DYNAMIC BEHAVIORS OF HISTORICAL WROUGHT IRON TRUSS BRIDGES – A FIELD TESTING CASE STUDY

Andrew C. Hedric

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APPROVED:

Zhenhua Huang, Major Professor
Elias Kougianos, Committee Member
Shuping Wang, Committee Member
Enrique Barbieri, Chair of Department of Engineering Technology
Costas Tsatsoulis, Dean of the Toulouse Graduate School

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Civil infrastructure throughout the world serves as main arteries for commerce and transportation, commonly forming the backbone of many societies. Bridges have been and remain a crucial part of the success of these civil networks. However, the crucial elements have been built over centuries and have been subject to generations of use. Many current bridges have outlived their intended service life or have been retrofitted to carry additional loads over their original design. A large number of these historic bridges are still in everyday use and their condition needs to be monitored for public safety. Transportation infrastructure authorities have implemented various inspection and management programs throughout the world, mainly visual inspections. However, careful visual inspections can provide valuable information but it has limitations in that it provides no actual stress-strain information to determine structural soundness. Structural Health Monitoring (SHM) has been a growing area of research as officials need to asses and triage the aging infrastructure with methods that provide measurable response information to determine the health of the structure.

A rapid improvement in technology has allowed researchers to start using new sensors and algorithms to understand the structural parameters of tested structures due to known and unknown loading scenarios. One of the most promising methods involves the use of wireless sensor nodes to measure structural responses to loads in real time. The structural responses can be processed to help understand the modal parameters, determine the health of the structure, and potentially identify damage. For example, modal parameters of structures are typically used

when designing the lateral system of a structure. A better understanding of these parameters can lead to better and more efficient designs. Usually engineers rely on a finite element analysis to identify these parameters. By observing the actual parameters displayed during field testing, the theoretical FE models can be validated for accuracy. This paper will present the field testing of a historic wrought iron truss bridge, in a case study, to establish a repeatable procedure to be used as reference for the testing of other similar structures.

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CHAPTER 1

INTRODUCTION

Civil infrastructure throughout the world serves as main arteries for commerce and transportation, commonly forming the backbone of many societies. Bridges have been and remain a crucial part of the success of these civil networks. However, the crucial elements have been built over centuries and have been subject to generations of use. Many current bridges have outlived their intended service life or have been retrofitted to carry additional loads over their original design. A large number of these historic bridges are still in everyday use and their condition needs to be monitored for public safety. As of 2014, the Federal Highway Commission lists 10% of bridges as structurally deficient and another 13.9% as functionally obsolete. The health of bridges has come into the spotlight with major structure collapses like the I-35 bridge in Minneapolis in august of 2007. Transportation infrastructure authorities have implemented various inspection and management programs throughout the world, mainly visual inspections. However, careful visual inspections can provide valuable information but it has limitations. Due to the nature of many of the structures design's not all parts of the bridges can be easy to visually inspect. Also visual inspection is limited in that it provides no actual stress-strain information to determine structural soundness. Structural Health Monitoring (SHM) has been a growing area of research as officials need to asses and triage the aging infrastructure with methods that provide measurable response information to determine the health of the structure.

For much of America's infrastructure growth from the 19^{th} through mid 20^{th} century wrought iron structures were the norm as they provided high strength and efficient sections to span longer distances. Wrought iron was phased out as a primary building material and replaced with more ductile steel in the early 20^{th} century. Diagnosing the health of the historic structures is important as many of these structures remain in use daily and have been subjected to aging, harsh conditions, excessive loading, and unpredictable or accidental damage [1].

A rapid improvement in technology has allowed researchers to start using new sensors and algorithms to understand the structural parameters of tested structures due to known and unknown loading scenarios. One of the most promising methods involves the use of wireless sensor nodes to measure structural responses to loads in real time. The structural responses can be processed to help understand the modal parameters, determine the health of the structure, and potentially identify damage. For example, modal parameters of structures are typically used when designing the lateral system of a structure. A better understanding of these parameters can lead to better and more efficient designs. Usually engineers rely on a finite element analysis to identify these parameters. By observing the actual parameters displayed during field testing, the theoretical FE models can be validated for accuracy. This paper will present the field testing of a historic wrought iron truss bridge, in a case study, to establish a repeatable procedure to be used as reference for the testing of other similar structures.

CHAPTER 2

LITERATURE REVIEW AND CASE STUDY DESIGN PLAN

This paper will explore a case study to develop a simplified method for the experimental system identification (ESI) for historic wrought iron truss bridges. The proposed simplified method can be used as a fast and fundamental way to conduct an ESI with this type of historical bridge structure as well as other constructions. The simplified methodology will include the following steps, as seen in figure 1:

- Bridge inventory, drawing, and information collection.
- Dynamic analysis of the structure, based on numerical modeling (for testing design).
- Field testing of the bridge: various excitation methods, such as human excitation and ambient test, etc., will be compared and discussed; different data acquisition methods such as wireless and wired will be discussed.
- Results interpretation and report.

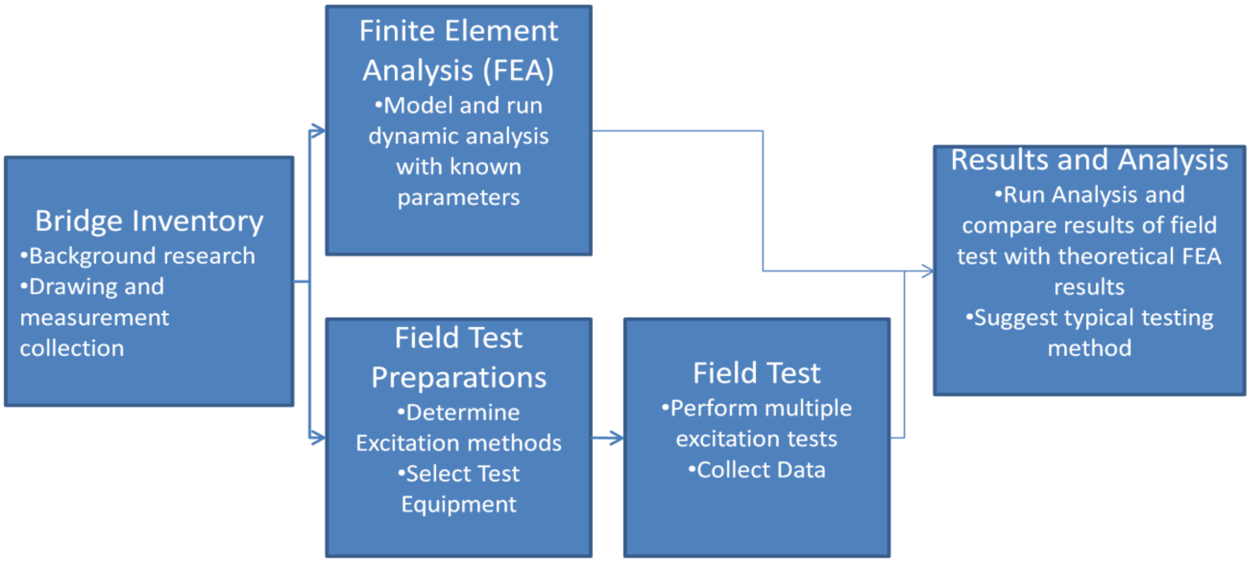


Figure 1: Proposed Case Study Design Plan

Bridge Inventory

In order to calculate the accurate modal parameters of a structure, a large amount of information needs to be acquired. In-depth field investigations of the structure are needed to gather as much information as possible, such as the overall measurements of members as well as the detailed section information. Access to original drawing and design information can often be very difficult to locate on these historic structures, so these field investigations become a vital part in gaining the information required to predict accurately the dynamic properties of the structure. Research on the manufacture and builders of the bridge can provide insight into the materials and construction techniques used in the structure.

Dynamic Analysis

One of the most commonly used techniques to understand the dynamic characteristics of a structure is to perform a Finite Element Analysis (FEA). The FEA is beneficial is several ways.

Using the geometries and measurements gathered from the field investigations, the FEA, provides a theoretical prediction of the first several mode shapes and frequencies. From these theoretical predictions, sensor locations can be picked to attempt to record the most beneficial data. The FEA will also better our understanding of the benefits and limitations to the current FEA techniques when compared to the actual tested shapes and frequencies.

For the test we will utilize the commercially available SAP2000 V14 (CSI, 2010) software to model and perform FEA analysis on the selected bridge. Bridge elements will be modeled as beam-column elements, on a grid based on the centerline dimensions of the current bridge elements. Nodes are added at the end of members and where section geometries change. The beam column elements are defined by sections modeled after the detailed section information from the field investigations and known material properties. Additional masses will be added at nodes to represent rode decks and railing that are not part of the support structure.

Field Testing – Excitation

In order to characterize an existing historical structure there are a number of dynamic testing excitation methods; these include ambient vibration testing and forced vibration testing. Ambient vibration testing refers to recording of responses from natural loads such as wind forces or micro tremors of the ground. Forced vibration testing refers to introducing a force from a force vibration generator in a sinusoidal pattern or from human or traffic impacts. Fernstrom et al. [2] used both ambient vibration testing and forced vibration testing on a 1930’s Parker pony truss located in Greenland. Fernstrom found the natural frequency and mode shapes were more accurately predicted with ambient vibration testing than with forced vibration testing. Modal identifications from ambient responses in normally associated with the identification of modal parameters from the natural responses of structures. For existing structures the loads are almost always unknown and so modal parameters can only be identified through observing the structures' reactions to loading scenarios [3]. The method for calculating the properties of an existing structure using the responses to ambient excitation is also called the Operational Modal Analysis (OMA) technique [8].

In 2000 Brincker and Zhang began exploring the use of certain algorithms in the data processing of the system identification. They built on a commonly used technique known as the Basic Frequency Domain (BFD) peak picking technique. Traditionally BFD has been used for its speed and simplicity. Using the simple signal processing tool Discrete Fourier Transform, researchers can quickly identify well separated frequency peaks from the power spectral density matrix. Unfortunately, this technique is limited in identifying frequencies that are close to each other and provides unreliable damping estimations. Therefore, another technique known as Frequency Domain Decomposition (FDD) was proposed. By taking a Singular Value Decomposition (SVD) of the spectral matrix, a set of auto spectral density functions can be obtained, each corresponding with a single degree of freedom (SDOF). This FDD eliminated the disadvantages of the BFD but kept the simplicity and ease of application [3].

Researchers have conducted many field experimental system identifications. Catbas, Brown, and Aktan used vibration testing to help in damage detection of the Seymour Bridge in Cincinnati Ohio [4,5]. Gentile and Saisi preformed ambient vibration testing and a condition assessment of the 1889 Padero iron arch bridge of Italy [7]. They found the bridge showed low values of damping ratios in both directional response and the natural frequencies of the vertical bending modes exhibited slightly vibrations for depending on the excitation level. In 2002 Magalhaes et al performed basic OMA for testing and monitoring of Infante D. Henrique, arch bridge in the city of Porto [9]. The researchers processed their testing data using the FDD technique and the SSI-COV method [10] and finally online automatic identification in 2009 [11].

One of the main identified objectives of this study is to investigate the effectiveness of different excitation methods for the experimental system identification. Basically which excitations method produces the most accurate identification of the bridges mode shapes and natural frequencies. Eight excitation methods were chosen to provide a wide range of methods, they are as follows:

- A group of 16 people jumping, up and down, in unison in the middle of the bridge multiple times
- A group of 16 people jumping, up and down, in unison only once
- A group of 16 people jumping randomly on the bridge
- 4 groups of four people marching through the bridge
- A single person jumping, up and down, in the middle of the bridge only once
- A single person jumping horizontality, in the transverse direction of the bridge, only once
- A group of people pulling a rope attached to the bridge multiple times
- A single person jumping, up and down, on a 1/3 point of the span only once

Sensors will record the raw acceleration data from the nine excitation tests. The sensors read in all three dimensions, the vertical direction (up-down), the transverse direction (North-South), and the horizontal direction (East-West). The raw data is processed using the Fast Fourier Transform (FFT) into a Fourier Spectra (Figure 2) from which the natural frequencies of the structure can be identified. The resulting abscissa on Fourier response function (FRF), provides easily identified peaks at the tested structure's natural frequencies.

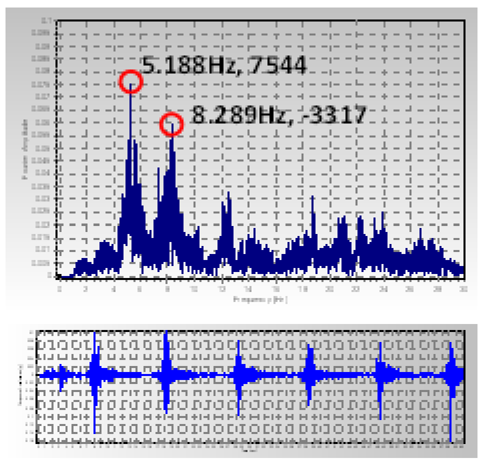


Figure 2: Fourier Repsonse Spectra

Field Testing – Data Acquisition

In 2009 Zaurin and Catbas, for the University of Central Florida, introduced computer imaging combined with sensors to monitor the structural health of bridges. This technology has been improved by using COD image analysis and new imagine processing tools. [12-16]

As technology improved more and more sensors were available for use in testing. However, the transmission of the data soon became very complicated and the processing very time consuming, when a multitude of sensors were placed on a structure. With the advent of wireless technology, it was soon much easier than hard wiring sensors together to report the live response data. Wireless sensors have become more popular as technology has become cheaper and more efficient at transferring the live data from the bridges responses. Lynch has been a critical researcher in this area. He pioneered the use of sensing skin, a thin film surrounded by electrodes to detect cracks and monitor corrosion on the steel. He then used acoustic emission sensors in a piezoelectric paint that was used in monitoring fatigue related cracks[17]. Hong-Nan Li used fiber optic sensors to perform the structural health monitoring. [18] others [19-23]. Mrad wrote a paper about the optical sensor technology in which he described the basic fundamentals about this new technology[24]. Wanqui used high resolution optical-phonotic images with a LiDAR based automatic bridge evaluation system LiDAR Bridge Evaluation to prefrom SHM on a historic bridge[25].

