THE EFFECT OF VEHICLE SPEED ON LOAD AND DEFLECTION OF TIMBER RAILROAD BRIDGES

An Undergraduate Research Scholars Thesis

by

CYNTHIA MARIE OBELENIS RYAN

Submitted to the Undergraduate Research Scholars program
Texas A&M University
in partial fulfillment of the requirements for the designation as an

UNDERGRADUATE RESEARCH SCHOLAR

Approved by
Research Advisor: Dr. Gary Fry

May 2016

Major: Civil Engineering

TABLE OF CONTENTS

Page

CHAPTER

Page

ABSTRACT

The Effect of Vehicle Speed on Load and Deflection of Timber Railroad Bridges

Cynthia Marie Obelenis Ryan
Department of Civil Engineering
Texas A&M University

Research Advisor: Dr. Gary Fry
Department of Civil Engineering

Timber railroad bridges comprise approximately 25% of the total railroad bridge inventory by length. Increasingly, the age of existing timber spans exceeds the original anticipated design life of the structures. This vehicle bridge interaction project is designed to investigate the effect of train speed on load and deflection of a timber railroad bridge. Direct load measurements of pile in bridges under train traffic will be obtained as well at deflections of stringers. The results and insight gained from this investigation will be presented to several stakeholder groups who have responsibility to design, inspect, and maintain timber railroad bridges, as well as Committee No. 7 of the American Railway Engineering and Maintenance of Way Association (AREMA). This committee publishes the recommended practice guidelines for timber railroad bridges that comprise Chapter 7 of the Manual for Railway Engineering (MRE).

DEDICATION

I dedicate this thesis to the memory of my father.

ACKNOWLEDGMENTS

I would like to thank my advisor Dr. Gary Fry for his guidance and support during the development of this project. Dr. Fry has been a great advisor and mentor throughout my college career and has encouraged me to pursue projects such as this one, and I am extremely grateful for his guidance. I would also like to thank my research group. They have been helpful and encouraging and for that I would like to express my gratitude.

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION

Background

Timber railroad bridges have been designed and built successfully for over a century and are still in common use today. Many of today's timber railroad bridges have been in continual service for several decades, experiencing many passages of heavy trains and exposure to environmental agents such as sunlight, rain, humidity, and temperature fluctuations and exposure to biological agents such as wood-eating insects and fungal organisms that cause wood to decay.

Acting individually, mechanical fatigue loading, environmental agents, and biological agents each cause the wood members used in a timber railroad bridges to lose strength. The combined effects of these agents are far more deleterious than any one agent acting alone. For example, cracks caused by the environmental effect of fiber shrinkage cause a concentration of the mechanical stresses from train loads which in turn cause the cracks to grow larger. As the existing cracks lengthen or grow in number, the strength of the member can rapidly decrease. Cracks which penetrate beyond the outer layers of wood that have been chemically treated to resist moisture and decay organisms may grow as a result of fatigue cycles caused by pulsating loads. As a result, moisture and insects have a path to penetrate deeply into the member and destroy the untreated wood in its core.

A typical timber bridge is composed of piles, bent-caps, stringers, and cross ties. Timber piles are columns that take the gravity and lateral loads from the elevated structure and distribute them into the ground. The piles may support the load in one of three ways; friction, bearing, or a combination of both. Timber piles are driven into the ground using pile drivers. Once in the ground, piles are attached to a bent cap that transfers the loads from the stringer chords into the piles. A timber bent usually consists of three or more piles with lateral bracing supporting a bent cap. Bents are typically spaced 15 feet apart and support stringers. Stringers are used to support shorter cross ties which provide support for the rails. To function safely, all elements of a bridge must be maintained in proper condition.

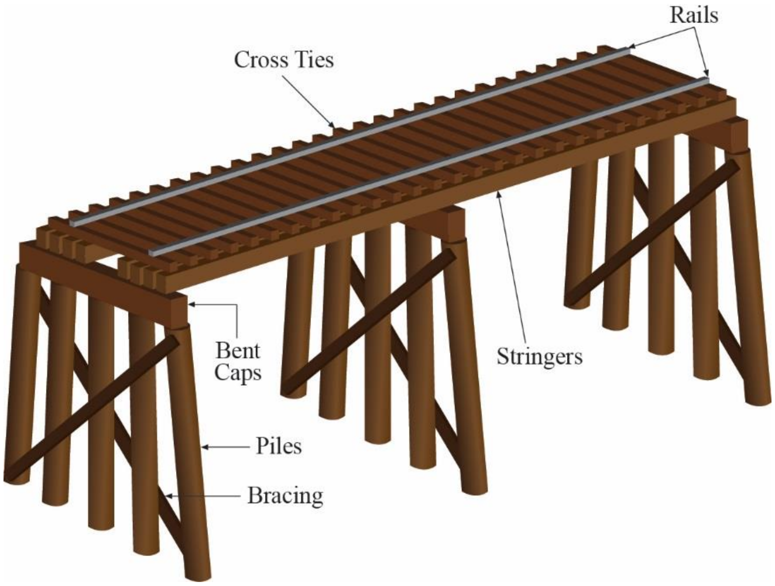


Figure 1. Configuration of a typical timber railroad bridge (Rachal 2015)

Bridge decks

The deck of a railroad bridge is the portion of the structure that provides support for the track rails. There are two types of bridge decks: open bridge decks and ballasted bridge decks. The choice of deck type is based on the requirements of each timber railroad bridge. Open deck bridges have rails anchored directly to the timber bridge ties, which are supported directly by the floor system of the superstructure. Ballast deck bridges have rails anchored directly to the timber bridge track ties, which are supported in the ballast section. The ballasted bridge decks require a floor to support the ballast section, which transfers loads directly to the superstructure (AREMA Practical Guide to Railway Engineering 2003). Variations of the two types of deck also exist to accommodate railroad requirements.

Open bridge decks

Open deck bridges have rails anchored directly to the timber bridge ties, which are supported directly by the floor system of the superstructure, as can be seen in Figure 2. This type of structure typically cost less to construct and does not require draining. However, open deck bridges often require extensive maintenance that can make them more expensive to maintain in comparison to a ballast deck bridge AREMA Practical Guide to Railway Engineering 2003).

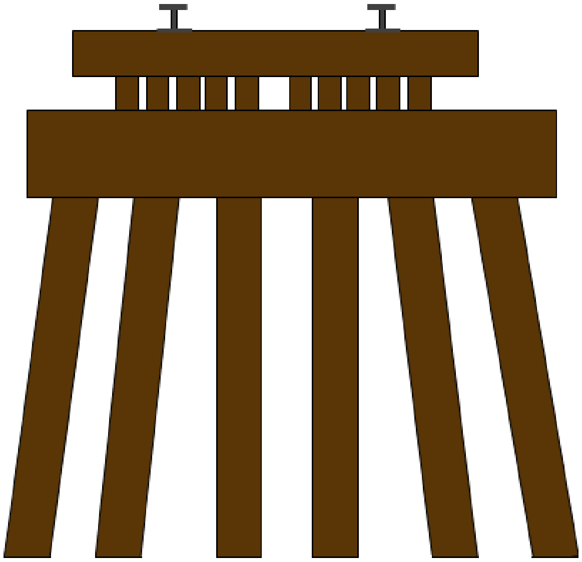


Figure 2. Open deck structure

Ballast bridge decks

The rails on a ballast deck bridge are anchored to cross ties. The cross ties are supported by ballast, which rests on a floor, typically a timber floor. The timber floor is in turn supported by stringers, as can be seen in Figure 3. A ballast bridge deck typically provides a better riding track. The functioning of the ballast depends, among other factors, on the depth of the ballast. There is a general consensus that a 6 to 12 inches ballast under the tracks is adequate for railway bridges, and more than 12 inches causes a potential of overload which is undesirable (AREMA Practical Guide to Railway Engineering 2003).

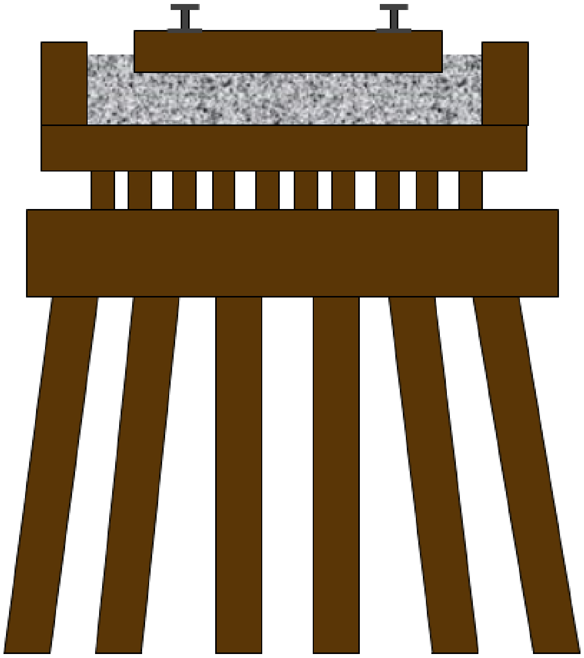


Figure 3. Ballast deck structure

Literature review

Timber structures have been in use for centuries. Over time, rules of thumb were developed to aid in the planning and construction of wood structures based on successful and unsuccessful experiences (Stalnaker and Harris 1997). Using these rules for guidance, many durable structures were built with adequate strength and serviceability capability. Today, timber bridges compose about 28 percent of the total bridge inventory of Class 1 railroads in the United States and Canada (Uppal and Otter 1998). These structures were designed and built by engineers and architects based on engineering principles, and research has helped guide designers to build safer and more economical structures. A limited amount of research was observed or needed in the use of timber piles in railroad bridges until the 1930s because of the availability of materials (Sculley 2003). In addition, the low cost of timber piles made it possible to use loads that were below the critical loads (Capozzoli 1966). These reasons allowed for conservative designs of timber piles. Also, there was not a real need for extensive experimentation on timber piles until then given the knowledge of pile behavior obtained through the driving process, when piles usually sustain their highest loads, as the data obtained from that process was considered a sufficient measure of strength (Sculley 2003).

Timber structures are generally frequently exposed to varying harsh conditions that can lead to deterioration due to decay, insect attach, weathering, and mechanical damage. Timber railroad bridges have long service life and over time this exposure to deterioration factors can lead to a loss of structural integrity. Decay, which can be measured by weight loss of timber members, has significant effects on structural performance. “Wood that contains early decay, identified by up to 10 percent weight loss, may have its mechanical properties reduced by up to 80 percent”

(Emerson and Pollock and McLean and Fridley and Pellerin and Ross 2002). Periodical inspection of timber railroad bridges for signs of decay helps ensure the soundness and safety of timber bridges currently in use. Assessing the strength of timber railroad bridge piles is also important to guarantee the safe operation of the bridges that may be structurally impaired due to decay. In addition to decay, structural overload, mechanical wear and fatigue are types of mechanical damage that can affect timber bridge deterioration. “Structural overload can irreversibly damage both timber members and steel connectors. Mechanical wear can eventually reduce the effective section of bridge deck surfaces and railings. Repetitive loading can gradually cause fatigue damage to metal connectors and the wood fibers in the connection region” (Emerson 1999).

Since the industrial revolution in the United States, railroads have played a major role in the country’s economy through the transportation of goods. Timber railroad bridges have been successfully designed and built for approximately 150 years. However, changes in the railroad business environment in recent times have led to operational changes that affect timber railroad bridges. The increase in the allowable axle loading for railcars has been the most important of these changes regarding timber railroad bridges. This increase is caused by the competitive environment of railroad transportation and also by improvements in rail dynamics technology that allow for heavier axle loading while ensuring safe operation (Peterson and Gutkowski 1997). As a result, railroad bridges have been subjected to heavier loads that may affect their safety and require more maintenance. It has become important to assess the performance of timber bridges as axle loading increases.

An inspection of the behavior of load on timber piles and deflection of stringer as trains at different speeds cross a bridge will lead to a better understanding of how timber bridges react to moving loads and could increase the usable life of timber bridges. The effect of train speed as it related to bridge stiffness and deflection is a focus point of interest in this vehicle bridge interaction research project.

Objectives

Tests conducted in this vehicle bridge interaction research project aim to assess the relationship between vehicle speed, load and deflection. Direct load measurements of pile and deflection of stringers in bridges under train traffic will be obtained. The field test data will be used to analyze the relationship between load on timber piles, deflection of the bridge and train speed and will provide a better understanding of how timber railroad bridges behave under live loading.

CHAPTER II

EXPERIMENTAL PROCEDURES

Instrumentation and data acquisition system

In this project, direct load measurements of pile as well as deflection measurements on stringers in bridges under train traffic will be obtained. To acquire this data, a timber railway bridge needs to be instrumented. Because this bridge is currently in use, any damage to the bridge or locomotive needs to be avoided. Therefore, the instrumentation needs to be installed in a non-destructive manner.

Load cell sensors

A load cell is a force transducer that measures the deformation in a material caused by a load applied to it and converts it into an electrical signal. The most common type of load cells are strain-gage based load cells. Strain-gages, which are devices capable of measuring the strain in a material, are attached to a structure in the load cell that deforms when a load in applied to it. When the deformation occurs, a change in the electrical resistance of the strain gages is measured and an electrical output is obtained (typically a voltage). The electrical output is proportional to the strain in the material, which in turn is proportional to the force applied to it. Using conversion factors, it is possible to obtain the load applied to the material. Load cell sensors are accurate, readily available and simple to use, which makes them appropriate sensors to obtain loads on timber railroad bridge pile.

String potentiometer sensors

A string potentiometer is a linear position transducer that can be used to measure displacement and deflection of a structure. There are four main components to a string potentiometer: a cable, a spool, a spring, and a rotational sensor. The cable is attached to the spring to maintain tension. The spring is attached to the spool and as the cable reels and unreels, the spool rotates. The rotational sensor attached to the spool generates an electrical output when the spool rotates that is proportional to the extension of the cable. String potentiometers are calibrated so that conversion factors can be used to obtain the extension of the cable. If the cable is attached to a structure, the extension of the cable will change when it moves and the deflection of the structure can be measured directly. String potentiometers are typically durable devices and simple to use, making them appropriate sensor to measure the deflection of the stringers in a timber railroad bridge as a train crosses the bridge.

Data acquisition system

A data acquisition system was used to receive signals from the load cells and string potentiometers. The primary module used was an IOTech StrainBook/616, to which were added expansion modules. These modules measured the changes in voltage that occurred in the load cells and string potentiometers and sent them to a laptop in order to transfer the data collected. A data acquisition software called DASYLab was used to import the voltage values from the StrainBook/616 and to store the data into files. Figure 4 shows a view of the laptop during a test displaying load data being recorded.

Figure 4. Laptop displaying load data during testing of the timber railroad bridge

Field testing procedures

In compliance with the regulations of the Canadian National Railway, the members of the research team that participated in field testing completed safety training before conduction experimentations. On track safety procedures and fall protection were reviewed as a part of this training.

Two bridges are discussed in this investigation. Load and deflection measurements were obtained from Bridge 816.9, a Canadian National Railway Company (CN) ballasted deck bridge located south of Magnolia, Mississippi. Deflection measurements were obtained from Bridge 17.14, a Union Pacific Railroad open deck bridge located south of Mumford, Texas. The instrumentation for the load measurements in this research consisted of load cells installed on top of the piles, under the bent caps. The load cells were surrounded by two steel plates that allowed the load to transfer from the bent caps to the piles. Vertical deflections were measured using string potentiometer-based displacement transducers. This type of instrumentation offers good accuracy and precision, as well as a high sample rate. Both load cells and string potentiometers were calibrated under laboratory conditions prior to testing.

Ballast deck bridge test

From September 2, 2015 through September 3, 2015, Texas A&M University conducted testing on a Canadian National Railway Company (CN) ballast deck bridge, Bridge 816.9, which was located south of Magnolia, Mississippi. The bridge can be seen in Figure 5 and consisted of two adjacent timber bridges. The experiment was performed on the east bridge on span 8.

Figure 5. Bridge 816.9

Six piles were instrumented with two load cells each to record load as a result of the train load. Figure 6 shows a representation of the bridge tested and the location of the load cell used in this experiment.

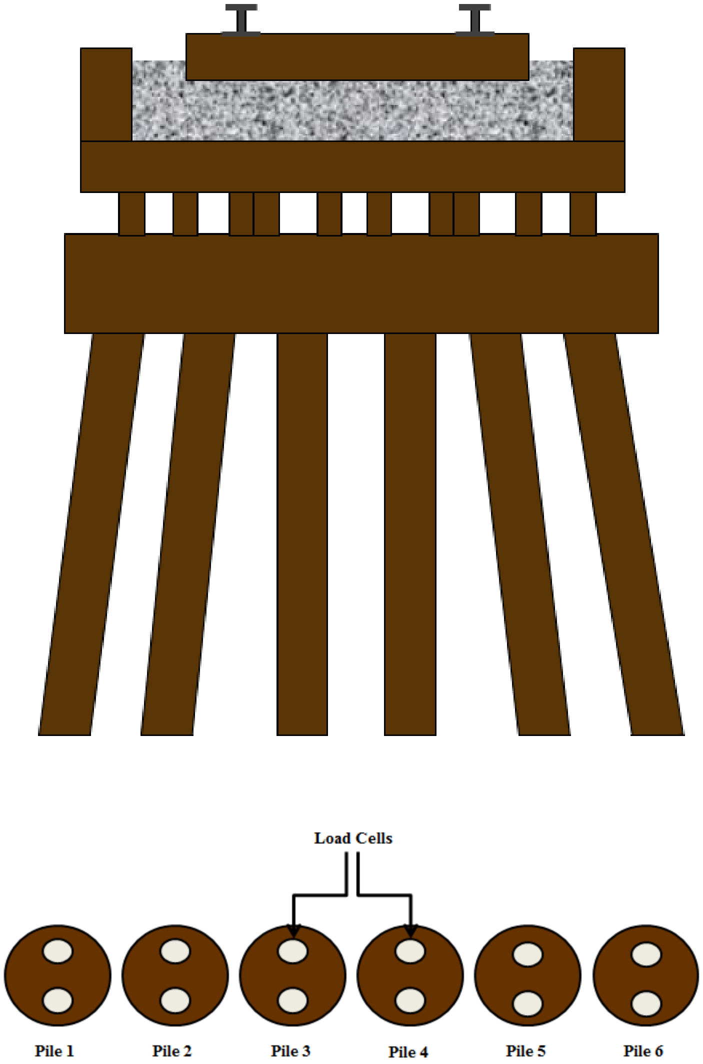


Figure 6. Representation of bridge and load cell layout on timber piles

Two steel plates surrounding the load cells ensured that the timber piles were not damaged by the load cells and provided stiffness to transfer the train load from the bent caps into the piles, as depicted in Figure 7.

Figure 7. Steel plate surrounding two load cells placed on top of timber pile

The stringer deflections of span 8 were measured using 30 string potentiometers. To install the string potentiometers, small holes were drilled into the wood so that cup hooks could be installed. The string potentiometer cables were attached to the hooks by fishing leader wire. The layout of the displacement transducers can be seen in Figure 8. A total of three string potentiometers were attached to each stringer, with one sensor attached to the end of each stringer and one was attached to the mid-span of the stringer.

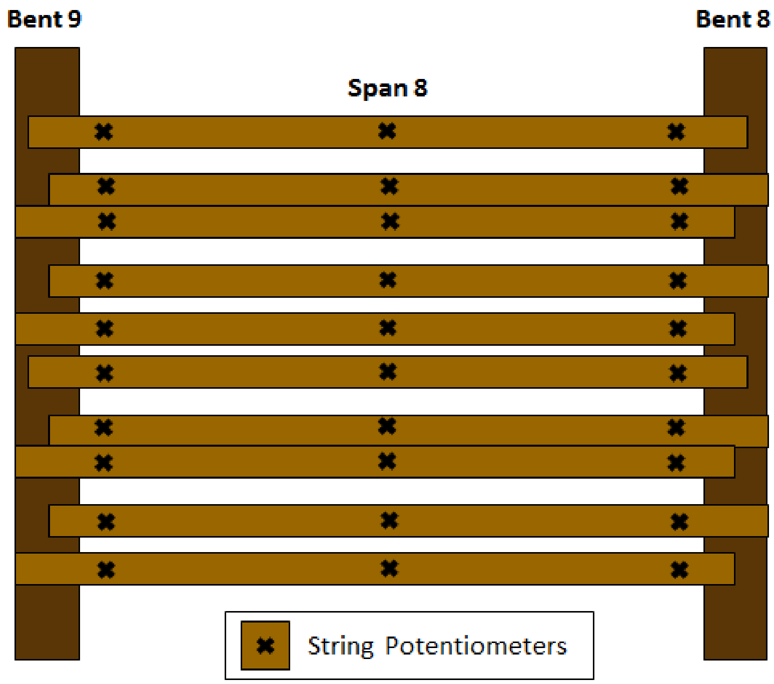


Figure 8. Bridge 816.9 string potentiometer layout

For this experiment, a Canadian National work train passed over Bridge 816.9 at different known speeds. Table 1 shows the test number and the corresponding vehicle type, direction and speed of each test. After the instrumentation was setup and the data acquisition system was set to record data, the work train began to make its crossings at the designated speeds. After the train had completely crossed the bridge, it would come to a complete stop and the data acquisition system was stopped and the data collected was saved. For the next test, the work train would cross over the bridge in reverse and the data would be recorded. This procedure was repeated for all the speeds shown in the table.

Table 1. Experimental parameters for field testing of Bridge 816.9

Test No.	**Vehicle Type**	**Vehicle Direction**	**Vehicle Speed (mph)**
1	Work Train	N	5
2	Work Train	S	10
3	Work Train	N	15
4	Work Train	S	20
5	Work Train	N	25
6	Work Train	S	30
7	Work Train	N	35
8	Work Train	S	40
9	Work Train	N	40
10	Work Train	S	45
11	Work Train	N	43
12	Work Train	S	45
13	Work Train	N	5
14	Work Train	N	52
15	Work Train	S	10
16	Work Train	N	54
17	Work Train	S	20
18	Work Train	N	63

The specific nomenclature is shown in Figure 9 was used when recording and analyzing the data for Bridge 816.9 in this project. The stringers were labelled according to their ply, from 1 to 10.

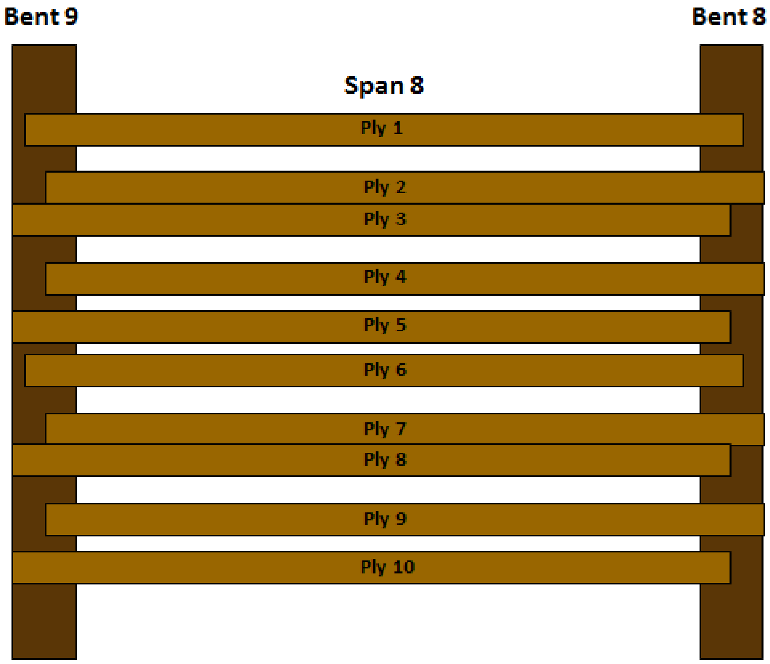


Figure 9. Bridge 816.9 nomenclature

Figure 10 shows a work train crossing Bridge 816.9 during one of the test discussed in this project.

Figure 10 - Train over Bridge 816.9 during test

Open deck bridge test

Testing of the Union Pacific Railroad Bridge 17.14, located south of Mumford, Texas, occurred on November 20, 2015. This open deck bridge can be seen in Figure 11.

Figure 11. Bridge 17.14

Two spans, between bents 7, 8, and 9, were instrumented with string potentiometer-based displacement transducers. The layout of these sensors can be seen in Figure 12. The instrumentation of the stringers with string potentiometers was done in the same way for the open deck bridge as it was for the ballast deck bridge. Small holes were drilled into the stringers so that cup hooks could be installed. The string potentiometer cables were attached to the hooks by fishing leader wire. A total of three string potentiometers were attached to each stringer, with one sensor attached to the end of each stringer and one was attached to the mid-span of the stringer.

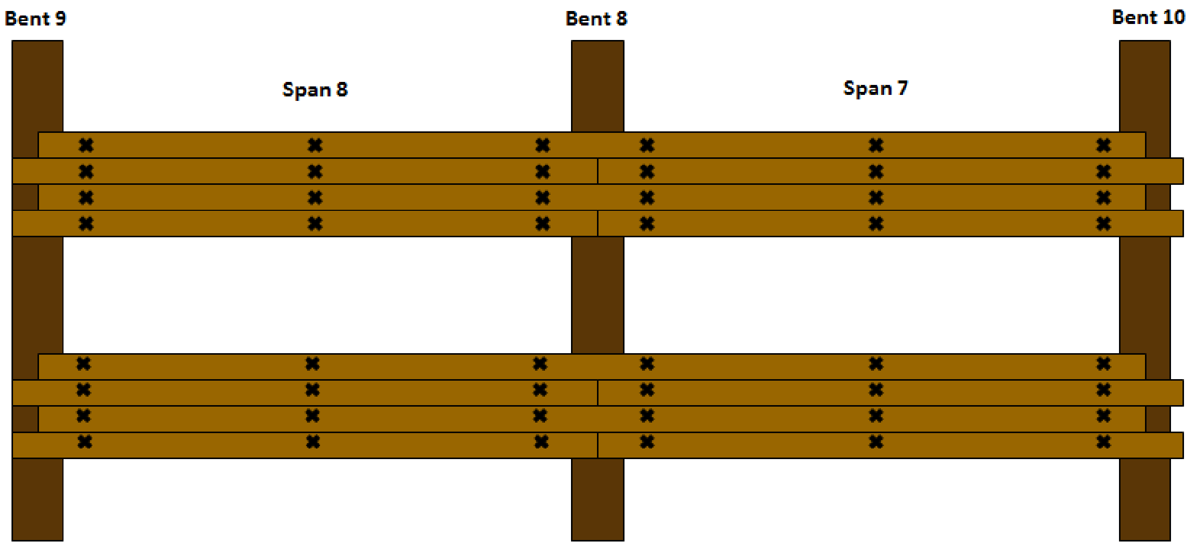


Figure 12. Bridge 17.14 string potentiometer layout

After the instrumentation was setup and the data acquisition system was set to record data, the work train began to make its crossings at the designated speeds. After the train had completely crossed the bridge, it would come to a complete stop and the data acquisition system was stopped and the data collected was saved. For the next test, the work train would cross over the bridge in reverse and the data would be recorded. This procedure was repeated for all the speeds shown in Table 2, which lists the test number and the corresponding vehicle type and speed of each test.

Table 2. Experimental parameters for field testing of Bridge 17.14

Test No.	Vehicle Type	Vehicle Speed (mph)
1	Work Train	12
2	Work Train	12
3	Work Train	19
4	Work Train	20
5	Work Train	29
6	Work Train	39
7	Work Train	40
8	Work Train	40
9	Work Train	50
10	Work Train	51

The specific nomenclature shown in Figure 13 was used when recording and analyzing the data for Bridge 17.14 in this project. The stringers were labelled according to their span, chord, and ply.

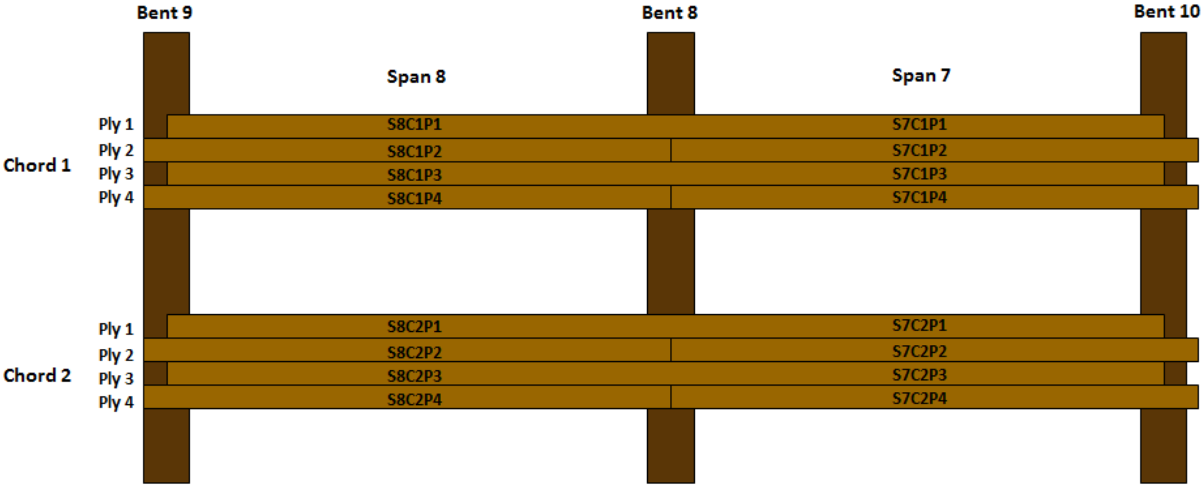


Figure 13. Bridge 17.14 nomenclature

Figure 14 shows a work train crossing Bridge 17.14 during one of the test discussed in this project.

Figure 14. Train over Bridge 17.14 during test

CHAPTER III

RESULTS AND DISCUSSION

Bridge deflection

As mentioned in Chapter 2, three deflection measurements were measured for each stringer in these tests. The deflection at both ends of the stringers and the total maximum deflection at the mid-span of the stringer were recorded so that the behavior of the bridge could be assessed. Two types of deflection will be mentioned in the research: the total deflection, referring to the maximum total deflection at the middle of the stringer, and the net deflection, which accounts for effect of the rigid body motion of the bridge and support settlement. The total deflection can be seen in Figure 15, designated by δ_{total}, as well as the deflection at the ends of the stringers, designated by δ_n and δ_s.

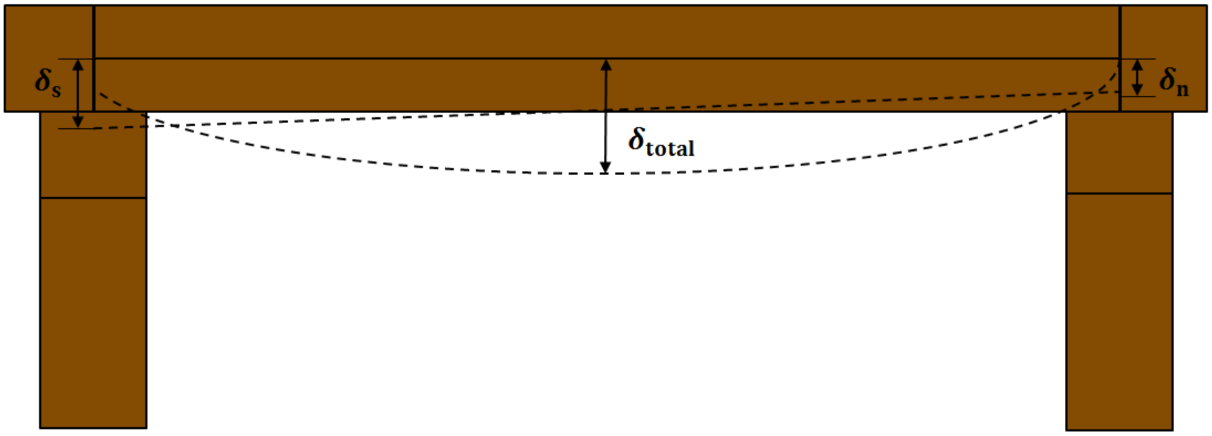


Figure 15. Total deflection at the middle of the stringer and end deflection of the stringer

To obtain the net deflection of the stringer, the average deflection of the ends of the stringers is calculated using the following equation:

$$\delta_{average} = \frac{\delta_s + \delta_n}{2} \tag{1}$$

After the average deflection is obtained, the net deflection or the actual maximum deflection of the stringer is calculated using the following relationship:

$$\delta_{net} = \delta_{total} - \delta_{average} \tag{2}$$

The relationship between net deflection and average deflection of the bridge can be seen in Figure 16.

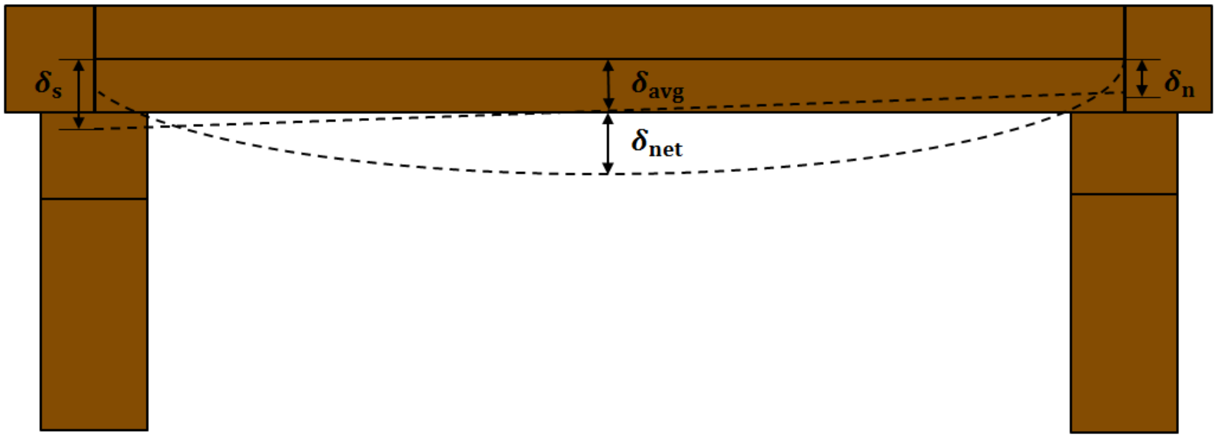


Figure 16. Net deflection and average deflection of the stringer

Ballast deck bridge test results

Load Data Analysis

The load data collected with the data acquisition system for the ballast deck bridge was analyzed in Microsoft Excel. The values obtained were voltages measured by the load cells that were converted to load values using known calibration factors. The first step of the data analysis was to filter noise out using a moving 21 point average. A moving average is a type of calculation that is used to analyze data points by creating series of averages of different subsets of the original data and is commonly used with time series data to reduce the effect of fluctuations, or smooth the data. After the data was smoothed, it was zeroed in order to remove the dead weight of the bridge.

The maximum total load experienced by the bridge in each test was obtained from the data. The summary of the results can be seen in Table 3. The result for test 2 is considerably lower than the other results, including test 4 which also considered a 10 miles per hour speed. When analyzing the time history plot of this test which can be found in the Appendix section, it appears that the entire test was not recorded by the data acquisition system, which stopped recording before the peak load was reached. Because of this deviation from the other results, test 2 was considered an outliner. The maximum load experienced by the bridge in this test series was 86044.11 pounds during test no. 14, with a speed of 45 miles per hour. The minimum load experienced by the bridge in this test series (disregarding the load value of test 2) was 75643.21 pounds for test no. 0, with a speed of 5 miles per hour. This different represents a percent increase of 13.75% from lowest to highest load experienced by the bridge.

Table 3. Maximum loads experienced by Bridge 816.9

Test No.	**Vehicle Type**	**Speed (mph)**	**Max Load (lb)**
1	Work Train	5	75643.21
2	Work Train	5	78858.16
3	Work Train	10	59525.20
4	Work Train	10	82879.58
5	Work Train	15	76883.12
6	Work Train	20	80507.70
7	Work Train	20	80944.26
8	Work Train	25	77650.96
9	Work Train	30	81750.65
10	Work Train	35	77627.64
11	Work Train	40	82626.53
12	Work Train	40	81523.38
13	Work Train	43	83087.71
14	Work Train	45	85917.07
15	Work Train	45	86044.11
16	Work Train	52	84289.72
17	Work Train	54	84156.02
18	Work Train	63	80729.42

It was expected that the load would increase as the speed of the work train increased. To investigate this assumption, maximum load was plotted against speed as can be seen in figure 17. An average was obtained for the tests with 10, 20, 40 and 45 miles per hour speed since multiple tests were conducted for these speeds. As can be seen in Figure 17, the trend line indicates a small increase in load as speed increased. A coefficient of determination of 0.39 for the trend line indicates the data is scattered.

