ASSESSMENT OF BRIDGE SERVICE LIFE USING WIRELESS SENSOR NETWORK

by

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ABSTRACT

This paper describes a method for estimating remaining service life of a bridge based on real-time responses of the bridge. Real-time responses were recorded using wireless sensor network. With a significant percentage of nation's bridges being structurally deficient or functionally obsolete and with no quantitative method of health monitoring being used in general practice, it has become the necessity to develop a SHM method, which will provide a quantitative assessment of overall bridge health. This research focuses on estimating overall condition of the bridge analyzing dynamic response rather than focusing on individual damage types, their severity and locations.

SHM process in this research uses dynamic responses of a bridge subjected to service loads, collects the response through a system of wireless sensor network, simulates an ideal and practical bridge using finite element model, and then estimates the remaining service life of the bridge based on the modal correlation between the existing and an ideal bridge condition. Results indicate that the bridge under this study has lost approximately 47% of its approximately 50 years of service life in 30 years of service. It was also observed that only higher order modes are more sensitive to damage compared to lower ones.

With limited budget available for bridge maintenance and repair, this research can help bridge owners, policy makers, transportation planners or any related professionals or organizations in prioritizing and allocating budgets based on actual bridge condition.

DEDICATION

To my parents, Md. Hussain Ali and Mrs. Ansari Hussain, and my loving wife, Shanzida Alam –

without your love, support and patience, this work would never have materialized.

ACKNOWLEDGEMENTS

This thesis would not have been possible without the guidance and the help of several individuals, who, in one way or another, have contributed and extended their valuable assistance in the preparation and completion of this research.

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Chapter 1

INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

The main indicator of a nation's economy is its transportation system; and infrastructure is the major element of a transportation system. For a country like the United States, whose major mode of transportation is a roadway network of 2.7 million miles of paved highways and railways, it is very important to keep this network functional. A recent statistics of the Federal Highway Administrations (FHWA) reveals that out of around 600,000 bridges, more than 25% of them are either structurally deficient or functionally obsolete (National Bridge Inventory, U.S. Department of Transportation, 2011). In the midst of the current global economic crisis, it is necessary to keep the transportation system functional to foster economic growth. But on the other hand, it is not feasible to improve the condition of a significant number of structurally deficient bridges with limited budgets. Therefore, it is necessary to prioritize bridges requiring repair or maintenance based on their current structural conditions. Traditional qualitative methods of structural health monitoring (SHM) of bridges are being used by the state Departments of Transportation (DOT) since early 70s while these methods are quite limited in estimating actual conditions of a bridge. Current practice of bridge health monitoring, which is called ‘Condition Rating’, involves visual observation and inspection of each of the bridge components (deck, superstructure, substructure, channel, culverts, approaches, etc.) and assign a single digit numerical value for that component based on the observation. These ratings are entered on the Bridge Inspection Record form, which is later used to update the electronic Bridge Inventory Files that contain a database (Maintenance and operation of the State inventory system, BMS) of all the past ratings of bridges (ODOT Manual of Bridge Inspection, 2010). Statistical analysis is performed using computer software to assess the present health of the bridge based on this database and present condition ratings. Along with the current bridge monitoring practice based on visual observation, the quantitative approach of SHM based on real-time bridge response data appears to be more realistic and effective in monitoring health of bridges. This approach uses advanced information technology to determine current bridge health through its dynamic structural response under vehicular loads.

The wireless sensor network (WSN) approach for SHM utilized in this study is a process of assessing the present structural condition of the entire bridge based on its real-time dynamic structural response under standard vehicular loads. The real-time dynamic response of the bridge under moving load is collected via a series of wireless sensor networks deployed on the bridge during the passing of a truck of known weight. The collected data are then processed and compared with a set of computer simulated responses of the same bridge under the same loading condition to estimate its current structural health.

The main distinguishing feature of this approach from other ongoing research is that, it does not focus on the damage of any specific elements of the bridge; rather it focuses on the overall condition of the bridge based on the combined effects of all individual damages irrespective of their type or extent on the overall behavior of the bridge.

1.2 Literature Review

By simple definition, SHM is a process of executing a damage detection, characterization and quantification technique for engineering structures/systems (Dawson, 1976; Farrar and Worden, 2006). For civil engineering structures, damage can be defined as any sort of deviation of the structure's geometric and/or material properties, boundary conditions, system's internal and/or external connectivity (bonding of reinforcement, stud connections, construction and expansion joints, shock absorbers, etc.) from its typical design values as a result of which the structure can no longer function at its desired service level (Dawson, 1976; Farrar and Worden, 2006). Presence of damage does not necessarily mean the imminent failure of the structure, but it indicates that the structure is not performing at its optimal performance level. Damage worsens as the structure continues to serve under normal loading conditions and at some time in future, the extent of damage reaches a threshold point where it can no longer be considered as safe operating condition. One of the main goals of SHM is to monitor the system's performance either continuously or at specified time intervals, and provide its safety and/or reliability status as well as a prognosis of its remaining service life.

The history of SHM can be traced back to the beginning of 19th century when railroad wheel-tappers used to use the sound of a hammer striking the train wheel to determine if there was any damage (Farrar and Worden, 2006). Since then, damage identification and monitoring have emerged as exciting fields in several branches of engineering and material science. At the earlier stage, the damage assessment was qualitative. But in the last 30 years with the development of modern day tools (high sensitivity sensors, larger computing capacity hard-wares, advanced soft-wares, etc.), SHM has shifted from a qualitative approach to a quantitative approach. Based on several key factors, such as objective, precision level, purpose, method, etc., SHM can be categorized as global or local and stochastic or deterministic.

1.2.1 Modal Frequency and Mode Shape

Equation of motion for any dynamic system having multi-degree of freedom (MDOF) can be described by Eq. 1.1 (Clough, 1993).

$$[\boldsymbol{M}]\{\ddot{\boldsymbol{x}}\} + [\boldsymbol{C}]\{\dot{\boldsymbol{x}}\} + [\boldsymbol{K}]\{\boldsymbol{x}\} = \{\boldsymbol{f}\} \tag{1.1}$$

Here, [**M**] = mass matrix, [**C**] = damping matrix, [**K**] = stiffness matrix, {**f**} = nodal force vector, $\{\boldsymbol{x}\} =$ nodal displacement vector, $\{\dot{\boldsymbol{x}}\} =$ nodal velocity vector and $\{\ddot{\boldsymbol{x}}\}=$ nodal acceleration vector.It is necessary to determine the modal frequencies and mode shapes in order to solve this equation. Modal frequencies and mode shapes are determined by solving Eq. 1.2 for $\boldsymbol{\omega_i}$and$\{\overline{\boldsymbol{x}}_i\}$:

$$\Big[[\boldsymbol{K}] - \boldsymbol{\omega}_i^2[\boldsymbol{M}]\Big]\{\overline{\boldsymbol{x}}_i\} = \{\boldsymbol{0}\} \tag{1.2}$$

Here, $\boldsymbol{\omega_i}$ = modal frequency for ithmode shape, and $\{\overline{\boldsymbol{x}}_i\} = \{\boldsymbol{\Phi}_i\} = \{\boldsymbol{x}\}\,\mathbf{sin}\,\boldsymbol{\omega_i t}$ = ith mode shape.

1.2.2 Deterministic and Stochastic SHM

Based on the type of method used to analyze structural health, SHM process falls mainly into two categories, deterministic approach and stochastic (probabilistic) approach. Deterministic SHM follows the deterministic mathematical model for processing and analyzing the collected real-time data to assess health. In this approach, all data points and variables are uniquely determined from structures or finite element models at current and earlier states. Since there is no random variable or probabilistic distribution in deterministic model, results obtained in this approach are more accurate and reliable but because of complex relationships between variables; it is not popular for applications where three or more sets of variables are involved. Yet deterministic approach of SHM has been widely used during the early days of health monitoring research despite complexity in numerical solutions. Numerous researchers (Loland and Dodds, 1976; Begg, et al., 1976; West, 1984; Yuen, 1985; Srinivasan and Kot, 1992; Salawu and Williams, 1994, 1995) have developed in the past various methods of health assessment based on the deterministic model.

Stochastic SHM process is developed based on the stochastic mathematical model where all variables and data sets do not have any unique values determined from the system, in fact, some or all of them are obtained from randomness or probability distributions. Since randomness is present, results of stochastic process have less accuracies and reliability compared to deterministic process. In recent years, stochastic approach of SHM has become more popular among researchers because of its capability of handling multiple variable and data sets with complex or undefined inter-relationships among variables. Farrar and Worden (2006) in an article divided stochastic model development process for

SHM into three categories: supervised learning, unsupervised learning and outlier or novelty detection. The authors also cited the four steps of SHM defined by Farrar, et al. (2001) as steps of “statistical pattern recognition paradigm”. These steps are also equally applicable with little or no modification for deterministic SHM approach. The steps are: “operational evaluation, data acquisition, normalization and cleansing, feature selection and information condensation, and statistical model development for feature discrimination”. Although stochastic approach is one of the promising approaches of SHM in solving large scale civil engineering structures with complex inter-relationship among environmental, geometric and material properties, existing technical available literature is not as advanced as the deterministic approach, therefore, needs more attention from researchers.

1.2.3 Global and Local SHM

Based on the objective and purpose of health monitoring, it can be categorized as global SHM or local SHM. In global SHM, overall structural condition of the structure is assessed based on real-time responses (dynamic or static) and results are interpreted in quantitative format in terms of a single or multiple numerical parameters. These quantitative results may be in either of the following terms: structural health index, percent of remaining design service life, remaining service life based on design life, etc. Global SHM does not identify and/or quantify each of the individual damage present in the structure, rather it emphasizes on the combined effect of all present damages on the overall performance of the structure. Global SHM, if developed to a level of practical use, can be very useful for transportation officials in prioritizing structurally deficient bridges for maintenance and repair.

Local SHM tries to identify all the damages present in a structure, such as damage types, locations and extents of damage. This type of SHM received the most attention from researchers since the evolution of modern SHM. Doebling, et al. (1996) summarized past significant works on local SHM and in the same article, they cited Rytter (1993) who classified SHM into four levels. These levels are:

Level 1: Determination that damage is present in the structure

Level 2: Determination of the geometric location of the damage

Level 3: Quantification of the severity of the damage

Level 4: Prediction of the remaining service life of the structure

Researchers have been trying different approaches and various methods using characteristic dynamic or static parameters for damage identification, localization and quantification. Some of these are effect of damage on modal frequencies and mode shapes or strain mode shapes, damage identification using changes in dynamically measured flexibility matrix or measured stiffness matrix, damage identification and localization by unity check in between mode shapes, damage detection by repeated update of structural property matrices (mass, stiffness and damping) to match measured static or dynamic responses, damage localization by locating structural nonlinearity, damage detection using fuzzy logic and neural network, etc. (Doebling, et al. 1996).

Since, this research methodology uses frequency and mode shape changes for assessing structural health using a unity check method called Modal Assurance Criterion (MAC), some of the previous works using similar methods cited by Doebling, et al. (1996) are summarized in this section of literature review.

Mode shape was used in damage identification and localization for the first time by West (1984). He tested a structure before and after damage occurred and determined the level of co-relation between the mode-shapes using modal assurance criteria (MAC). The change in MAC value is used to locate and quantify the structural damage.

Yuen (1985) developed two parameters to compare the changes in mode shape and mode-shape-slopes of damaged and undamaged structures. These parameters are shown in Eqs. 1.3 and 1.4.

$$\{\emptyset^*\}_i = \frac{\{\emptyset^d\}_i}{\omega_i^d} - \frac{\{\emptyset^u\}_i}{\omega_i^u} \tag{1.3}$$

$$\{\emptyset^*\}_i{}' = \frac{\{\emptyset^d\}_i{}'}{\omega_i^d} - \frac{\{\emptyset^u\}_i{}'}{\omega_i^u} \tag{1.4}$$

Where, $\{\emptyset^d\}_i$= i^{th}mode shape of damaged structure, $\{\emptyset^u\}_i$= i^{th}mode shape of undamaged structure, ω_i^d= frequency of i^{th}mode at damaged condition, ω_i^u= frequency of i^{th}mode at undamaged condition. Simulation was done with reducing stiffness to observe the change in these parameters and thereby to identify the damaged location from predicted values. He also suggested that the mode shapes need to be ortho-normalized in order to use higher mode shapes. Ortho-normalized mode shape is a form of orthogonal shape where the resulting vectors are all unit vectors. Mass ortho-normalization of a mode shape can be done using Eqs. 1.5 and 1.6.

$$\widehat{\Phi}_N = \frac{\Phi_N}{\sqrt{a_{NN}}} = \begin{Bmatrix} \frac{\bar{x}_1^{(N)}}{\sqrt{a_{NN}}} \\ \vdots \\ \frac{\bar{x}_N^{(N)}}{\sqrt{a_{NN}}} \end{Bmatrix} \tag{1.5}$$

Where, Φ_N = N^th^ mode shape, $\widehat{\Phi}_N$ = ortho-normalized N^th^ mode shape, $\bar{x}_1^{(N)}$ = displacement along DOF 1 of N^th^ mode shape, and

$$a_{NN} = m_1(\bar{x}_1^{(N)})^2 + m_2(\bar{x}_2^{(N)})^2 + \cdots + m_N(\bar{x}_N^{(N)})^2 = \sum_{i=1}^{N} m_i(\bar{x}_i^{(N)})^2 \tag{1.6}$$

Here, m_i = lumped mass associated with i^th^ DOF.

Fox (1992) proposed “Node Line MAC” instead of global MAC since the latter is less sensitive to damage. He also suggested that graphical comparison of relative mode shapes are the best way to detect damage if only mode shapes and resonant frequencies are analyzed. He also suggested a method to enhance the relative changes in order to better identify the damage location.

Srinivasan and Kot (1992) suggested that mode shape is more sensitive to damage than resonant frequencies, and the changes in mode shape is well quantified by MAC values of damaged and undamaged structures.

Ko, et al. (1994) to detect damage in steel framed structures described a method, which uses a combination of MAC, COMAC and sensitivity analysis. Sensitivity analysis is performed to determine the most relevant DOF, and then the MAC values between damaged and undamaged structures are analyzed to determine the most sensitive mode shape. With this pre-determined DOF and mode shape, COMAC is calculated to identify damage in a structure. They found that only particular mode shapes can indicate damage in structures.

Salawu and Williams (1994, 1995) demonstrated that the most important task in SHM is to select the mode shape, which is the most sensitive to damage. They compared results of mode shape relative change and mode shape curvature change to detect damage, and suggested that the MAC values can be used to identify the most sensitive mode to damage.

1.2.4 Use of MAC in SHM

Modal assurance criterion (MAC) is a tool for orthogonality check between two modal vectors (Allemang, 2003). This tool is used to determine the degree of correlation between two mode shapes. In this research, MAC is used to compare the similar mode shapes of damaged and undamaged structure. MAC value ranges from 0 to 1 with 1 indicating full correlation and 0 indicating no correlation at all. Mathematical derivation of MAC is shown in Eqn. 1.7 (Burns, 2004).

$$MAC = \frac{|\{\Phi_A\}_i^T\{\Phi_B\}_j|^2}{\{\Phi_A\}_i^T*\{\Phi_A\}_j*\{\Phi_B\}_i^T*\{\Phi_B\}_j} \qquad (1.7)$$

Where, $\{\Phi_A\}_j$= mode shape of model A, $\{\Phi_A\}_i^T$= transpose of mode shape of model A, $\{\Phi_B\}_j$= mode shape of model B, $\{\Phi_B\}_i^T$= transpose of mode shape of model B.

There are various other techniques used by researchers for determining the degree of correlation between analytical and experimental modal model. Some of these methods are: Modal Correlation Coefficient (MCC), Partial Modal Assurance Criterion (PMAC), Coordinate Modal Assurance Criterion (COMAC), Enhanced Coordinate Modal Assurance Criterion (ECOMAC), Weighted Modal Assurance Criterion (WMAC), Scaled Modal Assurance Criterion (SMAC), Cross Orthogonality and Pseudo-orthogonality check (COC and POC), Coordinate Orthogonality Check (CORTHOG), Modal Assurance Criterion Square Root (MACSR), Modulus Difference Method, Frequency Response Assurance Criterion (FRAC), Frequency Domain Assurance Criterion (FDAC) and Inverse Modal Assurance Criterion (IMAC) (Allemang, 2003; Avitabile, 1998). These methods usually fall into two categories, vector based methods and DOF based methods (Avitabile, 1998). Most of these techniques mentioned earlier are an extension, subset, or partial variation of MAC or another technique. MCC and IMAC are used instead of MAC in cases where higher sensitivity is desired because of small changes in magnitudes of modal vectors. PMAC was developed to investigate a particular set of DOFs of a system, which provides location specific correlation information. Further refined versions of this method are COMAC, ECOMAC and Modulus Difference, providing correlation between each individual pair of DOFs. WMAC, SMAC, MACSR, COC, POC and CORTHOG are correlation techniques based on normalized modal vector weighted by mass and stiffness matrices. FRAC and FDAC are similar tools which are suitable for frequency domain analysis. Choice of the suitable technique for a particular case is made based on the nature and objective of the study. Since this research is solely focused on the overall assessment of the bridge health and not individual damage location, methods providing spatial correlation information are not used; rather degree of correlation of the entire modal vector is determined using MAC.

SHM can be further classified as smart structures with wired or wireless sensors embedded into the structure during construction or sensors installed later on old structures for continuous health monitoring and intermittent health monitoring at specified interval, etc.

1.2.5 Research Methodology

This research method uses dynamic response data (acceleration) collected via a system of wireless sensor network installed during data collection process from a real-life bridge, which is in service for past 30 years and from a finite element model (FEM) simulation. All data points used in analyses are actual measured data; none of them are obtained from randomness or statistical probability distribution. Therefore, this research falls into the category of deterministic model. The collected and simulated acceleration data were then used to determine mode shapes of the bridge at both damaged and undamaged states, comparison of which using mode shape correlation gives an overall quantitative assessment of the structural condition of the bridge. Since this research does not determine type, location and severity of any individual damage, but only gives an overall assessment of current health and estimation of remaining serving life of the bridge, therefore, it is a global SHM process.

Chapter 2

PROBLEM STATEMENT AND METHODOLOGY

2.1 Problem Statement

This study focuses on quantitative assessment of structural health of a specific bridge in service, based on real-time dynamic response of the structure. This involves the following tasks and the flow diagram shown in Fig. 2.1.

- Development of wireless sensor networks in order to collect, transmit and store the dynamic response of the bridge subjected to moving loads.
- Estimation of the present equivalent stiffness of the entire bridge cross-section based on recorded dynamic response.
- Determination of the fundamental modal frequencies and mode shapes of the bridge in current condition using the estimated reduced stiffness.
- Development of a Finite Element (FE) model of the bridge from the original construction drawings in order to determine the fundamental modal frequencies and mode shapes, which will represent the condition of the bridge without any damage or loss of stiffness.

- Comparative study between these two stages, which are the existing bridge and the FE model bridge to replicate the original condition, and assess the present health of the structure based on their correlation.

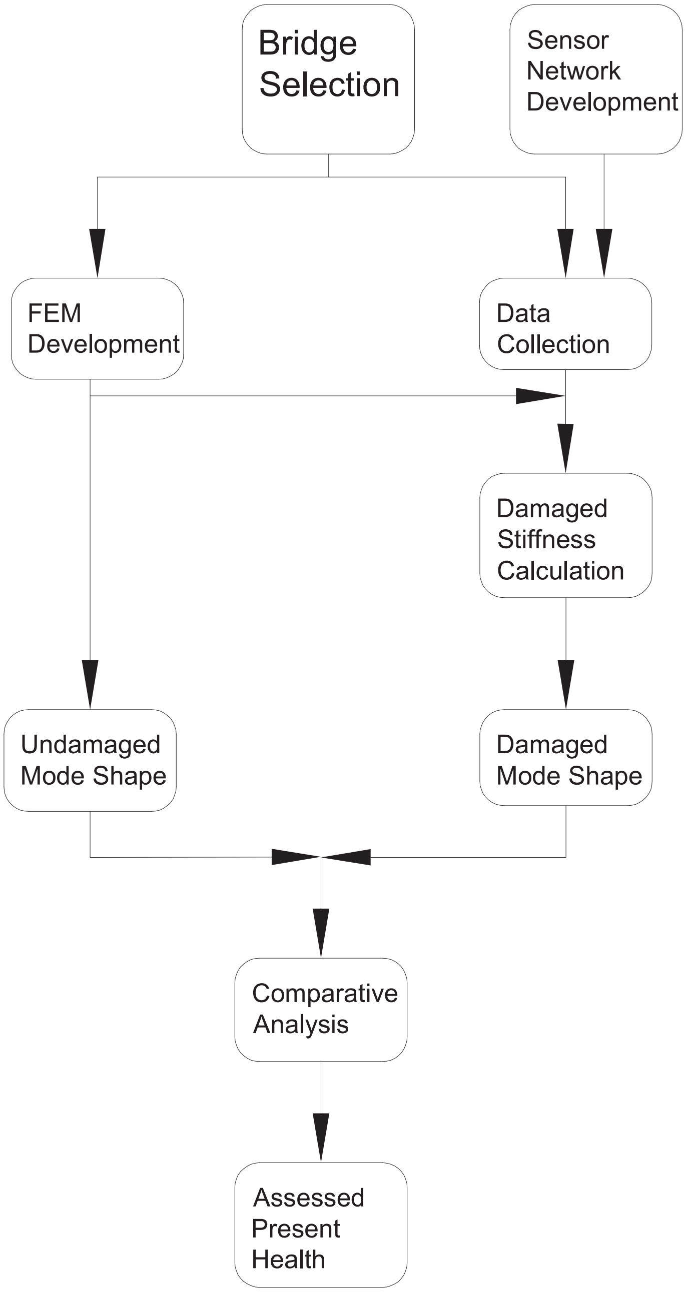

Figure 2.1: Flow Diagram of SHM.

2.1.1 Bridge Selection

The structure selected for the health monitoring study is a bridge on Market Street over the Mahoning River and CSX Railroads near City Hall in downtown Youngstown, Ohio, commonly known as the ‘Market Street Bridge’. The formal name of the bridge is ‘Vietnam Veterans Memorial Bridge’. It is owned and maintained by Mahoning County Engineer’s Office. The Bridge No. is MAH-62-17.75 and was designed by Glaus, Pyle, Schomer, Burns & De Haven, Inc. in 1978. It was opened to traffic in 1983 and has been in service since then. The reasons for selecting this bridge for health monitoring are: (1) it is on one of the major roads connecting downtown Youngstown with Boardman and Southside of Youngstown; (2) traffic volume is relatively high; (3) this bridge is old enough to have a potential need for health assessment; and (4) it is conveniently located near YSU campus, as shown in Fig. 2.2.

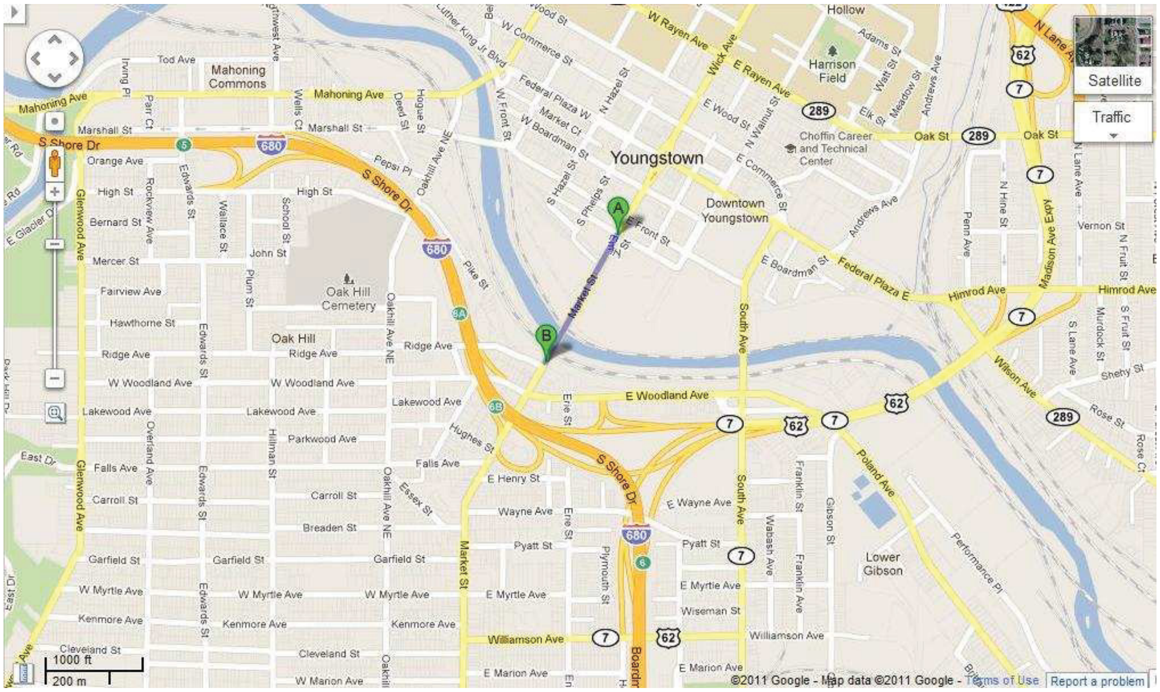

Image source: Google Maps, 2011

Figure 2.2: Location of the bridge selected for SHM study.

Image source: Bing Maps, 2011

Figure 2.3: Aerial view of the selected bridge.

2.1.2 Bridge Description

The selected bridge, an aerial view of which is shown in Fig. 2.3, is a four-lane steel plate girder bridge with concrete deck. It consists of thirteen spans supported by twelve concrete piers. The deck is 9.25 in. thick reinforced concrete slab spanning over seven equally spaced 5 ft deep steel plate girders. Transverse angle bracings are provided at a spacing of 14 ft on center for lateral stability of the girders. The vertical alignment of the bridge has a downward slope of 3.85% from southwest to northeast end of the bridge, as shown in Figs. 2.4 and 2.5. The entire bridge is divided into four units to allow for the thermal expansion and contraction. Units are joined together by three hinge joints occurring at Span No. 4, 8 and 11. The bridge has variable span lengths ranging from 78 ft 2 in. to 210 ft. Width of the bridge also varies along the length of the bridge. Table 2.1 provides a summary of the bridge geometry.

Table 2.1 – Market Street Bridge geometry

Span No.	Unit No.	Length (ft)	Left support	Right support	Deck Width
1	1	191	Abutment # 1	Pier # 1	82 ft to 67 ft 10 in.
2	1	210	Pier # 1	Pier # 2	67 ft 10 in.
3	1	168	Pier # 2	Pier # 3	67 ft 10 in.
4	2	99.33	Pier # 3	Pier # 4	67 ft 10 in.
5	2	111	Pier # 4	Pier # 5	67 ft 10 in.
6	2	111	Pier # 5	Pier # 6	67 ft 10 in.
7	2	111	Pier # 6	Pier # 7	67 ft 10 in.
8	3	116	Pier # 7	Pier # 8	67 ft 10 in. to 79 ft 6 in.
9	3	116	Pier # 8	Pier # 9	
10	3	93	Pier # 9	Pier # 10	79 ft 6 in.
11	4	85	Pier # 10	Pier # 11	79 ft 6 in.
12	4	85	Pier # 11	Pier # 12	79 ft 6 in.
13	4	78.2	Pier # 12	Abutment # 2	79 ft 6 in.

This bridge has four lanes of traffic (two lanes of traffic in each direction) of 12 ft width each and sidewalks on both sides. Width of each side walk is 5 ft and is separated from the traffic lanes by a continuous concrete barrier. Another continuous concrete railing is provided on the exterior edge of each side walk. The horizontal alignment of the bridge is straight.

Image source: Rdcatman, City-Data.com, 2007

Figure 2.4: View of Market Street Bridge from downtown Youngstown.

Image source: Daysleeper47, Wikimedia Commons, 2006

Figure 2.5: Market Street Bridge (looking towards downtown Youngstown).

2.1.3 Original Construction Drawings

Original construction drawings of the bridge were collected from the office of Mahoning County Engineer in order to develop an FE model of the bridge representing the undamaged state. The undamaged state herein refers to the new bridge immediately after construction while the damaged state refers to the existing bridge. Figs. 2.5, 2.6 and 2.7 show some images of the original construction drawings of the bridge.

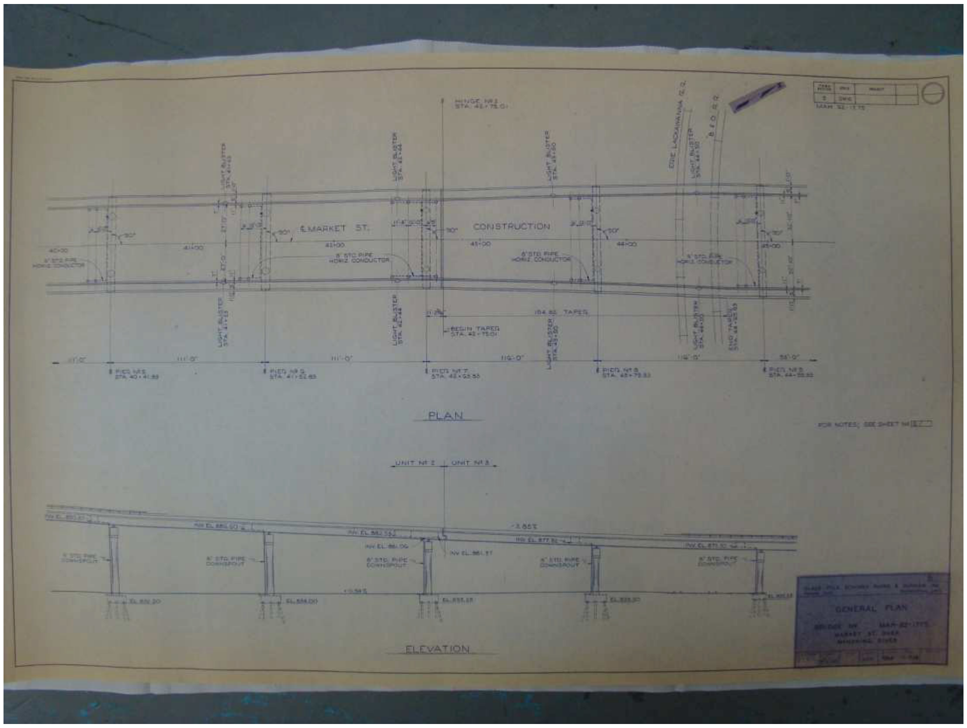

Figure 2.6: General plan (partial).

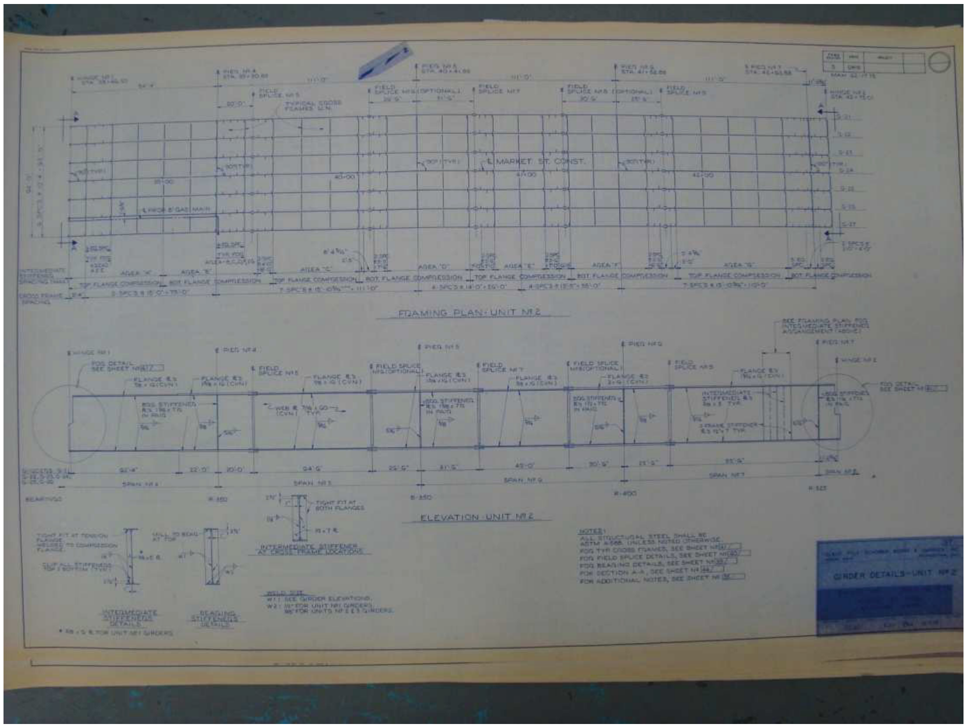

Figure 2.7: Girder details (Unit # 2).

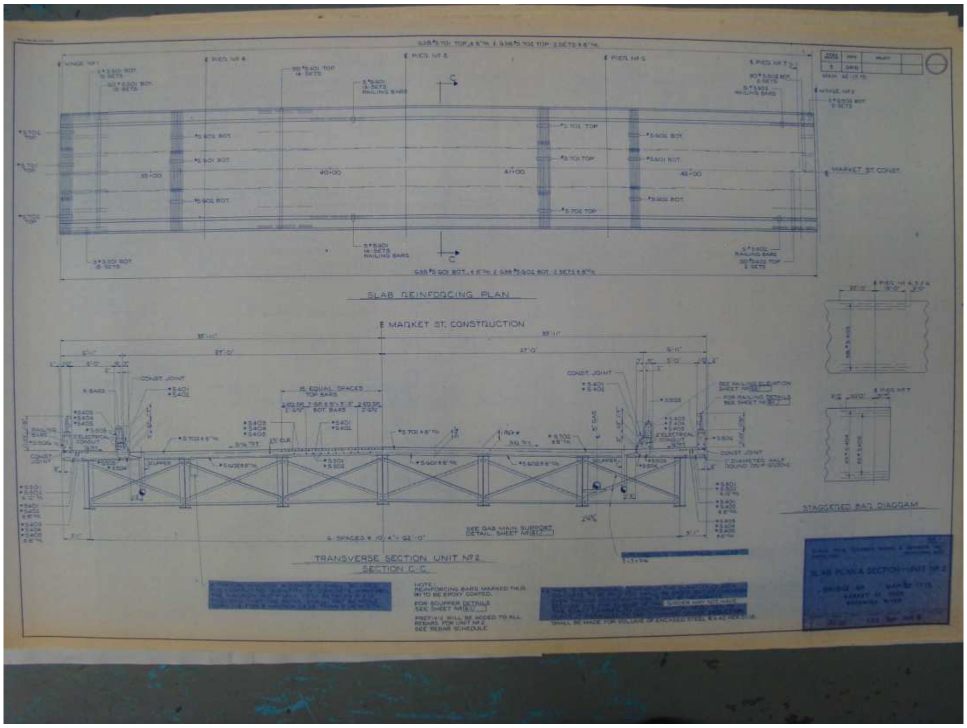

Figure 2.8: Slab plan and section (Unit # 2).