Identifying modal parameters through experimental system identification has typically been an extensive and invasive method to gain information on the behavior of the structure. The practice was never widely adopted due to the large time investment as well and the complicated instrumentation required to record and process the data. (Maha Armly, 2004) Westermo and Thompson et al, recently proved with the advent of wireless sensing technology experimental system identification can be a simple and accurate method for the identification of the modal parameters by using a cellular modem connected to a series of digital junctions that received incoming calls from the wireless sensors.

Soon a number of commercial platforms were developed to make SHM more widely available, such as Microstrain Technologies, Crossbow Technologies, Tmote Technology, and

Intel Technologies. By 2005 the University of Illinois had developed a commercially available SHM package using the new iMote2 platform and the ISHMP services toolsuite. The package uses a simple two part hardware package, including a single gateway node that sends commands and receives wireless data from the battery operated sensing nodes located throughout the structure. The remote sensing nodes can be equipped with three different types of sensors: a SHM-A sensor used for measuring vibration accelerations, a SHM-W sensor for measuring the wind with an anemometer, and a SHM-S sensor for measuring the member strains. [3] The toolsuite is comprised of four service packages: 1) foundation services, 2) application services, 3) tools and utilities, and 4) continues and autonomous monitoring services. The toolsuite also includes a number of supporting materials like commonly used algorithms in SHM like the fast Fourier transform (FFT) and singular value decomposition (SVD). The Illinois SHM package was selected for the on-site testing of this study for the following reasons:

1. Availability: the iMote2 platform is commercial available; the sensor boards (SHM-A, SHM-W, and SHM-S) and the operation software are developed by a group of researchers who are the professors or classmates of the professor of the author of this paper, therefore it is convenient for the author to obtain the instruments and technical support.

2. Functionality: the Illinois SHM package has a very powerful microprocessor; its embedded algorithms for modal analysis and health monitoring make the data analysis quick and accurate.

3. Sensitivity: the Illinois SHM sensor boards have high resolution and low noise, which can catch the vibration signal caused by a single person jumping on the bridge (one of the excitation methods of this study).

Results and Interpretation

Upon completion of both the theoretical dynamic analysis and the field test the result of the test will be processed and compared. With these results, several objectives will be evaluated:

1. Investigate the applicability of the wireless sensor network on bridge structure system identification and health monitoring. This applicability includes the advantage and disadvantage of using a WSSN.
2. Investigate the effectiveness of a few convenient bridge excitation methods and identify the best excitation method for this type of structure.
3. Compare results obtained from the system field tests with theoretical FE model's modal properties.
4. From results develop a repeatable System Identification method that can be used for similar structures.

CHAPTER 3

CASE STUDY OF OLD ALTON BRIDGE

Bridge Inventory

Figure 3: The Old Alton Bridge main span

The test structure proposed to be used in the testing is Old Alton Bridge located in Denton. Texas. It is a typical wrought iron truss bridge used for vehicle traffic originally built in 1884 by King Iron Bridge Manufacturing Company, of Cleveland Ohio, one of the largest bridge manufacturing companies from the late 19th century. Who built many wrought iron structures for the US highway and railway system from 1858 to 1920. The current Old Alton Bridge remained in use until 2001 when a new concrete and steel bridge was built. Previous to the new bridge the bridge operated as a single lane truss bridge. The new bridge eases sharp corners around the creek and allowed for more travels lanes to accommodate increased traffic. Currently the Old Alton Bridge serves as a crucial link for Elm Fork and Pilot Knoll Hiking and Equestrian Trails. The bridge is an important historic place in Denton County, the Denton County Master Naturalist maintains an annual cleanup project after Halloween and the bridge was included into the National Register of Historic Places on July 8, 1988.

Old Alton Bridge is a simple three span, wrought iron Pratt Truss. It consists of three spans, two approach spans of wrought iron beams and a single main wrought iron truss span. The main truss structure spans a total 109 ft, with the total bridge length as 145 feet, and is simply supported at both ends on concrete columns. The main truss is 16’1” wide and 18’ high vertically. The top chord of the main truss is comprised of two iron channels joined by an iron plate 12”x3/8”, riveted to the top flanges. The top chord is continuous for the entire length and forms a trapezoidal shape with the bottom chord. The bottom chords are made of two iron bars, 3”x3/4”, that span from intermediate vertical posts and are connected with pin connections. Three main vertical posts are suspended from the top chord at the three center panel points and smaller rods are used on the two panel points closest to the support columns. Non prismatic floor beams span from one truss to the other, starting as 11” deep wide flange beams to 24” deep in the center. These support w-shaped stringers and the road decking. For more detailed section information please see the following Table 1 which contains on site measurements for each member cross sections.

Table 1: Member sizes of the Old Alton Bridge truss

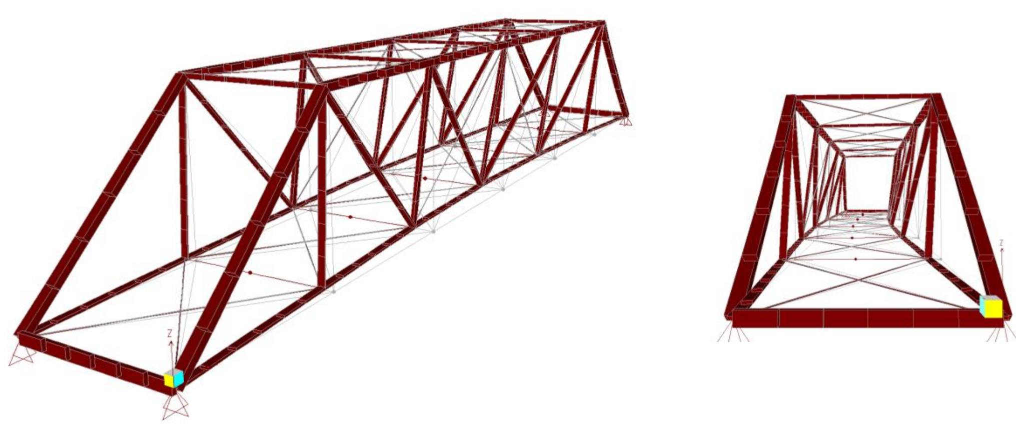
Truss Members	Cross-section	Detail Dimension
Top Chords	Build-up section: 2 Channels and 1 Plate	Channels: depth = 8-1/8”, web and flange thickness = 1/4”, flange width = 2” Plate: 12” x 3/8”
Bottom Chords	2 Plates	3” x ¾”
Vertical Posts	2 Channels	depth = 5” (4” for the middle one), web and flange thickness = 5/16”, flange width = 2”
End Posts	Build-up section: 2 Channels and 1 Plate	Channels: depth = 8-1/8”, web and flange thickness = 1/4”, flange width = 2” Plate: 12” x 3/8”
Diagonal Members	2 Plates or 1 Rod	Plates: 2-1/2” x ½” Rod: 1”▯
Vertical Hips	2 Rods	1” x 1”
Top Lateral Bracing	1 Rod	1”▯
Bottom Lateral Bracing	1 Rod	1”▯
Strut	1 W-shape	depth = 5”, web and flange thickness = 3/16”, flange width = 3”
Portal Strut	2 Tees	depth = 1-1/2”, web and flange thickness = 3/8”, flange width = 3”
Floor Beams	1 Non-prismatic W-shape	End: depth = 11”, web thickness = 3/16”, flange width = 4-1/2”, flange thickness = 3/8” Middle: depth = 24”, web thickness = 3/16”, flange width = 4-1/2”, flange thickness = 3/8”
End Floor Beams	1 W-shape	depth = 12-1/2”, web thickness = 3/16”, flange width = 4-1/2”, flange thickness = 5/16”
Stringers	1 W-shape	depth = 8-1/4”, web and flange thickness = 5/16”, flange width = 4-1/8”

Dynamic Analysis Results

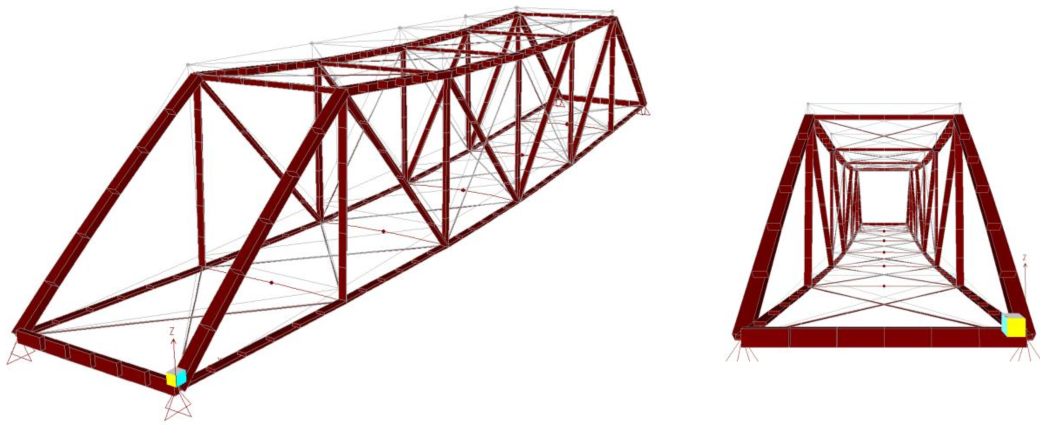
Using the above tables and figures a model of the Old Alton Bridge was developed in SAP2000. Without material tests, the material properties of the bridge were assumed to be the commonly used properties of late 19th century wrought iron. With a unit weight of 485 lb/ft^3 (76.2 kN/m^3), a Modulus of Elasticity of 28,000 ksi (193 GPa), and a yielding stress of 27 ksi (186 MPa). Masses were also applied to nodes on the bottom chord to account for the road deck and miscellaneous masses on the structure, such as the safety railings. The Pratt truss is a total of 20,717 pounds (92.2 kN), which is equal to 53.66 lb·s^2/in (9,397 kg) of mass. The weight of the bridge decking system is 39,790 pounds (177.0 kN), which is equal to 103.06 lb·s^2/in (18,048kg) of mass. The bridge decking system includes the wrought iron stringers, the wrought iron handrails, the 3 inch (76 mm) thick oak decking, and the 6x10 oak kickers. The estimated human weight of 16 students jumping on the bridge is around 16x175 = 2800 pounds.

SAP2000, using the information above and Eigen vectors identified the first three mode and frequencies as follows. The first or fundamental mode was found to be the side to side swaying motion of the bridge deck at a frequency of 3.557 Hz, Figure 4(a). The second on third modes are the balanced vertical vibration and rotation of the road deck, at 5.430 and 10.712 Hz respectively.

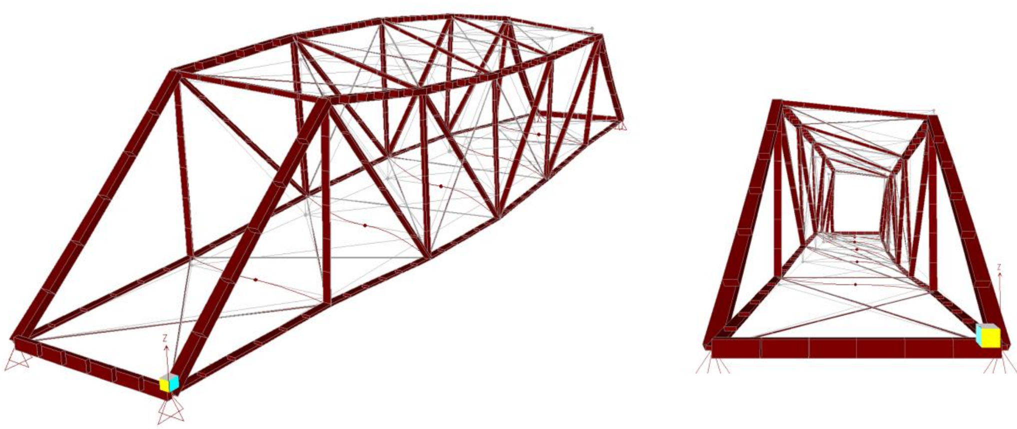
Figure 4: Predicted Mode Shapes and Frequencies



(a) Mode 1 Transverse sway of the bridge deck (f = 3.557 Hz)



(b) Mode 2 Balanced vertical vibration of the bridge deck (f = 5.430 Hz)



(c) Mode 3 Rotation of the bridge deck (f = 10.712 Hz)

Field Test

In order to ensure the network is laid out in an efficient and reliable geometry the predicted mode shapes, size of the network and communication range of the package must be considered. The tested truss length of the Old Alton Bridge is 109 feet (33.22 m) long, 16 feet 1 inch (4.90 m) wide, and 18 feet (5.49 m) high. The current range of the iMote2 WSSN with an external 2.4 GHz antenna is around 650 feet (200 m). The relatively small size of the bridge allows for just one base station to be used for the testing. The base station and corresponding computer are located near the center of the span to allow for the best transmission to and from the sensor nodes.

Previous FEA has predicted the first three modes shapes to involve the bridge deck vibrating in a vertical, horizontal and torsional motion. Since the bridge deck is where pedestrian traffic or loading would typically occur, the SHM-A sensor nodes for acceleration measurement were placed on the six center vertical members near their pin connection to the bottom chord. Because the pin joints are below the bridge deck and hard to access, the sensors were placed approximately 2 feet above the pin joints on the vertical members. The sensor nodes were placed in plastic sealed boxes and attached to the wrought iron members with magnets and, as a precaution, two-sided tape. The following Figure 5 shows the sensor node locations.

Figure 5: Sensor Node Attachment Locations

Eight excitation techniques were tested. The corresponding structural responses were recorded and plotted using a fast Fourier Transform. The resulting Fourier spectrum provides the peaks which identify the modal frequency due to the excitation. The results from the 8 tests can be summarized as the following figures. For each set of tests a graphic for both the vertical and horizontal vibrations were developed to show the raw acceleration data, the sensor locations, and the Fourier Spectra with the maxima clearly identified.