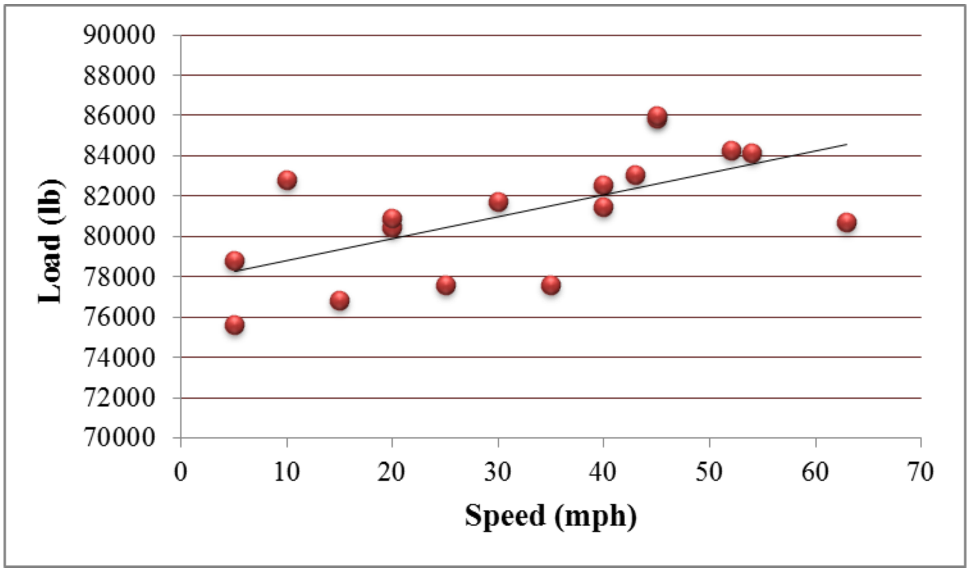


Figure 17. Relationship between maximum load on timber piles and speed

Deflection Data Analysis

As mentioned earlier in this chapter, two types of deflection are considered in this research: the total deflection of the stringers at mid-span, and the net deflection of the stringers at mid-span. Plots of the deflections versus time for all tests can be found in the Appendix section. Table 4 lists the results of the total mid-span deflection for the test for ply 1 though ply 5, and Table 5 lists the results of the total mid-span deflection for the test for ply 6 through ply 10.

Table 4. Maximum total deflection at mid-span for Ply 1-5

Test No.	**Speed (mph)**	**Ply 1**	**Ply 2**	**Ply 3**	**Ply 4**	**Ply 5**
1	**5**	-0.1801	-0.2299	-0.2407	-0.2444	-0.1684
2	**10**	-0.1814	-0.2329	-0.2453	-0.2471	-0.1647
3	**15**	-0.1811	-0.2325	-0.2440	-0.2452	-0.1654
4	**20**	-0.1842	-0.2367	-0.2456	-0.2478	-0.1643
5	**25**	-0.1962	-0.2474	-0.2520	-0.2507	-0.1647
6	**30**	-0.1790	-0.2335	-0.2434	-0.2465	-0.1614
7	**35**	-0.1888	-0.2422	-0.2535	-0.2524	-0.1722
8	**40**	-0.1755	-0.2322	-0.2420	-0.2438	-0.1654
9	**40**	-0.1746	-0.2251	-0.2391	-0.2401	-0.1677
10	**45**	-0.1752	-0.2314	-0.2442	-0.2423	-0.1658
11	**43**	-0.1858	-0.2385	-0.2469	-0.2517	-0.1665
12	**45**	-0.1747	-0.2330	-0.2424	-0.2450	-0.1638
13	**5**	-0.1776	-0.2300	-0.2458	-0.2488	-0.1716
14	**52**	-0.1801	-0.2344	-0.2485	-0.2527	-0.1748
15	**10**	-0.1814	-0.2329	-0.2453	-0.2471	-0.1647
16	**54**	-0.1766	-0.2258	-0.2353	-0.2350	-0.1655
17	**20**	-0.1867	-0.2341	-0.2379	-0.2355	-0.1596
18	**63**	-0.1618	-0.2122	-0.2323	-0.2313	-0.1688

The maximum total deflection obtained for these tests was -0.2894 inches which was obtained during test 14 for ply 8, when the work train’s speed was 52 miles per hour. The minimum total deflection obtained for these tests was -0.1498 which occurred during test 17 for ply 7 in which the work train’s speed was 20 miles per hour. The maximum total deflection is highlighted in Table 5 in red, and the minimum total deflection is highlighted in the table in blue.

Table 5. Maximum total deflection at mid-span for Ply 6-10

Test No.	**Speed (mph)**	**Ply 6**	**Ply 7**	**Ply 8**	**Ply 9**	**Ply 10**
1	**5**	-0.2505	-0.1715	-0.2625	-0.2145	-0.1664
2	**10**	-0.2458	-0.1575	-0.2476	-0.1971	-0.1505
3	**15**	-0.2530	-0.1702	-0.2614	-0.2107	-0.1611
4	**20**	-0.2438	-0.1581	-0.2492	-0.2022	-0.1568
5	**25**	-0.2513	-0.1655	-0.2576	-0.2064	-0.1577
6	**30**	-0.2445	-0.1569	-0.2483	-0.1984	-0.1533
7	**35**	-0.2542	-0.1747	-0.2717	-0.2218	-0.1703
8	**40**	-0.2451	-0.1578	-0.2445	-0.2012	-0.1566
9	**40**	-0.2596	-0.1754	-0.2737	-0.2278	-0.1761
10	**45**	-0.2460	-0.1600	-0.2499	-0.2113	-0.1626
11	**43**	-0.2618	-0.1750	-0.2732	-0.2243	-0.1722
12	**45**	-0.2471	-0.1658	-0.2552	-0.2089	-0.1562
13	**5**	-0.2620	-0.1774	-0.2689	-0.2201	-0.1682
14	**52**	-0.2714	-0.1941	-0.2894	-0.2422	-0.1882
15	**10**	-0.2458	-0.1575	-0.2476	-0.1971	-0.1505
16	**54**	-0.2591	-0.1785	-0.2793	-0.2333	-0.1874
17	**20**	-0.2384	-0.1498	-0.2455	-0.2007	-0.1614
18	**63**	-0.2594	-0.1769	-0.2833	-0.2422	-0.1951

Table 6 lists the results of the net mid-span deflection for the test for ply 1 though ply 5, and

Table 7 lists the results of the net mid-span deflection for the test for ply 6 through ply 10.

Table 6. Maximum net deflection at mid-span for Ply 1-5

Test No.	**Speed (mph)**	**Ply 1**	**Ply 2**	**Ply 3**	**Ply 4**	**Ply 5**
1	**5**	-0.0455	-0.1276	-0.1384	-0.1264	-0.0686
2	**10**	-0.0454	-0.1274	-0.1403	-0.1281	-0.0710
3	**15**	-0.0445	-0.1281	-0.1407	-0.1279	-0.0716
4	**20**	-0.0460	-0.1295	-0.1416	-0.1292	-0.0705
5	**25**	-0.0544	-0.1379	-0.1463	-0.1319	-0.0699
6	**30**	-0.0419	-0.1275	-0.1400	-0.1292	-0.0699
7	**35**	-0.0495	-0.1336	-0.1463	-0.1323	-0.0739
8	**40**	-0.0388	-0.1269	-0.1411	-0.1313	-0.0676
9	**40**	-0.0401	-0.1196	-0.1354	-0.1256	-0.0697
10	**45**	-0.0396	-0.1279	-0.1398	-0.1320	-0.0654
11	**43**	-0.0454	-0.1272	-0.1390	-0.1309	-0.0684
12	**45**	-0.0455	-0.1276	-0.1384	-0.1264	-0.0686
13	**5**	-0.0409	-0.1199	-0.1362	-0.1281	-0.0698
14	**52**	-0.0405	-0.1233	-0.1388	-0.1294	-0.0726
15	**10**	-0.0454	-0.1274	-0.1403	-0.1281	-0.0710
16	**54**	-0.0384	-0.1242	-0.1325	-0.1204	-0.0732
17	**20**	-0.0441	-0.1305	-0.1389	-0.1236	-0.0715
18	**63**	-0.0310	-0.1157	-0.1342	-0.1196	-0.0741

The maximum total deflection obtained for these tests was -0.1709 inches which was obtained during test 14 for ply 8, when the work train's speed was 52 miles per hour. The minimum total deflection obtained for these tests was -0.0310 which occurred during test 18 for ply 1 in which the work train's speed was 63 miles per hour. The maximum total deflection is highlighted in Table 6 in red, and the minimum total deflection is highlighted in the table in blue. Although the maximum total and net deflection occurred at ply 8 for test 14, the minimum total deflection occurred for a different ply and test than for the net deflection, demonstrating the importance of considering the settlement of the support.

Table 7. Maximum net deflection at mid-span for Ply 6-10

Test No.	Speed (mph)	Ply 6	Ply 7	Ply 8	Ply 9	Ply 10
1	**5**	-0.1366	-0.0896	-0.1493	-0.1288	-0.0711
2	**10**	-0.1366	-0.0831	-0.1441	-0.1199	-0.0646
3	**15**	-0.1381	-0.0914	-0.1482	-0.1258	-0.0664
4	**20**	-0.1367	-0.0845	-0.1443	-0.1256	-0.0696
5	**25**	-0.1375	-0.0866	-0.1491	-0.1267	-0.0690
6	**30**	-0.1370	-0.0852	-0.1425	-0.1203	-0.0645
7	**35**	-0.1407	-0.0921	-0.1530	-0.1356	-0.0750
8	**40**	-0.1322	-0.0786	-0.1412	-0.1269	-0.0708
9	**40**	-0.1454	-0.0918	-0.1556	-0.1397	-0.0776
10	**45**	-0.1344	-0.0846	-0.1459	-0.1311	-0.0758
11	**43**	-0.1466	-0.0931	-0.1614	-0.1390	-0.0763
12	**45**	-0.1366	-0.0896	-0.1493	-0.1288	-0.0711
13	**5**	-0.1435	-0.0938	-0.1521	-0.1329	-0.0720
14	**52**	-0.1522	-0.1051	-0.1709	-0.1495	-0.0856
15	**10**	-0.1366	-0.0831	-0.1441	-0.1199	-0.0646
16	**54**	-0.1454	-0.0966	-0.1612	-0.1453	-0.0881
17	**20**	-0.1329	-0.0820	-0.1419	-0.1248	-0.0741
18	**63**	-0.1461	-0.0937	-0.1606	-0.1500	-0.0945

The average deflection experienced by all the plies was obtained for each test and can be seen in Table 8. The maximum average total deflection was -0.2276 inches, while the maximum average net deflection was -0.1168 inches. Both maximum values occurred for test 14, when the work train had a speed of 52 miles per hour. The minimum average total deflection was -0.2050 for test 17, when the work train had a speed of 20 miles per hour, while the minimum average net deflection was -0.1055 for test 8 when the train had a speed of 40 miles per hour. The maximum values are highlighted in red and the minimum values are highlighted in blue in Table 8.

Table 8. Average deflection of Bridge 816.9

Test No.	**Speed (mph)**	**Average Total Deflection**	**Average Net Deflection**
1	**5**	-0.2129	-0.1082
2	**10**	-0.2070	-0.1060
3	**15**	-0.2125	-0.1083
4	**20**	-0.2089	-0.1077
5	**25**	-0.2150	-0.1109
6	**30**	-0.2065	-0.1058
7	**35**	-0.2202	-0.1132
8	**40**	-0.2064	-0.1055
9	**40**	-0.2159	-0.1100
10	**45**	-0.2089	-0.1076
11	**43**	-0.2196	-0.1127
12	**45**	-0.2092	-0.1082
13	**5**	-0.2170	-0.1089
14	**52**	-0.2276	-0.1168
15	**10**	-0.2070	-0.1060
16	**54**	-0.2176	-0.1125
17	**20**	-0.2050	-0.1064
18	**63**	-0.2163	-0.1119

It was expected that the deflections measurements would increase as the speed of the work train increased. To investigate this assumption, the average of the total and net deflections were plotted against speed. Figure 18 is a plot of the total deflection versus speed and the trend line indicates a small increase in the total deflection measurements as speed increased. A coefficient of determination of 0.17 for the trend line indicates the data is scattered.

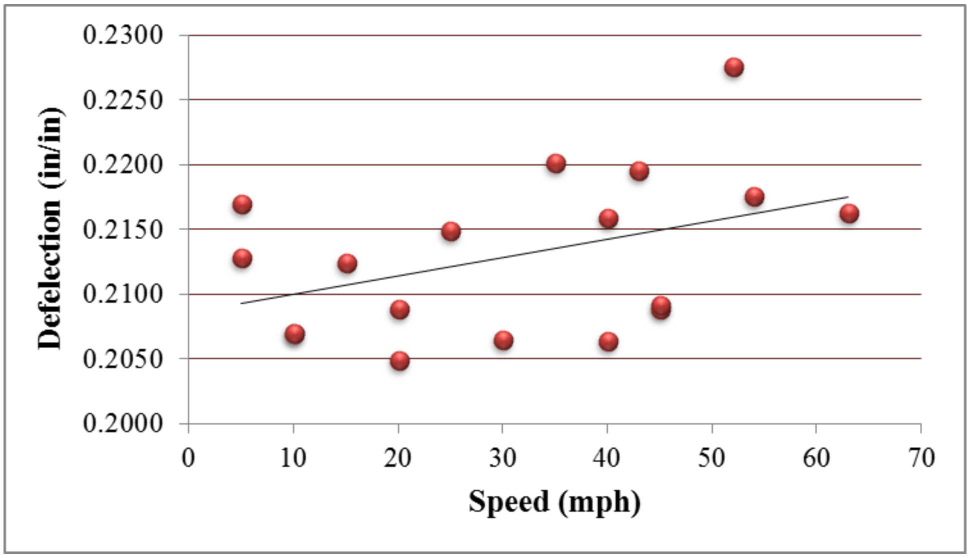


Figure 18. Average total deflection of Bridge 816.9 plotted against speed

Figure 19 is a plot of the net deflection versus speed and the trend line also indicates a small increase in the net deflection measurements as speed increased. The coefficient of determination obtained for the net deflection trend line was 0.32 which is larger than the coefficient of determination for the total deflection, yet still indicates the data is scattered.

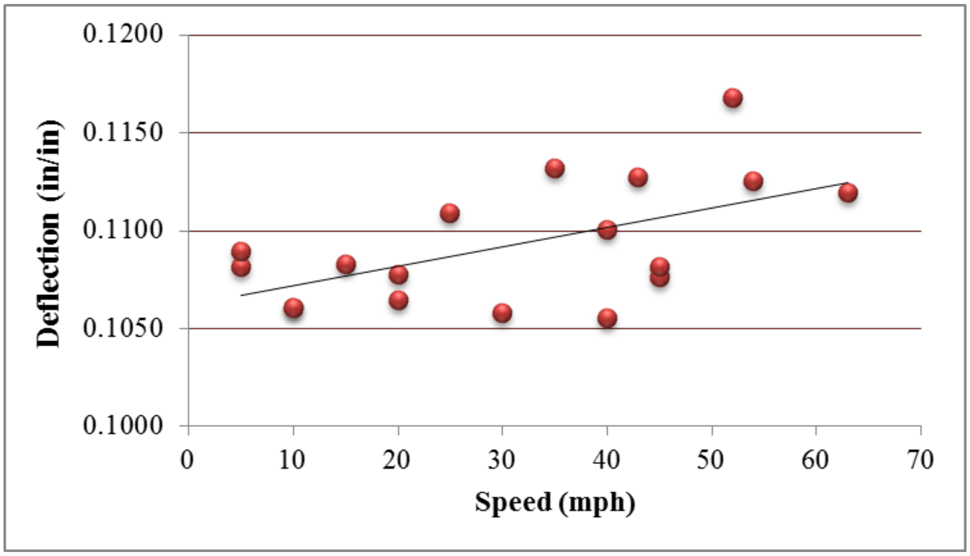


Figure 19. Average net deflection of Bridge 816.9 plotted against speed

The deflection results can be normalized by dividing the deflection value by the length of the span. Bridge 816.9 had a span length of 180 inches. This procedure was applied to the total deflections values and the net deflection values. Table 9 lists the normalized values of the total mid-span deflection for ply 1 through ply 5, and Table 10 lists the normalized values of the total mid span deflection for ply 6 through 10.

Table 9. Normalized maximum total deflection at mid-span for Ply 1-5

Test No.	**Speed (mph)**	**Ply 1**	**Ply 2**	**Ply 3**	**Ply 4**	**Ply 5**
1	**5**	-0.0010	-0.0013	-0.0013	-0.0014	-0.0009
2	**10**	-0.0010	-0.0013	-0.0014	-0.0014	-0.0009
3	**15**	-0.0010	-0.0013	-0.0014	-0.0014	-0.0009
4	**20**	-0.0010	-0.0013	-0.0014	-0.0014	-0.0009
5	**25**	-0.0011	-0.0014	-0.0014	-0.0014	-0.0009
6	**30**	-0.0010	-0.0013	-0.0014	-0.0014	-0.0009
7	**35**	-0.0010	-0.0013	-0.0014	-0.0014	-0.0010
8	**40**	-0.0010	-0.0013	-0.0013	-0.0014	-0.0009
9	**40**	-0.0010	-0.0013	-0.0013	-0.0013	-0.0009
10	**45**	-0.0010	-0.0013	-0.0014	-0.0013	-0.0009
11	**43**	-0.0010	-0.0013	-0.0014	-0.0014	-0.0009
12	**45**	-0.0010	-0.0013	-0.0013	-0.0014	-0.0009
13	**5**	-0.0010	-0.0013	-0.0014	-0.0014	-0.0010
14	**52**	-0.0010	-0.0013	-0.0014	-0.0014	-0.0010
15	**10**	-0.0010	-0.0013	-0.0014	-0.0014	-0.0009
16	**54**	-0.0010	-0.0013	-0.0013	-0.0013	-0.0009
17	**20**	-0.0010	-0.0013	-0.0013	-0.0013	-0.0009
18	**63**	-0.0009	-0.0012	-0.0013	-0.0013	-0.0009

The largest value obtained for the normalized total deflection for these tests was -0.0016, which was obtained during test 14 for ply 8, when the work train's speed was 52 miles per hour. The smallest value obtained for the normalized total deflection obtained for these tests was -0.0008 which occurred during test 17 for ply 7 in which the work train's speed was 20 miles per hour.

The largest value of the normalized deflection is highlighted in Table 10 in red, and the minimum value is highlighted in blue.

Table 10. Normalized maximum total deflection at mid-span for Ply 6-10

Test No.	**Speed (mph)**	**Ply 6**	**Ply 7**	**Ply 8**	**Ply 9**	**Ply 10**
1	**5**	-0.0014	-0.0010	-0.0015	-0.0012	-0.0009
2	**10**	-0.0014	-0.0009	-0.0014	-0.0011	-0.0008
3	**15**	-0.0014	-0.0009	-0.0015	-0.0012	-0.0009
4	**20**	-0.0014	-0.0009	-0.0014	-0.0011	-0.0009
5	**25**	-0.0014	-0.0009	-0.0014	-0.0011	-0.0009
6	**30**	-0.0014	-0.0009	-0.0014	-0.0011	-0.0009
7	**35**	-0.0014	-0.0010	-0.0015	-0.0012	-0.0009
8	**40**	-0.0014	-0.0009	-0.0014	-0.0011	-0.0009
9	**40**	-0.0014	-0.0010	-0.0015	-0.0013	-0.0010
10	**45**	-0.0014	-0.0009	-0.0014	-0.0012	-0.0009
11	**43**	-0.0015	-0.0010	-0.0015	-0.0012	-0.0010
12	**45**	-0.0014	-0.0009	-0.0014	-0.0012	-0.0009
13	**5**	-0.0015	-0.0010	-0.0015	-0.0012	-0.0009
14	**52**	-0.0015	-0.0011	-0.0016	-0.0013	-0.0010
15	**10**	-0.0014	-0.0009	-0.0014	-0.0011	-0.0008
16	**54**	-0.0014	-0.0010	-0.0016	-0.0013	-0.0010
17	**20**	-0.0013	-0.0008	-0.0014	-0.0011	-0.0009
18	**63**	-0.0014	-0.0010	-0.0016	-0.0013	-0.0011

Table 11 lists the normalized values of the net mid-span deflection for ply 1 through ply 5, and Table 12 lists the normalized values of the net mid span deflection for ply 6 through 10.

Table 11. Normalized maximum net deflection at mid-span for Ply 1-5

Test No.	**Speed (mph)**	**Ply 1**	**Ply 2**	**Ply 3**	**Ply 4**	**Ply 5**
1	**5**	-0.00025	-0.00071	-0.00077	-0.00070	-0.00038
2	**10**	-0.00025	-0.00071	-0.00078	-0.00071	-0.00039
3	**15**	-0.00025	-0.00071	-0.00078	-0.00071	-0.00040
4	**20**	-0.00026	-0.00072	-0.00079	-0.00072	-0.00039
5	**25**	-0.00030	-0.00077	-0.00081	-0.00073	-0.00039
6	**30**	-0.00023	-0.00071	-0.00078	-0.00072	-0.00039
7	**35**	-0.00028	-0.00074	-0.00081	-0.00073	-0.00041
8	**40**	-0.00022	-0.00070	-0.00078	-0.00073	-0.00038
9	**40**	-0.00022	-0.00066	-0.00075	-0.00070	-0.00039
10	**45**	-0.00022	-0.00071	-0.00078	-0.00073	-0.00036
11	**43**	-0.00025	-0.00071	-0.00077	-0.00073	-0.00038
12	**45**	-0.00025	-0.00071	-0.00077	-0.00070	-0.00038
13	**5**	-0.00023	-0.00067	-0.00076	-0.00071	-0.00039
14	**52**	-0.00022	-0.00069	-0.00077	-0.00072	-0.00040
15	**10**	-0.00025	-0.00071	-0.00078	-0.00071	-0.00039
16	**54**	-0.00021	-0.00069	-0.00074	-0.00067	-0.00041
17	**20**	-0.00024	-0.00072	-0.00077	-0.00069	-0.00040
18	**63**	-0.00017	-0.00064	-0.00075	-0.00066	-0.00041

The largest value obtained for the normalized total deflection for these tests was -0.00095, which was obtained during test 14 for ply 8, when the work train's speed was 52 miles per hour. The smallest value obtained for the normalized total deflection obtained for these tests was -0.00017 which occurred during test 18 for ply 1 in which the work train's speed was 63 miles per hour. The largest value of the normalized deflection is highlighted in Table 12 in red, and the minimum value is highlighted in blue in Table 11.

Table 12. Normalized maximum net deflection at mid-span for Ply 6-10

Test No.	**Speed (mph)**	**Ply 6**	**Ply 7**	**Ply 8**	**Ply 9**	**Ply 10**
1	**5**	-0.00076	-0.00050	-0.00083	-0.00072	-0.00040
2	**10**	-0.00076	-0.00046	-0.00080	-0.00067	-0.00036
3	**15**	-0.00077	-0.00051	-0.00082	-0.00070	-0.00037
4	**20**	-0.00076	-0.00047	-0.00080	-0.00070	-0.00039
5	**25**	-0.00076	-0.00048	-0.00083	-0.00070	-0.00038
6	**30**	-0.00076	-0.00047	-0.00079	-0.00067	-0.00036
7	**35**	-0.00078	-0.00051	-0.00085	-0.00075	-0.00042
8	**40**	-0.00073	-0.00044	-0.00078	-0.00070	-0.00039
9	**40**	-0.00081	-0.00051	-0.00086	-0.00078	-0.00043
10	**45**	-0.00075	-0.00047	-0.00081	-0.00073	-0.00042
11	**43**	-0.00081	-0.00052	-0.00090	-0.00077	-0.00042
12	**45**	-0.00076	-0.00050	-0.00083	-0.00072	-0.00040
13	**5**	-0.00080	-0.00052	-0.00085	-0.00074	-0.00040
14	**52**	-0.00085	-0.00058	-0.00095	-0.00083	-0.00048
15	**10**	-0.00076	-0.00046	-0.00080	-0.00067	-0.00036
16	**54**	-0.00081	-0.00054	-0.00090	-0.00081	-0.00049
17	**20**	-0.00074	-0.00046	-0.00079	-0.00069	-0.00041
18	**63**	-0.00081	-0.00052	-0.00089	-0.00083	-0.00053

An average normalized value was obtained for each test for the total and the net deflections and can be seen in Table 13. The maximum value obtained for the normalized total deflection was -0.00126 while the minimum value obtained was -0.00115. This represents a percent increase of 10.20% between smallest and largest normalized total deflection. The maximum value obtained for the normalized net deflection was -0.00065 while the minimum value obtained was -0.00059. This represents a percent increase of 10.40% between smallest and largest normalized net deflection.

Table 13. Normalized average deflection for Bridge 816.9

Speed (mph)	Normalized Total Deflection	Normalized Net Deflection
5	-0.00119	-0.00060
10	-0.00115	-0.00059
15	-0.00118	-0.00060
20	-0.00115	-0.00059
25	-0.00119	-0.00062
30	-0.00115	-0.00059
35	-0.00122	-0.00063
40	-0.00117	-0.00060
43	-0.00122	-0.00063
45	-0.00116	-0.00060
52	-0.00126	-0.00065
54	-0.00121	-0.00063
63	-0.00120	-0.00062

Open deck bridge test results

Deflection Data Analysis

As was done for the ballast deck bridge, two types of deflection are considered in this research: the total deflection of the stringers at mid-span, and the net deflection of the stringers at mid-span. Plots of the deflections versus time for all tests can be found in the Appendix section. Table 14 lists the results of the total mid-span deflection for the test for span 7. The maximum total deflection obtained for these tests was -1.0671 inches which was obtained during test 10 for ply 4 of chord 2, when the work train's speed was 51 miles per hour. The minimum total deflection obtained for these tests was -0.3304 which occurred during test 2 for ply 1 of chord 1 in which the work train's speed was 12 miles per hour. The maximum total deflection is highlighted in Table 14 in red, and the minimum total deflection is highlighted in the table in blue.

Table 14. Maximum total deflection at mid-span for span 7

Test No.	Speed (mph)	S7C1P1	S7C1P2	S7C1P3	S7C1P4	S7C2P1	S7C2P2	S7C2P3	S7C2P4
1	**12**	-0.3317	-0.3889	-0.4084	-0.4507	-0.7805	-0.9050	-0.9707	-1.0616
2	**12**	-0.3304	-0.3907	-0.4100	-0.4537	-0.7816	-0.9025	-0.9673	-1.0545
3	**19**	-0.3343	-0.3914	-0.4108	-0.4552	-0.7769	-0.9004	-0.9630	-1.0513
4	**20**	-0.3318	-0.3907	-0.4089	-0.4526	-0.7830	-0.9062	-0.9695	-1.0583
5	**29**	-0.3955	-0.4293	-0.4332	-0.4719	-0.7530	-0.8655	-0.9202	-0.9953
6	**29**	-0.3966	-0.4297	-0.4367	-0.4729	-0.7539	-0.8708	-0.9186	-0.9944
7	**40**	-0.3764	-0.4221	-0.4379	-0.4707	-0.7475	-0.8666	-0.9185	-1.0010
8	**40**	-0.3775	-0.4177	-0.4359	-0.4711	-0.7634	-0.8800	-0.9393	-1.0215
9	**50**	-0.3705	-0.4223	-0.4446	-0.4840	-0.7930	-0.9118	-0.9709	-1.0596
10	**51**	-0.3745	-0.4275	-0.4497	-0.4845	-0.7991	-0.9182	-0.9779	-1.0671

Table 15 lists the results of the total mid-span deflection for the test for span 8. The maximum total deflection obtained for these tests was -1.0000 inches which was obtained during test 4 for ply 4 of chord 2, when the work train's speed was 20 miles per hour. The minimum total deflection obtained for these tests was -0.2691 which occurred during test 4 for ply 1 of chord 1 in which the work train's speed was 12 miles per hour. The maximum total deflection is highlighted in Table 15 in red, and the minimum total deflection is highlighted in the table in blue.

Table 15. Maximum total deflection at mid-span for span 8

Test No.	Speed (mph)	S8C1P1	S8C1P2	S8C1P3	S8C1P4	S8C2P1	SC2P2	S8C2P3	S8C2P4
1	**12**	-0.2886	-0.3687	-0.4273	-0.4560	-0.8261	-0.7632	-0.7985	-0.9289
2	**12**	-0.2898	-0.3748	-0.4366	-0.4652	-0.8380	-0.7749	-0.8092	-0.9404
3	**19**	-0.2770	-0.3643	-0.4264	-0.4588	-0.8660	-0.8099	-0.8513	-0.9871
4	**20**	-0.2691	-0.3569	-0.4231	-0.4565	-0.8674	-0.8143	-0.8621	-1.0000
5	**29**	-0.2880	-0.3698	-0.4308	-0.4605	-0.8488	-0.7987	-0.8367	-0.9788
6	**29**	-0.2851	-0.3675	-0.4308	-0.4612	-0.8552	-0.8095	-0.8549	-0.9897
7	**40**	-0.2975	-0.3815	-0.4444	-0.4731	-0.8532	-0.7954	-0.8356	-0.9706
8	**40**	-0.2998	-0.3835	-0.4481	-0.4774	-0.8514	-0.7976	-0.8394	-0.9731
9	**50**	-0.3000	-0.3887	-0.4605	-0.4957	-0.8781	-0.8176	-0.8552	-0.9913
10	**51**	-0.2967	-0.3902	-0.4632	-0.4967	-0.8798	-0.8149	-0.8535	-0.9902

Table 16 lists the results of the net mid-span deflection for the test for span 7. The maximum net deflection obtained for these tests was -0.7112 inches which was obtained during test 10 for ply 4 of chord 2, when the work train’s speed was 51 miles per hour. The minimum net deflection obtained for these tests was -0.1377 which occurred during test 2 for ply 1 of chord 1 in which the work train’s speed was 12 miles per hour. The maximum net deflection is highlighted in Table 16 in red, and the minimum net deflection is highlighted in the table in blue.

Table 16. Maximum net deflection at mid-span for span 7

Test No.	**Speed (mph)**	**S7C1P1**	**S7C1P2**	**S7C1P3**	**S7C1P4**	**S7C2P1**	**S7C2P2**	**S7C2P3**	**S7C2P4**
1	**12**	-0.1377	-0.1651	-0.1420	-0.1580	-0.4012	-0.5427	-0.6125	-0.6879
2	**12**	-0.1411	-0.1686	-0.1427	-0.1588	-0.3972	-0.5416	-0.6089	-0.6846
3	**19**	-0.1389	-0.1676	-0.1429	-0.1592	-0.3978	-0.5420	-0.6070	-0.6837
4	**20**	-0.1417	-0.1719	-0.1455	-0.1625	-0.4016	-0.5439	-0.6103	-0.6879
5	**29**	-0.1748	-0.2004	-0.1612	-0.1676	-0.3833	-0.5221	-0.5786	-0.6498
6	**29**	-0.1755	-0.2003	-0.1595	-0.1673	-0.3830	-0.5215	-0.5768	-0.6486
7	**40**	-0.1591	-0.1864	-0.1491	-0.1584	-0.3823	-0.5286	-0.5847	-0.6618
8	**40**	-0.1596	-0.1819	-0.1491	-0.1619	-0.3806	-0.5268	-0.5823	-0.6649
9	**50**	-0.1509	-0.1792	-0.1584	-0.1760	-0.4087	-0.5605	-0.6189	-0.7091
10	**51**	-0.1528	-0.1833	-0.1606	-0.1772	-0.4126	-0.5656	-0.6255	-0.7112

Table 17 lists the results of the net mid-span deflection for the test for span 8. The maximum net deflection obtained for these tests was -0.6115 inches which was obtained during test 4 for ply 4 of chord 2, when the work train's speed was 20 miles per hour. The minimum net deflection obtained for these tests was -0.0864 which occurred during test 1 for ply 1 of chord 1 in which the work train's speed was 12 miles per hour. The maximum net deflection is highlighted in Table 17 in red, and the minimum net deflection is highlighted in the table in blue.

Table 17. Maximum net deflection at mid-span for span 8

Test No.	Speed (mph)	S8C1P1	S8C1P2	S8C1P3	S8C1P4	S8C2P1	SC2P2	S8C2P3	S8C2P4
1	**12**	-0.0864	-0.1356	-0.1955	-0.2573	-0.3805	-0.4508	-0.3221	-0.5688
2	**12**	-0.0899	-0.1422	-0.1983	-0.2671	-0.3814	-0.4593	-0.3265	-0.5765
3	**19**	-0.0865	-0.1381	-0.1960	-0.2617	-0.3984	-0.4800	-0.3489	-0.6003
4	**20**	-0.0865	-0.1376	-0.1965	-0.2550	-0.3986	-0.4844	-0.3545	-0.6115
5	**29**	-0.1035	-0.1548	-0.2146	-0.2732	-0.3895	-0.4780	-0.3495	-0.6009
6	**29**	-0.1094	-0.1592	-0.2197	-0.2795	-0.3934	-0.4833	-0.3558	-0.6051
7	**40**	-0.0964	-0.1514	-0.2099	-0.2680	-0.3926	-0.4744	-0.3432	-0.5885
8	**40**	-0.0983	-0.1487	-0.2117	-0.2676	-0.3929	-0.4737	-0.3458	-0.5945
9	**50**	-0.0943	-0.1464	-0.2180	-0.2808	-0.4091	-0.4830	-0.3538	-0.6071
10	**51**	-0.0967	-0.1488	-0.2169	-0.2811	-0.4108	-0.4851	-0.3526	-0.6054

The average total deflection experienced by each span was obtained for each test and can be seen in Table 18. The maximum average total deflection for span 7 was -0.9406 inches during test 10 for chord 2, while the minimum average total deflection was -0.3949 inches during test 1 for cord 1.The maximum average total deflection for span 7 was -0.4635 inches during test 10 for chord 2, while the minimum average total deflection was -0.3949 inches during test 1 for cord 1.

Table 18. Average total deflection at mid-span for spans 7 and 8

Test No.	Speed (mph)	S7C1	S7C2	S8C1	S8C2
1	**12**	-0.3949	-0.9295	-0.3852	-0.8292
2	**12**	-0.3962	-0.9265	-0.3916	-0.8406
3	**19**	-0.3979	-0.9229	-0.3816	-0.8786
4	**20**	-0.3960	-0.9293	-0.3764	-0.8860
5	**29**	-0.4325	-0.8835	-0.3873	-0.8658
6	**29**	-0.4340	-0.8844	-0.3862	-0.8773
7	**40**	-0.4268	-0.8834	-0.3991	-0.8637
8	**40**	-0.4256	-0.9011	-0.4022	-0.8654
9	**50**	-0.4304	-0.9338	-0.4112	-0.8856
10	**51**	-0.4341	-0.9406	-0.4117	-0.8846

The average net deflection experienced by each span was obtained for each test and can be seen in Table 19. The maximum average total deflection for span 7 was -0.5787 inches during test 10 for chord 2, while the minimum average total deflection was -0.1507 inches during test 1 for cord 1. The maximum average total deflection for span 7 was -0.4635 inches during test 10 for chord 2, while the minimum average total deflection was -0.1687 inches during test 1 for cord 1.

Table 19. Average net deflection at mid-span for spans 7 and 8

Test No.	**Speed (mph)**	**S7C1**	**S7C2**	**S8C1**	**S8C2**
1	**12**	-0.1507	-0.5611	-0.1687	-0.4305
2	**12**	-0.1528	-0.5581	-0.1744	-0.4359
3	**19**	-0.1521	-0.5576	-0.1706	-0.4569
4	**20**	-0.1554	-0.5609	-0.1689	-0.4622
5	**29**	-0.1760	-0.5334	-0.1865	-0.4544
6	**29**	-0.1756	-0.5325	-0.1919	-0.4594
7	**40**	-0.1632	-0.5393	-0.1814	-0.4497
8	**40**	-0.1631	-0.5386	-0.1815	-0.4517
9	**50**	-0.1661	-0.5743	-0.1848	-0.4632
10	**51**	-0.1685	-0.5787	-0.1859	-0.4635

As was done for the ballast deck bridge, the average total and net deflection of each span was obtained and plotted against speed to visualize the relationship between these two factors. Figure 20 is a plot of the total deflection of Span 7 versus speed and the trend line also indicates a small increase in the net deflection measurements as speed increased. The coefficient of determination obtained for the net deflection trend line was 0.41.

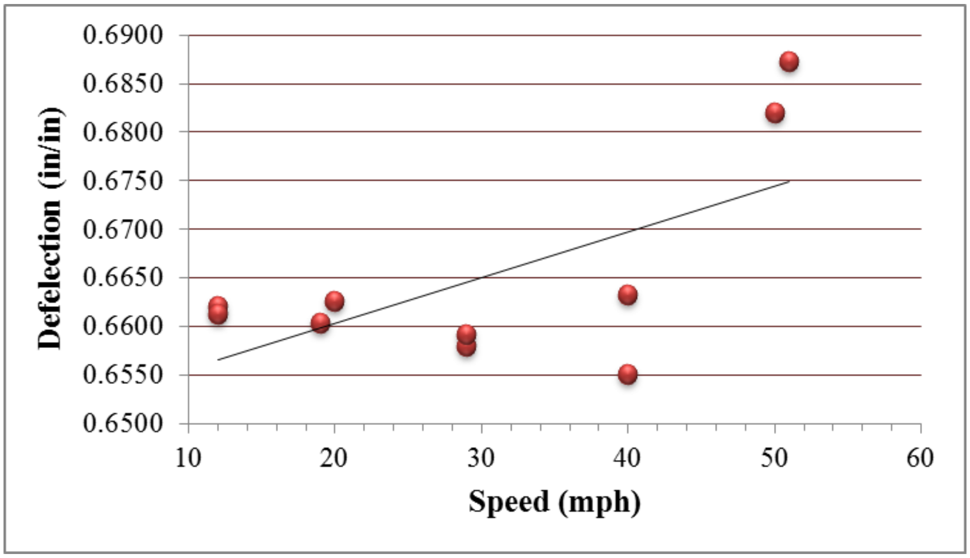


Figure 20. Average total deflection of Span 7 of Bridge 17.14 plotted against speed

Figure 21 is a plot of the total deflection of Span 8 versus speed and the trend line also indicates a small increase in the net deflection measurements as speed increased. The coefficient of determination obtained for the net deflection trend line was 0.78, and shows less scatter than the other tests.

