MD-16-SHA-UM-3-18

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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

PRECISION MONITORING OF BRIDGE DECK CURVATURE CHANGE DURING REPLACEMENT

MEHDI KALANTARI KHANDANI, PHD

UNIVERSITY OF MARYLAND, COLLEGE PARK

FINAL REPORT

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16. Abstract

This project was focused on development and deployment of a system for monitoring vertical displacement in bridge decks and bridge spans. The system uses high precision wireless inclinometer sensors to monitor inclinations at various points of a bridge deck. The inclination data is fed into a mathematical model which calculates vertical displacement. As a specific goal, this project was intended to monitor change in vertical displacement and curvature of a bridge deck during the deck replacement process. Wireless inclination/temperature sensors were developed and thoroughly tested in laboratory environment. Mathematical curvature calculation methods were used to convert inclination data into vertical displacement. Wireless precision inclination/temperature sensors were deployed on a bridge close to Pocomoke City in Maryland, which underwent deck replacement from January until August 2015. The sensor revealed that, temperature change could lead to z changes in inclination of bridge girders. The changes in inclination would lead into temperature induced vertical displacement of a bridge deck. As a result, comparing change in displacement of bridge deck before and after deck replacement is not meaningful unless temperature effects are characterized. The study also revealed shortcoming of surveying, being used to find change in curvature of a bridge, because unless two surveys for a bridge deck are taken place at the same time, their results cannot be directly compared. The method based on wireless inclinometer sensors characterizes the effect of temperature and therefore, it separates contribution of temperature from the change in the displacement caused by deck replacement.

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1. MOTIVATION AND OBJECTIVES

The objective of this project was to introduce a novel method for long term monitoring of vertical displacement and change in curvature in highway bridge decks. To monitor vertical displacement and changes in curvature, the approach used an array of high precision wireless inclination (tilt) sensors to constantly monitor changes in the inclination of the bridge deck at various points of a span. A special application of interest was to study the change in vertical displacement and curvature during bridge deck replacement. Accurate monitoring of bridge deck curvature and vertical displacement is important to ensure safe operation of the structure after deck replacement. Excessive changes in curvature after deck replacement will result in undesirable consequences, such as ponding and accelerated wearing of surface.

To monitor the changes in vertical displacement, wireless and small precision inclination (tilt) sensors are attached to the bridge superstructure (e.g., bridge girders) before the start of deck replacement. The sensors use an embedded electrolytic tilt measurement technology, which monitors changes in tilt and inclination with sub arc second resolution (typically 0.5 arc second or 0.00014 degree). The devices are relatively small and their approximate size is 4”x2.0”x1”. Such wireless precision orientation sensors constantly monitor deformation and changes in curvature of the bridge superstructure during deck replacement. By combining the precision tilt data from sensors with geometrical dimensions of the bridge, maximum deformation and change in curvature of the bridge is calculated. The advantages of the proposed system are (1) easy to install; (2) continuous monitoring of deformations and displacements in the bridge girders before, during, and after deck replacements; and (3) formulating the effect of temperature, and separating it from other factors affecting vertical displacement of girders.

2. RESEARCH APPROACH

2.1. Working Principles of Electrolytic Tilt Sensors

Electrolytic tilt sensors are a proven technology to measure tilt at very high accuracy and resolution. The working principle of such sensors is through simple movement of an air bubble inside a device filled with an electrolyte, as shown in Figure 1. The electrolytic tilt sensors are designed in such a way that change in tilt will lead to movement of the bubble. This is similar to commonly used leveling device with air bubble inside a vial filled with liquid.

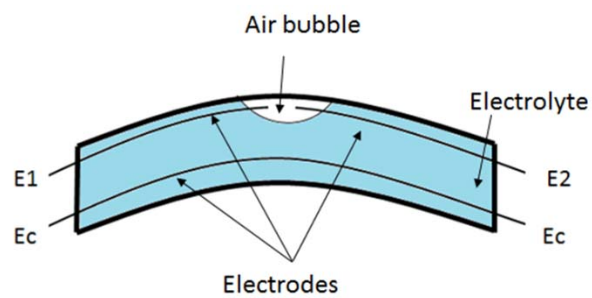


Figure 1: An illustration of an electrolytic tilt sensor.

To turn tilt data into an electric single, tilt sensors use electrodes inside the device. The device has a common electrode (**Ec**) and two excitation electrodes (**E1**, and **E2**), as shown in Figure 2. Change in the tilt of the device causes movement of the bubble, which will lead to change in exposed length of the two electrodes **E1** and **E2** to the electrolyte. The change in the exposure of the electrodes to electrolyte will cause changes in electric resistance between each of **E1** and **E2** electrodes and the common electrode, **Ec**.

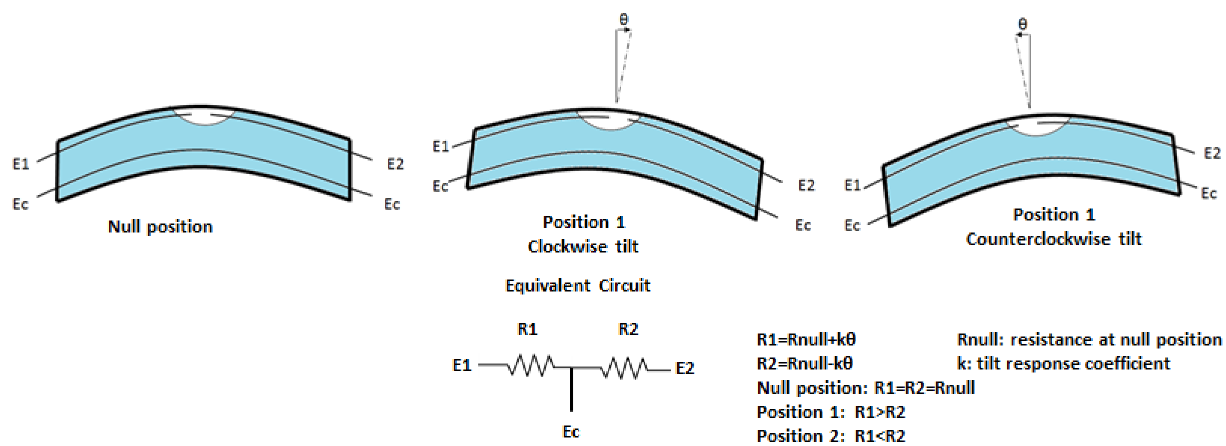


Figure 2: Illustrating response of an electrolytic tilt sensor to change of orientation.

2.2. Electrical Signal conditioning for Electrolytic Tilt Sensors

Reading an electrolytic tilt sensor requires applying an excitation voltage to electrode **E1** and **E2** of the device, while reading the voltage on Electrode **Ec**. Often, the device is part of a system with a digital microcontroller (or microprocessor), and therefore, the signals on **E1** and **E2** can be controlled using General Purpose Digital Input / Output (GPIO) pins. This is shown in Figure 3, where a microcontroller controls GPIO1 and GPOI2. To measure tilt, the microcontroller applies a voltage on GPIO1 for a period of time, **T1**, while the voltage on GPIO2 is zero. At the end of the period, a digital conversion of voltage on common electrode will be done by the

Analog to Digital Converter (ADC) as the first conversion. Then the microcontroller reverses the voltages on GPIO1 and GPIO2 by applying the same voltage on GPIO2 while voltage on GPIO1 is zero, and holds those voltage levels for another time period, **T2**. At the end of **T2**, a second conversion of common electrode voltage will be done. The difference of the two conversions is proportional to tilt of the device.

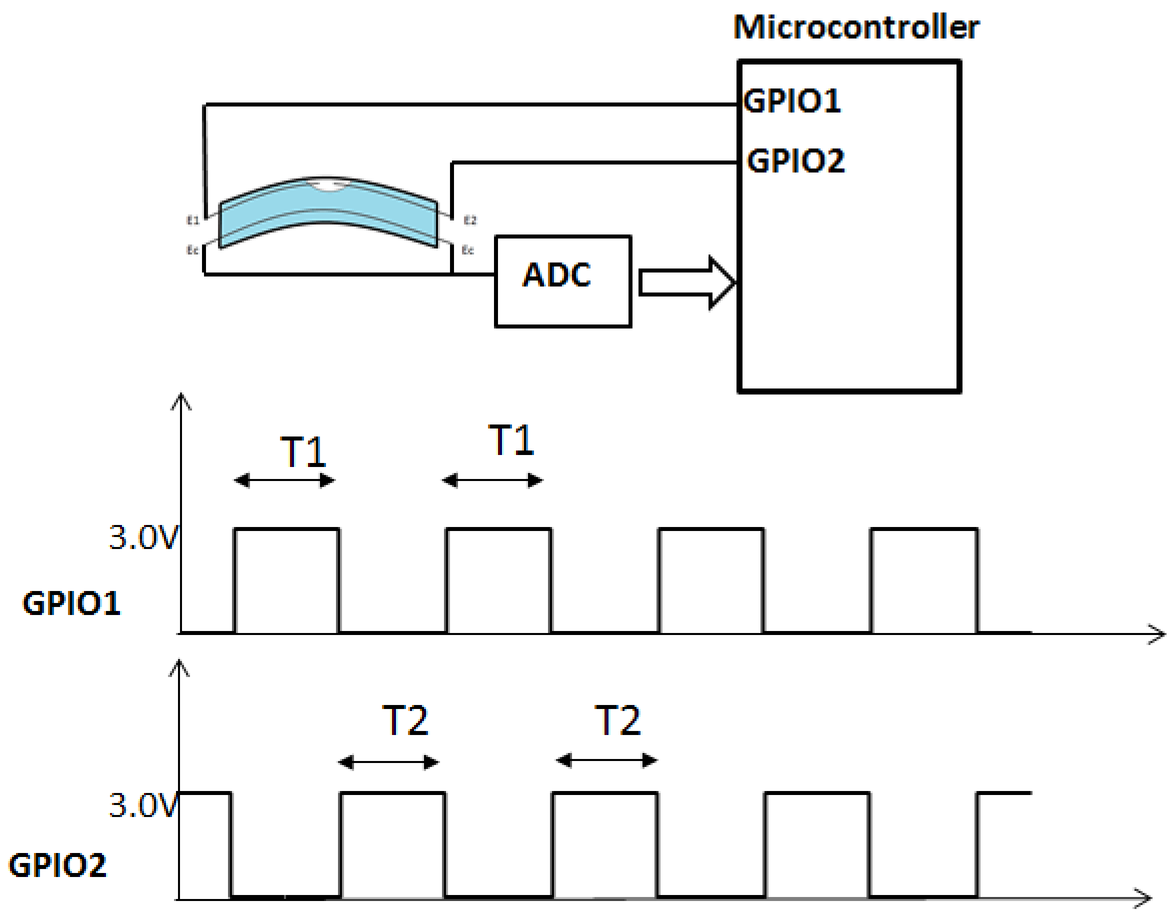


Figure 3: Electrical signal conditioning for electrolytic tilt sensors.

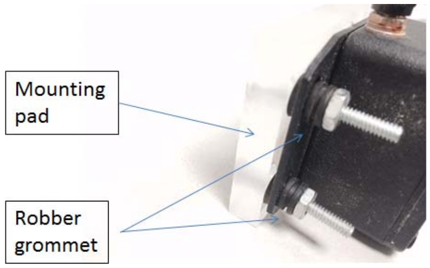
2.3. Design, Packaging and Integration

In order to produce a field operable wireless inclinometer sensor, electrolytic tilt sensors were integrated with CC2530, which is an 8-bit microcontroller by Texas Instrument [2]. The microcontroller was programmed to generate the excitation voltage on two GPIO pins. The voltage across the common electrode was amplified using a precision instrumentation amplifier. Additionally, an internal Sigma-Delta analog to digital converter of the microcontroller was used to read the electrolytic tilt sensor. The microcontroller used is also capable of RF transmission at 2.4GHz, compatible with the IEEE802.15.4 standard. Also, it has an internal temperature sensor, allowing temperature measurement in addition to tilt monitoring. The device was programmed to produce 10 readings of precision tilt and temperature per hour. The measurements were collected using a cellular gateway, which collected and transmitted the data to a cloud based server.

2.4. Shock Survival

Because the wireless inclination sensor device was meant to be used during the concrete deck removal and replacement process, special consideration was required to be given to its shock survival. The mechanical machines used during the deck removal processes apply significant vibration and shock to the devices, and designing the electronics and the enclosure of the wireless inclinometers for maximum shock survival is an important requirement.

In order to improve shock resistance, the wireless inclinometer was designed to be split into two portions. The first portion only included the electrolytic tilt sensor, while the second portion included all of the electronics, such as the signal conditioning unit, microcontroller, battery, etc. The electrolytic tilt sensor was encapsulated inside a small rectangular aluminum profile, which was potted with a high strength resin. A cable connects the electrolytic tilt sensor to the electronic portion of the device. This design is shown in Figure 4. The advantage of this design is that the electrolytic portion can be secured into the bottom flange of steel girders using a high strength epoxy. However, attachment of the electronic portion to the bottom flanges using a hard epoxy could lead to its failure as a result of high shocks occurring during deck removal operation. To improve shock survival, the electronic portions used a simple suspension mechanism, in which a mounting plate was attached to the bottom flange of steel girders; however, as shown in Figure 4, the electronic portions were attached to the mounted pads using small rubber grommets. Using this simple mounting method reduces the shock during deck removal process. The method proved to be effective during field evaluation of the sensors.



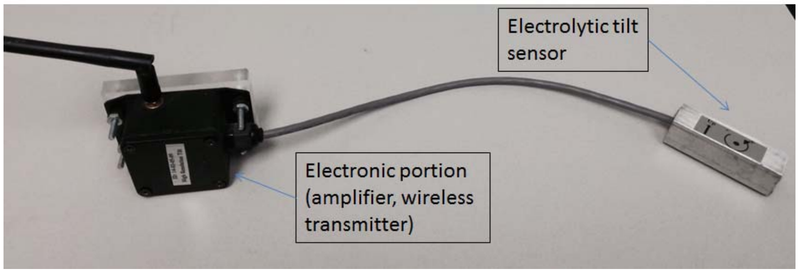


Figure 4: The design for the wireless inclinometer for maximum shock resistance for the purpose of withstanding high shocks and vibration during deck removal.

2.5. Evaluation and Calibration

The developed wireless inclinometer sensor was attached to a mechanical device often used in optical instruments. The device, which is manufactured by Newport Corporation, has a high-precision, adjustment screw, which can be used to change the tilt in tiny steps of 0.01 degrees. After attaching the wireless inclinometer to the test device (as shown in Figure 5), tilt was changed from -0.5 to +0.5 degrees with 0.05 degree steps. The graph on bottom of Figure 5 shows comparison of the measured tilt with the actual tilt. The data shows that the maximum error is approximately 0.009 degrees, which is considered to be a reasonable accuracy for monitoring bridge deck deformation. Since the mechanical device used had an accuracy of only 0.01 degrees, this experiment can verify the accuracy of the tilt to 0.01 degree, which is a reasonable accuracy; however, the theoretical accuracy of the developed tilt sensor is 0.001 degrees.