2.1.4 Span Selection for SHM

Because of resource and time limitation, it was not practically feasible to perform the health monitoring of the entire bridge. For such constraints, a representative specific span of the bridge was chosen for health assessment, which would indicate the overall current structural condition of the bridge. Considering all the factors, Span No. 6 of Unit No. 2 (Table 2.1), spanning between Piers5 and 6, was selected to be appropriate for this purpose. The main reasons for selecting this span are listed below:

- It has uniform roadway width and girder spacing throughout the entire span.
- Adjacent spans on both sides have the same span length, roadway width and other geometric properties.
- There are no hinge joints on the adjacent spans, therefore, the span can be considered continuous.
- The span is on the middle part of the bridge.
- During the data collection, the test truck will get enough distance to attain constant speed; also the sensor network operator will get enough time for data collection during the truck passes the hinge joint # 1.

2.2 Methodology

The current structural condition of the bridge under investigation is evaluated using the dynamic responses of the bridge. Basic structural properties (stiffness, mass, damping) of any structure are directly reflected on its dynamic responses, such as acceleration, vibration frequency, vibration amplitude, mode shape, etc. Total mass of a structure or the mass of its structural component does not change substantially over time resulting into any significant effect on its structural functionality. Which means, mass is not a parameter or variable in SHM. Also, there is no precise method to measure the actual damping of any structure at any point of time. Damping is only estimated as a ratio of its critical damping and it has certain values based on the type of material. Therefore, damping is also assumed as a constant throughout the life span of the structure. The only parameter that plays significant role in health monitoring of a structure is the stiffness, which is a function of material properties (modulus of elasticity, poisons ratio, etc.), cross-sectional properties (effective depth, crack location and extent of crack, reinforcement, etc.), length of the member and boundary conditions. Damage, as it is defined in SHM as changes in material or geometric property or any support conditions (Farrar and Worden, 2007); this study is limited to damages caused by changes only in material or geometric properties, i.e., change in stiffness of the structure.

In this study, acceleration and mode shape are used as the basis of health monitoring. At least two data points are needed for the analysis. First one is the undamaged state of the bridge and the second one being the current response of the bridge. For the first set of data, needed were acceleration and mode shape responses of the bridge from the undamaged state, which are the responses of the bridge after construction. Since no data have been collected at that time (almost 30 years ago), FE model (FEM) of the bridge has been developed to simulate the undamaged state of the bridge. FE model of the bridge is developed and analyzed using computer software named “Autodesk Simulation Multiphysics,” formerly known as “Algor”. One representative span of the bridge is modeled in this software using geometric and material properties from actual construction drawings. Some assumptions and simplifications were made in modeling, which are stated later, in order to increase the reliability of the model. A modal analysis of the resulting FEM was performed to get the first five fundamental modal frequencies and respective mode shapes. This is the response of the undamaged bridge representing the basic structural properties without any influence of external loads. Next, the computer model has been simulated for an equivalent truck load moving at a constant speed of 35 mph over the entire span. The response of the bridge in terms of vibration amplitude and acceleration were recorded.

The second set of data was obtained from the field response of the actual bridge representing the current damaged state. Several sets of data were collected through a series of wireless sensor network. A loaded truck was run over the bridge at a constant speed of 35 mph, and the acceleration of the bridge was collected and transmitted to a server via the wireless sensor network. Only the acceleration response was recorded in this process because there is no practical means of determining the fundamental mode shapes of any structure through any sensor or physical measurement. The mode shapes of the damaged structure were thus determined using a reduced stiffness computer model.

In order to simulate the mode shapes of the damaged structure, the stiffness of the FE model bridge was modified to match the stiffness of the damaged bridge since it was assumed that irrespective of the type, extent and location of damage, mode shapes will be directly affected by the stiffness of the bridge. Based on this assumption, the stiffness of each element (concrete deck and steel girders) of the model bridge was reduced by certain percentage so that it produces the same acceleration as the existing bridge would do. This reduced stiffness is then used for modal analysis to obtain the damaged mode shape.

The structural health is assessed from the correlation analysis of the similar mode shapes of the two structures. The correlation method used in this study is Modal Assurance Criteria (MAC) developed based on the orthogonality property of the mode shape. The deviation of the MAC values from the unity indicates the deterioration of the structural health.

2.2.1 Assumptions

Following assumptions were made for this study to simplify the SHM process:

- The effects of temperature and lateral wind force were neglected during the data collection process.
- Deck reinforcement was assumed to have less contribution towards the overall cross-sectional stiffness of the entire bridge.
- Concrete barriers were not included in the FE model for simpler analyses.
- Vibrations induced due to surface roughness of the deck and vehicle suspension system were ignored.
- The boundary conditions at both ends of the span were taken as fixed.
- It was assumed that the bearing pads supporting the girders have minimal effects on its vibration characteristics.

Chapter 3

DATA COLLECTION

3.1 Wireless Sensors

The actual process of structural health monitoring begins with the field data collection. Acceleration response of the selected representative span of the Market Street Bridge was recorded using a series of wireless sensor network while a truck with pre-defined load was passing over the bridge at a specific speed. The truck used in this experiment was a standard 20,000 lb dump truck with an axle distance of 13 ft 6 in.

Sensors used for data collection were SunSPOT (Sun Small Programmable Object Technology), as shown in Fig. 3.1, which is a Java based small programmable wireless sensor network (WSN), developed by Sun Microsystems, currently owned by Oracle. These sensors consist of three directional acceleration sensors operable within a scale of 2g to 6g with temperature, humidity and light sensors. The maximum supported sampling rate is 1 kHz. The main feature of SunSPOT is that it does not run under any conventional operating system (OS), rather it runs on squawk Java Virtual Machine (JVM), which acts both as an OS and as a software application platform. Another key feature is it has a built-in program controlled rechargeable battery, which can be charged using a universal serial bus (USB) port. Each development kit comes with two sensors and one base station, which collects data from sensors wirelessly.

Image source: Oracle Corporation, 2011

Figure 3.1: SunSPOT hardware developer's kit.

3.2 Sensor Networks

In this study, eight sensors with two base stations were used to build two wireless sensor networks. Each base station was connected to 4 sensors in a series network. Two laptops were connected to each of the base stations to store collected data. Two independent wireless networks were configured with each of them consisting of four sensors, one base station and a laptop, as shown in Fig. 3.2. In each of these networks, the sensor farthest from the base station transmits data to the nearest sensor and eventually to the base station, which transmits data to the laptop connected via a USB port. For example, in Sensor Network 1, Sensor A transmits data to Sensor B, sensor B transmits its own and data collected from Sensor A to sensor C, and so on. Consequently, Sensor D transmits all data to the base station, which then stores all collected data into the attached laptop.

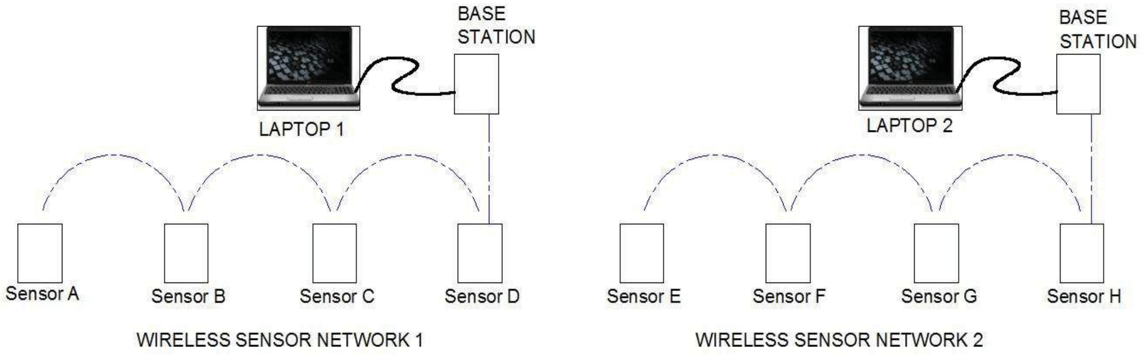

Figure 3.2: Wireless sensor network configurations.

Customized programs were written to operate the sensors for this project using a standard Java Integrated Development Environment (IDE), such as NetBeans. All the sensors and base stations were tested and calibrated before installing them in their designated critical locations on the bridge. Sensor Network 1 was deployed to collect data at a sampling rate of 1 kHz and Sensor Network 2 was set to collect data at a sampling rate of 10 Hz, and the scale for all the sensors was set to 2g. An additional extended battery pack was connected to each of the sensors via USB ports as a backup in case of primary battery failure leading to interruption in collecting data for an extended period of time. The sensors were then deployed on the bridge deck using tape. One sensor was placed at the center of the span under investigation, and others were placed on both sides of the center line at 5 ft spacing. The longitudinal distributions of sensors are shown in Fig. 3.3.

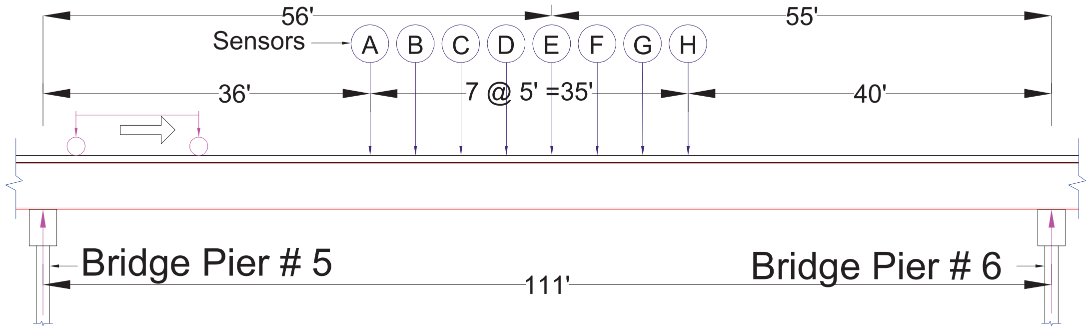

Figure 3.3: Locations of the sensors along the span.

3.3 System Configurations

The truck used in the data collection process was a dump truck, as shown in Fig. 3.4, owned by Mahoning County Engineer's Office. The truck was a standard dump truck having an axle distance of 13 ft 6 in. between rear and front axles and a track width of 6 ft, as shown in Fig. 3.5. A schematic diagram of transverse position of the truck during driving over the bridge is shown in Fig. 3.6. Prior to running the experiment, the truck was loaded to a total weight of 20,000 lb so that the front axle carries 4,000 lb and the rear axle carries 16,000 lb. The truck was driven along the rightmost northeast bound lane closer to the sidewalk, where the sensor networks were placed for data collection.

Image source: Country Fare, Inc., 2011

Figure 3.4: Standard dump truck used in this study.

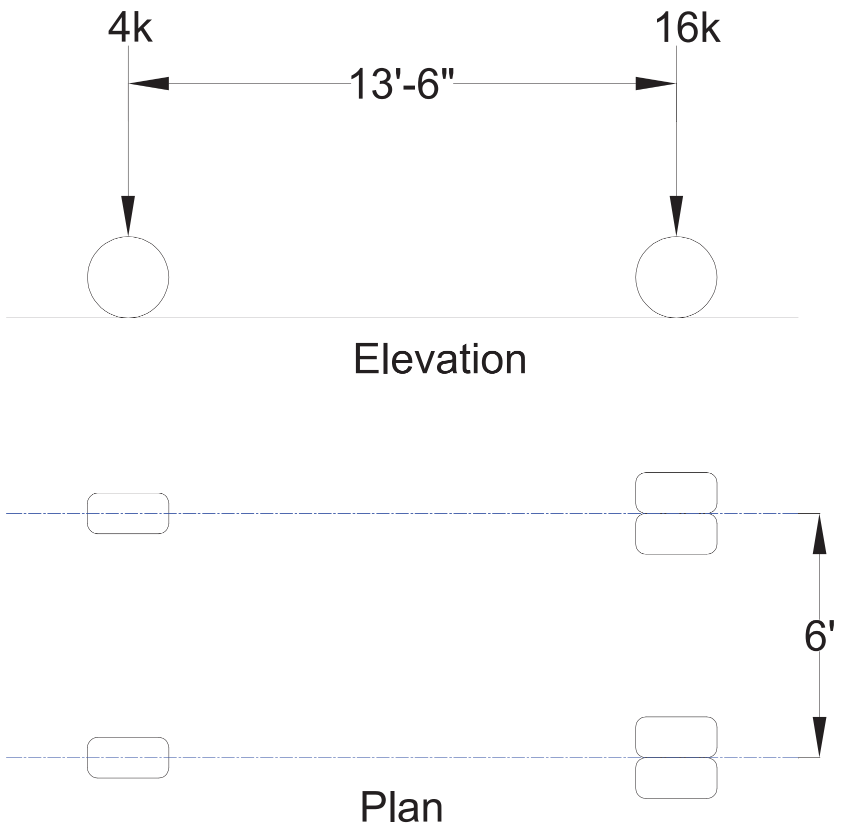

Figure 3.5: Truck axle load distribution with axle distance and track width.

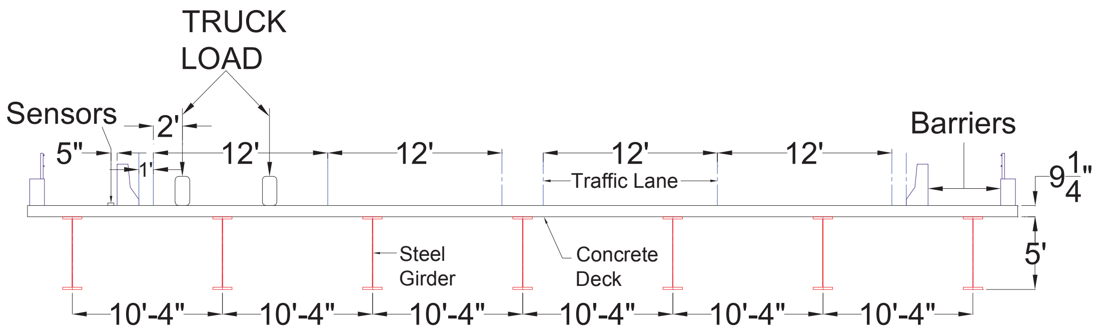

Figure 3.6: Transverse position of the truck on the traffic lane.

Since the sensors were very sensitive and the accuracy of health monitoring process is solely dependent on the quality of the bridge response data, the bridge was closed down for all traffic before running the truck so that the acceleration measured by the sensors are the response of the bridge due to the moving truck only. Thus, the accelerations recorded through the sensors are free of noise caused by vibration of other moving vehicles. The truck was run on the bridge three times at three different speeds of 15 mph, 25 mph and 35 mph. As the truck had to turn around after each pass and come back to the southwest side of the bridge for the next pass, the bridge was opened to traffic for a short period of time in between each pass to avoid long queue of vehicles and traffic jam.

The data were collected using two independent sensor networks each consisted of four sensors, one base station and one laptop used as a server, as stated earlier. Since two sets of sensor network were totally independent of each other, both sensor network and the truck timing were synchronized manually by visual observation. For manual synchronization, a point on the bridge was selected as a reference point so that when the truck was observed to pass that point, both sensor networks were activated for data collection. The criterion for choosing a reference point was to ensure visibility from both laptops locations, so that the person operating the laptop can turn on the sensors at the same time the truck hits the reference point. In this case, the Hinge Joint No. 1, as shown in Fig. 3.7, was selected as the reference point, which is located on Span No. 4 in between Piers 3 and 4. The distance of this joint from the span under investigation is approximately 200 ft, which will take four seconds at a speed of 35 mph (approximately 50 ft/sec) for the truck to reach the span after passing the reference point. In the FEM, the analysis starts when the front axle of the truck hits the span, which creates a four-second time lag between the data collected from the actual bridge and the data obtained from the FEM analysis. This time lag was incorporated in the comparative analysis of the collected data.

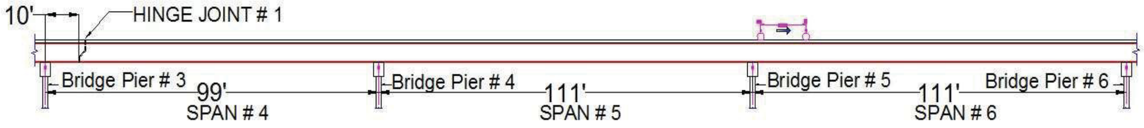

Figure 3.7: Location of Hinge Joint # 1.

3.4 Data Acquisition Process

As stated earlier, the truck was run at three constant speeds of 15mph (22ft per sec), 25mph (37 ft per sec), and 35 mph (50 ft per sec). The truck started from the southwest side of the bridge and achieved the required constant speed before reaching the reference point and continued until the end of the bridge. As soon as the front axle hit the reference point (Hinge Joint 1), an observer standing there signaled the laptop operators to start data collection. Data collected at each speed were stored using Microsoft Excel 'csv' file format. Table 3.1 shows the sample data from one of the sensors (full data set is attached in Appendix A).

Table 3.1 – Sample of data collected from Sensor C

IP Address	Time, (msec)	Sample no.	Acceleration, (g)		
			X	Y	Z
0014.4F01.0000.7B3C	0	0	0.1875	-0.03125	1.296875
0014.4F01.0000.7B3C	4	1	0.15625	-0.04688	1.3125
0014.4F01.0000.7B3C	9	2	0.15625	-0.04688	1.3125
0014.4F01.0000.7B3C	13	3	0.171875	-0.03125	1.296875
0014.4F01.0000.7B3C	18	4	0.1875	-0.03125	1.3125
0014.4F01.0000.7B3C	22	5	0.1875	-0.03125	1.3125
0014.4F01.0000.7B3C	27	6	0.171875	-0.04688	1.296875
0014.4F01.0000.7B3C	31	7	0.171875	-0.04688	1.296875
0014.4F01.0000.7B3C	36	8	0.171875	-0.03125	1.296875
0014.4F01.0000.7B3C	46	9	0.203125	-0.03125	1.3125
0014.4F01.0000.7B3C	49	10	0.203125	-0.03125	1.3125
0014.4F01.0000.7B3C	54	11	0.1875	-0.03125	1.296875
0014.4F01.0000.7B3C	58	12	0.1875	-0.01563	1.296875
0014.4F01.0000.7B3C	63	13	0.171875	-0.01563	1.296875
0014.4F01.0000.7B3C	67	14	0.1875	-0.0625	1.3125
0014.4F01.0000.7B3C	72	15	0.1875	-0.0625	1.3125
0014.4F01.0000.7B3C	77	16	0.171875	-0.01563	1.328125
0014.4F01.0000.7B3C	86	17	0.1875	-0.03125	1.296875
0014.4F01.0000.7B3C	90	18	0.1875	-0.03125	1.296875
0014.4F01.0000.7B3C	94	19	0.1875	-0.04688	1.296875
0014.4F01.0000.7B3C	99	20	0.1875	-0.04688	1.296875
0014.4F01.0000.7B3C	103	21	0.1875	-0.04688	1.296875
0014.4F01.0000.7B3C	108	22	0.1875	-0.04688	1.296875
0014.4F01.0000.7B3C	112	23	0.1875	-0.04688	1.296875
0014.4F01.0000.7B3C	117	24	0.203125	-0.04688	1.328125
0014.4F01.0000.7B3C	126	25	0.171875	-0.03125	1.3125
0014.4F01.0000.7B3C	130	26	0.171875	-0.03125	1.3125
0014.4F01.0000.7B3C	135	27	0.203125	-0.04688	1.296875
0014.4F01.0000.7B3C	139	28	0.203125	-0.04688	1.296875
0014.4F01.0000.7B3C	144	29	0.1875	-0.03125	1.3125
0014.4F01.0000.7B3C	148	30	0.171875	-0.03125	1.328125
0014.4F01.0000.7B3C	153	31	0.171875	-0.03125	1.328125
0014.4F01.0000.7B3C	164	32	0.203125	-0.03125	1.328125
..…………………….	….	…	……….	…………	……….
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Deployment and location of sensors over the bridge sidewalk are shown in Fig. 3.8. The locations were critical for the span under consideration, and were carefully chosen to produce and collect maximum possible dynamic structural response.

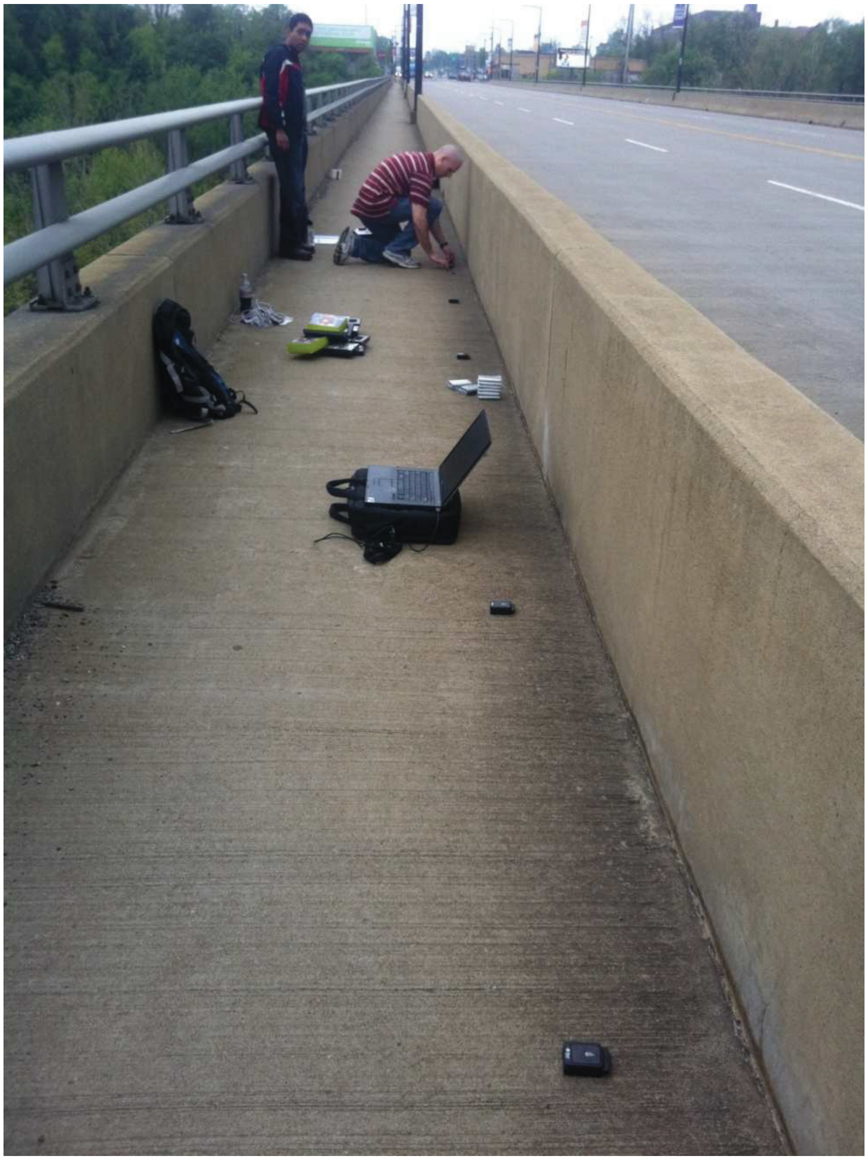


Figure 3.8: Installation of sensors on the sidewalk of Market Street Bridge.

3.5 Data Processing

Only acceleration in the vertical direction was needed for mode shape analysis. The orientation of the sensors was maintained in such a way that their z-axes coincide with the vertical axis. As the high pass filter of the sensors was turned off during the data collection process, the three dimensional accelerometers were indicating the device's orientation. As a result, the acceleration due to gravity was always present in the z-direction, which was later normalized to get the actual acceleration. This was done by taking the average of the values, and then subtracting this average value from each of the acceleration. The resulting column is the acceleration of the bridge in vertical direction in terms of g caused by the moving truck only. This was multiplied by the value of g =386.4 in./sec^2 for converting the responses into in./sec^2.

Due to some frequency interference problems, Sensor D of Network No. 1 and Sensors G and H of Network No. 2 did not transmit any of their own acceleration data. Graphical plots of the acceleration against time of the remaining sensors are shown in Figs. 3.9 to 3.13.

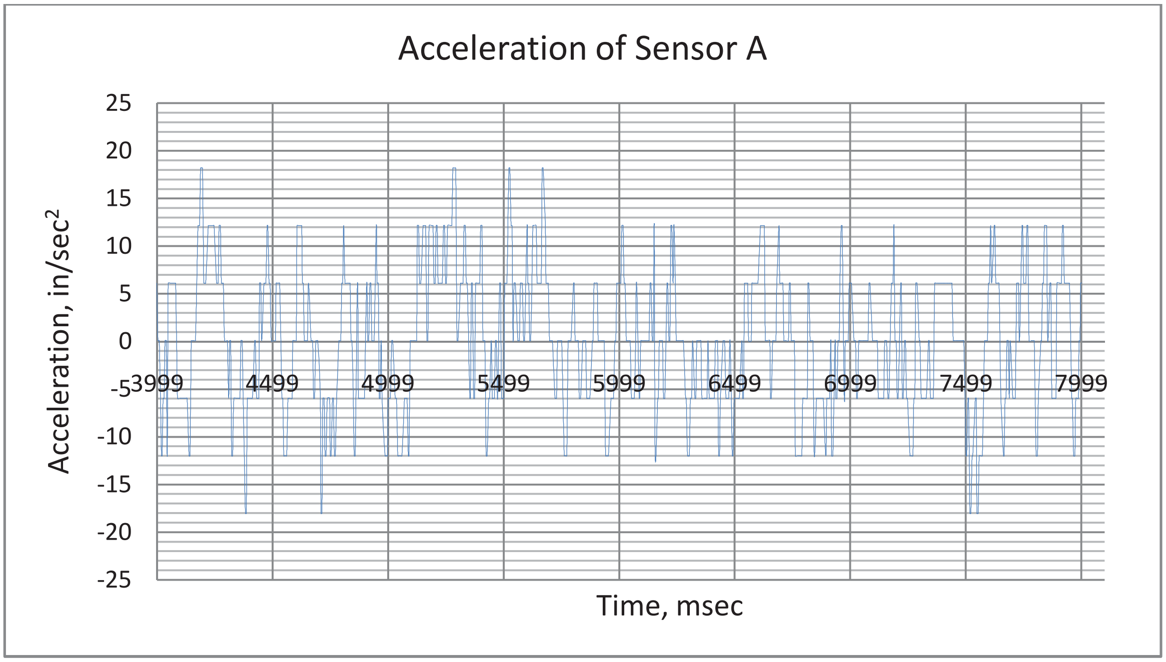


Figure 3.9: Acceleration of Sensor A.

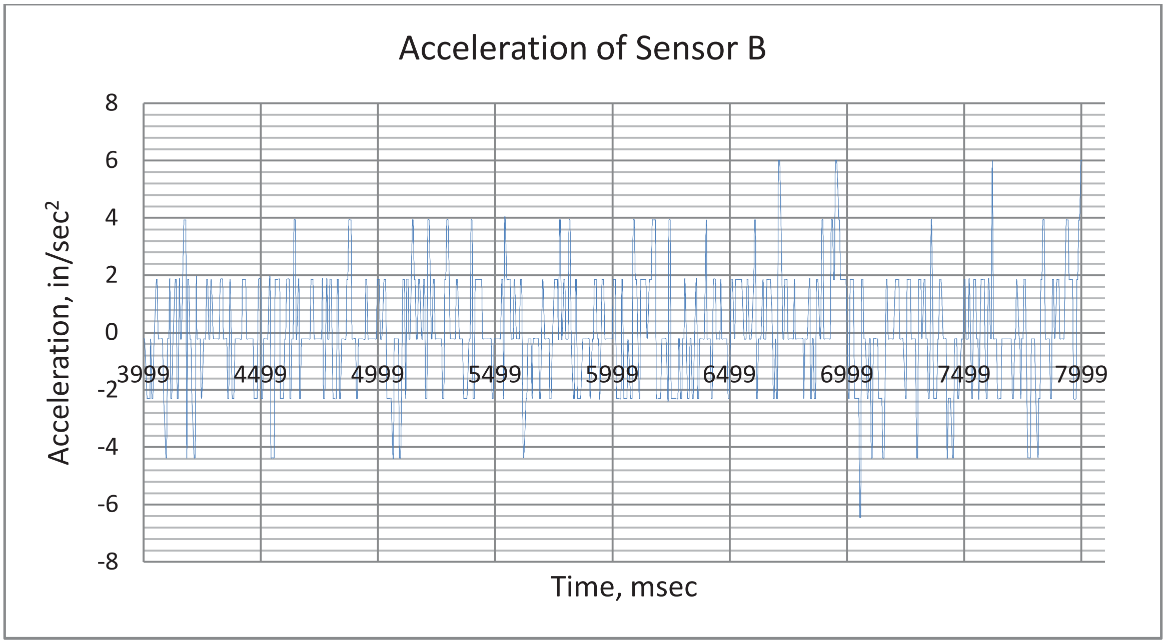


Figure 3.10: Acceleration of Sensor B.

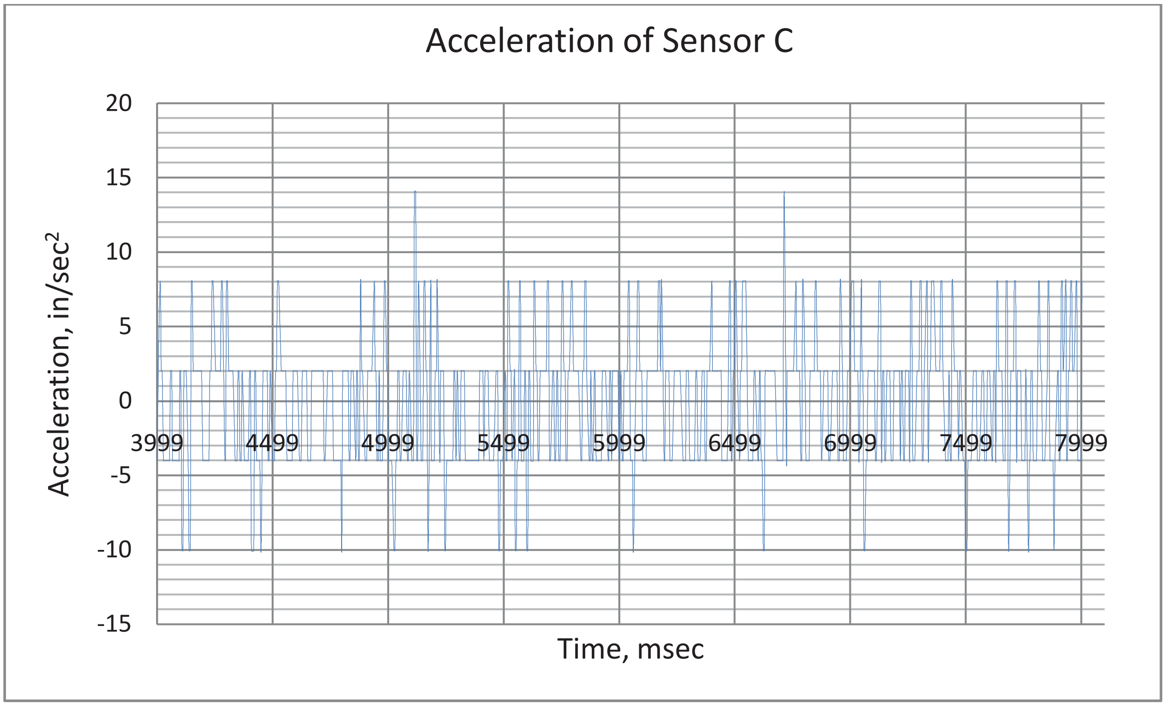


Figure 3.11: Acceleration of Sensor C.

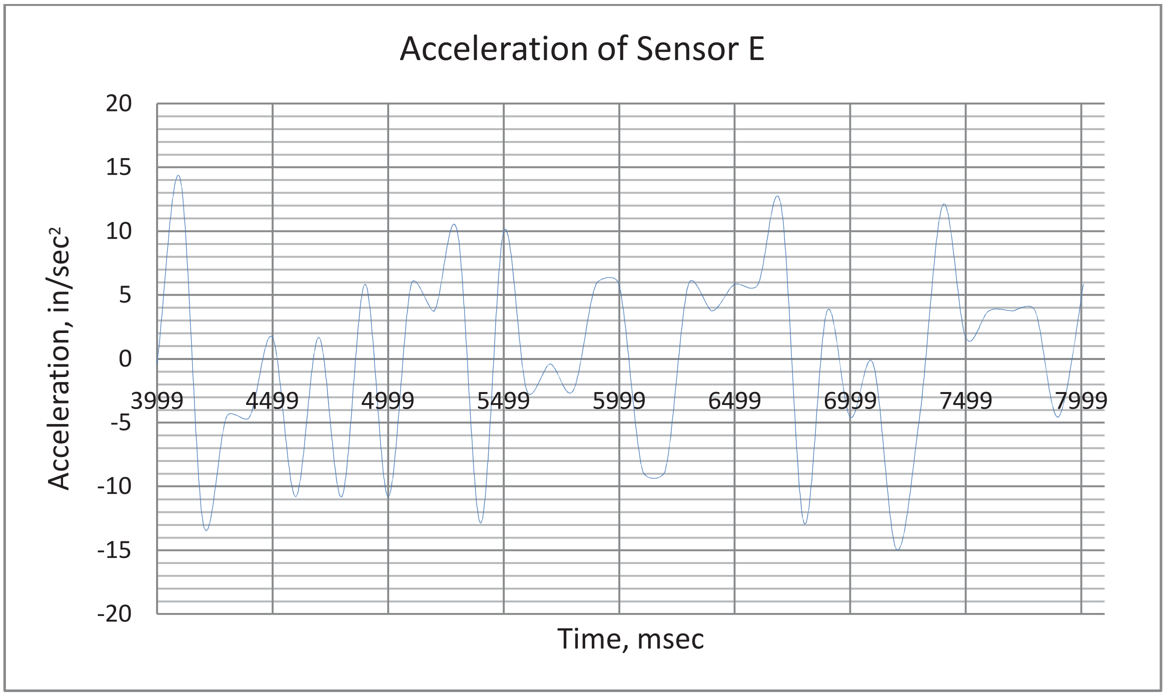


Figure 3.12: Acceleration of Sensor E.