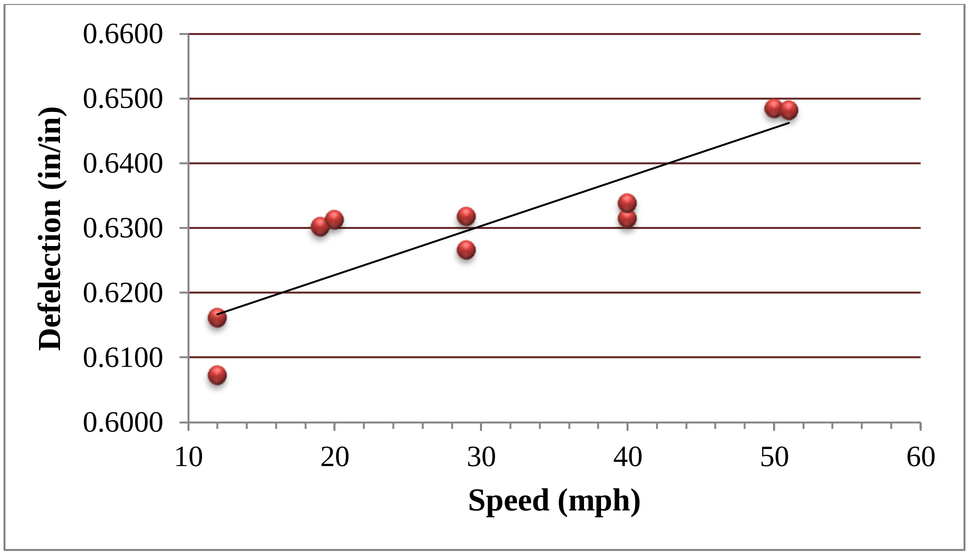


Figure 21. Average total deflection of Span 8 of Bridge 17.14 plotted against speed

Figure 22 is a plot of the net deflection of Span 7 versus speed and the trend line also indicates a small increase in the net deflection measurements as speed increased. The coefficient of determination obtained for the net deflection trend line was 0.30.

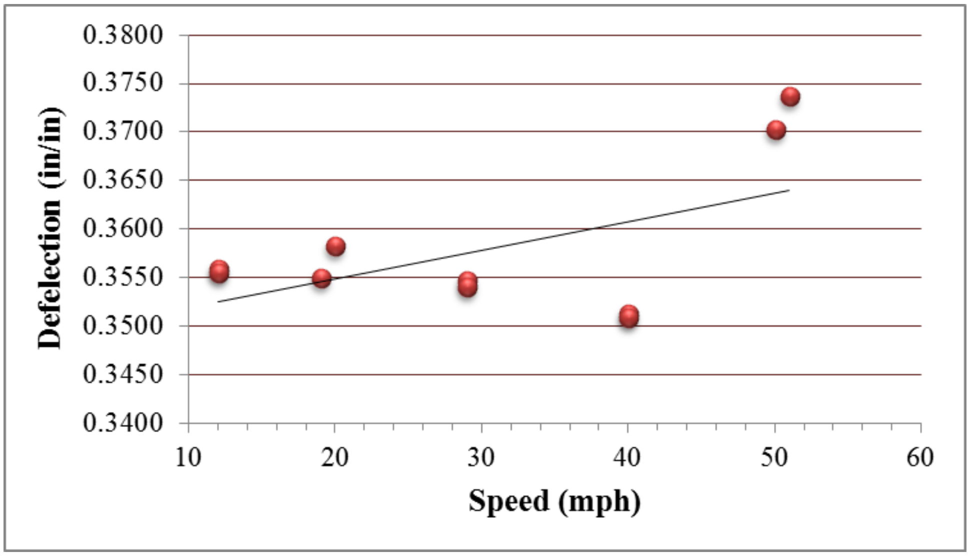


Figure 22. Average net deflection of Span 7 of Bridge 17.14 plotted against speed

Figure 23 is a plot of the total deflection of Span 8 versus speed and the trend line also indicates a small increase in the net deflection measurements as speed increased. The coefficient of determination obtained for the net deflection trend line is 0.58, and shows less scatter than the other tests.

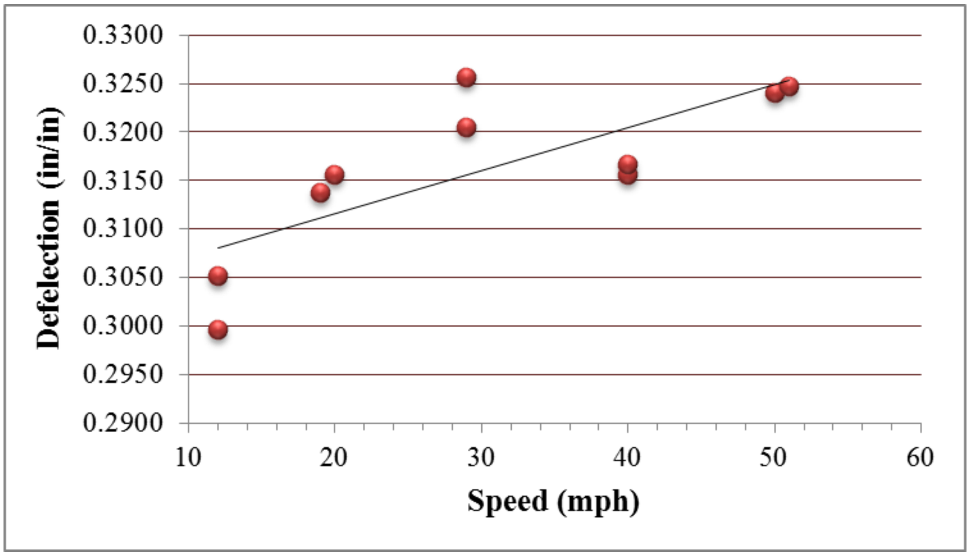


Figure 23. Average net deflection of Span 8 of Bridge 17.14 plotted against speed

As was done for the ballast deck bridge, the deflection values were normalized by dividing the deflection value by the length of the span. Bridge 17.14 had a span length of 180 inches. This procedure was applied to the average total deflections values and the average net deflection values of spans 7 and 8. Table 20 lists the normalized values of the total mid-span deflection and Table 21 lists the normalized values of the net mid span deflection.

The maximum normalized average total deflection value obtained for span 7 was -0.00523 during test 10, in which the work train had a speed of 51 miles per hour, while the minimum normalized average total deflection was -0.00219 during test 1, in which the work train has a speed of 12 miles per hour. The maximum normalized average total deflection value obtained for span 8 was -0.00492 during test 9 , in which the work train had a speed of 50 miles per hour, while the minimum normalized average total deflection was -0.00209 during test 4, in which the work train has a speed of 20 miles per hour.

Table 20. Normalized average total deflection of spans 7 and 8

Test No.	Speed (mph)	S7C1	S7C2	S8C1	S8C2
1	12	-0.00219	-0.00516	-0.00214	-0.00461
2	12	-0.00220	-0.00515	-0.00218	-0.00467
3	19	-0.00221	-0.00513	-0.00212	-0.00488
4	20	-0.00220	-0.00516	-0.00209	-0.00492
5	29	-0.00240	-0.00491	-0.00215	-0.00481
6	29	-0.00241	-0.00491	-0.00215	-0.00487
7	40	-0.00237	-0.00491	-0.00222	-0.00480
8	40	-0.00236	-0.00501	-0.00223	-0.00481
9	50	-0.00239	-0.00519	-0.00228	-0.00492
10	51	-0.00241	-0.00523	-0.00229	-0.00491

The maximum normalized average net deflection value obtained for span 7 was -0.00322 during test 10, in which the work train had a speed of 51 miles per hour, while the minimum normalized average total deflection was -0.00084 during test 1, in which the work train has a speed of 12 miles per hour. The maximum normalized average total deflection value obtained for span 8 was -0.00257 during test 10 , in which the work train had a speed of 51 miles per hour, while the minimum normalized average total deflection was -0.00094 during test 1, in which the work train has a speed of 12 miles per hour.

Table 21. Normalized average net deflection of spans 7 and 8

Test No.	**Speed (mph)**	**S7C1**	**S7C2**	**S8C1**	**S8C2**
1	**12**	-0.00084	-0.00312	-0.00094	-0.00239
2	**12**	-0.00085	-0.00310	-0.00097	-0.00242
3	**19**	-0.00085	-0.00310	-0.00095	-0.00254
4	**20**	-0.00086	-0.00312	-0.00094	-0.00257
5	**29**	-0.00098	-0.00296	-0.00104	-0.00252
6	**29**	-0.00098	-0.00296	-0.00107	-0.00255
7	**40**	-0.00091	-0.00300	-0.00101	-0.00250
8	**40**	-0.00091	-0.00299	-0.00101	-0.00251
9	**50**	-0.00092	-0.00319	-0.00103	-0.00257
10	**51**	-0.00094	-0.00322	-0.00103	-0.00257

According to the Section 3.1.15 of Chapter 7 of the AREMA Manual for Railway Engineering, the net chord deflections of a bridge under live load should not exceed L/250, where L is the span length in inches (AREMA 2015). Both bridges in this project have a span length of 180 inches, which means the deflection of the stringers under a live load should not exceed -0.72 inches. For Bridge 816.9, none of the maximum net stringer deflections exceeded this limit. The net stringer deflections of Bridge 17.14 also did not exceed this limit, but reached much higher values, having a maximum net deflection of -0.7112 during one of the tests. There was a significant difference between the total mid-span stringer deflections and the net stringer deflections of the open deck bridge and for the ballast deck bridge.

CHAPTER V

CONCLUSION

Conclusions

Many factors affect the load and deflection of timber bridges, including the weight of the train, the modulus of elasticity of the wood and the overall condition of the structure. This vehicle bridge interaction project was designed to investigate the effect of train speed on load and deflection of a timber railroad bridge in order to better understand the behavior of timber railroad bridges under live loading. Deflections measurements of stringers of a ballast deck bridge and an open deck bridge under live load were obtained using string potentiometers. Direct load measurements were also recorded for the ballast deck bridge using load cells. Each set of data was recorded and analyzed. The deflection values measured for the ballast deck bridge were overall smaller than the values obtained for the open deck bridge. While the maximum net deflection value obtained for the ballast deck bridge was -0.1709 inches, the maximum net deflection value obtained for the open deck bridge was three times larger, -0.7112 inches. This difference can be explained by the higher stiffness of the ballast deck bridge compared to the open deck bridge.

Although stiffness seems to be an important factor for the deflection of the timber bridges, increasing speed did not increase the deflection measurements for either bridge in the same way. Load and deflection measurements were plotted against the known speed of the tests and trend lines were obtained. The load measurements taken from the ballast deck bridge displayed a trend line with a positive slope, and the deflection measurements taken from both the ballast deck bridge and the open deck bridge also displayed trend lines with positive slopes, showing that these parameters had small increases as train speed increased. However, for both the load and the deflection measurements there was a large amount of scatter around the trend lines. The variability in the load and deflection measurements can be explained by the variability in the different factors that these measurements depend on, such as the modulus of elasticity of the timber members. While bridge stiffness and condition can strongly impact the deflection results, the effect of train speed on load and deflection of a timber railroad bridge is not as significant. If deflection and load are safety concerns for a timber railroad bridge, reducing train speed should not decrease these measurements enough to guarantee safe operations.

Future research

Future research on the effect of train speed on load and deflection of a timber railroad bridge should investigate the limits of the correlation between this factor and the outcomes. The analysis of the load and deflection of different timber railroad bridges in diverse condition subjected to live load will lead to a better understanding of the limitation of the effect of speed on deflection and load.

REFERENCES

AREMA (2015). *Manual for Railway Engineering Vol. 2.* American Railway Engineering Association, Washington, DC.

American Railway Engineering & Maintenance of Way Association. 2003. *AREMA Practical Guide to Railway Engineering.* 2nd edition. Committee 24: Education and Training.

Borchers, C. R. (2002). "Fatigue Tests of Under-Strength Timber Railroad Bridge Stringers." MS Thesis, Department of Civil Engineering, Texas A&M University, College Station, TX.

Donovan, K. A. (2004). "Field Tests of Timber Railroad Bridge Piles." M.S. Thesis, Department of Civil Engineering, Texas A&M University, College Station.

Emerson, R.N. "Nondestructive Evaluation of Timber Bridges." Ph.D. Dissertation, Department of Civil and Environmental Engineering, Washington State University, Pullman, WA.

Emerson, R.N., Pollock, D.G., McLean, D.I., Fridley, K.J., Pellerin, R., and Ross, R.J. (2002). "Ultrasonic Inspection of Large Bridge Timbers." Forest Products Journal, Vol. 52, No. 9 (September 2002), pp. 88-95.

Lewis, W. C. (1946). "Fatigue of Wood and Glued-wood Construction." *Proceedings of the American Society for Testing Materials,* Chicago, IL., pp. 53-54.

Orsak, J.P. (2012). "A Theoretical Structural Impairment Detection System for Timber Railway Bridges." M.S. Thesis, Department of Civil Engineering, Texas A&M University, College Station.

Peterson, M.L., Gutkowski, R.M. (1999). "Evaluation of the structural integrity of timber bridges." *Independent Nondestructive Testing and Evaluation International.* pp. 43-48.

Rachal, L. (2015). "Determination of Bent Cap and Stringer Deflections for Timber Railway Bridges Under Live Load." M.S. Thesis, Department of Civil Engineering ,Texas A&M University, College Station.

Ritter, M.A., Wipf, T.J., Wood, D.L. (2000). “Evaluation and Field Load Testing of Timber Railroad Bridge.” *Transportation Research Record.* pp. 323-333

Sculley, P. J. (2003). “Determination of a Strength Parameter for In-situ Evaluation of Timber Railroad Bridge Piles Subject to Decay and Fatigue Damage Accumulation.” M.S. Thesis, Texas A&M University, College Station.

Stalnaker, J. J. and E. C. Harris. (1997). *Structural Design in Wood*. 2nd Edition. Chapman & Hall. New York.

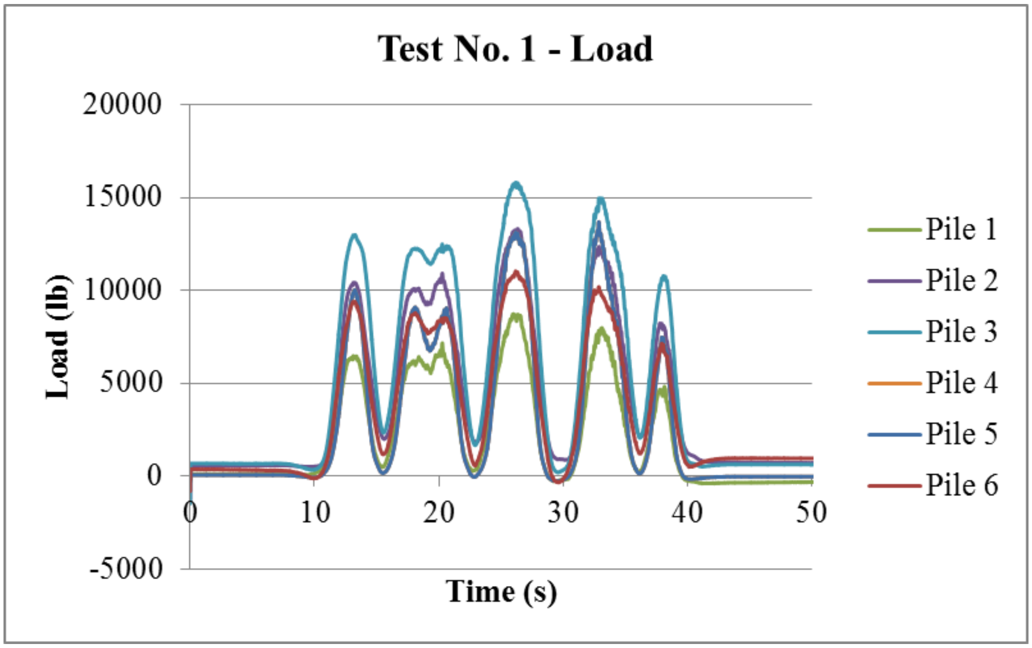
Story, B. (2012). “Structural Impairment Detection Using Arrays of Competitive Artificial Neural Networks.” Ph.D. Dissertation, Department of Civil Engineering, Texas A&M University, College Station, TX.

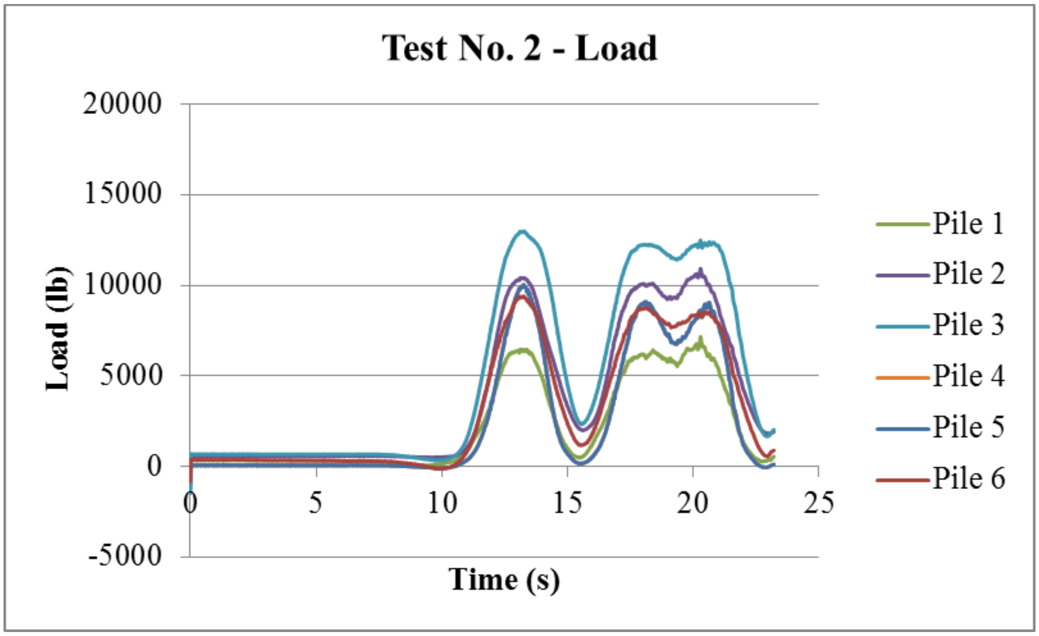
Capozzoli, L. J. (1966). “Current Status of Timber Foundation Piles.” *Wood Preserving News*. Vol. 44, No. 11, American Wood Preservers Institute, Washington, DC.

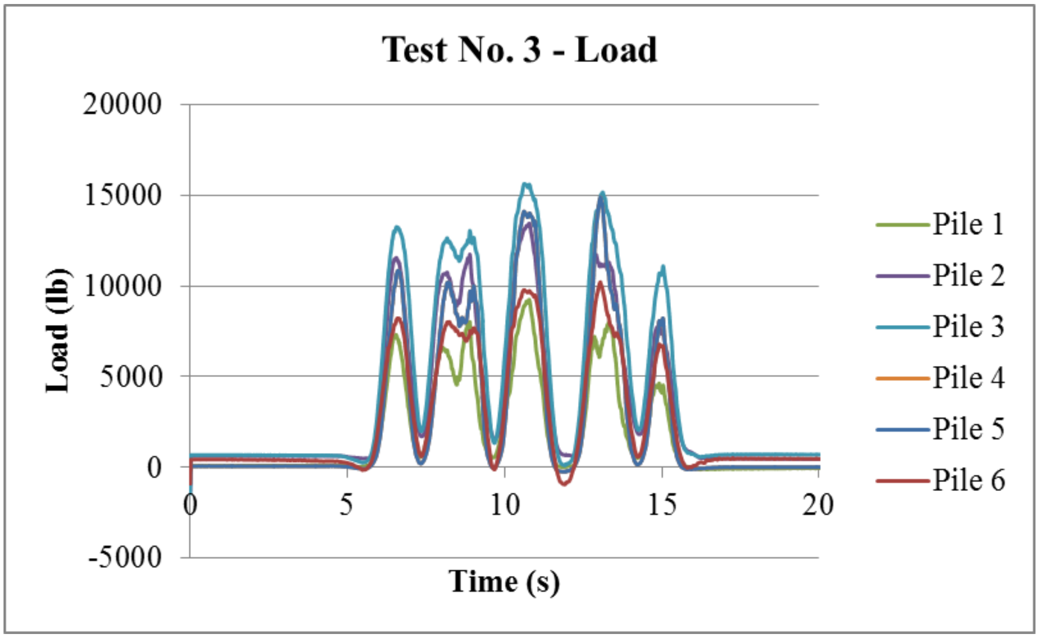
Uppal, A. S. and D. E. Otter. (1998). “Methodologies for Strengthening and Extending Life of Timber Railroad Bridges.” Association of American Railroads, Transportation Technology Center, Report No. R-922, Pueblo, CO.

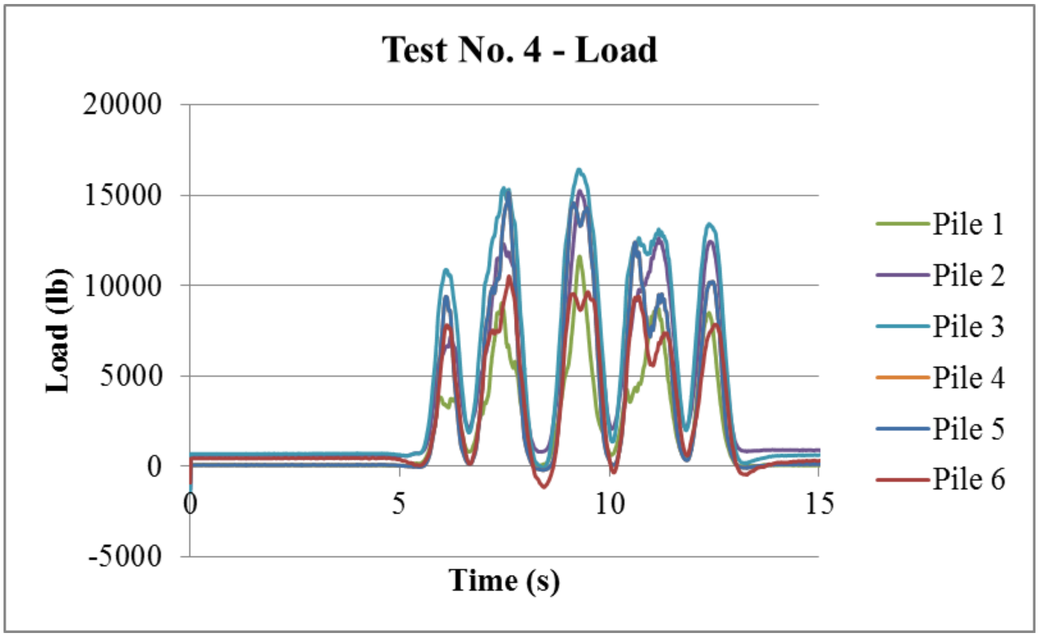
APPENDIX A

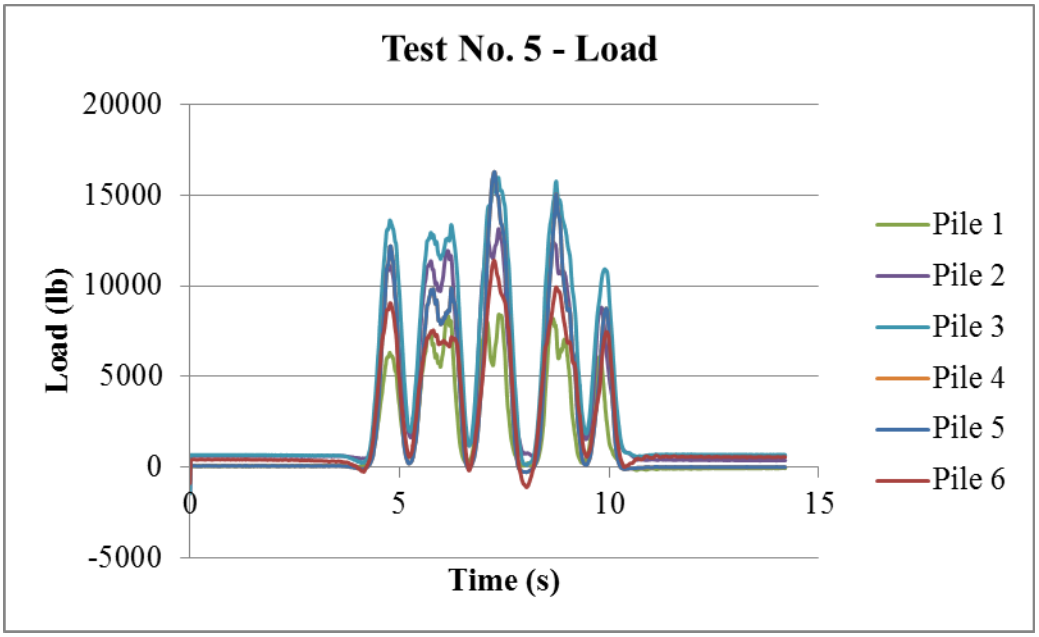
BRIDGE 816.9 LOAD TIME HISTORY PLOTS

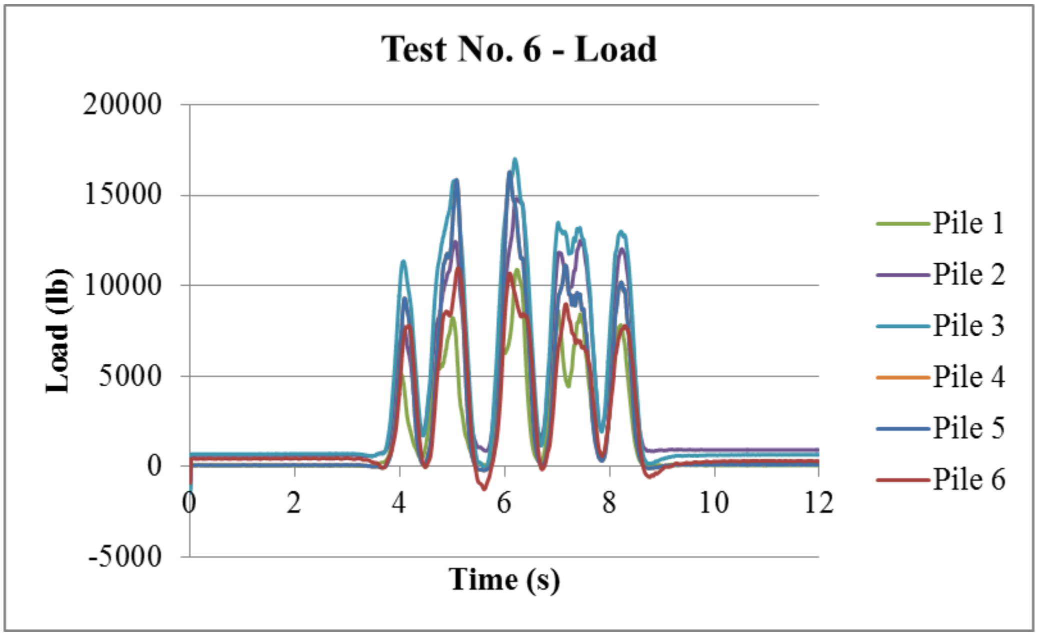


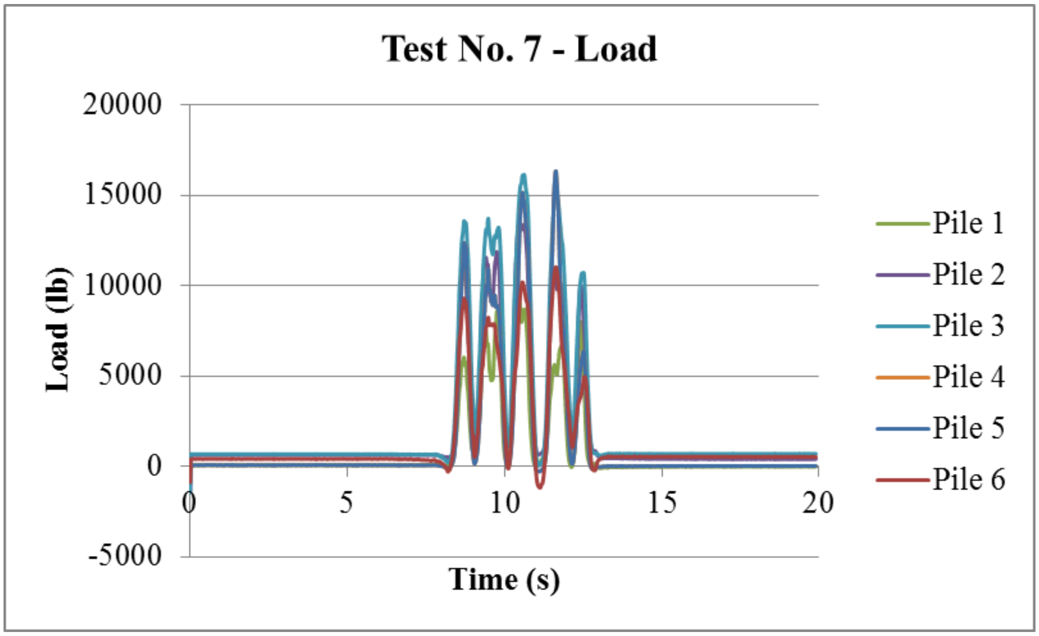


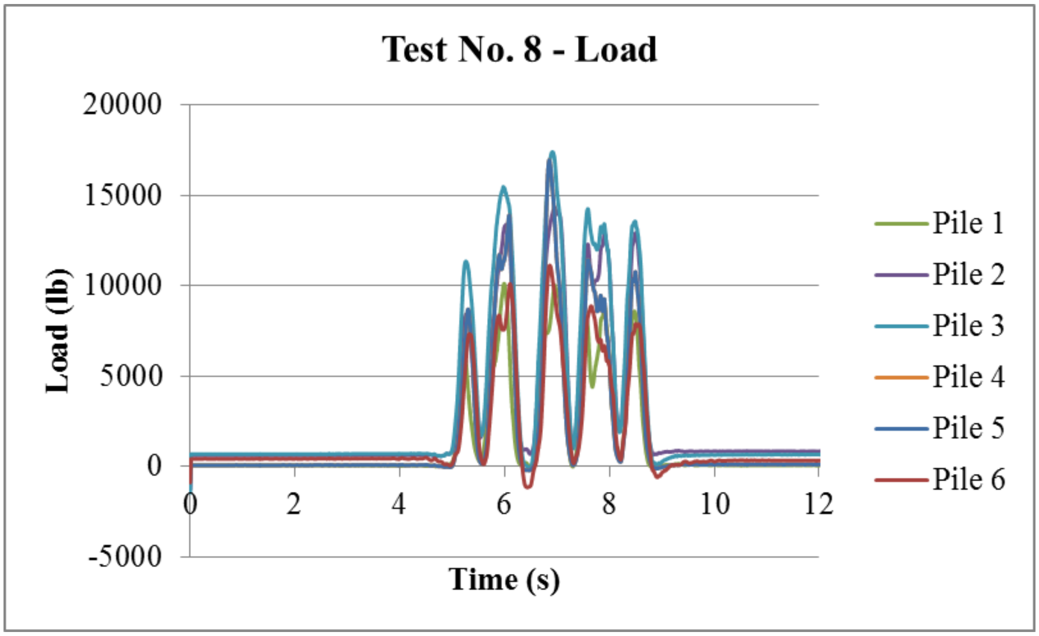

Test No. 3 - Load
Load (lb)
20000
15000
10000
5000
0
-5000
0
5
10
15
20
Time (s)
Pile 1
Pile 2
Pile 3
Pile 4
Pile 5
Pile 6

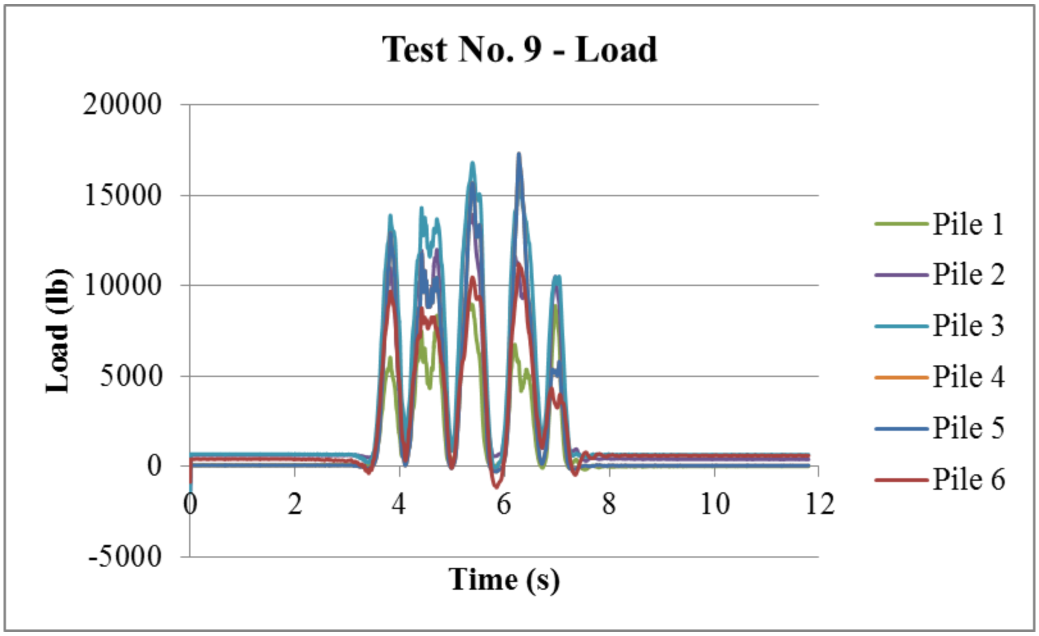

Test No. 4 - Load
Load (lb)
20000
15000
10000
5000
0
-5000
0
5
10
15
Time (s)
Pile 1
Pile 2
Pile 3
Pile 4
Pile 5
Pile 6

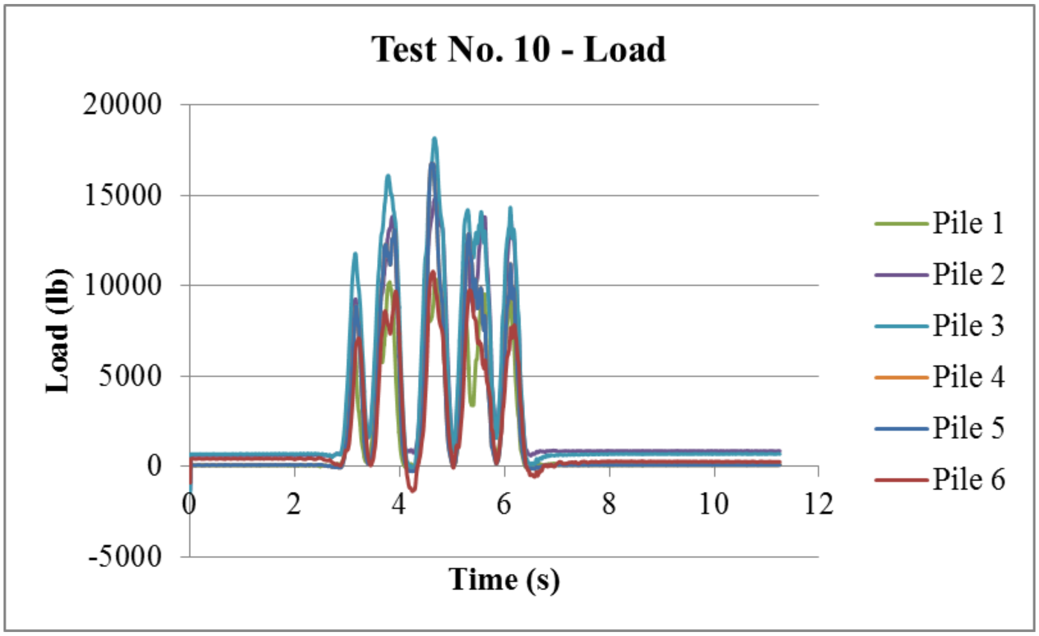

Test No. 5 - Load
Load (lb)
20000
15000
10000
5000
0
-5000
0
5
10
15
Time (s)
Pile 1
Pile 2
Pile 3
Pile 4
Pile 5
Pile 6

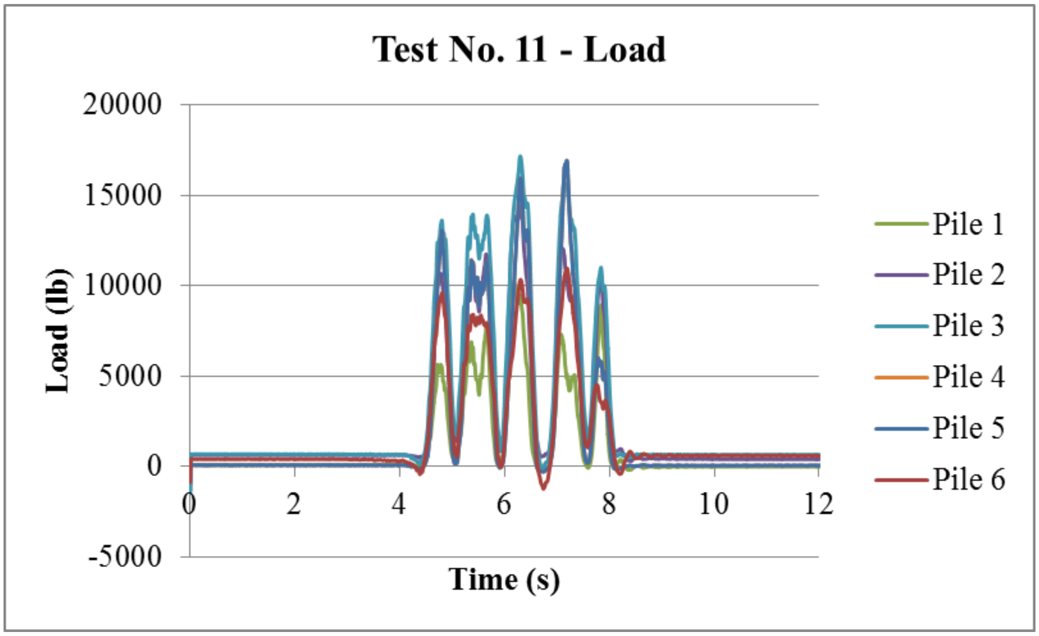

Test No. 6 - Load
Load (lb)
20000
15000
10000
5000
0
-5000
0
2
4
6
8
10
12
Time (s)
Pile 1
Pile 2
Pile 3
Pile 4
Pile 5
Pile 6

