Health Monitoring of a Lenticular Truss Bridge Using Wireless Strain Sensors and Finite Element Models: A Case Study

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ABSTRACT

An increasing number of new and old structures are instrumented with some sort of structural health monitoring (SHM) systems, which include a variety of sensors driven or governed by dedicated hardware and software. This paper presents the monitoring of the Smithfield Street Bridge, one of the oldest and most iconic bridges in the city of Pittsburgh (Pennsylvania). The bridge was instrumented with wireless strain, displacement, and rotation sensors by an independent party not involved with the research presented here. In order to interpret the sensors' data, a finite element model was developed, and a static analysis was performed to quantify the deformation at certain members of the bridge under known loading conditions. The results of the finite element analysis were then compared with the results of a test in which a truck of known weight crossed the bridge multiple times. Finally, the data from the strain sensors relative to three-years of uninterrupted monitoring were processed and analyzed to identify eventual anomalies.

INTRODUCTION

According to the Federal Highway Administration (FHWA) [1], there are over 600,000 highway bridges in the United States. Currently, 42% of them are at least 50 years old, and 7.5% of them are labeled in “poor” condition [2]. Therefore, each bridge must be inspected at least once every two years. In the case of bridges in not optimal conditions, these inspections occur more often and sometimes are carried out with the aid of nondestructive evaluation (NDE) methods. However, periodic inspections may miss the onset of critical issues between two consecutive inspections. This is raising the attention towards cost-effective structural health monitoring (SHM) strategies.

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These SHM strategies evolve the maintenance paradigm from time-based NDE in which a structure is inspected periodically, to permanent-based where sensors monitor 24/7 to flag, locate, and quantify damage as it happens.

A few years ago, the Pennsylvania Department of Transportation (PennDOT) started a pilot bridge instrumentation program. Under this program, ten bridges across south and southwest Pennsylvania were instrumented during the period 2017-2019 with an array of commercial wireless sensors able to provide real-time information about static and dynamic responses. The installation was completed by a company, hereinafter referred to as the Vendor, which owns and maintains the sensors. Each bridge was instrumented with wireless strain sensors and in some cases also with wireless inclinometers, displacement gages, and accelerometers.

One of the bridges included in this pilot program is the iconic Smithfield Street Bridge, built nearly 140 years ago in the city of Pittsburgh. The bridge is a riveted built-up lenticular through-trusses structure with rolled steel floorbeam-stringer floor system crossing the Monongahela River. The bridge connects Pittsburgh downtown to the Southside neighborhood. To interpret the readings from the SHM sensors and to simulate any loading scenarios, a high-fidelity finite element model of the lenticular through-trusses was developed using the commercial software ANSYS®. The use of commercial software to model a bridge for SHM applications is a common practice supported by the literature [3-7].

In the study presented in this paper, the ANSYS® model of the Smithfield Street Bridge was first used to predict the static deformation of the truss caused by the crossing of a truck used for a controlled test. The model was validated by comparing the numerical findings to the experimental results taken with the wireless strain gages installed by the Vendor and by using information provided by PennDOT to the authors. In addition, the strain data stored in a secure repository were extracted and analyzed to ascertain the condition of the Bridge and to identify any anomaly.

THE STRUCTURE AND THE HEALTH MONITORING SYSTEM

As mentioned above, the Smithfield Street Bridge is a riveted built-up lenticular through-trusses with rolled steel floorbeam-stringer floor system (Figure 1). The iconic parts of the bridge are Span 3, close to downtown, and Span 4, close to the South Side neighborhood. Span 4 is the subject of this study.

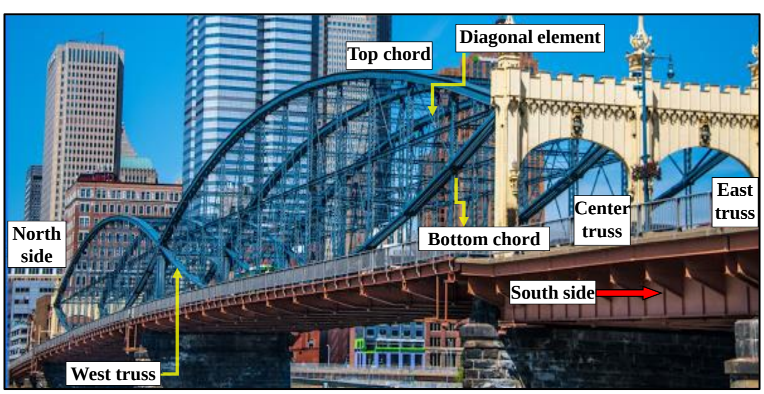

Figure 1. The Smithfield bridge with directions and nomenclature.