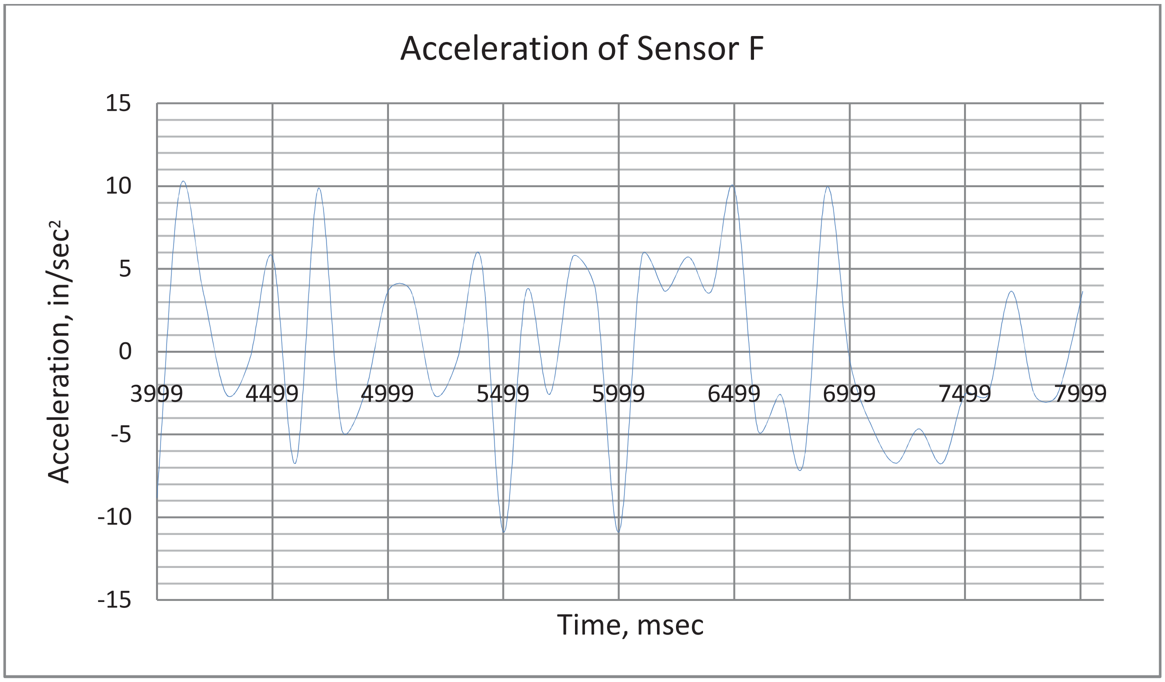


Figure 3.13: Acceleration of Sensor F.

Chapter 4

MODELING, SIMULATION AND MAC ANALYSIS

4.1 Finite Element Model Analysis

Three different types of finite element model (FEM) analyses were performed in this study. First one is a transient stress analysis (direct integration method) of the damaged bridge model, second one is a modal analysis of the damaged state of the bridge, and the third one is also a modal analysis of the undamaged state of the bridge. The software used for FEM analysis is Autodesk Simulation Multiphysics 2012 developed by Autodesk, Inc. (Autodesk, Inc., 2011), which was previously known as Algor.

4.1.1 Transient Stress Analysis by FEM

Transient stress analysis was performed in order to estimate the present equivalent stiffness of the entire cross-section of the damaged bridge by simulating the moving load in a similar manner as it was during the field data collection. This process can be divided into three phases: model development, moving load generation, and analysis and post-processing.

4.1.1.1 Model Development

Model development is the first step of any FE transient stress analysis. The success of the FE analysis is largely dependent on how the model is developed because one needs to select among the best suitable options, and make the best assumptions and simplifications depending on the nature, scope and type of analysis. Therefore, choice of best options is very critical for the accuracy and success of the FEM. For example, the finer the mesh will be, the more accurate the result will be; but on the other hand, finer mesh will complicate the model, which will require high performance computing hardware and will take more time to run. Therefore, the user has to decide the mesh size depending on the type of analysis, available resources and the level of accuracy desired.

As stated earlier, because of the practical limitations, it was not possible to perform SHM on the entire bridge, but only on a selected span. Following information were obtained from the original bridge drawings to incorporate into the FEM:

- Deck Type: Reinforced Concrete
- Deck width: 67 ft 10 in.
- Deck thickness: 9.25 in.
- Overhang: 3 ft 1 in.
- No. of girders: 7
- C/C spacing of girders: 10 ft 4 in.
- Girder type: Built-up steel plate girder
- Girder depth: 5 ft
- Flange width: 1 ft 4 in.

- Web thickness: 5/16 in.
- Flange thickness: 7/8 in. (at the mid-span of the girder), 1¾ in. (near both ends of the span)
- Steel cross frame members: $L_{5 \text{ X } 5 \text{ X } 5/16}$
- Cross frame spacing: 14 ft

Initially, the entire span along with all four barriers was modeled with brick elements, and the slab reinforcement was incorporated as embedded beam elements. Due to repeated crashing of the program while running, it became necessary to simplify the model by eliminating the barriers and by using plate elements instead of brick elements for the deck and girders. Also, deck reinforcement was replaced with equivalent thick slab under the assumption that the slab has developed cracks because of repeated traffic loads and being in service for long time. The moment of inertia of a reinforced cracked section was calculated. The equivalent slab thickness is the thickness of a pure concrete slab, which will produce the same moment of inertia as the reinforced cracked slab will. This thickness was calculated to be 5 in. (calculation is attached in Appendix B) since the slab thickness was reduced from 9.25 to 5 in., the software will only consider the mass of a 5 in. thick slab. Therefore, to account for the mass lost due to reduction in thickness, a pseudo-slab was modeled on top of this slab with a thickness of 4.25 in. having a concrete modulus of elasticity (E_c) equal to zero so that only the mass of the slab is accounted for in the analysis without increasing the stiffness of the entire deck slab.

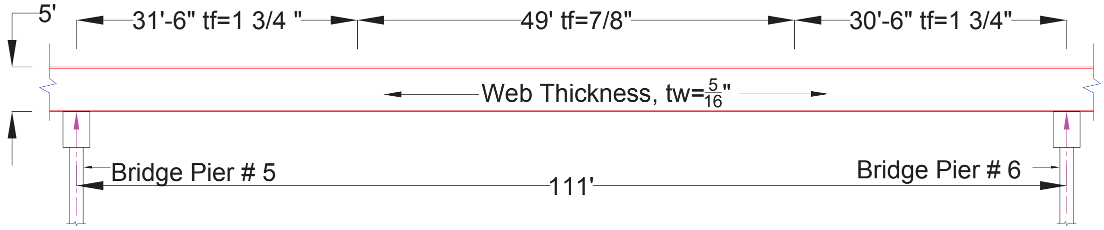


Figure 4.1: Girder web and flange thickness details.

The deck and the web of the girders, as shown in Fig. 4.1, were meshed with maximum mesh size of 1 ft X 1 ft. Because of the geometric limitation of the flange, it was not possible to keep the aspect ratio of the mesh as 1:1; therefore, it was meshed as 8 in X 1 ft. Intermediate cross frames at every 14 ft interval along the span were modeled as beam elements. Since the span was actually a continuous span, to make the FEM span behave as continuous, boundary conditions for all the end nodes of the girder and the deck were made as pin support. That way, each group of the end nodes will act as a support having stiffness in between a fixed support and a continuous span. The entire span was modeled as 6 different parts. The attributes of all the parts are summarized in Table 4.1.

Table 4.1 – Summary of element properties representing the Damaged Bridge

Part No.	Part Name	Element Type	Thickness/ Area	Material	Max Mesh Size
1	Web	Plate	0.3125 in.	Steel	1 ft X 1 ft
2	Flange 1	Plate	1.75 in.	Steel	8 in. X 1 ft
3	Deck	Plate	5 in.	Concrete	1 ft X 1 ft
4	Flange 2	Plate	.875 in.	Steel	8 in. X 1 ft
5	X Bracing	Truss	3 in.^{2}	Steel	N/A
6	Pseudo-Deck	Plate	4.25 in.	Concrete	1 ft X 1 ft

Fig. 4.2 shows the girders with cross frames and supports while Fig. 4.3 shows the entire FE model of the bridge span including girders, cross frames and the deck slab.

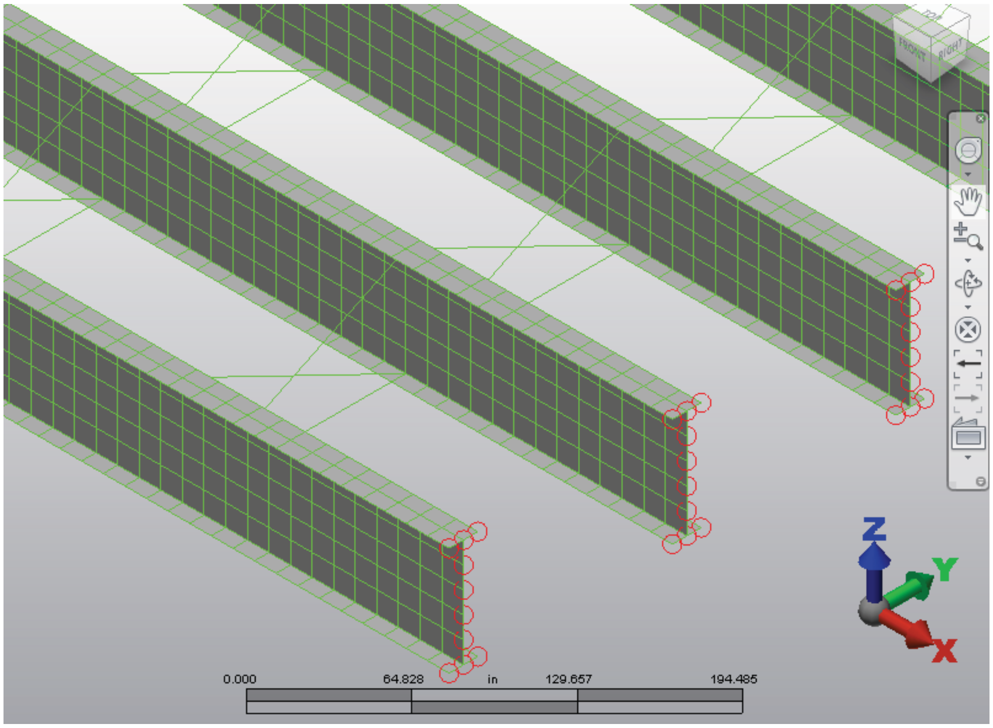


Figure 4.2: Girder and intermediate cross frames.

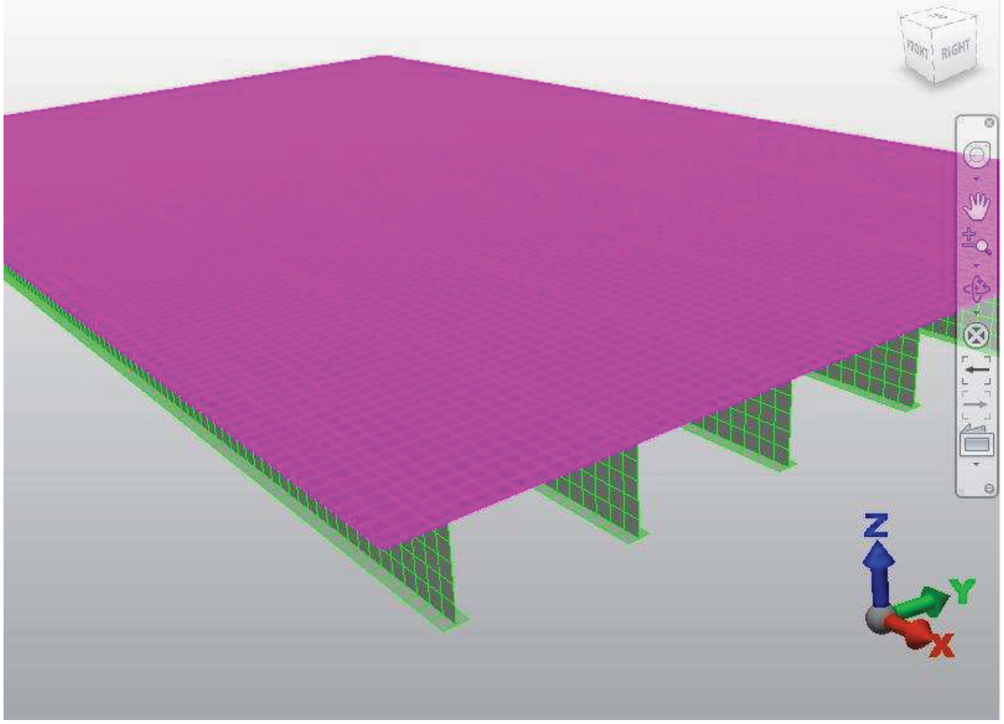


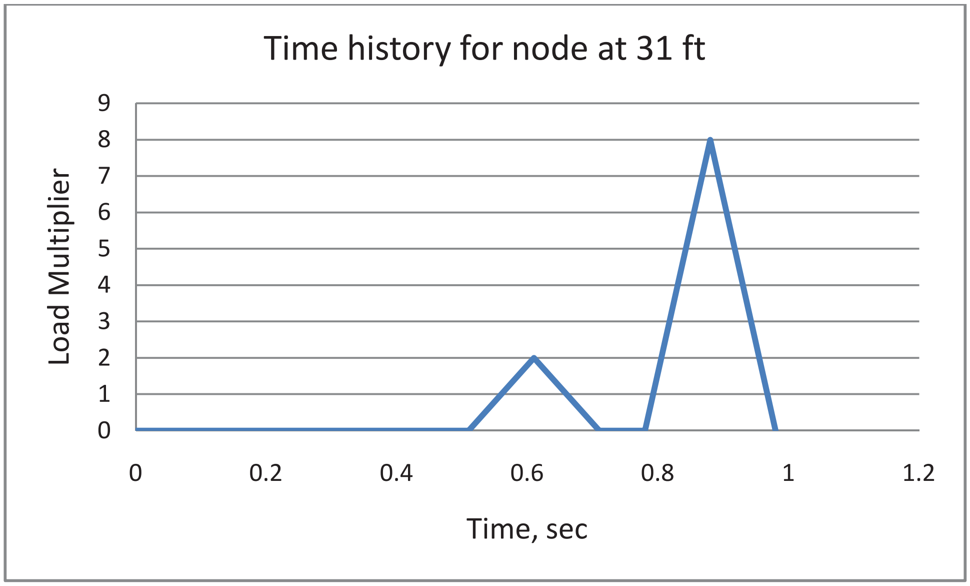
Figure 4.3: FE model showing all elements.

4.1.1.2 Moving Load Generation

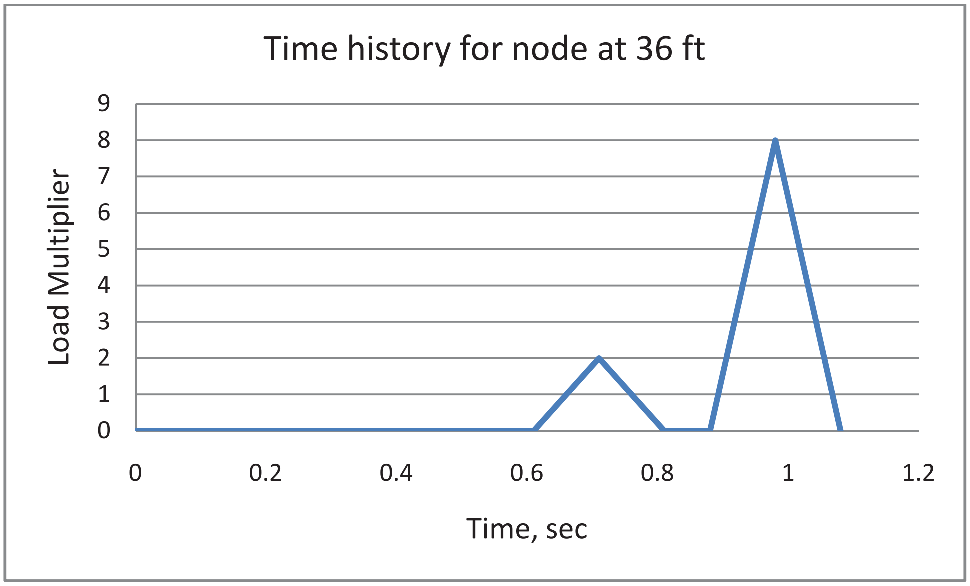
Autodesk Simulation Multiphysics does not have any built-in function for simulating moving load, therefore, the moving truck load was simulated by developing a series of time-history graphs equivalent to similar loading conditions during field data collection. The model was analyzed for the truck moving at a speed of 35 mph, which is equivalent to approximately 50 ft/sec. To make the model simple, the truck load was applied on nodes at 5 ft intervals, which will require 0.1 sec for the truck to reach the adjacent node. Therefore, a total of 22 time history graphs were developed for each 0.1 sec interval and applied to corresponding 44 nodes where the truck wheel is supposed to be at that time instance. A static 1 kip load was applied on each of these 44 nodes and this was converted into time synchronized truck wheel loads of magnitude 2 kip and 8 kip by multiplying the nodal loads with load multipliers, which are the y-axis values of the time history graphs developed. Table 4.2 shows samples of load multiplier (all 22 time history data is attached in Appendix C) for nodes at a distance of 31 ft and 36 ft. Each time history graph was developed by calculating the time required for the front and rear wheel to reach the corresponding node from the starting end of the span and then assigning the corresponding load multiplier values, as 2 for front wheel and 8 for rear wheel. Figs. 4.4 (a) and (b) show the time history graphs for these nodes.

Table 4.2 – Load multipliers for the node at 31 ft and 36 ft

Node @ 31 ft		Node @ 36 ft	
Time, (sec)	Load Multiplier	Time, (sec)	Load Multiplier
0	0	0	0
0.51	0	0.61	0
0.61	2	0.71	2
0.71	0	0.81	0
0.78	0	0.88	0
0.88	8	0.98	8
0.98	0	1.08	0



(a)



(b)

Figure 4.4: Sample time history graphs at (a) 31 ft and (b) 36 ft.

4.1.1.3 Analysis and Post-Processing

Linear transient stress analysis by direct integration method was performed on the developed model of the damaged bridge. Damping coefficient alpha (α) and beta (β) were assumed to be zero for this analysis. Other analysis parameters are listed below:

Number of time steps: 400

Time step size: 0.01 sec

Output interval: 1

Objective of this analysis was to find the stiffness of the damaged bridge by parametric iterations, which will produce the same acceleration as it was on the actual bridge. The parametric iterations were done by comparing the field accelerations obtained from sensors (Figs. 3.9 to 3.13) with the FE model accelerations (Figs 4.8 to 4.12) of the respective node. Fig. 4.5 shows a comparative graph of acceleration at node E obtained from sensor and FEM. The model acceleration of a particular node in the FEM was changed to match the field acceleration of the same node by gradually reducing the moduli of elasticity of the girder steel (E_s) and deck concrete (E_c) starting from their original values of 29,000 ksi and 3,000 ksi respectively. After several trial runs, it was determined that by setting E_s= 14,500 ksi and E_c= 1,400 ksi, both the field sensor and the FEM give the same maximum acceleration at a specific time. The reduced moduli of elasticity determined here from FEM simulation represent the equivalent stiffness of the bridge at current damaged condition. Table 4.3 shows the changes in modulus of elasticity for steel and concrete from undamaged to damaged condition as simulated in

FE model. Figs. 4.6 and 4.7 show the deflected shapes of the bridge while the truck is on the span and after the truck passes the span, respectively.

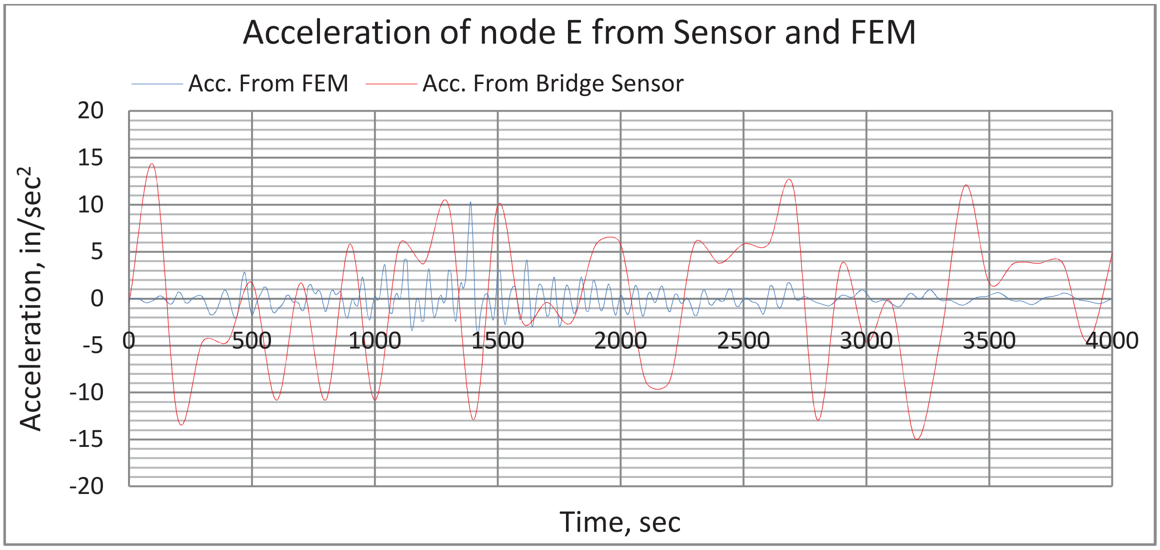


Figure 4.5: Acceleration of node E from Sensor and FEM.

Table 4.3 – Change in modulus of elasticity of undamaged and damaged bridge

Modulus of Elasticity	Undamaged Bridge (Standard value) (ksi)	Damaged Bridge (FEM simulation) (ksi)	Percent Reduction (%)
Steel Girder (E_s)	29,000	14,500 ksi	50.00
Concrete Deck (E_c)	3,000	1,400 ksi	53.33

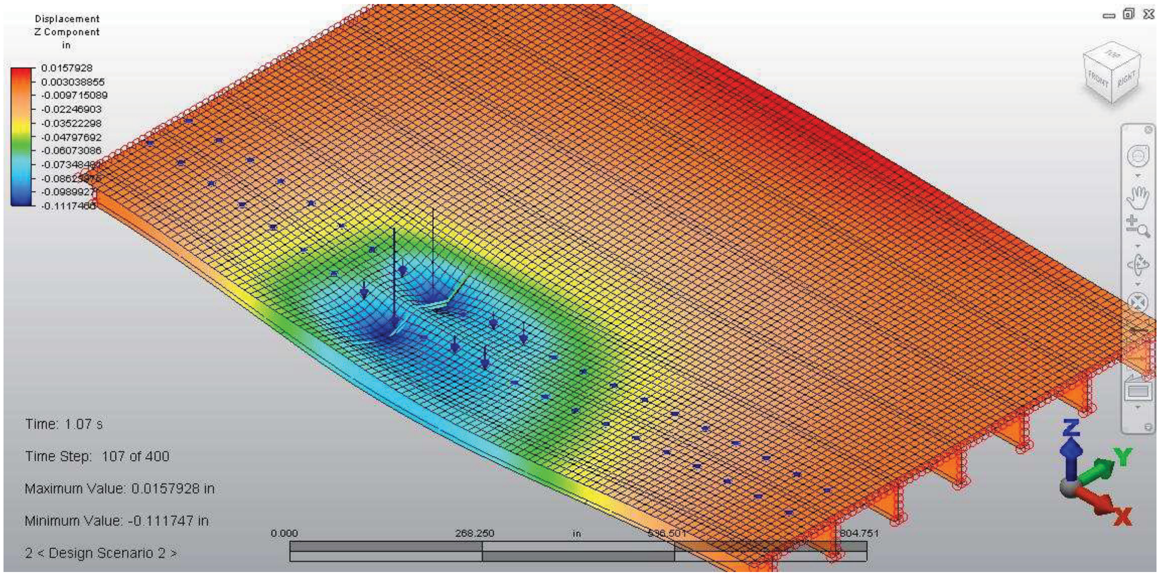


Figure 4.6: Vibration of the bridge while the truck is on the span.

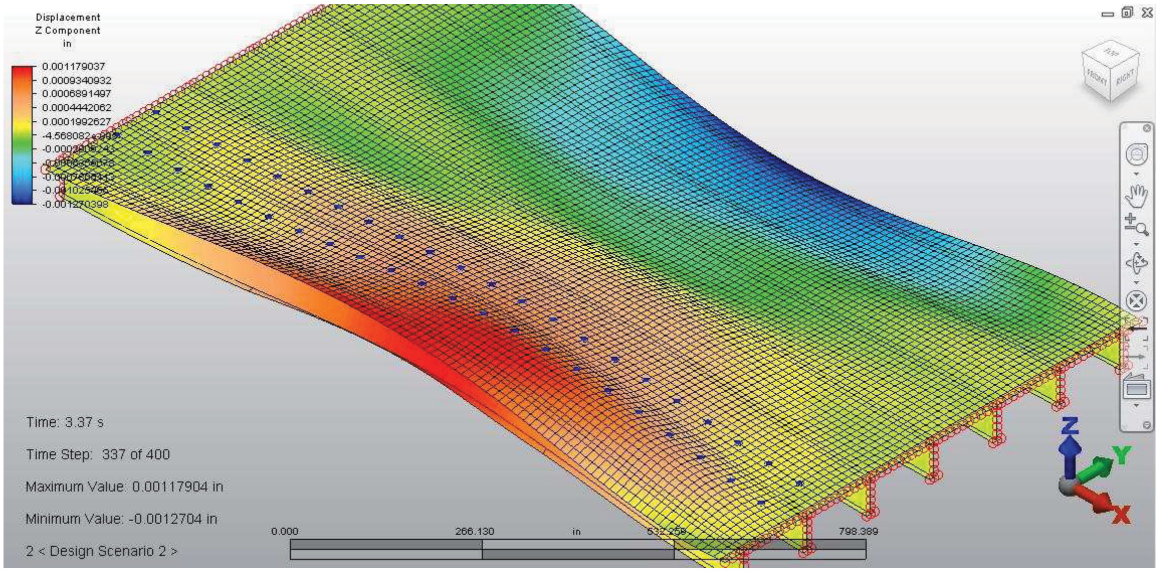


Figure 4.7: Vibration of the bridge after the truck passed the span.

Acceleration data were collected from this analysis at the points where the sensors were located on the field. Since the analysis was performed for a total time period of 4 sec (first 2.38 sec when both or either of the truck axles was on the bridge), all the results were generated only for 4 sec time period. Following graphs in Figs. 4.8 to 4.12 show the acceleration responses from the FEM at all sensor points under consideration.

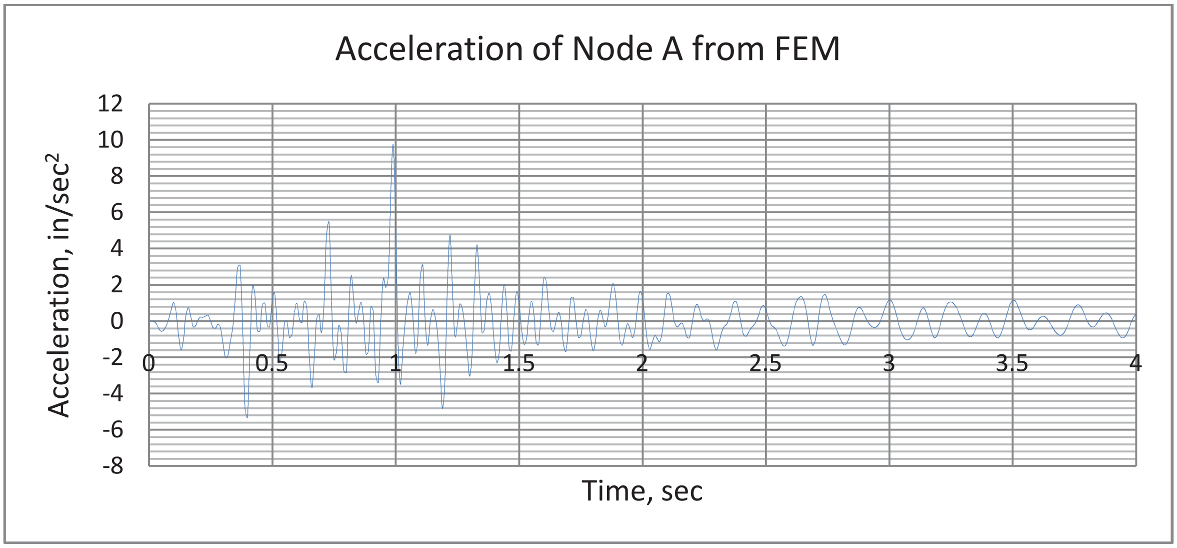


Figure 4.8: Acceleration of Node A.

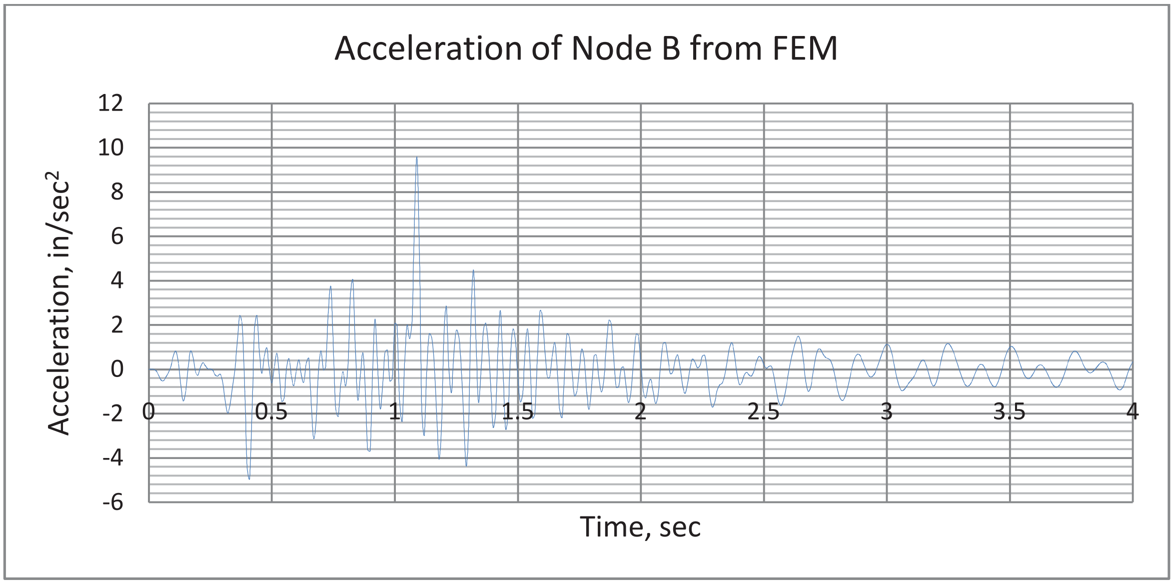


Figure 4.9: Acceleration of Node B.

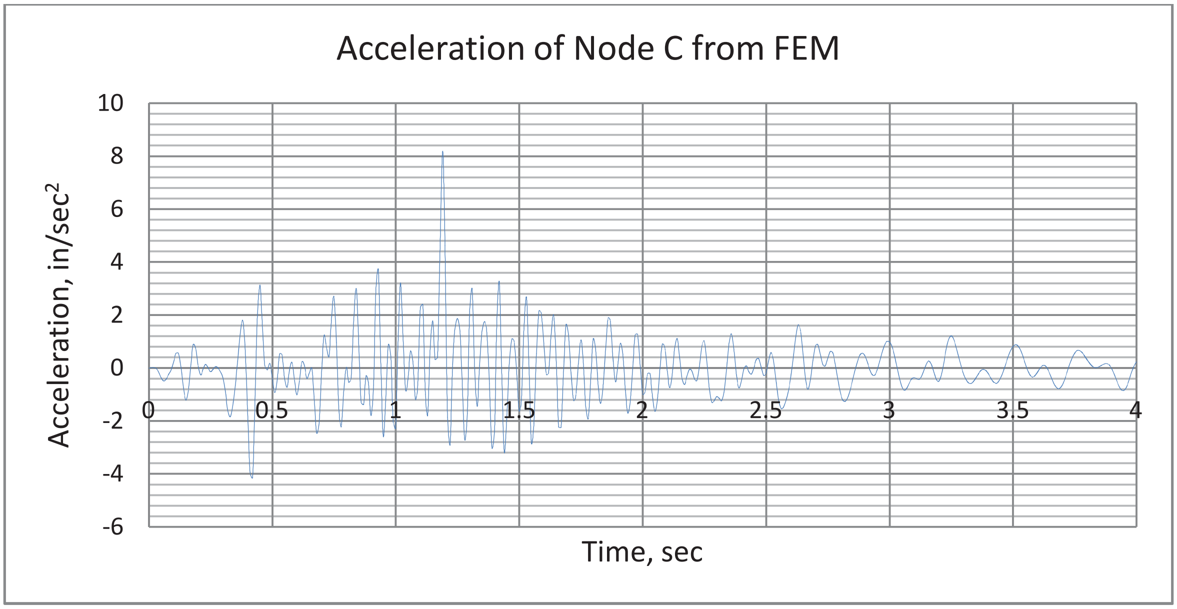


Figure 4.10: Acceleration of Node C.

