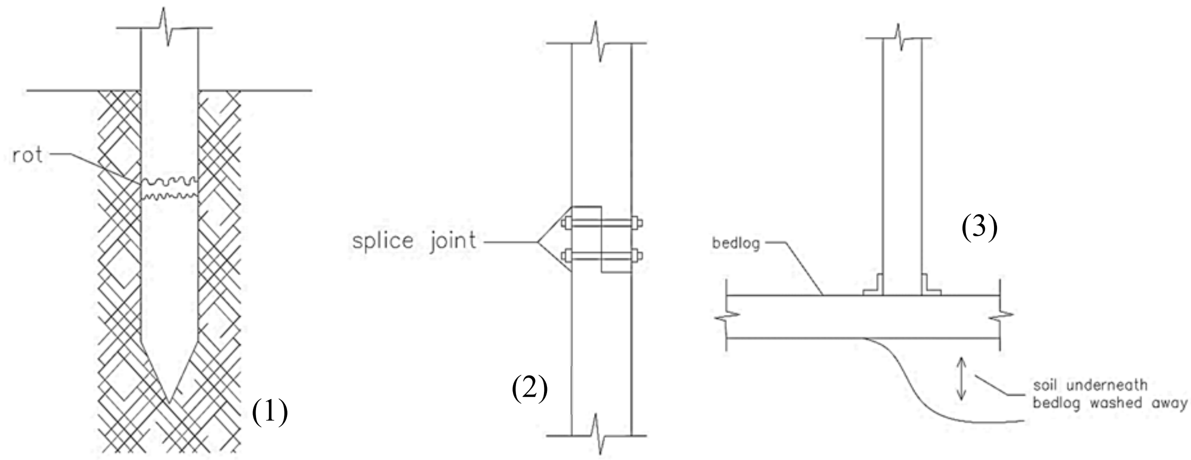

Figure 1 Deterioration of timber piles: (1) Rot on a driven pile; (2) Rust on the bolts on a splice joint and; (3) soil underneath the bedlog getting washed away

The overall contribution of this project is in developing a cost-effective way to monitor pile vibration on a timber bridge to determine whether the vibration response or natural frequency

1. Measured is indicative of timber deterioration;
2. Detected can be used for bridge inspection in practice.

Structural health monitoring of bridges to detect damage or inevitable degradation can allow the shift from schedule-based to condition-based maintenance strategies which is economically beneficial for the client (Carden & Brownjohn, 2008; Jojok et al, 2016; Mazurek & DeWolf, 1990). With an instrument that can remove the need for extra monitoring of timber piles, time and resources currently needed to further investigate suspected piles can be saved. The risk on safety is lessened due to less time spent driving on-site, as well as, less risk on inspecting underwater, and less personal risk to the inspection team itself. The new procedure can lessen the likelihood of replacing a good pile due to misinterpretation. Structural health monitroing can minimise the need to close bridges for repairs of retrofitting due to the late detection of possible defects on the pile (Feltrin et al., 2013).

2. Materials and Methods

2.1 Analytical Solution

The natural frequencies of vibration can be calculated analytically to compare their values to those obtained numerically using the finite element method or experimentally using accelerometers.
The fundamental (smallest) natural circular frequency in the transverse direction reads,

$$\boldsymbol{\omega_1}^2 = \boldsymbol{\beta_1}^4 \left(\frac{\mathbf{EI}}{\boldsymbol{\rho}\mathbf{A}}\right), \mathbf{where}\ \boldsymbol{\beta_1} = (\mathbf{1.875})\frac{\mathbf{1}}{\mathbf{L}} \qquad \text{(San Andres, 2008)}$$

And its counterpart in axial direction is,

$$\boldsymbol{\omega_k} = \frac{(\mathbf{2k-1})}{\mathbf{2}}\frac{\boldsymbol{\pi}}{\mathbf{L}}\left(\frac{\mathbf{E}}{\boldsymbol{\rho}}\right)^{\frac{1}{2}}\ \mathbf{where\ k = 1} \qquad \text{(San Andres, 2008)}$$

expressed in rad/s. Both equations can be divided by 2π to obtain the natural frequency expressed in Hz. From these equations, the natural frequencies obtained for the transverse and axial direction are 7.8286 Hz and 230.0678 Hz, respectively.

2.2 Modelling and Analysis

The timber pile is modelled as a cantilever beam using the software Ansys 2019 R3. A three dimensional model of the timber sample is constructed with the same material properties (density and Young's Modulus) as the sample. The 3D geometry was selected to take into account complex alterations such as grooves and/or damaged zones. The modelling process of the timber sample consisted of meshing the geometry, applying the boundary conditions, and analysing the resutls. The boundary conditions (as seen on Figure 2) applied to the 3D model are a fixed support on the bottom of the beam and free end on the top. The structure is subjected to the standard earth gravity applied in the y-direction. The results of the modal analysis will then be verified with analytical equations from the relevant literature. The cantilever beam was chosen to model the simplest configuration and analyse it to find the expected frequencies measured in the laboratory or on-site.