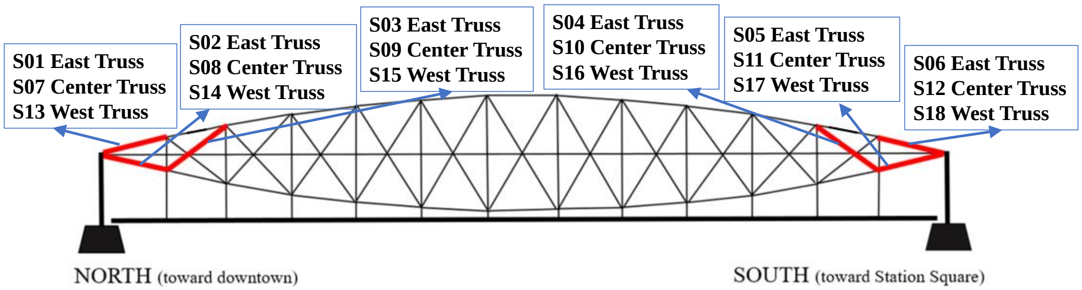

Figure 2. The members instrumented with a strain gage are labeled according to the gage number.

It is pinned north and has an expansion joint on its south end. For convenience, each lenticular truss is labeled as the west, center, and east trusses as shown in Figure 1. Each truss is composed of three main parts: the top chord, the bottom chord, and the diagonal element.

In July 2019, the Vendor, which was not involved in the study presented here, instrumented the south span (Span 4), with 30 strain gages. Figure 2 shows the location of the 18 strain gages bonded to the trusses. Strain gages 19 through 30 were bonded to the south portal, four on each of the three columns of the portal, one on each face of each column. These 12 gages, the displacement sensors, and the tiltmeters are not part of the study presented here and are ignored hereinafter. Shortly after installation, a truckload test was performed using a 26,272 kg truck. The steer axle was 7992 kg and the drive 'tandem' axles were 18280 kg.

First, the truck travelled over the bridge multiple times. The largest difference between the strain with and without the truck at each gage during each test run was calculated and reported by the Vendor.

Table I summarizes the largest strain difference calculated for each gage in the Vendor's tests. It shows that the top chords being monitored are in compression, whereas the other elements are in tension. Based on the data provided in Table I, with the exception of the south diagonal member and bottom chord on the east truss, the deformations on west truss are smaller than on the east truss.

THE FINITE ELEMENT MODEL

The model of Span 4 was created in ANSYS 2020 R2 using drawings provided to the authors by PennDOT. The bridge model is illustrated in Figure 3. The model consisted of 880 structural components, more than 244,700 finite elements, and over 698,700 nodes. Using the generated model, the numerical results relative to the truck test in the field on the left northbound lane were compared to the experimental results reported by the Vendor.

TABLE I. MAXIMUM STRAIN INCREASE DURING THE TRUCK TEST FOR EACH OF THE INSTRUMENTED MEMBERS IN MICROSTRAIN

East Truss	S01: -23.7	S02: 15.7	S03: 83	S04: 51.9	S05: 14.8	S06: -27.1
Center Truss	S07: -15.9	S08: 10.4	S09: 76.9	S10: 79.5	S11: 11.1	S12: -14.1
West Truss	S13: -18.1	S14: 14.3	S15: 78.2	S16: 72.1	S17: 15.6	S18: -12

