IDENTIFYING THE CONDITION OF MASONRY ARCH BRIDGES USING CX1 ACCELEROMETER

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SUMMARY

Masonry arch bridges are the oldest bridges in the traffic network. As for all bridges, masonry arch bridges also deteriorate over time, although at a slower rate. A series of tests have been carried out to monitor a large-scale masonry arch bridge destructively tested at the University of Salford, UK. The first author monitored these tests with a CX1 accelerometer and the second author has developed a number of computer programs to analyse the results. This paper sets out the results from the CX1 acceleration data and the early development of Finite Element programs to model the results. The key finding from this ongoing investigation is that a change occurs in the response of the bridge as it is damaged, the purpose of the FEM development is to outline the early gains we have made in theoretical understanding of the changes required in the underlying mathematical models to account for the damage.

Keywords: *Dynamic analysis, CX1 accelerometer, Fast Fourier Transform.*

1. INTRODUCTION

Masonry arch bridges provide a stable long term solution to the crossing of rivers, creeks and other objects for transportation systems. The utility of the structure is limited in high seismic regions, but in regions of low seismicity they are an economical and effective engineered solution to bridging something. The set of these bridges in the UK provides a significant impetus to the study of their long term capacity. Long term loads, such as train and highway traffic, causes deterioration in the bridge materials. This is an early study in this ongoing research into the structural capacity measurements of in-situ bridges. A sample bridge was constructed at Salford University, UK for this destructive set of tests as part of a large EPSRC testing program. As part of the test program, a set of static tests to failure were applied to a masonry bridge. Although the tests are static, the critical element of interest to all masonry bridge research groups is the vibration of the bridge due to thermal load, which provide strong guidance as to the current modal set. This vibration will ultimately allow for a comparison of the set of modes for the bridge over time. The purpose of this study is to review the experimental results for the slowly increasing applied pseudo-static loading on the Salford masonry arch bridge. This paper provides a brief literature review, outlines the test methods and the results, and provides conclusions.

2. LITERATURE REVIEW

2.1. Introduction

The literature review outlines the background to the research in masonry arches, the analysis of the results from the CX1 data and outlines the steps taken in the development of the FEM used to support the statistical analysis of the FFT data from the CX1 analysis.

2.2. Thermal Loads

Every object in the world is subjected to a thermal load, whether one is in the artic or the equator. The magnitude of the thermal load is clearly temperature dependent, but for a constant temperature it is reasonably constant. The thermal load causes acceleration in the ground of about 0.1 to 2 milli-g depending on the time of year and time of day. Kappler [1] studied this thermal load and showed that it is capable of vibrating non-micro sized structures at their lowest natural frequency. This thermal load provides a powerful tool to look at the changes in the stiffness matrix for a structure with time. This finding represents a major advance in the field of damage detection. The methods developed here rely on this loading to provide the Fast Fourier transform data to determine the failure modes.

2.3. Masonry Arches

Masonry arches were the predominant method of bridging rivers for millennia and represent ca. 40% of the current European bridge stock. Historically arches have been analysed with the help of thrust-lines and mechanism method as summarized by Harvey [2] and Heyman [3]. Since the Second World War the MEXE method has being used for quick assessment of capacity [4] and is still widely used as the first level of assessment in the UK and Europe. A similar method is proposed to be developed for steel bridges in Texas by TxDOT Nichols [5] investigated the possibility of using a simple program to identify the likely capacity of damaged arches following earthquakes. Recent advances in the development of accelerometer technology can help identify the response of any structure to applied loads at a fine scale as shown for the Pont-y-Prydd Bridge in Wales [6]. A limited number of load tests have been carried out during the past decade to measure the capacity of masonry arch bridges. Ten full-scale masonry arch bridges were tested in the field by the UK Transport Research Laboratory and results compared to the MEXE method [7]. A test series to test the behaviour of soil filled masonry arches is currently being undertaken at Salford University, UK.