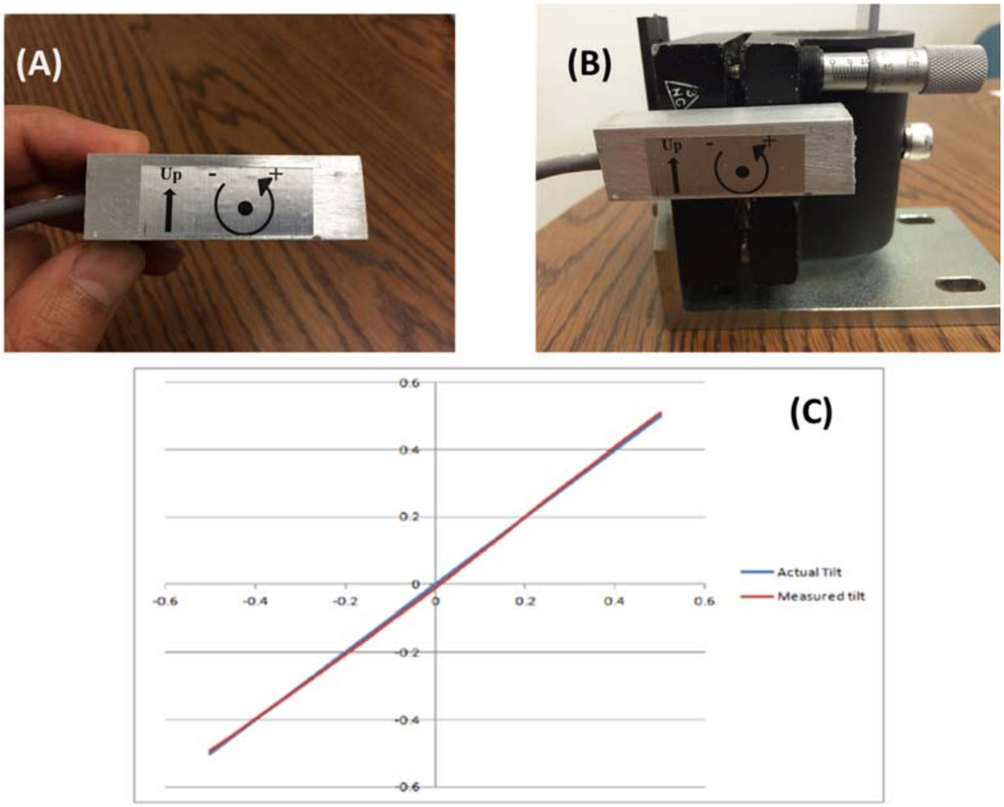


Figure 5: Test and calibration of the designed wireless inclinometer sensors.

3. MATHEMATICAL FORMULATION OF VERTICAL DISPLACEMENT MONITORING

In this section, the mathematical formulation of deck displacement calculation using the precision wireless inclinometer sensors was provided. For the mathematical model, a span between two piers, as shown in Figure 6, was considered.

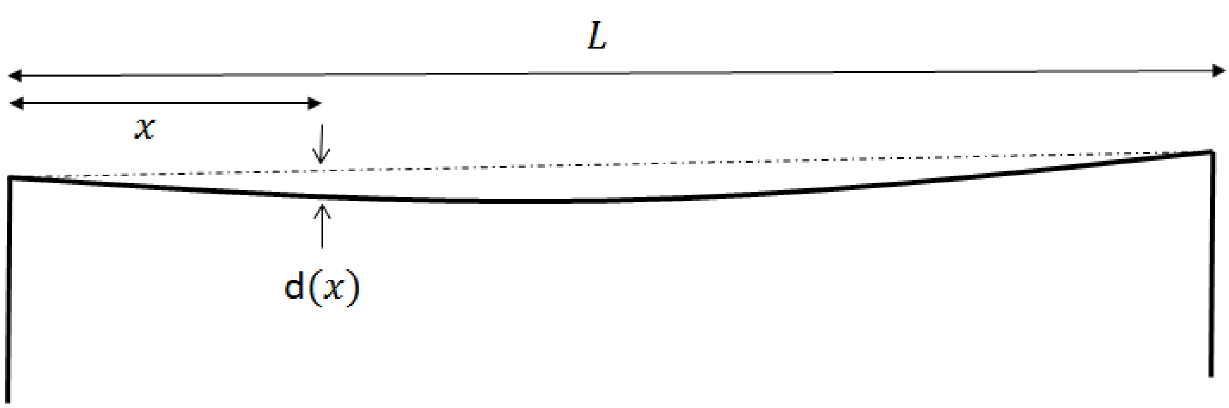


Figure 6: Illustrating parameters for the mathematical model.

According to plane section conservation law of Bernoulli, the vertical displacement of in a span which is a part of multi-span structure can be formulated as a 4th degree polynomial [3]:

$$d(x) = ax^4 + bx^3 + cx^2 + dx + e \qquad (1)$$

where $d(x)$ is the vertical displacement at location x of the span, and a, b c, d, and e, are constant (and unknown) coefficients. The above model was used to find change in curvature and displacement of a bridge deck during deck replacement operation. For this purpose, it is assumed that before deck replacement, the vertical displacement of a given span is specified using Equation (1). Because of change in loading, the polynomial describing vertical displacement of the span changes after deck replacement. As a result, vertical displacement in the given span after deck replacement will be described using the following polynomial:

$$d'(x) = a'x^4 + b'x^3 + c'x^2 + d'x + e' \qquad (2)$$

The net change in vertical displacement will be the difference of the displacement between before and after deck replacement. Such difference can be written as:

$$r(x) = d(x) - d'(x) = (a - a')x^4 + (b' - b)x^3 + (c - c')x^2 + (d - d')x + (e - e') \qquad (3)$$

where $r(x)$ is the net change of displacement at location x of the span as a result of deck replacement operation. Equation (3) can be rewritten in the following simpler form:

$$r(x) = Ax^4 + Bx^3 + Cx^2 + Dx + E \qquad (4)$$

in which $A = a - a'$, $B = b - b'$ $C = c - c'$, $D = d - d'$, and $E = e - e'$. In order to find net changes in displacement using equation (4), the five unknowns, namely$A$, B C, D, and E, must be found. Therefore, a total of five equations are needed. The first two equations use the fact that at the two end of the span, vertical displacement is zero:

$$r(0) = 0 \quad \rightarrow \quad E = 0 \qquad (5)$$

$$r(L) = 0 \quad \rightarrow \quad AL^4 + BL^3 + CL^2 + DL = 0 \qquad (6)$$

note that L is the length of the span. Assuming the use of inclination monitoring sensors at two different points of the span, namely x_1, x_2 to be s_1, s_2 respectively, two other equations can be written as follows:

$$4Ax_1^3 + 3Bx_1^2 + 2Cx_1 + D = s_1 \qquad (7)$$

$$4Ax_2^3 + 3Bx_2^2 + 2Cx_2 + D = s_2 \qquad (8)$$

Usually, the two points are chosen to be closer to the piers or abutments. This is because at those points, smaller shock caused of deck removal is applied to the sensors compared to the situation in which the sensors are deployed at the center of a span. It must be noted that Equations (7) and (8) have been written based on the fact that the inclination at a given point of the span is the derivative of vertical displacement function in Equation (4) with respect to x. The last equation is based on the simplifying assumption that change of inclination at center of the span is zero:

$$4Ax_3^3 + 3Bx_3^2 + 2Cx_3 + D = 0 \quad (9)$$

in which $x_3 = \frac{L}{2}$. Solving the linear set of equations (5)-(9) will give the unknown A, B C, D, and E, using which vertical displacement can be measured and monitored by equation (4).

As a remark on placement of wireless inclinometer sensors, it must be noted that for good numerical stability in calculations, it makes sense to choose inclination measurement points x_1, x_2 to have the maximum separation from each other on the span. For this purpose, two wireless inclinometer sensors can be installed close to the two piers at the either side of the span. This placement scheme is shown in Figure 7.

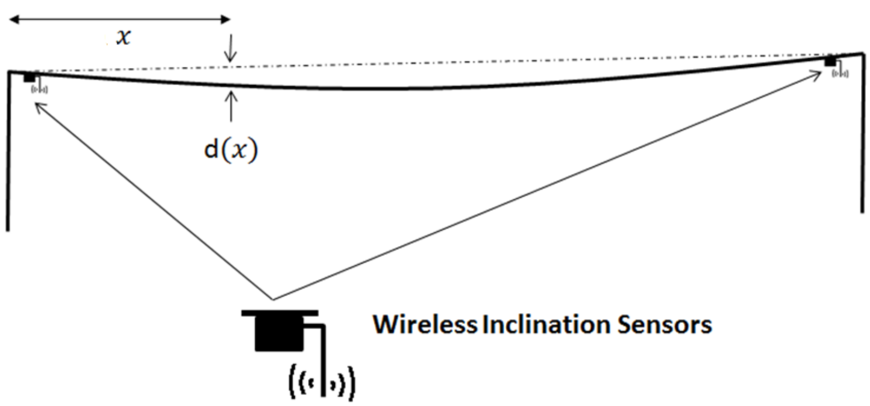


Figure 7: Illustrating locations of wireless inclinometers for monitoring deck vertical displacement.

As a final note, curvature at location x of the span can be found by finding the second derivative of vertical displacement with respect to x:

$$k(x) = 12Ax^2 + 6Bx + C \qquad (10)$$

where $k(x)$ is curvature of the bridge deck at location x.

3.1. Thermal Effects

Ideally, vertical displacement and curvature are only functions of loading. However, in most bridges temperature change also results in change in vertical displacement and curvature of the bridge spans, piers, and other components. Often such changes are due to non-functioning (or partially functioning) mechanisms such as bearings and expansion joints. As an example, Figure 8 shows inclination and temperature readings during September 2015 from one of the wireless inclinometers of this project deployed under the deck of a bridge to monitor curvature. In the figure, the blue graph is temperature and the red graph is tilt. The graph shows strong linear dependence of inclination on temperature. Such dependence on temperature has been observed in most of the deployed wireless inclinometers.

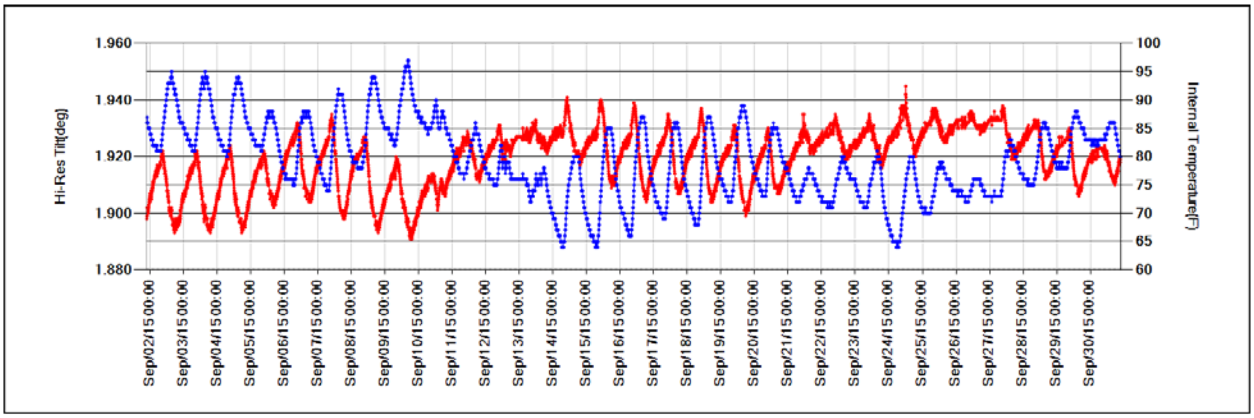


Figure 8: Illustrating effect of temperature change on inclination of spans.

As a further evidence of linear dependence of the inclination on temperature, the graph in Figure 9 shows a regression analysis of the inclination measurements of the wireless sensor versus temperature. As the graph shows, inclination of the deck is linearly dependent on temperature, and in this case, the regression analysis shows that the inclination and temperature are related by the following linear equation:

$$\theta = 2.016 - 0.0012t$$

where θ is inclination and *t* is temperature. The above equation implies that per degree of temperature change, the inclination changes by approximately -0.0012 degrees (or about -4.3 arc seconds). The temperature effect becomes more important considering large range of temperature variations. For example, in Maryland, where the evaluation was done, temperature could be as cold as 0°F during the winter while the summer temperature could exceed 100°F. This implies that at full temperature swing, the change in inclination could be close to 0.12 degree, which could cause significant vertical displacement, especially in long spans. The strong linear dependence of inclination on temperature indicates that monitoring curvature and vertical displacement for the purpose of determining change during deck replacement cannot be done without consideration of temperature effects. It also shows that traditional methods such as surveying could be insufficient because using such methods cannot easily separate thermal effects from the effects of loading. Additionally, another shortcoming of surveying is that the comparison of the results in two surveys of a structure cannot be done unless the two surveys of the structure were done at the exact same temperatures.

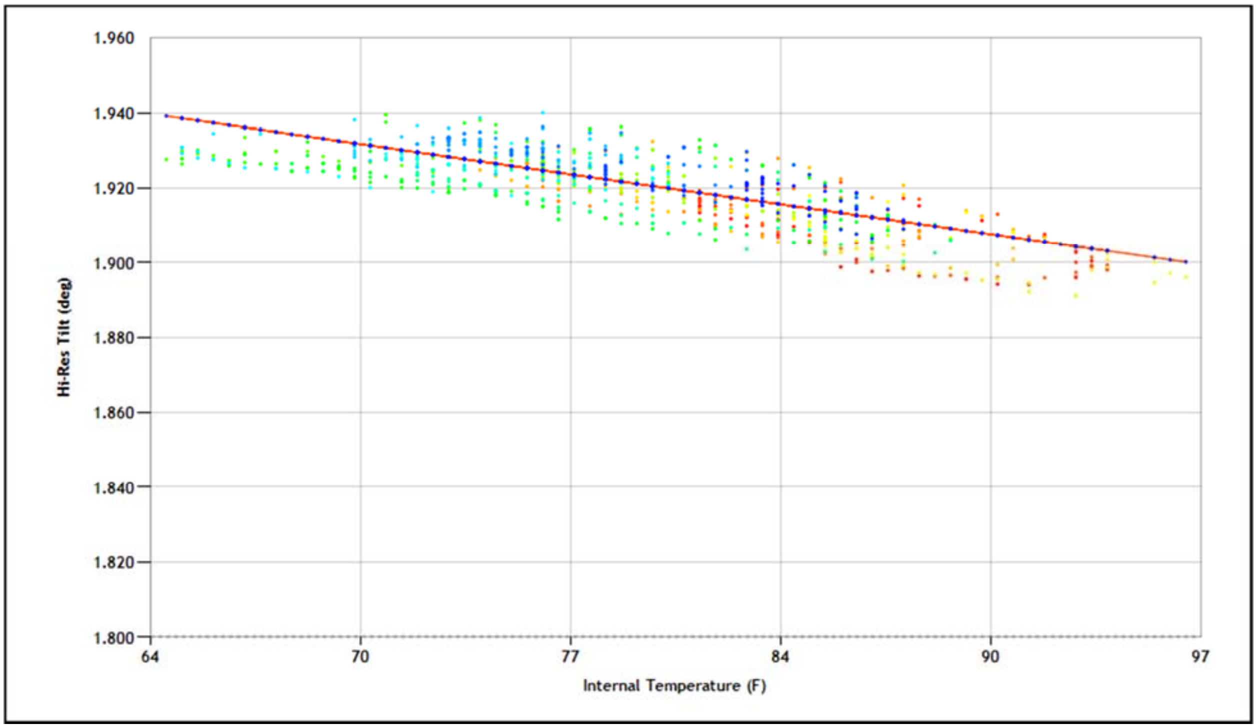


Figure 9: Sample regression analysis of tilt and temperature data.