Test 1 - Group Jumping Vertically with Multiple Impacts

Test 1 was a group test in which all 16 participants jumped in unison at the center point of the span, Figure 6. The group jumped six times to provide several impact responses. The data was collected at a sampling rate of 100 Hz and for duration of 60 seconds. Figure 7 is the graphical representation of the vertical response tests results. The center diagram reflects the sensor locations using their arbitrary assigned number identifiers. Next to each sensor location is first the raw acceleration data from each sensor. The acceleration data is plotted with the x-axis corresponding to time in seconds and the y-axis in gravitational units (g). The multiple impacts can clearly be seen as the initial excitation followed by a trail of the structure dissipating the impacts. Next to each acceleration graph is the corresponding Fourier Spectra with clearly identified maxima. For Test 1 the sensors all provided very similar results and varied little. The first identified vertical frequency was exactly 5.188 HZ at all the sensor locations and the second averaged to 8.324 Hz. Similarly Figure 8 shows the structural responses for vibrations in the transverse (side to side) direction. The transverse vibration showed a peak near 2.515 Hz and second peak ranging from 13.12 Hz to 18.59 Hz. The vertical jumping provided clear very tall peaks in the vertical Fourier Spectra, however the first mode was not as clearly defined in the transverse direction due to the vertical excitation. From these results the first and fundamental mode of the Old Alton Truss Bridge was determined to be a transverse sway in the bridge deck at a frequency of 2.515 hertz with the second and third corresponding to the identified maxima seen in the vertical response spectra as 5.188 Hz and 8.324 Hz respectively. The very clear peak between 13.12 Hz to 18.59 Hz seen in the transverse Reponses is identified as the local vibration frequencies of the individual vertical posts the sensors were attached to.

Figure 6: Test 1 Group Jumping with Multiple Impacts

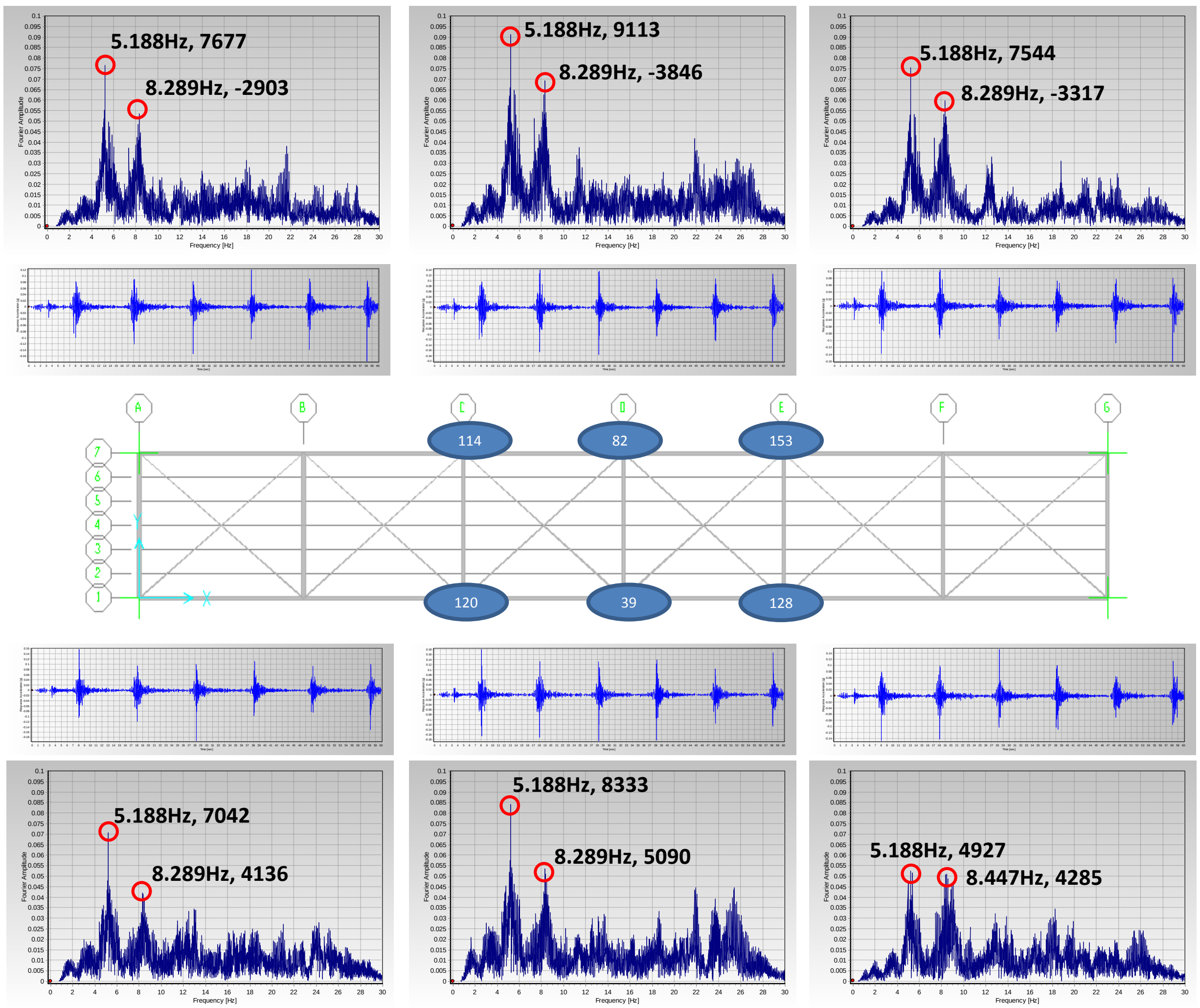


Figure 7: Test 1 Vertical Response Data

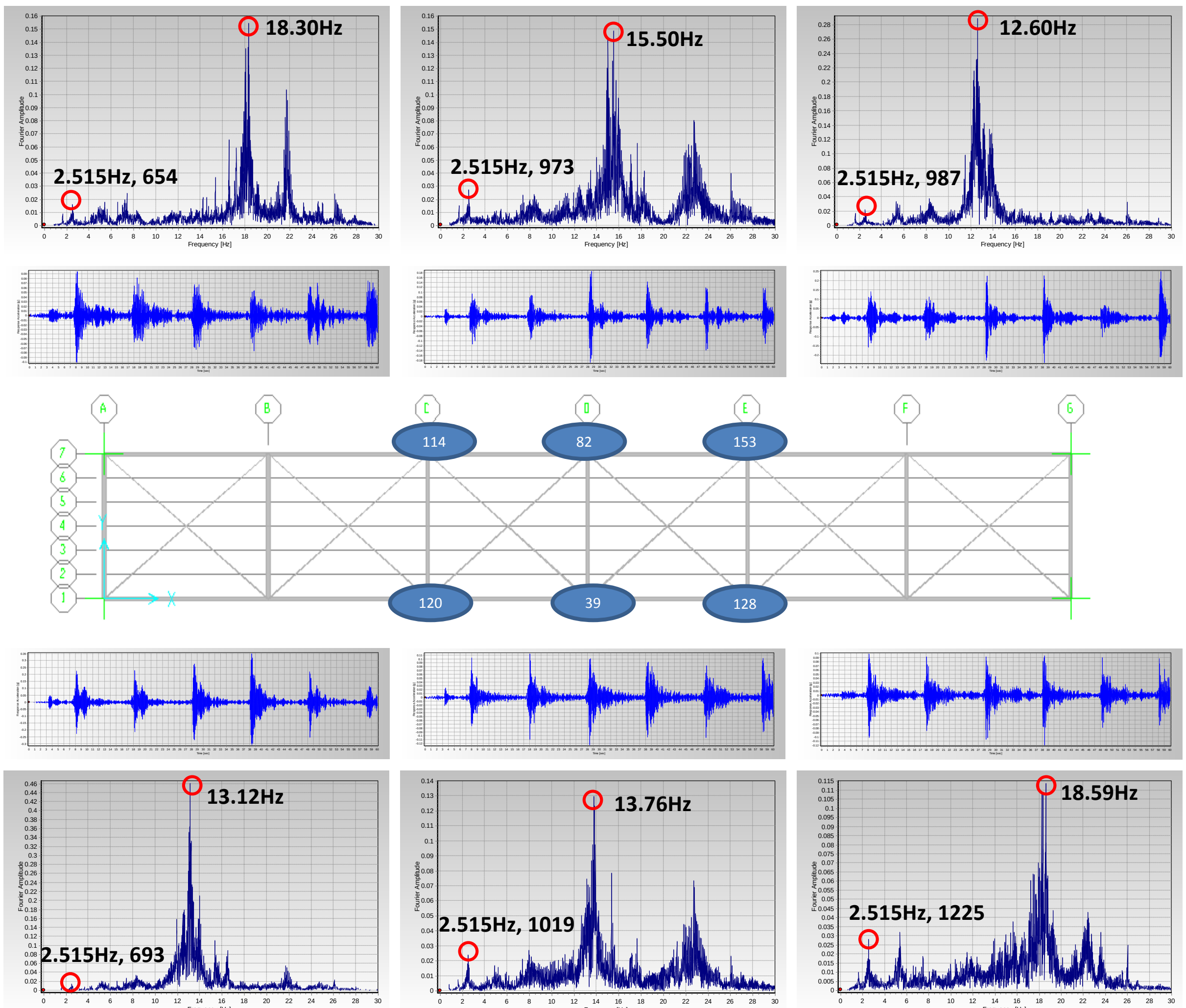


Figure 8: Test 1 Transverse Response Data

Test 2 - Group Jumping Vertically Once

Test 2 was a group test in which all 16 participants jumped in unison at the center point of the span, Figure 9. The group jumped only once to see if a single impact provided different responses. The data was collected at a sampling rate of 100 Hz and for duration of only 10 seconds. Figure 10 is the graphical representation of the vertical response tests results. The single impacts can clearly be seen as the initial excitation followed by a trail of the structure dissipating the impact. For Test 2 the sensors all provided very similar results and varied little. The first identified vertical frequency averaged to 5.209 HZ at all the sensor locations. The second peak can be seen as 8.203 Hz for north truss and 8.389 on the south truss. Figure 11 shows the structural responses for vibrations in the transverse (side to side) direction. The transverse vibration showed a peak near 2.539 Hz and second peak ranging from 12.30 Hz to 18.55 Hz. Again, the vertical jumping provided clear very tall peaks in the vertical Fourier Spectra, however the first mode was not as clearly defined in the transverse direction due to the vertical excitation. From these results the first and fundamental mode of the Old Alton Truss Bridge was determined to be a transverse sway in the bridge deck at a frequency of 2.539 Hz with the second and third corresponding to the identified maxima seen in the vertical response spectra as 5.209 Hz and 8.296 Hz respectively.