These recent Salford tests have been monitored with the CX1 by the first author and form the basis of some elements of this analysis. The CX1 accelerometer provides a device that is capable of resolving to 10 micro-g in the frequency domain, whilst there are more sensitive MEMS accelerometers none are configured with MILSPEC covers, tilt measurement and temperature measurement. These unique features make this device indispensable for bridge monitoring, whether long term or episodic. The resolution limit of 10 micro-g is ten times more sensitive than the thermal floor that limits all bridge accelerometer analysis [6]. This thermodynamic limit is a hard floor for all work such as for Salford [8]. It is possible to get below this limit by building a model bridge in a salt mine, but it not practical.

2.4. Salford Tests on a masonry arch

The bridge comprises an arch with 3000 mm span, 750 mm rise, 215 mm ring thickness and 1045 mm width. The backfill of the bridge was clay to the top of the arch with a limestone layer above the top of the arch. Flexural strength of masonry was 2.86 MPa. The tank holding the soil was designed to be stiff with a low side wall friction to provide plane strain conditions. The critical aspect for the CX1 is the wealth of data, the ability to monitor multiple devices on the same time monitor and the additional special purpose software developed to investigate the modal and other data.

The structure was tested under single point load to failure. The single point load was applied during load testing at the ¾ span. A 203x203x46 Universal Channel distributed the load across the width of the arch. Tab. 1 provides the load summary for each test.

Table 1. *Test Load Types and Test Load Data.*

Test Period	Duration (seconds)	Duration (hours)	Loading Condition
1	3344	0.93	Load: Thermal only
2	3344	0.93	Load: Thermal only
3	3344	0.93	Load: Small Dynamic Type: Hammer Drop Applied: three times
4	3344	0.93	Load: Thermal only
5	3344	0.93	Load: Quasi-static, Applied range: 35 – 65 kN

Fig. 1 shows the masonry arch bridge used at Salford for the experimental work. Acceleration signals were measured using the CX1, which was located on the road surface at the top of the arch. The directions for the signal recording are x being the longitudinal, y transverse and z vertical direction. Data from the CX1 accelerometer is measured using a program supplied by the manufacturer, modified by the second author. This data is stored in CSV files for analysis.

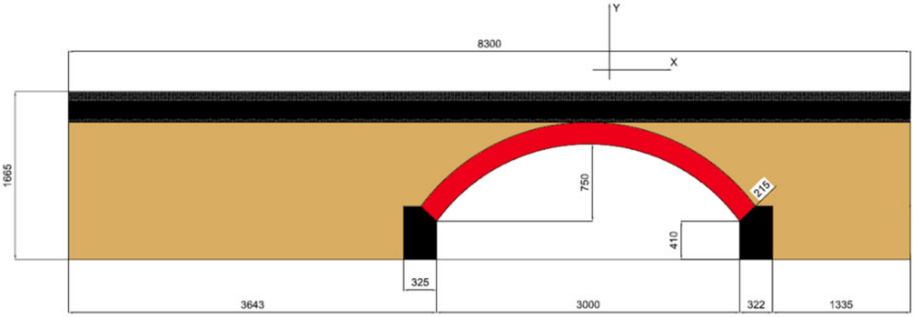

Fig.1. *Masonry Arch Test Arrangement.*

Fig. 2 shows the loading pattern.