In this project, the designed wireless inclinometers also report temperature. Using temperature readings, regression models which separated the effect of temperature on the vertical displacement of the deck from the effects of loadings were used. An advantage of the temperature compensated model is that it provides an unbiased method for comparison of the bridge deck curvature before and after deck replacement. Using this method, the curvature of the bridge deck can be compared at the same temperature. Such comparisons will provide an accurate determination of whether a change of curvature has indeed been the result of deck replacement.

4. FIELD DEPLOYMENT AND EVALUATION

The wireless inclinometer sensors were deployed on Jan 16th 2015 on a portion of the bridge on MD 13 over Pocomoke River in Worcester County, Maryland**.** Wireless inclinometer sensors were attached to the girders in Span 2 and Span 3. Figure 10 shows the layout of monitored spans and the locations of the wireless inclinometers, and Figure 11 shows the portions of the bridge plans for the spans where the placement was done. A Google Earth Satellite image of the bridge is shown in Figure 12. For condition awareness and feedback on loading, wireless strain sensors were also attached to one girder in each of the two monitored spans. Monitoring strain is very useful to add additional information about the loading on the girder. Additionally, it has the advantage of giving precise timing of deck removal process of the old deck as well as when the new deck is constructed. All of the 10 installed sensors have the capability of reporting temperature in addition to primary measurements (inclination and strain).Representative pictures of the deployed wireless inclinometer sensors and wireless strain sensors are shown in Figures 13 and 14 respectively.

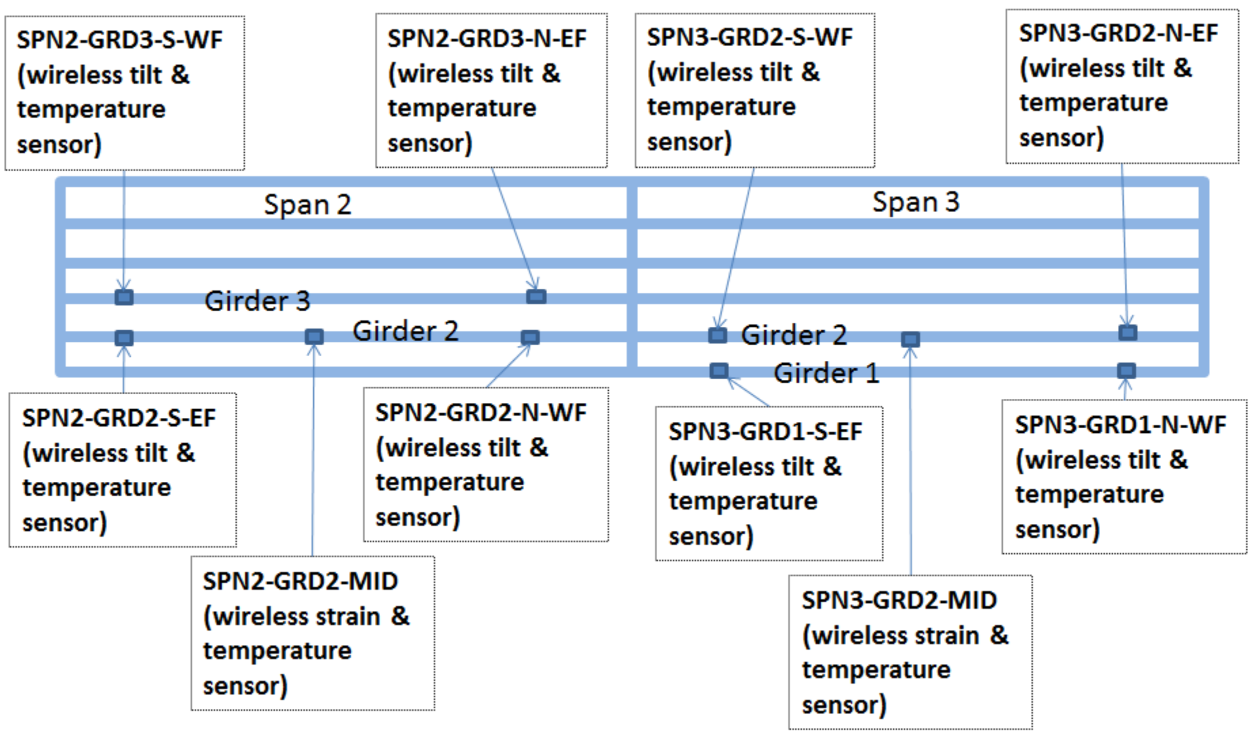


Figure 10: layout of the installed wireless inclination and wireless strain sensors in Span 2 and Span 3 of the bridge.

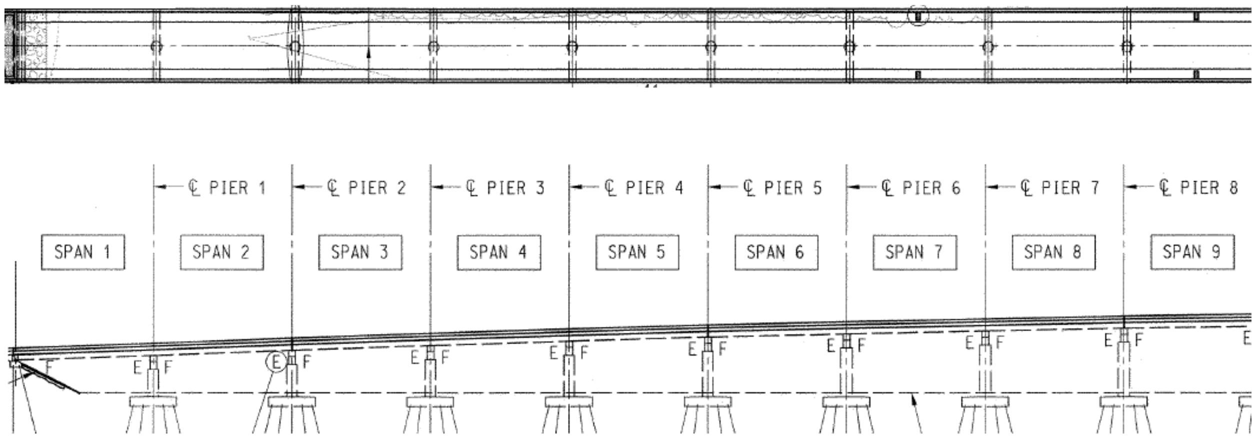


Figure 11: A portion of the bridge plans showing Span 2 and Span 3 where wireless inclinometer and wireless strain sensors were deployed.

Figure 12: A satellite view of the bridge where deployment was done (picture source: Google Earth).

Figure 13: Sample pictures of wireless inclinometer sensors deployed in Span 2 and Span 3 of the bridge.

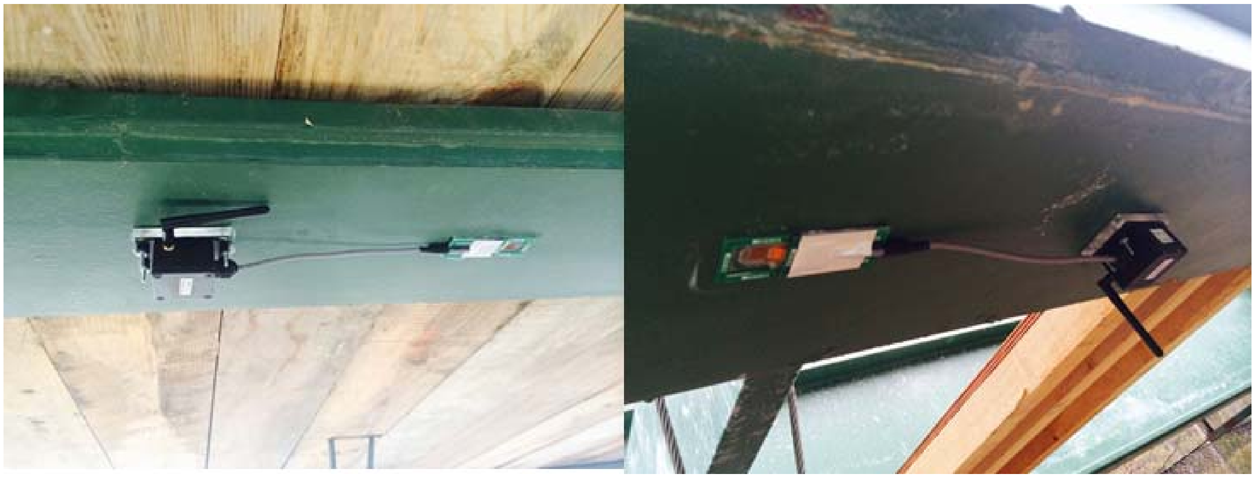


Figure 14: Wireless strain sensors deployed in Span 2 and Span 3 of the bridge.

To stream data from the sensors in real time, a cellular gateway was installed at the bridge location. The gateway, which is solar powered, had wireless receivers to collect data from all the wireless inclinometers and the wireless strain sensors. The gateway had cellular communication capability, and it transmitted data to a server at the University of Maryland. The picture of the cellular gateway is shown in Figure 15.

The deck replacement work was performed on the bridge from January until August 2015. The deck of the bridge was gradually removed during February-March 2015. The construction of the new deck was done late in July 2015.

Figure 15: Solar powered wireless cellular gateway.

5. RAW DATA FROM WIRELESS INCLINOMETER AND STRAIN SENSORS

The graphs, on the following pages, show the inclination data that was collected throughout the deck replacement process. The graphs of raw inclination, temperature and strain data are categorized into four groups. The first group of graphs shows the inclination, strain, and temperature data throughout the monitoring process, from January until August 2015. The second set of graphs shows the data collected during the last week of January 2015, before the deck replacement was started. Similarly, the third set of graphs shows the data collected during the last week of July 2015, when a new deck was being added to the bridge. Finally, the fourth set of graphs provides inclination, strain, and temperature data collected during the last week of August 2015, almost a month after the new deck was built.

As previously indicated the first group of graphs, Figures 16 – 19 show the inclination, strain and temperature of the girders in Span 2, from January 2015 until August 2015, throughout deck replacement process. As shown in the figures, changes in inclination can be observed in early March, when the old deck was removed, and late in July, when the new deck was added. The graph in Figure 18, which shows the strain measurements in the middle of Span 2, confirms that the old deck was indeed removed in early March and the new deck was added to the bridge in late July. This is because the strain graph shows the noticeable and sudden decrease of about 140 microstrain in early March, while the same amount of sudden increase is shown late in July. Finally, the graph in Figure 19 shows the temperature throughout the process. Figures 20- 23 provide the similar inclination, strain and temperature data from the girders in Span 3.

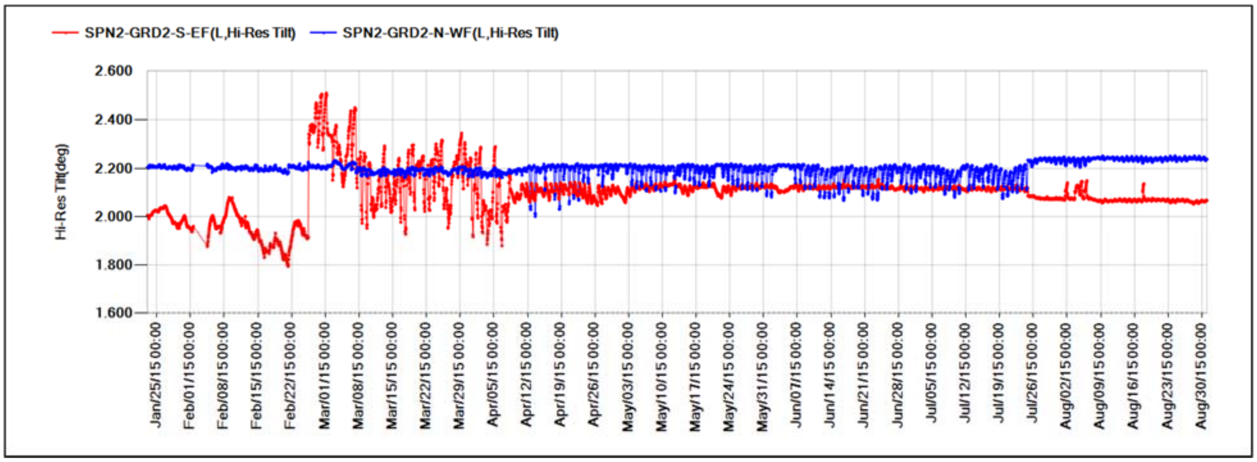


Figure 16: The 8-month inclination data, from January 2015-August 2015 for Span 2, Girder 2; the two graphs show inclination data for the wireless inclinometers attached to the north and the south sides of the girder.

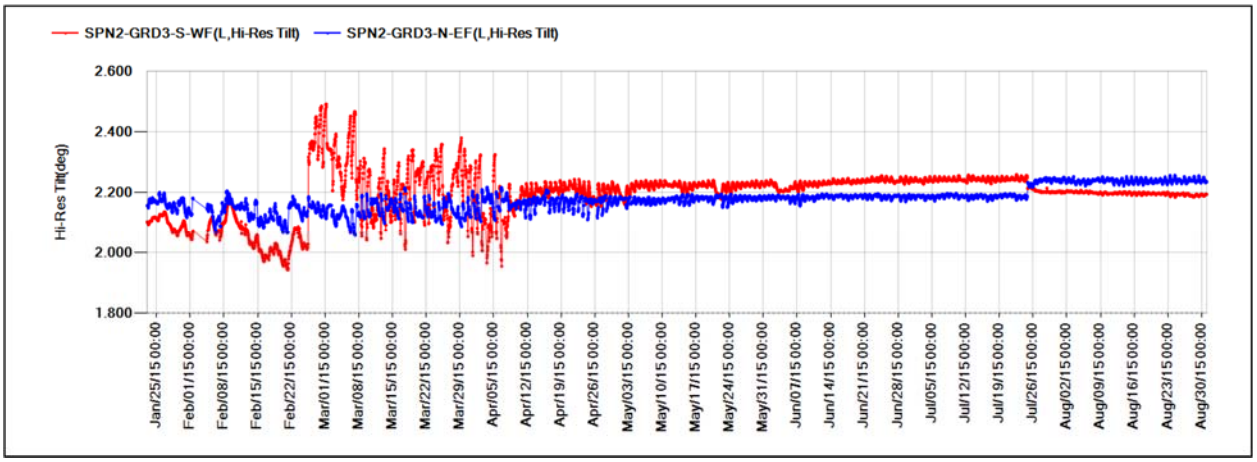


Figure 17: The 8-month inclination data, from January 2015-August 2015 for Span 2, Girder 3; the two graphs show inclination data for the wireless inclinometers attached to the north and the south sides of the girder.