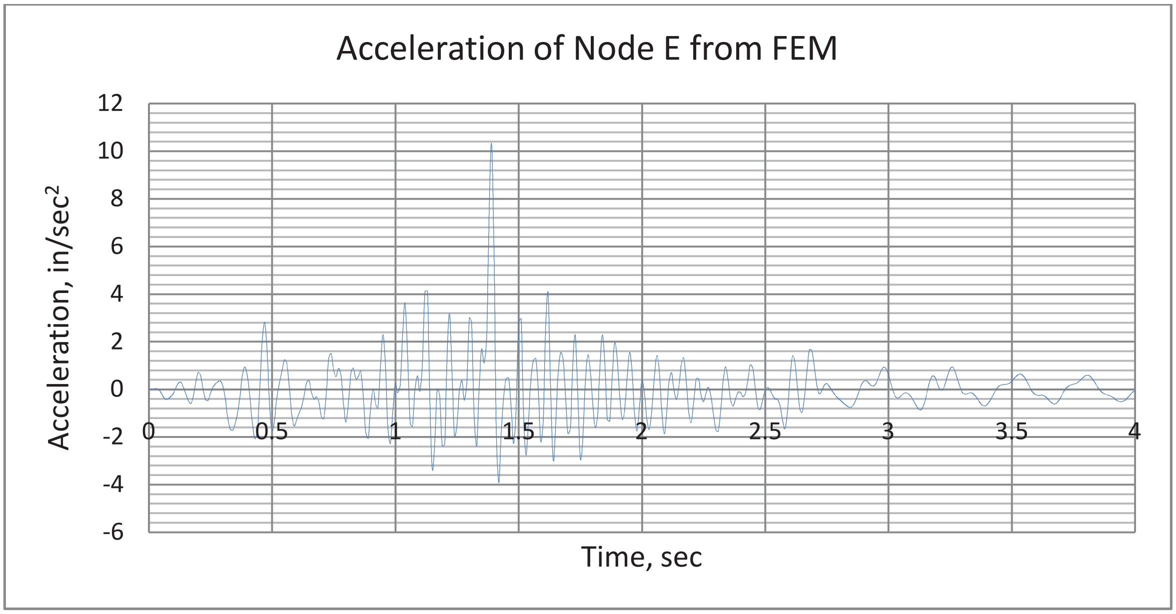


Figure 4.11: Acceleration of Node E.

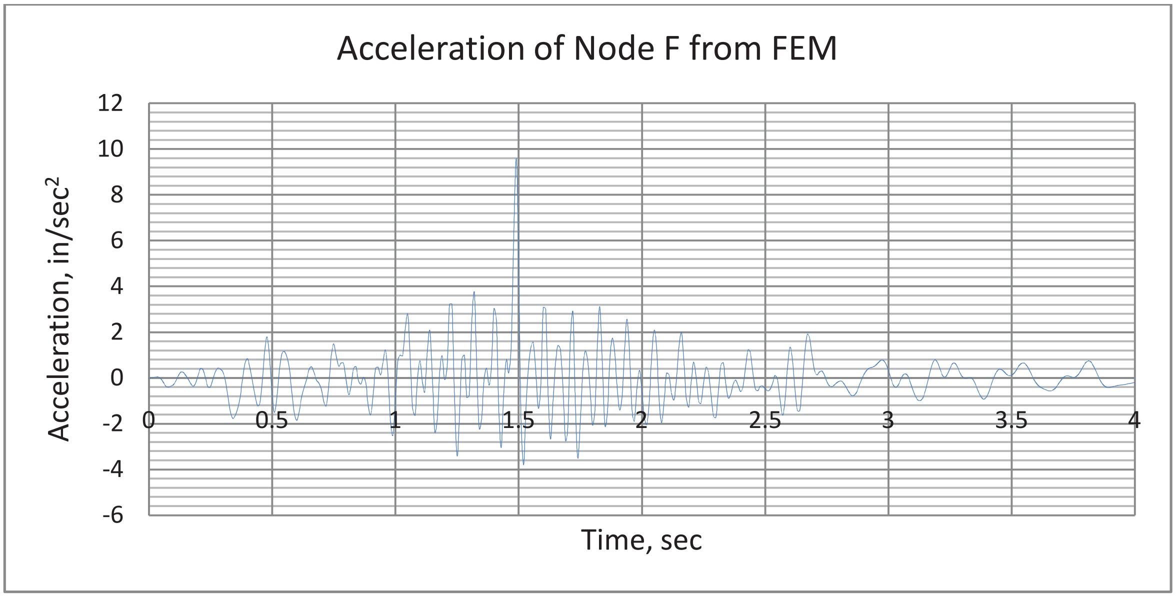


Figure 4.12: Acceleration of Node F.

4.1.2 Modal Analysis of Damaged Bridge

Modal analysis was done on the same FEM with the reduced stiffness determined in previous analysis. Modal frequencies and mode shapes obtained from this FEM represented the current damaged mode shape of the bridge. Mode shape of a vibrating body is the pattern of its deflected shape after subjected to excitation, in which all parts of the system is in phase and vibrates at same frequency. The frequencies of the natural mode shapes are called natural frequencies. Since the pattern of the displaced shape is the main feature of mode shape, the magnitude or sign of displacement is not significant; rather the relative displacements of the nodes are of more importance. In this study, only vertical mode shape was considered for analysis and it was represented mathematically as the vertical displacements of the nodes.

4.1.2.1 Model development

Development of the FEM is the same as the previous one. All geometric properties remained the same except the material properties were changed. Modulus of elasticity of the girder steel was set to E_s= 14,500 ksi, and that for the deck concrete was set to E_c= 1,400 ksi.

4.1.2.2 Analysis and Post-Processing

Analysis parameters for modal analysis:

Number of frequencies/ modes to calculate: 5

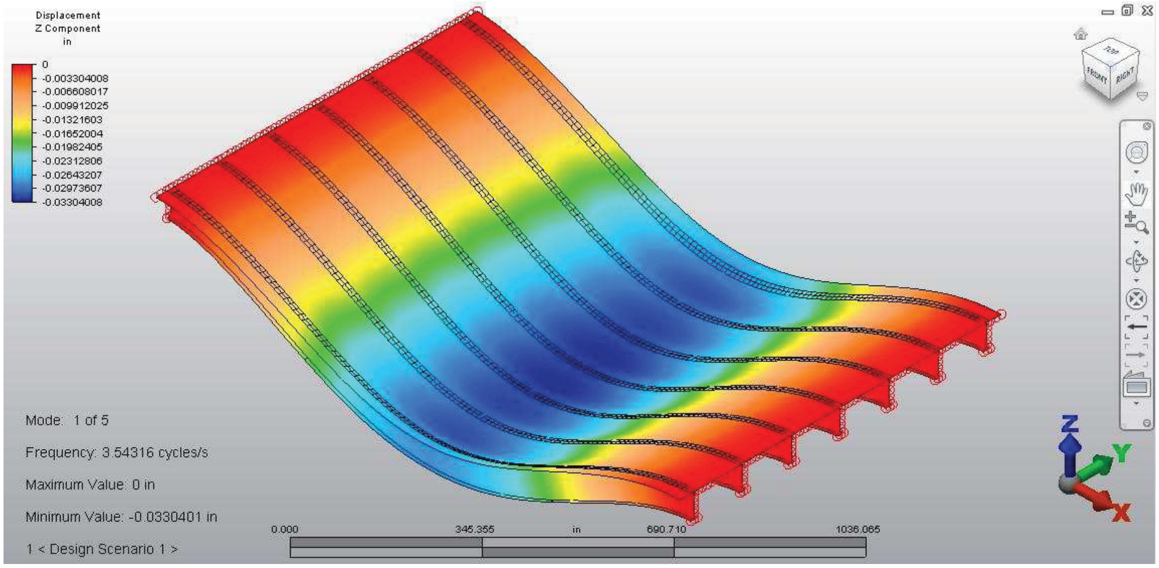
Lower cut-off frequencies: 0 cycle/sec.

Upper cut-off frequencies: 0 cycle/sec.

This FE model was analyzed for only first five natural mode shapes and their respective frequencies. Table 4.4 below shows the fundamental modal frequencies and Figs 4.13 to 4.17 show the mode shapes of the damaged bridge obtained from modal analysis,

Table 4.4 – Fundamental modal Frequencies of the Damaged Bridge

Mode Shape	Frequency, (cycle/sec)
1	3.54316
2	3.65891
3	5.96377
4	8.28727
5	8.3565



Mode: 1 of 5

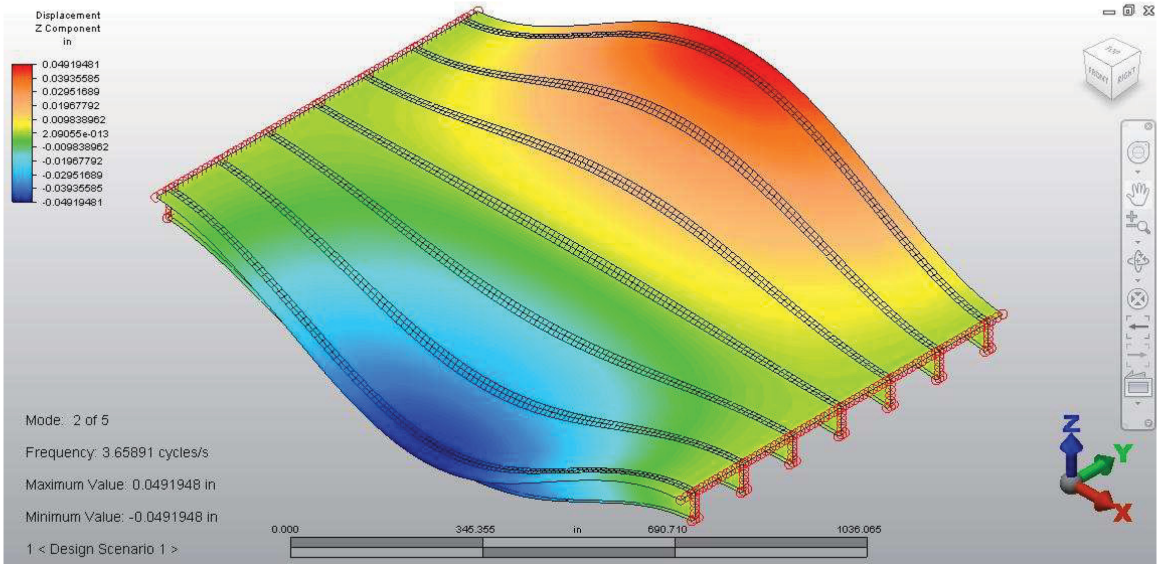
Frequency: 3.54316 cycles/s

Maximum Value: 0 in

Minimum Value: -0.0330401 in

1 < Design Scenario 1 >

Figure 4.13: First mode shape of the damaged bridge.



Mode: 2 of 5

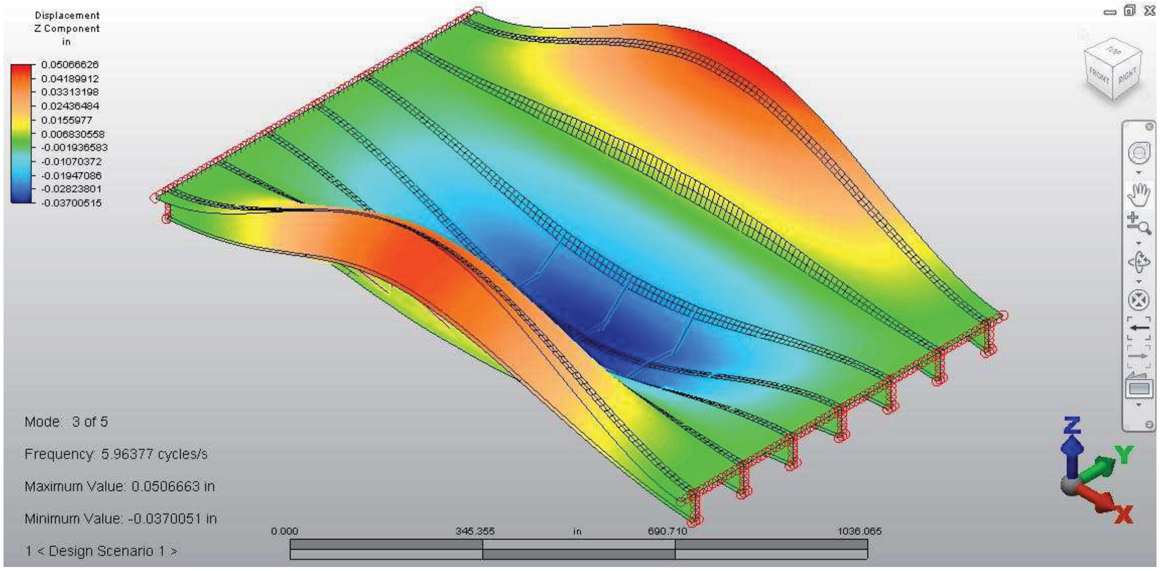
Frequency: 3.65891 cycles/s

Maximum Value: 0.0491948 in

Minimum Value: -0.0491948 in

1 < Design Scenario 1 >

Figure 4.14: Second mode shape of the damaged bridge.



Mode: 3 of 5

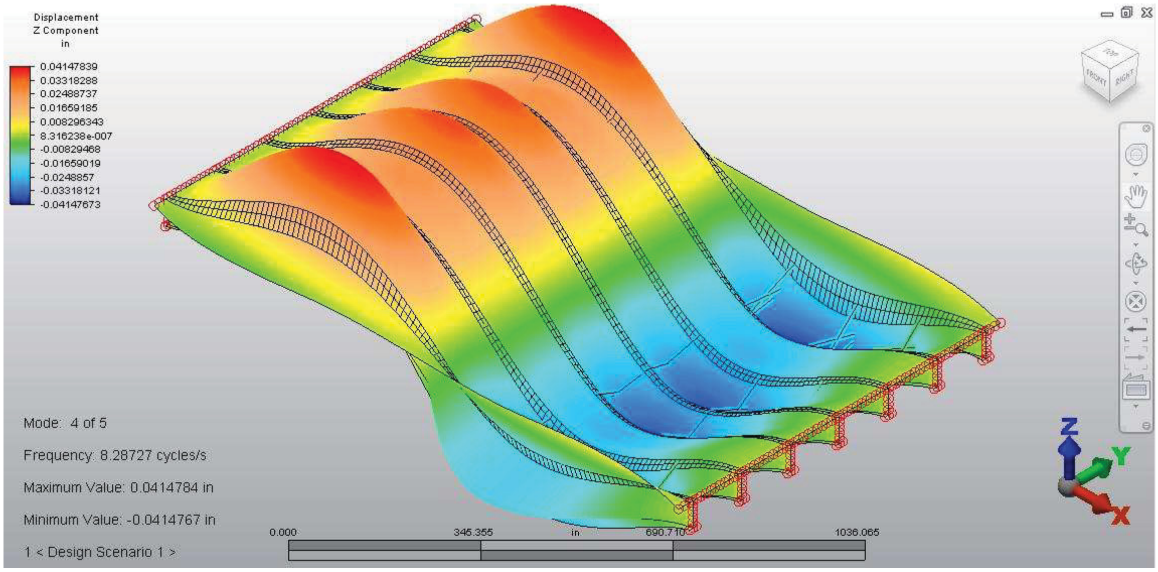
Frequency: 5.96377 cycles/s

Maximum Value: 0.0506663 in

Minimum Value: -0.0370051 in

1 < Design Scenario 1 >

Figure 4.15: Third mode shape of the damaged bridge.



Mode: 4 of 5

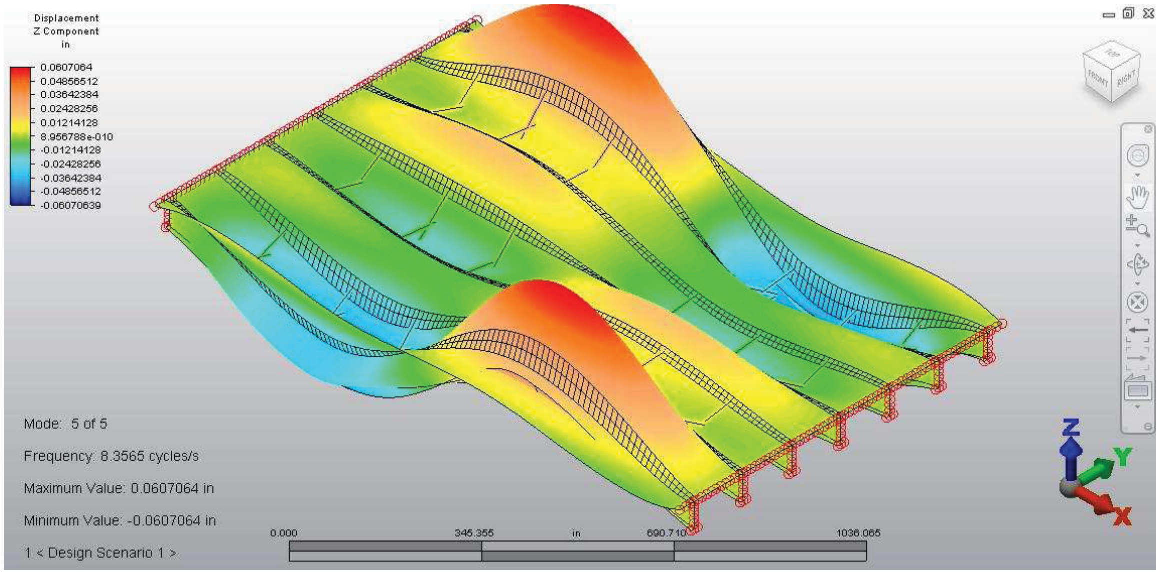
Frequency: 8.28727 cycles/s

Maximum Value: 0.0414784 in

Minimum Value: -0.0414767 in

1 < Design Scenario 1 >

Figure 4.16: Fourth mode shape of the damaged bridge.



Mode: 5 of 5

Frequency: 8.3565 cycles/s

Maximum Value: 0.0607064 in

Minimum Value: -0.0607064 in

1 < Design Scenario 1 >

Figure 4.17: Fifth mode shape of the damaged bridge.

4.1.3 Modal Analysis of Undamaged Bridge

Modal analysis of the undamaged bridge was done in order to determine the mode shape of the bridge when there was no damage present. As there were no data collected after the construction of the bridge, assumption was made that the bridge had the full stiffness according to its design from the archived bridge plans.

4.1.3.1 Model Development

Finite element model was developed in the same procedure as the previous one, except certain changes that were made in the deck elements and material properties. From the calculations according to the American Association of State Highway and Transportation

Officials (AASHTO) Bridge Design Specifications, 4th ed. [A4.6.2], it was determined that for the worst case scenario, the cracking moment of a slab strip is less than the actual moment for a HS-20 truck load, for which the bridge was designed in 1979 (calculation is attached in Appendix D). This indicates the slab did not crack initially under the design truck load. Therefore, the deck thickness was taken as 9.25 in. and there was no need for modeling a pseudo-deck, as no correction for mass was needed. Since this model represents undamaged state of the bridge, modulus of elasticity for steel was taken as E_s= 29,000 ksi and that for concrete was taken as E_c= 3,000 ksi, with compared to the damaged bridge where these were reduced to 14,500 ksi and 1,400 ksi respectively. Table 4.5 shows the summary of the FE model properties representing the Undamaged Bridge and their comparison with the Damaged Bridge.

Table 4.5 – Summary of the elements representing the Undamaged Bridge

Part No.	Part Name	Element Type	Thickness/ Area		Material	Max Mesh Size
			Undamaged Bridge	Damaged Bridge		
1	Web	Plate	0.3125 in.	0.3125 in.	Steel	1 ft x 1 ft
2	Flange 1	Plate	1.75 in.	1.75 in.	Steel	8 in. x 1 ft
3	Deck	Plate	9.25 in.	5 in.	Concrete	1 ft x 1 ft
4	Flange 2	Plate	.875 in.	.875 in.	Steel	8 in. x 1 ft
5	X Bracing	Truss	3 in.^{2}	3 in.^{2}	Steel	N/A
6	Pseudo-Deck	Plate	none	4.25 in.	Steel	1 ft x 1 ft

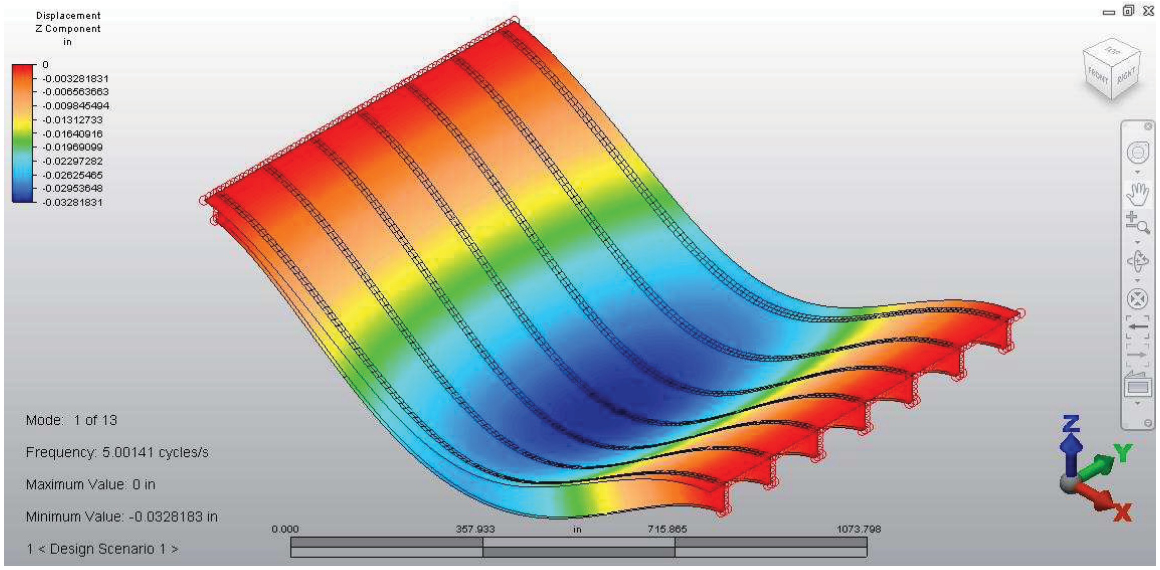
4.1.3.2 Analysis and Post-Processing

Analysis parameters in this case were same as they were for the damaged bridge except, this time it was analyzed for up to 13th mode shape to find the mode shapes similar to the damaged mode shape. Table 4.6 below shows the natural modal frequencies of undamaged bridge obtained from modal analysis of the FE model.

Table 4.6 – Fundamental modal frequencies of the undamaged bridge

Mode Shape	Frequency, (cycle/sec)
1	5.00141
2	5.21542
3	7.41937
4	11.5915
5	11.7539
6	11.9157
7	11.9299
8	11.9388
9	11.941
10	11.942
11	11.9492
12	12.0445
13	12.3868

It was observed that there were some unwanted mode shapes occurred due to the local buckling of the girder webs and flanges. Only mode shapes exhibiting vertical deflections and similar to the mode shapes found in the damaged bridge were considered for health monitoring purposes. These mode shapes are shown in Figs. 4.18 to 4.22.



Mode: 1 of 13

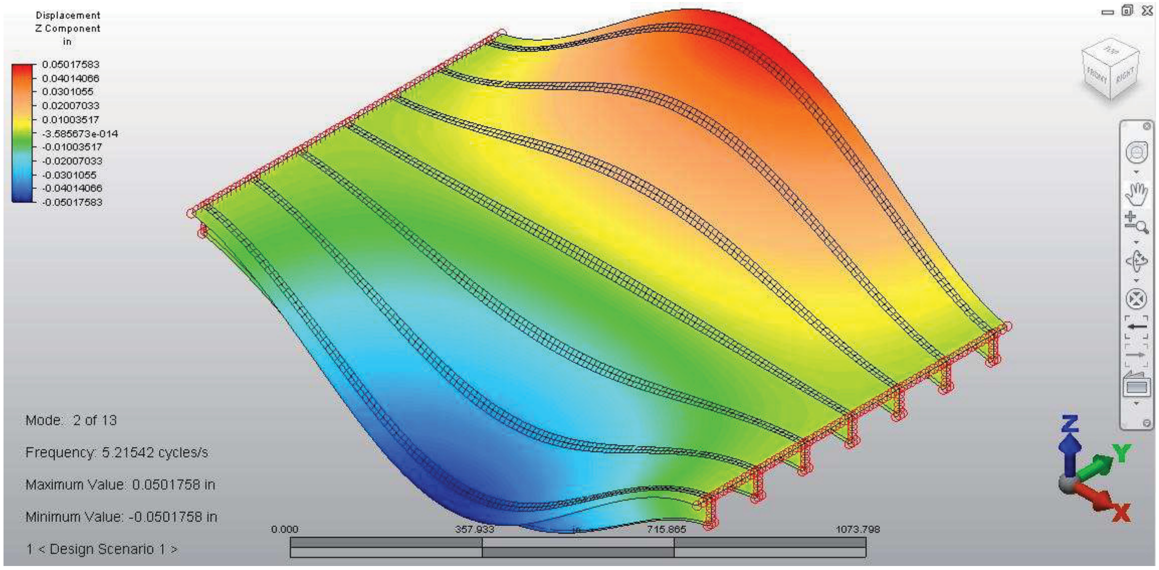
Frequency: 5.00141 cycles/s

Maximum Value: 0 in

Minimum Value: -0.0328183 in

1 < Design Scenario 1 >

Figure 4.18: First mode shape of the undamaged bridge.



Mode: 2 of 13

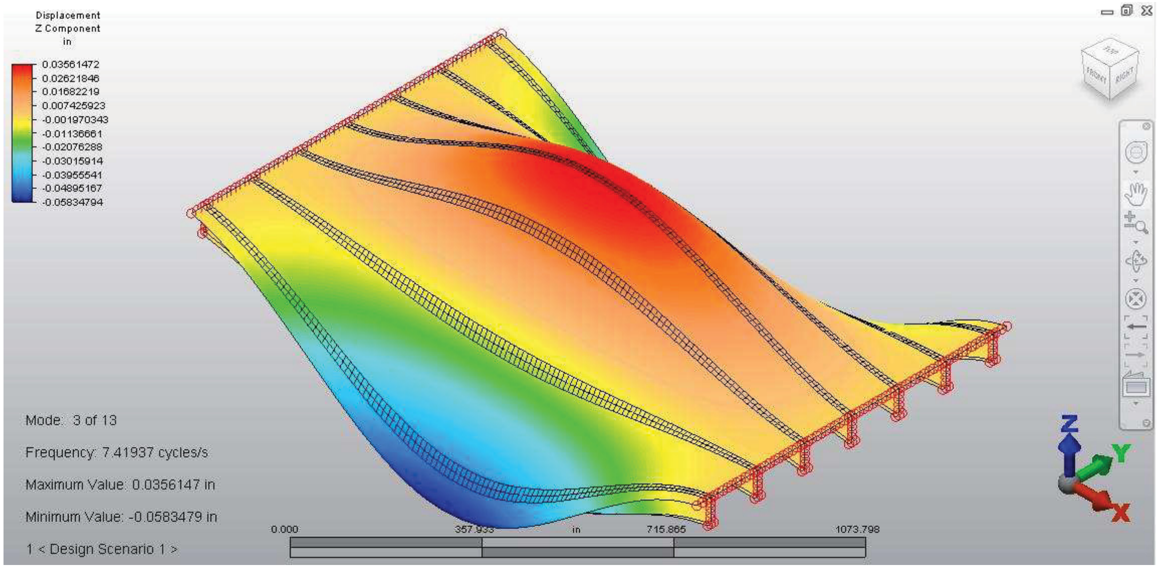
Frequency: 5.21542 cycles/s

Maximum Value: 0.0501758 in

Minimum Value: -0.0501758 in

1 < Design Scenario 1 >

Figure 4.19: Second mode shape of the undamaged bridge.



Mode: 3 of 13

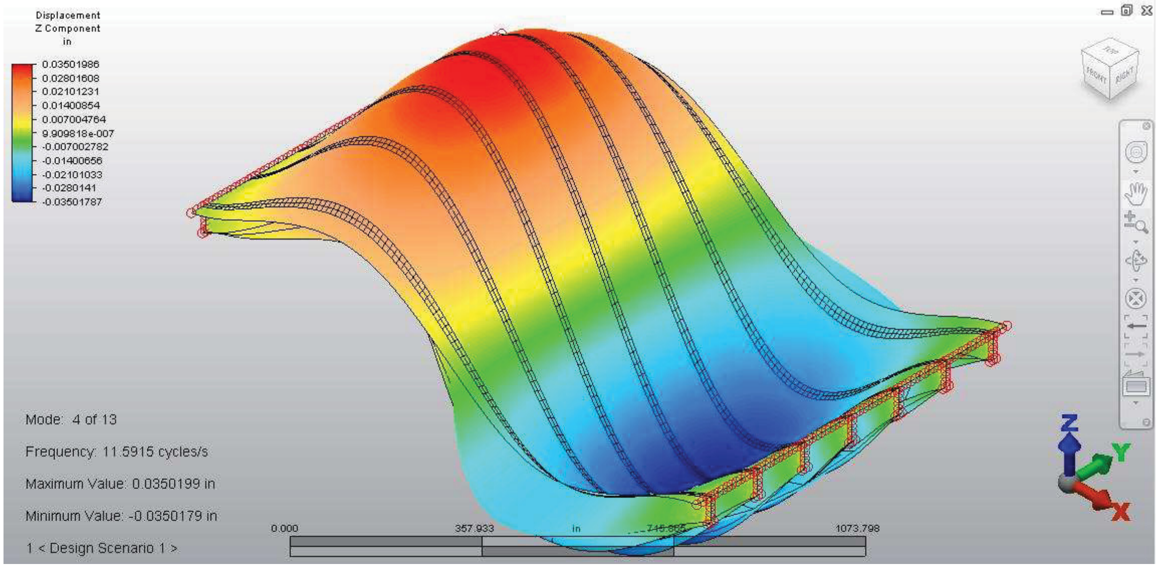
Frequency: 7.41937 cycles/s

Maximum Value: 0.0356147 in

Minimum Value: -0.0583479 in

1 < Design Scenario 1 >

Figure 4.20: Third mode shape of the undamaged bridge.



Mode: 4 of 13

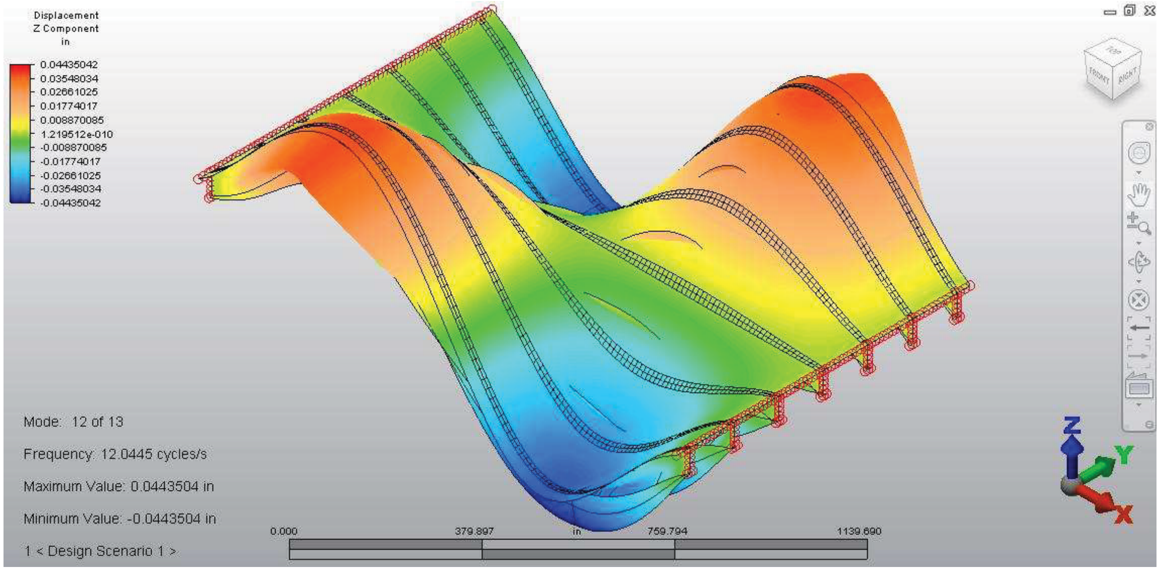
Frequency: 11.5915 cycles/s

Maximum Value: 0.0350199 in

Minimum Value: -0.0350179 in

1 < Design Scenario 1 >

Figure 4.21: Fourth mode shape of the undamaged bridge.



Mode: 12 of 13

Frequency: 12.0445 cycles/s

Maximum Value: 0.0443504 in

Minimum Value: -0.0443504 in

1 < Design Scenario 1 >

Figure 4.22: Twelfth mode shape of the undamaged bridge.

4.2 MAC Analysis

Correlation analyses of the similar mode shapes between undamaged and damaged bridge were carried out to determine the current structural condition of the bridge. Theory of MAC was applied in this process. MAC requires mode shape data from two similar modes of the structure under consideration. From the modal analysis of both structures, it was observed that similar mode shapes do not occur in the same order in the undamaged structure as in the damaged structure. In this case, the first four mode shapes of damaged bridge is similar to the first four mode shapes of undamaged bridge but the fifth mode of damaged bridge is similar to the twelfth mode of undamaged bridge. Modes fifth to eleventh of the undamaged bridge occurred due to local buckling and lateral displacement, which are excluded from this study since it is beyond the scope of this research. Similarity between mode shapes is shown in Table 4.7.

Table 4.7 – Similarity between mode shapes

Undamaged Bridge	Damaged Bridge
Mode # 1	Mode # 1
Mode # 2	Mode # 2
Mode # 3	Mode # 3
Mode # 4	Mode # 4
Mode # 12	Mode # 5

Also, because of the large size of the finite element models in terms of their number of nodes, it was not practically possible to include mode shapes of all the nodes into the analysis. Therefore, 22 nodes along the top flange of the center girder at an interval of 5 ft were chosen as the representative mode shapes. The mode shape values (vertical displacements) of these nodes are shown in Tables 4.8 and 4.9.