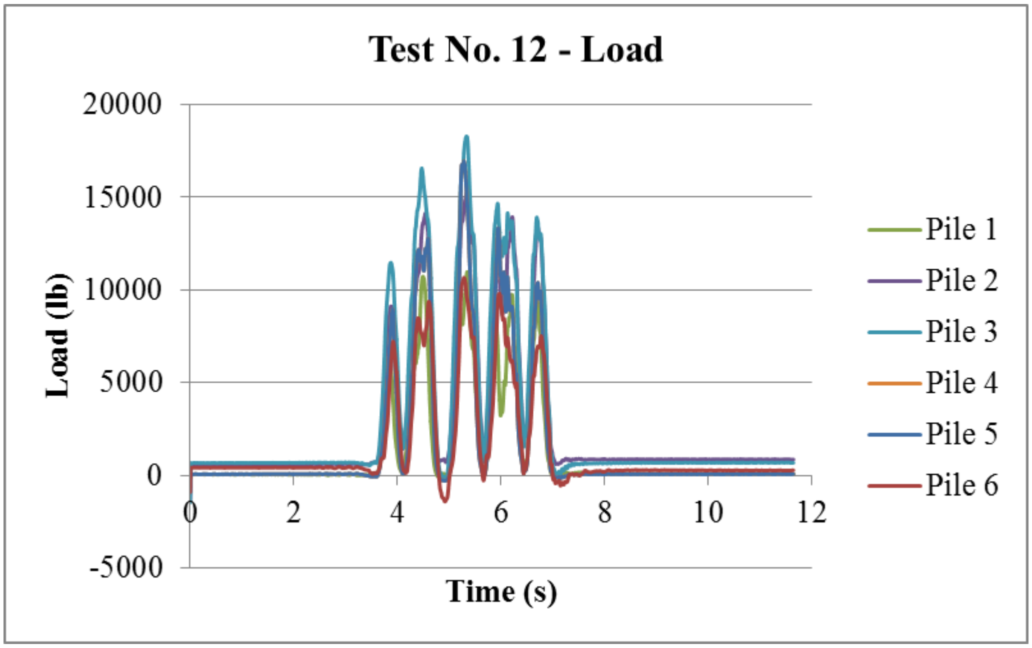

Test No. 7 - Load
Load (lb)
20000
15000
10000
5000
0
-5000
0
5
10
15
20
Time (s)
Pile 1
Pile 2
Pile 3
Pile 4
Pile 5
Pile 6

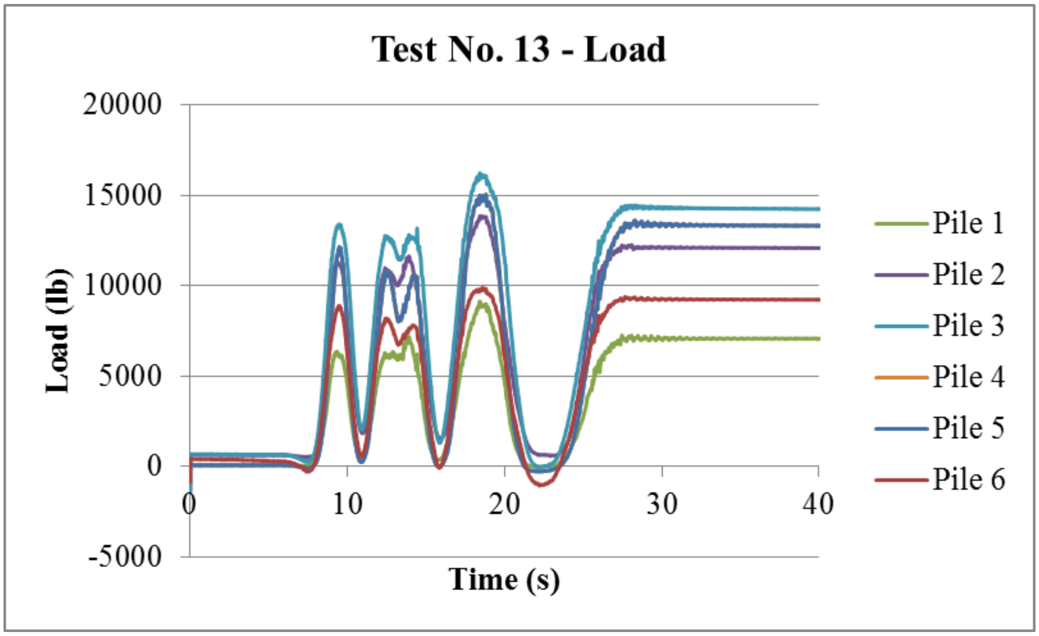

Test No. 8 - Load
Load (lb)
20000
15000
10000
5000
0
-5000
0
2
4
6
8
10
12
Time (s)
Pile 1
Pile 2
Pile 3
Pile 4
Pile 5
Pile 6

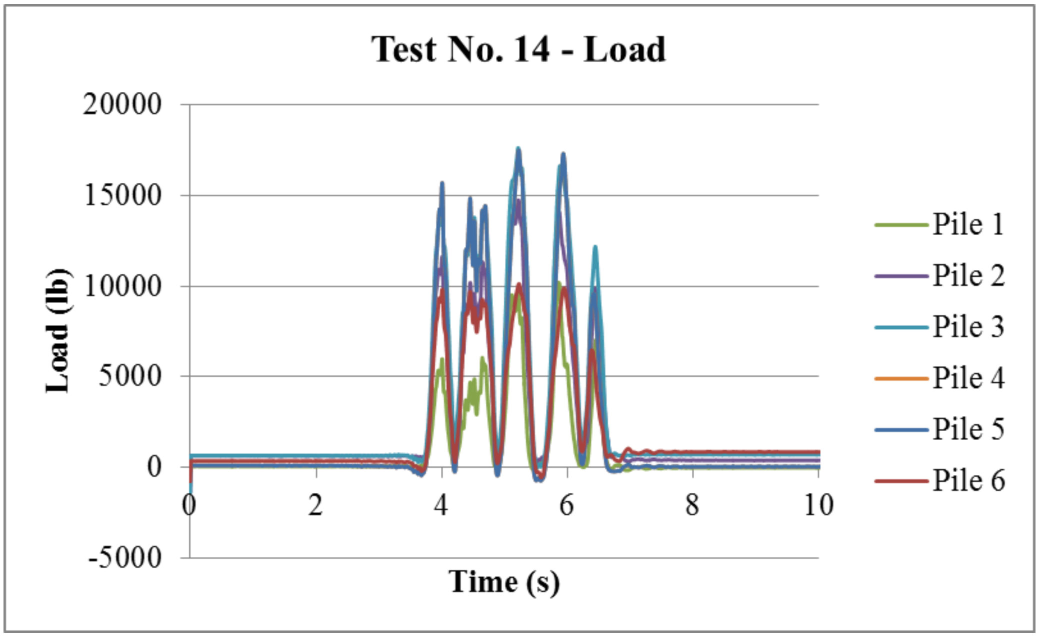

Test No. 9 - Load
Load (lb)
20000
15000
10000
5000
0
-5000
0
2
4
6
8
10
12
Time (s)
Pile 1
Pile 2
Pile 3
Pile 4
Pile 5
Pile 6

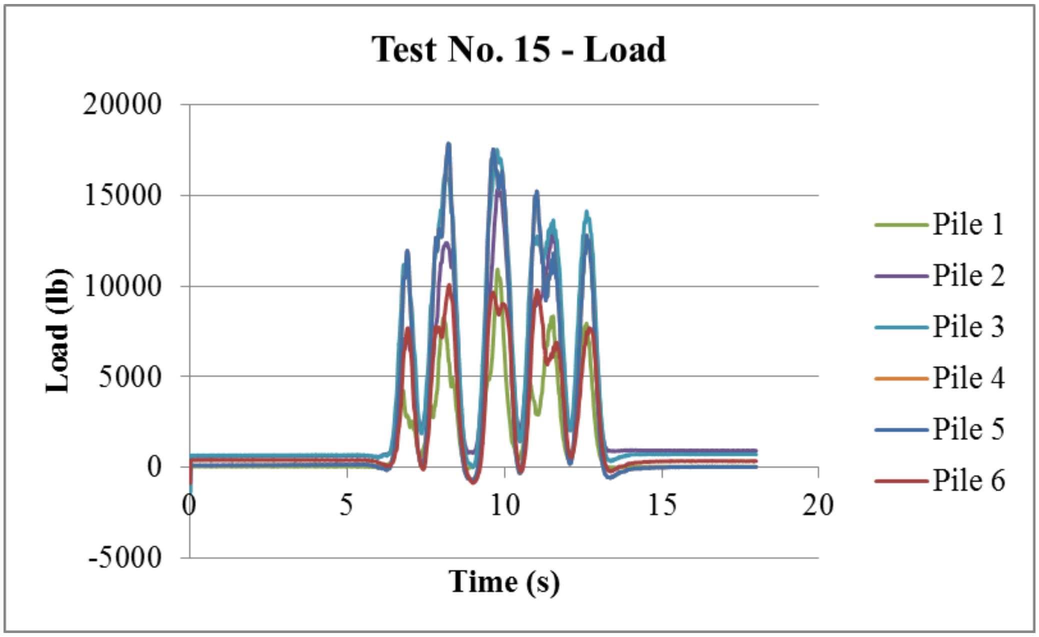

Test No. 10 - Load
Load (lb)
20000
15000
10000
5000
0
-5000
0
2
4
6
8
10
12
Time (s)
Pile 1
Pile 2
Pile 3
Pile 4
Pile 5
Pile 6

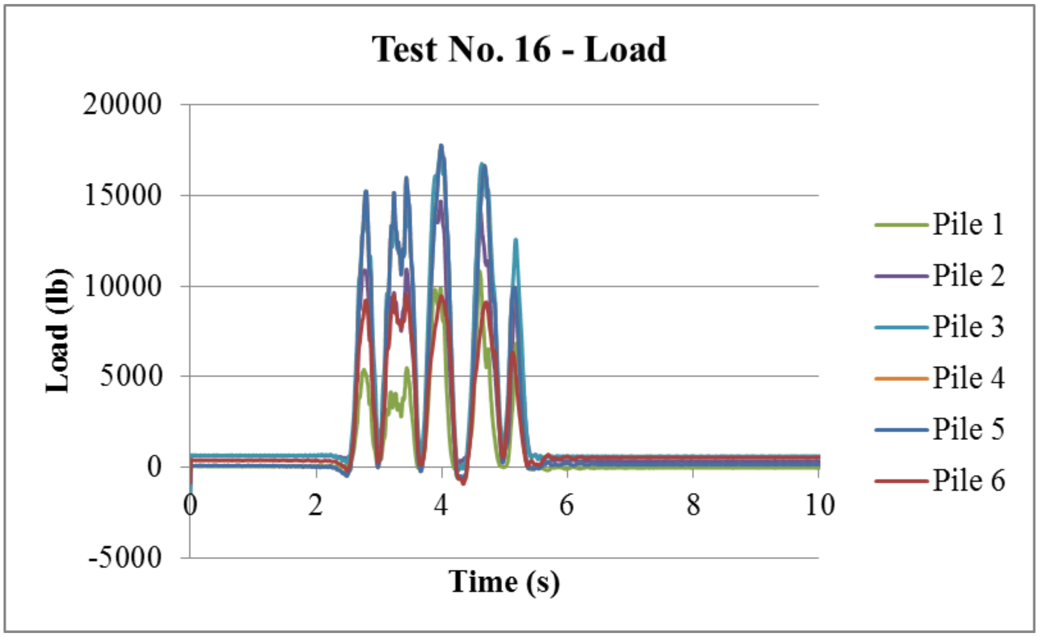

Test No. 11 - Load
Load (lb)
20000
15000
10000
5000
0
-5000
0
2
4
6
8
10
12
Time (s)
Pile 1
Pile 2
Pile 3
Pile 4
Pile 5
Pile 6

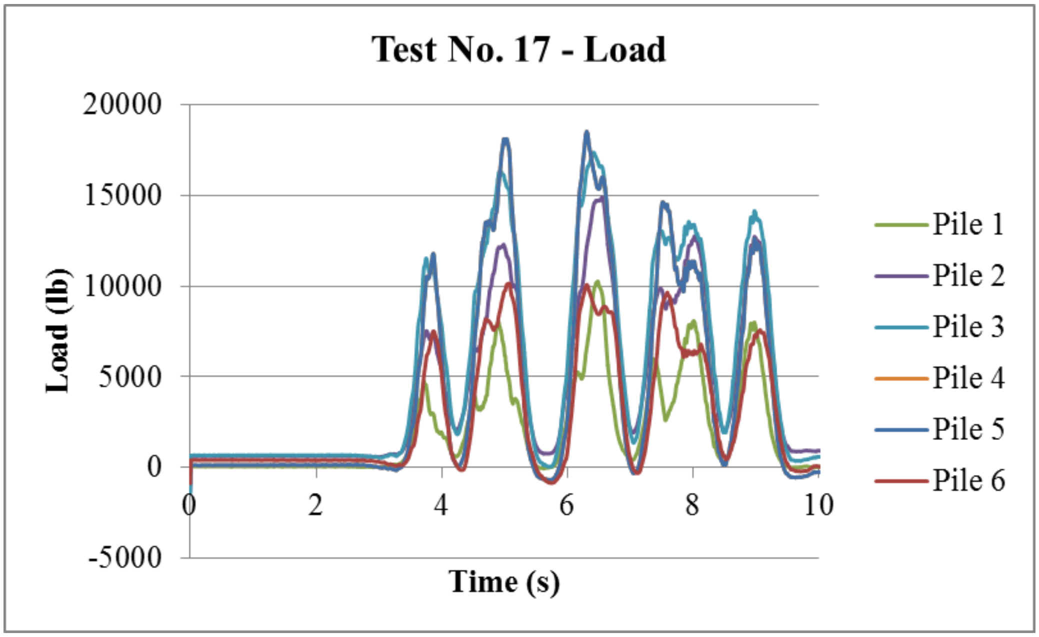

Test No. 12 - Load
Load (lb)
20000
15000
10000
5000
0
-5000
0
2
4
6
8
10
12
Time (s)
Pile 1
Pile 2
Pile 3
Pile 4
Pile 5
Pile 6

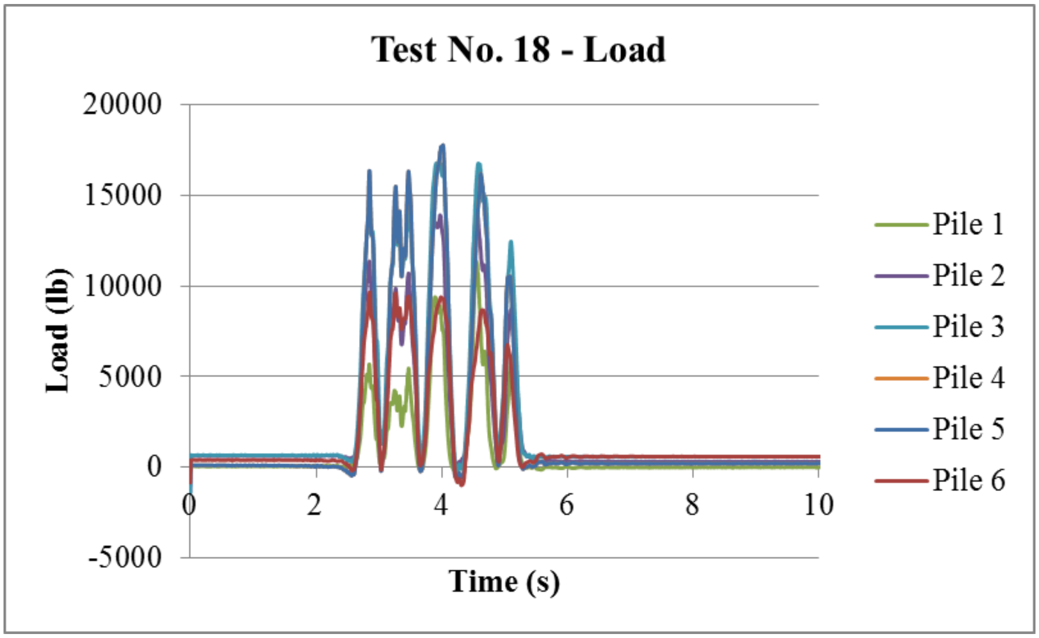

Test No. 13 - Load
20000
15000
10000
5000
0
-5000
Load (lb)
0
10
20
30
40
Time (s)
Pile 1
Pile 2
Pile 3
Pile 4
Pile 5
Pile 6


Test No. 14 - Load
20000
15000
10000
5000
0
-5000
Load (lb)
0
2
4
6
8
10
Time (s)
Pile 1
Pile 2
Pile 3
Pile 4
Pile 5
Pile 6


Test No. 15 - Load
Load (lb)
20000
15000
10000
5000
0
-5000
0
5
10
15
20
Time (s)
Pile 1
Pile 2
Pile 3
Pile 4
Pile 5
Pile 6


Test No. 16 - Load
Load (lb)
20000
15000
10000
5000
0
-5000
0
2
4
6
8
10
Time (s)
Pile 1
Pile 2
Pile 3
Pile 4
Pile 5
Pile 6

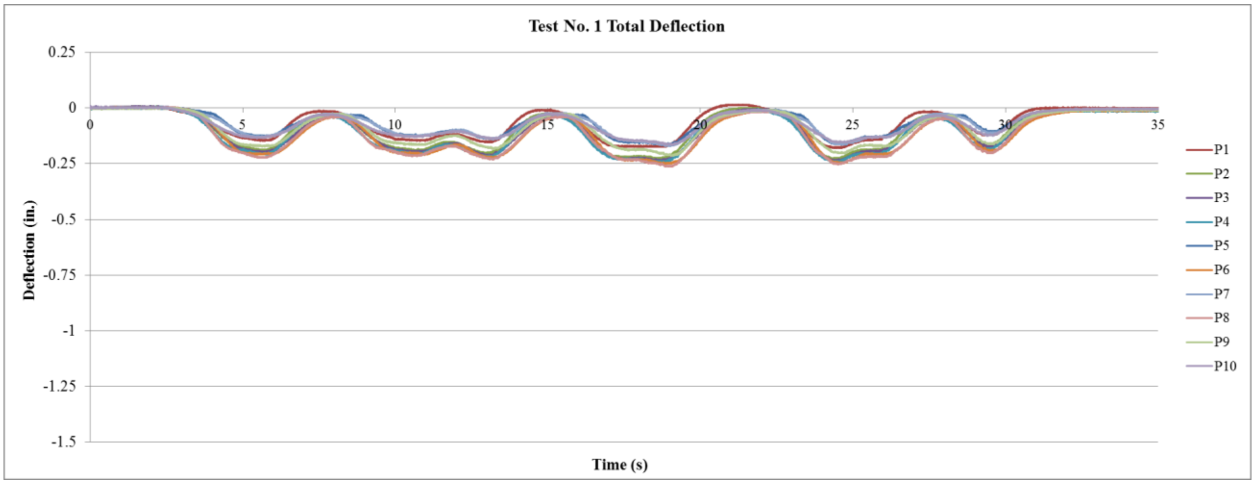

Test No. 17 - Load
Load (lb)
20000
15000
10000
5000
0
-5000
0
2
4
6
8
10
Time (s)
Pile 1
Pile 2
Pile 3
Pile 4
Pile 5
Pile 6

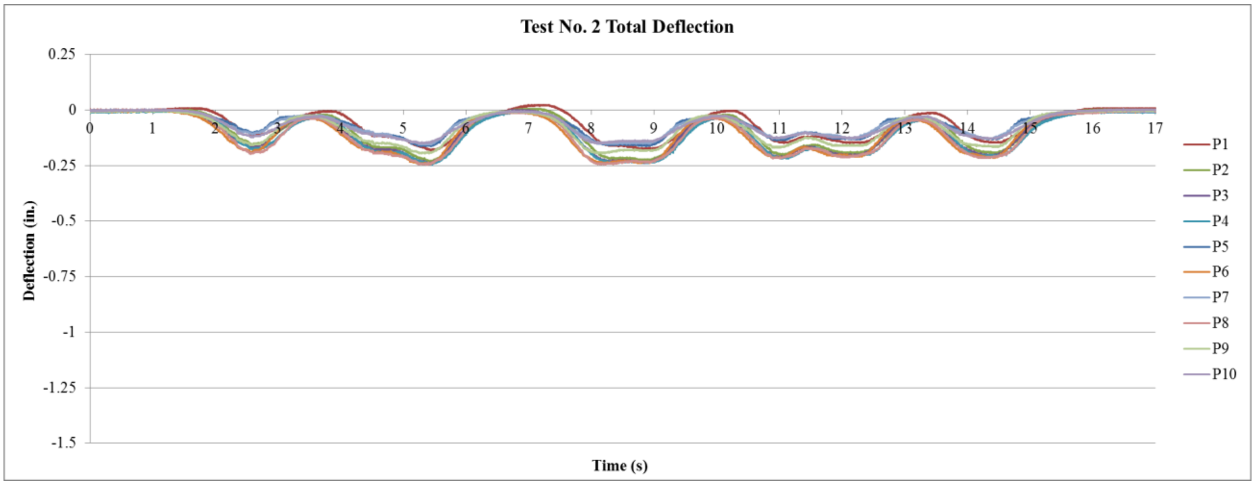

Test No. 18 - Load
Load (lb)
20000
15000
10000
5000
0
-5000
0
2
4
6
8
10
Time (s)
Pile 1
Pile 2
Pile 3
Pile 4
Pile 5
Pile 6

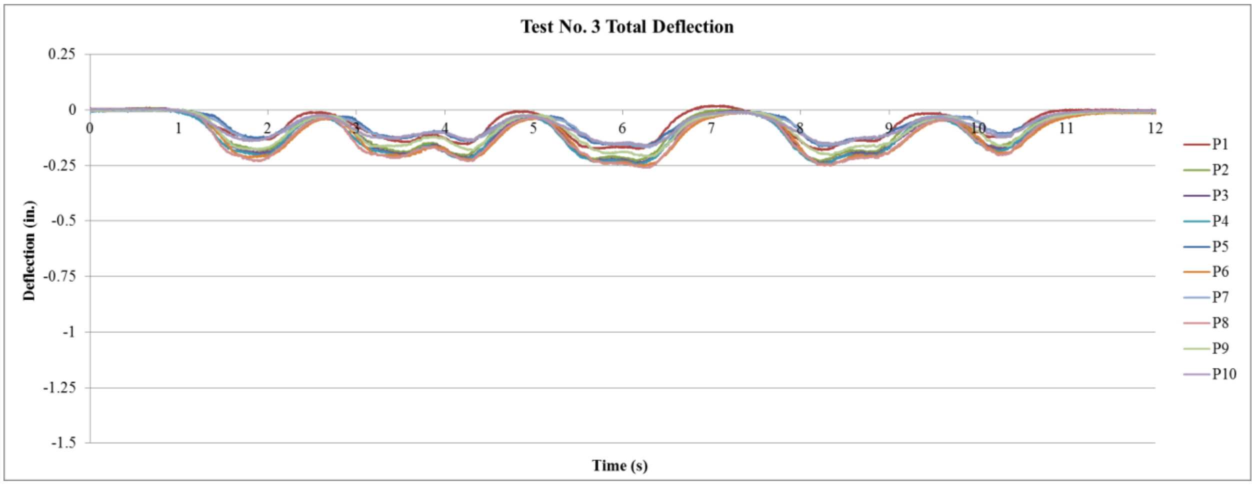
APPENDIX B

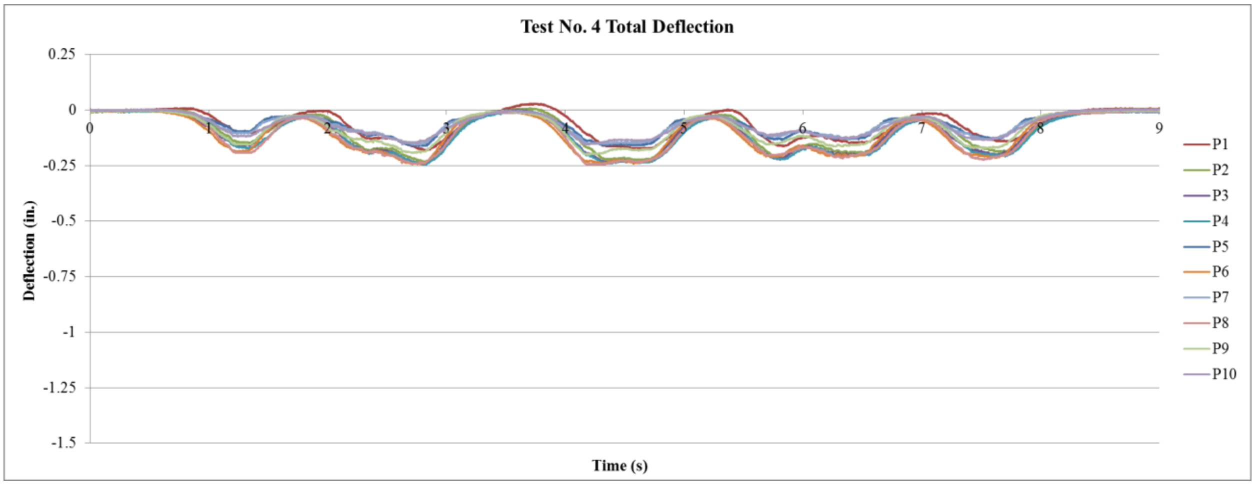
BRIDGE 816.9 DEFLECTION TIME HISTORY

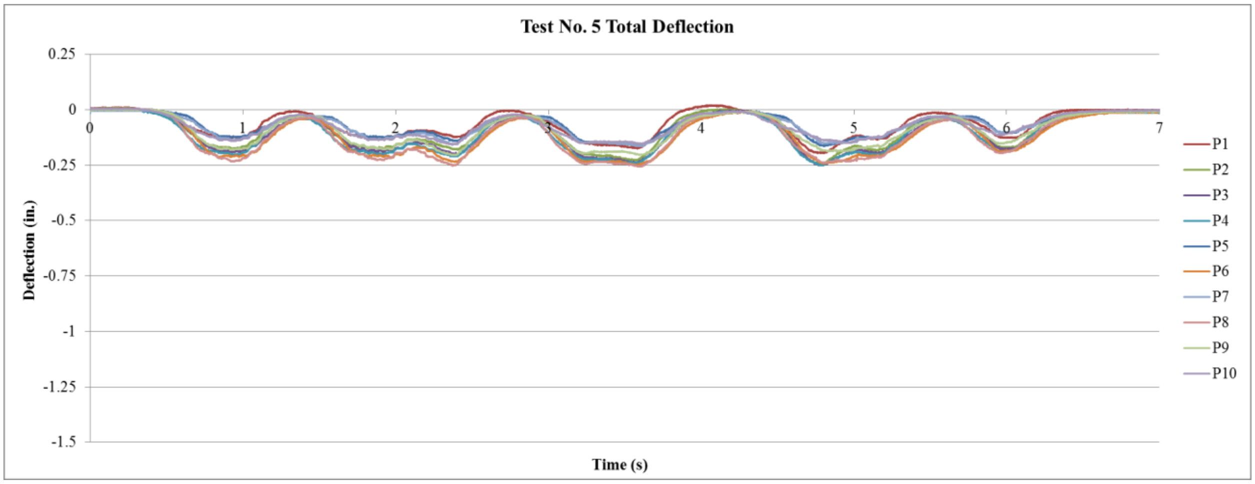
Total Deflection

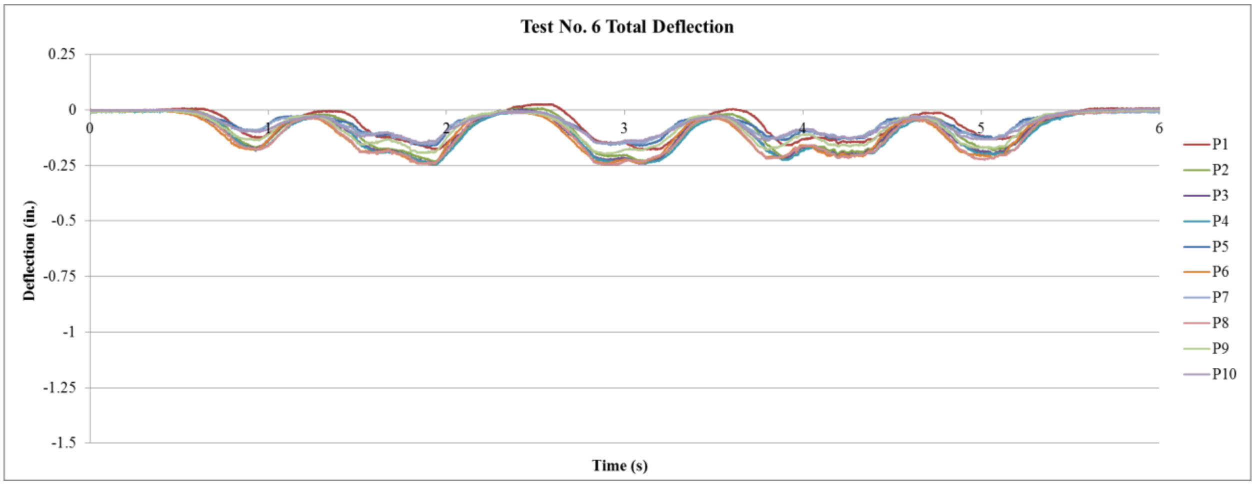


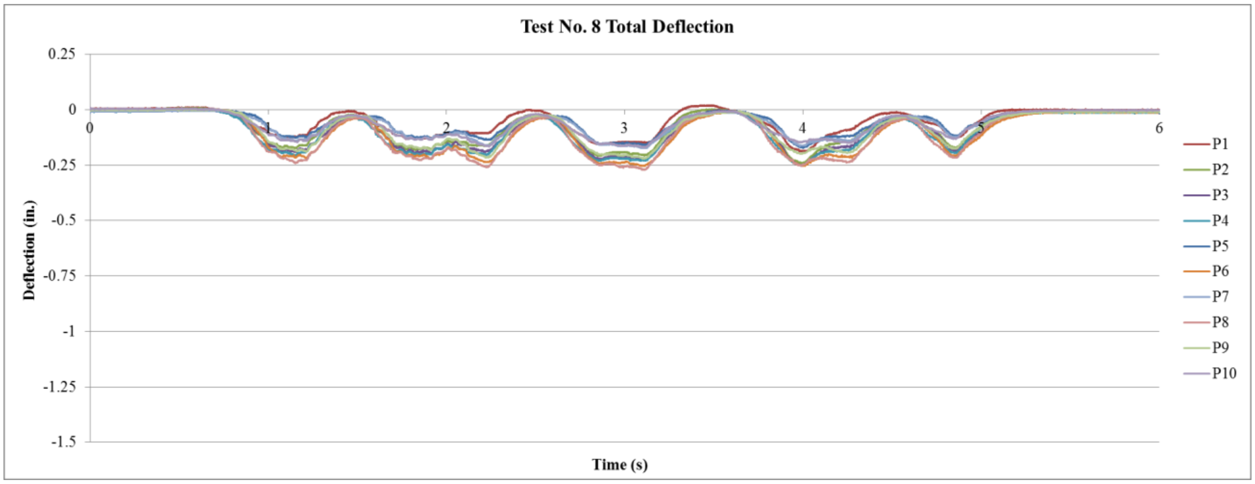


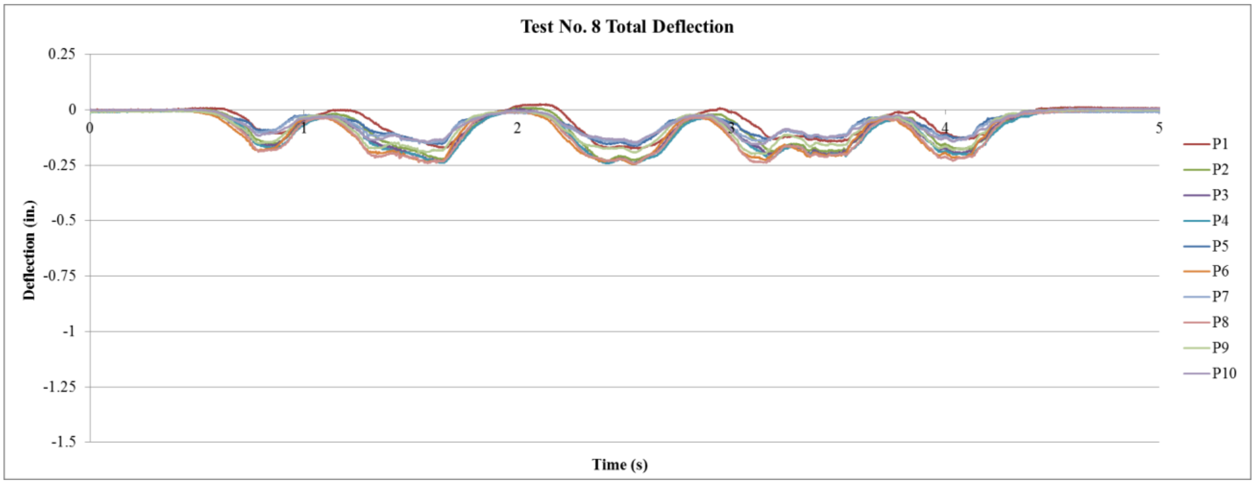

Test No. 3 Total Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
9
10
11
12
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

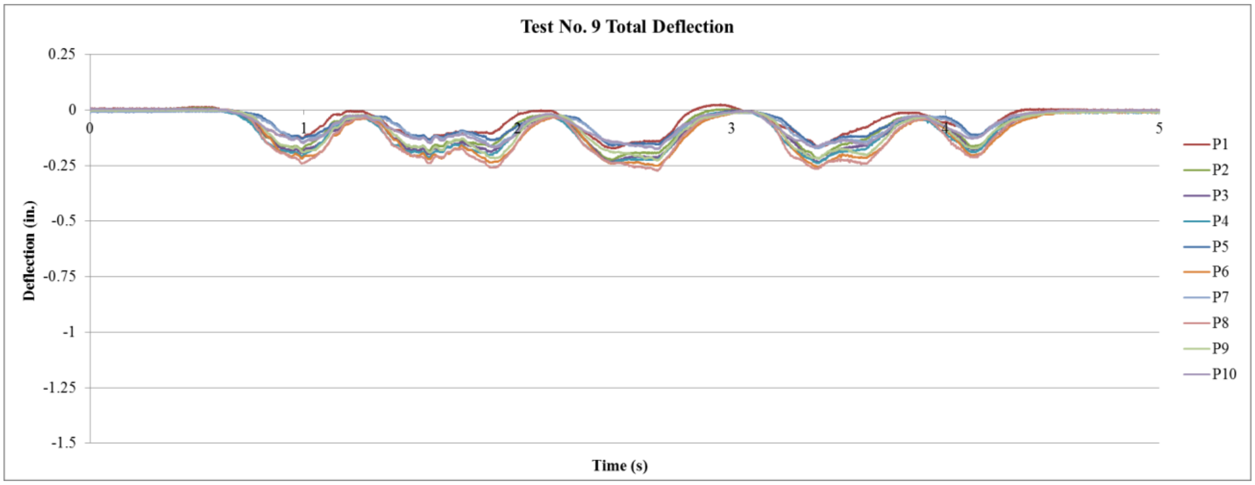

Test No. 4 Total Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
9
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