Figure 9: Test 2 Group Jumping with One Impact

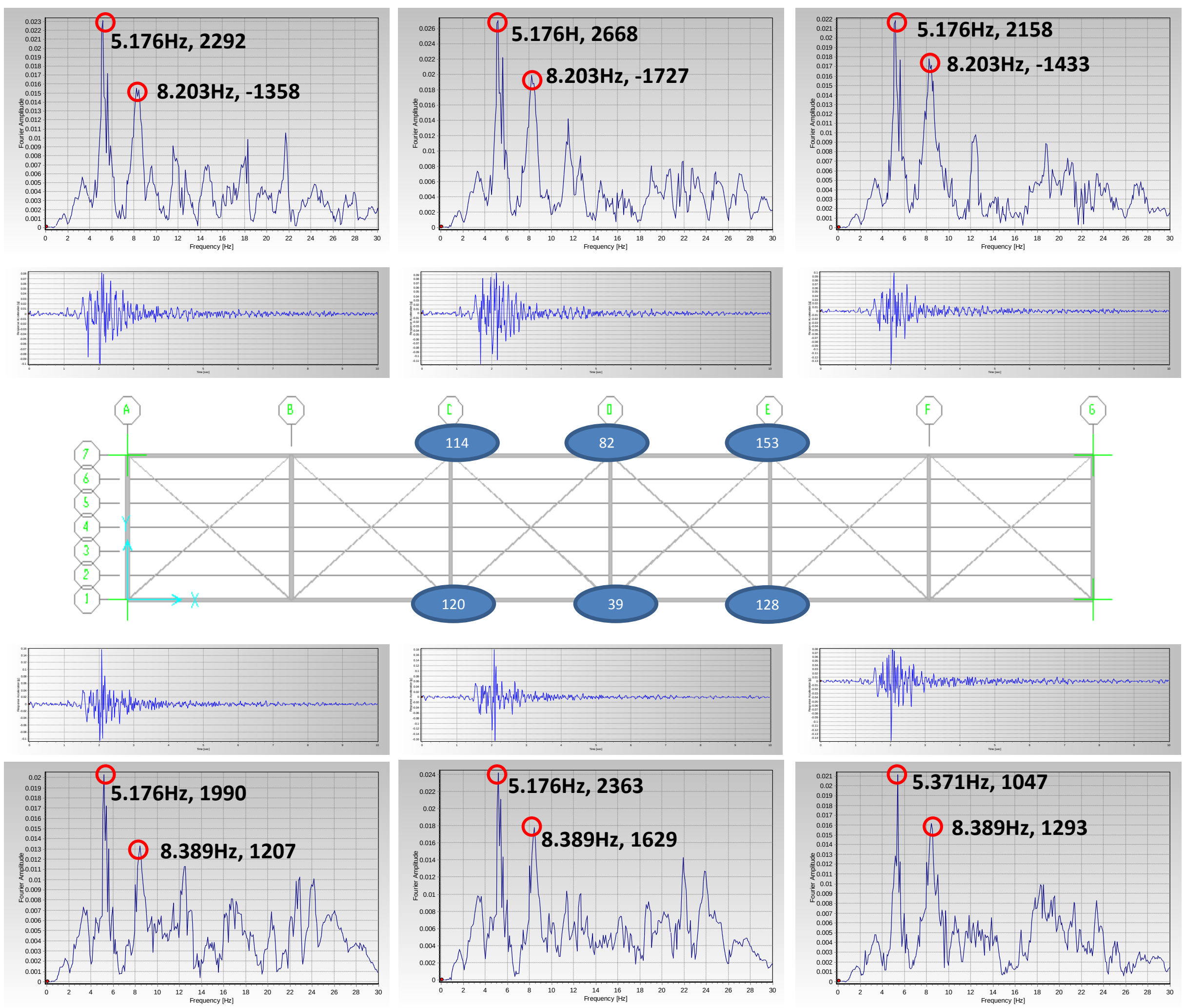


Figure 10: Test 2 Vertical Response Data

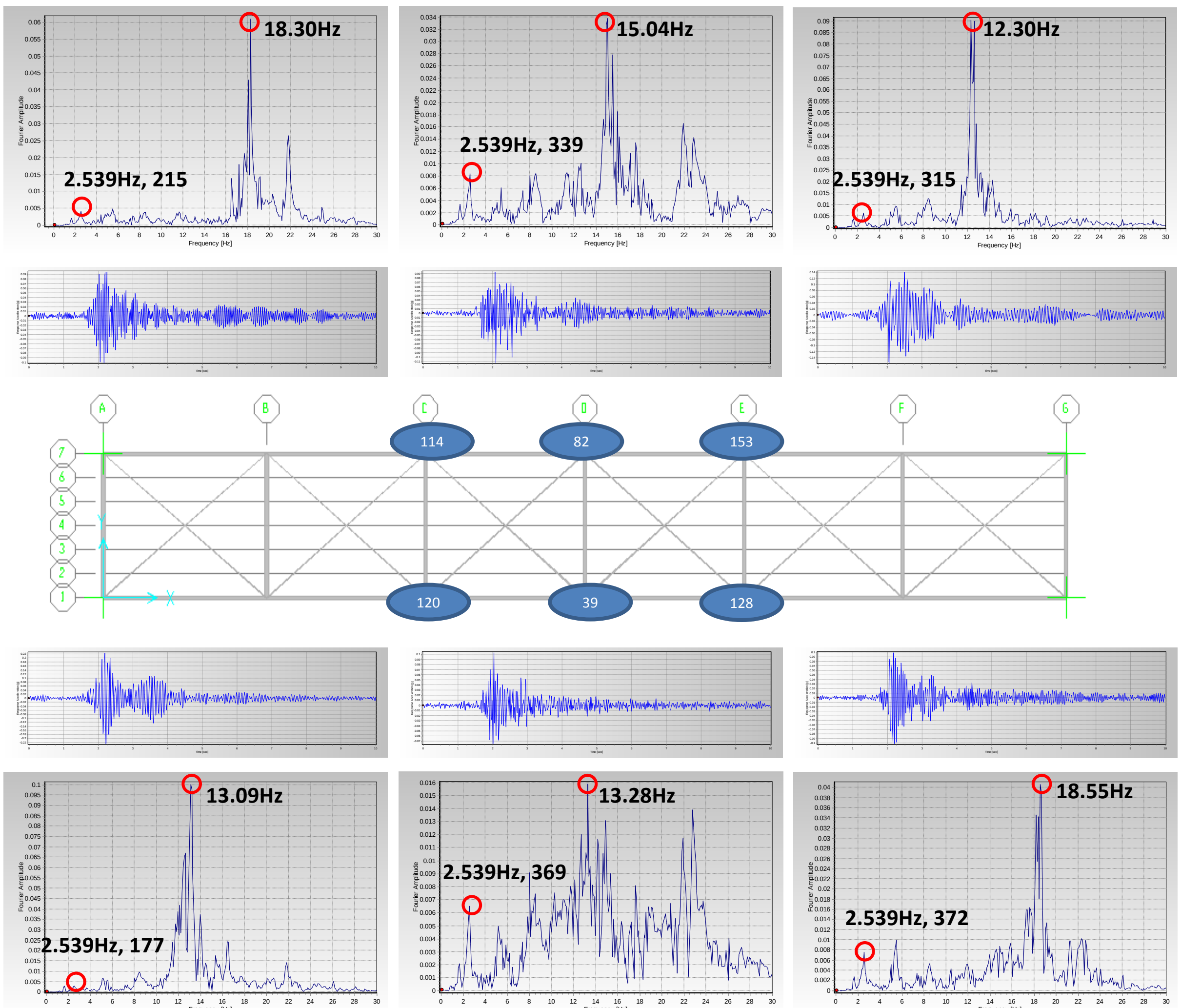


Figure 11: Test 2 Transverse Response Data

Test 3 - Group Jumping Vertically Randomly

Test 3 was a group test in which all 16 participants jumped randomly at the center point of the span, Figure 12. The group jumped at will for a total of 60 seconds. The data was collected at a sampling rate of 100 Hz and for duration of 60 seconds. Figure 13 is the graphical representation of the vertical response tests results. The unprocessed acceleration data does not show any clear impacts and looks much like noise as the vibrations were very irregular. For Test 3 the sensors all provided very similar results. The first identified vertical frequency averaged to 5.552 HZ across all the sensor locations. The second peak can be seen as 8.203 Hz for north truss and 8.389 on the south truss. Figure 14 shows the structural responses for vibrations in the transverse (side to side) direction. The transverse vibration showed a peak near 2.539 Hz and second peak ranging from 12.30 Hz to 18.55 Hz. Again the vertical jumping provided clear very tall peaks in the vertical Fourier Spectra, however the first mode was not as clearly defined in the transverse direction due to the vertical excitation. From these results the first and fundamental mode of the Old Alton Truss Bridge was determined to be a transverse sway in the bridge deck at a frequency of 2.539 Hz with the second and third corresponding to the identified maxima seen in the vertical response spectra as 5.209 Hz and 8.296 Hz respectively.

Figure 12: Test 3 Group Jumping Randomly

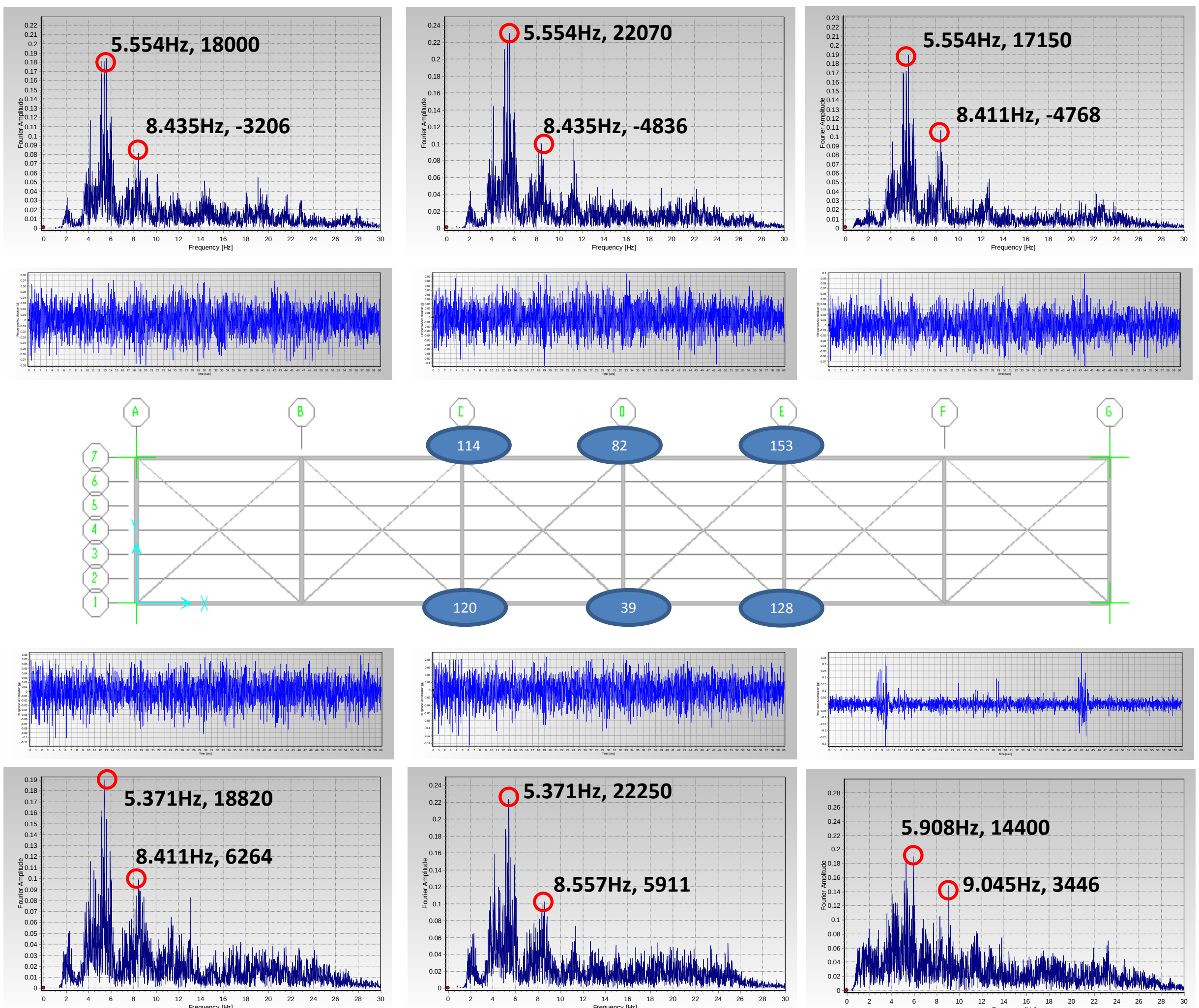


Figure 13: Test 3 Vertical Response Data

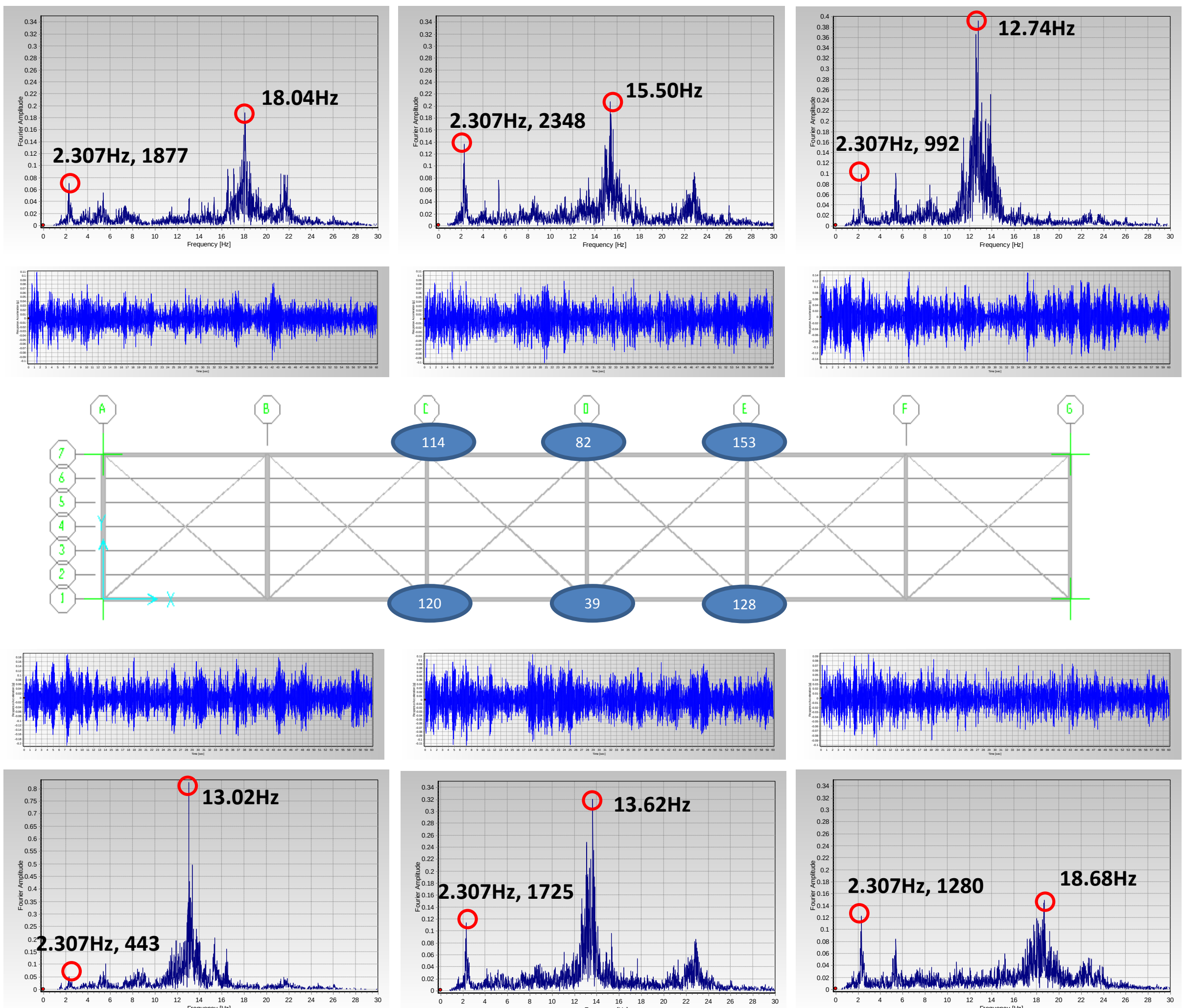


Figure 14: Test 3 Transverse Response Data

Test 4 - Four Groups of Four Marching across the bridge

Test 4 consisted of group of 4 marching from one end of the bridge to the other in equally spaced intervals, Figure 15. The groups marched in groups of four across the bridge and data was recorded for a total of 60 seconds. The data was collected at a sampling rate of 100 Hz. Figure 16 is the graphical representation of the vertical response tests results. The unprocessed acceleration data does not show any clear impacts and looks much like noise as the vibrations were very irregular. For Test 4 the sensors all provided irregular data with several close frequencies. The spectra shows several peaks with similar magnitudes and true modes are difficult to pick out of the data.