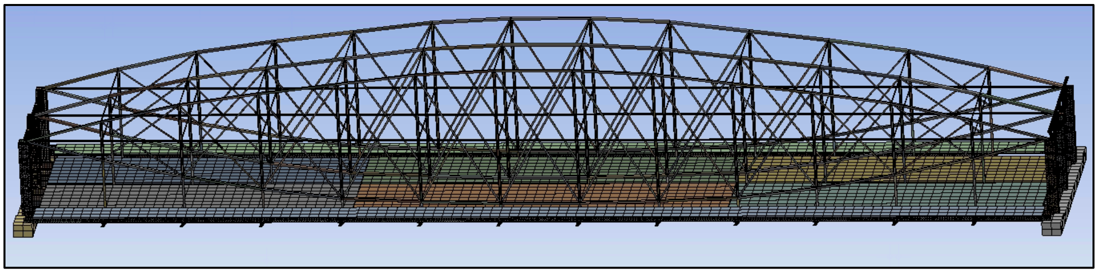

Figure 3. Finite element model of the Smithfield Street Bridge

The strains measured by sensor S09 during the two crossings of the truck were equal to 67.0 and 66.9 με. These values are about 17% lower than the calculated numerical deformation of 80.9 με. The experimental values recorded by S10 were equal to 71.5 and 71.2 με i.e., only 12.3% lower than the numerical prediction of 80.9 με. The difference is likely due to a discrepancy between numerical and the real (but unknown) lateral distance of the truck from the parapet. As a matter of fact, if the applied numerical load is 1.91 m away from the centerline instead of the originally considered 0.89 m, the numerical strain of S09 would be equal to 69.2 με, just 3.3% higher than the experimental values. Similarly, if the numerical truck is 1.27 m from the center truss, the numerical strain of S10 is equal to 77.09 με, just 7.8% higher than the recorded value. The outcome of this analysis is that a direct comparison between the finite element estimation and the experimental measurements suffers from the lack of knowledge about the exact lateral position of the truck. Nonetheless, the agreement between the numerical and the experimental results is quite good and proves the reliability of the finite element model.

STRUCTURE HEALTH MONITORING ALGORITHMS

The data from the 18 strain gages were processed using a general framework designed by the authors and implemented in MATLAB software. The framework aimed to: (1) characterize the overall response of the bridge to thermal load in order to identify element-to-elements difference that could be symptomatic of structural anomalies; (2) separate thermal effects from live load effects in order to capture transient events attributable to the crossing of heavy trucks, vehicle impacts, or barge collisions; (3) identify sensor drift. The framework was validated first by processing the data relative to the truckload test. Then, three years (August 1st, 2019 through July 31st 2022) worth of data were examined. It is noted here that at the time of this paper submission, the SHM system is still active.

Algorithm Validation: Truckload Test

Figure 4 shows the raw strains recorded during the truck test. The experiment lasted about 90 minutes during which the steel cooled about 3 °C. Here only, the values relative to the west trusses are displayed. Some symmetric elements exhibit significant difference. This is because the sensors were installed at different moments on a summer day, when the temperature of the steel may have differed by more than 10 °C.

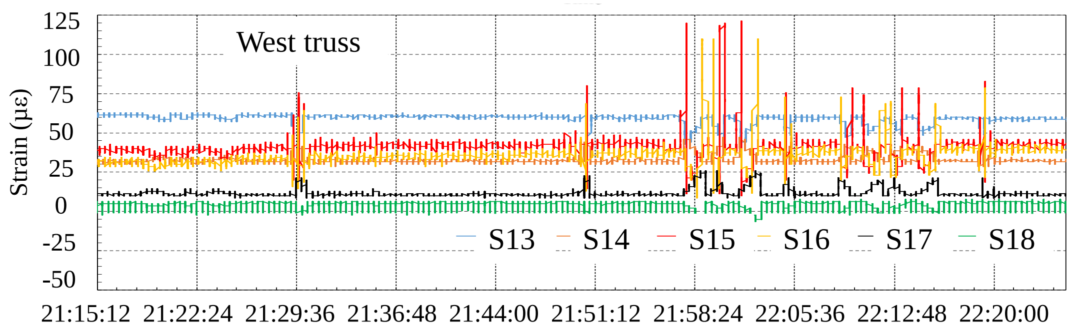

Figure 4. Strain measured during the truck test performed by Vendor.

The consequence is that the raw strains are offset with respect to each other because of the "reference temperature", i.e., the temperature at which the gages read zero deformation. To minimize or eliminate any bias attributable to the temperature, the following 3-steps procedure was implemented. First, the raw strain data and the raw temperature data were synchronized, and this required some up-sampling and interpolation of the temperature data. Then, the 15-minutes moving average for both parameters were calculated. Finally, the difference between the raw and the moving averaged strain was calculated to obtain what hereinafter is referred to as the "true strain". The hypothesis behind such a procedure is that the effect of any transient event, e.g., vehicle overload, vehicle crashes, or barge collisions, last much less than 15 minutes and therefore its effect on the moving average of the strain is negligible. In addition, the temperature effects on the structural steel are not instantaneous.