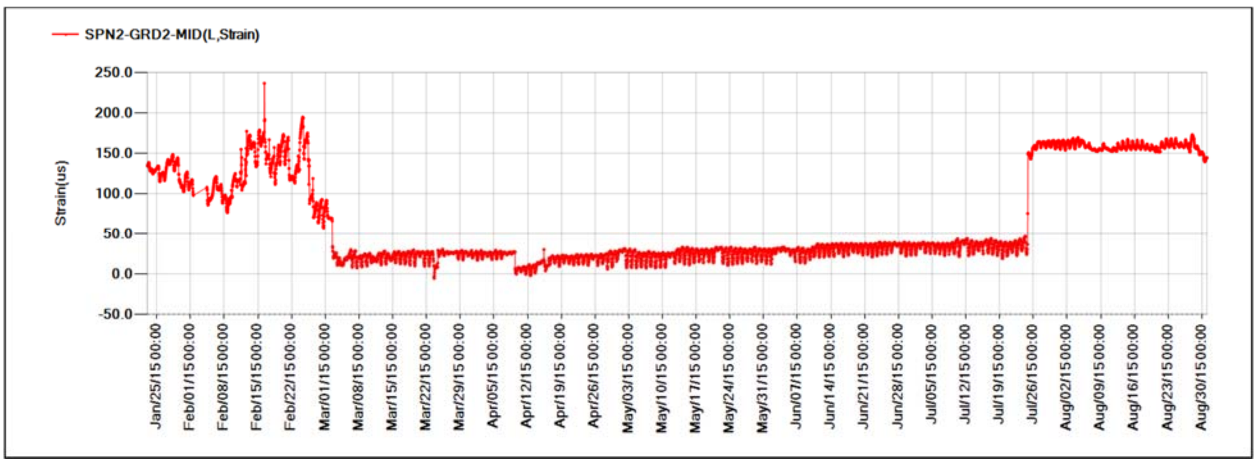


Figure 18: The 8-month strain data, from January 2015-August 2015 for Span 2, Girder 2.

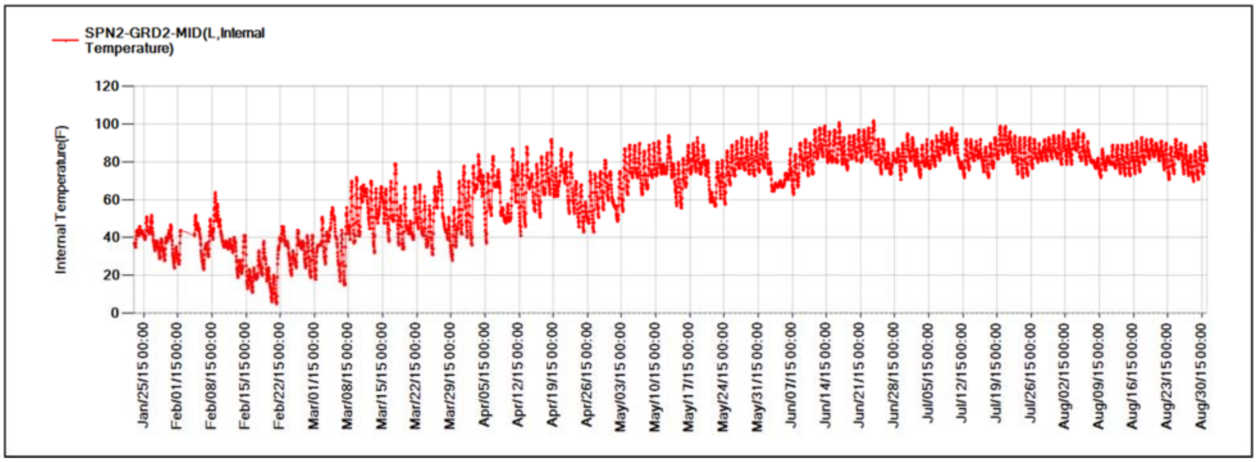


Figure 19: The 8-month temperature data, from January 2015-August 2015 for Span 2, Girder 2

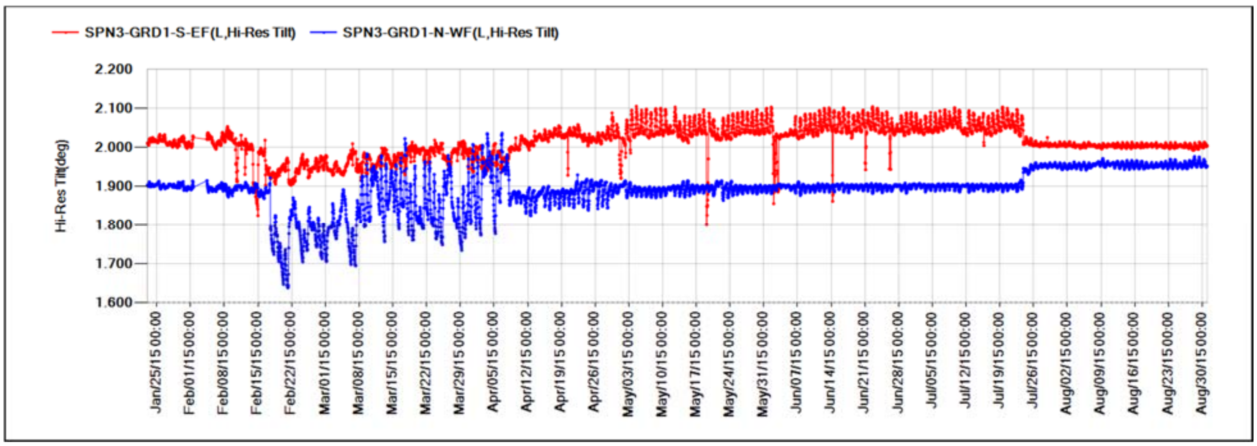


Figure 20: The 8-month inclination data, from January 2015-August 2015 for Span 3, Girder 1; the two graphs show inclination data for the wireless inclinometers attached to the north and the south sides of the girder.

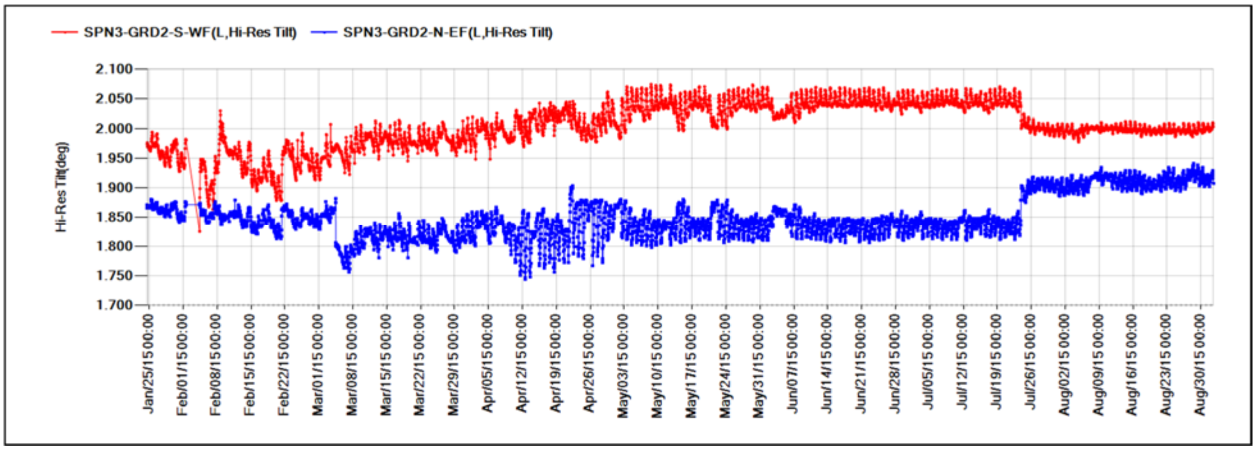


Figure 21: The 8-month inclination data, from January 2015-August 2015 for Span 3, Girder 2; the two graphs show inclination data for the wireless inclinometers attached to the north and the south sides of the girder.

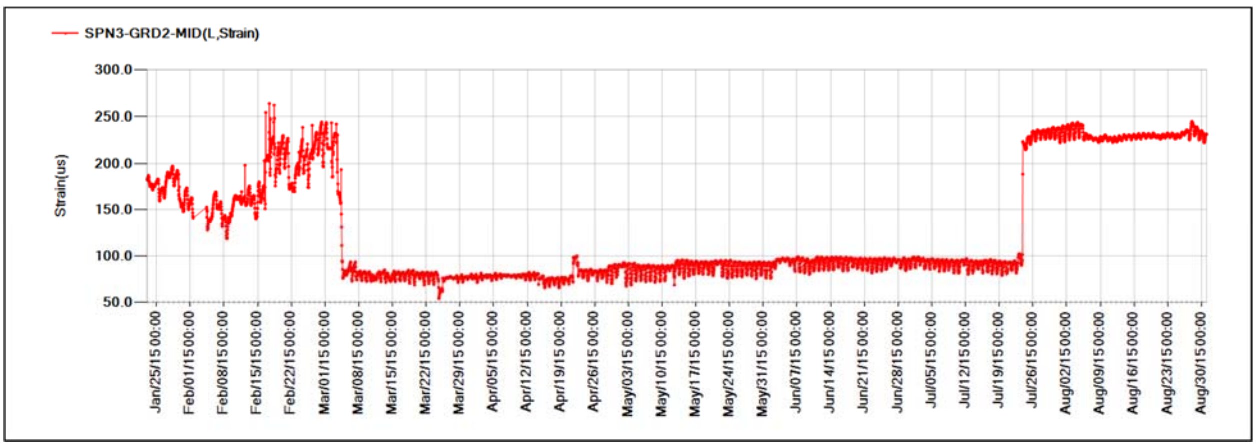


Figure 22: The 8-month strain data, from January 2015-August 2015 for Span 3, Girder 2

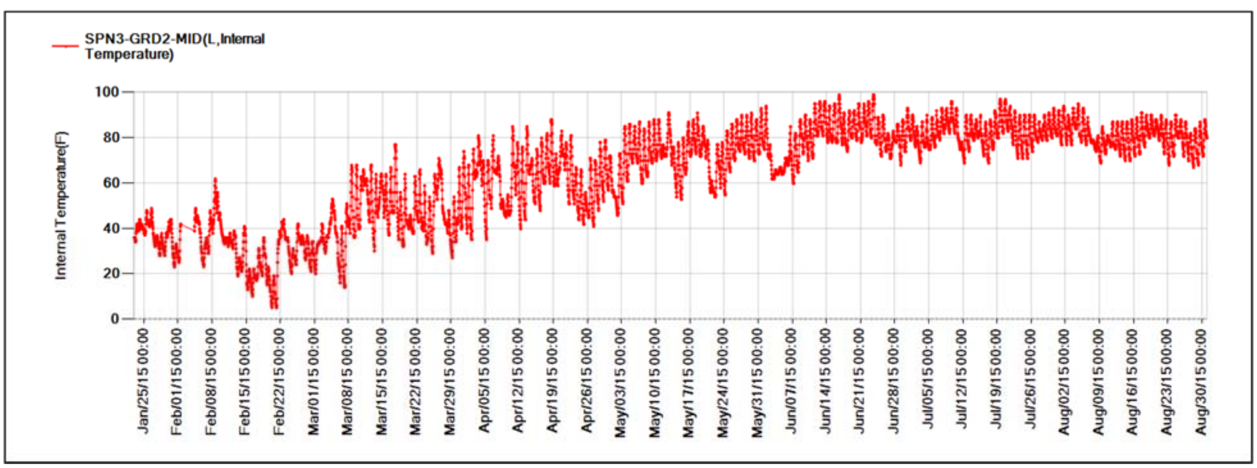


Figure 23: The 8-month temperature data, from January 2015-August 2015 for Span 3.

The second group of graphs shows a closer view of the inclination, strain, and temperature data before deck removal.

The graphs in Figure 24 show Span 2 inclination, temperature, and strain data during the last week of January, a few weeks before the old deck was removed. Each of the top four graphs simultaneously show inclination and temperature of the wireless inclinometer, while the graph at the bottom shows strain. The graphs in Figure 25 show the similar data for Span 3.

Graphs in Figure 26 show Span 2 inclination, temperature, and strain data during the last week of July, when the new deck in Span 2 was built. Each of the top four graphs simultaneously show inclination and temperature of the wireless inclinometer, while the graph at the bottom shows strain. The graphs show a visible change of inclination at around 8:00pm on July 24th, the speculated date and time when the new deck was added to the bridge. This speculation is further confirmed by the bottom graph of Figure 26, where the sudden change of strain data confirms that the new deck was built at around 8:00pm on July 24th. The graphs in Figure 27 show the similar data for Span 3. In case of Span 3, both tilt and strain data indicate that the new deck was added to the bridge at around 8:00pm on July 23rd.

Finally, the graphs in Figure 28 show Span 2 inclination, temperature, and strain data during the last week of August 2015, a few weeks after the new deck built. Each of the top four graphs simultaneously show inclination and temperature of the wireless inclinometer, while the graph at the bottom shows strain. The graphs in Figure 29 show the similar data for Span 3.

In the next chapter, the analysis for the purpose of calculating changes in bridge vertical displacement will be performed.