Figure 15: Test 4 Groups Marching in Groups of 4

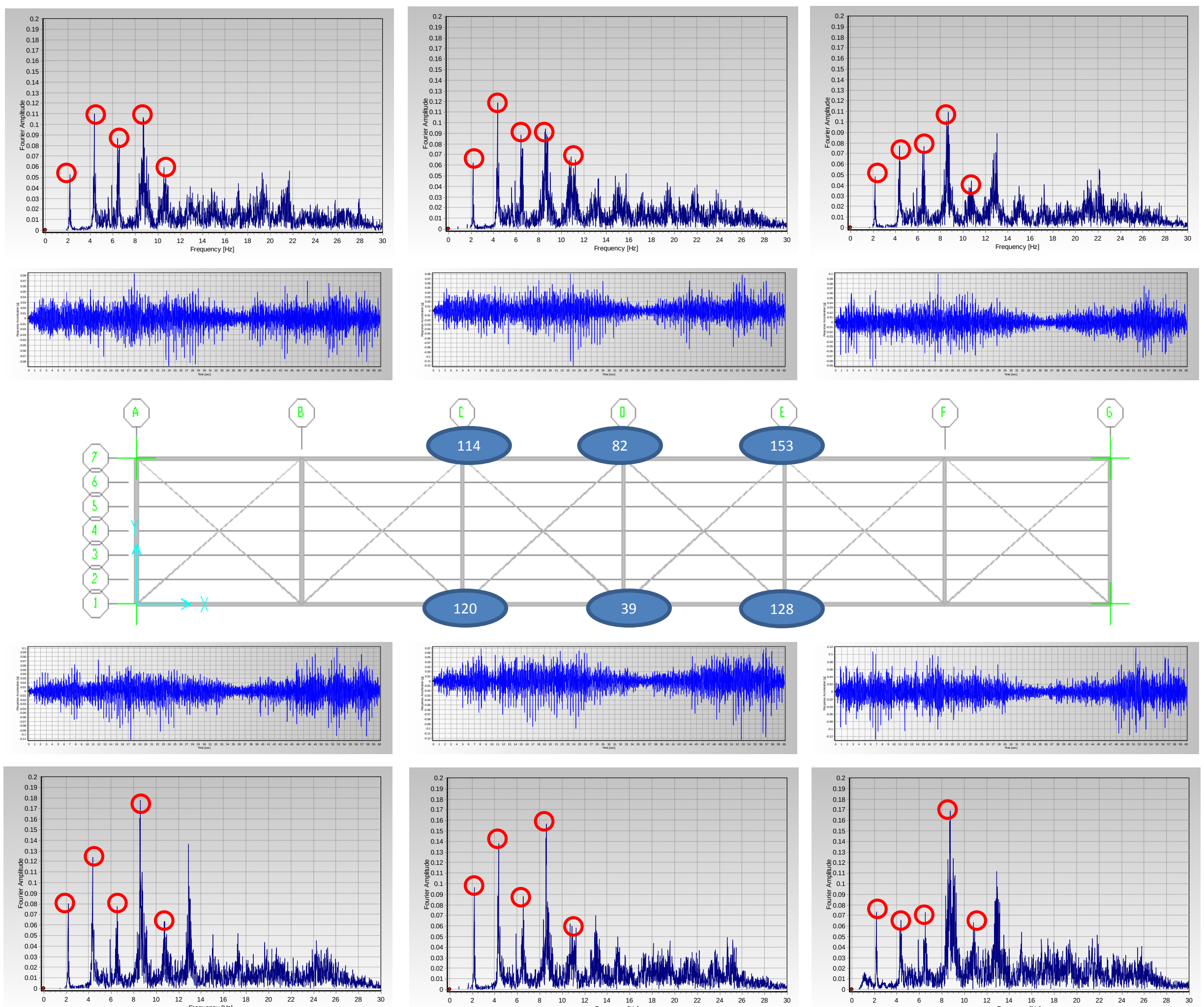


Figure 16: Test 4 Vertical Response Data

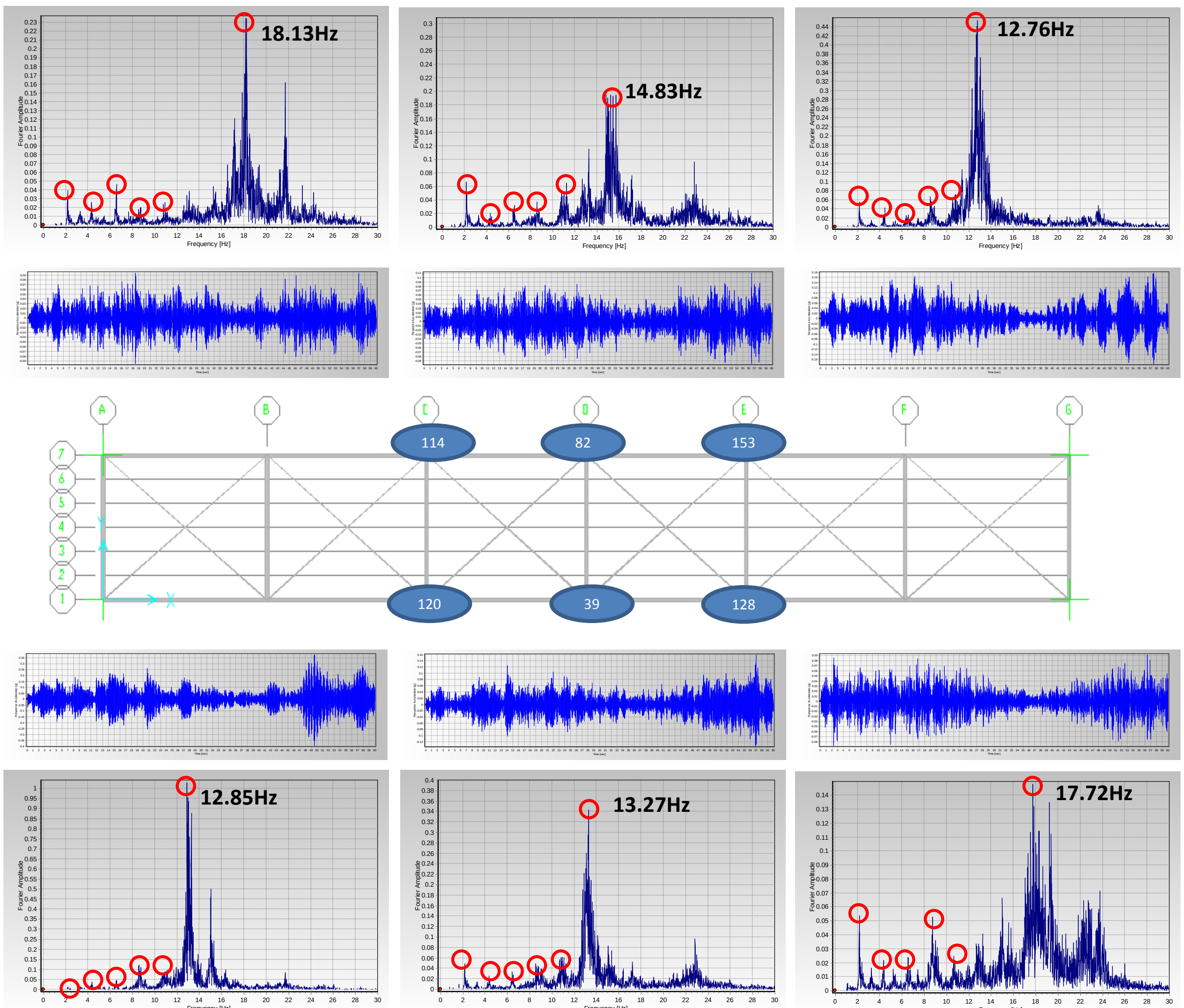


Figure 17: Test 4 Transverse Response Data

Test 5 - A Single Person Jumping Vertically Once

Test 5 was a test in which a single person jumping, only once, at the center point of the span, Figure 18. The data was collected at a sampling rate of 100 Hz and for duration of 10 seconds. Figure 19 is the graphical representation of the vertical response tests results. The unprocessed acceleration data shows a single clear impact. For Test 5 the sensors provided similar results on each truss but with only one clearly identifiable peak in both the vertical and transverse directions. The first and only identified vertical frequency averaged to 5.126 HZ across all the sensor locations, with the North truss averaging to 5.436 Hz and the South truss averaging to 4.818 Hz. Figure 20 shows the structural responses for vibrations in the transverse (side to side) direction. The transverse vibration did not show a clear peak near the first mode identified in other tests and showed a single peak ranging from 12.60 Hz to 18.26 Hz. Test 5 only provided a clear frequency for the first vertical mode; however the first mode was not as clearly defined in the transverse direction due to the vertical excitation. From these results the first and fundamental mode of the Old Alton Truss Bridge was determined to be a vertical vibration of the road deck at a frequency of 5.436 Hz.