The reliability of this procedure was applied to the data partially shown in Figure 4 and the results relative to twelve sensors were calculated. From all obtained results, the true strains relative to sensors S14 and S16 are presented in Figure 5. Here, the vertical axes are between -40 με and +100 με. In the absence of any live load, each gage value is centered to zero. The qualitative and quantitative comparison between Figure 5 and Figure 4 demonstrates the reliability of the data processing.

Long Term Monitoring

This section discusses the outcome of the analyses of three years (01 – August – 2019 to 31 – July - 2022) of active monitoring of the Smithfield Street Bridge. The SHM system was installed a few weeks earlier (July 2019) and the sensors are still active.

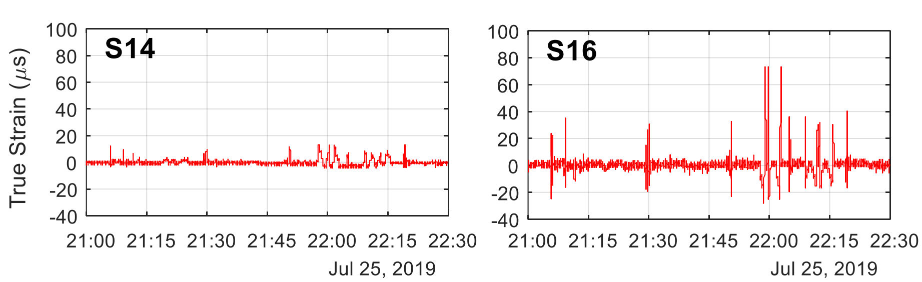

Figure 5. True strains from gages S04 and S16 extracted from the raw strains stored during the controlled load truck.

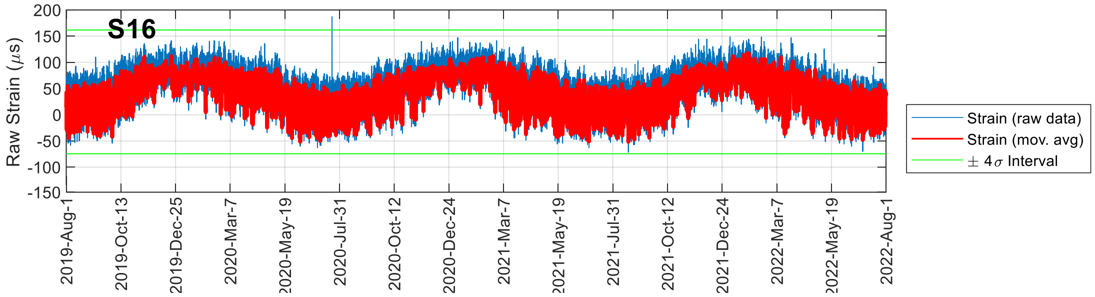

Figure 6. Raw strain and corresponding moving average recorded sensor S16 over the 12-month period.

RAW DATA ANALYSIS

Figure 6 shows the raw strain and the corresponding 15-minutes moving average of gage S16. The two horizontal lines identify the ±4σ range. If the modulus of the steel is assumed to be equal to E= 200 GPa, the selected range goes from 30 MPa in compression to 40 MPa in tension.

Figure 6 shows the raw strain and the corresponding 15-minutes moving average of gage S16. Similar graphs relative to all other gages (not shown here) were used to study the long-term response of the sensors. As expected, most deformations follow the seasonal changes of the temperature. This is particularly evident for the diagonal members. Only one isolated spike exceeded the ±4σ range and it was caused by an overweight truck crossing. Not shown here, another spike was for instance seen in gage S04 on 02/14/2020 at 9:15:48 AM. S10 also showed a spike on 07/22/2021 at 15:21:02.

THERMAL EFFECTS

The raw strains and the corresponding raw temperatures from each sensor were synchronized to create a matrix with three columns: strain, temperature, and corresponding timestamp. The strain vs temperature data of strain gage S16 are plotted in Figure 7. For the sake of space only one gage is provided here. However, based on all the 18 sensors data, it was found that except for sensor 17 bonded to the bottom chord on the south side of the west truss, the strain decreases with the increase of the temperature, i.e., as the bridge becomes warmer its structural members tend to compress. The response of S17 is believed to be caused by an error during the installation, which does not compromise the reliability of the information.