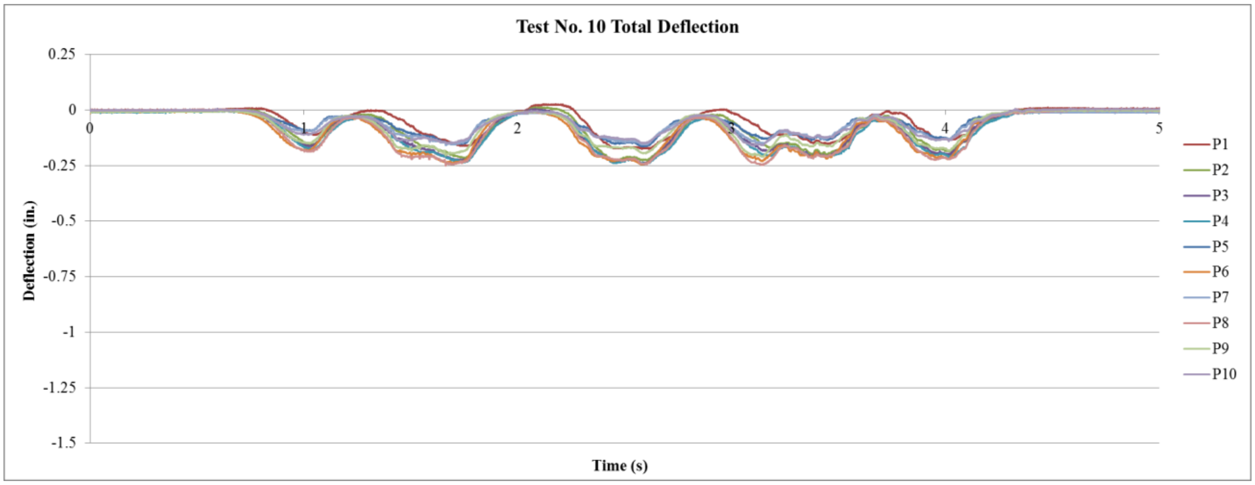

Test No. 5 Total Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

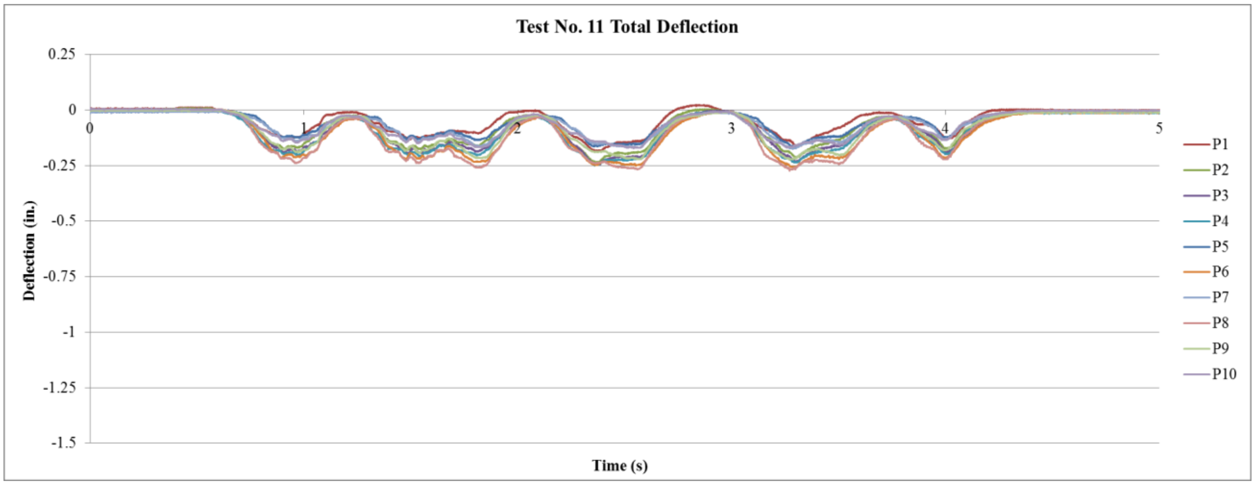

Test No. 6 Total Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

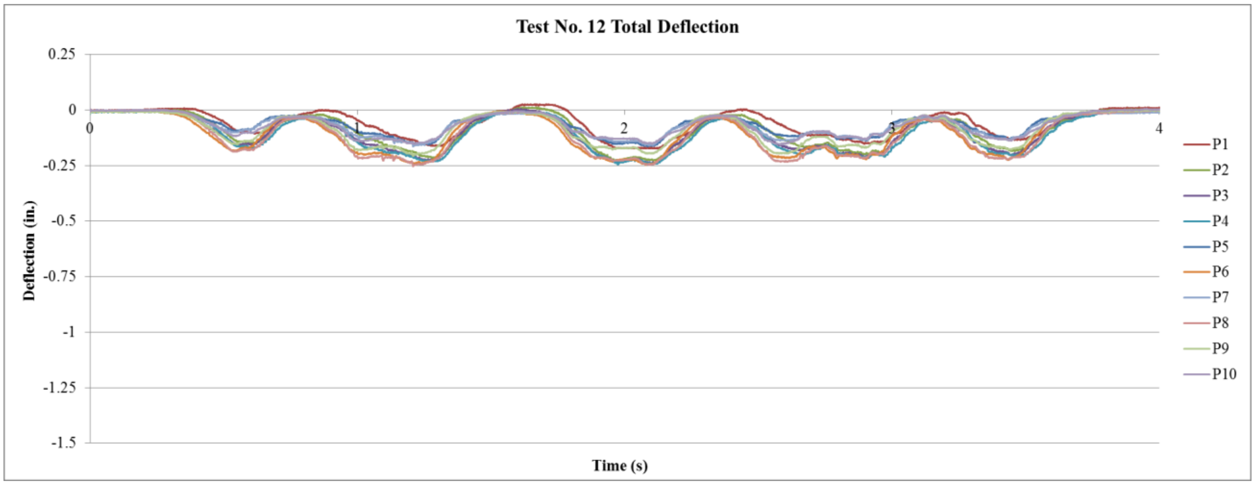

Test No. 8 Total Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

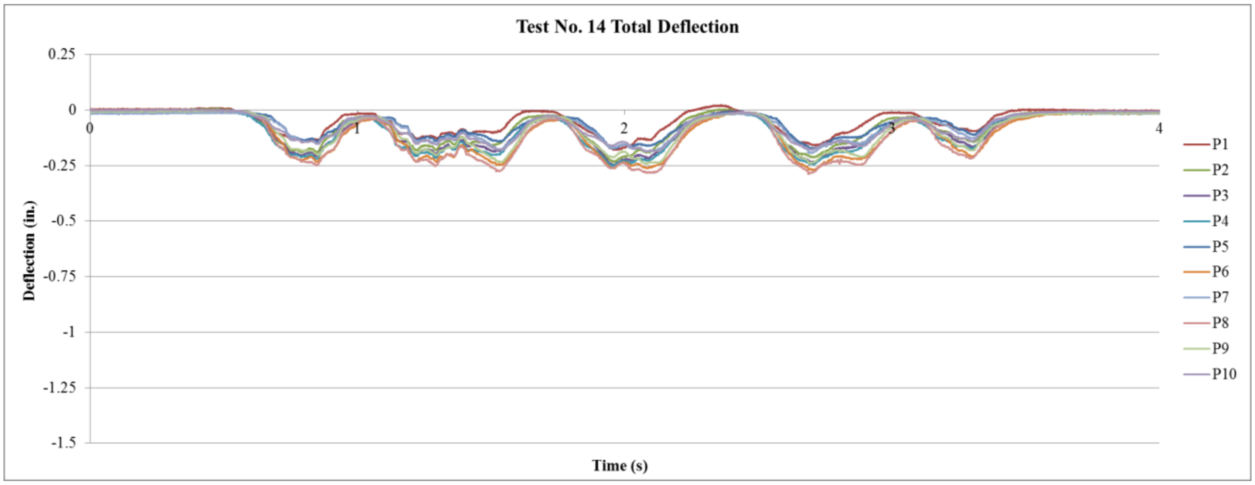

Test No. 8 Total Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

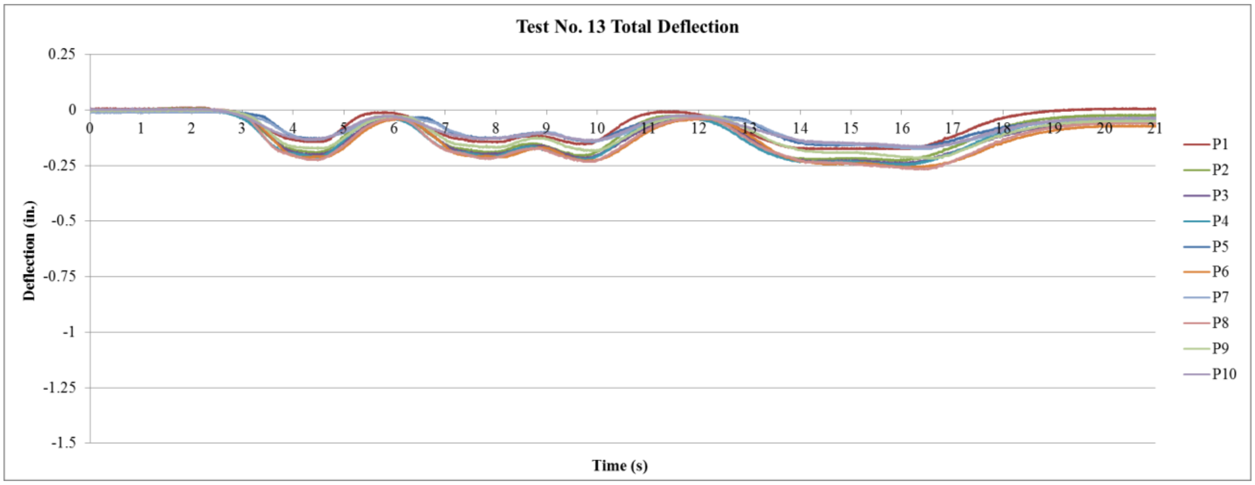

Test No. 9 Total Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

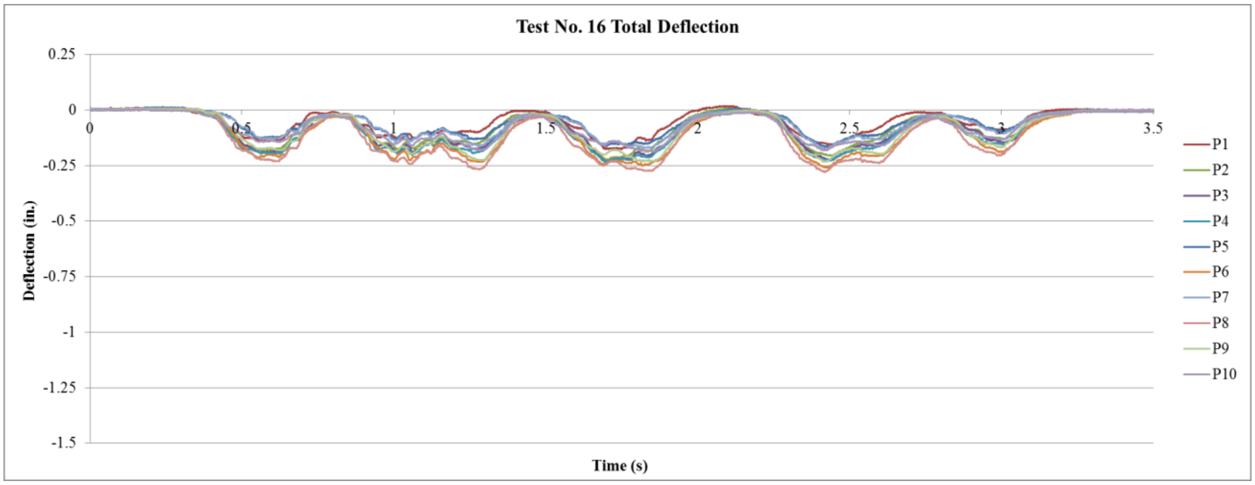

Test No. 10 Total Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

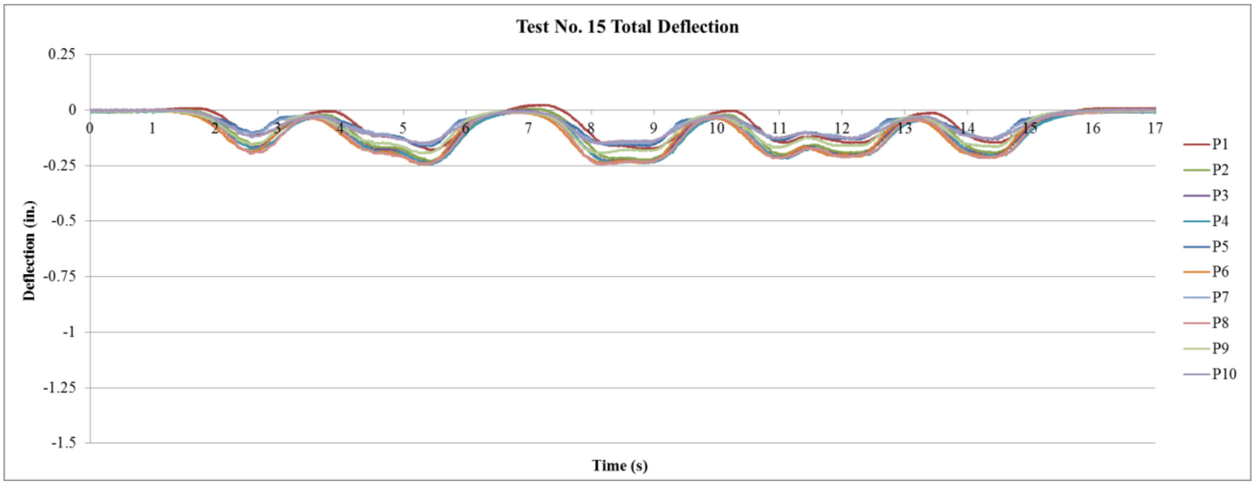

Test No. 11 Total Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

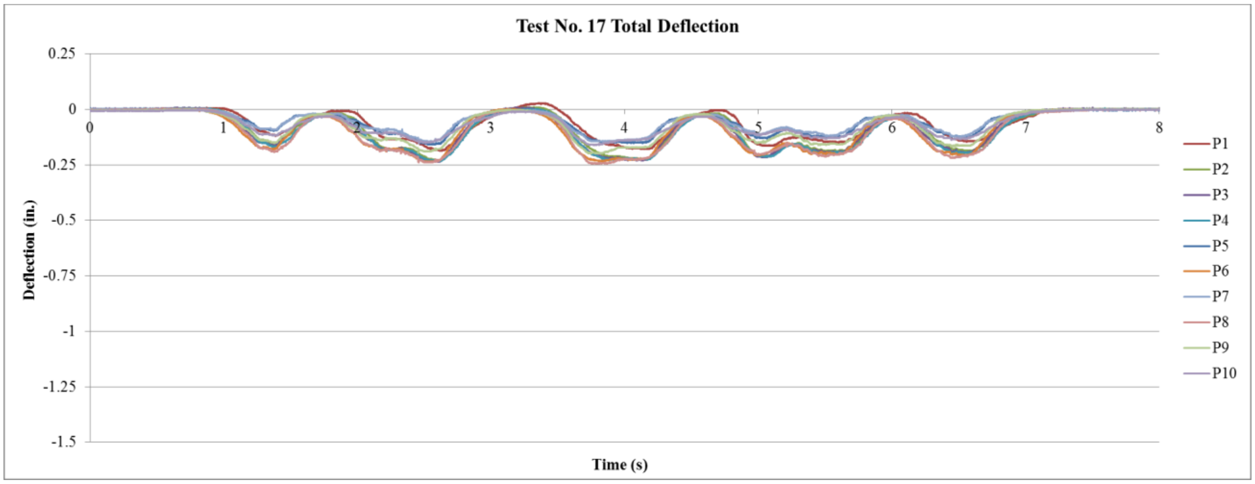

Test No. 12 Total Deflection
Deflection (in.)
Time (s)
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
1
2
3
4
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

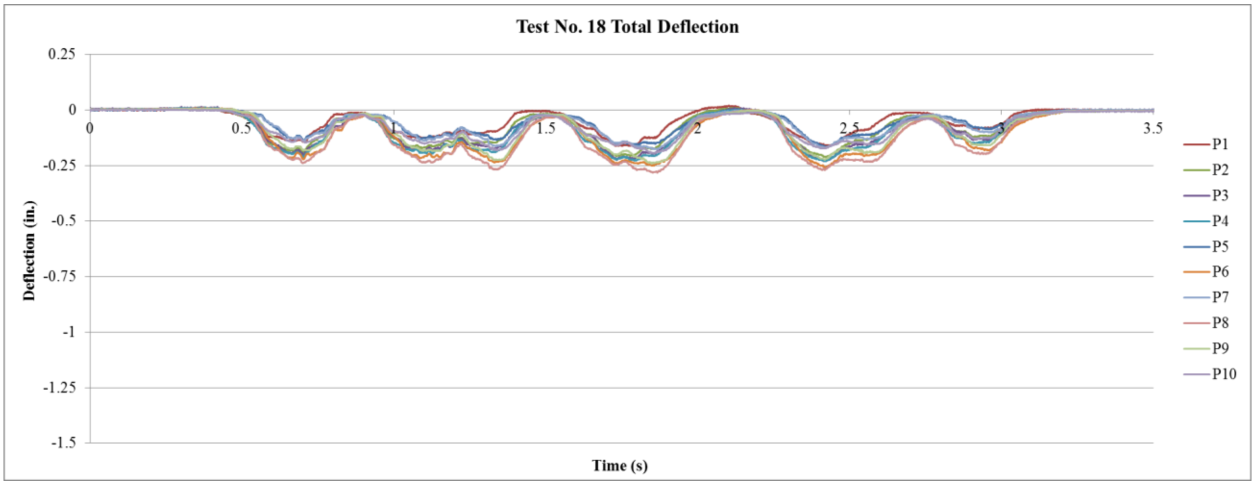

Test No. 14 Total Deflection
Deflection (in.)
Time (s)
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
1
2
3
4
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10


Test No. 13 Total Deflection
Deflection (in.)
Time (s)
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

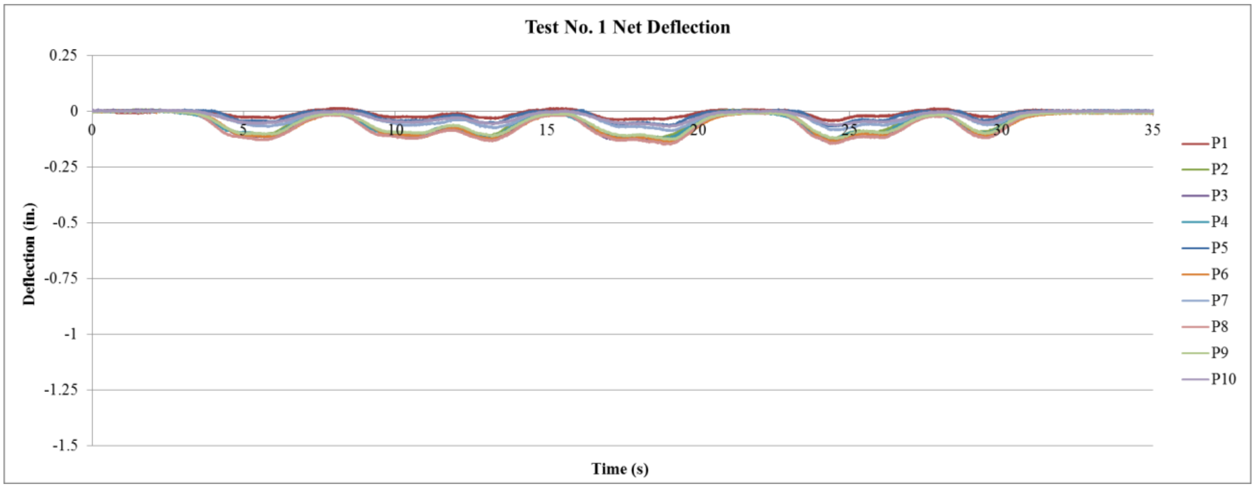

Test No. 16 Total Deflection
Deflection (in.)
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Time (s)
0
0.5
1
1.5
2
2.5
3
3.5
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

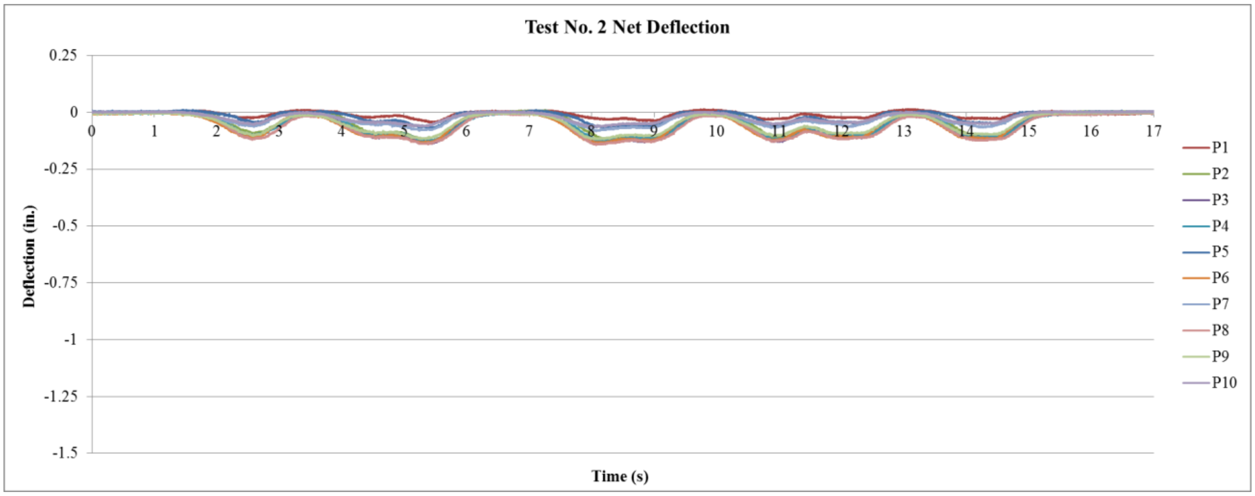

Test No. 15 Total Deflection
Deflection (in.)
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Time (s)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

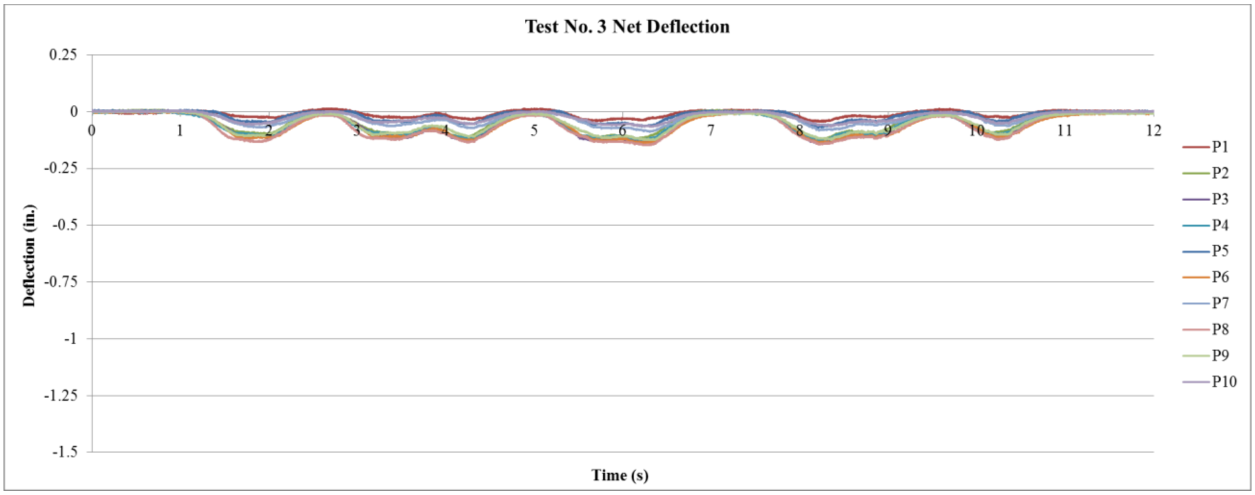

Test No. 17 Total Deflection
Deflection (in.)
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Time (s)
0
1
2
3
4
5
6
7
8
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

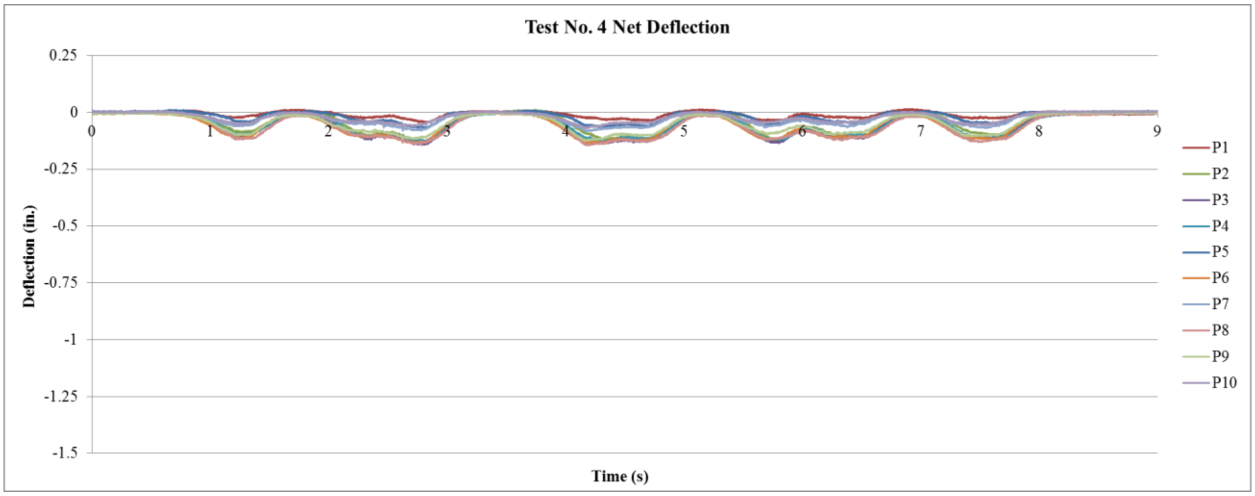


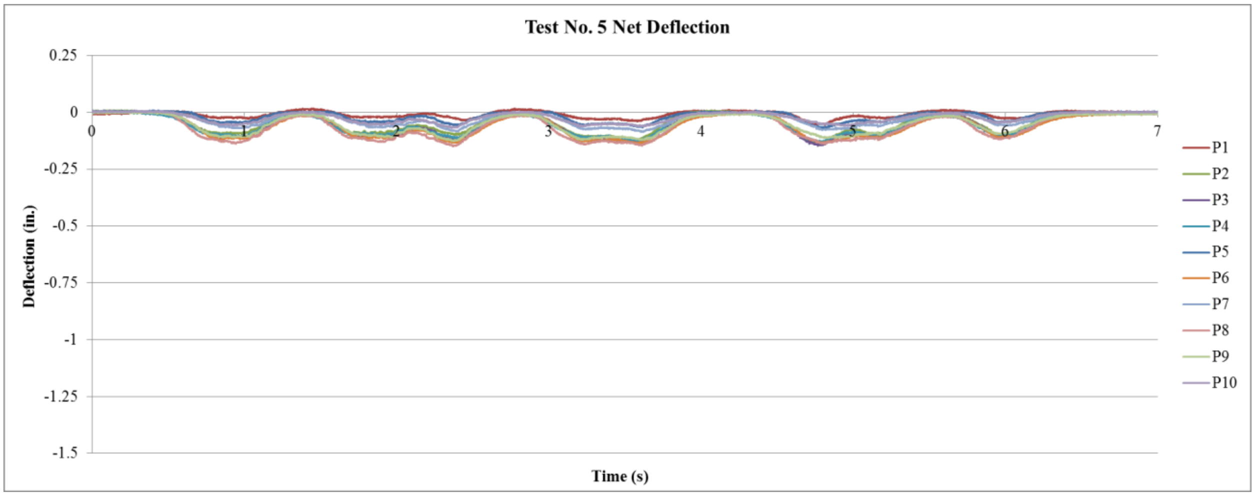
Net Deflection

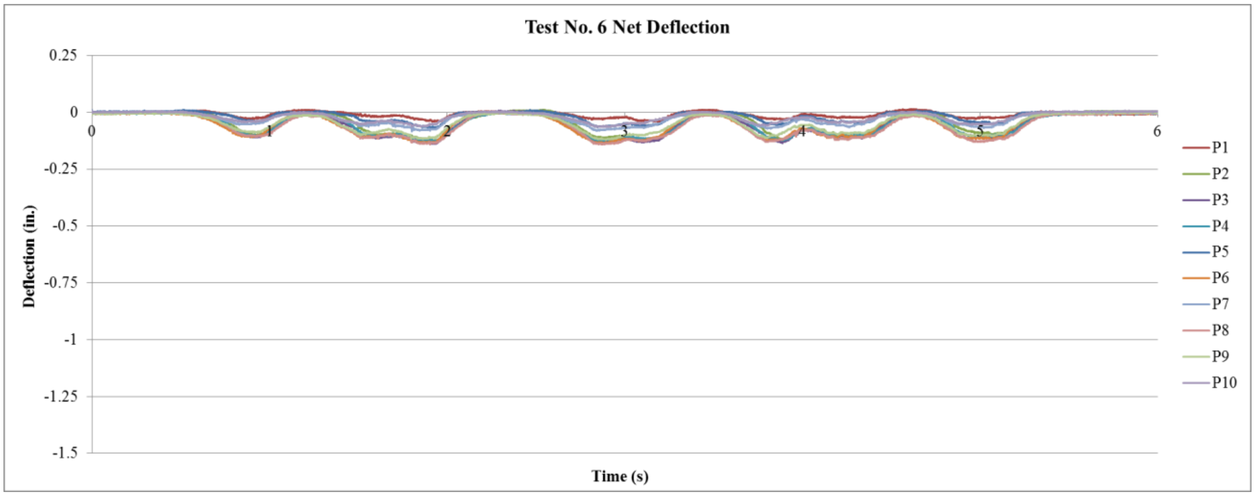


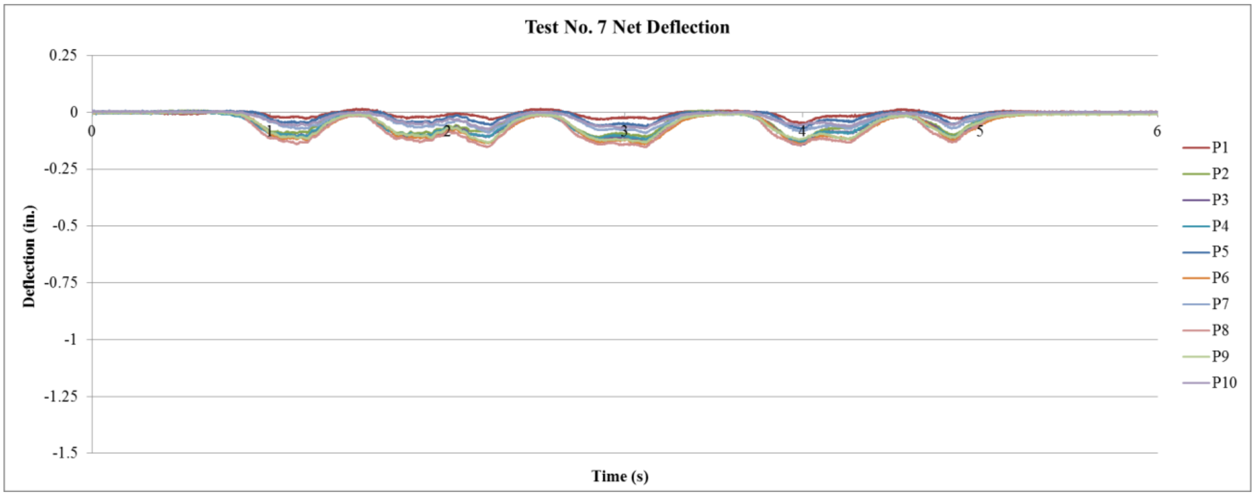


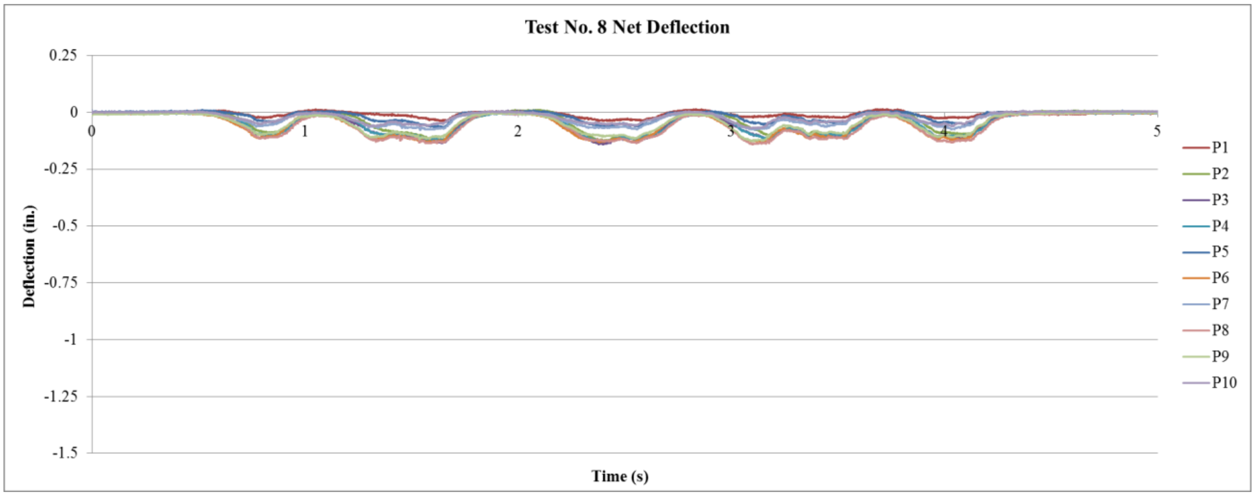

Test No. 3 Net Deflection
Deflection (in.)
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
1
2
3
4
5
6
7
8
9
10
11
12
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

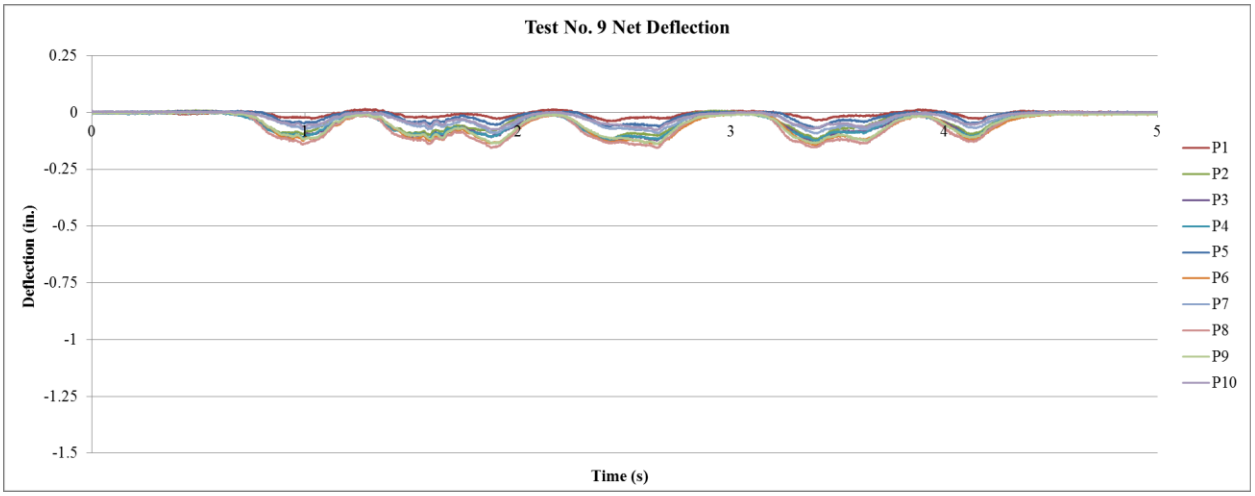

Test No. 4 Net Deflection
Deflection (in.)
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
1
2
3
4
5
6
7
8
9
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

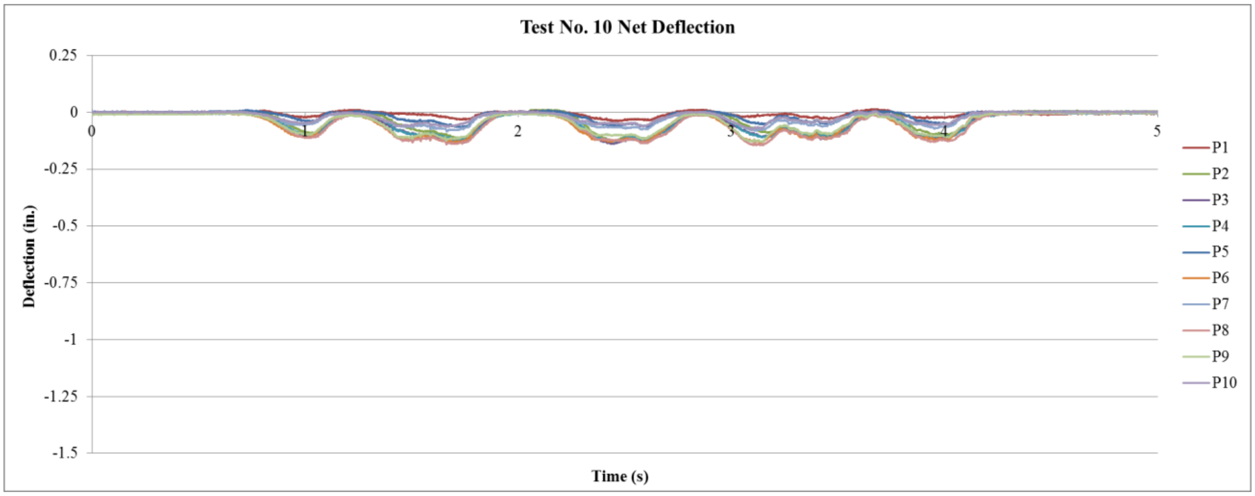

Test No. 5 Net Deflection
Deflection (in.)
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
1
2
3
4
5
6
7
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