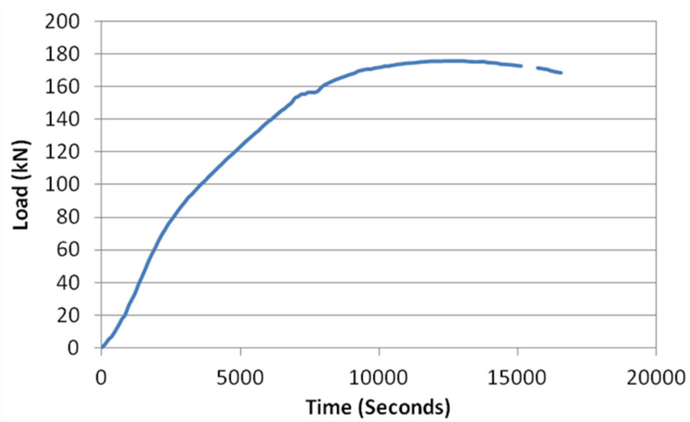

Fig. 2. *Loading pattern*

2.5. Thermal Load Use

Two types of loading can be studied with the help of CX1, Brownian motion [9] and loads from external sources. Brownian motion (Type 1 Load) is pervasive, whilst the applied live loads (Type 2 Load) have a specific time pattern and force vector. Type 2 does not exist in isolation from Type 1 loading. Figure 2 shows the loading pattern for the arch test. The arch was loaded up to 175 kN. This is a Type 2 Load; the underlying thermal load is continuously monitored by the high resolution accelerometers during the test program. Changes in the bridge material properties should be reflected in the dynamic response of the bridge to live loads. Changes in the baseline response should indicate property changes in the structure, in reality direct modal changes in the structure.

3. METHODOLOGY

The analysis programs have been developed over the last five years by Nichols [10] and have two stages of analysis. The first stage uses Fast Fourier transform (FFT) routines [11] to determine the frequency response for the recorded time signal. The FFT is set for a period of 8.192 seconds. This recording time has been shown to yield a high resolution of data across an acceptable frequency range. The second stage uses 51 consecutive FFT signals to create a contour plot of the signal frequency against test number. Each contour plot shows 417.8 seconds of records. The base contour package used for the analysis is CONREC developed by Bourke [12].

Fig. 3 shows the contoured FFT plot for the Y Direction for test period 5. The solid yellow line shows the maximum acceleration in the frequency domain for each 8 second test interval. The point of Figure 4 is to look to understand the basic patterns visible on the graph. Specific frequency information is available from the SQL Server database data and from frequency plots. The horizontal axis is the frequency from 0 to 62.5 Hz in 512 frequency steps. The vertical axis shows a set of 51 tests taken over about 8 minutes. The point is to look for patterns in the graph and to determine if the patterns are periodic or aperiodic. In this case four patterns are evident. The first occurs around zero and indicates that the instrument is not quite level, which is of no consequence, the second occurs at about the 16 Hz or third line on the X axis, and then at 20 Hz or the fourth line. These lines show 2 modes in the natural frequency set. The plot shows the modes are constant and periodic for this time span.

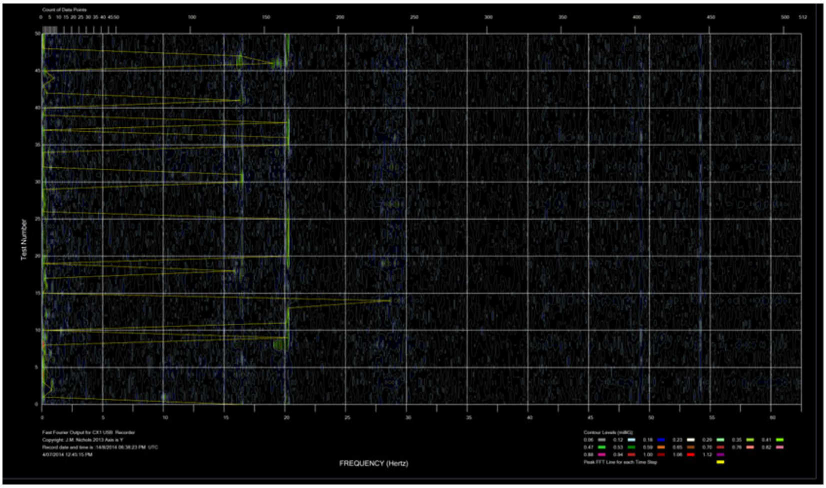

Fig. 3. *Test Period 5 - Direction Y.*

Fig. 4 shows the Z direction for the test period 5.