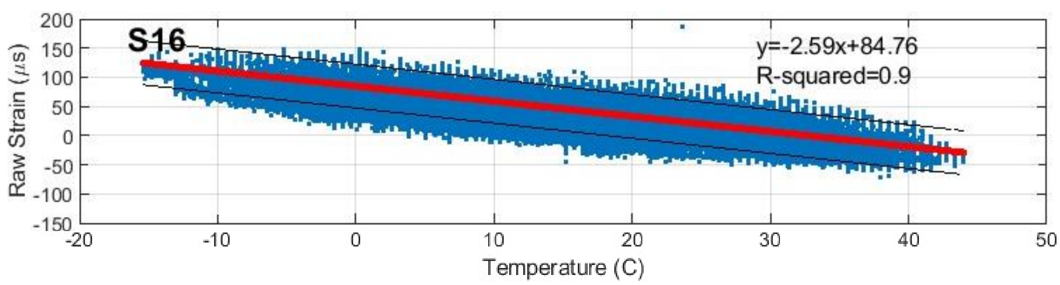

Figure 7. Raw strain vs raw temperature for sensor S16.

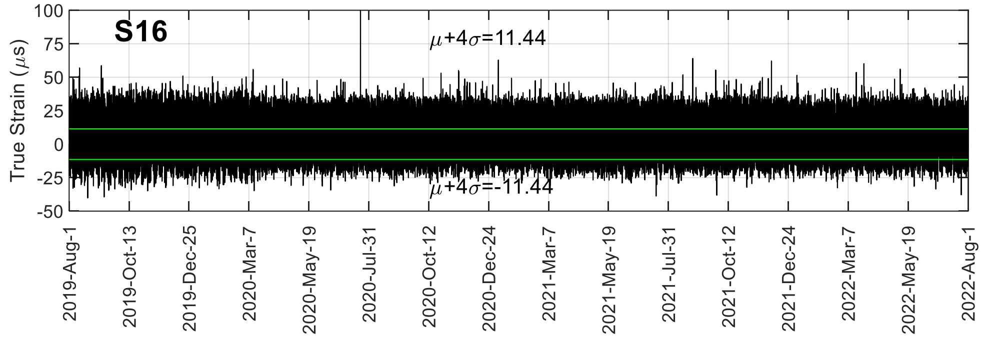

Figure 8. Live load strain for strain gages S16. The ±4σ interval is overlapped in green.

LIVE LOAD EFFECTS

This section discusses the "true strains" which represent an accurate quantification of the deformation triggered by the live loads. An example of live load for the same S16 strain gages is presented in Figure 8 along with two horizontal lines that bound the ±4σ range.

Based on the similar graph from all the 18 gages (not shown here), only on a few occasions, the sensors exceeded the maximum strain increase recorded during the truck test. Sensor S13 was subjected to an isolated event in November 2021 when the true stain was nearly 50 με, significantly higher than the values typically recorded by this sensor. Gage S16 displays a single spike much higher than 100 με (151 με), on July 21st, 2020, which is relative to the heavy truck crossing discussed previously. As observed for the raw strains, the selection of the ±4σ range may be too conservative to identify relevant transient events.

CONSLUSIONS

This paper presents some results relative to a holistic SHM study about one of the most iconic bridges in the city of Pittsburgh, the Smithfield Street Bridge. The bridge was modeled using a commercial finite element software to predict the deformation of those members of the bridge that are currently monitored with wireless strain sensors that are part of a more comprehensive the SHM system installed by a private company not involved in the research presented here. The numerical deformations were calculated under the assumption that the bridge is subjected to the presence of a truck of known geometry and weight. The experimental results of the truck test were compared with the numerical results predicted with the finite element model and they show very good agreement, despite uncertainties about the lateral distance of the truck from the centerline of the bridge. The study presented in this paper was then complemented with a thorough analysis of the SHM data made available to the authors. The effect of the temperature of the strains was examined to identify any anomalous behavior of the members being monitored. In addition, a simple algorithm was implemented and adopted to mitigate the effect of temperature and to extract the deformations that are associated with traffic and other transient events. However, live load graphs cannot reveal neither sensors drift nor permanent deterioration of the structure because the live load is obtained by subtracting the raw strain to the 15-minutes moving average.

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