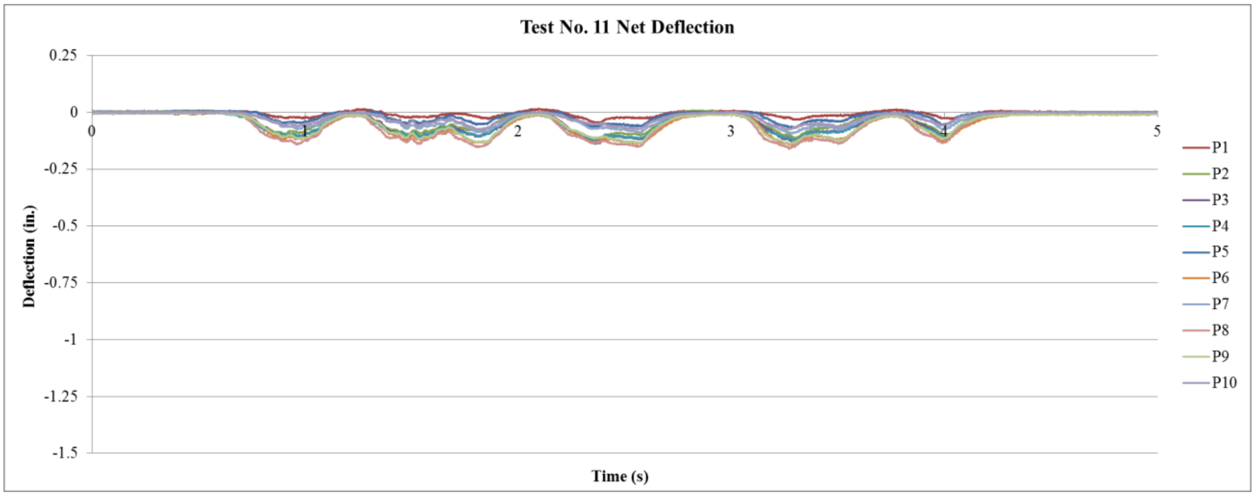

Test No. 6 Net Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

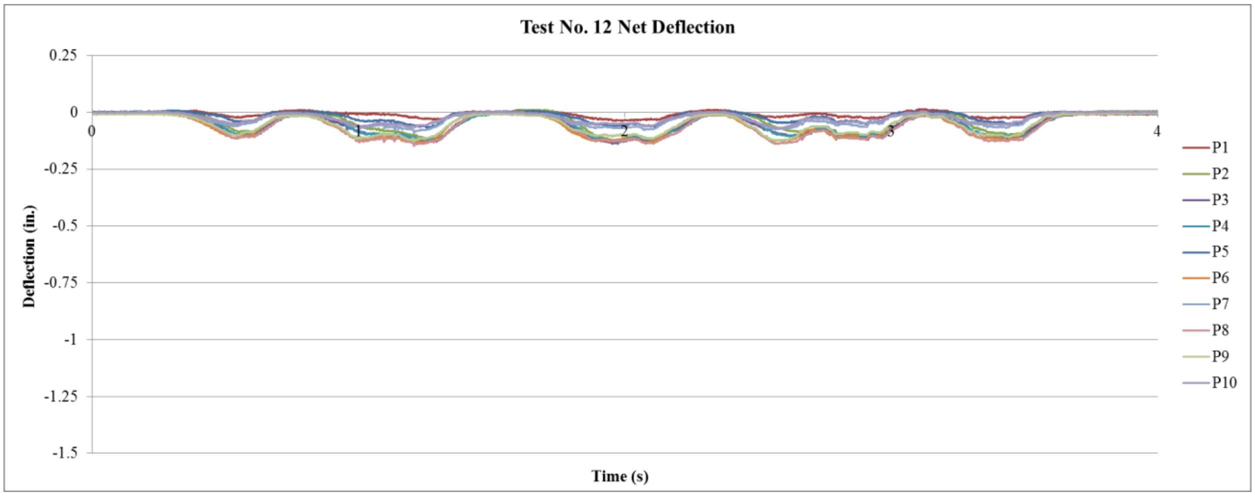

Test No. 7 Net Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

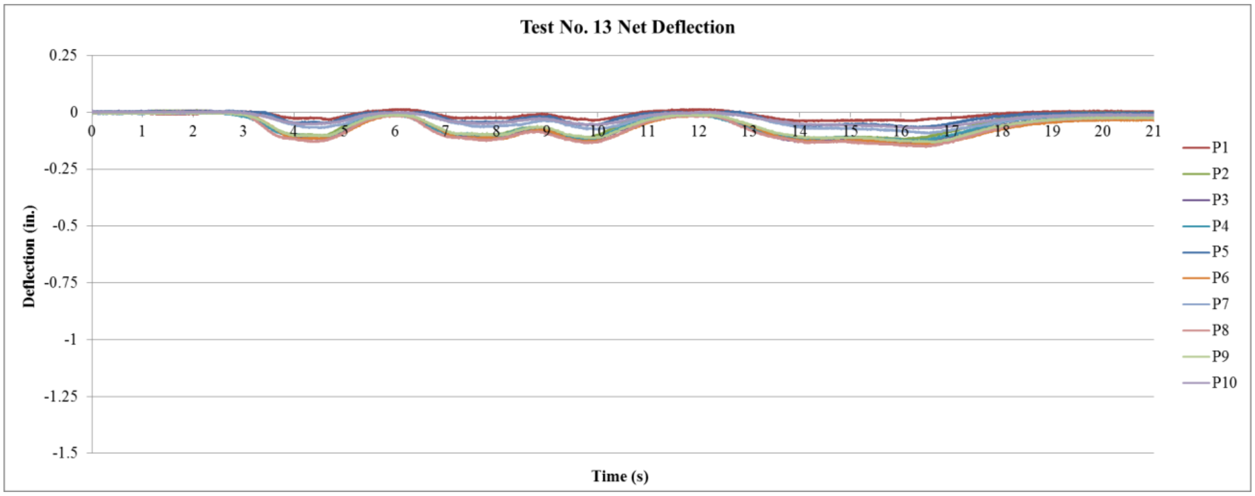

Test No. 8 Net Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

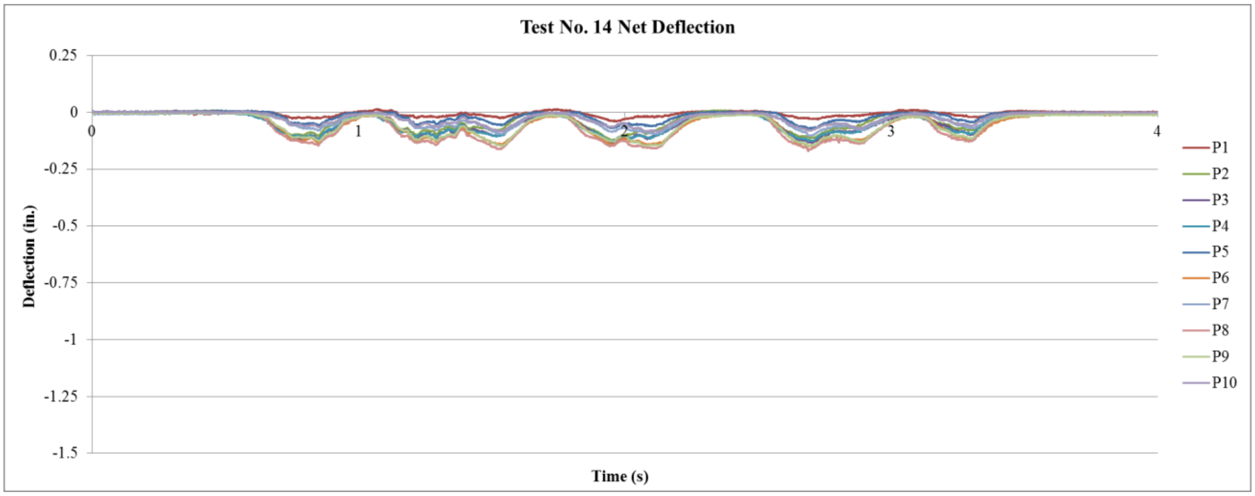

Test No. 9 Net Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

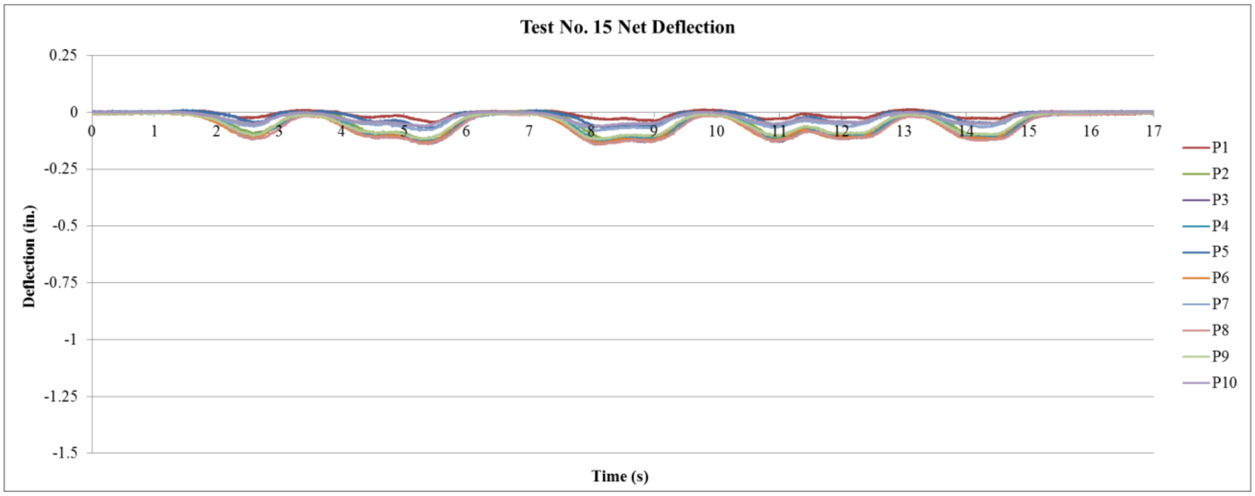

Test No. 10 Net Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

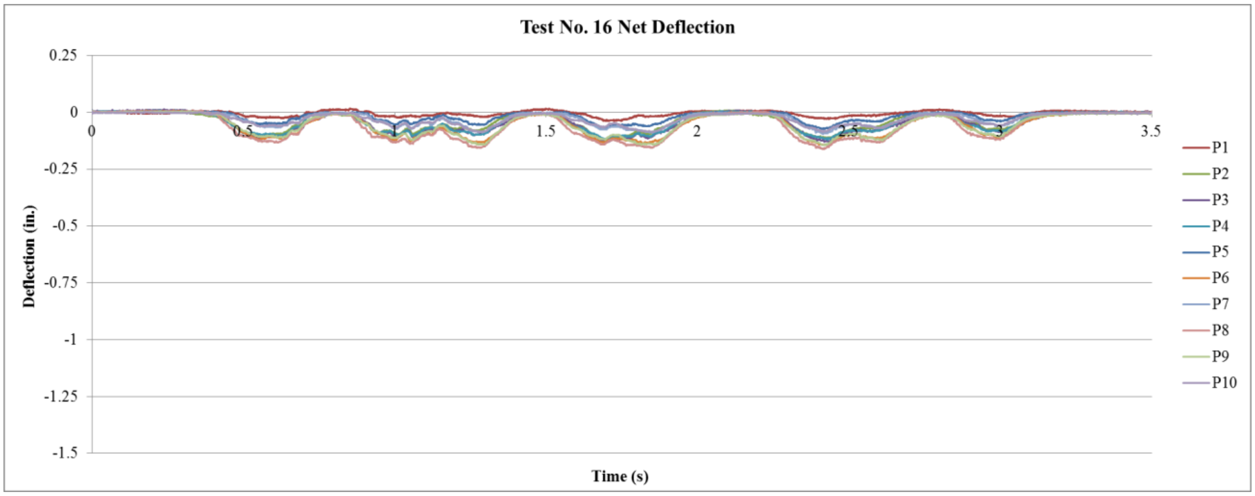

Test No. 11 Net Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

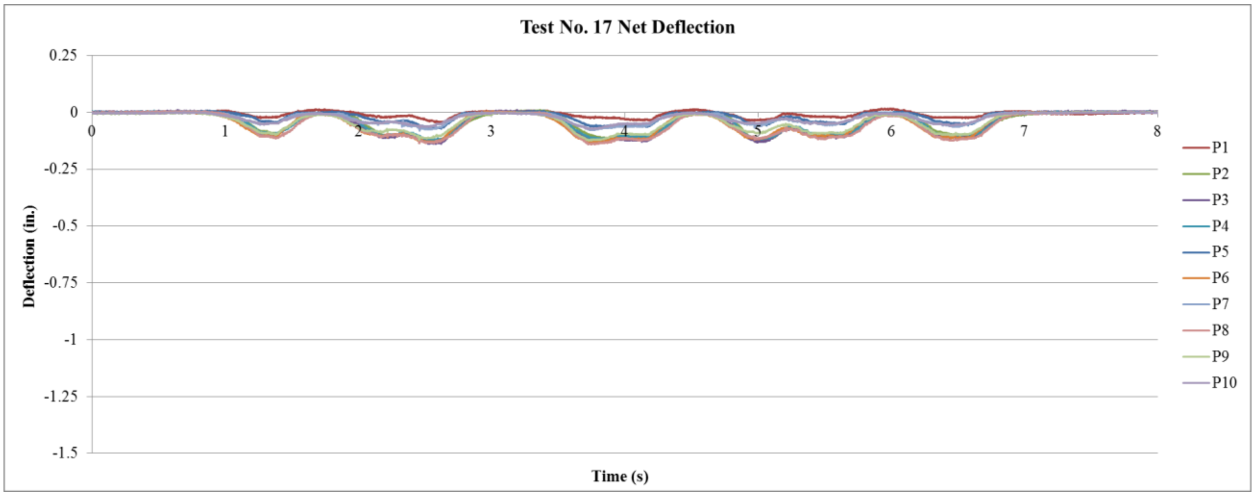

Test No. 12 Net Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

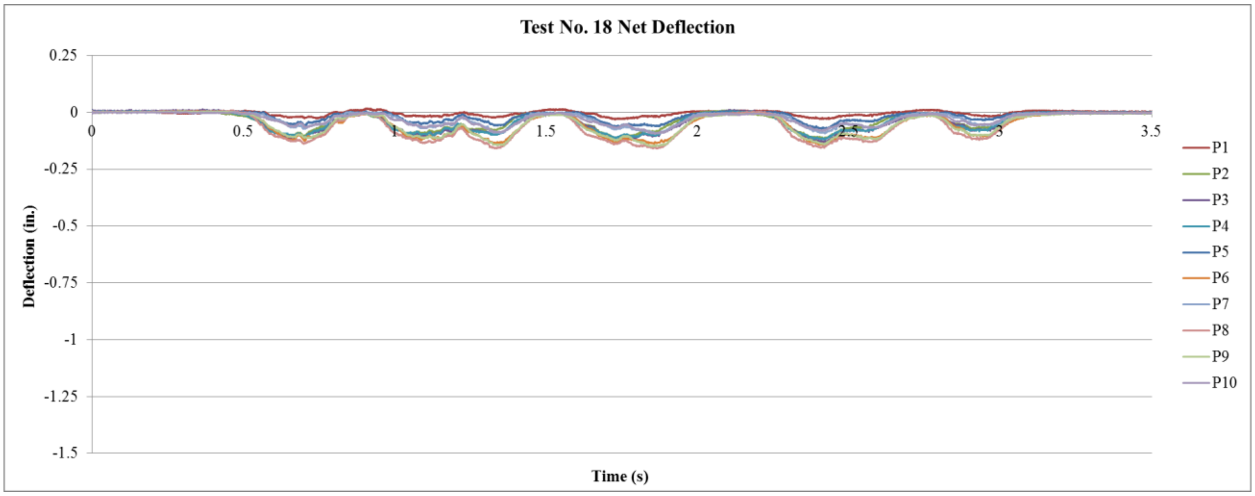

Test No. 13 Net Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10


Test No. 14 Net Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10


Test No. 15 Net Deflection
Deflection (in.)
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10


Test No. 16 Net Deflection
Deflection (in.)
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
0.5
1
1.5
2
2.5
3
3.5
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

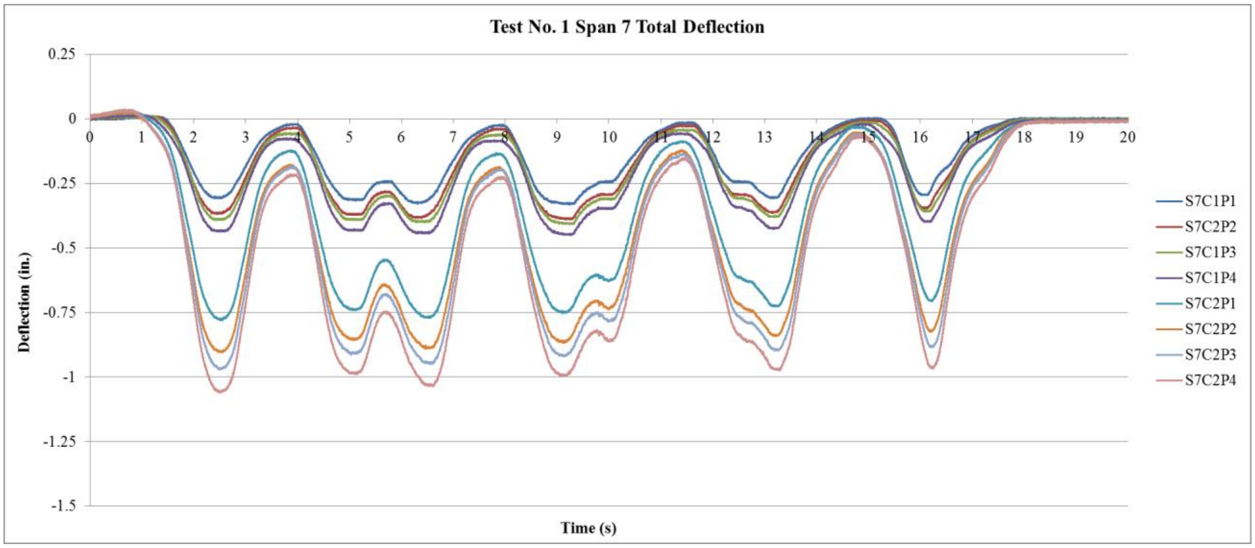

Test No. 17 Net Deflection
Deflection (in.)
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
1
2
3
4
5
6
7
8
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

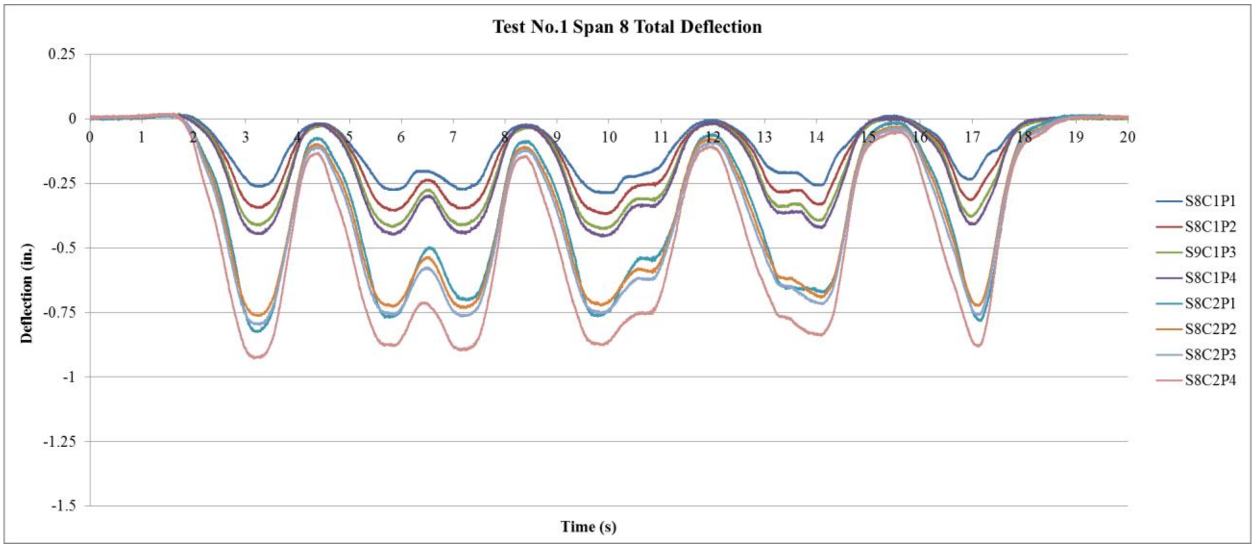

Test No. 18 Net Deflection
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
0.5
1
1.5
2
2.5
3
3.5
Time (s)
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10

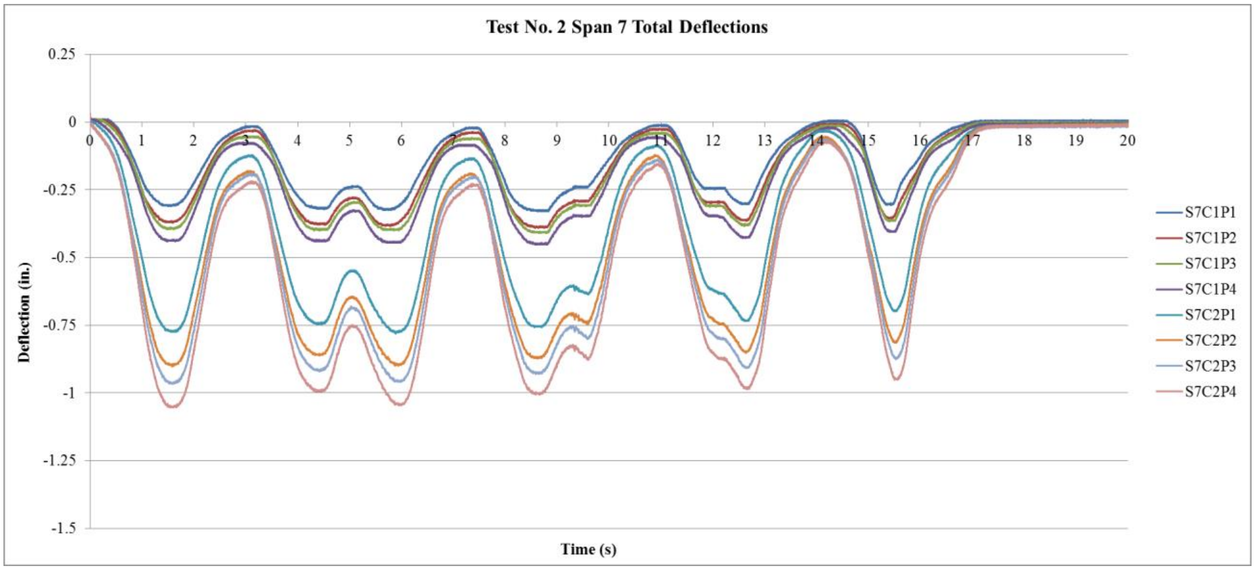
APPENDIX C

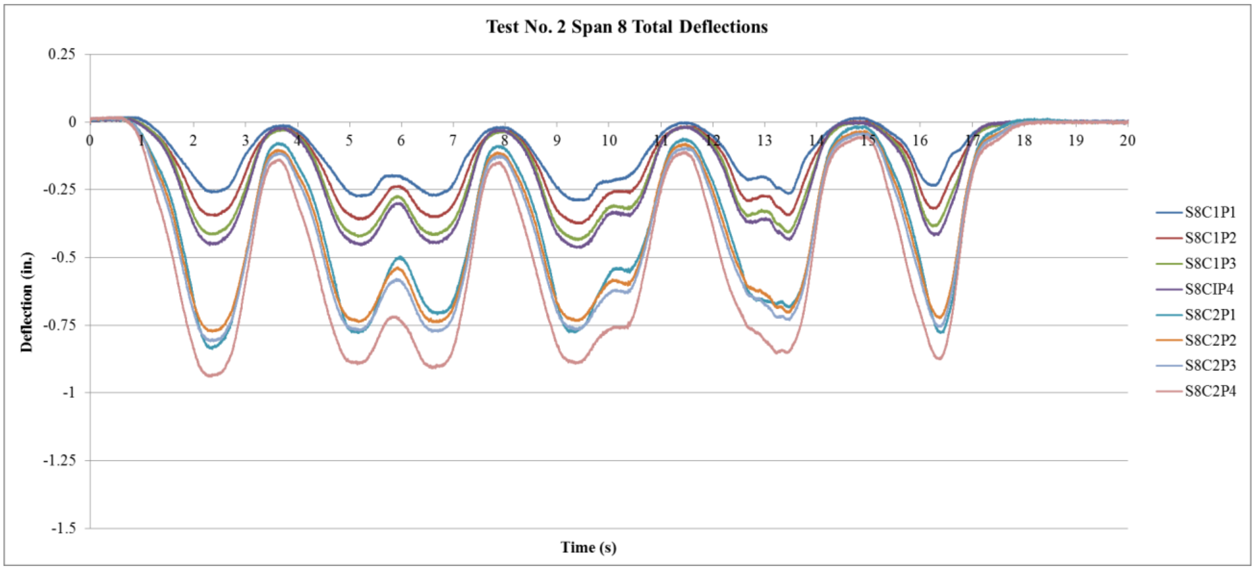
BRIDGE 17.14 DEFLECTION TIME HISTORY

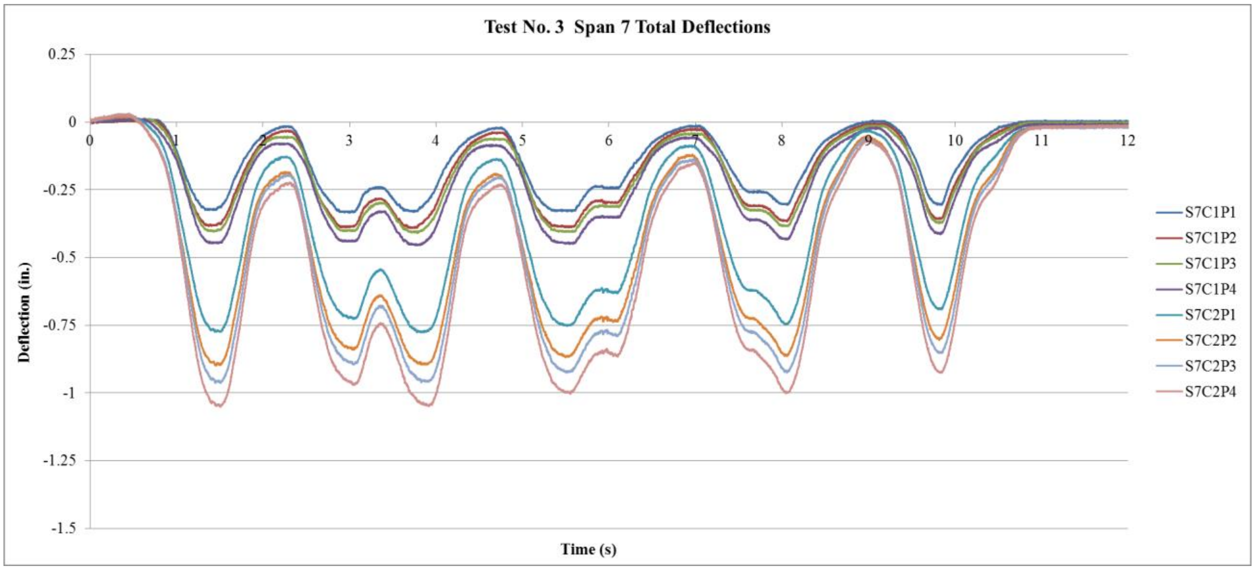
Total Deflection

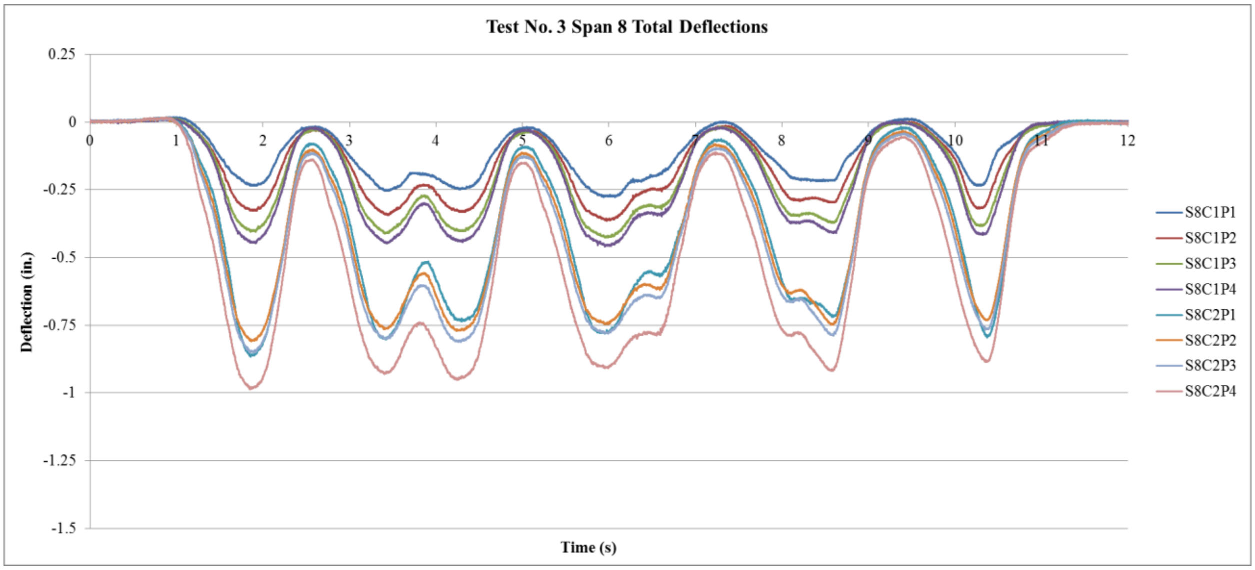

Test No. 1 Span 7 Total Deflection

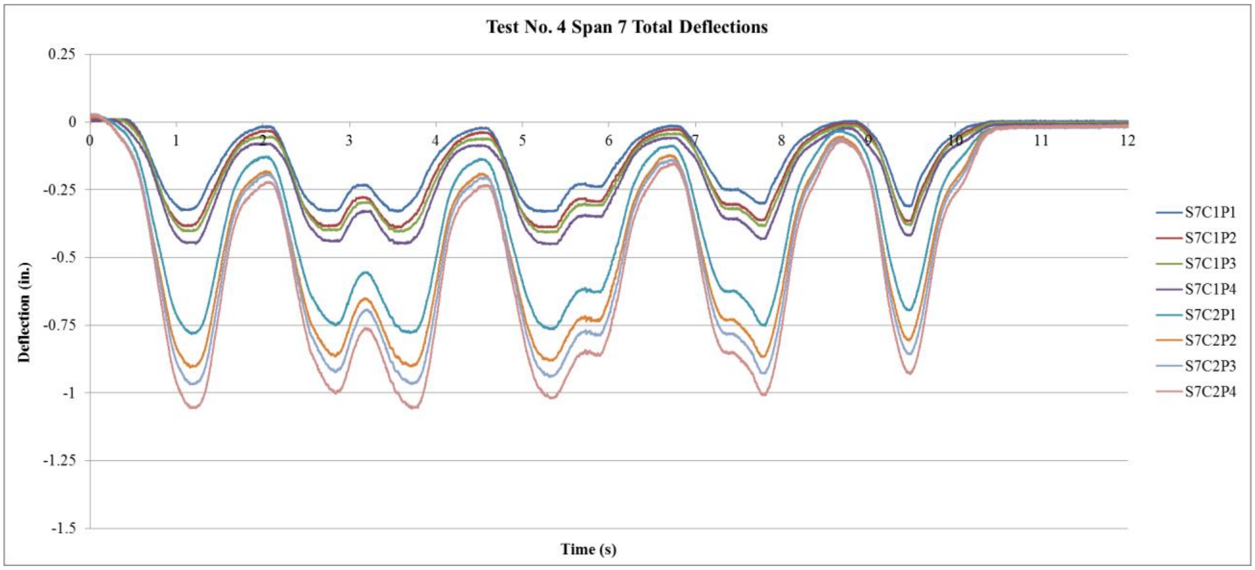

Test No.1 Span 8 Total Deflection

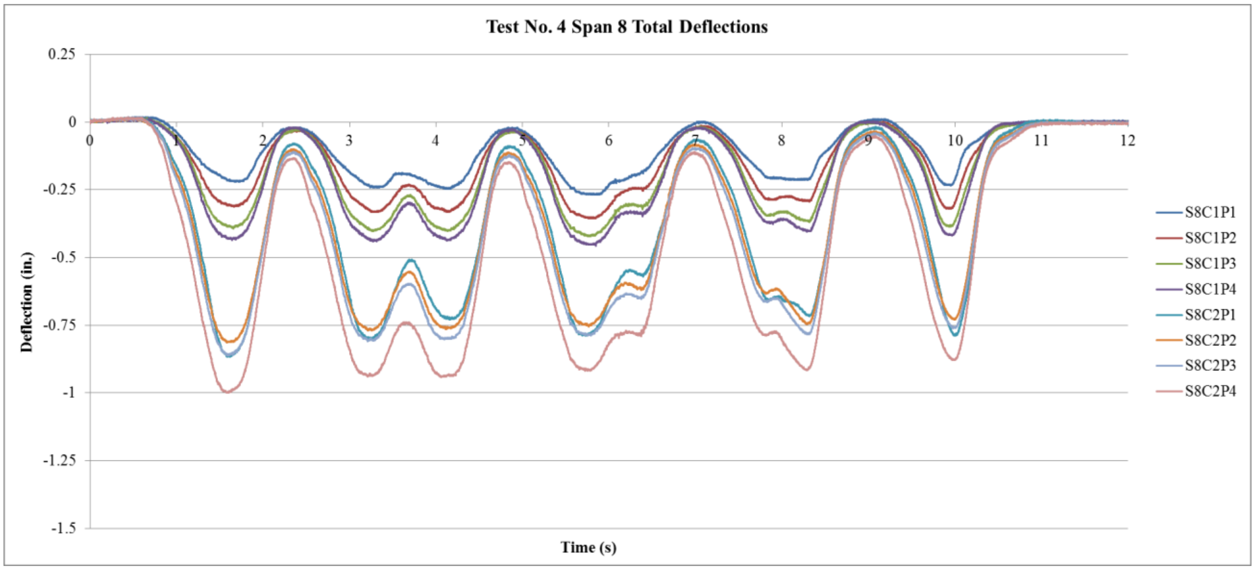

Test No. 2 Span 7 Total Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Time (s)
S7C1P1
S7C1P2
S7C1P3
S7C1P4
S7C2P1
S7C2P2
S7C2P3
S7C2P4

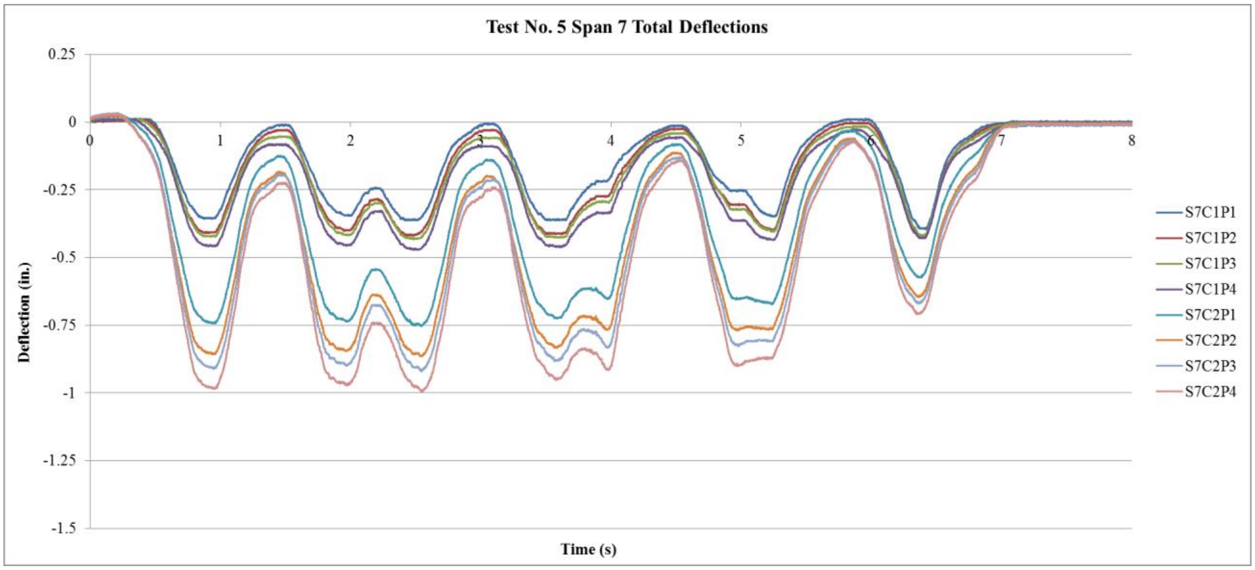

Test No. 2 Span 8 Total Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Time (s)
S8C1P1
S8C1P2
S8C1P3
S8CIP4
S8C2P1
S8C2P2
S8C2P3
S8C2P4

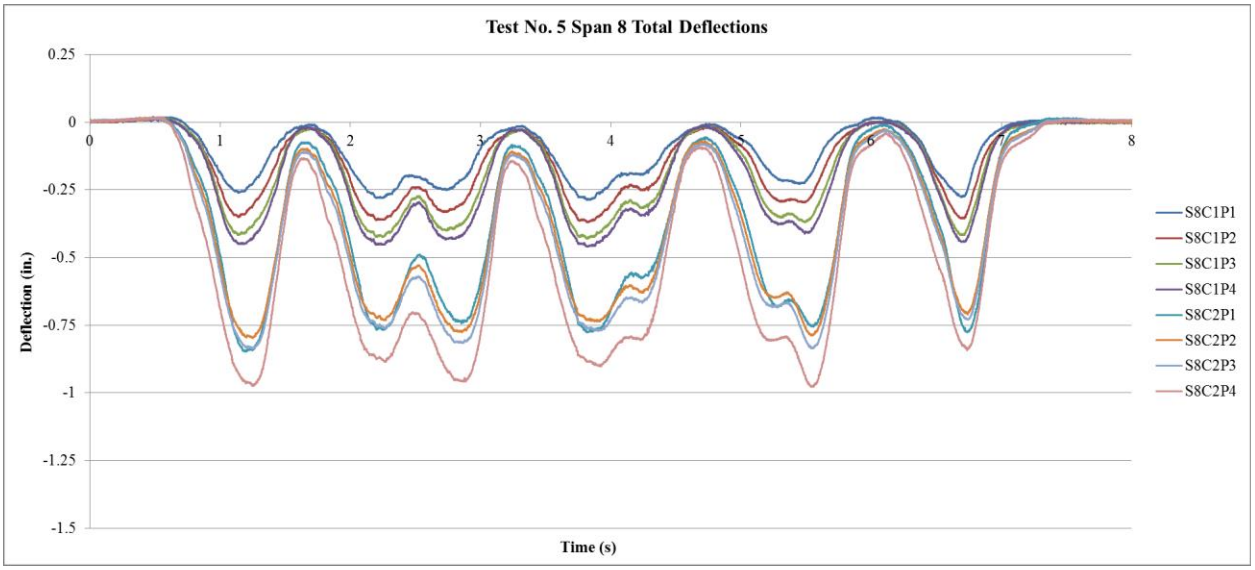

Test No. 3 Span 7 Total Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
9
10
11
12
Time (s)
S7C1P1
S7C1P2
S7C1P3
S7C1P4
S7C2P1
S7C2P2
S7C2P3
S7C2P4