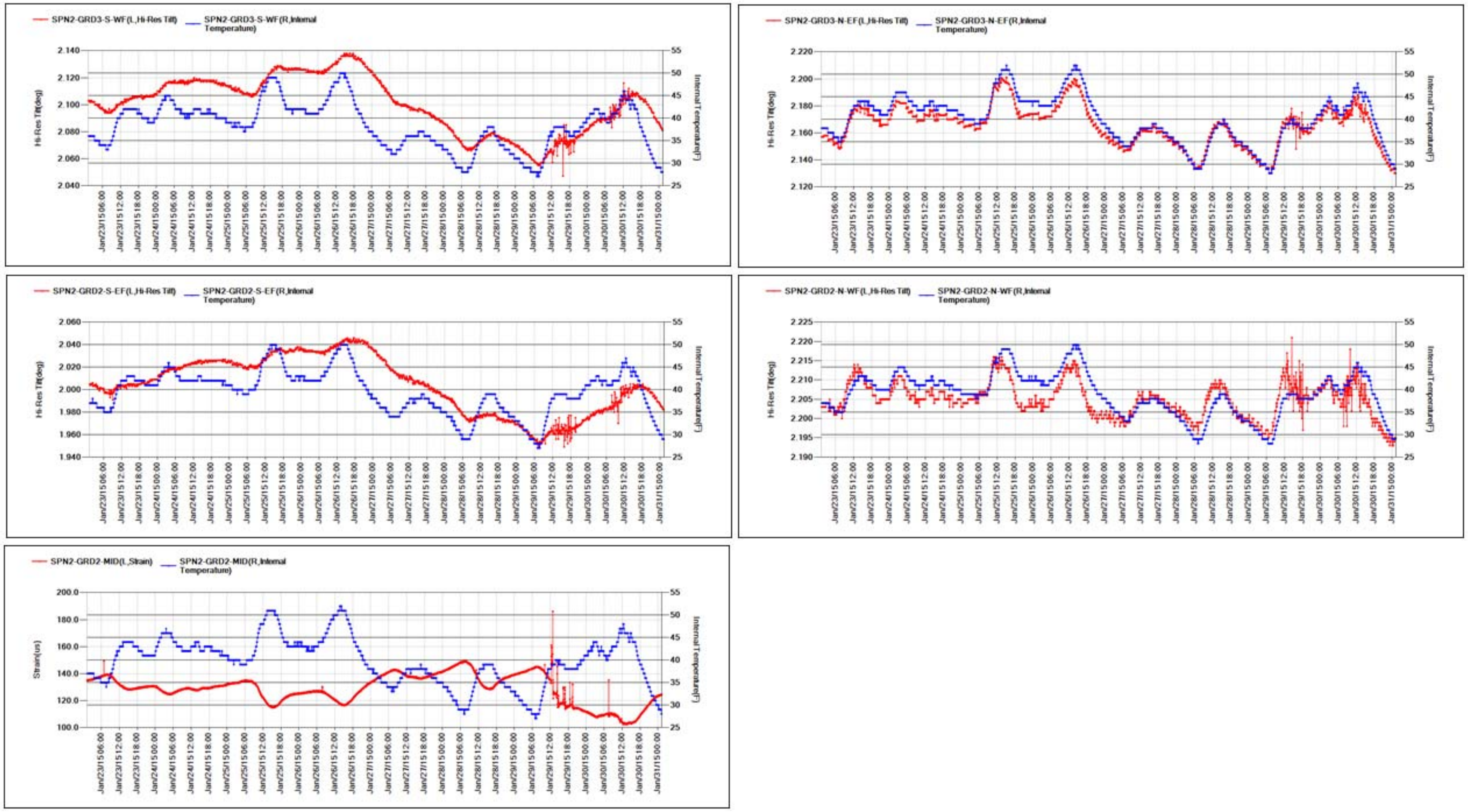


Figure 24: Inclination, temperature, and strain data from Span 2 wireless sensors; data from last week of January, 2015.

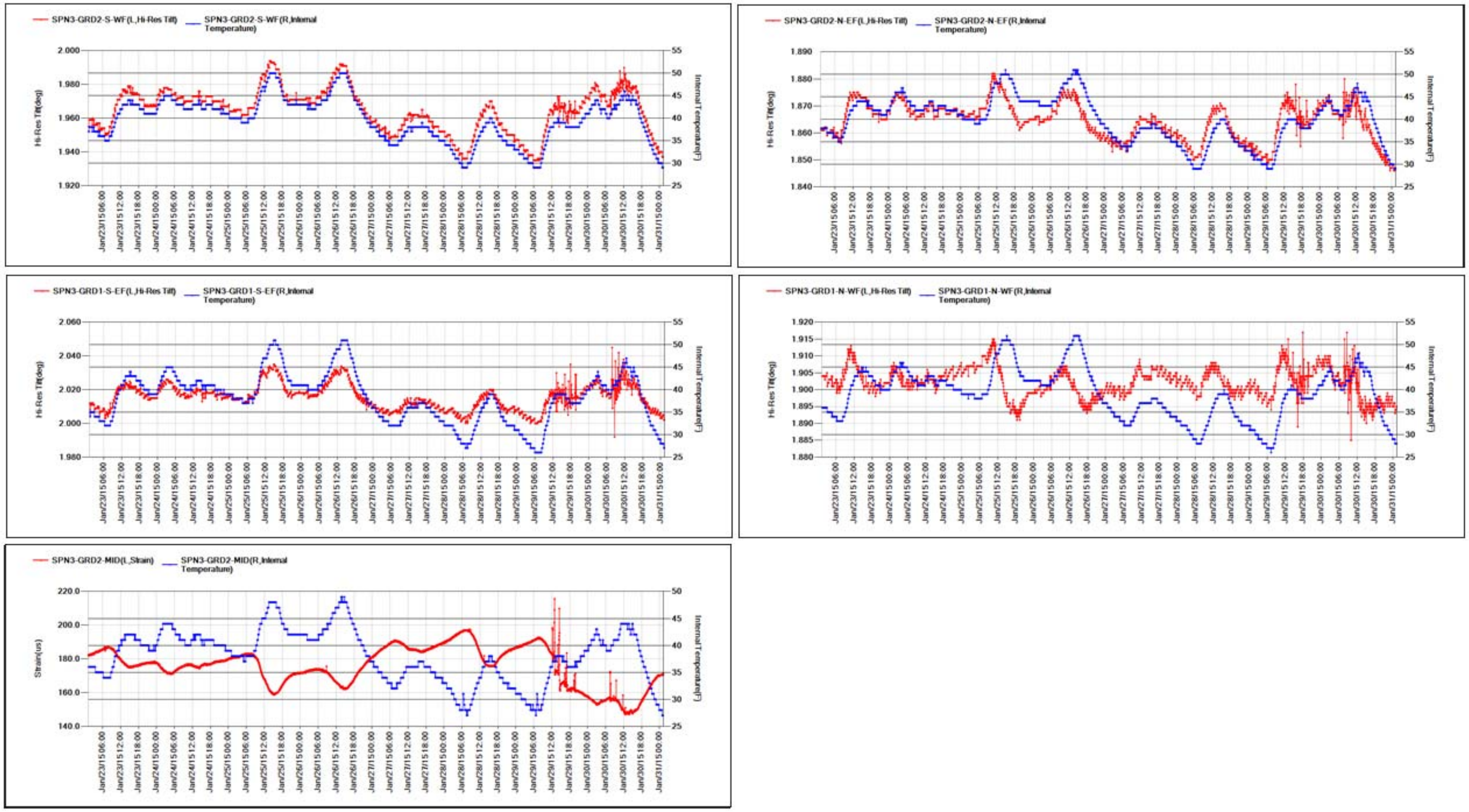


Figure 25: Inclination, temperature, and strain data from Span 3 wireless sensors; data from last week of January, 2015, before the start of deck replacement.

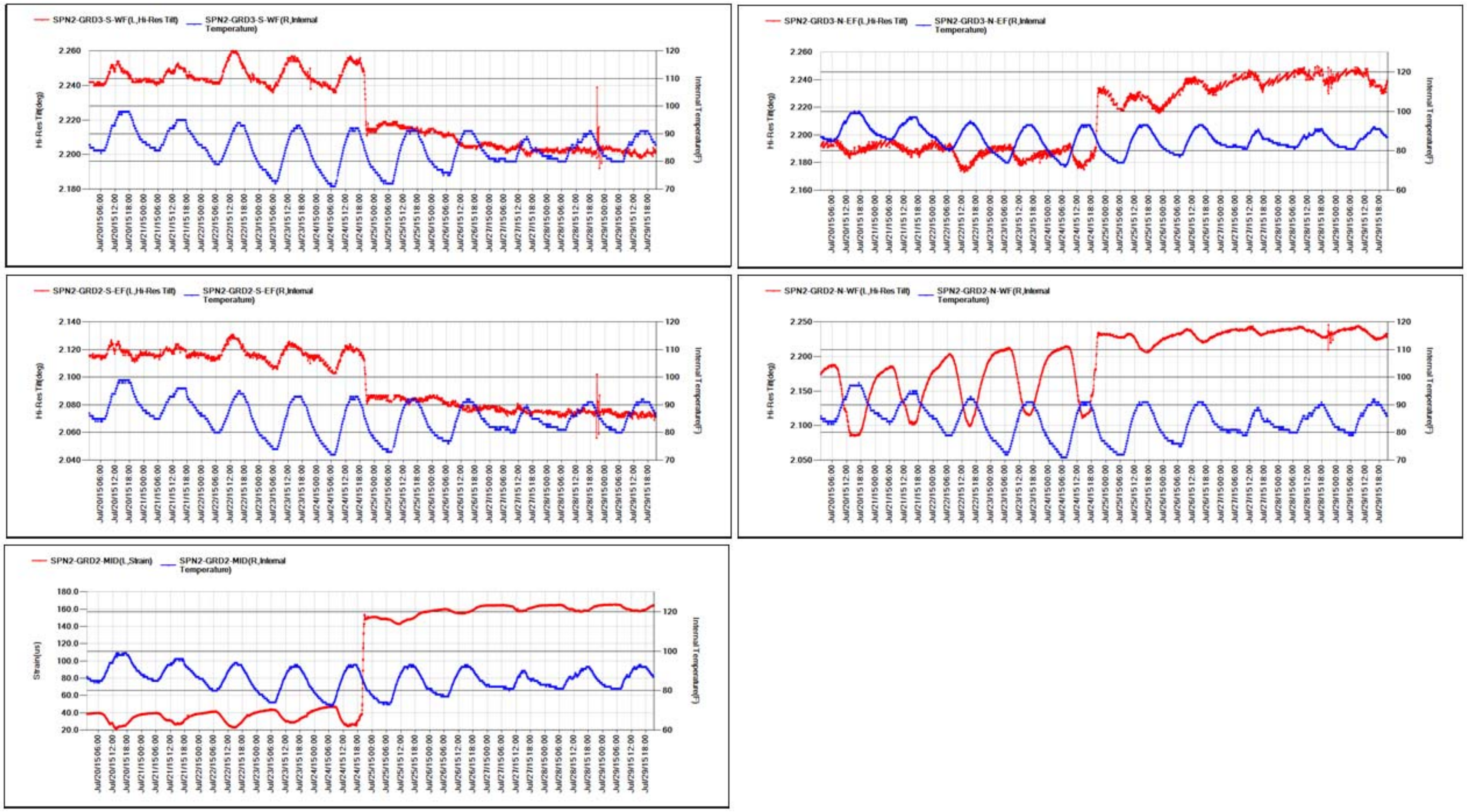


Figure 26: Inclination, temperature, and strain data from Span 2 wireless sensors; data from last week of July, 2015, when the new deck was added.

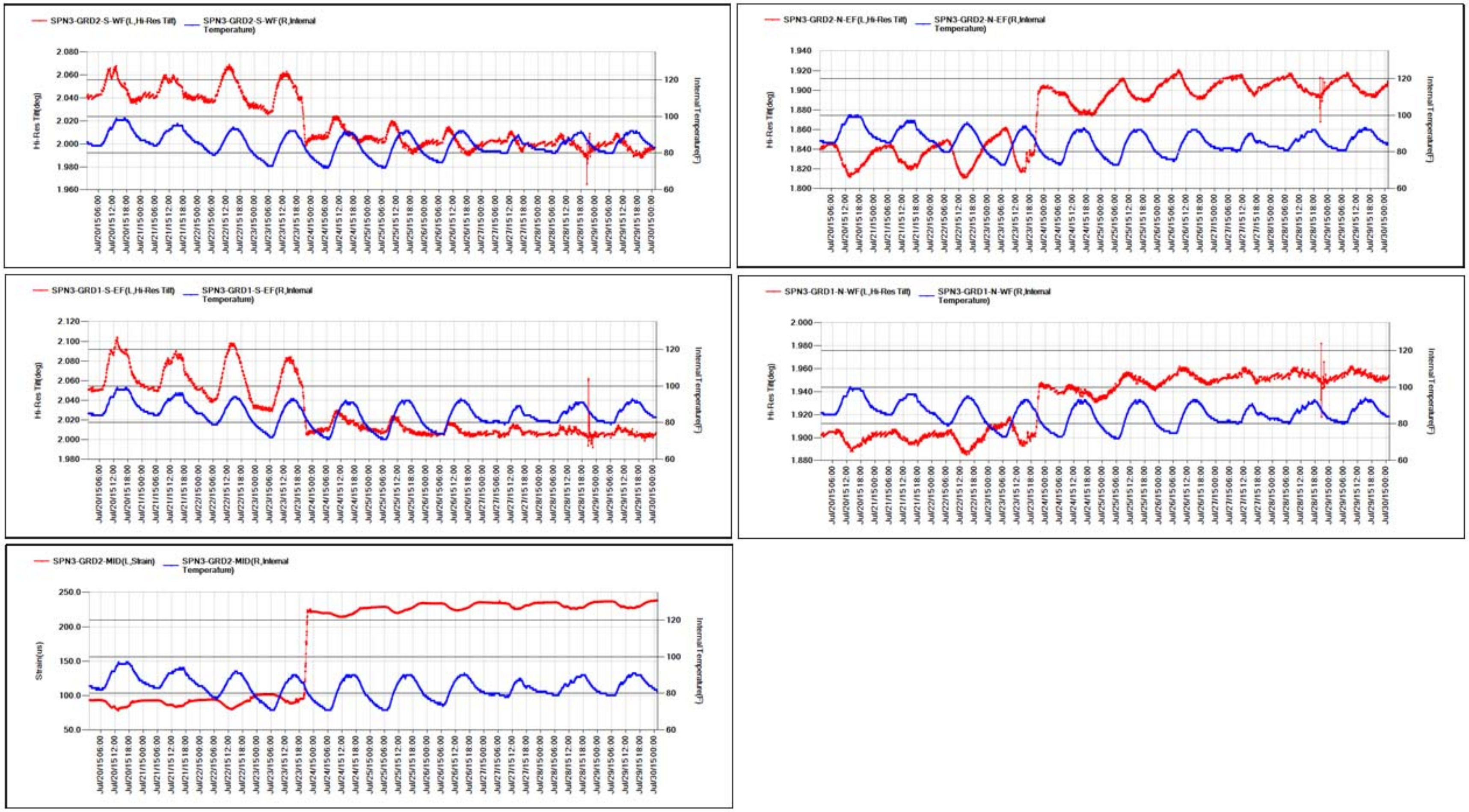


Figure 27: Inclination, temperature, and strain data from Span 3 wireless sensors; data from last week of July, 2015, when the new deck was added.

