13TH CANADIAN MASONRY SYMPOSIUM
HALIFAX, CANADA
JUNE 4TH – JUNE 7TH 2017

USE OF ACCELEROMETER TECHNOLOGY FOR QUANTIFYING CONDITION OF MASONRY ARCH BRIDGES

Nichols, John[1]; Tomor, Adrienn[2] and Benedetti, Andrea[3]

ABSTRACT

The majority of masonry arch bridges are over 100 years old and carry ever increasing loading regimes. Safety and reliability of masonry bridges and structures are primary concerns of structure owners and managers. Assessing the condition of masonry structures relies primarily on visual observation due to the complexity of the problem and variability of the materials. The paper proposes a method of quantifying the condition of masonry structures based on frequency measurement. Frequency data is analysed through Fast Fourier transform (FFT) analysis and provides the frequency signature of the structure. Changes in the frequency signature over time can indicate deterioration or sudden damage. Finite element analysis can be used to relate changes in the measured frequency signature (modes) to individual structural elements and identify the location of damage. The system can be easily used in conjunction with routine bridge/structural inspection to create a numerical record of the structural condition and develop an alert function to would notify structure owners about deterioration or sudden impact. The process is demonstrated through a masonry arch bridge study in Parma, Italy.

KEYWORDS: *accelerometer, frequency, non-destructive testing (NDT), monitoring, masonry arch bridges, finite element analysis*

INTRODUCTION

Masonry arch bridges represent around 40% of the European bridge stock and are generally well over 100 years old. Ensuring safe use of such bridges is a key concern for bridge owners. Assessing the condition of masonry arch bridges is generally carried out through regular visual and more in-depth principal inspections and assessing the load bearing capacity is carried out in increasing levels of complexity, using semi-empirical, limit analysis and solid mechanics methods (e.g. finite

[1] Associate Professor, Department of Construction Science, Texas A&M University, Department of Construction Science, Francis Hall 302, 400 Bizzell St, TX 77843, College Station, US, jm-nichols@tamu.edu
[2] Senior Lecturer, Faculty of Engineering and Technology, University of the West of England, Coldharbour Lane, BS16 1QY, Bristol, UK, Adrienn.tomor@uwe.ac.uk
[3] Professor, Department of Civil, Chemical, Environmental and Materials Engineering, Viale Risorgimento 2, 40136 Bologna, Italy, andrea.benedetti@unibo.it

element models). Identifying sudden or gradual deterioration relies in the first instance on visual inspection by the bridge inspector, although damage is often initiated inside the structure and only become visible on the surface once deterioration progressed. Damage index is widely used by bridge managers for identifying the condition of bridges, it is however almost entirely based on visual observation and there are few alternative techniques available for quantifying the condition of structure. The research aims to provide an easy to use monitoring tool to:

- identify early damage development (before becoming visible on the surface)
- quantify the condition of the structure and rate of damage development
- quantify remaining service life and assist with scheduling bridge-specific maintenance works.

LITERATURE REVIEW

Significant work has been done in the 20th century on damage and fracture mechanics, leading to the pioneering work of Hill on plasticity [1]. The research showed that changing stiffness properties occurred with increasing strain levels or for repetitive loads. Krajcinovic [2] summarised the development of damage mechanics that forms the basis for identifying changes in the stiffness properties of materials (e.g. due to gradual deterioration or sudden damage). The theory has been applied to a wide range of fields but its application has so far been limited for masonry. Nichols [3] identified changes in measured stiffness properties of masonry with increasing strain levels using a varying harmonic load.

Richter [4] provided the first review of the acceleration levels that can cause damage in structures and clearly relates the levels to the accelerations observed in earthquakes commonly observed in the modern world. Brigham [5] outlined the development of the Fast Fourier transform (FFT) method invented by Cooley and Tukey [6] that enables the data time series to be reviewed in the frequency domain and the frequency components to be determined in the original time series.