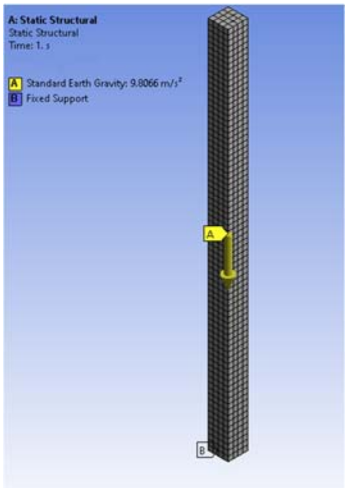

Figure 2 Boundary conditions applied to the 3D model of the timber sample

2.3 Laboratory Testing

The beam was fixed to the strong floor to simulate its service conditions. A load cell was placed to measure the load applied axially. The triaxial accelerometer was deployed to measure the vibrations of the beam. A hammer was used to manually apply the load axially and mimic the effect of traffic.

Four beams were considered (see Figure 3 for experimental set-up):

1. Simple cantilever beam – to simulate a pile that is completely fixed with no damage
2. Beam with grooves – to simulate the rotting on a driven pile
3. Beam with bolt – to simulate a splice joint with a rusted bolt that may have fallen out
4. Beam with a spring – to simulate the washing away of soil beneath the bedlog

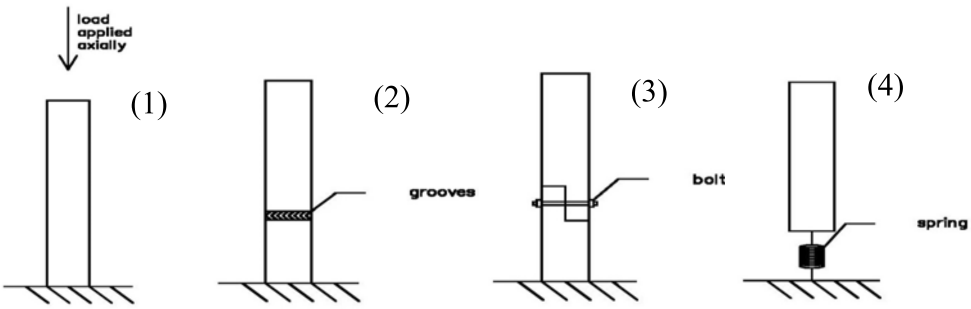

Figure 3 Beam Samples for Laboratory Testing: (1) Simple Cantilever Beam; (2) Beam with grooves; (3) Beam with Bolt and; (4) Beam with Spring

2.4 On – Site Testing

Field testing on the bridge would be done on two piles, namely a control pile and a suspected pile. The two pile will be selected on the same lane so that both piles will carry the same load. The accelerometer will be placed on the midspan of the top of the pile close to where the water line is. The triaxial accelerometer will be bolted on the steel plate on the mounting rod (see Figure 4). With the accelerometer all set-up on both piles, the device can be turned on to start the measurement and will be left on the bridge for a few hours to a day in order to assess the reaction of the piles to the traffic load.

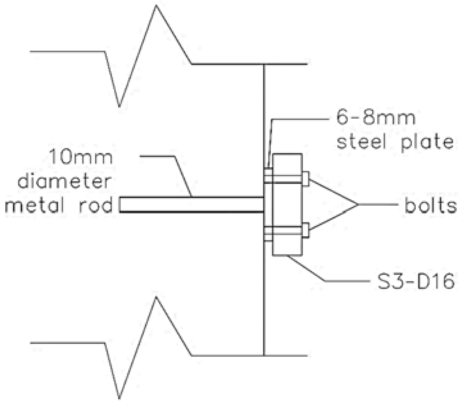

Figure 4 Mounting rod design for the accelerometer

3. Results and Discussion

3.1 Finite Element Analysis

Modal analysis is used to provide the natural frequencies at which a structure will resonate. The results were obtained after a convergence study. The model has the same dimensions as the timber sample, 79 mm in length, 79 mm in width, and 1500 mm in height. The measured material properties of the sample needed for the analysis are a density of 778.0543 kg/m^3 and a Young’s Modulus of 1.4826 GPa.