Figure 18: Test 5 Single Person Jumping Vertically Once

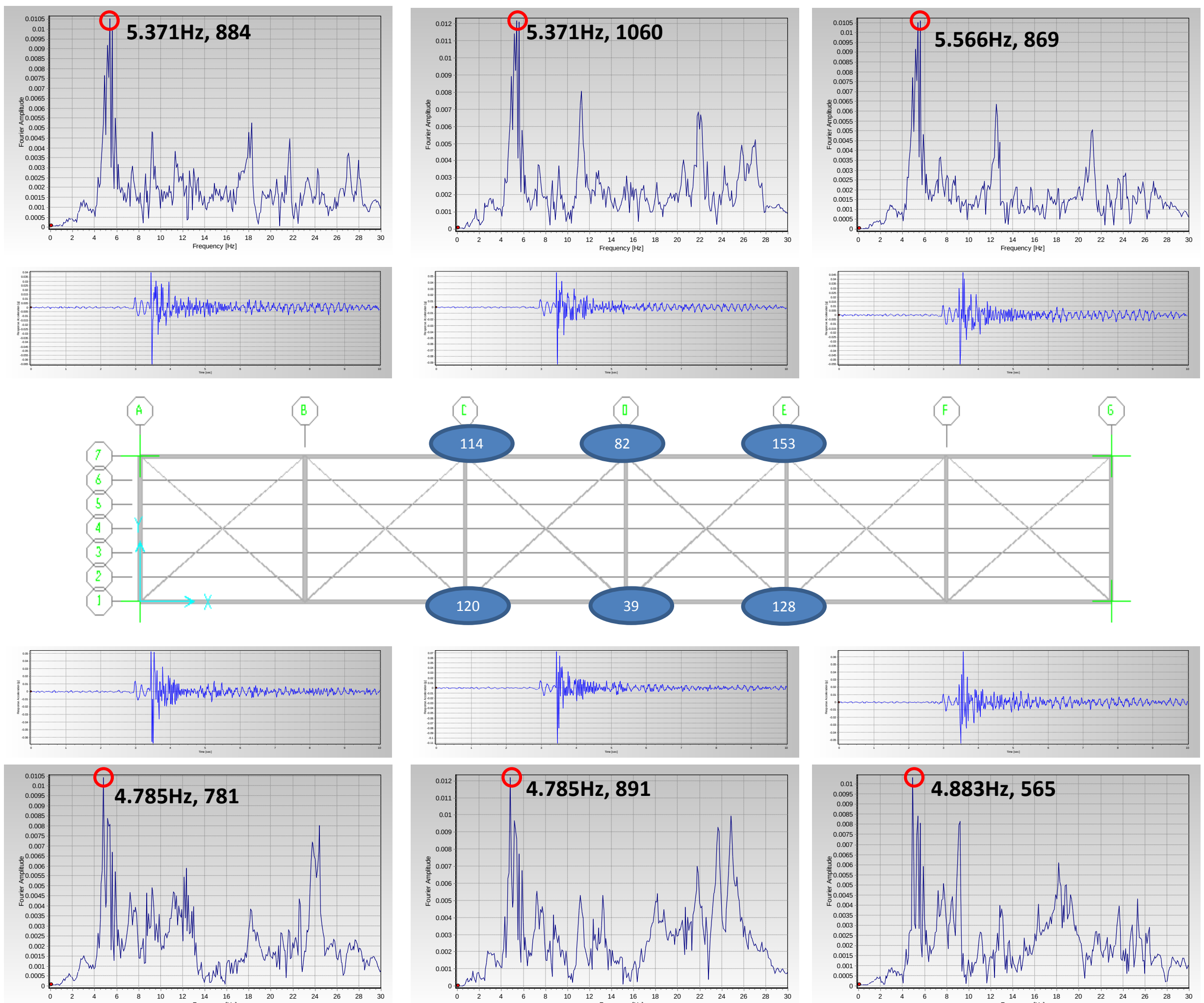


Figure 19: Test 5 Vertical Response Data

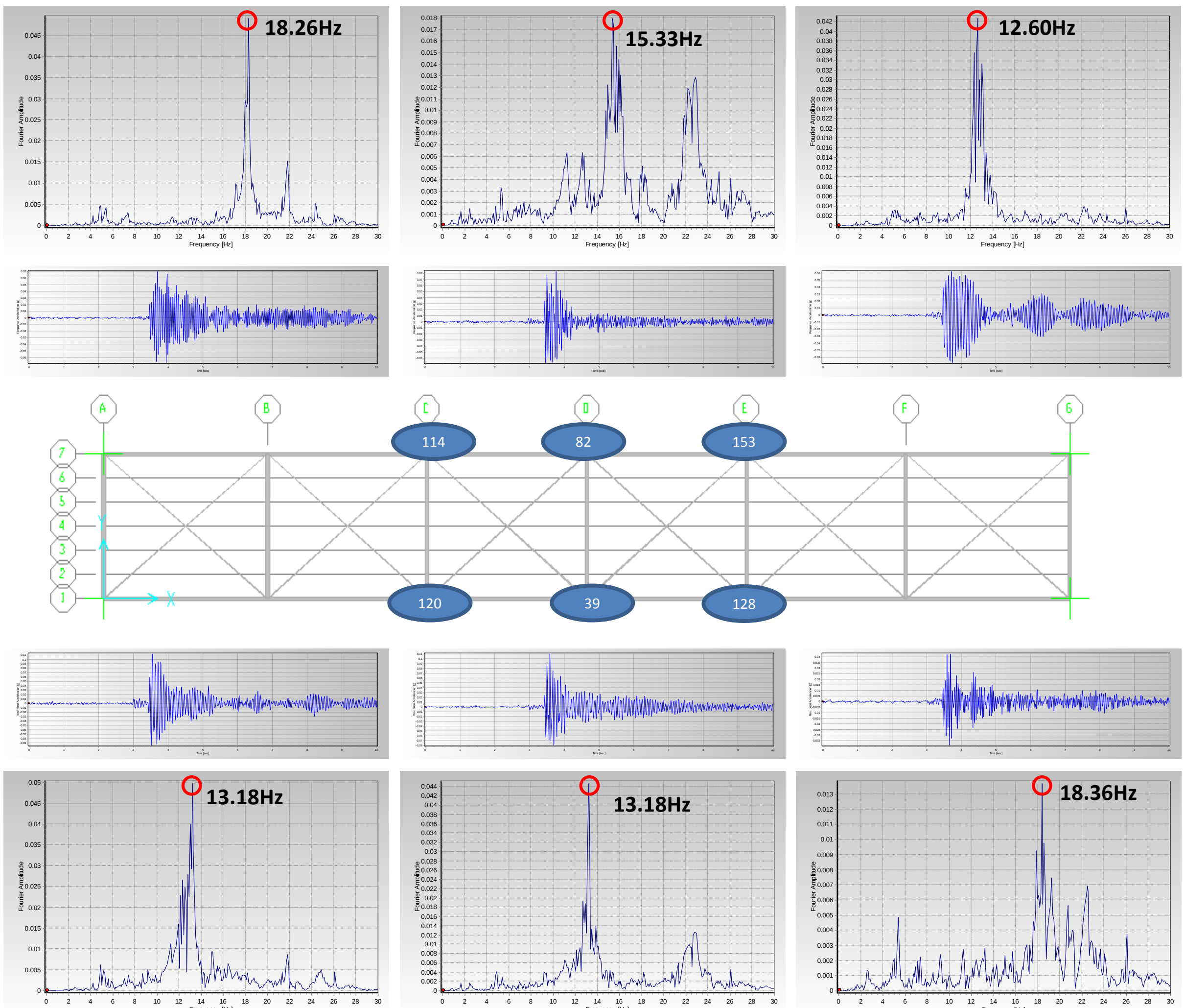


Figure 20: Test 5 Transverse Response Data

Test 6 - A Single Person Jumping Horizontally Once

Test 6 was a test in which a single person jumping, only once, at the center point of the span in the transverse direction, North-South. The data was collected at a sampling rate of 100 Hz and for duration of 10 seconds. Figure 21 is the graphical representation of the vertical response tests results. The unprocessed acceleration data shows a single clear impact. For Test 6 the sensors provided similar results for both the vertical responses and the transverse responses. The first identified vertical frequency averaged to 5.794 Hz across all the sensor locations, with the second identified frequency be seeing seen at an average of 8.415 Hz. Figure 22 shows the structural responses for vibrations in the transverse (side to side) direction. The transverse vibration does show a clear peak across of the sensors a 2.441 Hz and shows a single peak ranging from 12.60 Hz to 18.26 Hz. For this test the horizontal jumping motion provided clear very tall peaks in the vertical Fourier Spectra and a higher magnitude peak for the first or fundamental mode than the previous tests. From these results the first and fundamental mode of the Old Alton Truss Bridge was determined to be a transverse sway in the bridge deck at a frequency of 2.441 Hz with the second and third corresponding to the identified maxima seen in the vertical response spectra as 5.794 Hz and 8.415 Hz respectively.

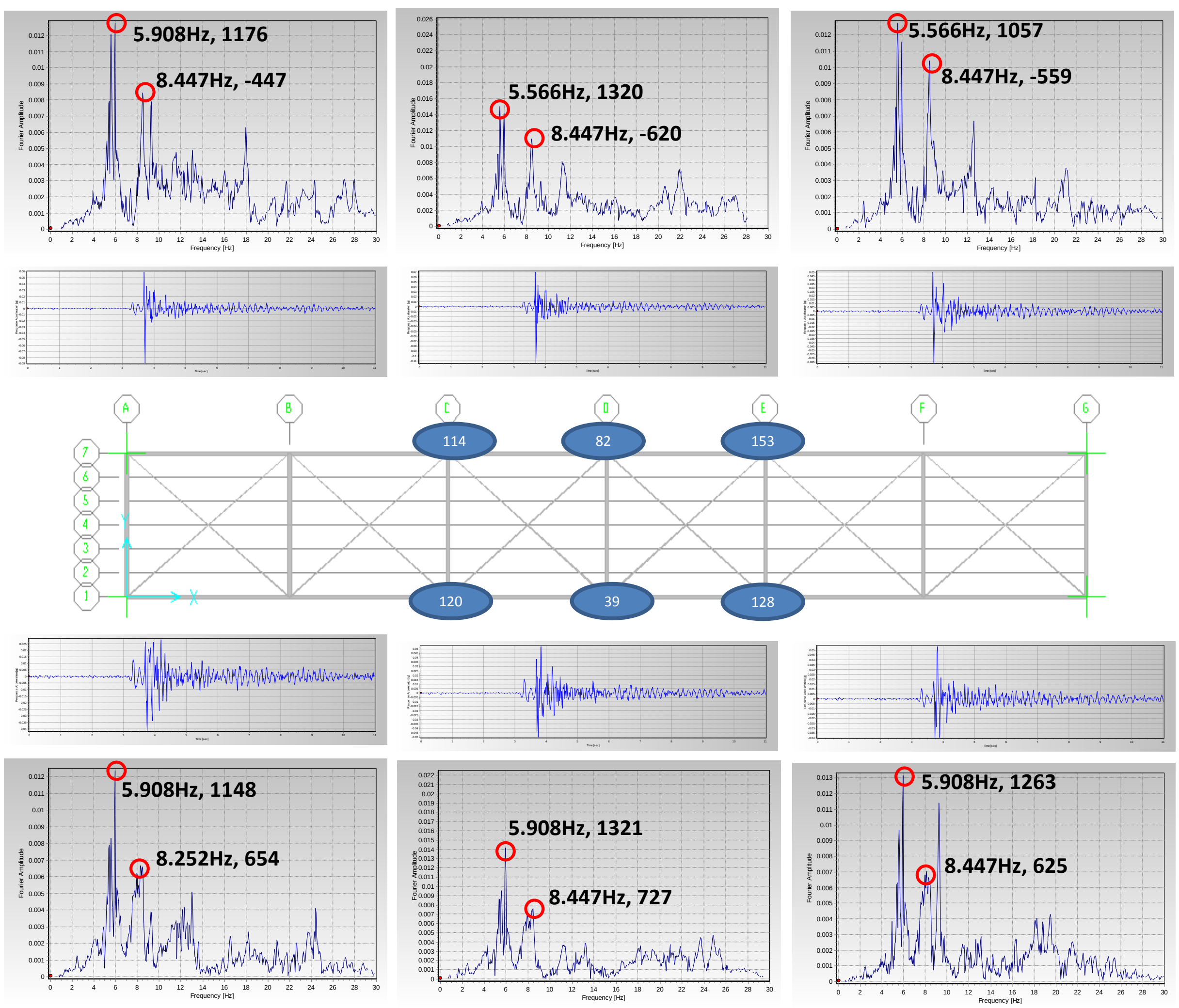


Figure 21: Test 6 Vertical Response Data

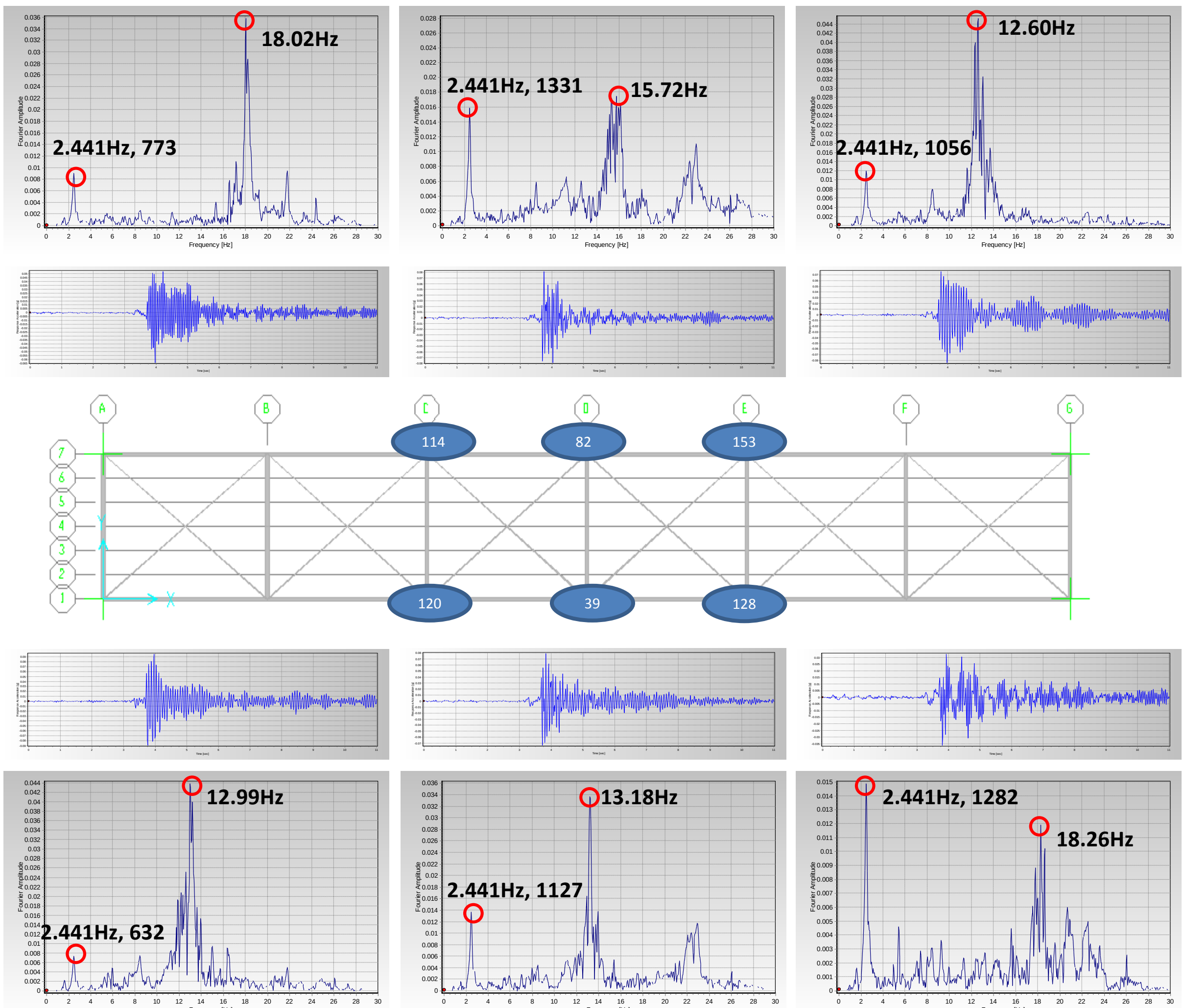


Figure 22: Test 6 Transverse Response Data

Test 7 - Group pulling rope attached to the side of the bridge

Test 7 was a test in which a group secured a rope to the midpoint of the span and pulled in the transverse direction, North-South, Figure 23. The data was collected at a sampling rate of 100 Hz and for duration of 130 seconds. Figure 24 is the graphical representation of the vertical response tests results. The unprocessed acceleration data shows what look like several pulls on the bridge. For Test 7 the sensors provided very consistent results for both the vertical responses and the transverse responses. The first identified vertical frequency was exactly 5.689 Hz across all the sensor locations, with the second identified frequency be seeing seen at an average of 8.447 Hz. Figure 25 shows the structural responses for vibrations in the transverse (side to side) direction. The transverse vibration does show a clear peak across of the sensors at an average of 2.441 Hz and shows a single peak ranging from 13.76 Hz to 18.19 Hz. For this test the horizontal pulling motion provided clear very tall peaks in the vertical Fourier Spectra and a very clear and high magnitude peaks for the first transverse mode. From these results the first and fundamental mode of the Old Alton Truss Bridge was determined to be a transverse sway in the bridge deck at a frequency of 2.441 Hz with the second and third corresponding to the identified maxima seen in the vertical response spectra as 5.689 Hz and 8.447 Hz respectively.