Soong and Grigoriu [7] outlined the use of random vibration to determine the properties of structures and structural elements and provided the basis for a mathematical technique to identify if changes have occurred in the FFT data series. Nelson [8] developed the theoretical method to use a random Gaussian based Brownian motion as the applied loading and limiting the deflections to lie within a linear range.

PROCESS OF QUANTIFYING DETERIORATION

The proposed monitoring system has been developed through the SHAPE Infravation project [9] and quantifies the condition of structures with the use of accelerometer technology, Fast Fourier transform (FFT) and finite element analysis in the following steps.

a) Frequency measurement

Acceleration measurements require the structure to be excited by some kind of loading. Artificial impact or live loading (e.g. using a hammer or vehicle) is generally used to increase the level of acceleration above the sensitivity of the sensor. Acceleration data of sudden impact is however non-Gaussian, usually of short duration and lacks statistical certainty. The current work is carried out using a single SENSR CX1 accelerometer (Figure 1) [10] that uses ambient vibration (often referred to as Brownian motion) [8,11] as a constant environmental load (only influenced by temperature). The resolution of the CX1 accelerometer is around 10 to 20 *micro-g* (where g is gravity) and the practical limit for the measurement system is set by Brownian motion with an acceleration around 0.1 to 0.5 *milli-g*, giving an accuracy of ca. ± 1%. The accelerometer records data up to 2000 times per second that allows the frequency up to 1000 Hz to be identified.

Figure 1: SENRS CX1 accelerometer

b) FFT analysis

The recorded CX1 accelerometer data (in time series) excited by ambient vibration is subsequently processed by Fourier Transform analysis (FFT) [5] to provide data in the frequency domain. The monitoring system using the CX1 accelerometer, automated cloud transfer and FFT analysis is currently being developed as the 'SHAPE' system for field applications. A typical recording period for FFT analysis is 8 seconds (16384 records with 8192 steps) with 0.122 Hz frequency steps. The FFT results provide a clear picture of the frequency modes and acceleration at any individual point in time. In order to identify changes in the frequency signatures over time (caused by changes to the structure, deterioration or impact), the FFT results of subsequent time intervals can be compared and differences identified.

c) Finite Element analysis

Changes in the frequency modes can highlight changes or damage in the structure. For simple structures with limited number of elements identifying the location of damage is relatively easy. For complex structures relating damage to structural elements is however much more difficult and cannot be done manually. In order to make damage identification easier for bridge owners, FE analysis can be used to identify the theoretical frequency modes and relate them to the individual structural elements.

FE analysis is based on isotropic theory and classic assumptions from beam theory [12] and is widely used for concrete and steel bridges. Such assumptions are however less well suited for masonry with complex anisotropic properties [13,14]. Nelson [8] developed the theoretical method to overcome the problem by maintaining the standard concepts from Classical Beam Theory during the experimental work.

d) Relating modes to structural elements

While FE analysis can provide all theoretical modes for the structure, accelerometer measurement identifies only a limited number, but key modes. By comparing the measured modes with the theoretical modes, any critical measured mode (with changes in the frequency spectrum over time) can be related to individual structural elements and the location of damage.

e) Quantifying rate of deterioration

For periodic or continuous monitoring, changes in the individual modes can be compared for subsequent time intervals and deterioration quantified over time. The rate of deterioration can (in theory) be subsequently related to the remaining service life of the individual structural elements and the overall structure.

APPLICATION

Quantifying deterioration can provide a useful tool for bridge owners, assessing engineers or for life cycle analysis to identify changes in structural condition over time. Due to the sensitivity of the system, changes can be identified early, generally before the effect of deterioration can be visually observed on the surface (through visual inspection). One of the intended direct application for SHAPE system is routine bridge inspection. As an example, every bridge in the UK is inspected every two years visually within the routine bridge inspection schedule. While visual inspection is critical for identifying the condition of the bridge and signs of damage, the system would provide an additional numerical record for the condition of the bridge that can be directly compared for subsequent inspections. The high sensitivity of the CX1 accelerometer enables changes in the structure to be identified before external visual changes become visible and alert bridge owners about progressive damage and rate of change in the structural condition. A CX1 accelerometer is ideally given to bridge inspectors who simply place it on the roadway/footpath while carrying out the inspection. Automated alert function can be provided for bridge owners to notify about deterioration or sudden impact (e.g. bridge strikes).