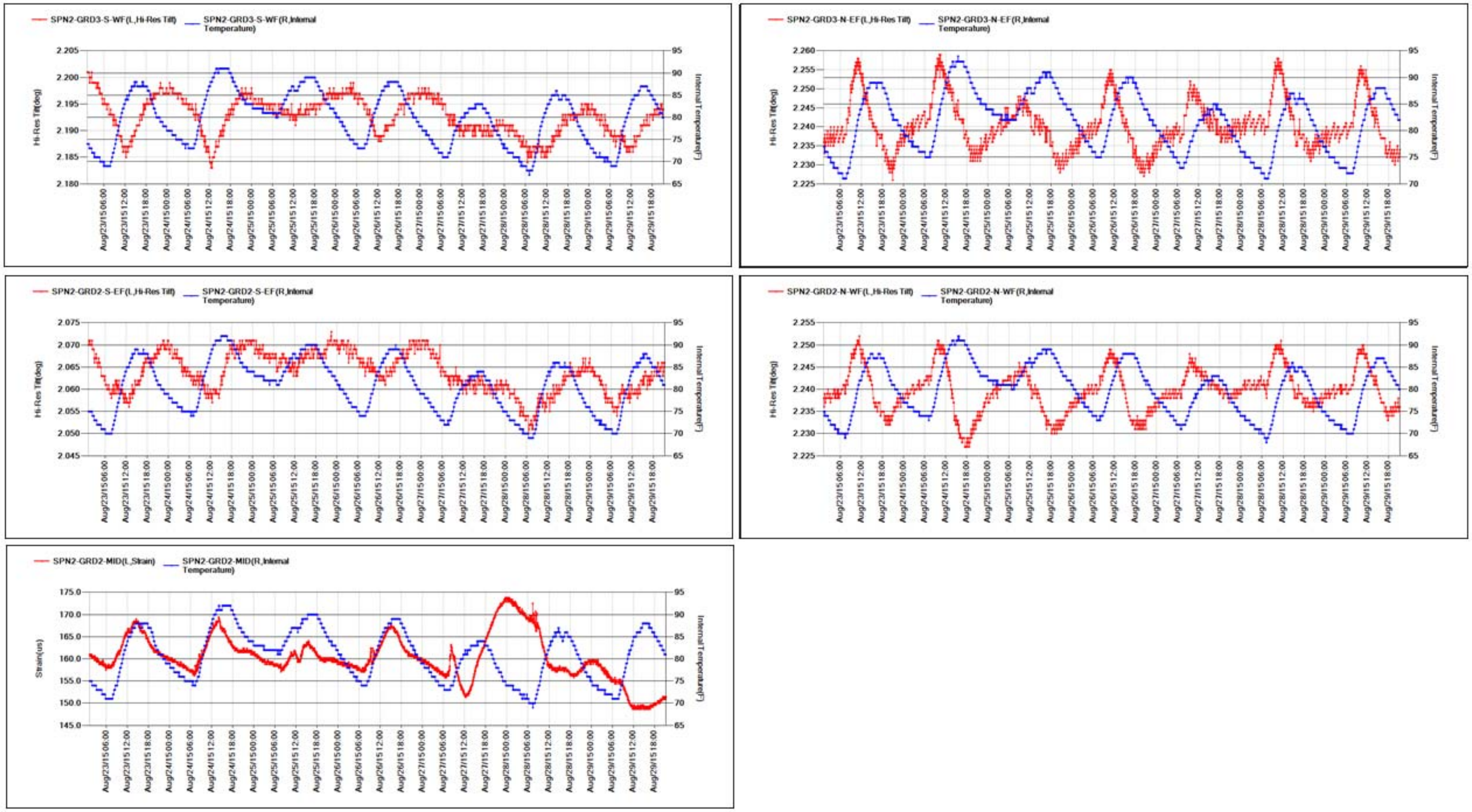


Figure 27: Inclination, temperature, and strain data from Span 2 wireless sensors; data from last week of August, 2015, a month after the new deck was built.

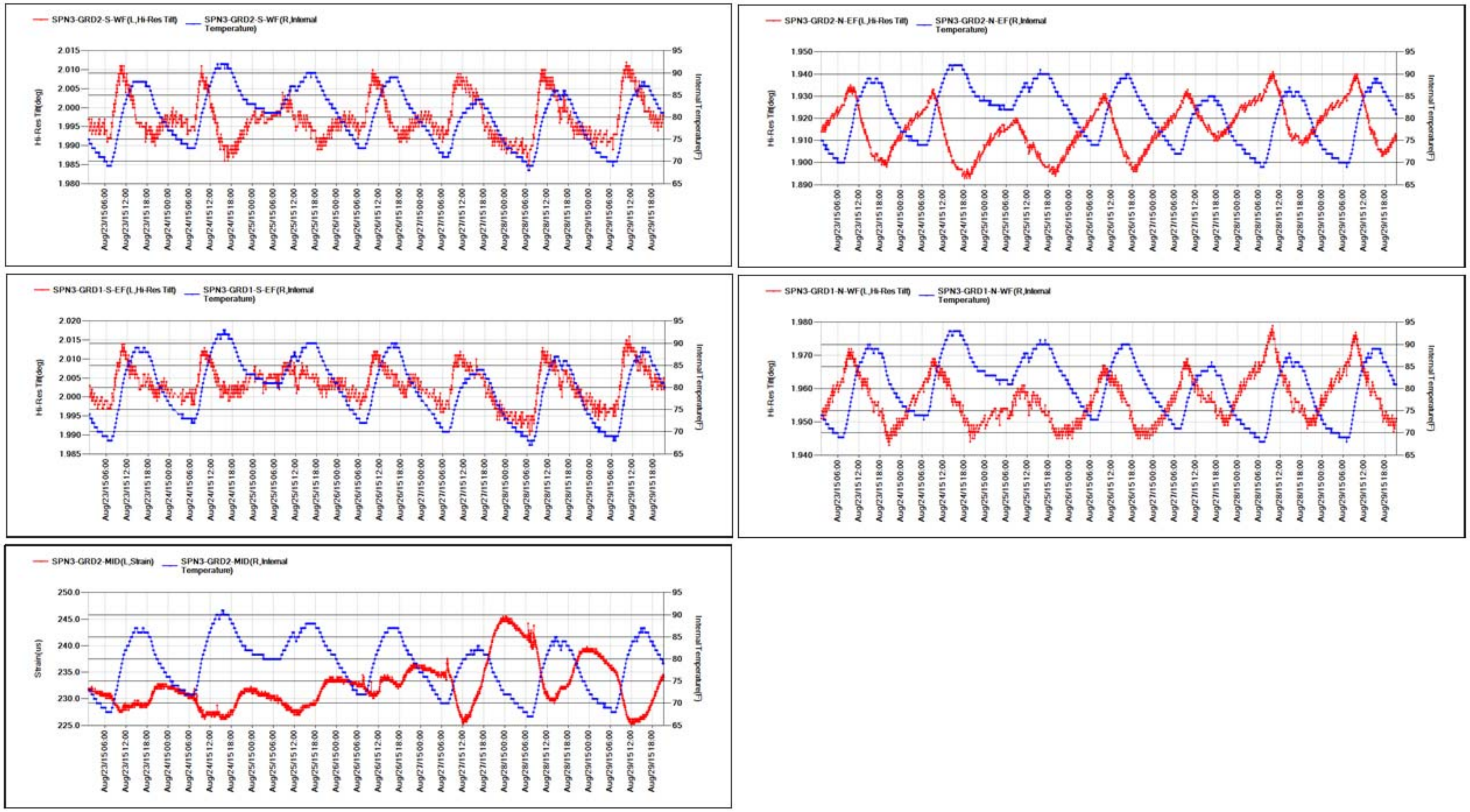


Figure 29: Inclination, temperature, and strain data from Span 3 wireless sensors; data from last week of August, 2015, a month after the new deck was built.

6. DATA ANALYSIS AND VERTICAL DISPLACEMENT MONITORING RESULT

As previously mentioned in this report, inclination data is dependent on temperature and careful analysis of inclination data required proper consideration of temperature effects. For this purpose, a linear regression of the inclination data versus temperature in order to find the dependency of inclination measurement on temperature at each point of monitoring was conducted. Such linear regression gives the linear coefficient of inclination dependence on temperature. In the next stage of the analysis, inclination data of the same temperature is used to find vertical displacement. The vertical displacement change has been calculated for two cases:

A. **Girder rebound calculation:** calculating vertical displacement change after deck removal, which is the comparison of the change of the vertical displacement from January 2015 (before deck removal) until July 2015 (after deck removal)
B. **Displacement change after deck replacement:** calculating the vertical displacement change after the new deck is constructed. For this purpose change in vertical displacement is conducted from January 2015 (before deck removal) until August 2015 (after construction of the new deck).

The remainder of this chapter provides details of the data analysis for the above two cases.

6.1. Girder Rebound Calculation

To find the vertical displacement after the removal of the deck, the first task is to characterize the temperature effect. For the readings of each wireless inclinometer sensor, a linear regression versus temperature was conducted to find the dependence of inclination on temperature. The summary of the regression analysis for each wireless inclination sensor is shown in Table 1. The table provides the linear function describing linear dependence of tilt and temperature. The calculation is performed for two different weeks. The first week is in January 2015, before the start of deck replacement. The second interval is the third week of July 2015 (from July 15th until July 22nd), when the old deck was removed and the bridge was prepared for the installation of the new deck. Based on linear regression result, inclination of the girders at three temperatures of t=0°F, t=50°F, and t=100°F were calculated. The last three columns of Table 1 show the change of the girder inclination during deck replacement.

Once the change in inclination is calculated, the data is fed into the mathematical models identified in Chapter 3 of this report. The model uses a fourth degree polynomial to find vertical displacement (rebound) after deck removal. The results of the calculation are shown in Figures 30-33. As shown in the figures, when compared at t=0°F, all the girders show an upward rebound. The amount at t=0°F is 153mil and 421mil for Girder 2 and Girder 3 of Span 2, respectively. Likewise, at t=0°F, vertical displacement is 269mil and 424mil for Girder 1 and Girder 2 or Span 3, respectively. Furthermore, the data shows that at t=0°F, the rebound is about 100mil for all of the monitored girders, except for Girder 3 in Span 2, whose rebound at t=50°F is -100mil. Finally, the data shows that at higher temperature of t=100°F, the rebound of all girders is negative (downward). The most likely explanation for the negative rebound at high temperature is non-functional or partially functional bearings. When bearings do not respond to temperature change, thermal expansion results in small deformation of the girders as well as small bending of the piers. However, when the bridge deck is removed, absence of the concrete deck will lead to greater deformation in the girders. This speculation is also evident in Figures 26 and 27, where the tilt variations before and after construction of the new deck are compared. As can be seen in both figures, temperature induced tilt variations are noticeably larger before construction of the new deck.

As a final note, the rebound calculations of this section can be used to set up the deck pouring machine to achieve desired curvature after construction of a new deck. One issue of this approach is that the readings are temperature dependent, and it is not clear as to which of the readings should be used to set up construction of the new deck. One simple approach to overcome this issue is to use the readings at worse case temperature, so the displacement is still positive. This implies that the bridge deck has moved upward by a small amount in those spans. Upward change is benign because it does not lead to ponding. In the case of this project, the readings at t=100°F are a worst case scenario, and setting up the deck pouring machine according to such readings will ensure positive displacement at all temperatures.

6.2. Vertical Displacement Change After Deck Replacement

Similar to the rebound calculation, displacements were calculated after the new deck was installed. For this case the calculations used the tilt readings in January 2015, before the start of deck replacement, with the tilt readings in the last week of August 2015 (from July 23th until July 30th), four weeks after the new deck was constructed. Similar to the previous case, first linear dependence coefficient of tilt versus temperature was calculated. The results are shown in Table 2. Then the results were fed into mathematical displacement calculation models of Section 3. The displacement calculations are shown in Figures 34-37. As shown in the figures, when compared at t=0°F and t =50°F, the vertical displacement at both monitored girders of Span 2 is positive. However, a small downward change of displacement is observed at t=100°F; the downward change is -46mil for Girder 2 and about -364mil for Girder 3 of Span 2.

For Span 3, the vertical displacement values at all temperatures have been positive, implying that the bridge deck has only made upward changes after deck replacement.

Finally, it should be noted that due to the strong effect of non-responsive bearings on vertical displacement and curvature of the girders, it is beneficial to evaluate the bearings of bridges on which deck replacement is being performed. If bearings are not functioning, replacement of the bearings during deck replacement will lead to a significant improvement in the endurance of the structure.

Table 1: The analysis results of the change in the inclination of girders resulting from temperature change: January 2015 readings versus July 2015 readings. The values in the table are used to calculate rebound.

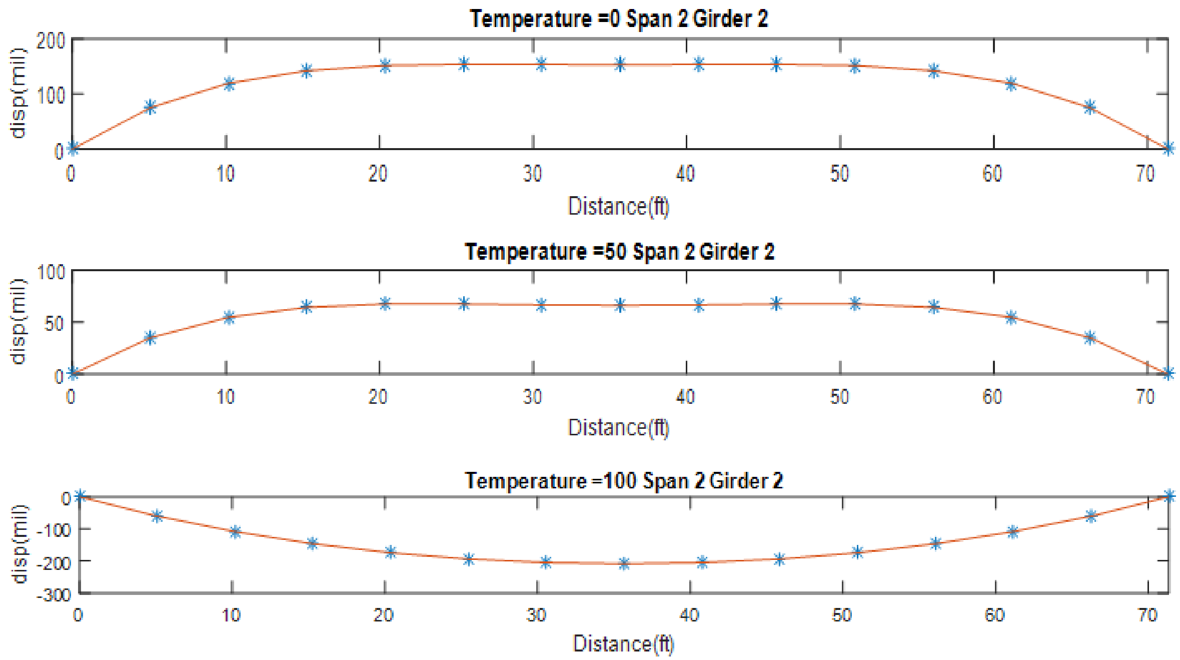
	Before deck removal (Jan 20 2015 – Jan 27 2015)				**Before placement of the new deck (July 15 2015 – July 22 2015)**				**Change in inclination (Δθ)**		
Wireless Inclination Sensor ID	Tilt as function of temperature	Inclination at temp. 0°F	50°F	100°F	Tilt as function of temperature	Inclination at temp. 0°F	50°F	100°F	0°F	50°F	100°F
SPN2-GRD2-N-WF	θ= 2.1712+0.0009*t	2.171	2.216	2.261	θ= 2.265-0.00054*t	2.254	2.227	2.200	0.083	0.011	-0.061
SPN2-GRD2-S-EF	θ= 1.9378+0.002*t	1.938	2.038	2.138	θ= 2.0692+0.0005*t	2.069	2.094	2.119	0.131	0.056	-0.019
SPN2-GRD3-N-EF	θ = 2.0417+0.003*t	2.042	2.192	2.342	θ= 2.1983-0.0001*t	2.198	2.193	2.188	0.156	0.001	-0.154
SPN2-GRD3-S-WF	θ = 2.049+0.0017*t	2.049	2.134	2.219	θ= 2.1877+0.0007*t	2.188	2.223	2.258	0.139	0.089	0.039
SPN3-GRD1-N-WF	θ = 1.9068-0.0001*t	1.907	1.902	1.897	θ= 1.9415-0.0005*t	1.941	1.916	1.891	0.034	0.014	-0.006
SPN3-GRD1-S-EF	θ = 1.9601+0.0014*t	1.960	2.030	2.100	θ= 1.8493+0.0025*t	1.849	1.974	2.099	-0.111	-0.056	-0.001
SPN3-GRD2-N-EF	θ = 1.8212+0.0006*t	1.821	1.851	1.881	θ= 1.9675-0.0015*t	1.968	1.893	1.818	0.147	0.042	-0.063
SPN3-GRD2-S-WF	θ= 1.8519+0.0014*t	1.852	1.922	1.992	θ= 1.9615+0.001*t	1.961	2.011	2.061	0.109	0.089	0.069