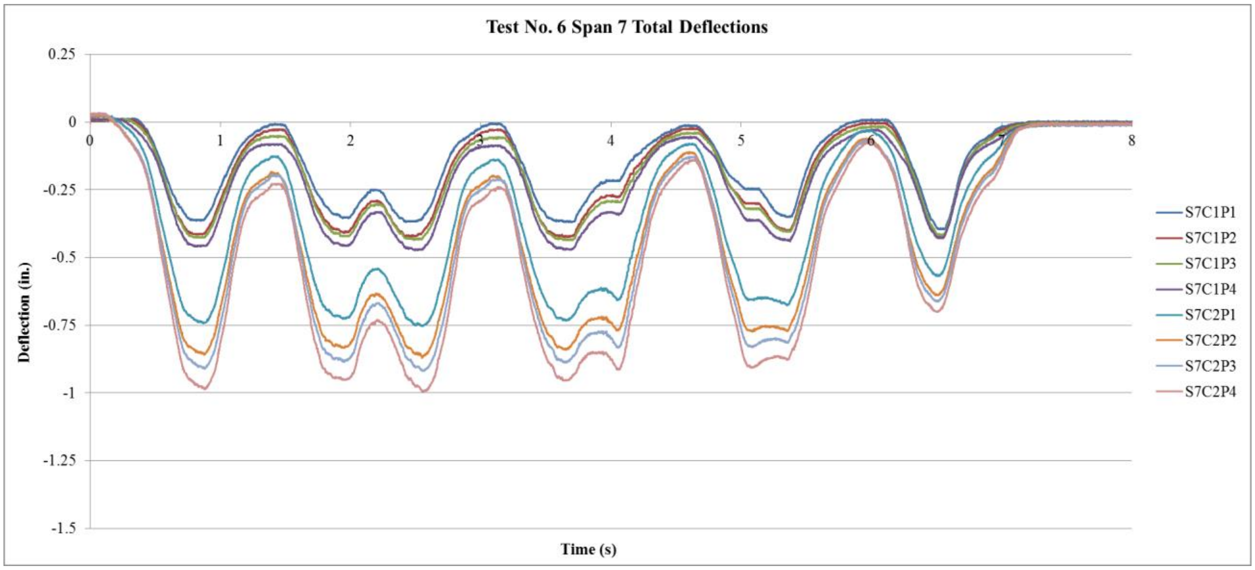

Test No. 3 Span 8 Total Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
9
10
11
12
Time (s)
S8C1P1
S8C1P2
S8C1P3
S8C1P4
S8C2P1
S8C2P2
S8C2P3
S8C2P4

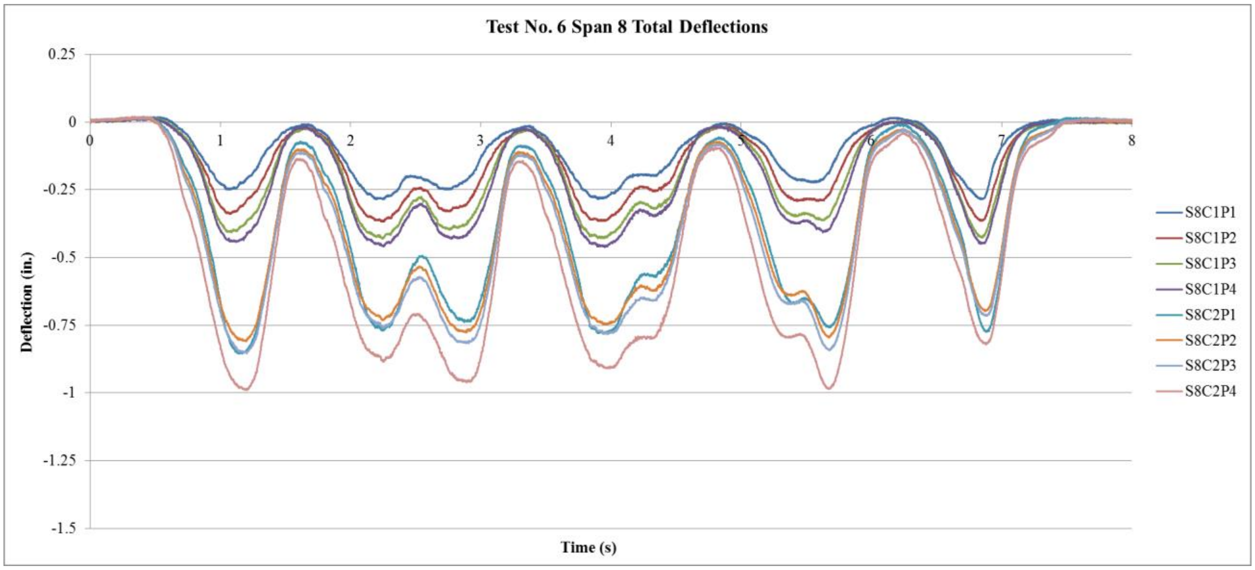

Test No. 4 Span 7 Total Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
9
10
11
12
Time (s)
S7C1P1
S7C1P2
S7C1P3
S7C1P4
S7C2P1
S7C2P2
S7C2P3
S7C2P4

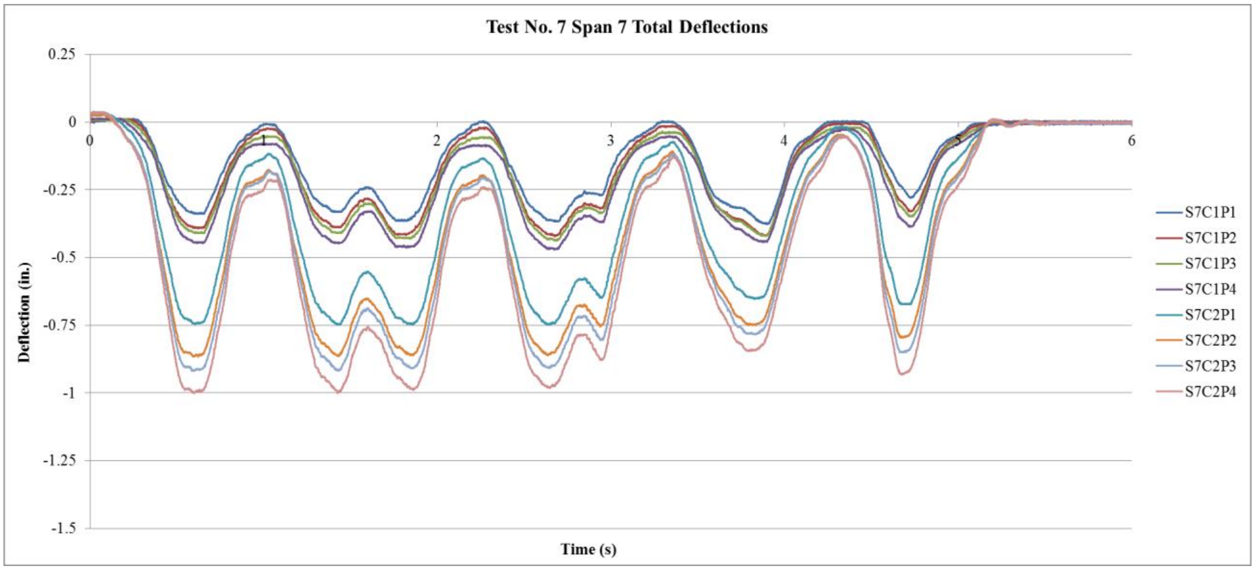

Test No. 4 Span 8 Total Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
9
10
11
12
Time (s)
S8C1P1
S8C1P2
S8C1P3
S8C1P4
S8C2P1
S8C2P2
S8C2P3
S8C2P4

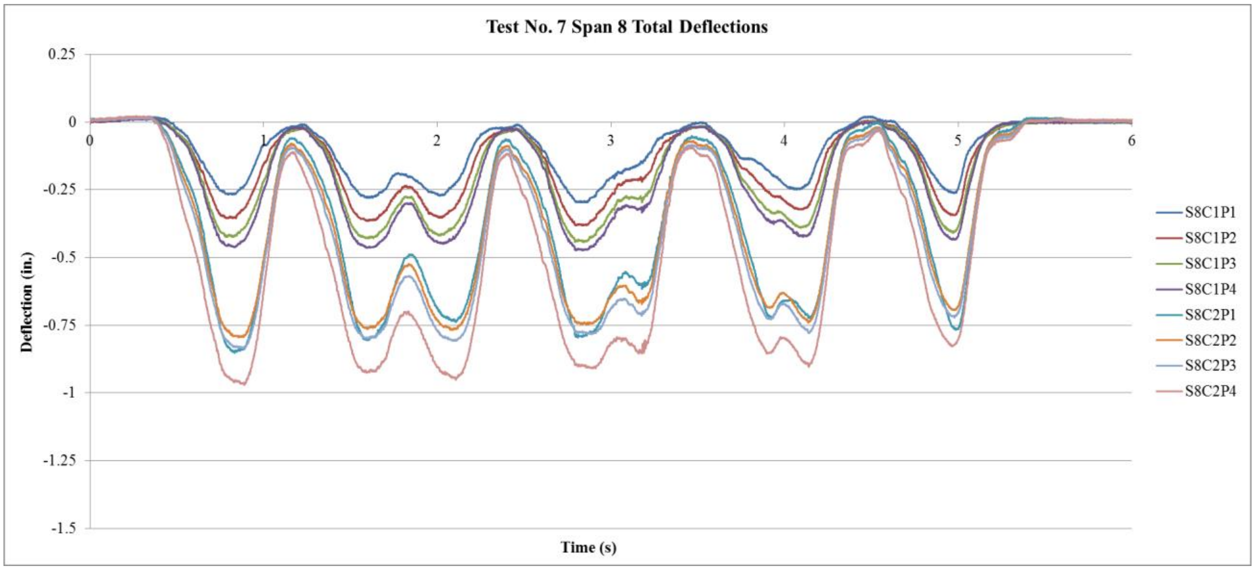

Test No. 5 Span 7 Total Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
1
2
3
4
5
6
7
8
Deflection (in.)
Time (s)
S7C1P1
S7C1P2
S7C1P3
S7C1P4
S7C2P1
S7C2P2
S7C2P3
S7C2P4

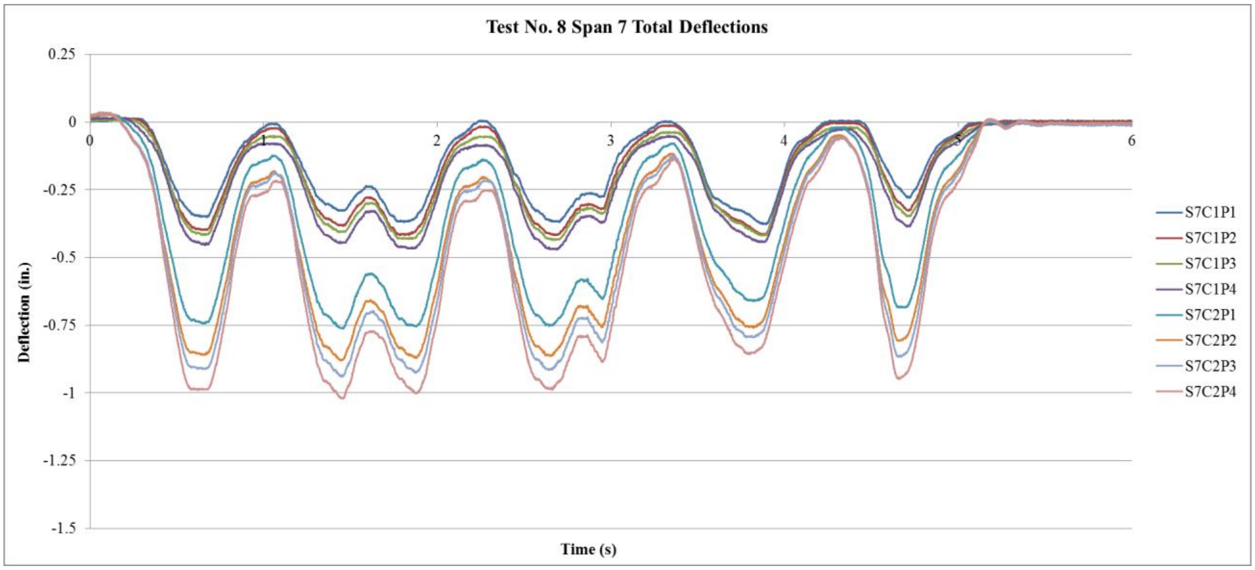

Test No. 5 Span 8 Total Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
1
2
3
4
5
6
7
8
Deflection (in.)
Time (s)
S8C1P1
S8C1P2
S8C1P3
S8C1P4
S8C2P1
S8C2P2
S8C2P3
S8C2P4

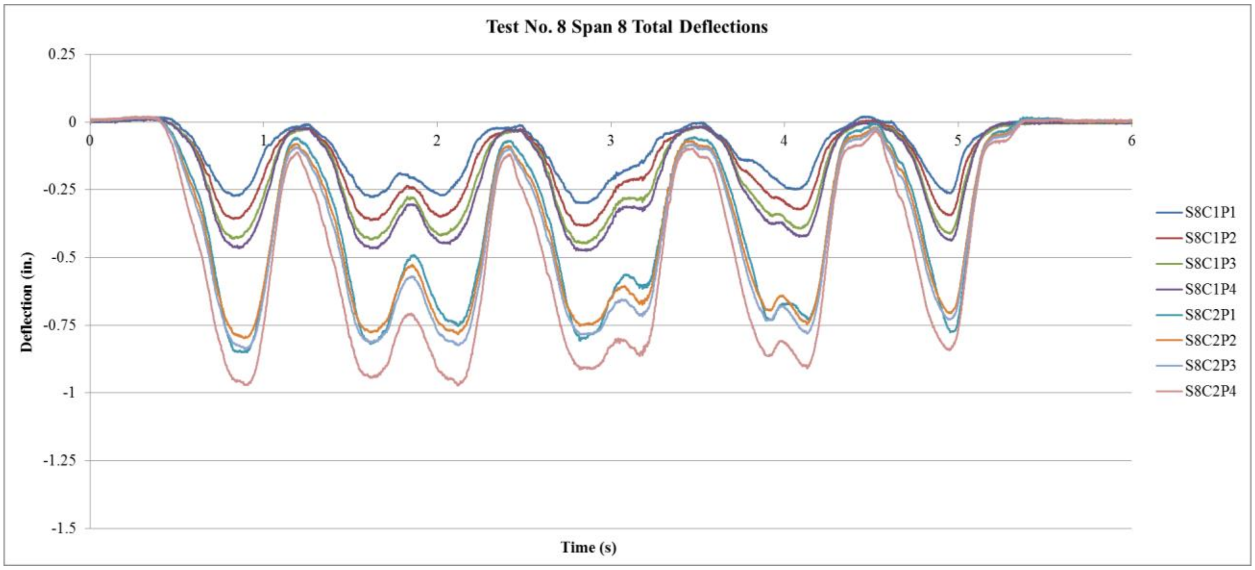

Test No. 6 Span 7 Total Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
Time (s)
S7C1P1
S7C1P2
S7C1P3
S7C1P4
S7C2P1
S7C2P2
S7C2P3
S7C2P4

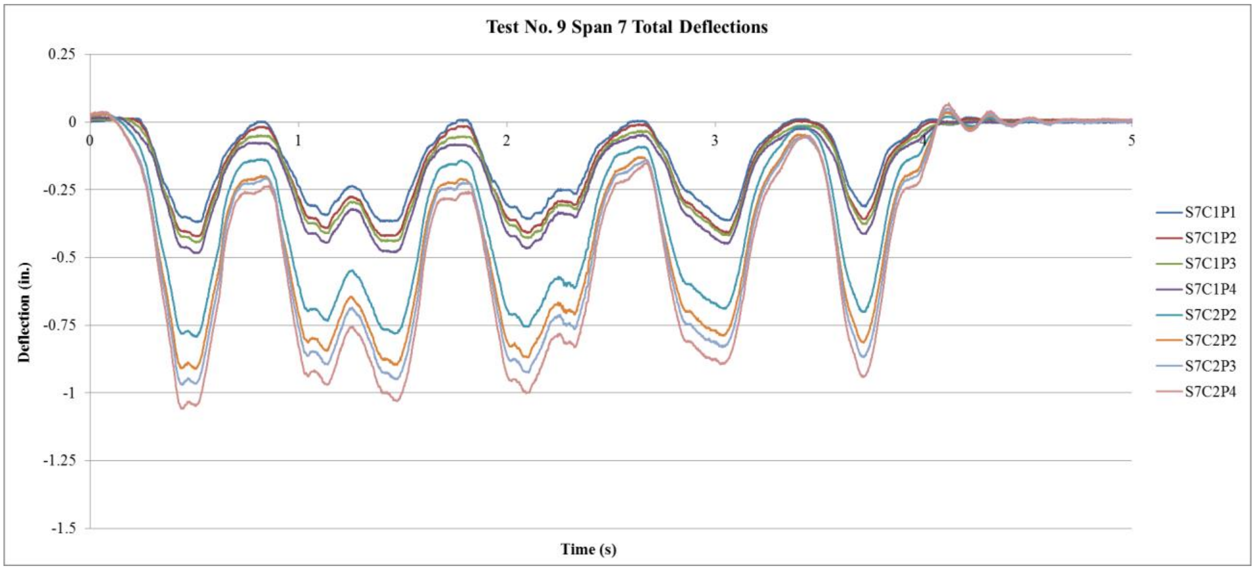

Test No. 6 Span 8 Total Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
Time (s)
S8C1P1
S8C1P2
S8C1P3
S8C1P4
S8C2P1
S8C2P2
S8C2P3
S8C2P4

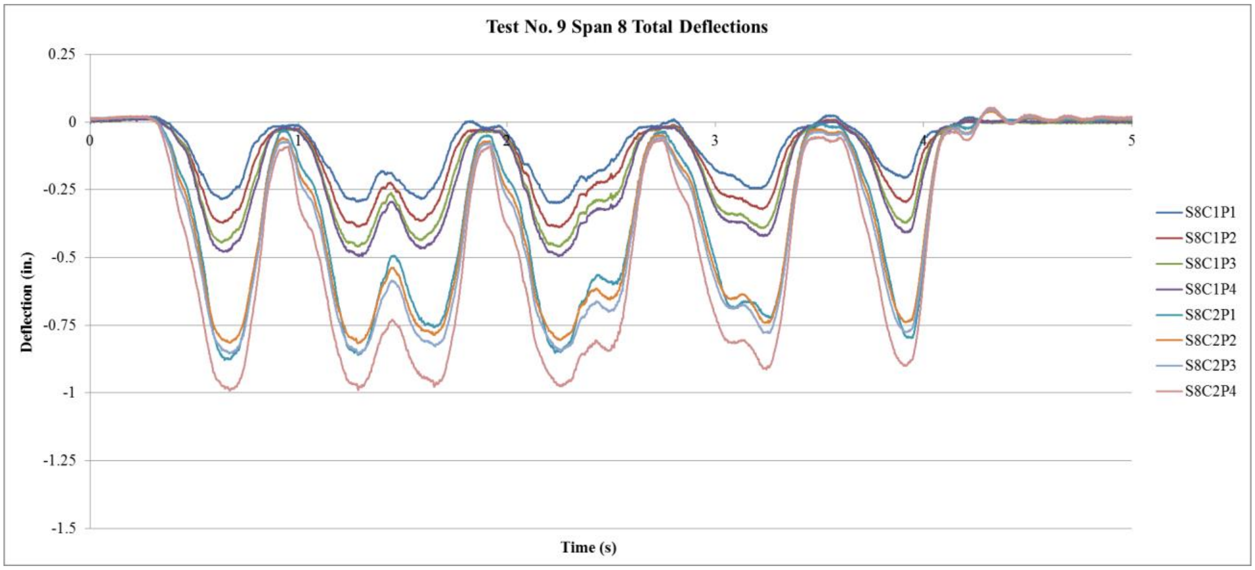

Test No. 7 Span 7 Total Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
Time (s)
S7C1P1
S7C1P2
S7C1P3
S7C1P4
S7C2P1
S7C2P2
S7C2P3
S7C2P4

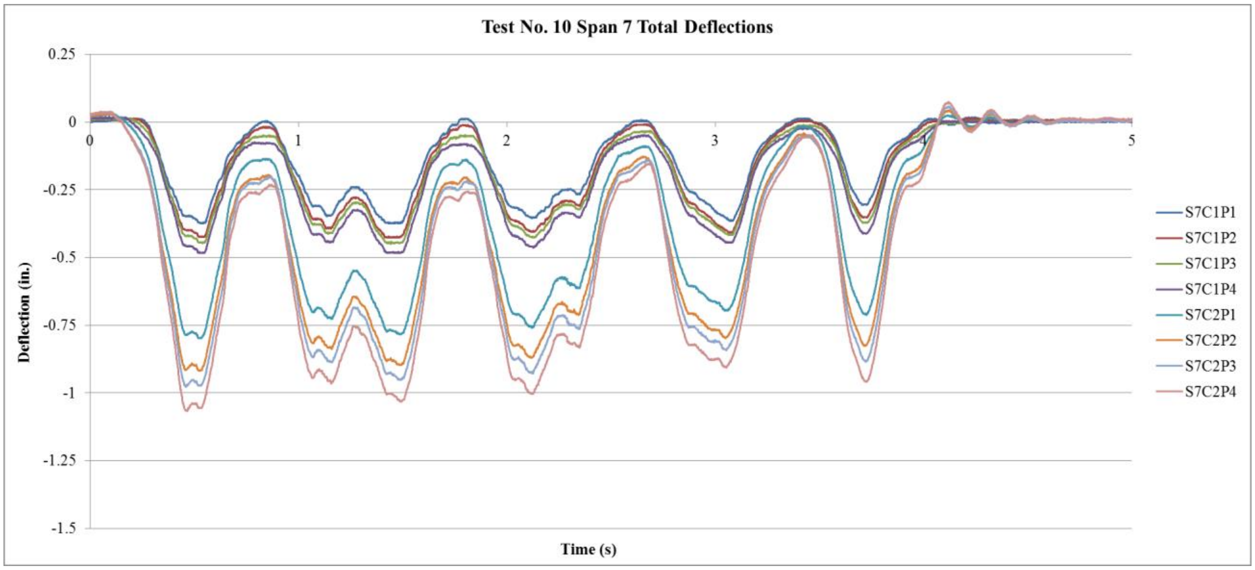

Test No. 7 Span 8 Total Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
Time (s)
S8C1P1
S8C1P2
S8C1P3
S8C1P4
S8C2P1
S8C2P2
S8C2P3
S8C2P4

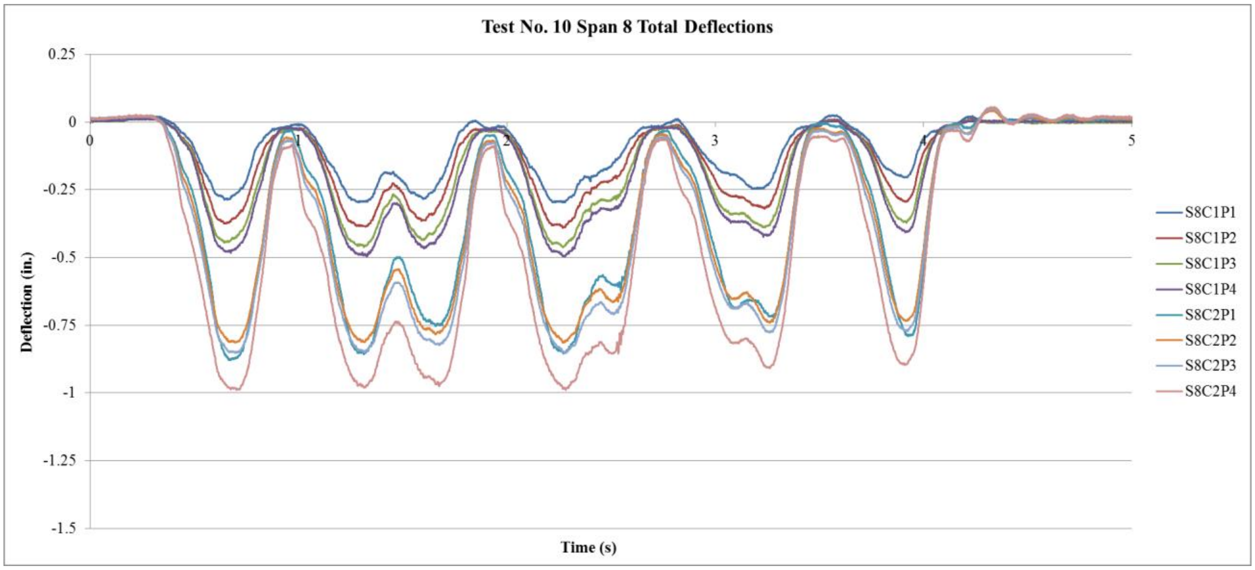

Test No. 8 Span 7 Total Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
1
2
3
4
5
6
Deflection (in.)
Time (s)
S7C1P1
S7C1P2
S7C1P3
S7C1P4
S7C2P1
S7C2P2
S7C2P3
S7C2P4


Test No. 8 Span 8 Total Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
1
2
3
4
5
6
Deflection (in.)
Time (s)
S8C1P1
S8C1P2
S8C1P3
S8C1P4
S8C2P1
S8C2P2
S8C2P3
S8C2P4

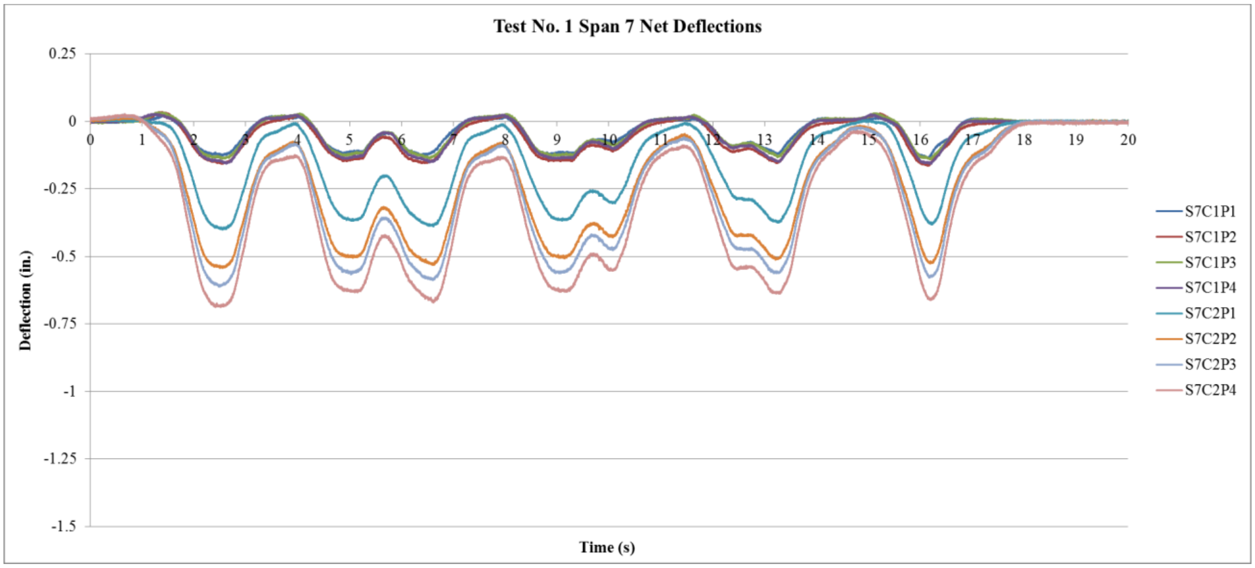

Test No. 9 Span 7 Total Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
1
2
3
4
5
Deflection (in.)
Time (s)
S7C1P1
S7C1P2
S7C1P3
S7C1P4
S7C2P2
S7C2P2
S7C2P3
S7C2P4

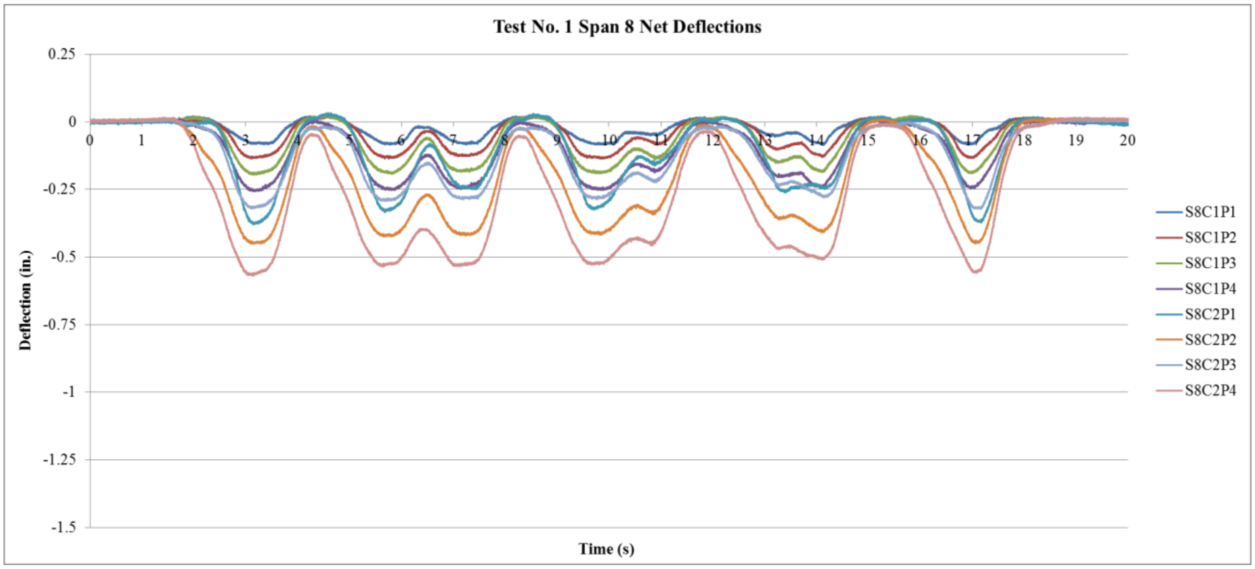

Test No. 9 Span 8 Total Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
1
2
3
4
5
Deflection (in.)
Time (s)
S8C1P1
S8C1P2
S8C1P3
S8C1P4
S8C2P1
S8C2P2
S8C2P3
S8C2P4

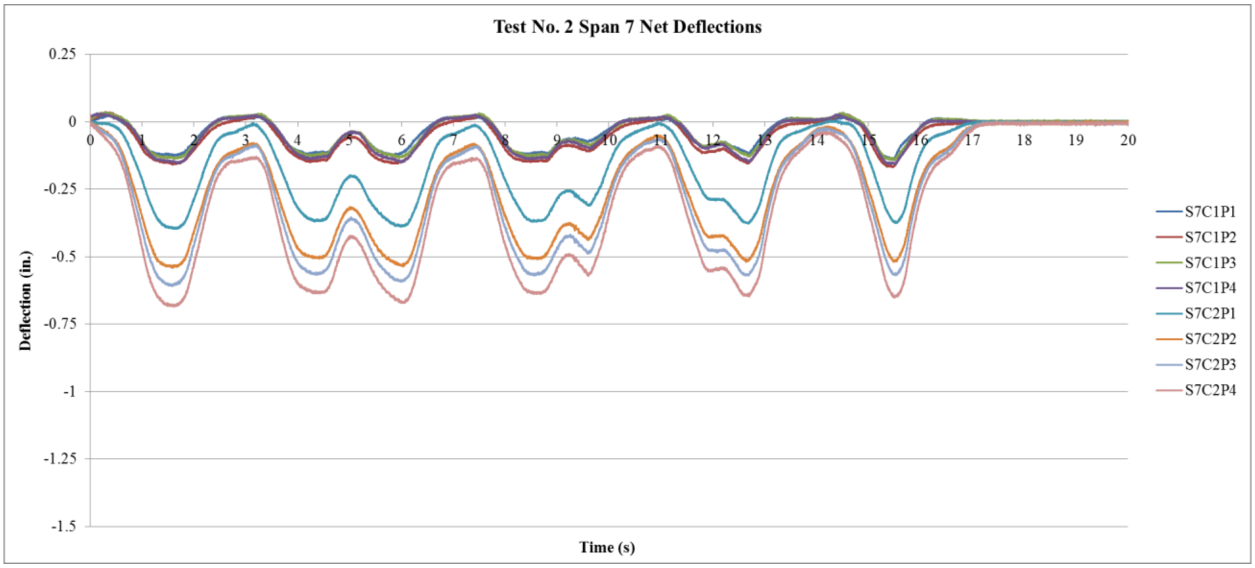

Test No. 10 Span 7 Total Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
1
2
3
4
5
Deflection (in.)
Time (s)
S7C1P1
S7C1P2
S7C1P3
S7C1P4
S7C2P1
S7C2P2
S7C2P3
S7C2P4

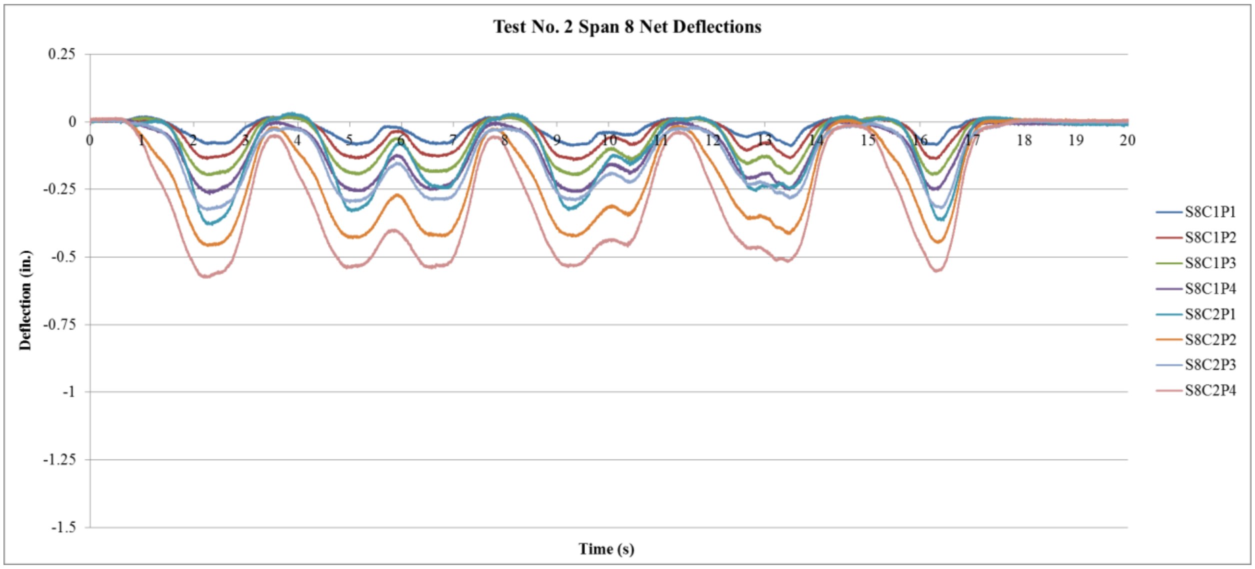

Test No. 10 Span 8 Total Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
1
2
3
4
5
Deflection (in.)
Time (s)
S8C1P1
S8C1P2
S8C1P3
S8C1P4
S8C2P1
S8C2P2
S8C2P3
S8C2P4