EXAMPLE

The process of identifying and quantifying damage with the use of the SHAPE system (including accelerometer technology, stochastic and FE analysis) is demonstrated through a case study for a masonry arch bridge. The 20 span 560 m long Taro bridge (see Figure 2) is located in Parma, Italy (built 1815-1821) [15]. Each span is 24 m long, constructed of brick masonry with three-centred arches and 4-metre circular openings in the spandrels. The bridge was damaged in the Second World War and has undergone significant repairs.

Figure 2: Taro bridge (Ponte Paro), Parma, Italy

a) Frequency measurement

Frequency measurements were taken using a single the SENSR CX1 accelerometer. The CX1 was placed on the road surface next to the parapet (Figure 3) around the ¼ of each span for 1 minute at each location. Data collection for all 20 span took about an hour and was a straightforward process.

Figure 3: CX1 monitoring

b) FFT analysis

The measured frequency data was processed using Fast Fourier Transform (FFT) analysis and representative examples of FFT output (for span 10) is shown in Figure 4 up to 62.5 Hz (X (transverse), Y (longitudinal) and Z (vertical) directions). There are few key modes visible in the X and Y directions, but the two key modes in the Z direction are 13.3 Hz and 17.7 Hz.

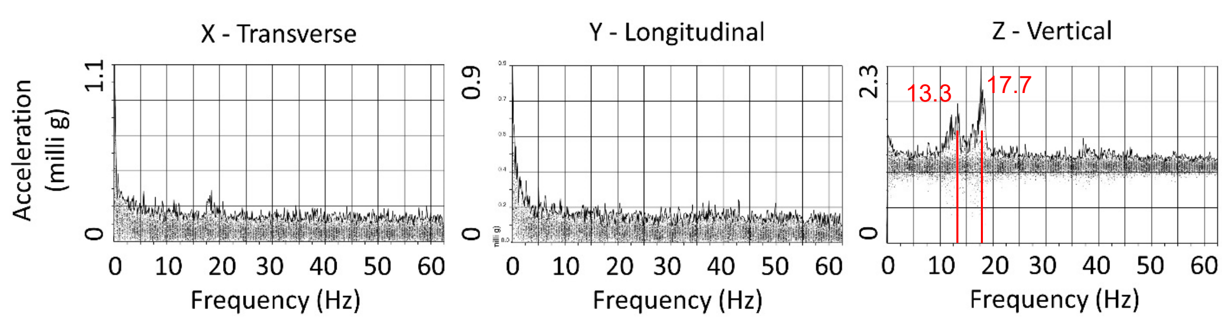

Figure 4: FFT Frequency output (span 10)

c) FE analysis

For the current case study RHINO 3D drawing package was used for modelling the geometry for its ease of use and compatibility with STRAND7 finite element package. The model can be reasonably easily developed using command files, i.e. simple geometric property text files written in Fortran. The software requires all XYZ co-ordinates of the structure to be accurate to 0.001 m. Accuracy of 0.001 m is clearly unrealistic for historical masonry arch bridges, but the models cannot be easily generated without it. Estimated values for the bridge geometry are shown in Table 1 together with revised values for modelling based on the arch geometry shown Figure 5a. The RHINO model provides a reverse image of the standard arch (Figure 5b) that is used for all the 20 spans along the bridge.