	South														North
Distance (ft)	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
Displacement (mil), T=0°F	0	75	119	142	151	153	153	153	153	153	151	142	119	75	0
Displacement (mil), T=50°F	0	35	55	64	67	67	67	66	67	67	67	64	55	35	0
Displacement (mil), T=100°F	0	-60	-109	-146	-174	-194	-205	-209	-205	-194	-174	-146	-109	-60	0

Displacement (mil) T=0°F

Displacement (mil) T=50°F

Displacement (mil) T=100°F



Rebound Calculation

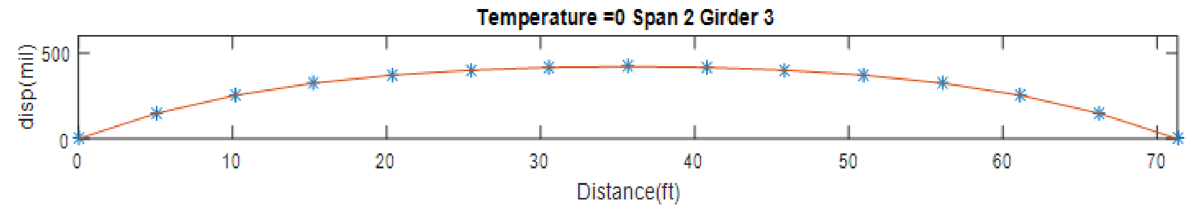
Span 2 Girder 2 vertical displacement change at various temperatures

Before deck removal (January 15) and after deck replacement (July 15)

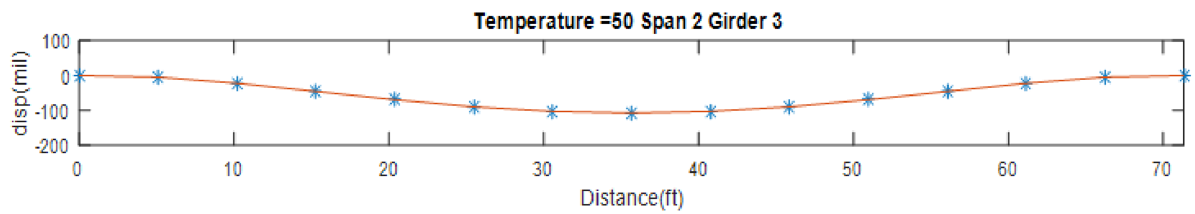
Figure 30: Rebound of Span 2, Girder 2, resulting from deck removal. Analysis conducted at various temperatures, T=0, T=50, and T=100 degrees Fahrenheit

South															North
Distance (ft)	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**
Displacement (mil), T=0°F	0	149	253	325	372	401	416	421	416	401	372	325	253	149	0
Displacement (mil), T=50°F	0	-5	-22	-46	-70	-90	-103	-108	-103	-90	-70	-46	-22	-5	0
Displacement (mil), T=100°F	0	-158	-298	-417	-511	-580	-622	-636	-622	-580	-511	-417	-298	-158	0

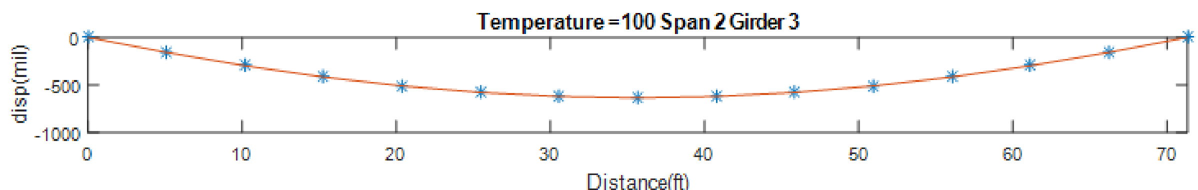
Displacement (mil)
T=0°F



Displacement (mil)
T=50°F



Displacement (mil)
T=100°F



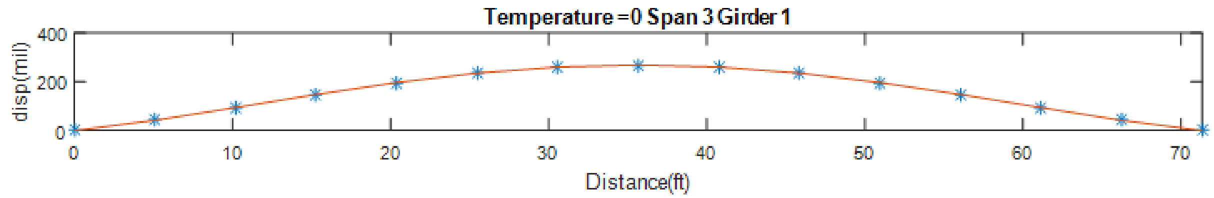
Rebound Calculation

Span 2 Girder 3 vertical displacement change at various temperatures
Before deck removal (January 15) and after deck replacement (July 15)

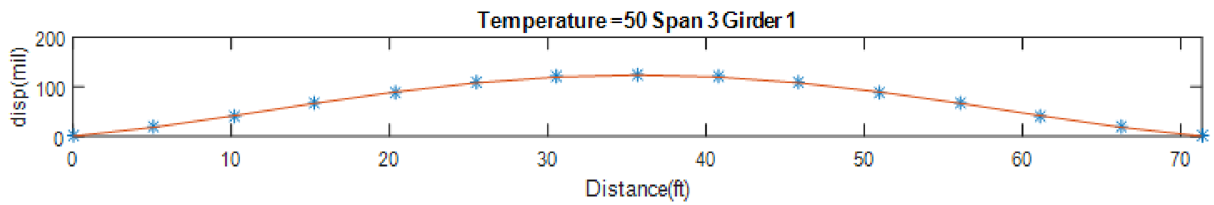
Figure 31: Rebound of Span 2, Girder 3, resulted by deck removal. Analysis conducted at various temperatures, T=0, T=50, and T=100 degrees Fahrenheit.

Distance (ft)	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
	South														**North**
Displacement (mil), T=0°F	0	42	94	148	197	235	260	269	260	235	197	148	94	42	0
Displacement (mil), T=50°F	0	18	41	66	89	108	119	123	119	108	89	66	41	18	0
Displacement (mil), T=100°F	0	-6	-11	-15	-18	-20	-21	-22	-21	-20	-18	-15	-11	-6	0

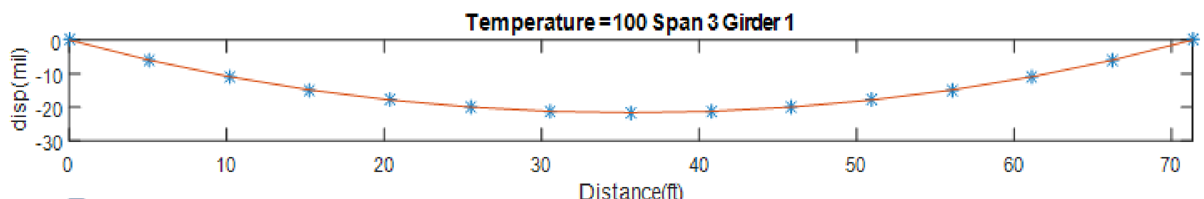
Displacement (mil) T=0°F



Displacement (mil) T=50°F



Displacement (mil) T=100°F



Rebound Calculation

Span 3 Girder 1 vertical displacement change at various temperatures
Before deck removal (January 15) and after deck replacement (July 15)

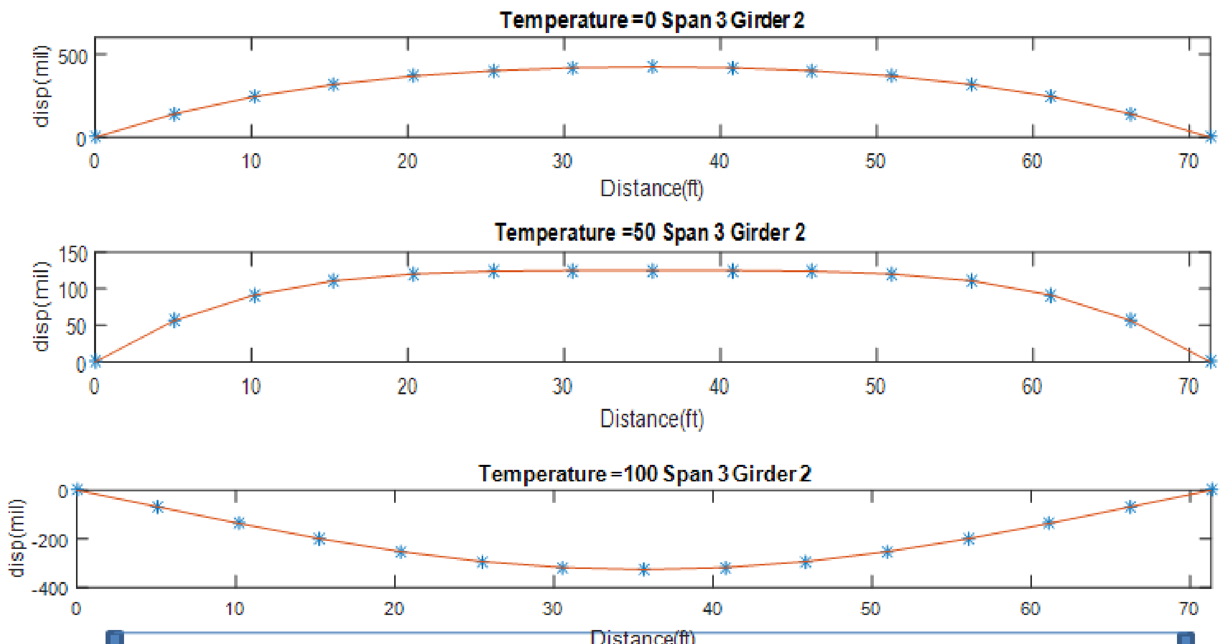
Figure 32: Rebound of Span 3, Girder 1, resulted by deck removal. Analysis conducted at various temperatures, T=0, T=50, and T=100 degrees Fahrenheit.

	South														North
Distance (ft)	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
Displacement (mil), T=0°F	0	141	245	318	368	401	418	424	418	401	368	318	245	141	0
Displacement (mil), T=50°F	0	57	91	111	120	124	125	125	125	124	120	111	91	57	0
Displacement (mil), T=100°F	0	-68	-137	-199	-253	-293	-318	-327	-318	-293	-253	-199	-137	-68	0

Displacement (mil) T=0°F

Displacement (mil) T=50°F

Displacement (mil) T=100°F



Rebound Calculation

Span 3 Girder 2 vertical displacement change at various temperatures
Before deck removal (January 15) and after deck replacement (July 15)

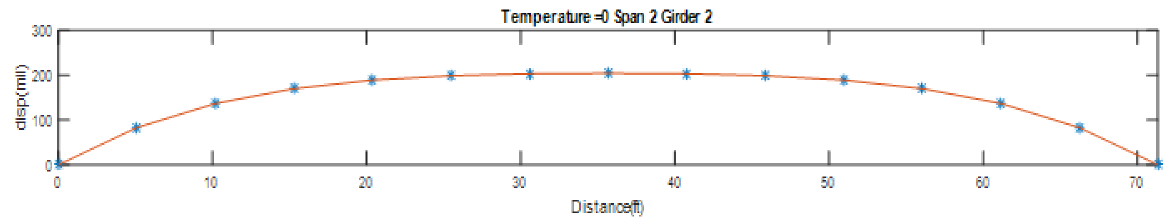
Figure 33: Rebound of Span 3, Girder 2, resulting from deck removal. Analysis conducted at various temperatures, T=0, T=50, and T=100 degrees Fahrenheit.

Table 2: The analysis results of the change in the inclination of girders resulting from temperature change: January 2015 readings versus August 2015 readings. The values in the table are used to calculate total change in the vertical displacement resulting from deck replacement.

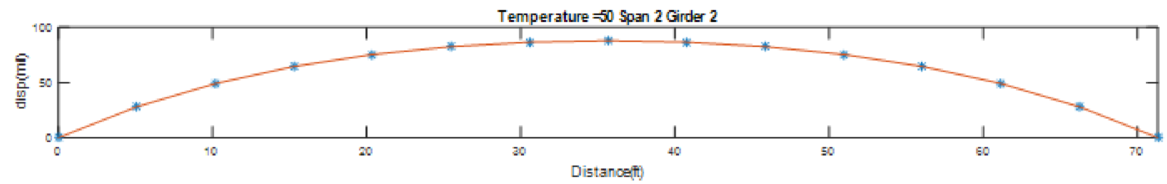
	Before deck replacement (Jan 20 2015 – Jan 27 2015)				After deck replacement (Aug 23 2015 – Aug 30 2015)				Change in inclination (Δθ)		
Wireless Inclination Sensor ID	Tilt as function of temperature	Inclination at temp 0°F	50°F	100°F	Tilt as function of temperature	Inclination at temp 0°F	50°F	100°F	0°F	50°F	100°F
SPN2-GRD2-N-WF	θ= 2.1712+0.0009*t	2.171	2.216	2.261	θ = 2.2603-0.0003*t	2.260	2.245	2.230	0.089	0.029	-0.031
SPN2-GRD2-S-EF	θ= 1.9378+0.002*t	1.938	2.038	2.138	θ = 2.0461+0.0002*t	2.046	2.056	2.066	0.108	0.018	-0.072
SPN2-GRD3-N-EF	θ = 2.0417+0.003*t	2.042	2.192	2.342	θ = 2.2467-0.0001*t	2.246	2.241	2.236	0.204	0.049	-0.106
SPN2-GRD3-S-WF	θ = 2.049+0.0017*t	2.049	2.134	2.219	θ = 2.1976-0.0001*t	2.197	2.192	2.187	0.148	0.058	-0.032
SPN3-GRD1-N-WF	θ = 1.9068-0.0001*t	1.907	1.902	1.897	θ = 1.9798-0.0003*t	1.980	1.965	1.950	0.073	0.063	0.053
SPN3-GRD1-S-EF	θ = 1.9601+0.0014*t	1.960	2.030	2.100	θ = 1.9702+0.0004*t	1.970	1.990	2.010	0.010	-0.040	-0.090
SPN3-GRD2-N-EF	θ = 1.8212+0.0006*t	1.821	1.851	1.881	θ = 2.0106-0.0006*t	2.010	1.980	1.950	0.189	0.129	0.069
SPN3-GRD2-S-WF	θ= 1.8519+0.0014*t	1.852	1.922	1.992	θ = 1.9842+0.0002*t	1.984	1.994	2.004	0.132	0.072	0.012

	South														North
Distance (ft)	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
Displacement (mil), T=0°F	0	83	137	170	189	199	203	204	203	199	189	170	137	83	0
Displacement (mil), T=50°F	0	28	49	65	76	83	87	88	87	83	76	65	49	28	0
Displacement (mil), T=100°F	0	-27	-42	-48	-49	-48	-46	-46	-46	-48	-49	-48	-42	-27	0

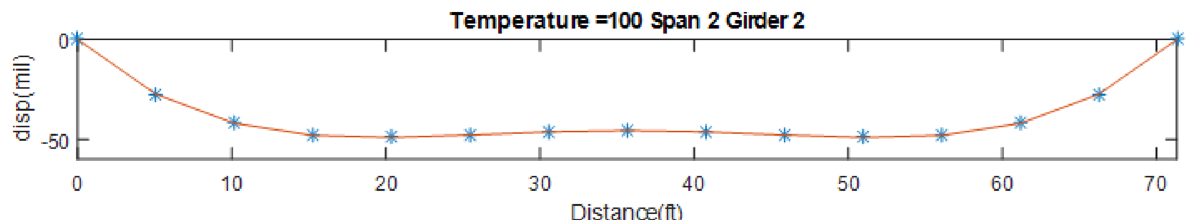
Displacement (mil) T=0°F



Displacement (mil) T=50°F



Displacement (mil) T=100°F



Total vertical displacement change

Span 2 Girder 2 vertical displacement change at various temperatures
Before deck removal (January 15) and after deck replacement (August15)

Figure 34: Change in the vertical displacement of Span 2, Girder 2, resulting from deck replacement. Analysis conducted at various temperatures, T=0, T=50, and T=100 degrees Fahrenheit.