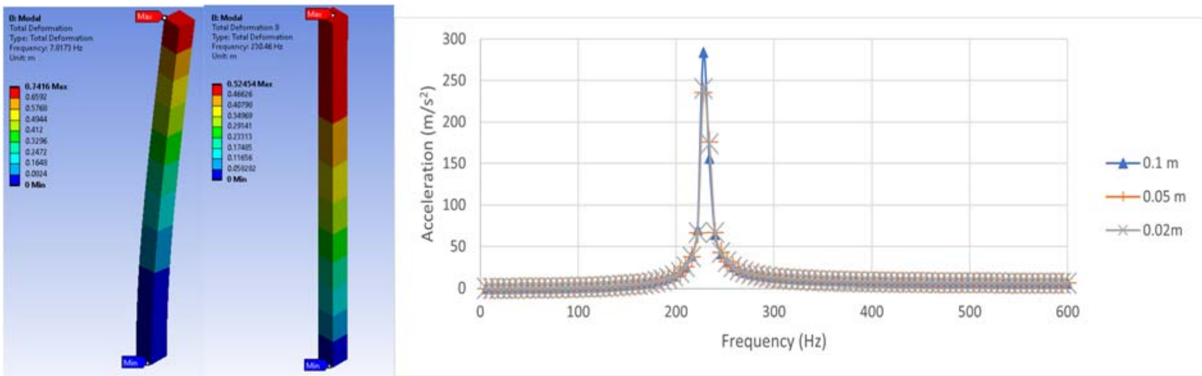

Figure 5 Modal analysis results: First Mode Shape and Eighth Mode Shape; Convergence Study

From the modal analysis results, the eighth mode shape is the relevant result as it is the analysis for axial vibration on the model. The first mode shape is the transverse vibration of the model. As seen from Figure 4, the natural frequency that resonates axially is 230.08 Hz and for its transverse counterpart is 7.796 Hz.

3.2 Laboratory Testing

Load was applied axially on the timber sample using a hammer. A software package was supplied with the triaxial accelerometer, it analyses the signal obtained from the experiment and uses Fast Fourier Transform (FFT) to graph the natural frequency measured. The results obtained from the laboratory testing can be seen in Table 1 and the FFT graph is shown in Figure 6.

	Frequency (Hz)		
	Analytical Solution	**FEM**	**Accelerometer**
Transverse	7.8286	7.796	6.64
Axial (Beam only)	230.0678	230.08	216.8
Axial (Beam with spring)			13.98

Table 1 Natural frequencies obtained from the analytical solution, FEM, and laboratory testing

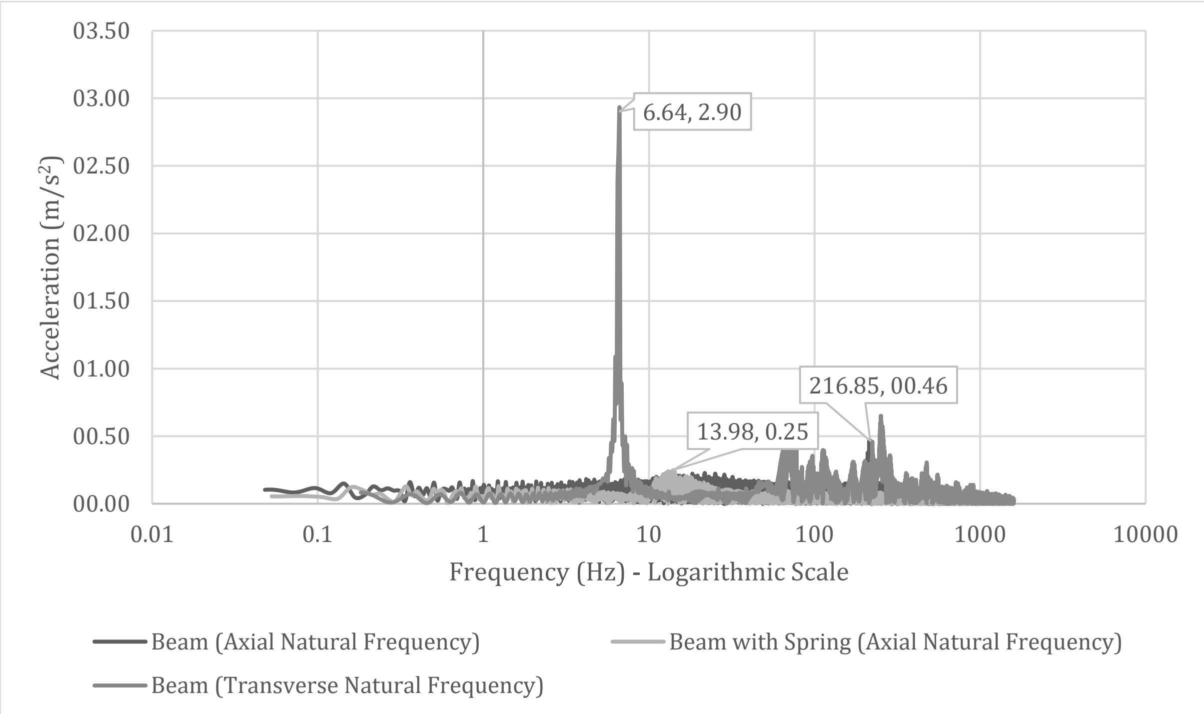

Figure 6 Laboratory test results [Acceleration – Frequency (Logarithmic Scale) graph]