Table 1: Geometric properties

Description	**Theoretical Data**	**Geometric Data**
Bridge width	28 m	28 m
Arch span	24 m	24 m
Arch radius (central)	19.7 m	19.7 m
Arch radius (end)	4.7 m	4.5856 m (revised)
Angle (end)	60 deg	60.6232 deg (revised)
Intrados height	6.7 m	6.596 m (revised)

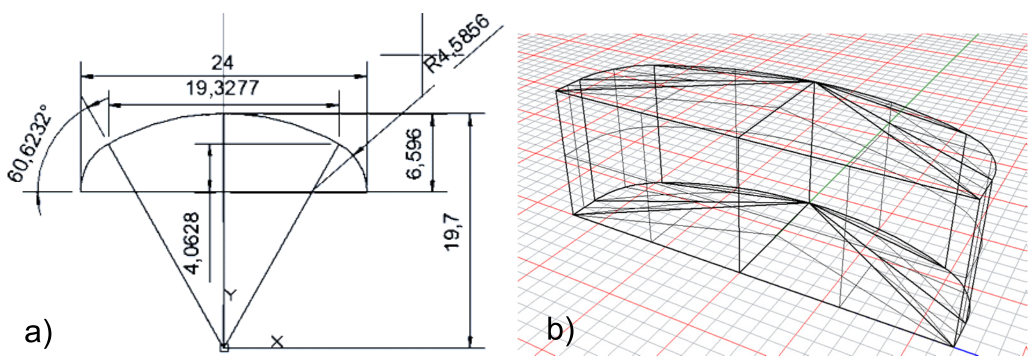

Figure 5: a) Arch geometry and b) RHINO Model for the arch element

The twenty arches are then removed from the solid bridge element to minimize meshing problems (Figure 6). Surfaces are subsequently developed in the RHINO model using 'eight-node plate' elements and solid meshing using 'tetrahedral' elements. Alternative models and elements can be used, but the key issue is optimizing complexity to provide a representative and conceptually acceptable solution.

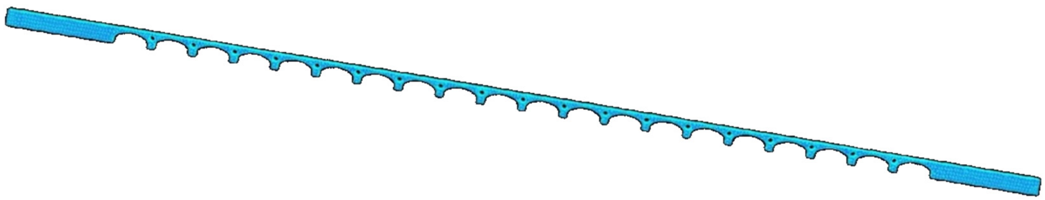

Figure 6: RHINO model for the bridge

After the model of the bridge was generated using RHINO, it was imported into STRAND7 FE package [16] and meshed to identify the natural frequencies of the bridge. The material parameters are established as mean estimates with standard deviations to allow a sensitivity analysis to be completed using the FE model. For the case study a Poisson's ratio of 0.15 was used with ± 10% SD. The elastic modulus for brick masonry of 15.7 GPa was used with ± 3.2% SD and variance of 10. All other Young's moduli are assumed to have a standard deviation of 20 % which is consistent with current measured values. The shape of the first mode for the bridge is shown in Figure 7 (exaggerated for display purposes) together with the undeformed bridge.

Table 2: Masonry properties

Description of the Property	**Mean Value** (μ)
Stonework Young's Modulus	5 GPa
Stonework Poisson's ratio	0.15
Stonework Density of Stone	1800 kg/m^3
Asphalt Young's Modulus at 35 °C	20 GPa
Asphalt Young's Modulus 0 °C	2 GPa
Rubble fill in the bridge	2 GPa