Table 4.8 – Mode shape values of the undamaged bridge along center girder

Nodal distance along x axis, (in.)	Mode Shape of Undamaged Bridge				
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 12
12	-0.00025	-6.3E-16	0.00029	0.00091	2.46E-12
72	-0.00207	-5.4E-15	0.002396	0.006543	1.19E-11
132	-0.0049	-1.3E-14	0.00557	0.013606	1.34E-11
192	-0.00847	-2.3E-14	0.009521	0.020898	8.7E-12
252	-0.0125	-3.4E-14	0.013935	0.027318	5.96E-14
312	-0.01674	-4.6E-14	0.018516	0.032004	-1.1E-11
372	-0.02096	-5.8E-14	0.023065	0.034264	-2.4E-11
432	-0.02489	-7E-14	0.027276	0.033276	-3.6E-11
492	-0.02824	-8E-14	0.030817	0.028594	-4.6E-11
552	-0.03076	-8.9E-14	0.033493	0.020634	-5.6E-11
612	-0.03229	-9.4E-14	0.035126	0.010327	-5.6E-11
672	-0.03275	-9.6E-14	0.035615	-0.00117	-4.5E-11
732	-0.03207	-9.5E-14	0.03489	-0.01252	-3.1E-11
792	-0.03033	-9.1E-14	0.033038	-0.02245	-2.2E-11
852	-0.02763	-8.3E-14	0.030169	-0.02982	-2.1E-11
912	-0.02415	-7.3E-14	0.026476	-0.03377	-2.5E-11
972	-0.02013	-6.1E-14	0.022173	-0.03404	-2.4E-11
1032	-0.01589	-4.8E-14	0.017592	-0.03124	-2.1E-11
1092	-0.01167	-3.6E-14	0.013028	-0.02615	-1.8E-11
1152	-0.00771	-2.4E-14	0.008686	-0.01948	-1.2E-11
1212	-0.00427	-1.3E-14	0.004862	-0.01214	-5.5E-12
1272	-0.00162	-5E-15	0.001876	-0.00526	-4.8E-13

Table 4.9 – Mode shape values of the damaged bridge along center girder

Nodal distance along x axis, (in.)	Mode Shape of Damaged Bridge				
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
12	-0.00013	1.27E-15	0.000155	0.000433	2.48E-12
72	-0.00152	1.46E-14	0.001788	0.003937	2.02E-11
132	-0.00405	3.88E-14	0.004664	0.00917	2.01E-11
192	-0.00741	7.09E-14	0.008432	0.015015	3.01E-11
252	-0.01133	1.08E-13	0.012746	0.020478	3.42E-11
312	-0.01553	1.48E-13	0.017329	0.02472	-3.9E-11
372	-0.01976	1.88E-13	0.021926	0.027153	-1.7E-10
432	-0.02374	2.26E-13	0.026224	0.026897	-3.2E-10
492	-0.02715	2.58E-13	0.029924	0.023386	-4.2E-10
552	-0.02973	2.83E-13	0.032638	0.017018	-4.3E-10
612	-0.0313	2.97E-13	0.034326	0.00856	-3.3E-10
672	-0.03178	3.01E-13	0.034979	-0.00097	-1.5E-10
732	-0.03108	2.94E-13	0.034081	-0.01038	3.27E-11
792	-0.02929	2.77E-13	0.032167	-0.01849	2.07E-10
852	-0.02653	2.51E-13	0.029254	-0.02434	3.54E-10
912	-0.02298	2.17E-13	0.025404	-0.02721	4.37E-10
972	-0.01893	1.79E-13	0.021021	-0.02685	4.22E-10
1032	-0.01468	1.39E-13	0.016403	-0.024	3.66E-10
1092	-0.01051	9.93E-14	0.011853	-0.01946	2.92E-10
1152	-0.00669	6.31E-14	0.007627	-0.01385	1.86E-10
1212	-0.00347	3.27E-14	0.004009	-0.00804	8.35E-11
1272	-0.00114	1.08E-14	0.001347	-0.00306	2.75E-11

Pairs of similar mode shapes of the center girder at both undamaged and damaged conditions are presented in Figs. 4.23 to 4.27. These graphs were developed by plotting the vertical mode shape displacements of each node along the top of the center girder against their respective x-coordinate values. It was observed that each of the first four pairs of mode shapes is almost identical in shape (as shown in Figs. 4.23 to 4.26), which also reflected in their MAC values. Significant deviations have been observed between the mode shapes of the last pair (Fig. 4.27), therefore, the MAC value of the corresponding pair also deviates significantly from unity.

For the matrix operations of the mode shape matrices and MAC value calculations, MathCAD 14.0 (Parametric Technology Corporation, 2007) has been used.

Following notations have been used in the MAC analysis:

Un = Undamaged mode shape matrix of the nth similar mode

Dn = Damaged mode shape matrix of the nth similar mode

Un^{T} = Transpose of the mode shape matrix Un

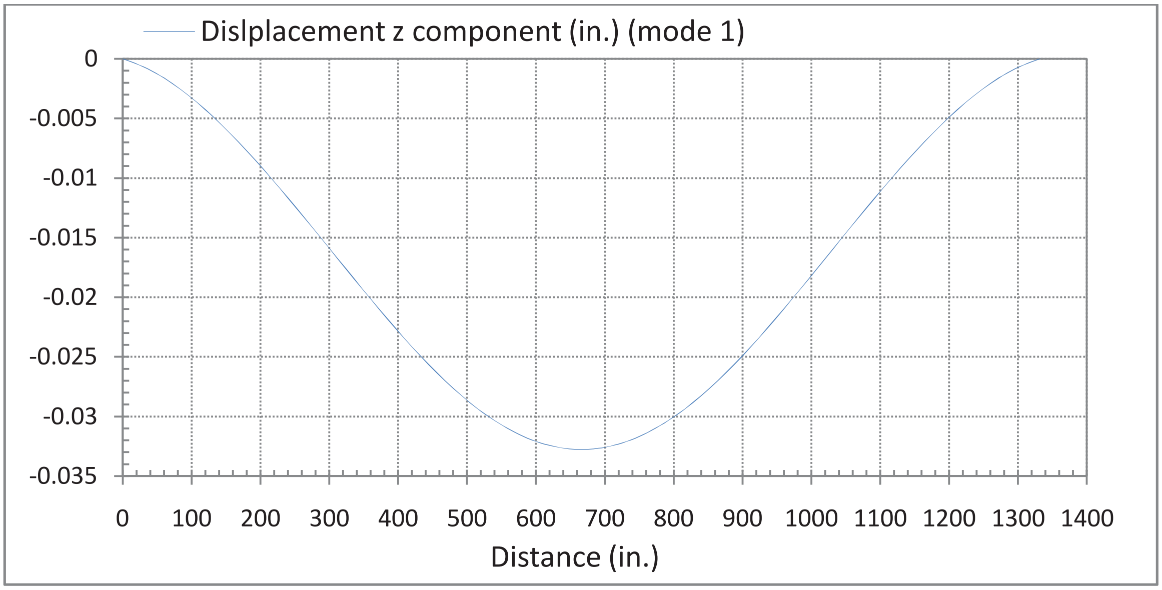
MACn = MAC value for the nth similar mode shapes

For example, first mode shape matrix of the undamaged condition is denoted as U1 in MathCAD and formed as a column matrix using the values of first column of Table 4.8, similarly, same matrix of damaged condition is denoted as D1 and formed using the values from first column of Table 4.9. Transpose of these two matrices is denoted as U1^{T} and D1^{T} and transpose operation is performed using MathCAD built-in transpose command. MAC value for each set is calculated in MathCAD using Eq. 4.1.

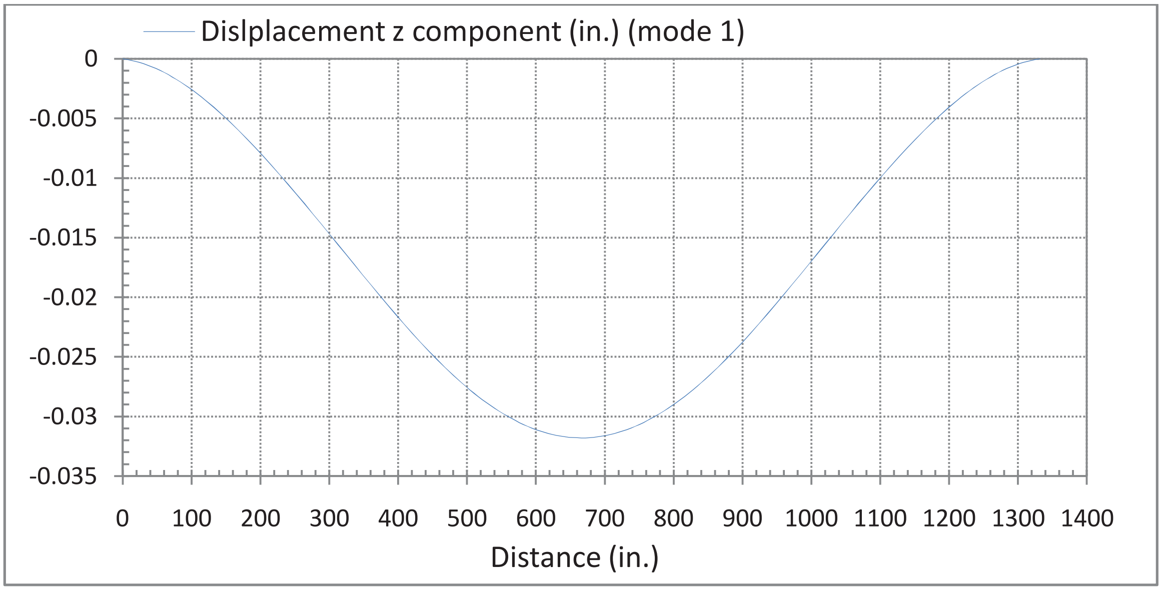
$$MACn = \frac{(Un^T . Dn^T)^2}{(Un^T . Un) * (Dn^T . Dn)} \tag{4.1}$$

Formulation of the mode shape matrices, their transpose matrices and MAC calculation using Eq. 4.1 for all five cases are shown in MathCAD format in subsequent sections following the mode shape graphs of each case.

4.2.1 MAC Value of First Similar Mode Shapes



(a) At undamaged condition



(b) At damaged condition

Figure 4.23: First similar mode shapes of center girder.

MAC value calculation using MathCAD for first similar mode shapes:

$$U1 := \begin{pmatrix} -0.000246393 \\ -0.00206899 \\ -0.00490081 \\ -0.00846656 \\ -0.012498 \\ -0.0167446 \\ -0.0209645 \\ -0.0248928 \\ -0.0282385 \\ -0.0307563 \\ -0.0322907 \\ -0.0327451 \\ -0.0320685 \\ -0.0303264 \\ -0.0276291 \\ -0.0241452 \\ -0.0201338 \\ -0.0158899 \\ -0.0116665 \\ -0.00770766 \\ -0.00426696 \\ -0.00161522 \end{pmatrix} \qquad D1 := \begin{pmatrix} -0.000131662 \\ -0.00151984 \\ -0.00405037 \\ -0.00741336 \\ -0.0113283 \\ -0.0155291 \\ -0.0197623 \\ -0.0237431 \\ -0.0271543 \\ -0.0297305 \\ -0.0313049 \\ -0.0317766 \\ -0.0310768 \\ -0.02929 \\ -0.0265319 \\ -0.0229833 \\ -0.0189253 \\ -0.0146785 \\ -0.010514 \\ -0.00668768 \\ -0.00346855 \\ -0.00113933 \end{pmatrix}$$

$U1^T =$

	0	1	2	3	4
0	$-2.464\cdot10^{-4}$	$-2.069\cdot10^{-3}$	$-4.901\cdot10^{-3}$	$-8.467\cdot10^{-3}$	...

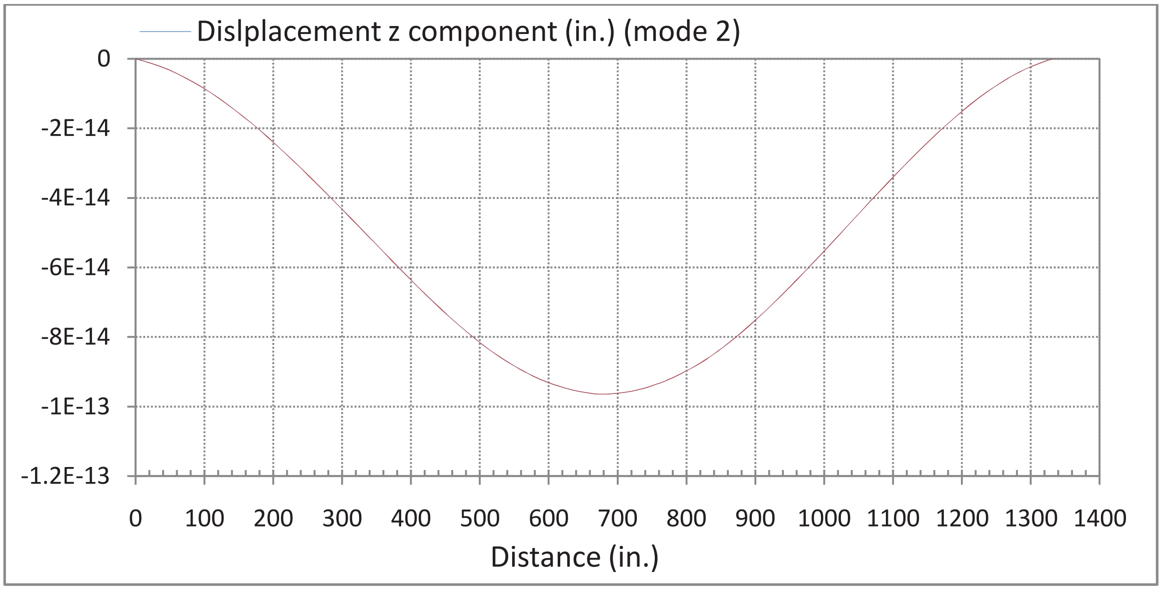
$D1^T =$

	0	1	2	3	4
0	$-1.317\cdot10^{-4}$	$-1.52\cdot10^{-3}$	$-4.05\cdot10^{-3}$	$-7.413\cdot10^{-3}$	...

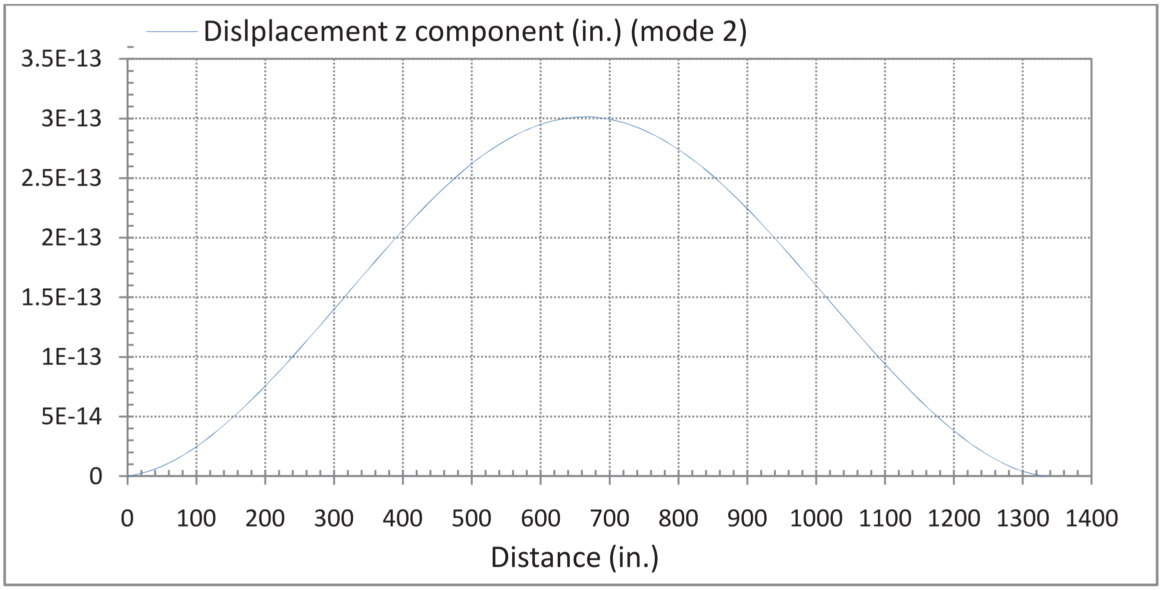
$$MAC1 := \frac{\left(U1^T\cdot D1\right)^2}{\left(U1^T\cdot U1\right)\cdot\left(D1^T\cdot D1\right)}$$

$MAC1 = 1$

4.2.2 MAC Value of Second Similar Mode Shapes



(a) At undamaged condition



(b) At damaged condition

Figure 4.24: Second similar mode shapes of center girder.

MAC value calculation using MathCAD for second similar mode shapes:

$$U2 := \begin{pmatrix} -6.3253E\text{-}16 \\ -5.39737E\text{-}15 \\ -1.29126E\text{-}14 \\ -2.25515E\text{-}14 \\ -3.37527E\text{-}14 \\ -4.57159E\text{-}14 \\ -5.79431E\text{-}14 \\ -6.97901E\text{-}14 \\ -8.032E\text{-}14 \\ -8.85444E\text{-}14 \\ -9.39624E\text{-}14 \\ -9.63693E\text{-}14 \\ -9.50163E\text{-}14 \\ -9.05378E\text{-}14 \\ -8.31055E\text{-}14 \\ -7.29662E\text{-}14 \\ -6.111E\text{-}14 \\ -4.84277E\text{-}14 \\ -3.56972E\text{-}14 \\ -2.36821E\text{-}14 \\ -1.31776E\text{-}14 \\ -5.02025E\text{-}15 \end{pmatrix} \qquad D2 := \begin{pmatrix} 1.26989E\text{-}15 \\ 1.45978E\text{-}14 \\ 3.88069E\text{-}14 \\ 7.0912E\text{-}14 \\ 1.08204E\text{-}13 \\ 1.48167E\text{-}13 \\ 1.88376E\text{-}13 \\ 2.26121E\text{-}13 \\ 2.58389E\text{-}13 \\ 2.82556E\text{-}13 \\ 2.97167E\text{-}13 \\ 3.01441E\text{-}13 \\ 2.94401E\text{-}13 \\ 2.77242E\text{-}13 \\ 2.50999E\text{-}13 \\ 2.17279E\text{-}13 \\ 1.7885E\text{-}13 \\ 1.38661E\text{-}13 \\ 9.93001E\text{-}14 \\ 6.31465E\text{-}14 \\ 3.27453E\text{-}14 \\ 1.07532E\text{-}14 \end{pmatrix}$$

$U2^T =$

	0	1	2	3	4
0	0	$-5.397 \cdot 10^{-15}$	$-1.291 \cdot 10^{-14}$	$-2.255 \cdot 10^{-14}$	...

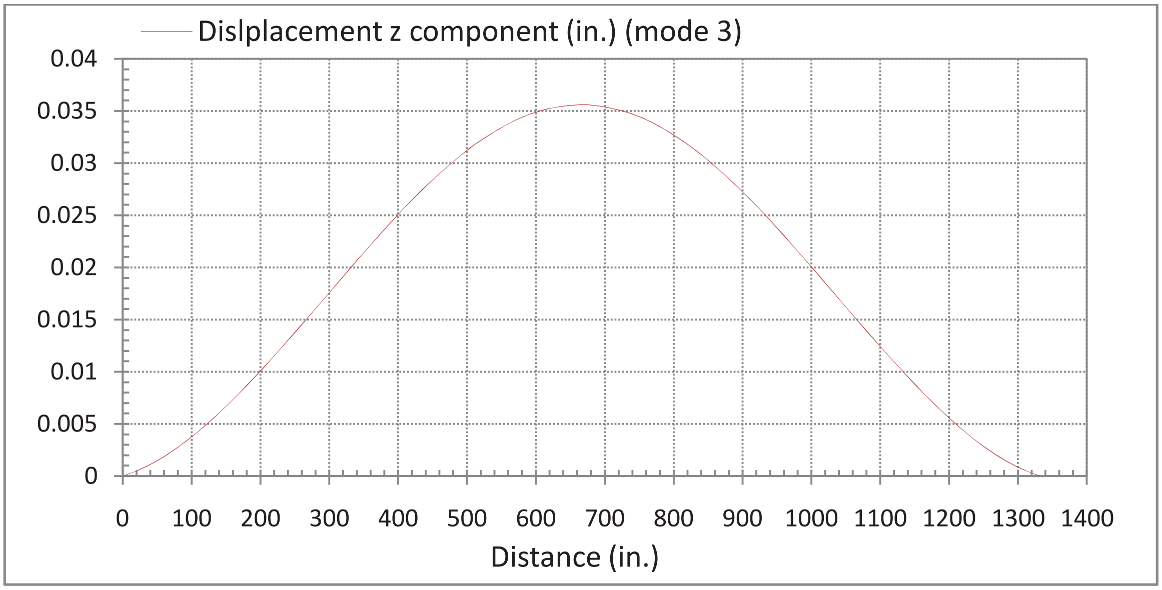
$D2^T =$

	0	1	2	3	4
0	$1.27 \cdot 10^{-15}$	$1.46 \cdot 10^{-14}$	$3.881 \cdot 10^{-14}$	$7.091 \cdot 10^{-14}$	...

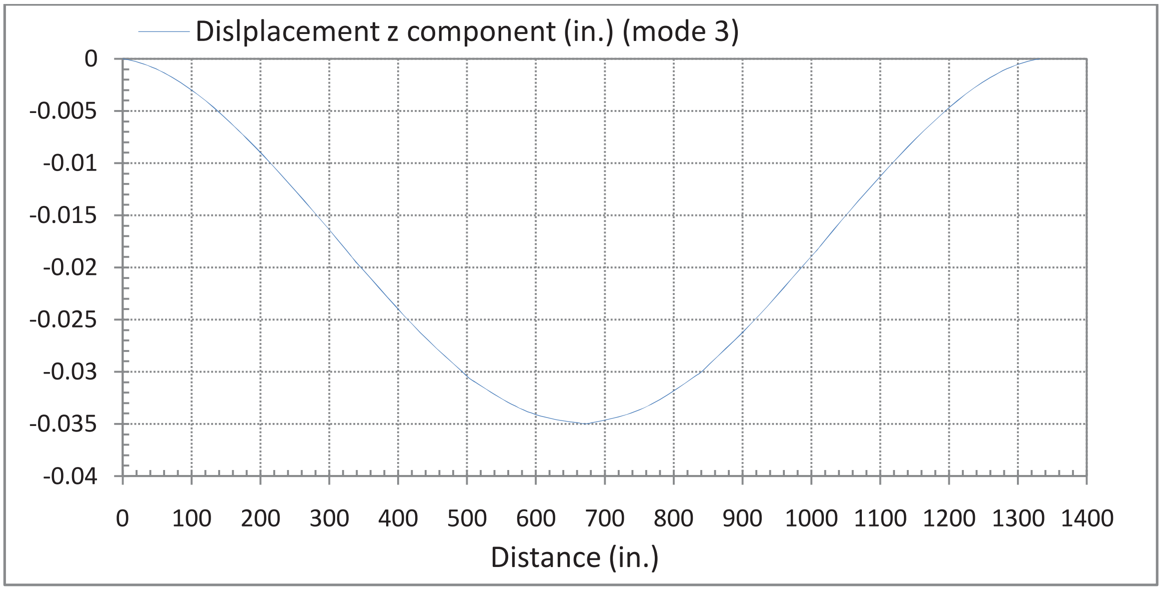
$$MAC2 := \frac{\left(U2^T \cdot D2\right)^2}{\left(U2^T \cdot U2\right) \cdot \left(D2^T \cdot D2\right)}$$

$MAC2 = 0.999$

4.2.3 MAC Value of Third Similar Mode Shapes



(a) At undamaged condition



(b) At damaged condition

Figure 4.25: Third similar mode shapes of center girder.

MAC value calculation using MathCAD for third similar mode shapes:

$$U3 := \begin{pmatrix} 0.000290274 \\ 0.0023955 \\ 0.00556964 \\ 0.00952134 \\ 0.013935 \\ 0.0185156 \\ 0.0230645 \\ 0.0272756 \\ 0.030817 \\ 0.0334934 \\ 0.0351257 \\ 0.0356147 \\ 0.0348899 \\ 0.0330377 \\ 0.0301686 \\ 0.0264763 \\ 0.0221726 \\ 0.017592 \\ 0.0130281 \\ 0.00868569 \\ 0.00486211 \\ 0.0018762 \end{pmatrix} \qquad D3 := \begin{pmatrix} 0.000154883 \\ 0.00178843 \\ 0.00466425 \\ 0.0084323 \\ 0.0127464 \\ 0.0173291 \\ 0.0219264 \\ 0.026224 \\ 0.0299235 \\ 0.0326381 \\ 0.0343256 \\ 0.0349789 \\ 0.0340813 \\ 0.0321669 \\ 0.029254 \\ 0.0254039 \\ 0.0210214 \\ 0.0164026 \\ 0.0118525 \\ 0.0076271 \\ 0.00400902 \\ 0.00134652 \end{pmatrix}$$

$U3^T =$

	0	1	2	3	4
0	$2.903\cdot10^{-4}$	$2.396\cdot10^{-3}$	$5.57\cdot10^{-3}$	$9.521\cdot10^{-3}$	...

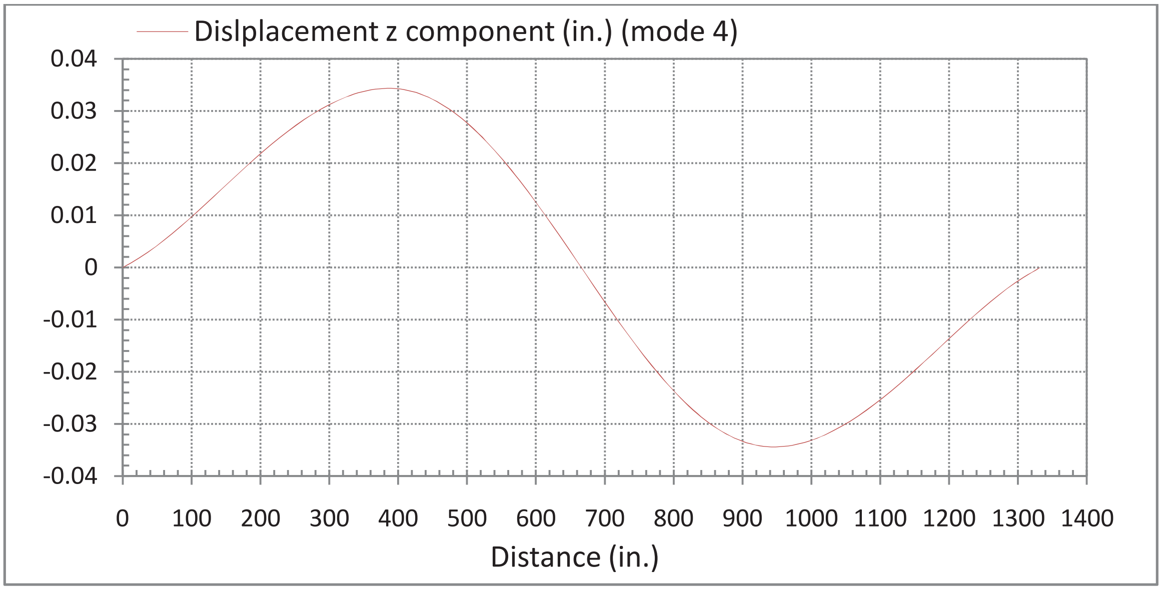
$D3^T =$

	0	1	2	3	4
0	$1.549\cdot10^{-4}$	$1.788\cdot10^{-3}$	$4.664\cdot10^{-3}$	$8.432\cdot10^{-3}$	...

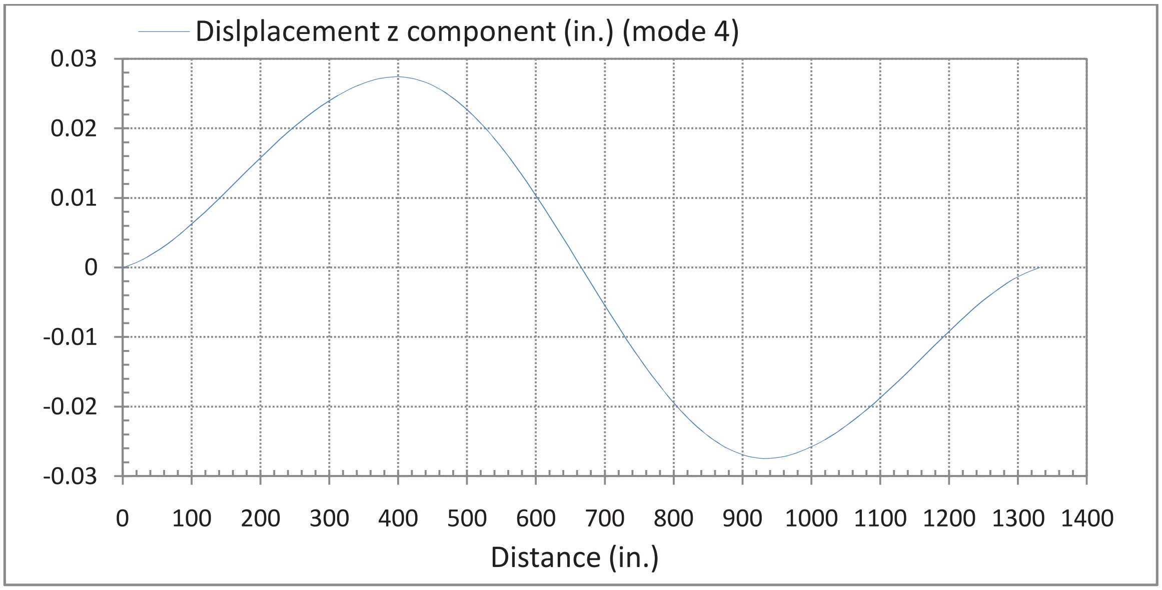
$$MAC3 := \frac{\left(U3^T \cdot D3\right)^2}{\left(U3^T \cdot U3\right)\cdot\left(D3^T \cdot D3\right)}$$

$$MAC3 = 0.999$$

4.2.4 MAC Value of Fourth Similar Mode Shapes



(a) At undamaged condition



(b) At damaged condition

Figure 4.26: Fourth similar mode shapes of center girder.

MAC value calculation using MathCAD for fourth similar mode shapes:

$$U4 := \begin{pmatrix} 0.000910117 \\ 0.00654276 \\ 0.0136064 \\ 0.0208982 \\ 0.0273181 \\ 0.0320038 \\ 0.0342638 \\ 0.0332755 \\ 0.0285944 \\ 0.0206338 \\ 0.0103266 \\ -0.00116705 \\ -0.0125247 \\ -0.0224462 \\ -0.0298177 \\ -0.0337732 \\ -0.0340375 \\ -0.0312428 \\ -0.0261485 \\ -0.0194766 \\ -0.0121383 \\ -0.00526403 \end{pmatrix} \qquad D4 := \begin{pmatrix} 0.000432669 \\ 0.00393707 \\ 0.0091698 \\ 0.0150146 \\ 0.0204783 \\ 0.0247204 \\ 0.0271532 \\ 0.0268965 \\ 0.0233863 \\ 0.0170181 \\ 0.00855996 \\ -0.000967776 \\ -0.0103756 \\ -0.0184898 \\ -0.0243356 \\ -0.0272096 \\ -0.0268504 \\ -0.0239984 \\ -0.0194601 \\ -0.0138472 \\ -0.00803987 \\ -0.00305718 \end{pmatrix}$$

$U4^T =$

	0	1	2	3	4
0	$9.101\cdot10^{-4}$	$6.543\cdot10^{-3}$	0.014	0.021	...

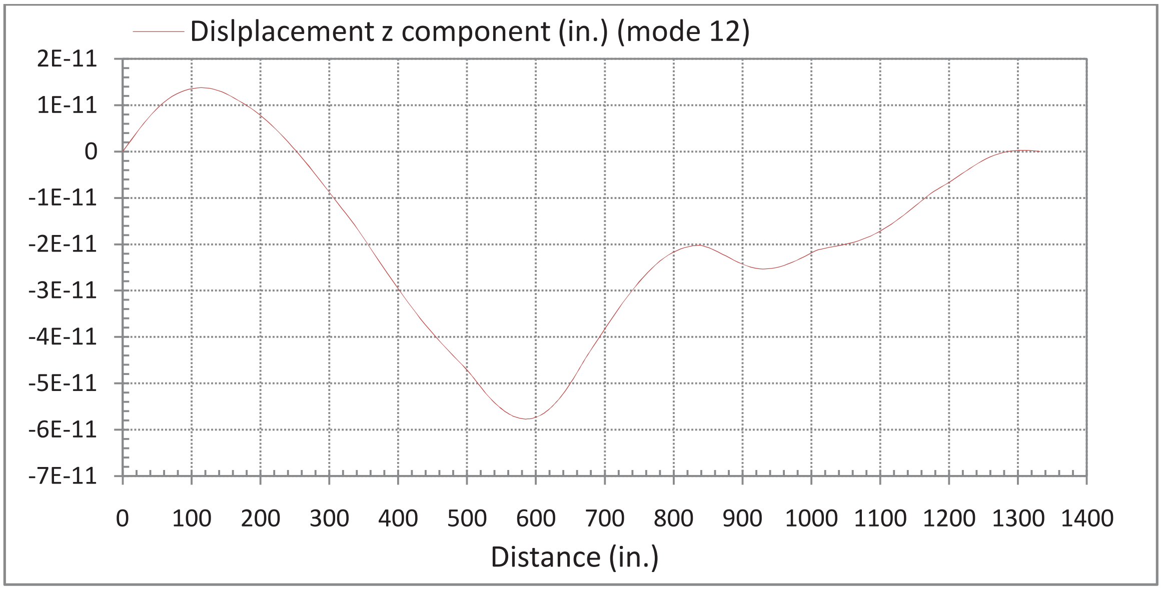
$D4^T =$

	0	1	2	3	4
0	$4.327\cdot10^{-4}$	$3.937\cdot10^{-3}$	$9.17\cdot10^{-3}$	0.015	...