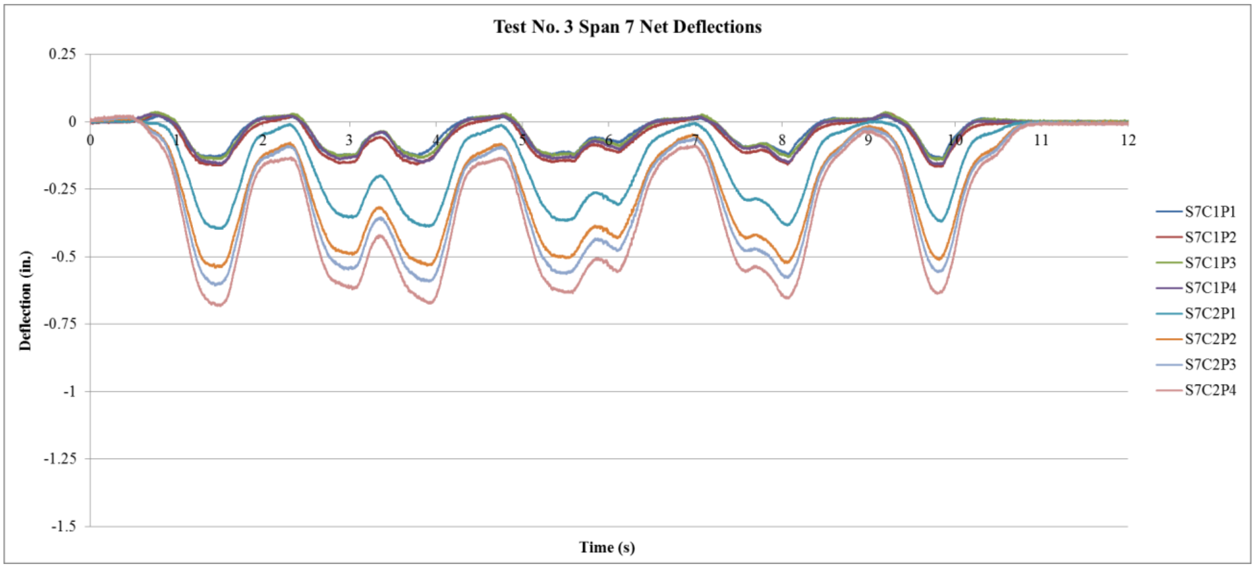
Net Deflection

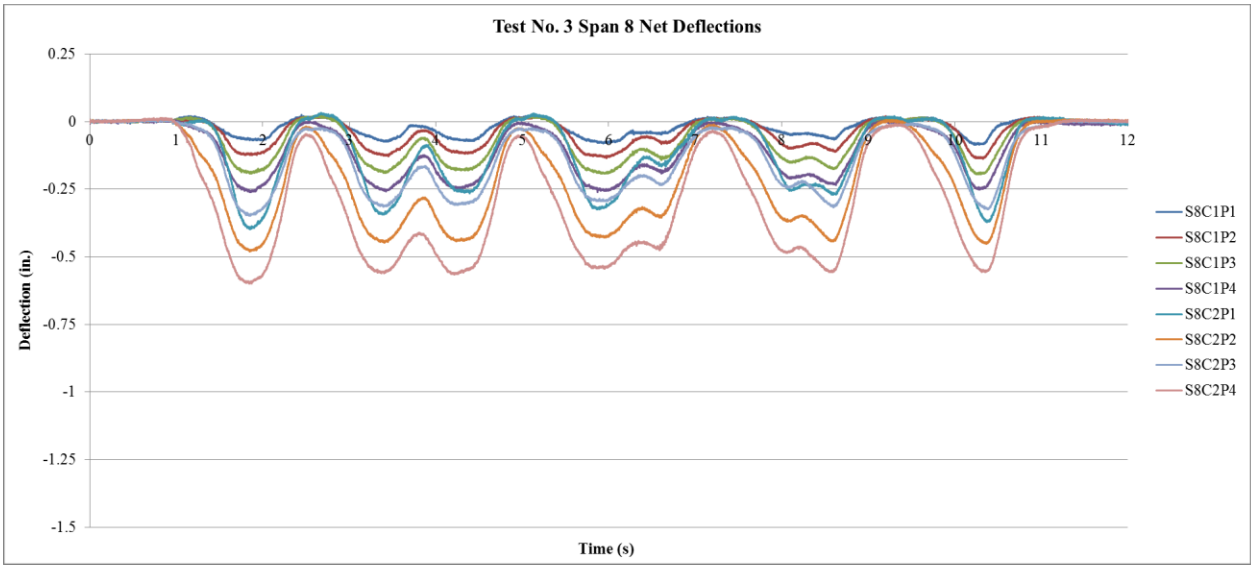


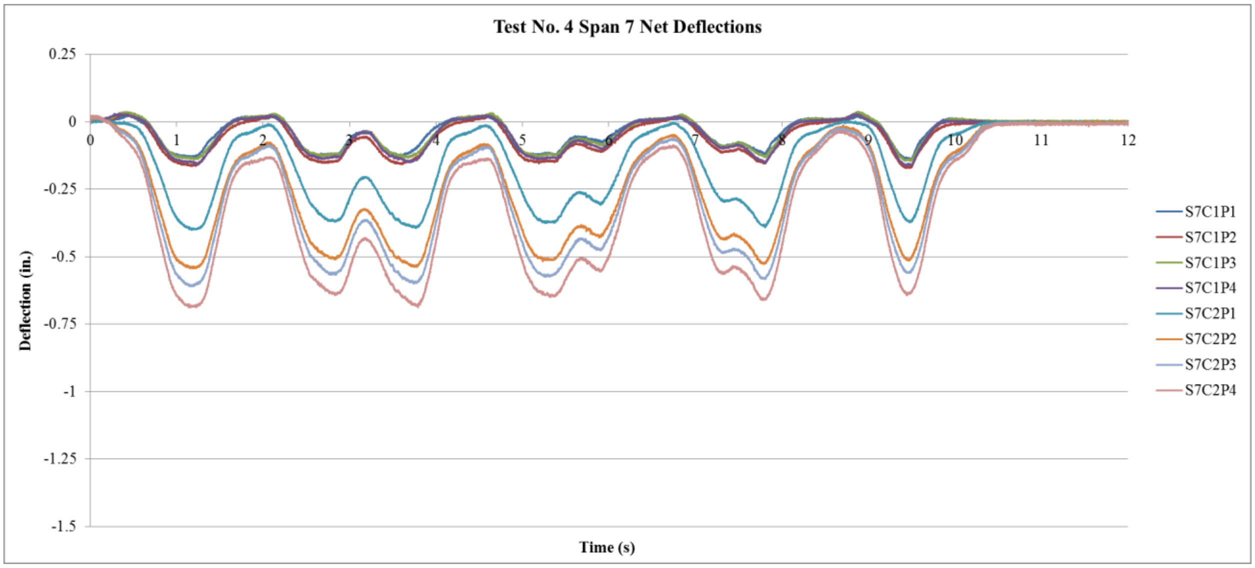


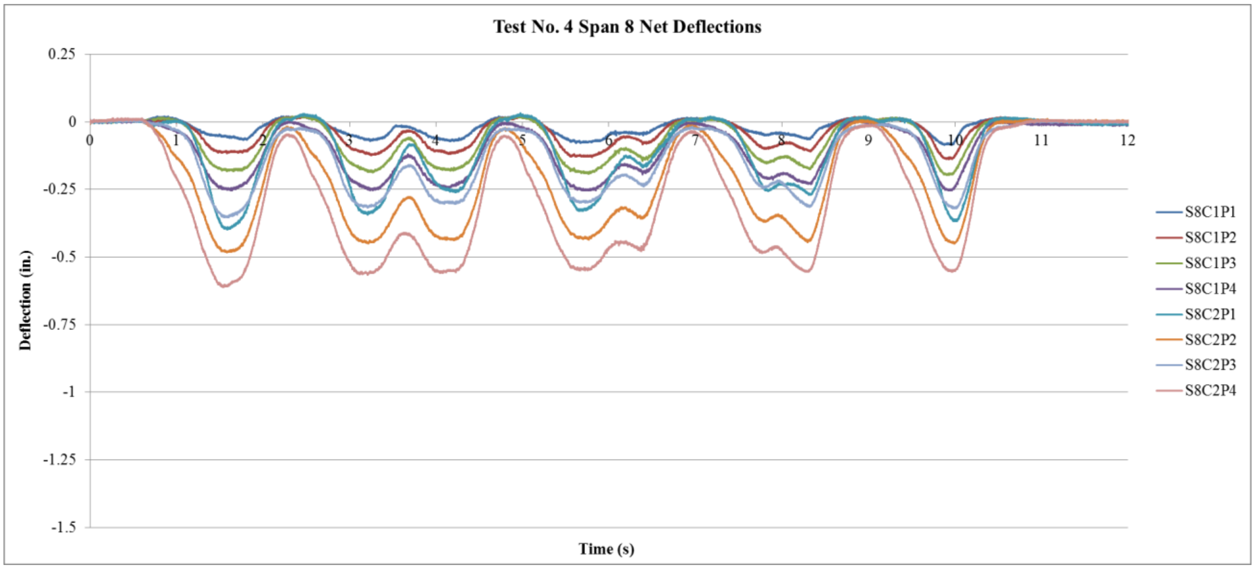

Test No. 2 Span 7 Net Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Time (s)
S7C1P1
S7C1P2
S7C1P3
S7C1P4
S7C2P1
S7C2P2
S7C2P3
S7C2P4

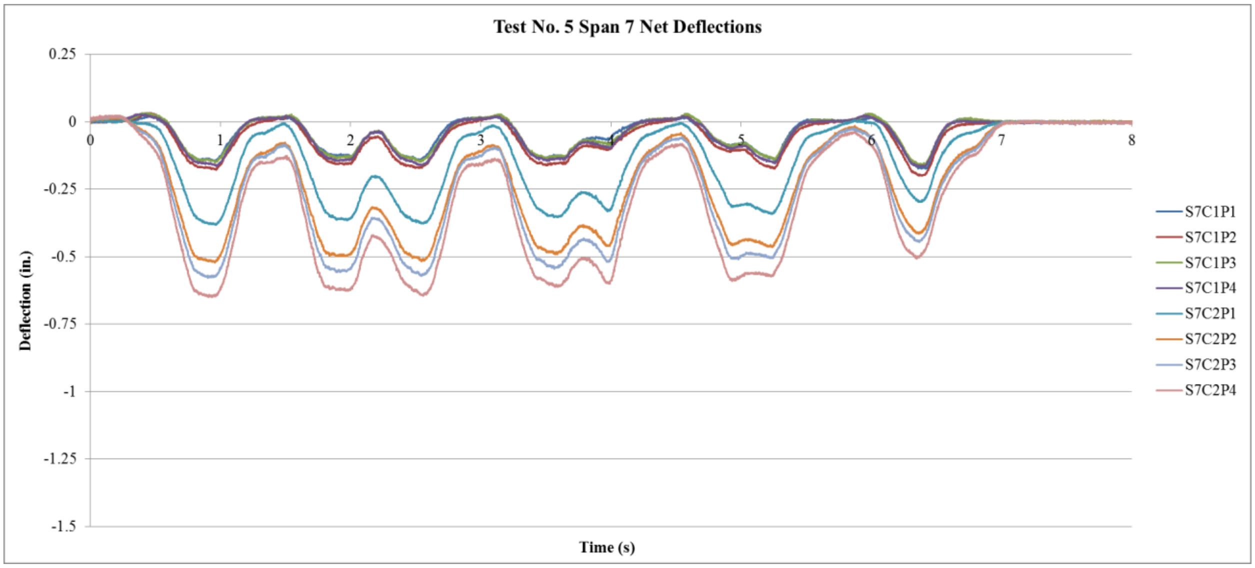

Test No. 2 Span 8 Net Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Time (s)
S8C1P1
S8C1P2
S8C1P3
S8C1P4
S8C2P1
S8C2P2
S8C2P3
S8C2P4

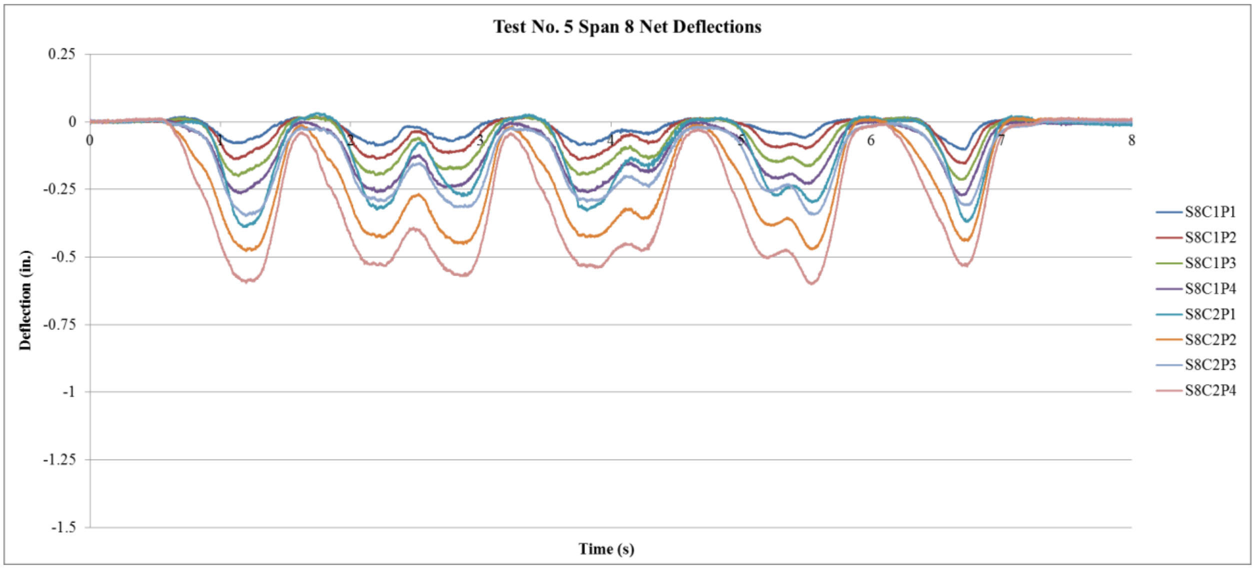

Test No. 3 Span 7 Net Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
9
10
11
12
Time (s)
S7C1P1
S7C1P2
S7C1P3
S7C1P4
S7C2P1
S7C2P2
S7C2P3
S7C2P4

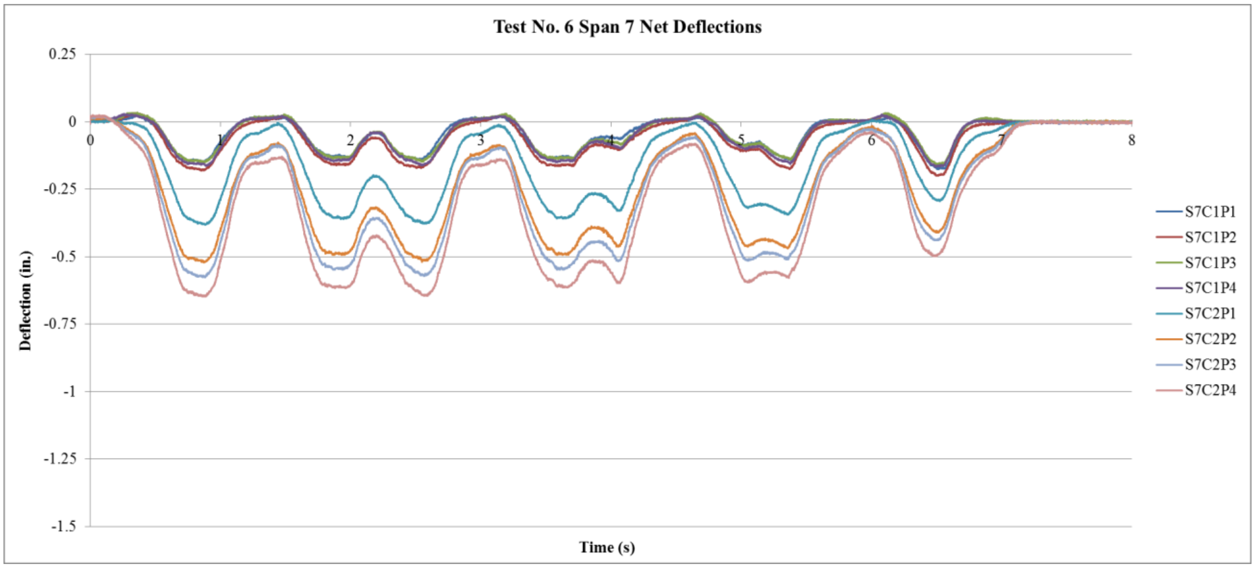

Test No. 3 Span 8 Net Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
9
10
11
12
Time (s)
S8C1P1
S8C1P2
S8C1P3
S8C1P4
S8C2P1
S8C2P2
S8C2P3
S8C2P4

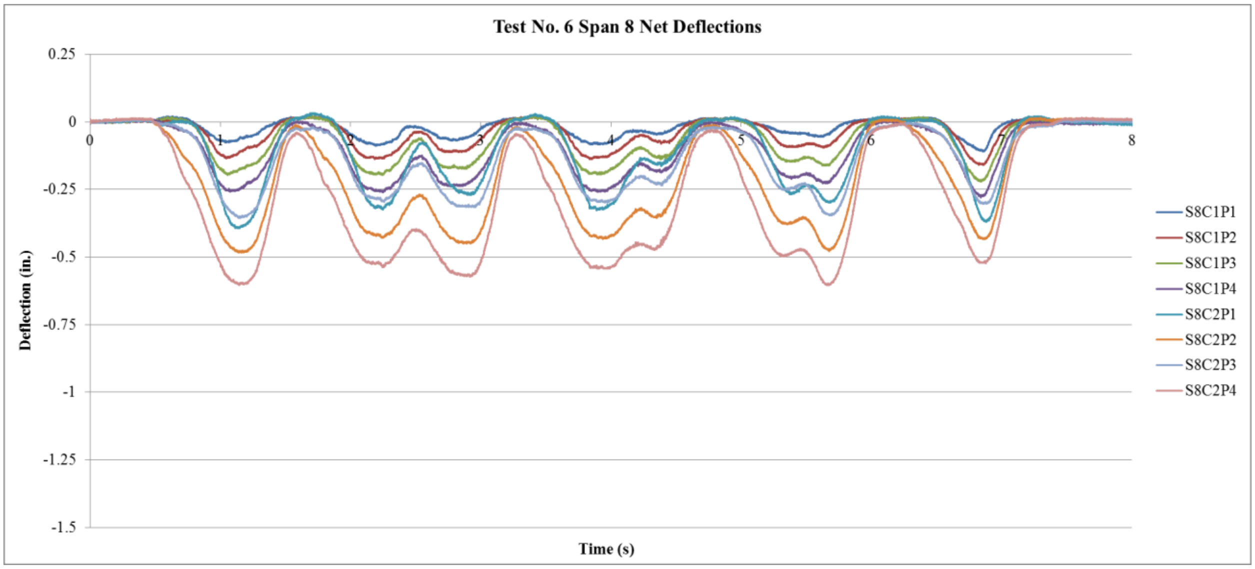

Test No. 4 Span 7 Net Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
9
10
11
12
Time (s)
S7C1P1
S7C1P2
S7C1P3
S7C1P4
S7C2P1
S7C2P2
S7C2P3
S7C2P4

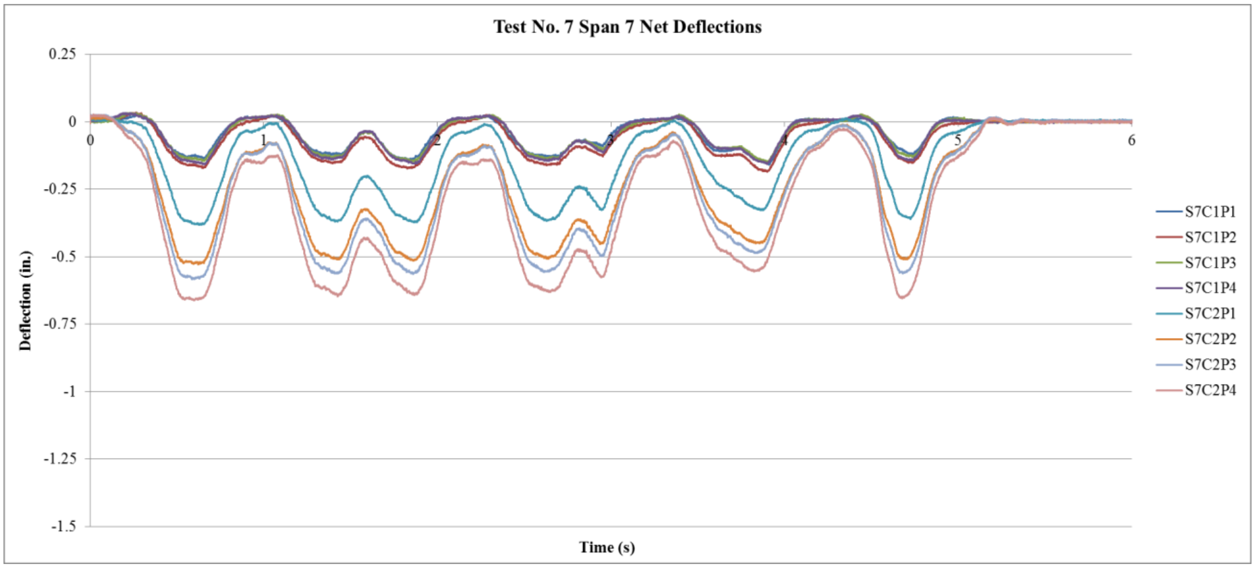

Test No. 4 Span 8 Net Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
9
10
11
12
Time (s)
S8C1P1
S8C1P2
S8C1P3
S8C1P4
S8C2P1
S8C2P2
S8C2P3
S8C2P4

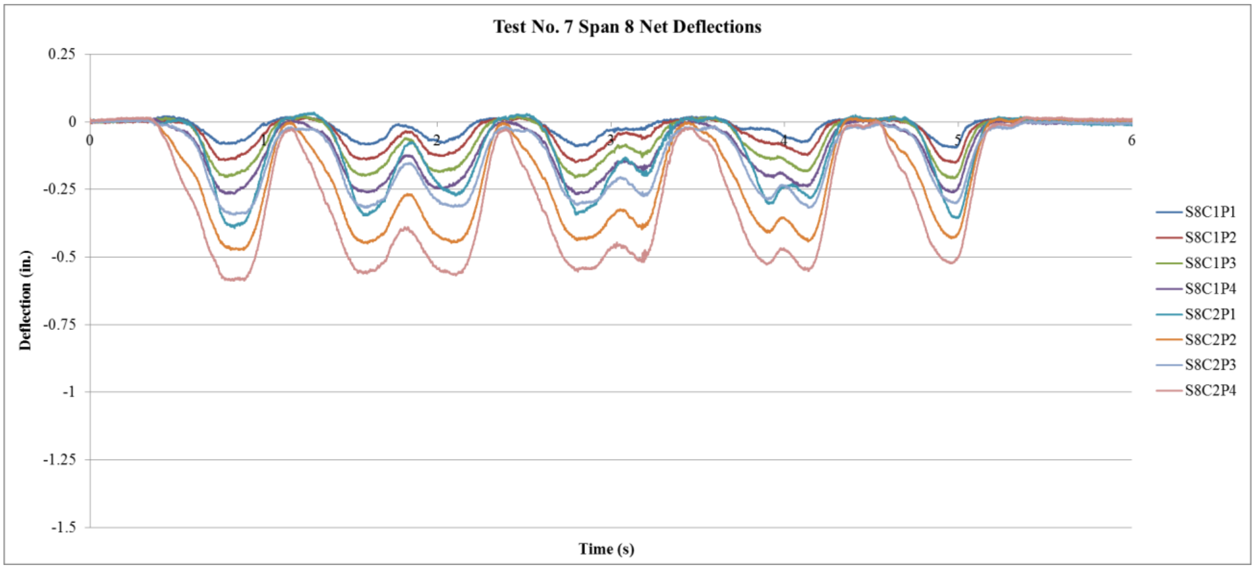

Test No. 5 Span 7 Net Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
Time (s)
S7C1P1
S7C1P2
S7C1P3
S7C1P4
S7C2P1
S7C2P2
S7C2P3
S7C2P4

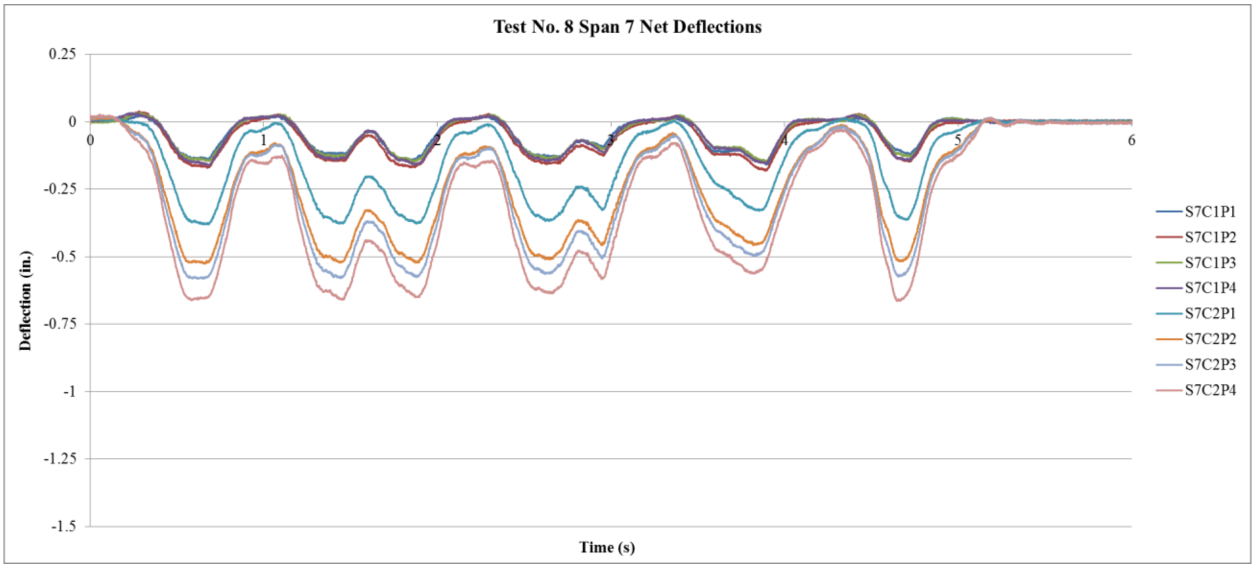

Test No. 5 Span 8 Net Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
Time (s)
S8C1P1
S8C1P2
S8C1P3
S8C1P4
S8C2P1
S8C2P2
S8C2P3
S8C2P4

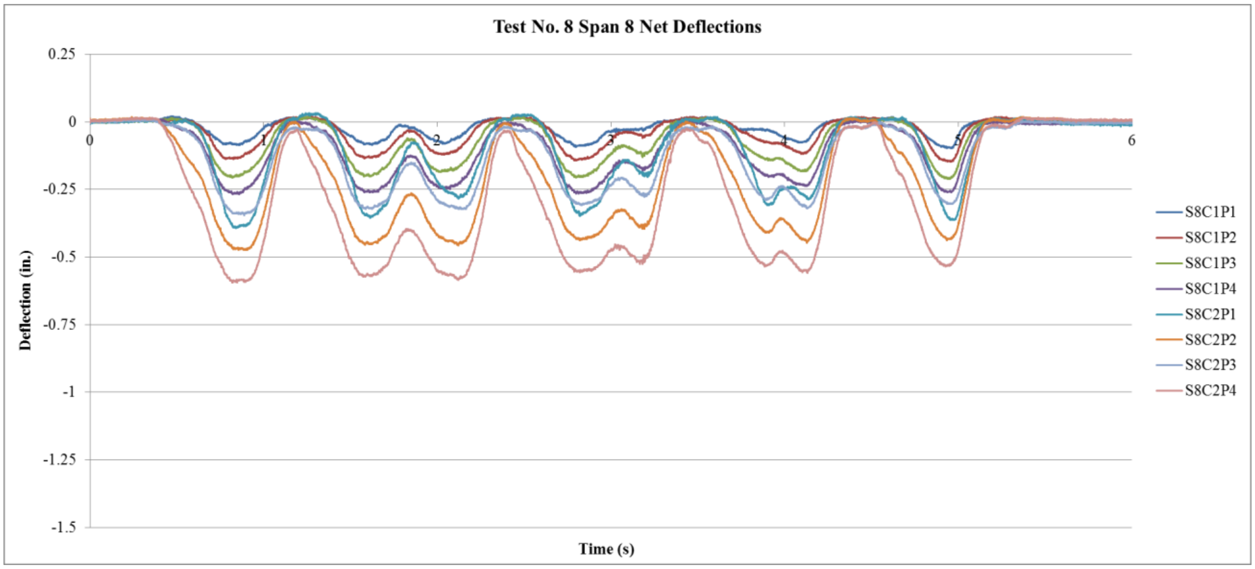

Test No. 6 Span 7 Net Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
Time (s)
S7C1P1
S7C1P2
S7C1P3
S7C1P4
S7C2P1
S7C2P2
S7C2P3
S7C2P4

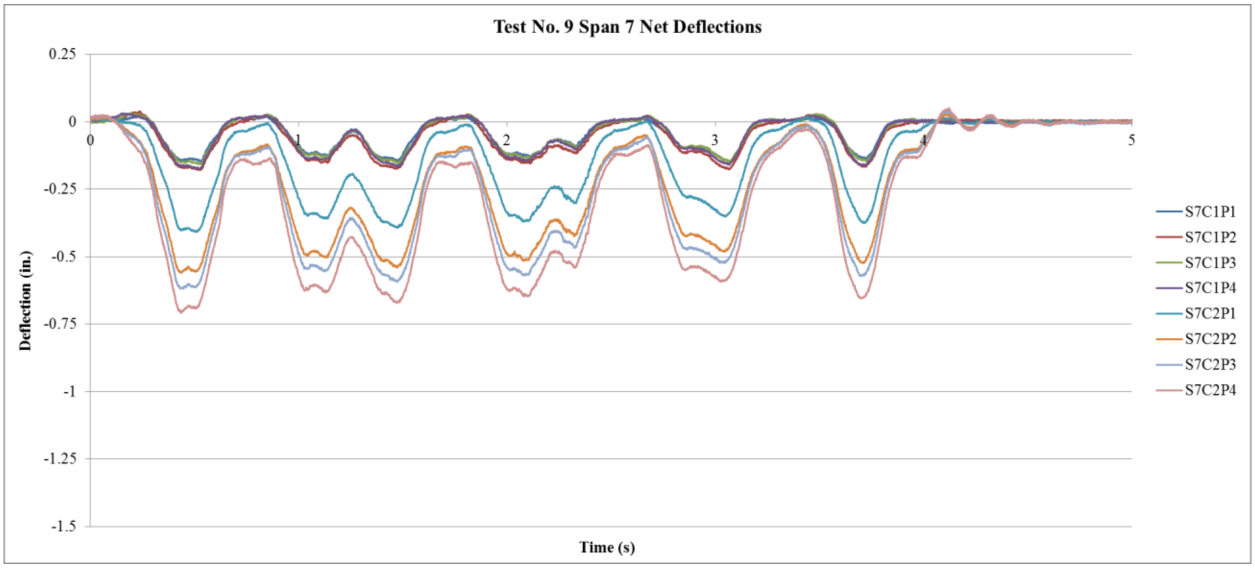

Test No. 6 Span 8 Net Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
7
8
Time (s)
S8C1P1
S8C1P2
S8C1P3
S8C1P4
S8C2P1
S8C2P2
S8C2P3
S8C2P4

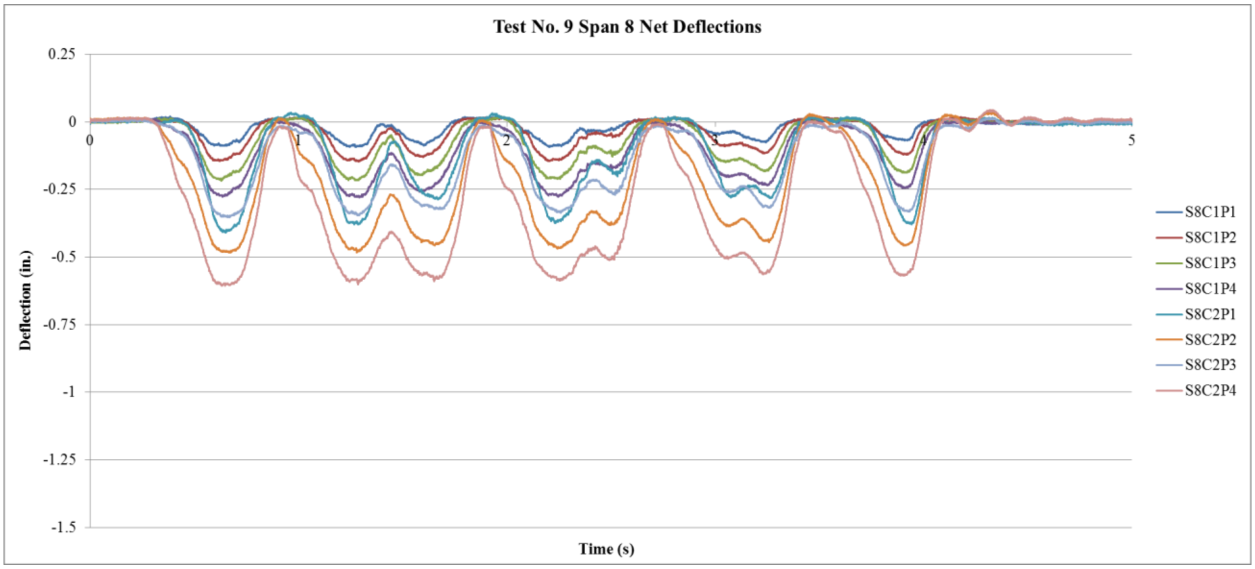

Test No. 7 Span 7 Net Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
Time (s)
S7C1P1
S7C1P2
S7C1P3
S7C1P4
S7C2P1
S7C2P2
S7C2P3
S7C2P4

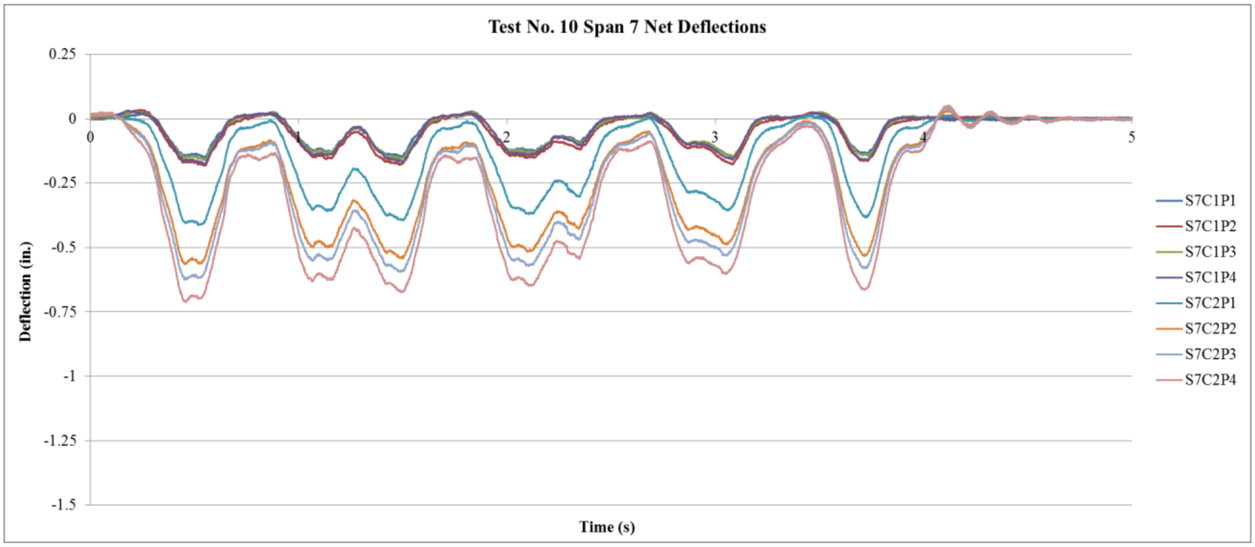

Test No. 7 Span 8 Net Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
Time (s)
S8C1P1
S8C1P2
S8C1P3
S8C1P4
S8C2P1
S8C2P2
S8C2P3
S8C2P4

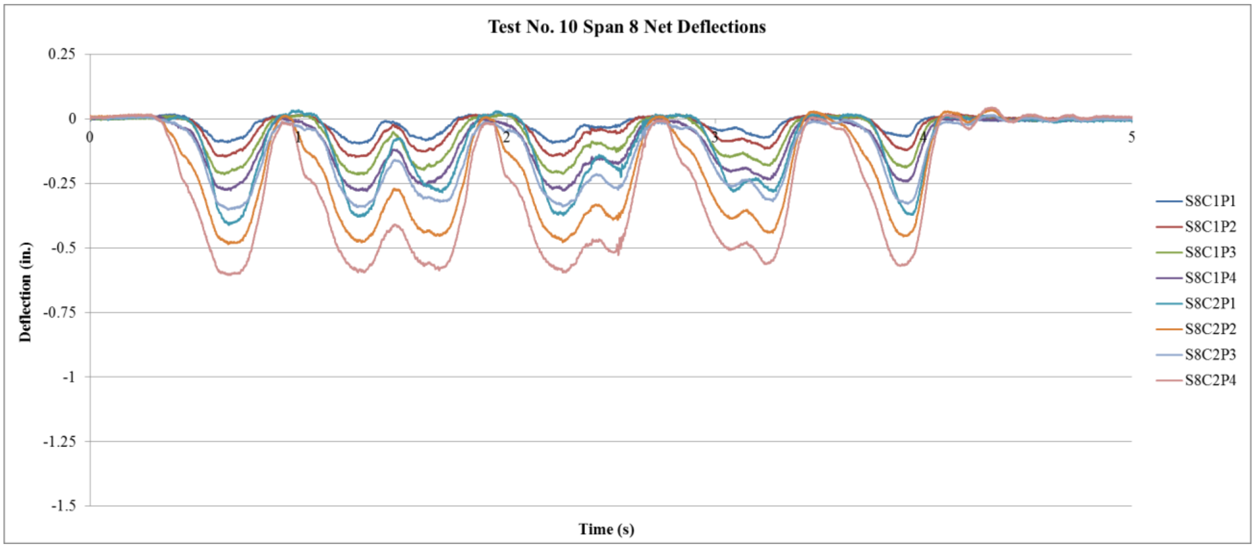

Test No. 8 Span 7 Net Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
Time (s)
S7C1P1
S7C1P2
S7C1P3
S7C1P4
S7C2P1
S7C2P2
S7C2P3
S7C2P4


Test No. 8 Span 8 Net Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
6
Time (s)
S8C1P1
S8C1P2
S8C1P3
S8C1P4
S8C2P1
S8C2P2
S8C2P3
S8C2P4


Test No. 9 Span 7 Net Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
1
2
3
4
5
Deflection (in.)
Time (s)
S7C1P1
S7C1P2
S7C1P3
S7C1P4
S7C2P1
S7C2P2
S7C2P3
S7C2P4


Test No. 9 Span 8 Net Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0
1
2
3
4
5
Deflection (in.)
Time (s)
S8C1P1
S8C1P2
S8C1P3
S8C1P4
S8C2P1
S8C2P2
S8C2P3
S8C2P4


Test No. 10 Span 7 Net Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
Time (s)
S7C1P1
S7C1P2
S7C1P3
S7C1P4
S7C2P1
S7C2P2
S7C2P3
S7C2P4


Test No. 10 Span 8 Net Deflections
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
Deflection (in.)
0
1
2
3
4
5
Time (s)
S8C1P1
S8C1P2
S8C1P3
S8C1P4
S8C2P1
S8C2P2
S8C2P3
S8C2P4