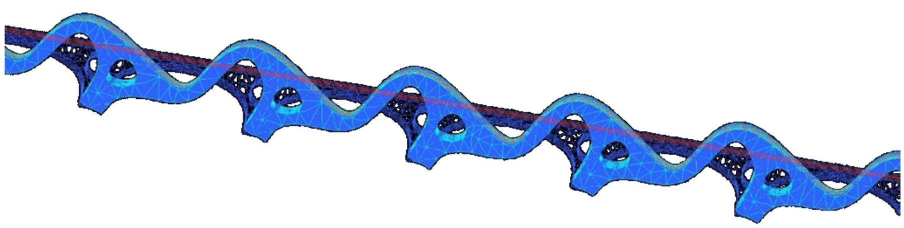

Figure 7: Strand7 results for the first mode

d) Relating modes to structural elements

The first 100 theoretical modes from the FE model are shown in Figure 8 together with the two key measured frequencies (13.3 Hz and 17.7 Hz in the Z direction). The measured frequencies however do not match the calculated frequencies exactly. This is not surprising due to difficulties in defining the geometrical and material properties of historical bridges and their inherent variability. The case study highlights one of the fundamental difficulties using FE analysis for masonry structures. A number of reasonable approaches are however possible at this stage.

Sensitivity or probability assessment can be carried or simply the neighbouring modes considered in the vicinity of the measured key frequencies. For the current case study the neighbouring modes are identified (mode 58 (13.02Hz) and mode 59 (13.53Hz) either side of 13.3Hz and mode 85 (17.67Hz) and mode 86 (17.73Hz) for 17.7 Hz) are considered and the description of modes is listed Table 3.

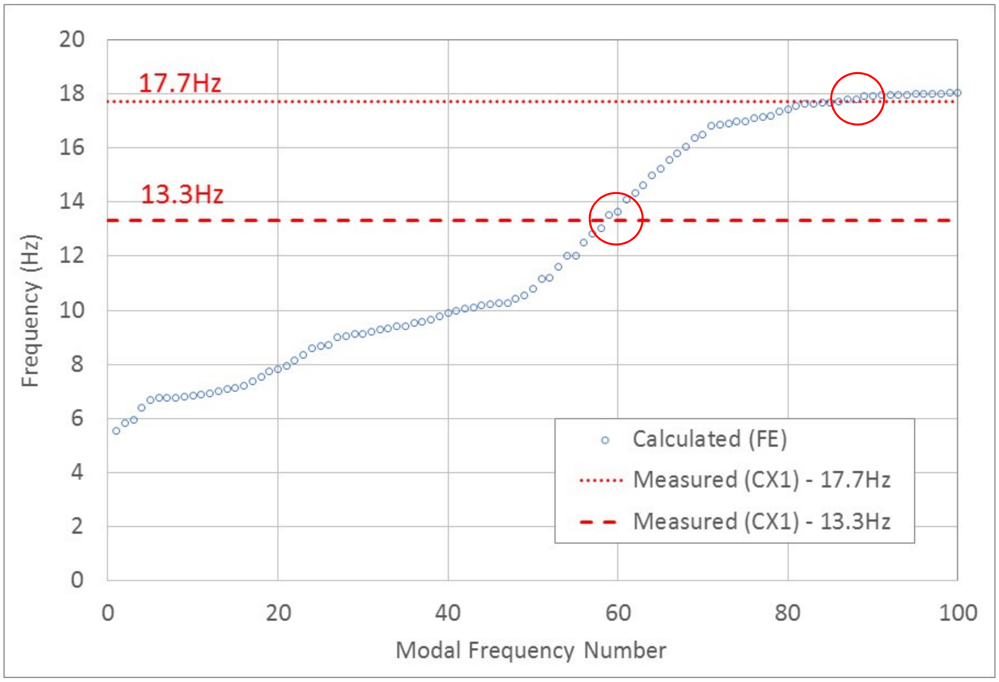

Figure 8: Comparison of measured and calculated modal frequencies

Table 3: Modes and relevant elements

Mode	Frequency	Description
58	13.02	Two piers rocking about their longitudinal (Y) axis 180 degrees out of phase. Road plate twisting into vertical sine wave. The two kerb sides of plate are 180 degrees out of phase, but movement is in phase with the piers.
59	13.53	Pier on the N side rocking about short (X) axis and pier on S side rotating about vertical (Z) direction. Plate follows a sine wave shape along the X axis with two kerb sides 180 degrees out of phase.
85	17.67	Piers not moving, arch plate rotating about center of the road (Y axis), eastern kerb 180 degrees out of phase with the western kerb. See-saw movement at the center of the arch.
86	17.73	Two piers rocking in phase about longitudinal (Y) axis, a stationary point exists along centreline of arch (Y axis), ¼ and ¾ points 180 degrees out of phase in a sine wave.