4. Conclusions and Future Work

The project investigated the behaviour of timber beams using theoretical and experimental techniques. On-site tests are still to be conducted, but the equations used in the analytical solution can be used to predict the possible natural frequency the control pile will have in the timber bridge. The results obtained from the lab-testing shows that the natural frequencies obtained from the beam (axially applied load) and beam (transversely applied load) correspond well with the natural frequencies obtained from both the finite element analysis and manual calculation. Comparing the frequency from the beam (axially applied load) and the beam with spring, it can be seen that there is a significant decrease of the frequency measured from the accelerometer. This supports the theory that damage on a pile or a stiffness reduction can cause changes to the natural frequencies along the pile. The next phase of this project will further investigate testing other situations of deterioration along the pile in a lab set-up. Following this, the final stage would be testing the piles on the timber bridges picked by the client that has been reported with pumping piles.

5. Acknowledgements

I would like to express my deepest appreciation to my company mentor, Bruce Hall and my academic supervisor, Ali Karrech for their immensely valuable guidance and support throughtout the project. I am also grateful to the team at Main Roads Western Australia, particularly, Andrew Rankine, Jarrod Pink, Yasoja Gunawardena, Anthony Scasserra, Greg Underhayes, and Gavin Johnston for sharing their expert knowledge on timber bridges and assisting with queries and materials needed for the project. An additional thanks to the Structures Laboratory technicians, Stephen Naulls, Richard Bowles and Shane Robinson and the Mechanical Workshop technician, Mark Henderson for assisting during the lab set-up and testing.

6. References

Altunişik, A., Kalkan, E., Okur, F., Karahasan, O., & Ozgan, K. (2020). Finite-Element Model Updating and Dynamic Responses of Reconstructed Historical Timber Bridges using Ambient Vibration Test Results. Journal of Performance of Constructed Facilities, 34(1), 4019085–. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001344

Andrawes, B., & Caiza, P. (2012). Bridge Timber Piles Load Rating under Eccentric Loading Conditions. Journal of Bridge Engineering, 17(4), 700–710. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000300

Björngrim, N., Hagman, O., & Wang, X. (2016). Moisture content monitoring of a timber footbridge. Bioresources, 11(2), 3904–3913. https://doi.org/10.15376/biores.11.2.3904-3913

Carden, E., & Brownjohn, J. (2008). Fuzzy Clustering of Stability Diagrams for Vibration-Based Structural Health Monitoring. Computer-Aided Civil and Infrastructure Engineering, 23(5), 360–372. https://doi.org/10.1111/j.1467-8667.2008.00543.x

Feltrin, G., Jalsan, K., & Flouri, K. (2013). Vibration monitoring of a footbridge with a wireless sensor network. Journal of Vibration and Control, 19(15), 2285–2300. https://doi.org/10.1177/1077546313501929

He, K., & Zhu, W. . (2011). Structural damage detection using changes in natural frequencies: Theory and applications. Journal of Physics: Conference Series, 305(1), 12054–. https://doi.org/10.1088/1742-6596/305/1/012054

Jojok, W. S., Tri Joko, W. A., & Anwar, N. (2016). System Dynamics Approach for Bridge Deterioration Monitoring System. International Journal of Engineering and Technology Innovation, 6(4), 264-273. https://www-proquest-com.ezproxy.library.uwa.edu.au/scholarly-journals/system-dynamics-approach-bridge-deterioration/docview/2206339868/se-?accountid=14681

Mazurek, D., & DeWolf, J. (1990). Experimental Study of Bridge Monitoring Technique. Journal of Structural Engineering (New York, N.Y.), 116(9), 2532–2549. https://doi.org/10.1061/(ASCE)0733-9445(1990)116:9(2532)

Ritter, M. A., U. S. Forest Service, Engineering Staff. (1990). Timber Bridges: Design, Construction, Inspection, and Maintenance. U. S. Department of Agriculture, Forest Service, Engineering Staff. http://www.dot.state.mn.us/bridge/pdf/insp/USFS-TimberBridgeManual/em7700_8_chapter01.pdf

Salawu, O. (1997). Detection of structural damage through changes in frequency: a review. Engineering Structures, 19(9), 718–723. https://doi.org/10.1016/S0141-0296(96)00149-6

San Andres, L. (2008). Notes 14. Dynamic response of continuum systems. Oaktrust.library.tamu.edu. Retrieved 28 June 2021, from https://oaktrust.library.tamu.edu/handle/1969.1/93279.