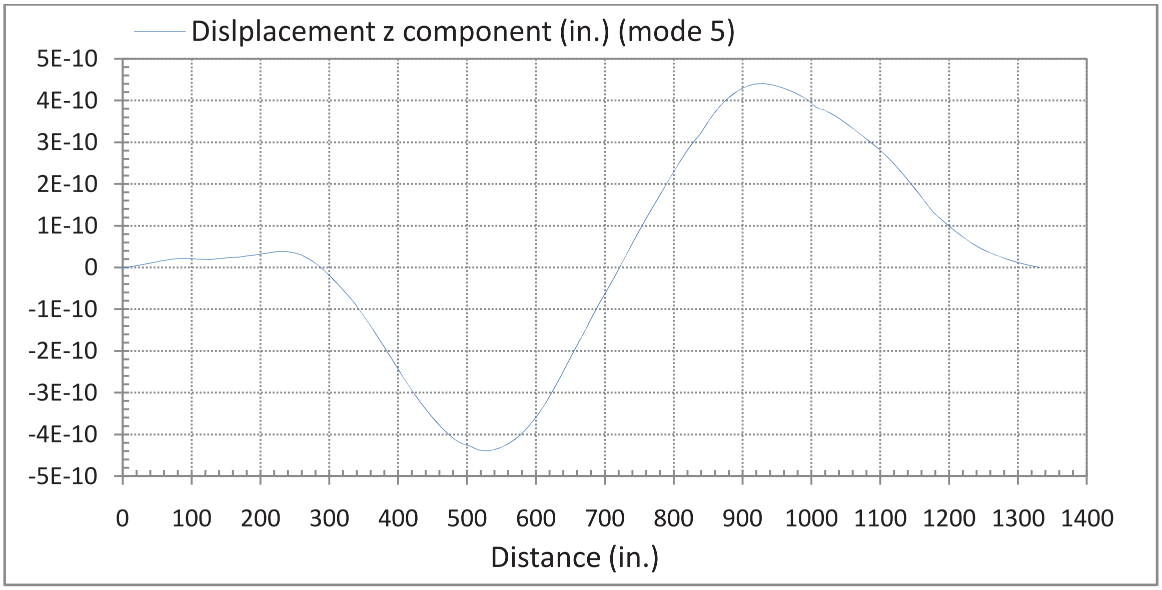
$$MAC4 := \frac{\left(U4^T \cdot D4\right)^2}{\left(U4^T \cdot U4\right)\cdot\left(D4^T \cdot D4\right)}$$

$MAC4 = 0.998$

4.2.5 MAC Value of Fifth Similar Mode Shapes



(a) At undamaged condition



(b) At damaged condition

Figure 4.27: Fifth similar mode shapes of center girder.

MAC value calculation using MathCAD for fifth similar mode shapes:

$$U5 := \begin{pmatrix} 2.46182E-12 \\ 1.19035E-11 \\ 1.34347E-11 \\ 8.69827E-12 \\ 5.9638E-14 \\ -1.10972E-11 \\ -2.35865E-11 \\ -3.59704E-11 \\ -4.58563E-11 \\ -5.5685E-11 \\ -5.6341E-11 \\ -4.45272E-11 \\ -3.14162E-11 \\ -2.23334E-11 \\ -2.0806E-11 \\ -2.48866E-11 \\ -2.38913E-11 \\ -2.05009E-11 \\ -1.77792E-11 \\ -1.16013E-11 \\ -5.47314E-12 \\ -4.83006E-13 \end{pmatrix} \qquad D5 := \begin{pmatrix} 2.47768E-12 \\ 2.01557E-11 \\ 2.01342E-11 \\ 3.01267E-11 \\ 3.41823E-11 \\ -3.92054E-11 \\ -1.70281E-10 \\ -3.21883E-10 \\ -4.21237E-10 \\ -4.28503E-10 \\ -3.29566E-10 \\ -1.48945E-10 \\ 3.27475E-11 \\ 2.07009E-10 \\ 3.54203E-10 \\ 4.37185E-10 \\ 4.21702E-10 \\ 3.65798E-10 \\ 2.92077E-10 \\ 1.85702E-10 \\ 8.35252E-11 \\ 2.7497E-11 \end{pmatrix}$$

$U5^T =$

	0	1	2	3	4
0	$2.462 \cdot 10^{-12}$	$1.19 \cdot 10^{-11}$	$1.343 \cdot 10^{-11}$	$8.698 \cdot 10^{-12}$	...

$D5^T =$

	0	1	2	3	4
0	$2.478 \cdot 10^{-12}$	$2.016 \cdot 10^{-11}$	$2.013 \cdot 10^{-11}$	$3.013 \cdot 10^{-11}$	...

$$MAC5 := \frac{\left(U5^T \cdot D5\right)^2}{\left(U5^T \cdot U5\right) \cdot \left(D5^T \cdot D5\right)}$$

$MAC5 = 0.054$

Chapter 5

RESULTS AND DISCUSSIONS

5.1 Results

It is clear from the FEM results that there are distinct differences in the behavior of the two models. Acceleration graphs from the damaged model of the bridge show that the acceleration is the maximum at the instant when the truck reaches that corresponding node, which is desirable from practical standpoint. After the truck passes the span, the acceleration started diminishing out. This behavior is also expected, which explains the effectiveness of the FEM. Comparison of the natural frequencies of the structure at the damaged and undamaged conditions shows that the frequencies of the damaged structure is around 30% less than that of the undamaged structure for majority of the mode shapes. Table 5.1 below summarizes the frequencies of mode shapes for both conditions and also shows the percent reduction between undamaged and damaged condition for each mode shape.

Table 5.1 – Reduction in frequency from undamaged to damaged bridge

Similar Mode Shape	Undamaged frequency, (cycle/sec)	Damaged frequency, (cycle/sec)	% Reduction in frequency, (%)
1	5.00141	3.54316	29.16
2	5.21542	3.65891	29.84
3	7.41937	5.96377	19.62
4	11.5915	8.28727	28.51
5	12.0445	8.3565	30.62

It is known from structural dynamics that natural frequency is directly proportional to square root of stiffness and inversely proportional to square root of mass. Since mass was constant for both cases, therefore, frequency decrease indicates a reduction in stiffness, which means that stiffness of the bridge has been reduced due to the presence of some type of damage in the bridge. Identification of type, nature, intensity and location of damages is beyond the scope of this research.

The MAC values of the first four similar mode shapes are 1 or almost close to 1 but the MAC value for the fifth similar mode shape is 0.054. According to theory of MAC, if the mode shapes are unique, the MAC value should be ideally 1, and it reduces down to 0 with reducing degree of correlation, 1 indicating full correlation and 0 indicating no correlation at all. Based on this theory, it can be concluded that first four mode shapes are not sensitive to damage; whereas fifth one is a very good indication of the presence and extent of damage.

This MAC value can be used to quantify the present structural condition of the bridge by normalizing the effect of stiffness reduction corresponding to this value. The bridges were usually designed to last around 50 years in service. Therefore, the reduction in service life of girders and deck can be estimated by the product of MAC deviation and percentage of reduction in member stiffness. Sample calculations are shown below.

MAC value $= 0.054$

Deviation in MAC $= (1 - 0.054) = 0.946$

Calculations of structural service life of girders:

Reduction in equivalent stiffness in girder of damaged structure $= \frac{(29000-14500)}{29000} * 100 = 50\%$

Normalized reduction in equivalent stiffness of girder $= (0.946 * 50\%) = 47.3\%$

Reduction in estimated structural service life of 50 years $= (47.3\%) * 50\ years = 23.7\ years$

Remaining structural service life of the girder $= 50 - 23.7 = 26.3\ years \approx 26\ years$

Theoretically, for an average design service life of 50 years, remaining structural service life is 20 years after 30 years of construction.

Calculations of structural service life of deck:

Reduction in equivalent stiffness in deck of damaged structure $= \frac{(3000-1400)}{3000} * 100 = 53.33\%$

Normalized reduction in equivalent stiffness of deck $= (0.946 * 53.33\%) = 50.45\%$

Reduction in estimated structural service life of 50 years $= (50.45\%) * 50\, years = 25.2\, years$

Remaining structural service life of the deck $= 50 - 25.2 = 24.8\, years \approx 24\, years$

Theoretically, for an average design service life of 50 years, remaining structural service life is 20 years after 30 years of construction.

5.2 Discussions

The main objective of this health monitoring research was to express the current overall structural condition of the bridge analyzing real-time dynamic response data. From the data collected and analysis performed, it can be suggested that this bridge has lost approximately 47% of its service life since it was built 30 years ago. This conclusion is based on certain facts, assumptions and simplifications. This appears to be very practical and reasonable because of the fact that those bridges were usually designed and built to last around 50 years. After 30 years in service, the bridge has lost almost half of its service life. Therefore, the effectiveness and applicability of the FEM have been validated to some extent during the various stages of this structural health monitoring process.

The acceleration recorded through the sensors show that the amplitude does not diminish over time as it does in case of acceleration measured from FEM. One of the possible reasons is because the acceleration recorded in the sensors are not only the vibration caused by the horizontal movement of the truck over the span, but also due to the vibration induced by the surface roughness of the deck and the vehicle suspension system, which is a continuous source of vibration. On the other hand, the acceleration given by the FEM is only due to the horizontal motion of the truck at a constant speed, however, it does not account for the surface roughness and vehicle suspension.

Srinivasan and Kot (1992) suggested based on their study that changes in mode shapes are more sensitive to damage than change in resonant frequencies. This study also shows that frequencies change only 30% whereas the damage is almost 50%.

Ko, et al. (1994), Salawu and Williams (1994) and Lam, et al. (1995) observed in their individual studies that not all mode shapes are sensitive to damage and higher order mode shapes are likely to be more sensitive of damage. Same behavior also observed in this study. First four mode shapes were found to be insensitive to damage but the fifth similar mode (which is actually the twelfth mode in the undamaged bridge and fifth mode in the damaged bridge) shows significant changes in MAC values.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Health monitoring is one of the most researched topics in the field of civil, mechanical and materials engineering. In bridge engineering, the aspects of health monitoring are very wide, considering the fact that percentage of structurally deficient bridges in the nation is very high. The method described in this study provides a more realistic quantitative health assessment of the bridge based on real-time structural response compared to traditional theoretical load rating and visual qualitative inspection. The first step of this process is to record the dynamic responses of the bridge when subjected to a standard truck load. Second step is to simulate the same loading on a finite element model of the bridge in order to determine the equivalent stiffness of the bridge cross-section, which will produce the same dynamic responses as in the real bridge. Third step is to determine the fundamental modal frequencies and mode shapes of the bridge with reduced stiffness determined in the previous step. This represented the mode shape of the bridge at damaged state. Fourth step is to determine the fundamental modal frequencies and mode shapes of the bridge with full stiffness, which represented mode shapes of the bridge at a state without any damage. Final step of this method is to compare the similar mode shapes of two conditions and correlate them using a popular mode shape correlation algorithm known as Modal Assurance Criteria (MAC). Resulting MAC values are the indicator of the current structural condition of the bridge. It was observed that only higher order modes are sensitive to damage. Therefore, in this case, MAC value of fifth similar mode pair has been used to interpret the result in terms of remaining structural service life. Final results show that girders and deck of the selected bridge span under study have an estimated remaining service life of approximately 26 years and 24 years, respectively. Main functional feature of this method is that it does not focus on any individual discrete defect in the bridge; rather it gives an overall assessment of the remaining service life of the bridge by taking into account the effects of any type of damage present.

Further refinement and justification of this method may be necessary before incorporating it into real life application due to the assumptions undertaken at the beginning of the process and due to the hardware, resources and technical limitations faced in several stages of this study. Despite all the limitations, it can be concluded that this process of SHM can be a useful source of information regarding structural service life and health data in every aspect of bridge maintenance, repair and rehabilitation, including budget allocation, strategic planning, etc.

6.2 Recommendations

Based on the experience, challenges faced and technical difficulties, following recommendations were made for further investigations, studies and extension of this research:

- Effects of temperature and transverse wind may be considered during the data collection.
- Vibrations induced from the surface roughness and vehicle suspension system should be considered while performing finite element analysis.
- Traffic railing barriers should be included to represent actual condition with greater stiffness.
- Deck reinforcement may be included in the FEM.
- Boundary conditions at the end of the span can be modified as elastic support with stiffness equivalent to the adjoining elements in order to more accurately represent the continuous span.
- The effect of bearing pads at the base of the girders should be included.
- Bridge can be simulated with truck running on interior lane or on multiple traffic lanes.
- The effect of structural damage on lateral mode shapes or higher order mode shapes should be investigated.

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APPENDICES

APPENDIX A

Acceleration data of Sensors A, B and C

Sensor A			Sensor B			Sensor C		
	Acceleration			Acceleration			Acceleration	
Time, msec	From Sensor, g	Normalized, in/sec^2	Time, msec	From Sensor, g	Normalized, in/sec^2	Time, msec	From Sensor, g	Normalized, in/sec^2
3998	1.2813	6.12114295	3999	-1.45	-0.2224351	3999	1.2969	-4.0199243
4003	1.2656	0.08364295	4004	-1.45	-0.2224351	4004	1.3125	2.01757566
4008	1.2656	0.08364295	4014	-1.455	-2.297623	4013	1.3281	8.05507566
4018	1.2344	-11.991357	4017	-1.455	-2.297623	4017	1.3125	2.01757566
4021	1.2344	-11.991357	4021	-1.455	-2.297623	4021	1.3125	2.01757566
4025	1.25	-5.9538571	4026	-1.455	-2.297623	4026	1.2969	-4.0199243
4030	1.25	-5.9538571	4030	-1.45	-0.2224351	4030	1.2969	-4.0199243
4034	1.2656	0.08364295	4035	-1.455	-2.297623	4035	1.2969	-4.0199243
4039	1.2656	0.08364295	4039	-1.455	-2.297623	4039	1.2969	-4.0199243
4043	1.2344	-11.991357	4044	-1.45	-0.2224351	4050	1.2969	-4.0199243
4048	1.2813	6.12114295	4054	-1.445	1.85275311	4053	1.2969	-4.0199243
4057	1.2813	6.12114295	4057	-1.445	1.85275311	4057	1.3125	2.01757566
4061	1.2813	6.12114295	4062	-1.45	-0.2224351	4062	1.3125	2.01757566
4066	1.2813	6.12114295	4066	-1.45	-0.2224351	4066	1.2969	-4.0199243
4070	1.2813	6.12114295	4071	-1.45	-0.2224351	4071	1.2969	-4.0199243
4075	1.2813	6.12114295	4075	-1.45	-0.2224351	4075	1.2969	-4.0199243
4079	1.2813	6.12114295	4080	-1.45	-0.2224351	4080	1.2969	-4.0199243
4084	1.2656	0.08364295	4085	-1.455	-2.297623	4085	1.2969	-4.0199243
4088	1.25	-5.9538571	4095	-1.461	-4.3728109	4094	1.2969	-4.0199243
4099	1.25	-5.9538571	4098	-1.461	-4.3728109	4098	1.3125	2.01757566
4102	1.25	-5.9538571	4102	-1.45	-0.2224351	4102	1.3125	2.01757566
4106	1.25	-5.9538571	4107	-1.45	-0.2224351	4107	1.2813	-10.057424
4111	1.25	-5.9538571	4111	-1.445	1.85275311	4111	1.2813	-10.057424
4115	1.25	-5.9538571	4116	-1.455	-2.297623	4116	1.3125	2.01757566
4120	1.25	-5.9538571	4120	-1.455	-2.297623	4120	1.3125	2.01757566
4124	1.25	-5.9538571	4125	-1.45	-0.2224351	4125	1.3125	2.01757566
4129	1.25	-5.9538571	4135	-1.445	1.85275311	4134	1.2969	-4.0199243
4138	1.2344	-11.991357	4138	-1.445	1.85275311	4138	1.2813	-10.057424

4142	1.2344	-11.991357	4143	-1.455	-2.297623	4143	1.2813	-10.057424
4147	1.2656	0.08364295	4147	-1.455	-2.297623	4147	1.3281	8.05507566
4151	1.2656	0.08364295	4152	-1.445	1.85275311	4152	1.3281	8.05507566
4156	1.2656	0.08364295	4156	-1.45	-0.2224351	4156	1.3125	2.01757566
4160	1.2656	0.08364295	4161	-1.45	-0.2224351	4161	1.3125	2.01757566
4165	1.2656	0.08364295	4172	-1.439	3.92794097	4172	1.3125	2.01757566
4176	1.2969	12.1586429	4175	-1.439	3.92794097	4175	1.3125	2.01757566
4180	1.2969	12.1586429	4179	-1.439	3.92794097	4179	1.3125	2.01757566
4183	1.2969	12.1586429	4183	-1.461	-4.3728109	4183	1.3125	2.01757566
4187	1.3125	18.1961429	4188	-1.445	1.85275311	4188	1.3125	2.01757566
4192	1.3125	18.1961429	4192	-1.445	1.85275311	4192	1.3125	2.01757566
4196	1.3125	18.1961429	4197	-1.45	-0.2224351	4197	1.2969	-4.0199243
4201	1.2813	6.12114295	4201	-1.45	-0.2224351	4201	1.2969	-4.0199243
4205	1.2813	6.12114295	4206	-1.455	-2.297623	4212	1.2969	-4.0199243
4210	1.2813	6.12114295	4215	-1.461	-4.3728109	4215	1.2969	-4.0199243
4220	1.2969	12.1586429	4219	-1.461	-4.3728109	4219	1.2969	-4.0199243
4223	1.2969	12.1586429	4224	-1.445	1.85275311	4224	1.2969	-4.0199243
4228	1.2969	12.1586429	4228	-1.45	-0.2224351	4228	1.3125	2.01757566
4232	1.2969	12.1586429	4233	-1.45	-0.2224351	4233	1.3125	2.01757566
4237	1.2969	12.1586429	4237	-1.45	-0.2224351	4237	1.3281	8.05507566
4241	1.2969	12.1586429	4241	-1.45	-0.2224351	4242	1.3281	8.05507566
4246	1.2969	12.1586429	4246	-1.455	-2.297623	4253	1.3125	2.01757566
4257	1.2813	6.12114295	4256	-1.45	-0.2224351	4256	1.3125	2.01757566
4261	1.2813	6.12114295	4260	-1.45	-0.2224351	4260	1.3125	2.01757566
4264	1.2813	6.12114295	4264	-1.45	-0.2224351	4264	1.3125	2.01757566
4268	1.2969	12.1586429	4268	-1.445	1.85275311	4268	1.3125	2.01757566
4273	1.2969	12.1586429	4273	-1.445	1.85275311	4273	1.3125	2.01757566
4277	1.2813	6.12114295	4278	-1.45	-0.2224351	4277	1.3281	8.05507566
4282	1.2813	6.12114295	4282	-1.45	-0.2224351	4282	1.3281	8.05507566
4286	1.2813	6.12114295	4287	-1.445	1.85275311	4293	1.2969	-4.0199243
4291	1.2656	0.08364295	4297	-1.45	-0.2224351	4296	1.2969	-4.0199243
4301	1.2656	0.08364295	4300	-1.45	-0.2224351	4300	1.3281	8.05507566
4304	1.2656	0.08364295	4304	-1.45	-0.2224351	4304	1.3281	8.05507566
4309	1.25	-5.9538571	4309	-1.45	-0.2224351	4309	1.3125	2.01757566
4313	1.2656	0.08364295	4313	-1.45	-0.2224351	4313	1.3125	2.01757566
4317	1.2656	0.08364295	4318	-1.45	-0.2224351	4318	1.3125	2.01757566
4322	1.2344	-11.991357	4322	-1.45	-0.2224351	4322	1.3125	2.01757566
4326	1.2344	-11.991357	4327	-1.445	1.85275311	4327	1.3125	2.01757566
4331	1.25	-5.9538571	4336	-1.445	1.85275311	4337	1.2969	-4.0199243
4341	1.25	-5.9538571	4340	-1.45	-0.2224351	4340	1.2969	-4.0199243
4345	1.25	-5.9538571	4345	-1.45	-0.2224351	4345	1.2969	-4.0199243

4349	1.25	-5.9538571	4349	-1.45	-0.2224351	4349	1.3125	2.01757566
4353	1.25	-5.9538571	4354	-1.45	-0.2224351	4354	1.3125	2.01757566
4358	1.25	-5.9538571	4358	-1.455	-2.297623	4358	1.2969	-4.0199243
4362	1.2656	0.08364295	4363	-1.455	-2.297623	4363	1.2969	-4.0199243
4367	1.2656	0.08364295	4368	-1.445	1.85275311	4368	1.3125	2.01757566
4372	1.25	-5.9538571	4377	-1.455	-2.297623	4377	1.2969	-4.0199243
4382	1.2188	-18.028857	4381	-1.455	-2.297623	4381	1.2969	-4.0199243
4385	1.2188	-18.028857	4385	-1.455	-2.297623	4385	1.2969	-4.0199243
4389	1.25	-5.9538571	4390	-1.45	-0.2224351	4390	1.2969	-4.0199243
4394	1.25	-5.9538571	4394	-1.45	-0.2224351	4394	1.2969	-4.0199243
4398	1.25	-5.9538571	4399	-1.45	-0.2224351	4399	1.3125	2.01757566
4403	1.25	-5.9538571	4403	-1.45	-0.2224351	4403	1.3125	2.01757566
4407	1.25	-5.9538571	4408	-1.45	-0.2224351	4408	1.2813	-10.057424
4412	1.25	-5.9538571	4417	-1.45	-0.2224351	4417	1.2813	-10.057424
4421	1.2656	0.08364295	4421	-1.445	1.85275311	4421	1.3125	2.01757566
4425	1.2656	0.08364295	4426	-1.445	1.85275311	4426	1.3125	2.01757566
4430	1.25	-5.9538571	4430	-1.445	1.85275311	4430	1.2969	-4.0199243
4434	1.25	-5.9538571	4435	-1.445	1.85275311	4435	1.2969	-4.0199243
4439	1.25	-5.9538571	4439	-1.45	-0.2224351	4439	1.2969	-4.0199243
4443	1.2813	6.12114295	4444	-1.45	-0.2224351	4444	1.2969	-4.0199243
4448	1.2813	6.12114295	4455	-1.45	-0.2224351	4449	1.2813	-10.057424
4452	1.2656	0.08364295	4458	-1.45	-0.2224351	4458	1.3125	2.01757566
4462	1.2813	6.12114295	4462	-1.45	-0.2224351	4462	1.3125	2.01757566
4466	1.2813	6.12114295	4466	-1.45	-0.2224351	4466	1.3125	2.01757566
4470	1.2813	6.12114295	4471	-1.455	-2.297623	4471	1.3125	2.01757566
4475	1.2969	12.1586429	4475	-1.455	-2.297623	4475	1.3125	2.01757566
4479	1.2969	12.1586429	4480	-1.455	-2.297623	4480	1.2969	-4.0199243
4484	1.2813	6.12114295	4484	-1.455	-2.297623	4484	1.2969	-4.0199243
4488	1.2813	6.12114295	4489	-1.445	1.85275311	4489	1.3125	2.01757566
4493	1.2656	0.08364295	4499	-1.445	1.85275311	4498	1.2969	-4.0199243
4503	1.2656	0.08364295	4502	-1.455	-2.297623	4502	1.2969	-4.0199243
4506	1.2656	0.08364295	4507	-1.455	-2.297623	4507	1.2969	-4.0199243
4511	1.2656	0.08364295	4511	-1.45	-0.2224351	4511	1.3125	2.01757566
4515	1.2813	6.12114295	4516	-1.45	-0.2224351	4516	1.3125	2.01757566
4520	1.2813	6.12114295	4520	-1.45	-0.2224351	4520	1.3281	8.05507566
4524	1.2813	6.12114295	4525	-1.45	-0.2224351	4525	1.3281	8.05507566
4529	1.2813	6.12114295	4529	-1.45	-0.2224351	4536	1.3125	2.01757566
4540	1.25	-5.9538571	4539	-1.445	1.85275311	4539	1.3125	2.01757566
4543	1.25	-5.9538571	4543	-1.461	-4.3728109	4543	1.3125	2.01757566
4547	1.2344	-11.991357	4547	-1.461	-4.3728109	4547	1.3125	2.01757566
4551	1.2344	-11.991357	4552	-1.461	-4.3728109	4552	1.3125	2.01757566

4556	1.2344	-11.991357	4556	-1.461	-4.3728109	4556	1.3125	2.01757566
4560	1.2344	-11.991357	4561	-1.445	1.85275311	4561	1.2969	-4.0199243
4565	1.25	-5.9538571	4565	-1.445	1.85275311	4565	1.2969	-4.0199243
4569	1.25	-5.9538571	4570	-1.445	1.85275311	4576	1.2969	-4.0199243
4574	1.25	-5.9538571	4580	-1.445	1.85275311	4579	1.2969	-4.0199243
4584	1.25	-5.9538571	4583	-1.455	-2.297623	4583	1.2969	-4.0199243
4587	1.2656	0.08364295	4587	-1.455	-2.297623	4588	1.3125	2.01757566
4592	1.2656	0.08364295	4592	-1.455	-2.297623	4592	1.3125	2.01757566
4596	1.2656	0.08364295	4596	-1.455	-2.297623	4596	1.3125	2.01757566
4601	1.2656	0.08364295	4601	-1.45	-0.2224351	4601	1.3125	2.01757566
4605	1.2969	12.1586429	4605	-1.45	-0.2224351	4606	1.3125	2.01757566
4610	1.2969	12.1586429	4610	-1.445	1.85275311	4616	1.2969	-4.0199243
4621	1.2969	12.1586429	4620	-1.445	1.85275311	4619	1.2969	-4.0199243
4625	1.2969	12.1586429	4623	-1.455	-2.297623	4623	1.2969	-4.0199243
4628	1.2813	6.12114295	4628	-1.455	-2.297623	4628	1.3125	2.01757566
4632	1.2813	6.12114295	4632	-1.45	-0.2224351	4632	1.3125	2.01757566
4636	1.2656	0.08364295	4637	-1.45	-0.2224351	4637	1.3125	2.01757566
4641	1.2656	0.08364295	4641	-1.439	3.92794097	4641	1.3125	2.01757566
4646	1.2656	0.08364295	4646	-1.439	3.92794097	4646	1.3125	2.01757566
4650	1.2656	0.08364295	4651	-1.45	-0.2224351	4651	1.2969	-4.0199243
4655	1.2813	6.12114295	4661	-1.445	1.85275311	4660	1.2969	-4.0199243
4665	1.2656	0.08364295	4664	-1.455	-2.297623	4664	1.2969	-4.0199243
4668	1.2656	0.08364295	4668	-1.455	-2.297623	4668	1.3125	2.01757566
4672	1.2656	0.08364295	4673	-1.45	-0.2224351	4673	1.3125	2.01757566
4677	1.25	-5.9538571	4677	-1.45	-0.2224351	4677	1.3125	2.01757566
4681	1.25	-5.9538571	4682	-1.45	-0.2224351	4682	1.3125	2.01757566
4686	1.2656	0.08364295	4686	-1.45	-0.2224351	4686	1.3125	2.01757566
4690	1.2656	0.08364295	4691	-1.45	-0.2224351	4691	1.3125	2.01757566
4695	1.2656	0.08364295	4700	-1.45	-0.2224351	4700	1.3125	2.01757566
4705	1.25	-5.9538571	4704	-1.45	-0.2224351	4704	1.3125	2.01757566
4708	1.2188	-18.028857	4709	-1.45	-0.2224351	4709	1.3125	2.01757566
4713	1.2188	-18.028857	4713	-1.445	1.85275311	4713	1.3125	2.01757566
4717	1.25	-5.9538571	4718	-1.445	1.85275311	4718	1.3125	2.01757566
4722	1.25	-5.9538571	4722	-1.445	1.85275311	4722	1.2969	-4.0199243
4726	1.2344	-11.991357	4727	-1.45	-0.2224351	4727	1.2969	-4.0199243
4731	1.2344	-11.991357	4732	-1.45	-0.2224351	4738	1.3125	2.01757566
4736	1.25	-5.9538571	4742	-1.45	-0.2224351	4741	1.3125	2.01757566
4746	1.25	-5.9538571	4745	-1.45	-0.2224351	4745	1.3125	2.01757566
4749	1.2344	-11.991357	4749	-1.45	-0.2224351	4749	1.3125	2.01757566
4753	1.2344	-11.991357	4754	-1.45	-0.2224351	4754	1.3125	2.01757566
4758	1.25	-5.9538571	4758	-1.45	-0.2224351	4758	1.3125	2.01757566

4762	1.25	-5.9538571	4763	-1.445	1.85275311	4763	1.2969	-4.0199243
4767	1.2344	-11.991357	4767	-1.455	-2.297623	4767	1.2969	-4.0199243
4771	1.2344	-11.991357	4772	-1.455	-2.297623	4778	1.2969	-4.0199243
4776	1.25	-5.9538571	4781	-1.445	1.85275311	4781	1.2969	-4.0199243
4786	1.2656	0.08364295	4785	-1.45	-0.2224351	4785	1.2969	-4.0199243
4789	1.2656	0.08364295	4790	-1.45	-0.2224351	4790	1.2969	-4.0199243
4794	1.2656	0.08364295	4794	-1.445	1.85275311	4794	1.2969	-4.0199243
4798	1.2813	6.12114295	4799	-1.445	1.85275311	4799	1.2813	-10.057424
4803	1.2813	6.12114295	4803	-1.45	-0.2224351	4803	1.3125	2.01757566
4807	1.2969	12.1586429	4808	-1.455	-2.297623	4808	1.3125	2.01757566
4812	1.2813	6.12114295	4813	-1.455	-2.297623	4819	1.3125	2.01757566
4819	1.2813	6.12114295	4822	-1.455	-2.297623	4822	1.3125	2.01757566
4826	1.2813	6.12114295	4826	-1.445	1.85275311	4826	1.3125	2.01757566
4830	1.2813	6.12114295	4830	-1.445	1.85275311	4830	1.2969	-4.0199243
4834	1.2813	6.12114295	4835	-1.455	-2.297623	4835	1.2969	-4.0199243
4839	1.2656	0.08364295	4839	-1.455	-2.297623	4839	1.3125	2.01757566
4843	1.2656	0.08364295	4844	-1.45	-0.2224351	4844	1.3125	2.01757566
4848	1.25	-5.9538571	4848	-1.45	-0.2224351	4848	1.3125	2.01757566
4852	1.2344	-11.991357	4853	-1.45	-0.2224351	4859	1.2969	-4.0199243
4857	1.2344	-11.991357	4863	-1.45	-0.2224351	4862	1.3125	2.01757566
4867	1.2813	6.12114295	4866	-1.445	1.85275311	4866	1.3125	2.01757566
4870	1.25	-5.9538571	4871	-1.445	1.85275311	4871	1.2969	-4.0199243
4875	1.25	-5.9538571	4875	-1.439	3.92794097	4875	1.2969	-4.0199243
4879	1.25	-5.9538571	4880	-1.439	3.92794097	4880	1.3281	8.05507566
4884	1.25	-5.9538571	4884	-1.439	3.92794097	4884	1.3125	2.01757566
4888	1.25	-5.9538571	4889	-1.45	-0.2224351	4889	1.3125	2.01757566
4893	1.25	-5.9538571	4893	-1.45	-0.2224351	4900	1.2969	-4.0199243
4897	1.25	-5.9538571	4903	-1.45	-0.2224351	4903	1.2969	-4.0199243
4907	1.2813	6.12114295	4907	-1.455	-2.297623	4907	1.2969	-4.0199243
4911	1.2656	0.08364295	4911	-1.455	-2.297623	4911	1.3125	2.01757566
4915	1.2656	0.08364295	4916	-1.45	-0.2224351	4916	1.3125	2.01757566
4920	1.2813	6.12114295	4920	-1.45	-0.2224351	4920	1.3125	2.01757566
4924	1.2813	6.12114295	4925	-1.45	-0.2224351	4924	1.3125	2.01757566
4929	1.2656	0.08364295	4929	-1.45	-0.2224351	4929	1.3125	2.01757566
4933	1.2656	0.08364295	4934	-1.45	-0.2224351	4940	1.3281	8.05507566
4938	1.2656	0.08364295	4944	-1.45	-0.2224351	4943	1.3125	2.01757566
4948	1.2969	12.1586429	4947	-1.445	1.85275311	4947	1.3125	2.01757566
4951	1.2813	6.12114295	4951	-1.445	1.85275311	4951	1.2969	-4.0199243
4956	1.2813	6.12114295	4956	-1.45	-0.2224351	4956	1.2969	-4.0199243
4960	1.25	-5.9538571	4960	-1.45	-0.2224351	4960	1.3125	2.01757566
4964	1.25	-5.9538571	4965	-1.45	-0.2224351	4965	1.2969	-4.0199243

4969	1.2656	0.08364295	4969	-1.45	-0.2224351	4969	1.2969	-4.0199243
4973	1.25	-5.9538571	4974	-1.45	-0.2224351	4974	1.2969	-4.0199243
4985	1.2344	-11.991357	4984	-1.45	-0.2224351	4983	1.3281	8.05507566
4989	1.2344	-11.991357	4987	-1.45	-0.2224351	4987	1.3281	8.05507566
4992	1.2344	-11.991357	4992	-1.45	-0.2224351	4992	1.3125	2.01757566
4996	1.2344	-11.991357	4996	-1.445	1.85275311	4996	1.3125	2.01757566
5000	1.25	-5.9538571	5001	-1.445	1.85275311	5001	1.2969	-4.0199243
5005	1.25	-5.9538571	5005	-1.445	1.85275311	5005	1.2969	-4.0199243
5009	1.25	-5.9538571	5010	-1.45	-0.2224351	5010	1.2969	-4.0199243
5014	1.2656	0.08364295	5015	-1.45	-0.2224351	5015	1.2969	-4.0199243
5019	1.2656	0.08364295	5025	-1.445	1.85275311	5024	1.2813	-10.057424
5030	1.25	-5.9538571	5028	-1.445	1.85275311	5028	1.2813	-10.057424
5032	1.25	-5.9538571	5032	-1.445	1.85275311	5032	1.2969	-4.0199243
5036	1.25	-5.9538571	5037	-1.455	-2.297623	5037	1.2969	-4.0199243
5041	1.2344	-11.991357	5041	-1.455	-2.297623	5041	1.3125	2.01757566
5045	1.2344	-11.991357	5046	-1.455	-2.297623	5046	1.3125	2.01757566
5050	1.2344	-11.991357	5050	-1.455	-2.297623	5050	1.2969	-4.0199243
5054	1.2344	-11.991357	5055	-1.455	-2.297623	5055	1.2969	-4.0199243
5059	1.2344	-11.991357	5065	-1.461	-4.3728109	5064	1.3125	2.01757566
5070	1.25	-5.9538571	5068	-1.45	-0.2224351	5068	1.3125	2.01757566
5073	1.25	-5.9538571	5073	-1.45	-0.2224351	5073	1.3125	2.01757566
5077	1.25	-5.9538571	5077	-1.45	-0.2224351	5077	1.3125	2.01757566
5081	1.25	-5.9538571	5082	-1.45	-0.2224351	5082	1.2969	-4.0199243
5086	1.2344	-11.991357	5086	-1.45	-0.2224351	5086	1.2969	-4.0199243
5090	1.2344	-11.991357	5091	-1.461	-4.3728109	5091	1.3125	2.01757566
5095	1.2656	0.08364295	5096	-1.461	-4.3728109	5102	1.2969	-4.0199243
5099	1.2656	0.08364295	5106	-1.445	1.85275311	5105	1.2969	-4.0199243
5109	1.2656	0.08364295	5109	-1.445	1.85275311	5109	1.2969	-4.0199243
5113	1.2656	0.08364295	5113	-1.445	1.85275311	5113	1.3438	14.0925757
5117	1.2656	0.08364295	5118	-1.455	-2.297623	5118	1.3438	14.0925757
5122	1.2656	0.08364295	5122	-1.445	1.85275311	5122	1.2969	-4.0199243
5126	1.2969	12.1586429	5127	-1.445	1.85275311	5127	1.2969	-4.0199243
5131	1.2969	12.1586429	5131	-1.45	-0.2224351	5131	1.3281	8.05507566
5135	1.2813	6.12114295	5136	-1.45	-0.2224351	5142	1.2969	-4.0199243
5140	1.2813	6.12114295	5146	-1.439	3.92794097	5145	1.2969	-4.0199243
5150	1.2969	12.1586429	5149	-1.439	3.92794097	5149	1.2969	-4.0199243
5153	1.2969	12.1586429	5154	-1.445	1.85275311	5154	1.3281	8.05507566
5158	1.2969	12.1586429	5158	-1.445	1.85275311	5158	1.3281	8.05507566
5162	1.2969	12.1586429	5163	-1.45	-0.2224351	5163	1.3125	2.01757566
5167	1.2656	0.08364295	5167	-1.45	-0.2224351	5167	1.3125	2.01757566
5171	1.2656	0.08364295	5172	-1.445	1.85275311	5172	1.2813	-10.057424