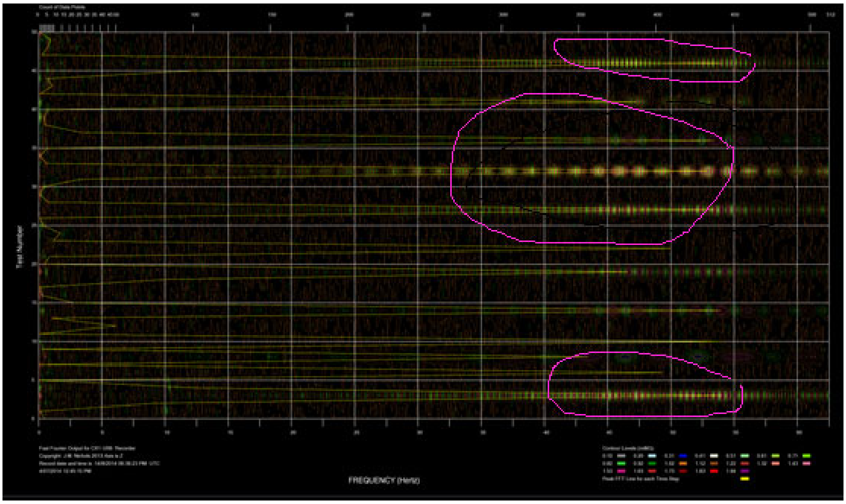

Fig. 4. *Test Period 5 - Direction Z.*

These contour plots were an early development in the analysis for the CX1. The extensive testing on a wide variety of bridges since the development of this plot has had the purpose of looking for visual patterns in the data. One such visible pattern is the scalloped pattern in the region above 30 Hz on the plot. It has been discovered by reference to numerical data from the test results that this an indicator of damage. The type of damage is not determined from this graph, it merely provides a broad overview of the results for a set of tests. Three of these graphs for the XY and Z axis shows the visual results from 2.4 million data points. These graphs can be turned into a movie for rapid review.

Tomor's recent and extensive work on episodically monitoring European bridges [13] pointed to the issue of analysis of these structures, particularly trying to understand the cause of the scallop patterns. Benedetti (personal communication, 2016) used STRAND 7 [14] to model some of the structures monitored by Tomor. Nichols [15] used Strand 6 [16] to model a building that had been tested on a shaking table by Benedetti and Pezzoli [17] in the early 1990s. This work showed the difficulty of matching the boundary conditions in Finite Element models to reality.

The next stage in the research is development of a FEM tool that has the robustness, elements, speed and ability to be used anywhere. Clearly, STRAND7 or Abaqus [18, 19] provide some of the required elements in very mature packages, but they lack the ability to be field deployed on small computers at a reasonable cost to a bridge owner.

4. FINITE ELEMENT METHOD DEVELOPMENT

Structural health monitoring is an area of active research interest and the FFT results from the data collected on the masonry arch provides numerical data that can be compared to a FEM model. There are very many FEM packages, which are however generally based on the code developed by a very few groups, including Powell's group , [20], and Felippa's code, [21]. Each of these groups used distinct and specially coded matrix inversion procedures, eigenvector analysis and Newmark –Beta analysis programs. Recent advances in the development of special libraries provides access to exceptionally fast matrix inversion procedures, eigenvector analysis and Newmark –Beta analysis programs. The provision of a FEM routine to develop the structure, damping and mass matrix can then be based on the unique work of Powell and Felippa for example and the standard routines substituted for the superior performance of the latest standard packages.

Harrison [22] provides an elegant development of the Finite Element Method and a set of Fortran programs for FEM analysis, which provided a useful starting point for the new FEM development. These Harrison programs are reasonably easy to implement on a modern compiler, such as INTEL Fortran. Harrison's program provide a base for testing development of the code and provides test examples. Harrison starts with the simple beam element as shown in Fig. 5. The beam element is assumed to have an invariant Young's modulus, E. The standard beam element for a typical structural analysis package has a constant moment of inertia, I , end moments matrix, M , flexural stiffness matrix, K , and end rotations matrix, Θ . The matrix equation relating the end moments to the end rotations for the prismatic beam element shown in equ. 2 is:

$$\mathrm{M} = \frac{EI}{L}\Theta \tag{2}$$

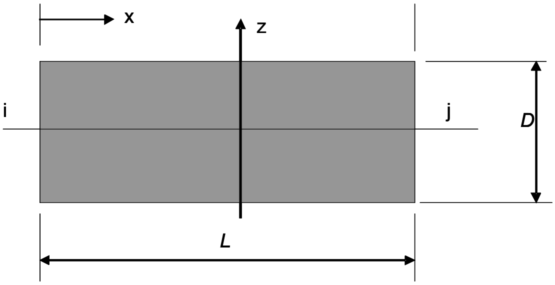

Fig. 5. *A Finite Element Beam Conceptual Model.*

The first stage in the development of the required analysis program is to replace the Gaussian elimination program with PARDISO [23]. The increase in speed is measured at 100 fold, with no loss in accuracy of the results. ULARC and Harrison's program are static solvers. The second major addition is making the program into Eigenvector solvers to determine the modal characteristics. FEAST [24] takes the stiffness and mass matrix and returns the eigenvectors and eigenvalues. Figure 6 shows the results for the first twenty eigenmodes for a simple model of the arch and infill.

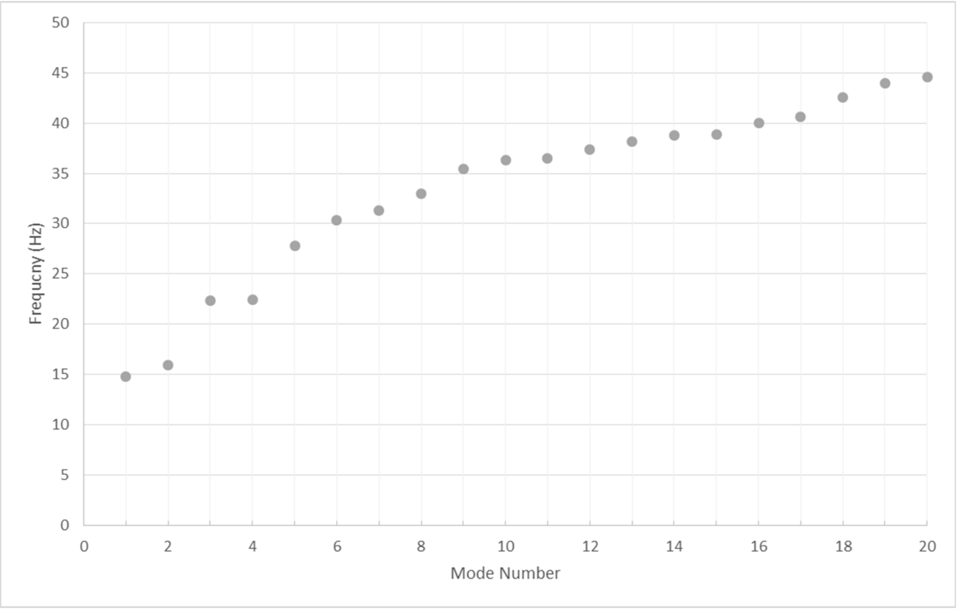

Fig. 6. *Eigenvalue Frequencies for Arch and Infill Model.*

The model was created as a simple arch using 22 nodes and beam elements in the Harrison program. The first stage of the analysis looked at the arch as a simple beam and showed a first natural frequency of about 25 Hz, as would normally be expected. The difficulty in modelling masonry arches is the imposed load from the arch fill, which adds significant mass without an appreciable increase in the stiffness of the main element as the main fill is usually soil. An alternative technique was used for this model using the Lothuur program [22], a set of short beams to model the clay infill were placed vertically above the arch beam. Each beam was modelled to the center of the infill strip as shown.