e) Quantifying rate of deterioration

In order to demonstrate the process of quantifying deterioration over time for increasing damage, at least two acceleration recordings with some sort of change in the frequency spectrum are needed. As only one acceleration recording is however available for the Taro bridge, recordings for a simply supported timber beam are used (35 mm (H), 87 mm (W), 2400 mm (L)). The beam was damaged at mid-span by an increasing depth of cut at the bottom and acceleration was measured under ambient vibration. Figure 9 shows the FFT output up to ca. 60 Hz a) for the undamaged beam and b) for a 6mm cut. The first mode is around 15.7 Hz for the undamaged beam and ca. 15.3 Hz for the 6mm cut with a hardly noticeable ca. 2.5% change in frequency. (Standard statistical analysis identifies change to be significant at 5%). Figure 10 shows the measured frequency of the first mode against increasing damage (remaining depth).

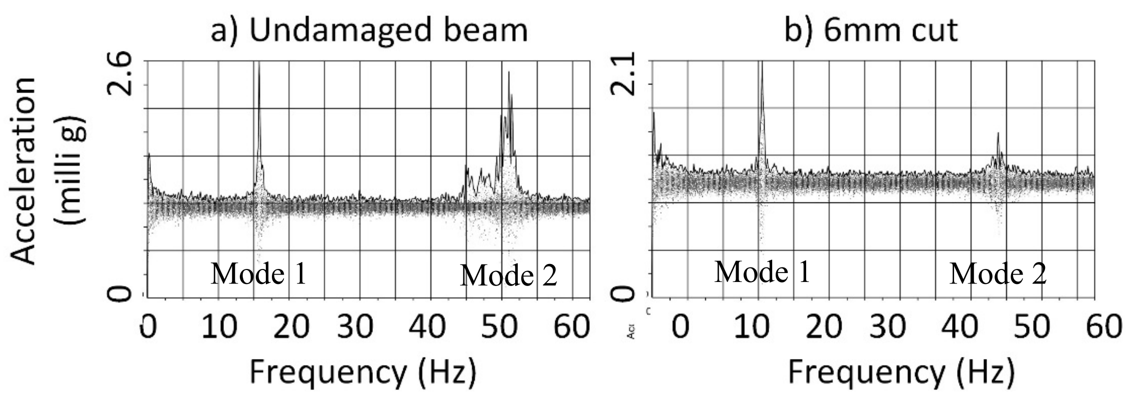

Figure 9: FFT output for a) undamaged beam and b) damaged beam with 6mm cut

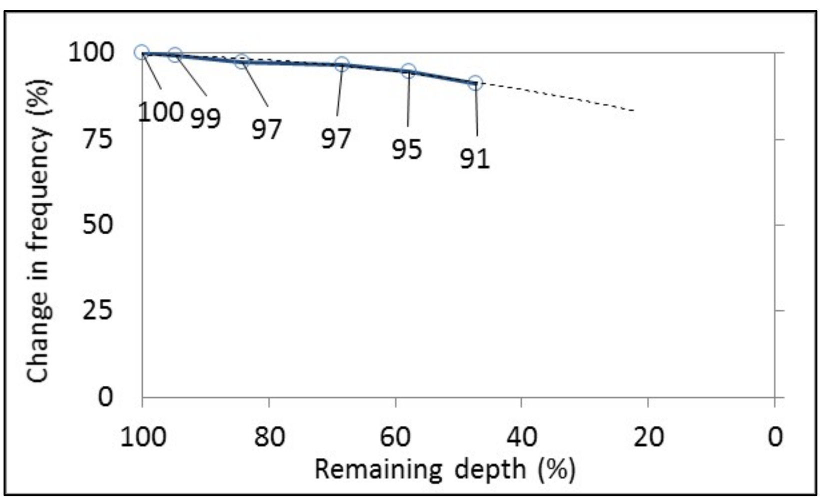

Figure 10: Rate of deterioration for a beam

CONCLUSIONS

Masonry arch bridges are generally over 100 years old and subjected to ever increasing loading regimes. Condition assessment and structural analysis of masonry structures is difficult and is generally based on visual observation. The paper outlines a method of identifying and quantifying the condition of structures based on frequency measurement. The SENSR CX1 accelerometer was used for its quick and easy application under field conditions and is based on ambient vibration. The measured frequency data is processed by Fourier Transform analysis (FFT) and the frequency signature for the structure identified. Changes in the frequency signature over time can indicate changes in the structural condition (e.g. deterioration or damage) and quantify the rate of deterioration for subsequent measurements. Measured key modes can be related to individual structural elements and location of damage with the help of FE analysis. The system provides an easy to use monitoring non-destructive technique (NDT) that can be conveniently used in conjunction with routine bridge/structural inspection or for permanent installation. Automated alert functions can be developed to notify bridge/structure managers about critical deterioration or sudden events (e.g. bridge strikes).