Figure 23: Test 7 Group Pulling Rope

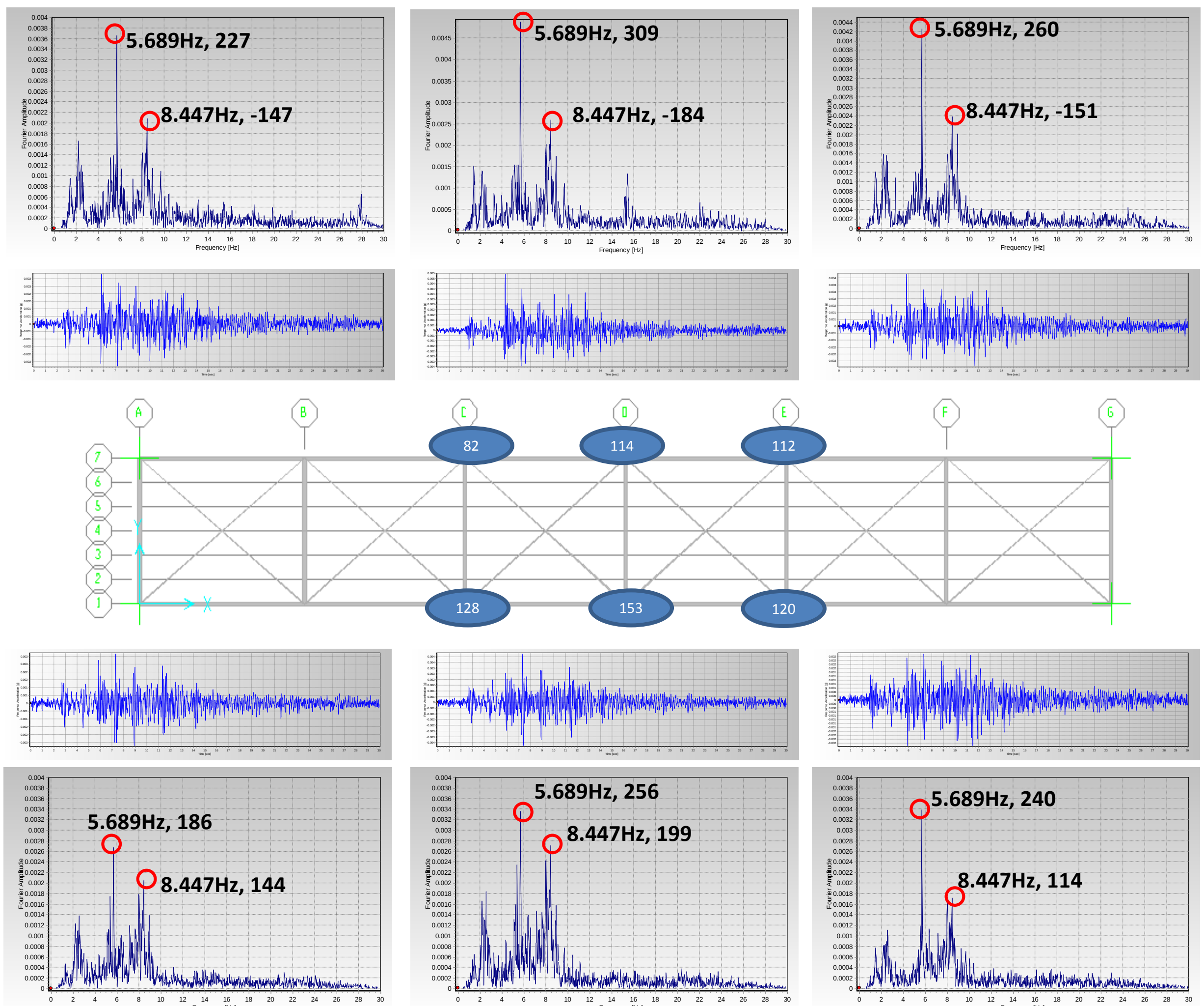


Figure 24: Test 7 Vertical Response Data

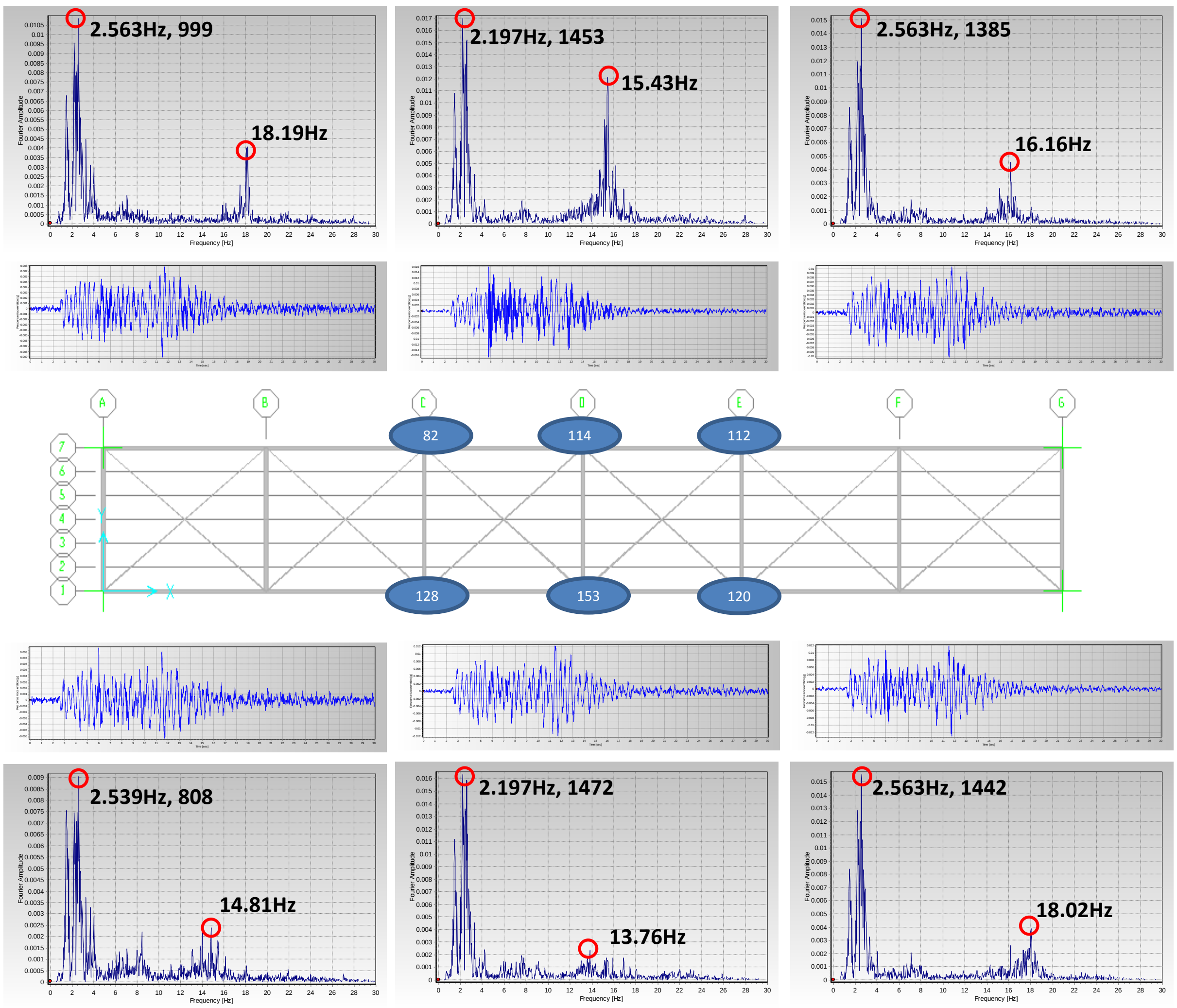


Figure 25: Test 7 Transverse Response Data

Test 8 - A single Person Jumping Vertically at 1/3 points of span.

Test 8 was a test in which a single person jumping, only once, at the 1/3 point of the span. The data was collected at a sampling rate of 100 Hz and for duration of 15 seconds. Figure 26 is the graphical representation of the vertical response tests results. The unprocessed acceleration data shows a single clear impact. For Test 8 the sensors provided similar results across all the sensors with some variations. The first identified vertical frequency averaged to 5.672 HZ across all the sensor locations, with a second frequency identified at an average 9.098 Hz. Figure 27 shows the structural responses for vibrations in the transverse (side to side) direction. The transverse vibration did not show a clear peak but a low magnitude peak can be seen at 2.441 Hz and showed a single peak ranging from 13.33 Hz to 18.26 Hz. Test 8 provided a clear frequency for the first and second vertical modes; however the first mode was not as clearly defined in the transverse direction due to the vertical excitation. From these results the first and fundamental mode of the Old Alton Truss Bridge was determined to be the transverse sway of the bridge deck at a frequency of 2.4412 Hz and the second and third modes vertical vibration modes were present 5.672 Hz and 9.098 Hz respectively.

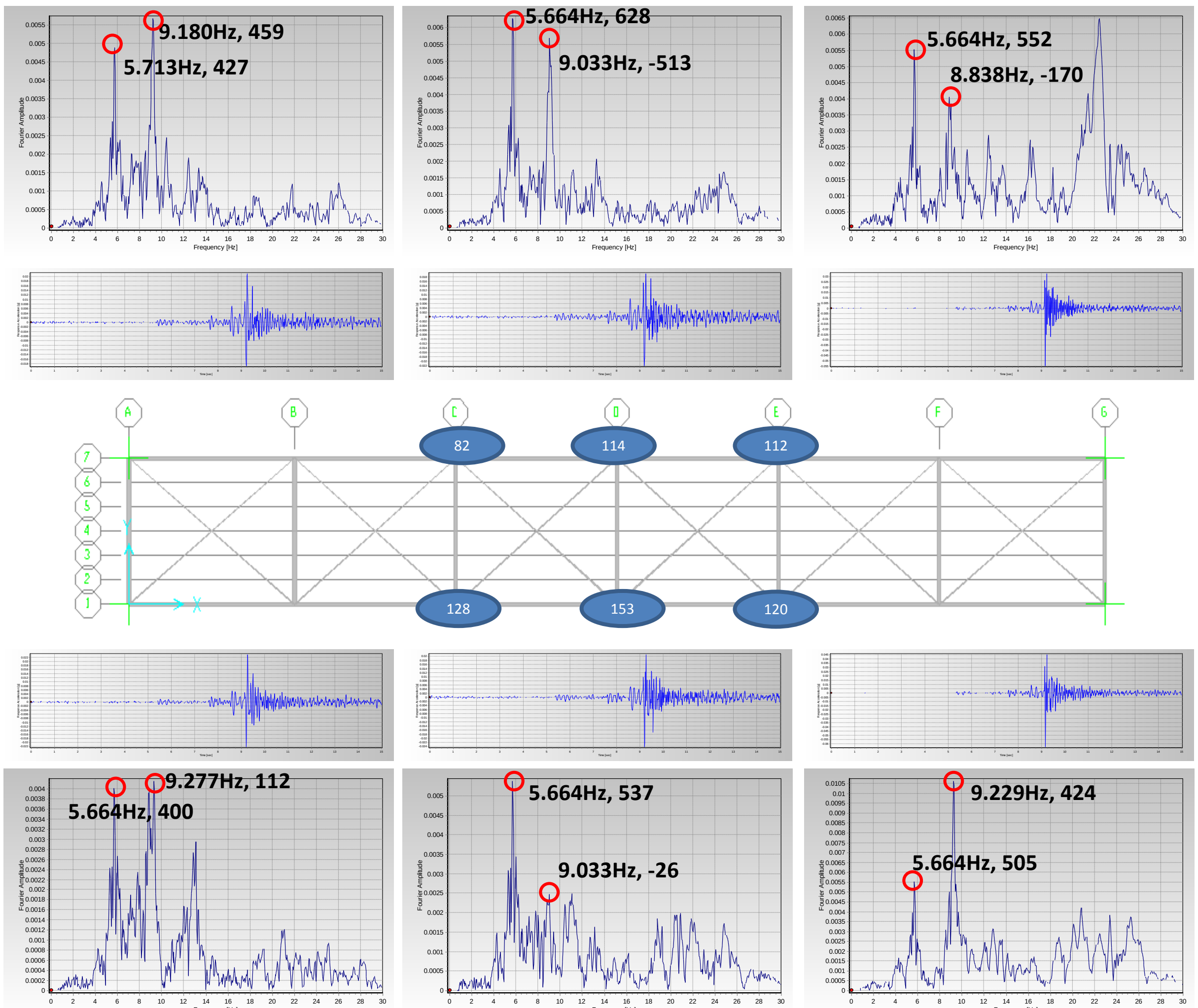


Figure 26: Test 8 Vertical Response Data

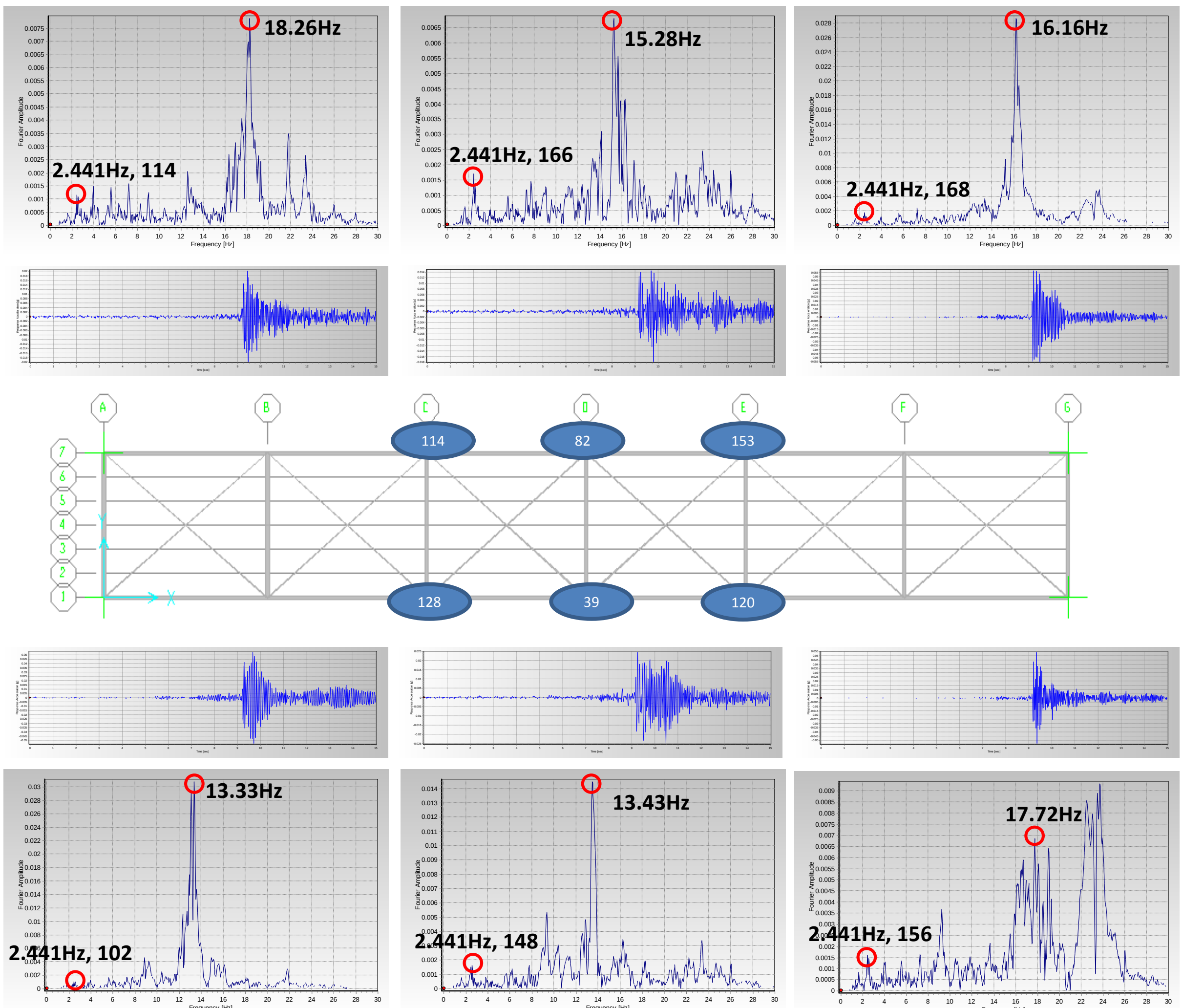


Figure 27: Test 8 Transverse Response Data

Measured Mode Shapes

The Fourier spectra provides a very clear peak at the frequency that a structure vibrates but it is not immediately clear the modal shape associated with each of the frequencies. By using the peak picking method and calculating the imaginary peak or FRF to represent the displacement at individual sensor nodes we can show the displacement of the nodes in relation to one another. Figure 28 shows each of the calculated FRFs for each sensor and each test in relation to one another, to display the mode shape for the first or fundamental mode. From the graphs it is evident both the North Truss and South Truss were vibrating in the transverse direction together. Please note Tests 4 & 5 were not included as these tests did not produce significant vibration for this mode. Figure 29 is the graphical representation of the second modal shape present in the Old Alton Bridge. The vertical vibration of the bridge deck up and down can be seen with both trusses vibrate up and down with similar displacements. For this set of examples Test 4 was again left out since it did not produce significant results for this mode. The third and last mode looked at was also clearly shown in Figure 30 where the North and South Trusses vibrated up and down but in inverse to one another. While one truss rises the other falls, giving the rotation movement of the bridge deck. All three modes were very similar in shape to the predicted modes from the Finite Element Analysis pera formed earlier.