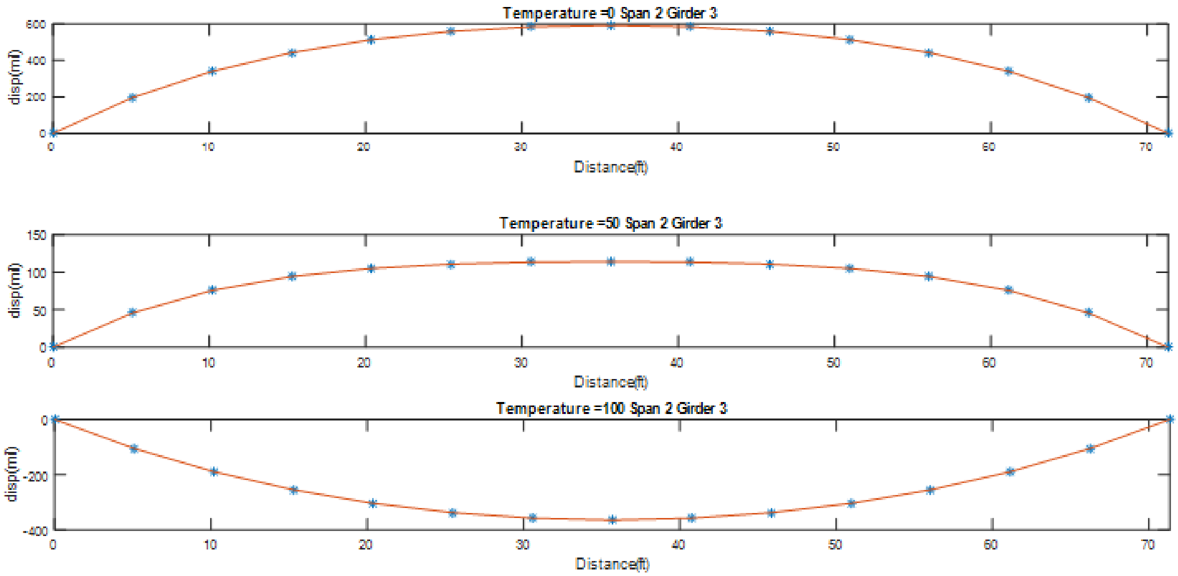
South — North

Distance (ft)	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
Displacement (mil), T=0°F	0	196	341	443	514	559	585	593	585	559	514	443	341	196	0
Displacement (mil), T=50°F	0	46	76	94	105	111	114	114	114	111	105	94	76	46	0
Displacement (mil), T=100°F	0	-105	-189	-255	-304	-338	-358	-364	-358	-338	-304	-255	-189	-105	0

Displacement (mil) T=0°F

Displacement (mil) T=50°F

Displacement (mil) T=100°F



Total vertical displacement change

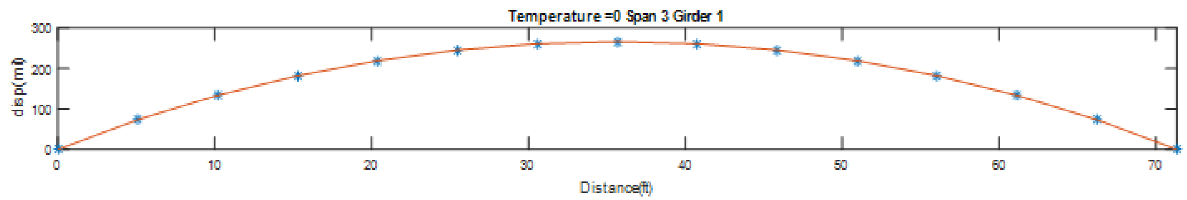
Span 2 Girder 3 vertical displacement change at various temperatures
Before deck removal (January 15) and after deck replacement (August15)

Figure 35: Change in the vertical displacement of Span 2, Girder 3, resulting from deck replacement. Analysis conducted at various temperatures, T=0, T=50, and T=100 degrees Fahrenheit.

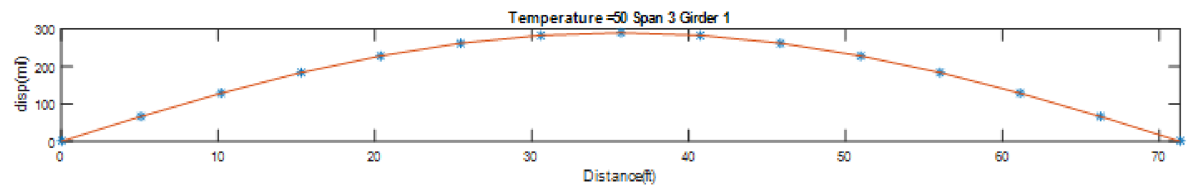
Distance (ft)	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
Displacement (mil), T=0°F	0	73	134	182	219	245	261	266	261	245	219	182	134	73	0
Displacement (mil), T=50°F	0	66	129	184	229	263	283	290	283	263	229	184	129	66	0
Displacement (mil), T=100°F	0	60	124	185	239	280	306	315	306	280	239	185	124	60	0

South — North

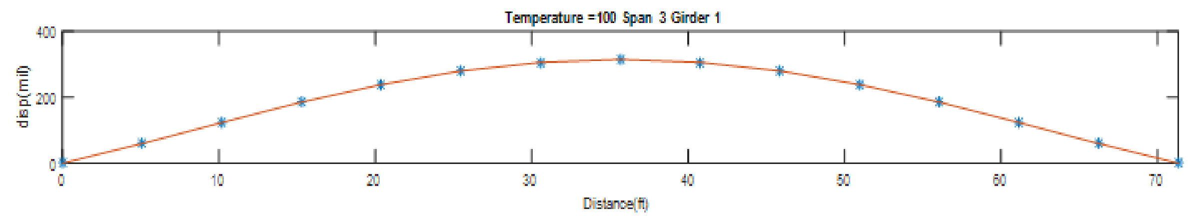
Displacement (mil) T=0°F



Displacement (mil) T=50°F



Displacement (mil) T=100°F



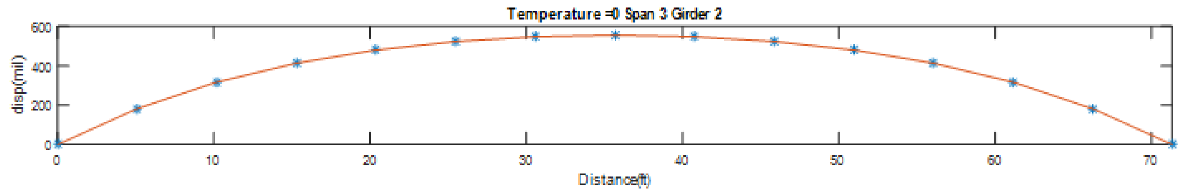
Total vertical displacement change

Span 3 Girder 1 vertical displacement change at various temperatures
Before deck removal (January 15) and after deck replacement (August15)

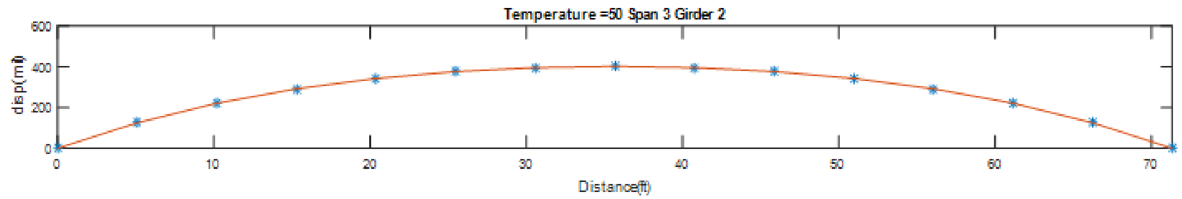
Figure 36: Change in the vertical displacement of Span 3, Girder 1, resulting from deck replacement. Analysis conducted at various temperatures, T=0, T=50, and T=100 degrees Fahrenheit.

	South														North
Distance (ft)	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
Displacement (mil), T=0°F	0	182	317	414	480	524	548	556	548	524	480	414	317	182	0
Displacement (mil), T=50°F	0	126	221	292	343	376	396	402	396	376	343	292	221	126	0
Displacement (mil), T=100°F	0	69	126	171	205	229	243	248	243	229	205	171	126	69	0

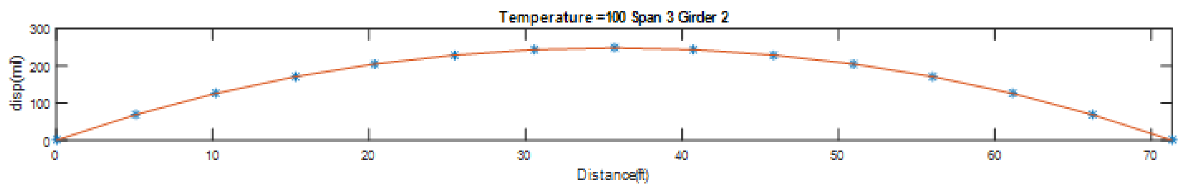
Displacement (mil)
T=0°F



Displacement (mil)
T=50°F



Displacement (mil)
T=100°F



Total vertical displacement change

Span 3 Girder 2 vertical displacement change at various temperatures
Before deck removal (January 15) and after deck replacement (August 15)

Figure 37: Change in the vertical displacement of Span 3, Girder 2, resulting from replacement. Analysis conducted at various temperatures, T=0, T=50, and T=100 degrees Fahrenheit.

7. IMPLEMENTATION AND LONG TERM VERTICAL DISPLACEMENT MONITORING

The research results of this project can be used as a basis for a vertical displacement monitoring system based on wireless inclinometer sensors. To monitor change in vertical displacement, 2-3 wireless inclinometer sensors are attached to the bridge girders in each span. Generally, for the purpose of long term monitoring, the data from sensors are fed into a computational algorithm which calculates the vertical displacement in an automated way. When used for the purpose of monitoring change in the curvature and vertical displacement during bridge deck replacement, the wireless inclinometer sensors should be attached to the bridge girders before the removal of the old deck. For the best results, it is recommended to attach the device a few weeks before the removal of the old deck. The reason is that the vertical displacement is often dependent on temperature, and careful characterization of temperature dependence is important. Therefore, attaching the wireless inclinometer sensors a few weeks (typically 2-3 weeks or more) before the deck removal means that the sensors will be able to capture enough inclination and temperature information to accurately find the linear dependency of the coefficient of inclination on temperature. After such initial characterization, the inclination data from the sensors can be used to find the vertical displacement at any point in time.

Although the displacement monitoring of this project was developed for monitoring the change of curvature during deck replacement, it could be used in much broader applications. Of course, because the wireless inclinometer sensors are suitable for long term monitoring, they can be used to monitor vertical displacement of the deck over time. Such monitoring is useful for purposes such as determining the long term structural integrity of the deck. Additionally, the monitoring system could be used for other purposes such as monitoring the deck where there are concerns related to settling of the bridge’s foundations. Additionally, the system could be used to monitor stability, movement, and displacement of other important bridge elements such as piers and pylons. Although we used the mathematical models for calculating the vertical displacement on horizontal elements (i.e., a bridge deck), similar models can be adopted for monitoring the horizontal displacement of vertical elements (e.g. piers and pylons). In either case, typically two or three high precision wireless inclinometer sensors can be attached to the monitored components and the data is fed into the algorithms which would calculate the vertical or horizontal displacement automatically.

As a final remark, it should be noted that the vertical (or horizontal) displacement monitoring system of this project can be used on structures where there are concerns related to foundation stability. This includes situations where the structure is located in areas of possible ground movement, landslide, or instability of slopes where a bridge’s piers or abutments are located. Additionally, the system would be useful to monitor displacement, and hence to determine the stability, in scour critical bridges. This displacement can happen for the bridges passing over rivers, where the strong flow of water may remove sediment around the bridge piers, leading to instability, settling, and movement.

8. CONCLUSIONS

This project focused on developing and deploying a system for monitoring displacement on bridges. The system used high precision, wireless inclinometer sensors to monitor inclinations at various points of a bridge deck. The collected inclination data was fed into a mathematical model that calculated vertical displacement. As a specific goal, this project intended to monitor the change in the vertical displacement and curvature of a bridge deck during the deck replacement process. For this purpose, special wireless sensors were developed. The sensors are capable of monitoring and reporting inclination and temperature concurrently. Being wireless is an advantage of this system because it will allow for the easy attachment of sensors on bridge girders before deck removal. Additionally, due to the hostile environment created from falling debris during deck removal, protecting a sensor's wires is a challenge; however, wireless sensors do not suffer from such a limitation. The wireless sensors monitor inclination and temperature during deck removal process, which could take several months. Mathematical curvature calculation methods were used to convert inclination data into vertical displacement. A system of eight wireless inclinometer sensors and two wireless strain sensors were deployed on a bridge close to Pocomoke City in Maryland, which underwent the deck replacement process from January until August 2015. Interestingly, the collected data revealed that temperature change could lead to small changes in the inclination of bridge girders and the changes in inclination would correspond to the temperature induced vertical displacement of a bridge deck. As a result, comparing the change in displacement of a bridge deck before and after deck replacement is not meaningful, unless the temperature effects are characterized. Additionally, this study revealed a previously unrecognized shortcoming in the survey methods used to find the change in the curvature of a bridge. Unless two surveys, for a bridge deck, are taking place at the same time, their results cannot be directly compared with each other. The method used in this project characterizes the effect of temperature and therefore, it separates the contribution of temperature from the change in the displacement caused by deck replacement.

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