5176	1.2969	12.1586429	5176	-1.445	1.85275311	5183	1.3281	8.05507566
5187	1.2969	12.1586429	5186	-1.45	-0.2224351	5186	1.2969	-4.0199243
5190	1.2969	12.1586429	5190	-1.45	-0.2224351	5191	1.2969	-4.0199243
5194	1.2969	12.1586429	5194	-1.445	1.85275311	5195	1.2969	-4.0199243
5198	1.2813	6.12114295	5199	-1.445	1.85275311	5199	1.2969	-4.0199243
5203	1.2813	6.12114295	5203	-1.455	-2.297623	5203	1.3125	2.01757566
5207	1.2969	12.1586429	5208	-1.455	-2.297623	5208	1.3125	2.01757566
5212	1.2969	12.1586429	5212	-1.439	3.92794097	5212	1.3281	8.05507566
5216	1.2813	6.12114295	5217	-1.439	3.92794097	5223	1.2969	-4.0199243
5221	1.2813	6.12114295	5227	-1.45	-0.2224351	5226	1.3125	2.01757566
5231	1.2813	6.12114295	5230	-1.45	-0.2224351	5230	1.3125	2.01757566
5234	1.2813	6.12114295	5235	-1.445	1.85275311	5235	1.3125	2.01757566
5239	1.2969	12.1586429	5239	-1.445	1.85275311	5239	1.3125	2.01757566
5243	1.2969	12.1586429	5243	-1.45	-0.2224351	5244	1.2813	-10.057424
5248	1.2813	6.12114295	5248	-1.45	-0.2224351	5248	1.2813	-10.057424
5252	1.2813	6.12114295	5252	-1.45	-0.2224351	5253	1.2969	-4.0199243
5257	1.2969	12.1586429	5257	-1.45	-0.2224351	5263	1.2969	-4.0199243
5268	1.2969	12.1586429	5267	-1.45	-0.2224351	5266	1.2969	-4.0199243
5272	1.2969	12.1586429	5271	-1.45	-0.2224351	5270	1.2969	-4.0199243
5275	1.2969	12.1586429	5275	-1.455	-2.297623	5275	1.2969	-4.0199243
5279	1.3125	18.1961429	5280	-1.455	-2.297623	5279	1.2969	-4.0199243
5284	1.3125	18.1961429	5284	-1.445	1.85275311	5284	1.3125	2.01757566
5288	1.3125	18.1961429	5288	-1.445	1.85275311	5288	1.3125	2.01757566
5292	1.3125	18.1961429	5293	-1.439	3.92794097	5293	1.2969	-4.0199243
5297	1.2656	0.08364295	5298	-1.439	3.92794097	5298	1.3125	2.01757566
5302	1.2656	0.08364295	5308	-1.45	-0.2224351	5307	1.2969	-4.0199243
5312	1.2813	6.12114295	5311	-1.45	-0.2224351	5311	1.2969	-4.0199243
5315	1.2813	6.12114295	5315	-1.45	-0.2224351	5315	1.3125	2.01757566
5319	1.2813	6.12114295	5320	-1.45	-0.2224351	5320	1.3125	2.01757566
5324	1.2813	6.12114295	5324	-1.45	-0.2224351	5324	1.3125	2.01757566
5328	1.2969	12.1586429	5329	-1.45	-0.2224351	5329	1.3125	2.01757566
5333	1.2969	12.1586429	5333	-1.445	1.85275311	5333	1.2969	-4.0199243
5337	1.2813	6.12114295	5338	-1.445	1.85275311	5338	1.2969	-4.0199243
5342	1.2813	6.12114295	5347	-1.45	-0.2224351	5347	1.2969	-4.0199243
5352	1.25	-5.9538571	5351	-1.45	-0.2224351	5351	1.2969	-4.0199243
5355	1.25	-5.9538571	5356	-1.45	-0.2224351	5356	1.2969	-4.0199243
5360	1.2813	6.12114295	5360	-1.45	-0.2224351	5360	1.2969	-4.0199243
5364	1.2813	6.12114295	5365	-1.455	-2.297623	5365	1.2969	-4.0199243
5369	1.25	-5.9538571	5369	-1.455	-2.297623	5369	1.2969	-4.0199243
5373	1.25	-5.9538571	5374	-1.455	-2.297623	5374	1.2969	-4.0199243
5378	1.2813	6.12114295	5379	-1.455	-2.297623	5379	1.2969	-4.0199243

5383	1.2813	6.12114295	5388	-1.45	-0.2224351	5388	1.2969	-4.0199243
5393	1.2813	6.12114295	5392	-1.45	-0.2224351	5392	1.2969	-4.0199243
5396	1.2813	6.12114295	5396	-1.439	3.92794097	5396	1.3125	2.01757566
5400	1.2969	12.1586429	5401	-1.439	3.92794097	5401	1.3125	2.01757566
5405	1.2969	12.1586429	5405	-1.455	-2.297623	5405	1.3125	2.01757566
5409	1.2656	0.08364295	5410	-1.455	-2.297623	5410	1.3125	2.01757566
5414	1.2656	0.08364295	5414	-1.445	1.85275311	5414	1.2969	-4.0199243
5418	1.2656	0.08364295	5419	-1.445	1.85275311	5419	1.3125	2.01757566
5423	1.2344	-11.991357	5429	-1.445	1.85275311	5428	1.3125	2.01757566
5428	1.2344	-11.991357	5432	-1.445	1.85275311	5432	1.3125	2.01757566
5435	1.25	-5.9538571	5437	-1.445	1.85275311	5437	1.2969	-4.0199243
5438	1.25	-5.9538571	5441	-1.445	1.85275311	5441	1.2969	-4.0199243
5445	1.2656	0.08364295	5446	-1.45	-0.2224351	5446	1.2969	-4.0199243
5449	1.25	-5.9538571	5450	-1.45	-0.2224351	5450	1.2969	-4.0199243
5453	1.25	-5.9538571	5455	-1.45	-0.2224351	5455	1.2969	-4.0199243
5456	1.25	-5.9538571	5466	-1.45	-0.2224351	5466	1.3125	2.01757566
5459	1.25	-5.9538571	5469	-1.45	-0.2224351	5469	1.3125	2.01757566
5464	1.2656	0.08364295	5473	-1.45	-0.2224351	5473	1.3125	2.01757566
5468	1.2656	0.08364295	5477	-1.45	-0.2224351	5477	1.2813	-10.057424
5473	1.25	-5.9538571	5482	-1.45	-0.2224351	5482	1.2813	-10.057424
5482	1.2813	6.12114295	5486	-1.455	-2.297623	5486	1.2969	-4.0199243
5486	1.2813	6.12114295	5491	-1.455	-2.297623	5491	1.2969	-4.0199243
5490	1.25	-5.9538571	5495	-1.45	-0.2224351	5495	1.2969	-4.0199243
5495	1.25	-5.9538571	5500	-1.45	-0.2224351	5506	1.3125	2.01757566
5499	1.25	-5.9538571	5510	-1.45	-0.2224351	5509	1.2969	-4.0199243
5504	1.2813	6.12114295	5513	-1.45	-0.2224351	5514	1.2969	-4.0199243
5508	1.2813	6.12114295	5518	-1.45	-0.2224351	5518	1.3281	8.05507566
5513	1.2813	6.12114295	5522	-1.45	-0.2224351	5522	1.3281	8.05507566
5522	1.3125	18.1961429	5527	-1.445	1.85275311	5527	1.3125	2.01757566
5526	1.3125	18.1961429	5531	-1.445	1.85275311	5531	1.3125	2.01757566
5531	1.2969	12.1586429	5536	-1.455	-2.297623	5536	1.2969	-4.0199243
5535	1.2969	12.1586429	5540	-1.439	3.92794097	5547	1.3125	2.01757566
5540	1.2656	0.08364295	5550	-1.445	1.85275311	5550	1.2813	-10.057424
5544	1.2813	6.12114295	5554	-1.445	1.85275311	5554	1.2813	-10.057424
5549	1.2813	6.12114295	5558	-1.445	1.85275311	5558	1.2969	-4.0199243
5560	1.2656	0.08364295	5563	-1.445	1.85275311	5563	1.2969	-4.0199243
5563	1.2656	0.08364295	5567	-1.45	-0.2224351	5567	1.3281	8.05507566
5567	1.2656	0.08364295	5572	-1.45	-0.2224351	5572	1.3281	8.05507566
5571	1.2813	6.12114295	5576	-1.45	-0.2224351	5576	1.2969	-4.0199243
5576	1.2813	6.12114295	5581	-1.445	1.85275311	5587	1.2969	-4.0199243
5580	1.2813	6.12114295	5591	-1.45	-0.2224351	5590	1.3125	2.01757566

5585	1.2656	0.08364295	5594	-1.45	-0.2224351	5594	1.3125	2.01757566
5589	1.2656	0.08364295	5598	-1.45	-0.2224351	5599	1.2813	-10.057424
5600	1.2969	12.1586429	5603	-1.45	-0.2224351	5603	1.2813	-10.057424
5603	1.2813	6.12114295	5607	-1.445	1.85275311	5607	1.3125	2.01757566
5607	1.2813	6.12114295	5612	-1.445	1.85275311	5612	1.3125	2.01757566
5612	1.2656	0.08364295	5616	-1.455	-2.297623	5617	1.2969	-4.0199243
5616	1.2656	0.08364295	5621	-1.461	-4.3728109	5627	1.2969	-4.0199243
5621	1.2813	6.12114295	5631	-1.455	-2.297623	5630	1.3281	8.05507566
5625	1.2969	12.1586429	5634	-1.455	-2.297623	5634	1.3281	8.05507566
5630	1.2969	12.1586429	5639	-1.45	-0.2224351	5639	1.3125	2.01757566
5640	1.2969	12.1586429	5643	-1.45	-0.2224351	5643	1.3125	2.01757566
5643	1.2813	6.12114295	5648	-1.45	-0.2224351	5648	1.2969	-4.0199243
5647	1.2813	6.12114295	5652	-1.45	-0.2224351	5652	1.2969	-4.0199243
5652	1.2813	6.12114295	5657	-1.455	-2.297623	5657	1.3125	2.01757566
5656	1.2813	6.12114295	5662	-1.45	-0.2224351	5662	1.3125	2.01757566
5661	1.2813	6.12114295	5672	-1.45	-0.2224351	5671	1.3125	2.01757566
5666	1.3125	18.1961429	5675	-1.45	-0.2224351	5675	1.3125	2.01757566
5670	1.3125	18.1961429	5679	-1.45	-0.2224351	5679	1.3125	2.01757566
5679	1.2969	12.1586429	5684	-1.45	-0.2224351	5684	1.3125	2.01757566
5683	1.2813	6.12114295	5688	-1.455	-2.297623	5688	1.3281	8.05507566
5688	1.2813	6.12114295	5693	-1.455	-2.297623	5693	1.3281	8.05507566
5692	1.2813	6.12114295	5697	-1.45	-0.2224351	5697	1.2969	-4.0199243
5697	1.2656	0.08364295	5702	-1.445	1.85275311	5702	1.2969	-4.0199243
5701	1.2656	0.08364295	5711	-1.45	-0.2224351	5711	1.3125	2.01757566
5706	1.2656	0.08364295	5715	-1.45	-0.2224351	5715	1.3125	2.01757566
5710	1.2656	0.08364295	5720	-1.45	-0.2224351	5720	1.2969	-4.0199243
5721	1.25	-5.9538571	5724	-1.45	-0.2224351	5724	1.2969	-4.0199243
5724	1.25	-5.9538571	5729	-1.45	-0.2224351	5729	1.3125	2.01757566
5728	1.25	-5.9538571	5733	-1.455	-2.297623	5733	1.3125	2.01757566
5733	1.2656	0.08364295	5738	-1.455	-2.297623	5738	1.2969	-4.0199243
5737	1.2656	0.08364295	5743	-1.45	-0.2224351	5743	1.2969	-4.0199243
5742	1.2656	0.08364295	5753	-1.445	1.85275311	5752	1.3281	8.05507566
5747	1.2656	0.08364295	5756	-1.445	1.85275311	5756	1.3281	8.05507566
5751	1.2656	0.08364295	5760	-1.445	1.85275311	5760	1.3125	2.01757566
5761	1.2344	-11.991357	5765	-1.445	1.85275311	5765	1.3125	2.01757566
5764	1.2344	-11.991357	5769	-1.45	-0.2224351	5769	1.2969	-4.0199243
5769	1.2344	-11.991357	5774	-1.439	3.92794097	5774	1.2969	-4.0199243
5773	1.2344	-11.991357	5778	-1.439	3.92794097	5778	1.3125	2.01757566
5778	1.2656	0.08364295	5783	-1.45	-0.2224351	5783	1.3125	2.01757566
5782	1.2656	0.08364295	5793	-1.445	1.85275311	5792	1.3281	8.05507566
5787	1.2656	0.08364295	5796	-1.445	1.85275311	5796	1.3281	8.05507566

5791	1.2656	0.08364295	5801	-1.45	-0.2224351	5801	1.3125	2.01757566
5802	1.2813	6.12114295	5805	-1.45	-0.2224351	5805	1.3125	2.01757566
5805	1.2813	6.12114295	5810	-1.45	-0.2224351	5810	1.3125	2.01757566
5809	1.2656	0.08364295	5814	-1.439	3.92794097	5814	1.3125	2.01757566
5814	1.2656	0.08364295	5819	-1.439	3.92794097	5820	1.3125	2.01757566
5818	1.2656	0.08364295	5824	-1.45	-0.2224351	5823	1.3125	2.01757566
5823	1.2656	0.08364295	5833	-1.455	-2.297623	5834	1.2969	-4.0199243
5827	1.25	-5.9538571	5837	-1.455	-2.297623	5837	1.2969	-4.0199243
5832	1.25	-5.9538571	5841	-1.445	1.85275311	5841	1.3125	2.01757566
5842	1.2656	0.08364295	5846	-1.445	1.85275311	5846	1.3125	2.01757566
5845	1.2656	0.08364295	5850	-1.455	-2.297623	5850	1.3281	8.05507566
5850	1.2656	0.08364295	5855	-1.455	-2.297623	5855	1.3281	8.05507566
5854	1.2656	0.08364295	5859	-1.455	-2.297623	5859	1.3125	2.01757566
5859	1.25	-5.9538571	5864	-1.455	-2.297623	5870	1.2969	-4.0199243
5863	1.25	-5.9538571	5873	-1.45	-0.2224351	5873	1.2969	-4.0199243
5868	1.25	-5.9538571	5877	-1.45	-0.2224351	5877	1.3125	2.01757566
5872	1.25	-5.9538571	5882	-1.45	-0.2224351	5882	1.2969	-4.0199243
5883	1.2656	0.08364295	5886	-1.45	-0.2224351	5886	1.2969	-4.0199243
5886	1.2656	0.08364295	5891	-1.45	-0.2224351	5891	1.3125	2.01757566
5890	1.2813	6.12114295	5895	-1.45	-0.2224351	5895	1.3125	2.01757566
5895	1.2813	6.12114295	5900	-1.45	-0.2224351	5900	1.2969	-4.0199243
5899	1.2813	6.12114295	5904	-1.455	-2.297623	5911	1.2969	-4.0199243
5904	1.2813	6.12114295	5914	-1.45	-0.2224351	5914	1.2969	-4.0199243
5908	1.2656	0.08364295	5918	-1.45	-0.2224351	5918	1.2969	-4.0199243
5913	1.2656	0.08364295	5922	-1.445	1.85275311	5922	1.2969	-4.0199243
5923	1.2656	0.08364295	5927	-1.445	1.85275311	5926	1.3125	2.01757566
5926	1.2656	0.08364295	5931	-1.445	1.85275311	5931	1.3125	2.01757566
5931	1.2656	0.08364295	5935	-1.45	-0.2224351	5935	1.3125	2.01757566
5935	1.2656	0.08364295	5940	-1.45	-0.2224351	5940	1.3125	2.01757566
5940	1.2344	-11.991357	5945	-1.455	-2.297623	5951	1.2969	-4.0199243
5944	1.2344	-11.991357	5955	-1.445	1.85275311	5954	1.2969	-4.0199243
5949	1.2344	-11.991357	5958	-1.445	1.85275311	5958	1.3125	2.01757566
5953	1.2344	-11.991357	5962	-1.445	1.85275311	5962	1.3125	2.01757566
5964	1.25	-5.9538571	5967	-1.45	-0.2224351	5967	1.2969	-4.0199243
5967	1.25	-5.9538571	5971	-1.45	-0.2224351	5971	1.3125	2.01757566
5971	1.25	-5.9538571	5976	-1.45	-0.2224351	5976	1.3125	2.01757566
5975	1.25	-5.9538571	5980	-1.45	-0.2224351	5981	1.3125	2.01757566
5980	1.2656	0.08364295	5985	-1.45	-0.2224351	5991	1.3125	2.01757566
5984	1.2656	0.08364295	5995	-1.45	-0.2224351	5994	1.3125	2.01757566
5989	1.2813	6.12114295	5998	-1.45	-0.2224351	5998	1.2969	-4.0199243
5993	1.2813	6.12114295	6003	-1.445	1.85275311	6003	1.2969	-4.0199243

6004	1.2813	6.12114295	6007	-1.445	1.85275311	6007	1.3125	2.01757566
6007	1.2813	6.12114295	6012	-1.445	1.85275311	6012	1.2969	-4.0199243
6011	1.2969	12.1586429	6016	-1.455	-2.297623	6016	1.2969	-4.0199243
6016	1.2969	12.1586429	6021	-1.455	-2.297623	6021	1.3125	2.01757566
6020	1.2813	6.12114295	6026	-1.455	-2.297623	6026	1.3125	2.01757566
6025	1.2813	6.12114295	6035	-1.455	-2.297623	6035	1.3125	2.01757566
6030	1.2656	0.08364295	6039	-1.445	1.85275311	6039	1.3281	8.05507566
6034	1.2656	0.08364295	6043	-1.445	1.85275311	6043	1.3281	8.05507566
6044	1.2656	0.08364295	6048	-1.455	-2.297623	6048	1.2969	-4.0199243
6047	1.2656	0.08364295	6052	-1.455	-2.297623	6052	1.2969	-4.0199243
6052	1.25	-5.9538571	6057	-1.455	-2.297623	6057	1.2969	-4.0199243
6056	1.25	-5.9538571	6061	-1.455	-2.297623	6061	1.2813	-10.057424
6061	1.25	-5.9538571	6066	-1.45	-0.2224351	6072	1.3125	2.01757566
6065	1.25	-5.9538571	6076	-1.455	-2.297623	6075	1.3125	2.01757566
6070	1.2656	0.08364295	6079	-1.455	-2.297623	6079	1.3281	8.05507566
6074	1.2813	6.12114295	6084	-1.455	-2.297623	6084	1.3281	8.05507566
6085	1.25	-5.9538571	6088	-1.439	3.92794097	6088	1.3125	2.01757566
6088	1.25	-5.9538571	6093	-1.439	3.92794097	6093	1.3125	2.01757566
6092	1.2656	0.08364295	6097	-1.445	1.85275311	6097	1.3125	2.01757566
6097	1.2656	0.08364295	6102	-1.445	1.85275311	6102	1.2969	-4.0199243
6101	1.2656	0.08364295	6113	-1.455	-2.297623	6113	1.2969	-4.0199243
6106	1.2656	0.08364295	6116	-1.455	-2.297623	6116	1.2969	-4.0199243
6111	1.2656	0.08364295	6120	-1.445	1.85275311	6120	1.3125	2.01757566
6115	1.2656	0.08364295	6124	-1.445	1.85275311	6124	1.3125	2.01757566
6125	1.2656	0.08364295	6129	-1.445	1.85275311	6129	1.3125	2.01757566
6128	1.2656	0.08364295	6133	-1.445	1.85275311	6133	1.3125	2.01757566
6133	1.2813	6.12114295	6138	-1.445	1.85275311	6138	1.3125	2.01757566
6137	1.2813	6.12114295	6142	-1.445	1.85275311	6142	1.3125	2.01757566
6142	1.2656	0.08364295	6147	-1.45	-0.2224351	6153	1.3125	2.01757566
6146	1.2656	0.08364295	6157	-1.445	1.85275311	6156	1.3125	2.01757566
6151	1.2969	12.1586429	6160	-1.445	1.85275311	6160	1.3125	2.01757566
6155	1.2344	-11.991357	6165	-1.445	1.85275311	6165	1.3125	2.01757566
6166	1.25	-5.9538571	6169	-1.439	3.92794097	6169	1.3281	8.05507566
6169	1.25	-5.9538571	6174	-1.439	3.92794097	6174	1.3281	8.05507566
6173	1.2656	0.08364295	6178	-1.439	3.92794097	6178	1.3125	2.01757566
6178	1.2656	0.08364295	6183	-1.439	3.92794097	6183	1.3281	8.05507566
6182	1.2656	0.08364295	6187	-1.455	-2.297623	6194	1.2969	-4.0199243
6187	1.2656	0.08364295	6197	-1.455	-2.297623	6197	1.2969	-4.0199243
6191	1.25	-5.9538571	6201	-1.455	-2.297623	6201	1.3125	2.01757566
6196	1.25	-5.9538571	6205	-1.455	-2.297623	6205	1.3125	2.01757566
6206	1.2813	6.12114295	6210	-1.45	-0.2224351	6210	1.3125	2.01757566

6209	1.2813	6.12114295	6214	-1.45	-0.2224351	6214	1.3125	2.01757566
6214	1.2656	0.08364295	6219	-1.45	-0.2224351	6219	1.2969	-4.0199243
6218	1.2656	0.08364295	6223	-1.45	-0.2224351	6223	1.2969	-4.0199243
6223	1.2969	12.1586429	6228	-1.45	-0.2224351	6228	1.2969	-4.0199243
6227	1.2969	12.1586429	6237	-1.455	-2.297623	6238	1.3125	2.01757566
6232	1.2813	6.12114295	6241	-1.439	3.92794097	6241	1.3125	2.01757566
6236	1.2969	12.1586429	6246	-1.439	3.92794097	6246	1.3125	2.01757566
6247	1.2656	0.08364295	6250	-1.455	-2.297623	6250	1.3125	2.01757566
6250	1.2656	0.08364295	6254	-1.455	-2.297623	6254	1.3125	2.01757566
6254	1.2656	0.08364295	6259	-1.455	-2.297623	6259	1.3125	2.01757566
6259	1.2656	0.08364295	6263	-1.455	-2.297623	6263	1.3125	2.01757566
6263	1.2656	0.08364295	6268	-1.455	-2.297623	6275	1.2969	-4.0199243
6268	1.2656	0.08364295	6278	-1.455	-2.297623	6278	1.2969	-4.0199243
6272	1.2656	0.08364295	6281	-1.45	-0.2224351	6281	1.2969	-4.0199243
6277	1.2656	0.08364295	6286	-1.45	-0.2224351	6286	1.2969	-4.0199243
6287	1.25	-5.9538571	6290	-1.455	-2.297623	6290	1.3125	2.01757566
6290	1.25	-5.9538571	6295	-1.455	-2.297623	6295	1.3125	2.01757566
6295	1.2344	-11.991357	6299	-1.45	-0.2224351	6299	1.3125	2.01757566
6299	1.2344	-11.991357	6304	-1.45	-0.2224351	6304	1.2969	-4.0199243
6303	1.2344	-11.991357	6309	-1.445	1.85275311	6309	1.2969	-4.0199243
6308	1.25	-5.9538571	6319	-1.455	-2.297623	6319	1.2969	-4.0199243
6313	1.25	-5.9538571	6322	-1.455	-2.297623	6322	1.2969	-4.0199243
6317	1.2656	0.08364295	6326	-1.455	-2.297623	6326	1.2969	-4.0199243
6327	1.25	-5.9538571	6331	-1.45	-0.2224351	6331	1.3125	2.01757566
6331	1.25	-5.9538571	6335	-1.45	-0.2224351	6335	1.3125	2.01757566
6335	1.2656	0.08364295	6340	-1.455	-2.297623	6340	1.2969	-4.0199243
6339	1.2656	0.08364295	6344	-1.455	-2.297623	6344	1.2969	-4.0199243
6344	1.2656	0.08364295	6349	-1.45	-0.2224351	6349	1.2969	-4.0199243
6348	1.2656	0.08364295	6358	-1.445	1.85275311	6359	1.3125	2.01757566
6353	1.2656	0.08364295	6362	-1.455	-2.297623	6362	1.3125	2.01757566
6357	1.25	-5.9538571	6367	-1.455	-2.297623	6367	1.3125	2.01757566
6368	1.25	-5.9538571	6371	-1.45	-0.2224351	6371	1.2969	-4.0199243
6371	1.25	-5.9538571	6376	-1.45	-0.2224351	6376	1.2969	-4.0199243
6375	1.25	-5.9538571	6380	-1.45	-0.2224351	6380	1.3125	2.01757566
6380	1.25	-5.9538571	6385	-1.45	-0.2224351	6385	1.3125	2.01757566
6384	1.2656	0.08364295	6390	-1.45	-0.2224351	6390	1.3125	2.01757566
6389	1.25	-5.9538571	6400	-1.439	3.92794097	6400	1.3281	8.05507566
6394	1.25	-5.9538571	6403	-1.45	-0.2224351	6403	1.3125	2.01757566
6398	1.25	-5.9538571	6407	-1.45	-0.2224351	6407	1.3125	2.01757566
6408	1.25	-5.9538571	6412	-1.45	-0.2224351	6412	1.3125	2.01757566
6411	1.25	-5.9538571	6416	-1.45	-0.2224351	6416	1.3125	2.01757566

6416	1.2656	0.08364295	6421	-1.455	-2.297623	6421	1.3125	2.01757566
6420	1.2656	0.08364295	6425	-1.455	-2.297623	6425	1.3125	2.01757566
6425	1.2656	0.08364295	6430	-1.445	1.85275311	6430	1.3125	2.01757566
6429	1.2344	-11.991357	6439	-1.445	1.85275311	6440	1.3125	2.01757566
6434	1.2344	-11.991357	6443	-1.45	-0.2224351	6443	1.2969	-4.0199243
6438	1.25	-5.9538571	6448	-1.45	-0.2224351	6448	1.2969	-4.0199243
6449	1.2656	0.08364295	6452	-1.45	-0.2224351	6452	1.2969	-4.0199243
6452	1.2656	0.08364295	6457	-1.45	-0.2224351	6457	1.2969	-4.0199243
6456	1.2656	0.08364295	6461	-1.445	1.85275311	6461	1.2969	-4.0199243
6461	1.25	-5.9538571	6466	-1.45	-0.2224351	6466	1.2969	-4.0199243
6465	1.25	-5.9538571	6471	-1.45	-0.2224351	6477	1.3281	8.05507566
6470	1.25	-5.9538571	6480	-1.45	-0.2224351	6480	1.3281	8.05507566
6474	1.25	-5.9538571	6484	-1.45	-0.2224351	6484	1.2969	-4.0199243
6479	1.2656	0.08364295	6488	-1.45	-0.2224351	6488	1.2969	-4.0199243
6489	1.2344	-11.991357	6493	-1.455	-2.297623	6493	1.3125	2.01757566
6492	1.2344	-11.991357	6497	-1.455	-2.297623	6497	1.3125	2.01757566
6497	1.25	-5.9538571	6502	-1.45	-0.2224351	6502	1.3281	8.05507566
6501	1.25	-5.9538571	6506	-1.445	1.85275311	6506	1.3281	8.05507566
6506	1.25	-5.9538571	6511	-1.445	1.85275311	6511	1.3125	2.01757566
6510	1.25	-5.9538571	6521	-1.45	-0.2224351	6521	1.2969	-4.0199243
6515	1.25	-5.9538571	6524	-1.445	1.85275311	6524	1.3125	2.01757566
6519	1.25	-5.9538571	6529	-1.445	1.85275311	6529	1.3125	2.01757566
6530	1.2656	0.08364295	6533	-1.445	1.85275311	6533	1.3281	8.05507566
6533	1.25	-5.9538571	6538	-1.445	1.85275311	6538	1.3281	8.05507566
6537	1.25	-5.9538571	6542	-1.445	1.85275311	6542	1.3281	8.05507566
6542	1.2813	6.12114295	6547	-1.445	1.85275311	6547	1.3281	8.05507566
6546	1.2813	6.12114295	6551	-1.445	1.85275311	6558	1.2969	-4.0199243
6551	1.2813	6.12114295	6561	-1.45	-0.2224351	6561	1.2969	-4.0199243
6555	1.2813	6.12114295	6565	-1.45	-0.2224351	6565	1.2969	-4.0199243
6560	1.2656	0.08364295	6569	-1.45	-0.2224351	6569	1.2969	-4.0199243
6570	1.2656	0.08364295	6574	-1.445	1.85275311	6574	1.2969	-4.0199243
6573	1.2813	6.12114295	6578	-1.445	1.85275311	6578	1.2969	-4.0199243
6578	1.2813	6.12114295	6583	-1.45	-0.2224351	6583	1.3125	2.01757566
6582	1.2813	6.12114295	6587	-1.45	-0.2224351	6587	1.3125	2.01757566
6587	1.2813	6.12114295	6592	-1.45	-0.2224351	6600	1.2969	-4.0199243
6591	1.2813	6.12114295	6602	-1.445	1.85275311	6603	1.2969	-4.0199243
6596	1.2813	6.12114295	6605	-1.439	3.92794097	6607	1.3125	2.01757566
6600	1.2813	6.12114295	6609	-1.439	3.92794097	6610	1.3125	2.01757566
6611	1.2969	12.1586429	6614	-1.455	-2.297623	6614	1.2969	-4.0199243
6614	1.2969	12.1586429	6618	-1.455	-2.297623	6618	1.2969	-4.0199243
6618	1.2969	12.1586429	6623	-1.45	-0.2224351	6623	1.2813	-10.057424

6623	1.2969	12.1586429	6627	-1.45	-0.2224351	6627	1.2813	-10.057424
6627	1.2969	12.1586429	6632	-1.45	-0.2224351	6632	1.3125	2.01757566
6632	1.2656	0.08364295	6642	-1.445	1.85275311	6642	1.3125	2.01757566
6636	1.2656	0.08364295	6645	-1.45	-0.2224351	6645	1.3125	2.01757566
6640	1.2656	0.08364295	6650	-1.45	-0.2224351	6650	1.3125	2.01757566
6651	1.2656	0.08364295	6654	-1.45	-0.2224351	6654	1.3125	2.01757566
6654	1.25	-5.9538571	6659	-1.445	1.85275311	6659	1.3125	2.01757566
6658	1.25	-5.9538571	6663	-1.445	1.85275311	6663	1.3125	2.01757566
6663	1.2656	0.08364295	6668	-1.445	1.85275311	6668	1.3125	2.01757566
6667	1.2656	0.08364295	6673	-1.445	1.85275311	6673	1.3125	2.01757566
6672	1.2656	0.08364295	6683	-1.45	-0.2224351	6683	1.2969	-4.0199243
6677	1.2656	0.08364295	6686	-1.455	-2.297623	6686	1.2969	-4.0199243
6681	1.2813	6.12114295	6690	-1.455	-2.297623	6690	1.2969	-4.0199243
6691	1.2969	12.1586429	6695	-1.45	-0.2224351	6695	1.2969	-4.0199243
6694	1.2813	6.12114295	6699	-1.455	-2.297623	6699	1.2969	-4.0199243
6699	1.2813	6.12114295	6704	-1.455	-2.297623	6704	1.2969	-4.0199243
6703	1.2813	6.12114295	6708	-1.434	6.00312883	6708	1.2969	-4.0199243
6708	1.2813	6.12114295	6713	-1.434	6.00312883	6713	1.3438	14.0925757
6712	1.2656	0.08364295	6723	-1.445	1.85275311	6723	1.2969	-4.0199243
6717	1.2656	0.08364295	6726	-1.45	-0.2224351	6726	1.3125	2.01757566
6721	1.2656	0.08364295	6731	-1.45	-0.2224351	6731	1.3125	2.01757566
6732	1.2656	0.08364295	6735	-1.445	1.85275311	6735	1.3125	2.01757566
6735	1.2813	6.12114295	6740	-1.445	1.85275311	6740	1.3125	2.01757566
6739	1.2813	6.12114295	6744	-1.445	1.85275311	6744	1.3125	2.01757566
6744	1.2656	0.08364295	6749	-1.45	-0.2224351	6749	1.3125	2.01757566
6748	1.2656	0.08364295	6754	-1.45	-0.2224351	6754	1.3125	2.01757566
6753	1.2656	0.08364295	6764	-1.45	-0.2224351	6764	1.3281	8.05507566
6758	1.2656	0.08364295	6767	-1.45	-0.2224351	6767	1.3125	2.01757566
6762	1.2344	-11.991357	6771	-1.45	-0.2224351	6771	1.3125	2.01757566
6772	1.2344	-11.991357	6776	-1.445	1.85275311	6776	1.3125	2.01757566
6775	1.2344	-11.991357	6780	-1.45	-0.2224351	6780	1.3125	2.01757566
6780	1.2344	-11.991357	6785	-1.45	-0.2224351	6785	1.2969	-4.0199243
6784	1.2344	-11.991357	6789	-1.45	-0.2224351	6789	1.2969	-4.0199243
6789	1.2344	-11.991357	6794	-1.45	-0.2224351	6794	1.3281	8.05507566
6793	1.25	-5.9538571	6804	-1.45	-0.2224351	6804	1.3125	2.01757566
6798	1.25	-5.9538571	6807	-1.45	-0.2224351	6807	1.2969	-4.0199243
6802	1.25	-5.9538571	6812	-1.45	-0.2224351	6812	1.2969	-4.0199243
6813	1.25	-5.9538571	6816	-1.455	-2.297623	6816	1.2969	-4.0199243
6816	1.2813	6.12114295	6821	-1.45	-0.2224351	6821	1.2969	-4.0199243
6820	1.2813	6.12114295	6825	-1.45	-0.2224351	6825	1.3125	2.01757566
6825	1.2656	0.08364295	6830	-1.45	-0.2224351	6830	1.3125	2.01757566