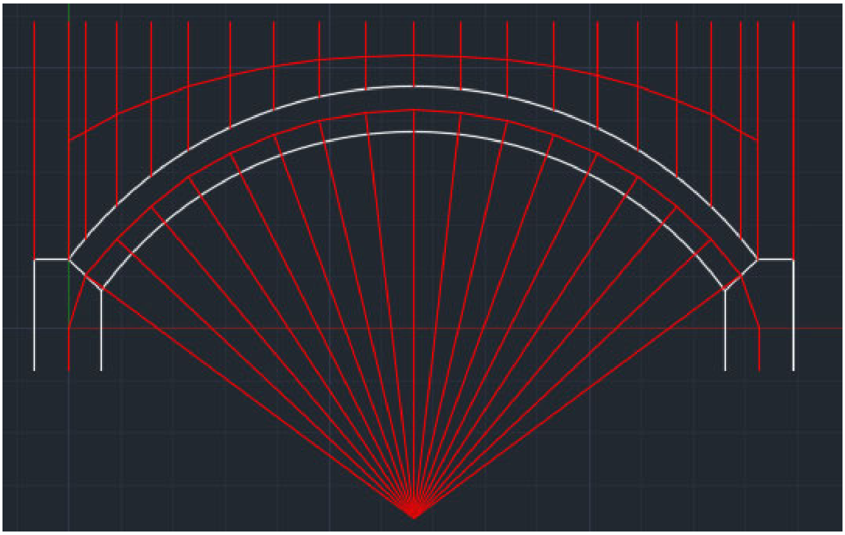

Fig. 7. *Arch and Infill Model Geometry.*

The program now provides a vehicle for studying the changes in the modes as the evolution of damage occurs in bridges, currently work proceeds on the masonry arch bridges, whilst the basic mechanism of failure of the Salford Bridge has been identified, the work proceeds to replicate this in an FEM model, which is a non-trivial exercise, given the multiple mechanisms postulated by Tomor. The benefits of using PARDISO and FEAST are the speed and ability to deploy onto small computers such as the Intel NUC. The main advantage is the ability to deal with the underlying mathematics of the elements directly. Current work is focussing on adding additional elements such as the 18 degree of freedom triangular plate element for studying concrete bridge decks to the new program.

5. CONCLUSIONS

Historical infrastructure is naturally prone to deterioration and needs maintenance to preserve its structural integrity. Quantifying deterioration is however a difficult task. Developments in Fast Fourier Transform and accelerometer technology have recently made it possible to develop an easy to use monitoring method to estimate of the natural frequency response of structures and potentially quantify the rate of deterioration.

The paper presents the results for a series of tests carried out on a large-scale masonry arch bridge under laboratory testing with and without live loading while being monitored by a CX1 accelerometer. The results for the bridge show strong 17.5 Hz and 20 Hz peaks for the natural frequency without live loading (thermal motion only) in the undamaged bridge and significant changes in the frequency pattern once the structure has deteriorated under live loading. The current stage of the research is focussing on development of a fast, efficient, cost effective and deployable dynamic analysis package to allow direct review of the FFT results. The package requires only a modal analysis component at this stage so the changes in the frequency patterns evident in the CX1 data are modelled against the FEM results using standard statistical techniques. The results point to the tensor changes for the structure. As with all FE modelling, the need is to check the results against the experimental data, but the CX1 provides data to 1000 Hz, and the new program can provide 30 modes in less than 1 second for a tolerably complex bridge model.

The results from a Finite Element analysis coupled with an eigenvalue analysis has shown for a simple model of 44 nodes that 130 modes exist in the frequency range of 0 to 1000 Hz, which is the range that can be measured by the CX1. The modes show reasonable approximation to the measured modes when comparing Figure 3 and Figure 5. The number of modes able to be calculated by the FEAST program provides a wealth of data for checking the theoretical model against the practical results. Tomor shows a plurality of measured modes for arch bridges with fill and the model shows that these modes are caused by vibration of the short columns of soil above the arch. The other rather interesting feature of Figure 3 is the first 15 Hz mode has a scattered set of points, and the model predicts the first mode, but really predicts a pair of modes at close proximity. A significant number of the results for other bridges shows this dual pattern.

The analysis of structures will undergo a sea change in the next 20 years. The days of assuming that loads are static and that one can perform a simple linear analysis are rapidly passing. Significant advances in the numerical routines provide a tool for the average engineer to provide complex dynamic analysis, unfortunately as with all advances it will take a while for the knowledge to disseminate into the profession. The point of this paper is not to fully detail the masonry arch analysis, there is simply not room, but to point to the tools that are available to model the damage, and the current state of knowledge in the use of these tools.

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