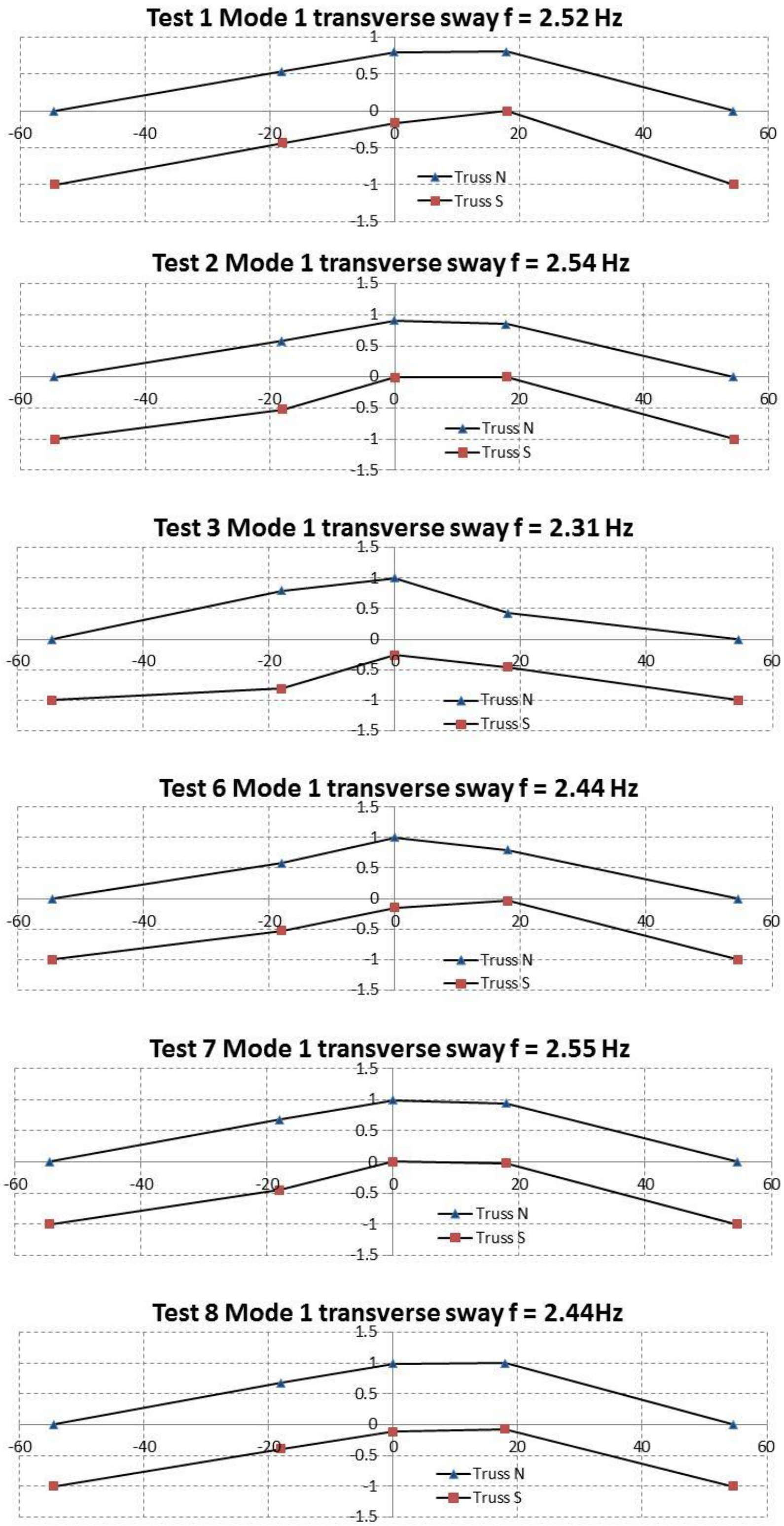


Figure 28: Mode 1 Truss Transverse Displacement for Different Tests

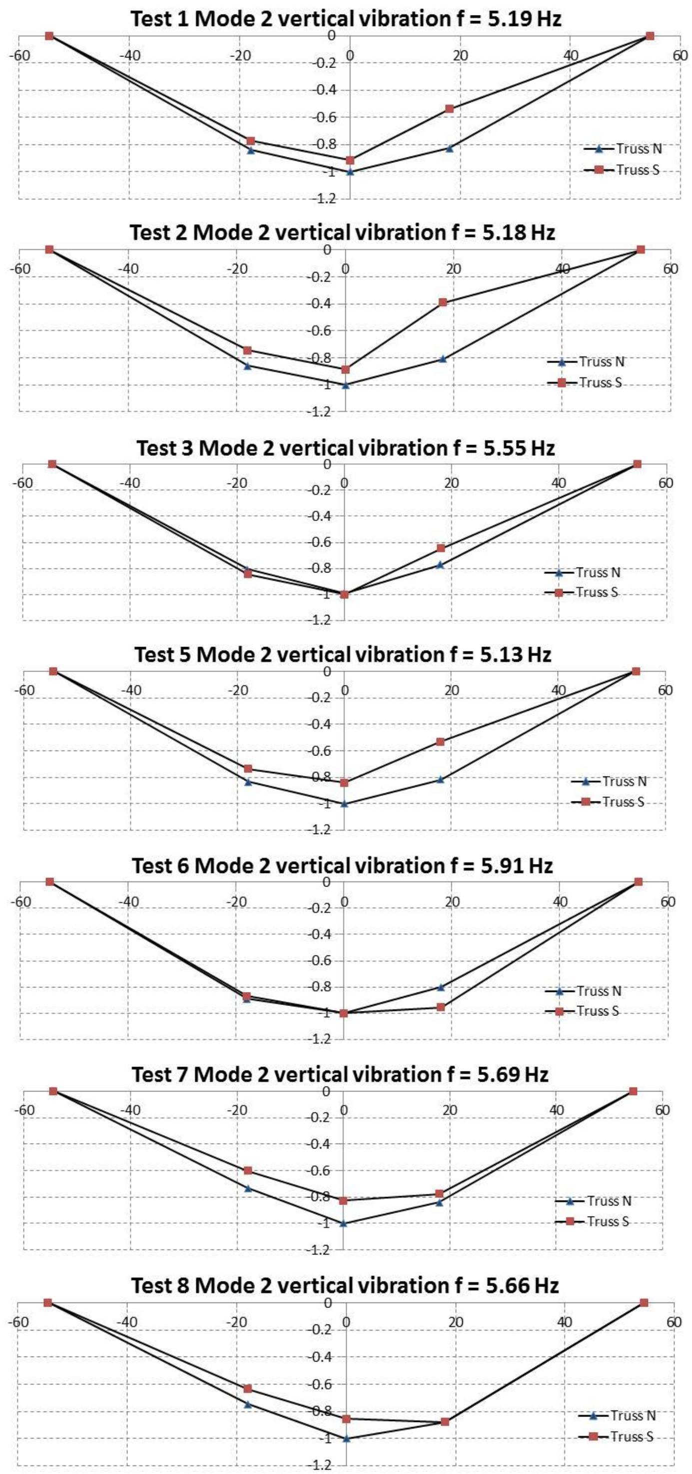


Figure 29: Mode 2 Truss Vertical Displacement for Different Tests

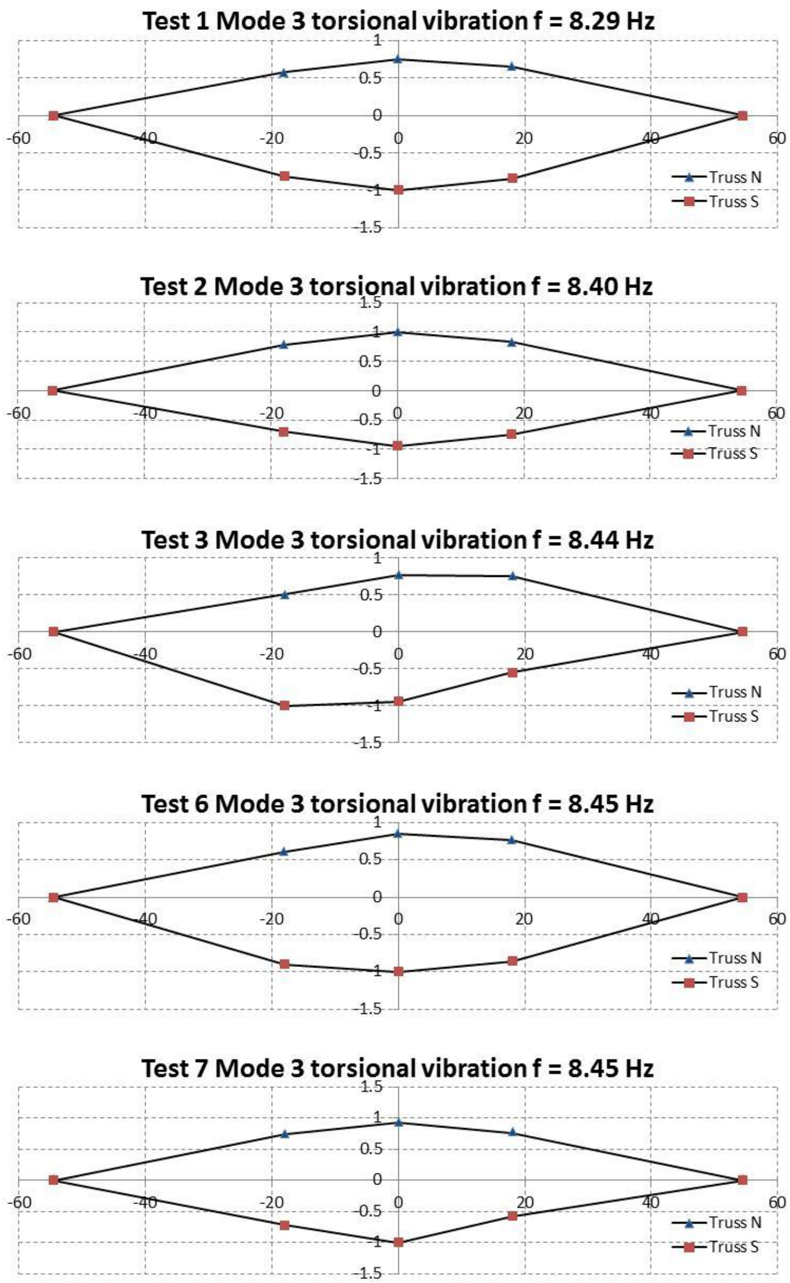


Figure 30: Mode 3 Truss Vertical Displacement for Different Tests

CHAPTER 4

CONCLUSION AND DISCUSSION

After the tests were conducted the applicability of the wireless sensor networks (WSSN) was proved with the successful system identification of the Old Alton truss bridge. The WSSN was a simple and quick way to measure the structural responses on this structure. The easy to use interface allowed data to be analyzed on site and ensure successful tests were conducted. The identified natural frequencies through sensors at different locations were close to each other and the differences of the identified natural frequencies were relatively small (less than 1.4%, 2.4%, and 0.7% for mode 1, 2, and 3, respectively). The measured natural frequencies and shapes also closely matched the predict periods and shapes given from in the Finite Element Analysis.

The identified natural frequency of the fundamental mode of the Old Alton Bridge main span truss structure was measured at 2.31 – 2.55 Hz. The vibration of this mode is in the transverse direction (north–south) as he bridge deck sways side to side. The identified natural frequencies of the second and third modes of the Old Alton Bridge main span truss structure were around 5.13 – 5.91 Hz and 8.29 – 8.45 Hz, respectively. Both modes vibrate in the vertical direction. The second mode shape is the vertical vibration (up-down) of the bridge deck. The third mode shape is the rotation of the bridge deck along its longitudinal axis. The dominant mode in the transverse direction were the local vibration of the vertical posts. The natural frequencies of those posts' local vibrations are in a range of 12.30 to 18.68 Hz. The vibrations of these posts were consistent throughout the tests but varied from post to post.

The calculated modal properties by SAP2000 were very similar to the tested modal properties. The calculated natural frequencies of the first three modes are 3.557, 5.430 and 10.712 Hz, respectively. The average tested natural frequencies of the first three modes are 2.447, 5.462, and 8.511Hz, respectively. The differences between the SAP2000 calculated and the average tested natural frequencies are 45.4%, 0.6%, and 25.9% for the 1st, 2nd, and 3rd modes, respectively. These results demonstrate the FEA techniques are best at predicting the vertical (gravity) vibration behavior and the horizontal behavior may require changes to the stiffness matrix

The various excitation methods provided a wide array of results in predicting and clearly identifying the modal properties. The excitations that best predicted the fundamental mode of the Old Alton Bridge were the methods that had the clearest peaks on the Fourier spectra. The tests that did this best were the tests that introduced lateral forces into the structure such as test 6 and test 7, horizontal jumping and pulling on the side of the bridge respectively. Other tests that identified the fundamental mode just not as clearly were test 1 (group vertical jumping for multiple times), test 2 (group vertical jumping once), test 3 (group jumping randomly). The second and third modes were predicted accurately for most of the tests and usually presented with clear peak across most sensors. The group marching, test 4, produced very little useable results as the vibrations generated presented with too much noise and the modal frequencies were obscured by the noise. Marching was the worst excitation method for the experimental system identification and was not useful for this structure.

The Case study proved the proposed Study plan seen in Figure 1, was an effective method for experimental system identification for a historic iron truss bridge. By first performing a detailed inventory of the structure and gathering as much information as possible the researcher will have a solid foundation to begin both the finite element analysis and begin preparing for field testing of the structure. The finite element analysis will provide a close prediction of the structure's modal parameters that may influence the testing methods and equipment used. After determining where sensors would best pick up these predicted modes and picking equipment that will work for the structure being tested, the actual field testing of the structure can be performed. When these results are obtained the comparison between the predicted and measured modal shapes and parameters are examined some important characteristics of the structure can be understood.

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