6829	1.2656	0.08364295	6841	-1.445	1.85275311	6841	1.3125	2.01757566
6834	1.2656	0.08364295	6844	-1.455	-2.297623	6844	1.3125	2.01757566
6838	1.2656	0.08364295	6848	-1.455	-2.297623	6848	1.3281	8.05507566
6843	1.2344	-11.991357	6852	-1.45	-0.2224351	6852	1.3281	8.05507566
6853	1.25	-5.9538571	6857	-1.45	-0.2224351	6857	1.3125	2.01757566
6856	1.25	-5.9538571	6861	-1.455	-2.297623	6861	1.3125	2.01757566
6861	1.25	-5.9538571	6866	-1.455	-2.297623	6866	1.3125	2.01757566
6865	1.25	-5.9538571	6870	-1.445	1.85275311	6870	1.3125	2.01757566
6870	1.25	-5.9538571	6875	-1.445	1.85275311	6875	1.2969	-4.0199243
6874	1.25	-5.9538571	6885	-1.45	-0.2224351	6885	1.3125	2.01757566
6879	1.25	-5.9538571	6888	-1.45	-0.2224351	6888	1.3125	2.01757566
6883	1.25	-5.9538571	6893	-1.439	3.92794097	6893	1.3125	2.01757566
6894	1.2344	-11.991357	6897	-1.439	3.92794097	6897	1.3125	2.01757566
6897	1.25	-5.9538571	6901	-1.45	-0.2224351	6902	1.3125	2.01757566
6901	1.25	-5.9538571	6906	-1.45	-0.2224351	6906	1.2969	-4.0199243
6906	1.25	-5.9538571	6910	-1.45	-0.2224351	6911	1.2969	-4.0199243
6910	1.25	-5.9538571	6915	-1.45	-0.2224351	6922	1.3125	2.01757566
6915	1.2656	0.08364295	6924	-1.45	-0.2224351	6925	1.3125	2.01757566
6919	1.2344	-11.991357	6929	-1.45	-0.2224351	6929	1.3125	2.01757566
6924	1.2344	-11.991357	6933	-1.439	3.92794097	6933	1.3125	2.01757566
6934	1.2656	0.08364295	6938	-1.439	3.92794097	6938	1.3125	2.01757566
6937	1.25	-5.9538571	6942	-1.445	1.85275311	6942	1.3125	2.01757566
6942	1.25	-5.9538571	6946	-1.445	1.85275311	6946	1.2969	-4.0199243
6946	1.2656	0.08364295	6951	-1.434	6.00312883	6951	1.2969	-4.0199243
6951	1.2656	0.08364295	6956	-1.434	6.00312883	6956	1.3281	8.05507566
6955	1.2813	6.12114295	6966	-1.439	3.92794097	6966	1.3125	2.01757566
6960	1.2969	12.1586429	6969	-1.439	3.92794097	6969	1.2969	-4.0199243
6964	1.2969	12.1586429	6973	-1.445	1.85275311	6973	1.2969	-4.0199243
6974	1.25	-5.9538571	6978	-1.445	1.85275311	6978	1.2969	-4.0199243
6978	1.2656	0.08364295	6982	-1.445	1.85275311	6982	1.2969	-4.0199243
6982	1.2656	0.08364295	6987	-1.445	1.85275311	6987	1.3125	2.01757566
6986	1.2656	0.08364295	6991	-1.445	1.85275311	6991	1.3125	2.01757566
6991	1.2656	0.08364295	6996	-1.445	1.85275311	6996	1.3125	2.01757566
6995	1.2813	6.12114295	7006	-1.455	-2.297623	7006	1.3281	8.05507566
7000	1.2813	6.12114295	7009	-1.455	-2.297623	7009	1.3281	8.05507566
7004	1.2813	6.12114295	7014	-1.445	1.85275311	7014	1.3281	8.05507566
7015	1.2656	0.08364295	7018	-1.445	1.85275311	7018	1.3125	2.01757566
7018	1.2656	0.08364295	7023	-1.445	1.85275311	7023	1.3125	2.01757566
7022	1.2656	0.08364295	7027	-1.445	1.85275311	7027	1.3125	2.01757566
7027	1.25	-5.9538571	7032	-1.455	-2.297623	7032	1.3125	2.01757566
7031	1.25	-5.9538571	7037	-1.455	-2.297623	7037	1.2969	-4.0199243

7036	1.2656	0.08364295	7047	-1.455	-2.297623	7047	1.3281	8.05507566
7041	1.2656	0.08364295	7050	-1.455	-2.297623	7050	1.3125	2.01757566
7045	1.2656	0.08364295	7054	-1.466	-6.4479991	7054	1.3125	2.01757566
7055	1.2656	0.08364295	7059	-1.466	-6.4479991	7059	1.2813	-10.057424
7058	1.2656	0.08364295	7063	-1.445	1.85275311	7063	1.2813	-10.057424
7063	1.2656	0.08364295	7068	-1.445	1.85275311	7068	1.2969	-4.0199243
7067	1.2656	0.08364295	7072	-1.45	-0.2224351	7072	1.2969	-4.0199243
7072	1.2656	0.08364295	7077	-1.45	-0.2224351	7077	1.3125	2.01757566
7076	1.2656	0.08364295	7087	-1.455	-2.297623	7087	1.3125	2.01757566
7081	1.2813	6.12114295	7090	-1.455	-2.297623	7090	1.3125	2.01757566
7085	1.2813	6.12114295	7095	-1.45	-0.2224351	7095	1.3125	2.01757566
7096	1.2656	0.08364295	7099	-1.45	-0.2224351	7099	1.3125	2.01757566
7099	1.2656	0.08364295	7104	-1.461	-4.3728109	7104	1.3125	2.01757566
7103	1.2656	0.08364295	7108	-1.461	-4.3728109	7108	1.2969	-4.0199243
7108	1.2656	0.08364295	7113	-1.45	-0.2224351	7113	1.2969	-4.0199243
7112	1.2656	0.08364295	7124	-1.45	-0.2224351	7124	1.3281	8.05507566
7117	1.2656	0.08364295	7127	-1.45	-0.2224351	7127	1.3281	8.05507566
7121	1.25	-5.9538571	7131	-1.45	-0.2224351	7131	1.3281	8.05507566
7126	1.25	-5.9538571	7135	-1.455	-2.297623	7135	1.2969	-4.0199243
7136	1.25	-5.9538571	7140	-1.455	-2.297623	7140	1.3125	2.01757566
7139	1.25	-5.9538571	7144	-1.455	-2.297623	7144	1.3125	2.01757566
7144	1.25	-5.9538571	7149	-1.455	-2.297623	7149	1.2969	-4.0199243
7148	1.2656	0.08364295	7153	-1.461	-4.3728109	7153	1.2969	-4.0199243
7153	1.2656	0.08364295	7158	-1.461	-4.3728109	7158	1.3125	2.01757566
7157	1.2656	0.08364295	7168	-1.445	1.85275311	7168	1.3125	2.01757566
7162	1.25	-5.9538571	7171	-1.445	1.85275311	7171	1.3125	2.01757566
7166	1.25	-5.9538571	7176	-1.45	-0.2224351	7176	1.2969	-4.0199243
7177	1.2813	6.12114295	7180	-1.45	-0.2224351	7180	1.2969	-4.0199243
7180	1.2813	6.12114295	7185	-1.45	-0.2224351	7185	1.2969	-4.0199243
7184	1.2813	6.12114295	7189	-1.45	-0.2224351	7189	1.3125	2.01757566
7189	1.2969	12.1586429	7194	-1.45	-0.2224351	7194	1.3125	2.01757566
7193	1.2656	0.08364295	7198	-1.45	-0.2224351	7205	1.3125	2.01757566
7198	1.2656	0.08364295	7208	-1.445	1.85275311	7208	1.3125	2.01757566
7202	1.25	-5.9538571	7212	-1.445	1.85275311	7212	1.3125	2.01757566
7207	1.25	-5.9538571	7216	-1.445	1.85275311	7216	1.2969	-4.0199243
7217	1.2813	6.12114295	7221	-1.445	1.85275311	7221	1.3125	2.01757566
7220	1.2813	6.12114295	7225	-1.45	-0.2224351	7225	1.3125	2.01757566
7225	1.25	-5.9538571	7230	-1.45	-0.2224351	7230	1.2969	-4.0199243
7229	1.25	-5.9538571	7234	-1.45	-0.2224351	7234	1.2969	-4.0199243
7234	1.2656	0.08364295	7239	-1.45	-0.2224351	7239	1.3125	2.01757566
7238	1.2656	0.08364295	7249	-1.455	-2.297623	7249	1.3125	2.01757566

7243	1.25	-5.9538571	7252	-1.455	-2.297623	7252	1.3125	2.01757566
7247	1.25	-5.9538571	7256	-1.445	1.85275311	7257	1.2969	-4.0199243
7258	1.2344	-11.991357	7261	-1.445	1.85275311	7261	1.3281	8.05507566
7261	1.2344	-11.991357	7265	-1.445	1.85275311	7265	1.3281	8.05507566
7265	1.2344	-11.991357	7270	-1.445	1.85275311	7270	1.2969	-4.0199243
7270	1.2344	-11.991357	7274	-1.45	-0.2224351	7274	1.2969	-4.0199243
7274	1.25	-5.9538571	7279	-1.45	-0.2224351	7279	1.2969	-4.0199243
7279	1.25	-5.9538571	7289	-1.45	-0.2224351	7289	1.3125	2.01757566
7283	1.2813	6.12114295	7292	-1.45	-0.2224351	7292	1.3125	2.01757566
7288	1.2813	6.12114295	7297	-1.461	-4.3728109	7297	1.3125	2.01757566
7298	1.2656	0.08364295	7301	-1.461	-4.3728109	7301	1.3281	8.05507566
7301	1.2656	0.08364295	7306	-1.445	1.85275311	7306	1.3281	8.05507566
7306	1.25	-5.9538571	7310	-1.445	1.85275311	7310	1.2969	-4.0199243
7310	1.25	-5.9538571	7315	-1.445	1.85275311	7315	1.2969	-4.0199243
7314	1.25	-5.9538571	7320	-1.45	-0.2224351	7320	1.3125	2.01757566
7319	1.25	-5.9538571	7329	-1.445	1.85275311	7330	1.3281	8.05507566
7324	1.25	-5.9538571	7333	-1.445	1.85275311	7333	1.3281	8.05507566
7328	1.25	-5.9538571	7337	-1.45	-0.2224351	7337	1.2969	-4.0199243
7338	1.2656	0.08364295	7342	-1.45	-0.2224351	7342	1.3125	2.01757566
7341	1.2656	0.08364295	7346	-1.455	-2.297623	7346	1.3125	2.01757566
7346	1.25	-5.9538571	7351	-1.455	-2.297623	7351	1.3281	8.05507566
7350	1.25	-5.9538571	7355	-1.45	-0.2224351	7355	1.3281	8.05507566
7355	1.25	-5.9538571	7360	-1.439	3.92794097	7360	1.3281	8.05507566
7359	1.25	-5.9538571	7370	-1.455	-2.297623	7370	1.3125	2.01757566
7364	1.2813	6.12114295	7373	-1.455	-2.297623	7373	1.3125	2.01757566
7369	1.2813	6.12114295	7378	-1.455	-2.297623	7378	1.3125	2.01757566
7379	1.2813	6.12114295	7382	-1.455	-2.297623	7382	1.3125	2.01757566
7382	1.2813	6.12114295	7387	-1.45	-0.2224351	7387	1.3125	2.01757566
7386	1.2813	6.12114295	7391	-1.45	-0.2224351	7391	1.3281	8.05507566
7391	1.2813	6.12114295	7396	-1.445	1.85275311	7396	1.3281	8.05507566
7395	1.2813	6.12114295	7401	-1.445	1.85275311	7401	1.3125	2.01757566
7400	1.2813	6.12114295	7411	-1.45	-0.2224351	7411	1.2969	-4.0199243
7405	1.2813	6.12114295	7414	-1.45	-0.2224351	7414	1.2969	-4.0199243
7409	1.2813	6.12114295	7418	-1.45	-0.2224351	7418	1.2969	-4.0199243
7419	1.2813	6.12114295	7423	-1.45	-0.2224351	7423	1.2969	-4.0199243
7422	1.2813	6.12114295	7427	-1.461	-4.3728109	7427	1.3125	2.01757566
7427	1.2813	6.12114295	7432	-1.455	-2.297623	7432	1.2969	-4.0199243
7431	1.2813	6.12114295	7436	-1.455	-2.297623	7436	1.2969	-4.0199243
7436	1.2813	6.12114295	7441	-1.455	-2.297623	7441	1.3281	8.05507566
7440	1.2813	6.12114295	7451	-1.461	-4.3728109	7451	1.3125	2.01757566
7445	1.2656	0.08364295	7454	-1.461	-4.3728109	7454	1.3125	2.01757566

7449	1.2656	0.08364295	7459	-1.45	-0.2224351	7459	1.3125	2.01757566
7460	1.2656	0.08364295	7463	-1.45	-0.2224351	7463	1.3125	2.01757566
7463	1.2656	0.08364295	7468	-1.45	-0.2224351	7468	1.2969	-4.0199243
7467	1.2656	0.08364295	7472	-1.455	-2.297623	7472	1.3125	2.01757566
7472	1.2656	0.08364295	7477	-1.455	-2.297623	7477	1.3125	2.01757566
7476	1.2656	0.08364295	7488	-1.45	-0.2224351	7488	1.2969	-4.0199243
7481	1.2656	0.08364295	7491	-1.45	-0.2224351	7491	1.2969	-4.0199243
7485	1.2656	0.08364295	7495	-1.45	-0.2224351	7495	1.2969	-4.0199243
7490	1.2656	0.08364295	7499	-1.445	1.85275311	7499	1.2813	-10.057424
7500	1.2344	-11.991357	7504	-1.445	1.85275311	7504	1.2813	-10.057424
7503	1.2344	-11.991357	7508	-1.45	-0.2224351	7508	1.2969	-4.0199243
7508	1.25	-5.9538571	7513	-1.45	-0.2224351	7513	1.2969	-4.0199243
7512	1.25	-5.9538571	7517	-1.45	-0.2224351	7517	1.2969	-4.0199243
7517	1.2188	-18.028857	7522	-1.445	1.85275311	7522	1.2969	-4.0199243
7521	1.2188	-18.028857	7532	-1.455	-2.297623	7532	1.3125	2.01757566
7526	1.2344	-11.991357	7535	-1.455	-2.297623	7535	1.3125	2.01757566
7530	1.2344	-11.991357	7540	-1.445	1.85275311	7540	1.3125	2.01757566
7541	1.25	-5.9538571	7544	-1.445	1.85275311	7544	1.3125	2.01757566
7544	1.25	-5.9538571	7549	-1.445	1.85275311	7549	1.2969	-4.0199243
7548	1.2188	-18.028857	7553	-1.45	-0.2224351	7553	1.2969	-4.0199243
7553	1.2188	-18.028857	7558	-1.45	-0.2224351	7558	1.2969	-4.0199243
7557	1.2344	-11.991357	7562	-1.455	-2.297623	7569	1.3125	2.01757566
7562	1.2344	-11.991357	7572	-1.445	1.85275311	7572	1.3125	2.01757566
7566	1.2344	-11.991357	7576	-1.445	1.85275311	7576	1.3125	2.01757566
7571	1.2344	-11.991357	7580	-1.445	1.85275311	7580	1.2969	-4.0199243
7581	1.2656	0.08364295	7585	-1.445	1.85275311	7585	1.2969	-4.0199243
7584	1.2656	0.08364295	7589	-1.45	-0.2224351	7589	1.2969	-4.0199243
7589	1.2656	0.08364295	7594	-1.455	-2.297623	7593	1.3125	2.01757566
7593	1.2656	0.08364295	7598	-1.455	-2.297623	7598	1.3125	2.01757566
7598	1.2813	6.12114295	7603	-1.445	1.85275311	7603	1.3125	2.01757566
7602	1.2813	6.12114295	7613	-1.45	-0.2224351	7613	1.2969	-4.0199243
7607	1.2969	12.1586429	7616	-1.45	-0.2224351	7616	1.2969	-4.0199243
7611	1.2813	6.12114295	7620	-1.434	6.00312883	7620	1.3125	2.01757566
7622	1.2969	12.1586429	7625	-1.45	-0.2224351	7625	1.3125	2.01757566
7625	1.2969	12.1586429	7629	-1.45	-0.2224351	7629	1.2969	-4.0199243
7629	1.2813	6.12114295	7634	-1.45	-0.2224351	7634	1.3281	8.05507566
7633	1.2813	6.12114295	7638	-1.45	-0.2224351	7638	1.3281	8.05507566
7638	1.2813	6.12114295	7643	-1.455	-2.297623	7643	1.3125	2.01757566
7643	1.2813	6.12114295	7652	-1.455	-2.297623	7653	1.3125	2.01757566
7647	1.2656	0.08364295	7656	-1.455	-2.297623	7656	1.3125	2.01757566
7651	1.25	-5.9538571	7661	-1.45	-0.2224351	7661	1.2969	-4.0199243

7662	1.2344	-11.991357	7665	-1.45	-0.2224351	7665	1.2969	-4.0199243
7665	1.2344	-11.991357	7670	-1.45	-0.2224351	7670	1.2969	-4.0199243
7669	1.25	-5.9538571	7674	-1.45	-0.2224351	7674	1.3281	8.05507566
7674	1.25	-5.9538571	7679	-1.45	-0.2224351	7679	1.3281	8.05507566
7678	1.2656	0.08364295	7684	-1.45	-0.2224351	7684	1.2813	-10.057424
7683	1.2656	0.08364295	7694	-1.45	-0.2224351	7694	1.3125	2.01757566
7688	1.25	-5.9538571	7697	-1.45	-0.2224351	7697	1.3125	2.01757566
7692	1.2656	0.08364295	7701	-1.45	-0.2224351	7701	1.3125	2.01757566
7702	1.25	-5.9538571	7706	-1.455	-2.297623	7706	1.3125	2.01757566
7705	1.25	-5.9538571	7710	-1.455	-2.297623	7710	1.3281	8.05507566
7710	1.25	-5.9538571	7715	-1.45	-0.2224351	7715	1.3281	8.05507566
7714	1.25	-5.9538571	7719	-1.45	-0.2224351	7719	1.2969	-4.0199243
7719	1.2813	6.12114295	7724	-1.445	1.85275311	7724	1.3125	2.01757566
7723	1.2813	6.12114295	7734	-1.45	-0.2224351	7734	1.3125	2.01757566
7728	1.2813	6.12114295	7737	-1.45	-0.2224351	7737	1.3125	2.01757566
7732	1.2656	0.08364295	7742	-1.455	-2.297623	7742	1.2969	-4.0199243
7743	1.2969	12.1586429	7746	-1.45	-0.2224351	7746	1.2969	-4.0199243
7746	1.2969	12.1586429	7751	-1.45	-0.2224351	7751	1.2969	-4.0199243
7750	1.2813	6.12114295	7755	-1.445	1.85275311	7755	1.2969	-4.0199243
7755	1.2813	6.12114295	7760	-1.445	1.85275311	7760	1.3125	2.01757566
7759	1.2813	6.12114295	7771	-1.461	-4.3728109	7771	1.2813	-10.057424
7764	1.2969	12.1586429	7774	-1.461	-4.3728109	7774	1.2969	-4.0199243
7768	1.2969	12.1586429	7778	-1.461	-4.3728109	7778	1.2969	-4.0199243
7773	1.2656	0.08364295	7782	-1.461	-4.3728109	7782	1.3125	2.01757566
7783	1.2656	0.08364295	7787	-1.45	-0.2224351	7787	1.3125	2.01757566
7786	1.2656	0.08364295	7791	-1.45	-0.2224351	7791	1.2969	-4.0199243
7791	1.2656	0.08364295	7796	-1.45	-0.2224351	7796	1.2969	-4.0199243
7795	1.2656	0.08364295	7800	-1.45	-0.2224351	7800	1.2969	-4.0199243
7800	1.25	-5.9538571	7805	-1.455	-2.297623	7805	1.2969	-4.0199243
7804	1.2344	-11.991357	7815	-1.461	-4.3728109	7815	1.3281	8.05507566
7809	1.2344	-11.991357	7818	-1.455	-2.297623	7818	1.3281	8.05507566
7813	1.25	-5.9538571	7823	-1.455	-2.297623	7823	1.3125	2.01757566
7824	1.2656	0.08364295	7827	-1.445	1.85275311	7827	1.3125	2.01757566
7827	1.2656	0.08364295	7832	-1.445	1.85275311	7832	1.2969	-4.0199243
7831	1.2813	6.12114295	7836	-1.439	3.92794097	7836	1.2969	-4.0199243
7836	1.2813	6.12114295	7841	-1.439	3.92794097	7841	1.2969	-4.0199243
7840	1.2969	12.1586429	7846	-1.45	-0.2224351	7852	1.3125	2.01757566
7845	1.2969	12.1586429	7855	-1.45	-0.2224351	7855	1.3281	8.05507566
7849	1.2969	12.1586429	7859	-1.45	-0.2224351	7859	1.3281	8.05507566
7854	1.2656	0.08364295	7863	-1.45	-0.2224351	7863	1.2969	-4.0199243
7864	1.2813	6.12114295	7868	-1.455	-2.297623	7868	1.2969	-4.0199243

7867	1.2813	6.12114295	7872	-1.455	-2.297623	7872	1.2969	-4.0199243
7872	1.25	-5.9538571	7877	-1.445	1.85275311	7877	1.2969	-4.0199243
7876	1.25	-5.9538571	7881	-1.445	1.85275311	7881	1.2813	-10.057424
7881	1.25	-5.9538571	7886	-1.45	-0.2224351	7886	1.2969	-4.0199243
7885	1.25	-5.9538571	7895	-1.445	1.85275311	7896	1.3125	2.01757566
7890	1.25	-5.9538571	7899	-1.445	1.85275311	7899	1.3125	2.01757566
7894	1.2813	6.12114295	7904	-1.445	1.85275311	7904	1.2969	-4.0199243
7905	1.2813	6.12114295	7908	-1.45	-0.2224351	7908	1.2969	-4.0199243
7908	1.2813	6.12114295	7912	-1.45	-0.2224351	7913	1.3281	8.05507566
7913	1.2813	6.12114295	7917	-1.45	-0.2224351	7917	1.3281	8.05507566
7917	1.2969	12.1586429	7921	-1.45	-0.2224351	7921	1.3125	2.01757566
7921	1.2969	12.1586429	7926	-1.45	-0.2224351	7933	1.3281	8.05507566
7926	1.2813	6.12114295	7935	-1.439	3.92794097	7936	1.2969	-4.0199243
7930	1.2813	6.12114295	7940	-1.439	3.92794097	7939	1.2969	-4.0199243
7935	1.2813	6.12114295	7944	-1.439	3.92794097	7944	1.3125	2.01757566
7945	1.2813	6.12114295	7948	-1.445	1.85275311	7948	1.3125	2.01757566
7948	1.2813	6.12114295	7953	-1.445	1.85275311	7953	1.3281	8.05507566
7953	1.2656	0.08364295	7957	-1.445	1.85275311	7957	1.3281	8.05507566
7957	1.25	-5.9538571	7962	-1.445	1.85275311	7962	1.3125	2.01757566
7961	1.25	-5.9538571	7967	-1.455	-2.297623	7967	1.3125	2.01757566
7966	1.2344	-11.991357	7977	-1.455	-2.297623	7977	1.3281	8.05507566
7971	1.2344	-11.991357	7980	-1.445	1.85275311	7980	1.3281	8.05507566
7975	1.25	-5.9538571	7984	-1.445	1.85275311	7984	1.2969	-4.0199243
7986	1.25	-5.9538571	7989	-1.439	3.92794097	7989	1.2969	-4.0199243
7989	1.2656	0.08364295	7993	-1.439	3.92794097	7993	1.2969	-4.0199243
7993	1.2656	0.08364295	7998	-1.434	6.00312883	7998	1.2969	-4.0199243
7997	1.2813	6.12114295	8002	-1.434	6.00312883	8002	1.3281	8.05507566
8002	1.2813	6.12114295		-1.449			1.3073	
	1.2654							

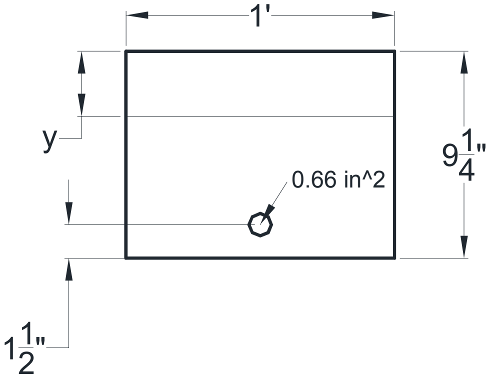
Acceleration data of Sensors E and F

Sensor E			Sensor F		
Time, msec	Acceleration		Time, msec	Acceleration	
	From Sensor, g	Normalized, in/sec^2		From Sensor, g	Normalized, in/sec^2
3999	0.967742	-0.40535012	3999	0.860215	-8.81636507
4099	1.005376	14.13658537	4099	0.908602	9.880409127
4199	0.935484	-12.8698662	4199	0.892473	3.648151062
4299	0.956989	-4.56018883	4299	0.876344	-2.584107
4400	0.956989	-4.56018883	4400	0.88172	-0.50668765
4499	0.973118	1.672069237	4499	0.897849	5.725570417
4599	0.94086	-10.7924469	4599	0.865591	-6.73894571
4699	0.973118	1.672069237	4699	0.908602	9.880409127
4799	0.94086	-10.7924469	4799	0.870968	-4.66152636
4899	0.983871	5.826907946	4899	0.876344	-2.584107
4999	0.94086	-10.7924469	4999	0.892473	3.648151062
5099	0.983871	5.826907946	5099	0.892473	3.648151062
5199	0.978495	3.749488592	5199	0.876344	-2.584107
5299	0.994624	9.981746656	5299	0.88172	-0.50668765
5400	0.935484	-12.8698662	5400	0.897849	5.725570417
5500	0.994624	9.981746656	5500	0.854839	-10.8937844
5599	0.962366	-2.48276947	5599	0.892473	3.648151062
5699	0.967742	-0.40535012	5699	0.876344	-2.584107
5800	0.962366	-2.48276947	5800	0.897849	5.725570417
5899	0.983871	5.826907946	5899	0.892473	3.648151062
5999	0.983871	5.826907946	5999	0.854839	-10.8937844
6099	0.946237	-8.71502754	6099	0.897849	5.725570417
6199	0.946237	-8.71502754	6199	0.892473	3.648151062
6299	0.983871	5.826907946	6299	0.897849	5.725570417
6400	0.978495	3.749488592	6400	0.892473	3.648151062
6499	0.983871	5.826907946	6499	0.908602	9.880409127
6600	0.983871	5.826907946	6600	0.870968	-4.66152636
6699	1	12.05916601	6699	0.876344	-2.584107
6799	0.935484	-12.8698662	6799	0.865591	-6.73894571
6899	0.978495	3.749488592	6899	0.908602	9.880409127
6999	0.956989	-4.56018883	6999	0.88172	-0.50668765
7099	0.967742	-0.40535012	7099	0.870968	-4.66152636
7199	0.930108	-14.9472856	7199	0.865591	-6.73894571
7299	0.956989	-4.56018883	7299	0.870968	-4.66152636
7400	1	12.05916601	7400	0.865591	-6.73894571

7499	0.973118	1.672069237	7499	0.876344	-2.584107
7599	0.978495	3.749488592	7599	0.876344	-2.584107
7700	0.978495	3.749488592	7700	0.892473	3.648151062
7799	0.978495	3.749488592	7799	0.876344	-2.584107
7899	0.956989	-4.56018883	7899	0.876344	-2.584107
8009	0.983871	5.826907946	8009	0.892473	3.648151062
	0.968791			0.883032	

APPENDIX B

Calculation of equivalent deck width:



Deck reinforcement: #6 @ 8” o.c. = 0.66 in.^{2}/ft

f_c' = 4,000 psi,

n = 8

For equilibrium:

$$12 * y * \frac{y}{2} = 8 * 0.66 * (7.75 - y)^2$$

By solving, y = 2.21 in.

Cracked moment of inertia of 1 ft width deck strip,

$$I_{cr} = \frac{12 * 2.21^3}{3} + 8 * 0.66 * (7.75 - 2.21)^2$$

$$I_{cr} = 205.23\ in.^4$$

Say, thickness of equivalent deck is, h_e

$$\frac{bh_e^3}{12} = 205.23$$

$$h_e = 5.9\ in. \approx 5\ in.$$

(it is rounded down to be on conservative side).

APPENDIX C

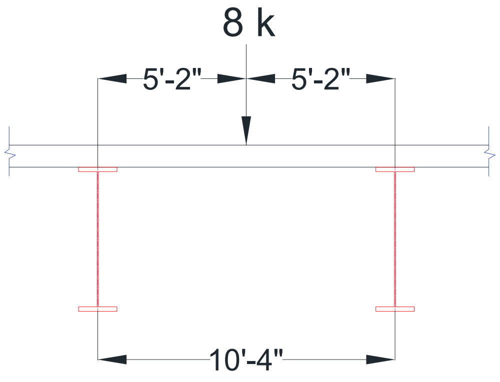
Time history data:

Time History Index	Time, sec	Load Multiplier	Time History Index	Time, sec	Load Multiplier
1	0	0	7	0	0
	0.01	2		0.51	0
	0.11	0		0.61	2
	0.27	0		0.71	0
	0.28	8		0.78	0
	0.38	0		0.88	8
	0.48	0		0.98	0
2	0	0	8	0	0
	0.01	0		0.61	0
	0.11	2		0.71	2
	0.21	0		0.81	0
	0.28	0		0.88	0
	0.38	8		0.98	8
	0.48	0		1.08	0
3	0	0	9	0	0
	0.11	0		0.71	0
	0.21	2		0.81	2
	0.31	0		0.91	0
	0.38	0		0.98	0
	0.48	8		1.08	8
	0.58	0		1.18	0
4	0	0	10	0	0
	0.21	0		0.81	0
	0.31	2		0.91	2
	0.41	0		1.01	0
	0.48	0		1.08	0
	0.58	8		1.18	8
	0.68	0		1.28	0
5	0	0	11	0	0
	0.31	0		0.91	0
	0.41	2		1.01	2
	0.51	0		1.11	0
	0.58	0		1.18	0
	0.68	8		1.28	8
	0.78	0		1.38	0
6	0	0	12	0	0
	0.41	0		1.01	0
	0.51	2		1.11	2
	0.61	0		1.21	0
	0.68	0		1.28	0
	0.78	8		1.38	8
	0.88	0		1.48	0

Time History Index	Time, sec	Load Multiplier	Time History Index	Time, sec	Load Multiplier
13	0	0	18	0	0
	1.11	0		1.61	0
	1.21	2		1.71	2
	1.31	0		1.81	0
	1.38	0		1.88	0
	1.48	8		1.98	8
	1.58	0		2.08	0
14	0	0	19	0	0
	1.21	0		1.71	0
	1.31	2		1.81	2
	1.41	0		1.91	0
	1.48	0		1.98	0
	1.58	8		2.08	8
	1.68	0		2.18	0
15	0	0	20	0	0
	1.31	0		1.81	0
	1.41	2		1.91	2
	1.51	0		2.01	0
	1.58	0		2.08	0
	1.68	8		2.18	8
	1.78	0		2.28	0
16	0	0	21	0	0
	1.41	0		1.91	0
	1.51	2		2.01	2
	1.61	0		2.11	0
	1.68	0		2.18	0
	1.78	8		2.28	8
	1.88	0		2.38	0
17	0	0	22	0	0
	1.51	0		2.01	0
	1.61	2		2.11	2
	1.71	0		2.21	0
	1.78	0		2.28	0
	1.88	8		2.38	8
	1.98	0		2.48	0

APPENDIX D

Calculations of cracking moment and actual moment on AASHTO design slab strip width:



Design slab strip width for positive moment (AASHTO [A4.6.2] eqn. 6.16a-US):

M^+: $SW^+ = 26.0 + 6.6S$

here, SW^+ = design slab strip width, in.

S = girder centre to centre distance in ft

$SW^+ = 26.0 + 6.6 * 10.33 = 94.18\ in. = 7.85\ ft$

Cracking moment, M_{cr}:

$f_r = 7.5\sqrt{f_c'} = 7.5\sqrt{4000} = 474.34\ psi$

$$I_g = \frac{12 * 9.25^3}{12} = 791.45 in.^4$$

$$M_{cr} = \frac{f_r I_g}{y_c} = \frac{474.34 * 791.45}{\frac{9.25}{2}} * \frac{1}{12000} * 7.85 = 53.1 \text{ k-ft}$$

Assuming the worst case scenario that the slab strip will act as a simple support, actual maximum moment on slab due to single wheel load could be:

$$M_a = \frac{Pl}{4} = \frac{8 * 10.33}{4} = 20.66 \text{ k-ft}$$

Therefore, $M_{cr} > M_a$; Deck was not initially cracked.