ACKNOWLEDGEMENTS

The research forms part of the SHAPE project, funded by the EU-US Infravation grant. The authors greatly appreciate the opportunities given by Infravation.

REFERENCES

[1] Hill, R. (1956). "New horizons in the mechanics of solids." *J. Mechanics and Physics of Solids*, 5(1), 66-74.
[2] Krajcinovic, D. (1996). *Damage Mechanics*, Elsevier, New York.
[3] Nichols, J. M. Kavars, C. and Nichols A. B. (2009). "Measurement of Damage in Masonry". *Proc. 11th Canadian Masonry Symposium*, Toronto, Canada.
[4] Richter, C. F. (1958). *Elementary Seismology*, W.F. Freeman and Company, San Francisco and Bailey Bros. & Swinfen Ltd., London.
[5] Brigham, E. O. (1987). *The Fast Fourier transform and its applications*, Englewood Cliffs, Prentice Hall, US.
[6] Cooley, J. W. and Tukey, J. W. (1965). "An algorithm for the machine calculation of Complex Fourier Series." *Mathematics of Computation*, 19(90), 297-301.
[7] Soong T. T. and Grigoriu, M. (1993). *Random Vibration of Mechanical and Structural Systems*, Englewood Cliffs, NJ. Prentice Hall, US.
[8] Nelson, E. (1967). *Dynamical Theories of Brownian Motion*, Princeton University Press, New York, US.
[9] http://www.infravation.net/projects/SHAPE [accessed 3 April 2017].
[10] https://sensr.com/Products/CX1 [accessed 3 April 2017].
[11] Kappler, E. (1931). "Versuche zur Messung der Avagadro-Loschmidtschen Zahl aus der Brownshcen Bewegung einer Drehwagge". *Annalen der Physick*, 11, 233-256.
[12] Timoshenko, S. and Goodier, J. N. (1951). *Theory of Elasticity*, McGraw-Hill Book Company Inc., New York, US.
[13] Harrison, H. B. (1973). *Computer Methods in Structural Analysis*, Englewood Cliffs, Prentice Hall, New York, US.

[14] Nichols, J. M., (2011). “A Finite Element Study of an Indonesian Single Storey Masonry Dwelling”, *Proc. 11th North American Masonry Conference*, Ed. Schultz, A., The Masonry Society, Minneapolis, US.
[15] Cocconcelli, A. (1825). *Descrizione dei progetti e dei lavori per l’innalzamento dei due ponti sul Taro e sulla Trebbia*, Tipografia Ducale, Parma, Italy.
[16] http://www.strand7.com/html/docu_usingstrand7.htm