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# STREICKER BRIDGE: ASSESSMENT OF STRUCTURAL HEALTH CONDITION THROUGH STATIC AND DYNAMIC MONITORING

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Streicker Bridge is a new pedestrian bridge built on the Princeton University campus. Structural Health Monitoring (SHM) is applied with the aim of transforming the bridge into an on-site laboratory for various research and educational purposes. The research focuses on addressing some general SHM challenges, but it includes specific studies in the domain of monitoring approaches, methods, and instrumentation as well. Two fiber-optic sensing technologies are currently permanently deployed: discrete long-gage sensing technology based on Fiber Bragg-Gratings (FBG) and truly distributed sensing technology based on Brillouin Optical Time Domain Analysis (BOTDA). The sensors were embedded in concrete during the construction. The post-tensioning of each part of the bridge was performed about one week after the pouring. A two-year overview of the project is presented including: monitoring systems, applied monitoring strategy, and comparison of numerical model with monitoring results: bridge behavior at early age and post-tensioning, under temperature load, and under various static and dynamic load tests. The results showed that the selected monitoring strategy was suitable for monitoring of this complex bridge, and that the selected monitoring systems were able to capture the main features related to the real structural behavior of the bridge (e.g. early age cracking, post-tensioning etc.). Comparison with numerical model confirmed that the bridge is in very good condition.

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ABSTRACT:

Streicker Bridge is a new pedestrian bridge built on the Princeton University campus. Structural Health Monitoring (SHM) is applied with the aim of transforming the bridge into an on-site laboratory for various research and educational purposes. The research focuses on addressing some general SHM challenges, but it includes specific studies in the domain of monitoring approaches, methods, and instrumentation as well. Two fiber-optic sensing technologies are currently permanently deployed: discrete long-gage sensing technology based on Fiber Bragg-Gratings (FBG) and truly distributed sensing technology based on Brillouin Optical Time Domain Analysis (BOTDA). The sensors were embedded in concrete during the construction. The post-tensioning of each part of the bridge was performed about one week after the pouring. A two-year overview of the project is presented including: monitoring systems, applied monitoring strategy, and comparison of numerical model with monitoring results: bridge behavior at early age and post-tensioning, under temperature load, and under various static and dynamic load tests. The results showed that the selected monitoring strategy was suitable for monitoring of this complex bridge, and that the selected monitoring systems were able to capture the main features related to the real structural behavior of the bridge (e.g. early age cracking, post-tensioning etc.). Comparison with numerical model confirmed that the bridge is in very good condition.

## 1 INTRODUCTION: STREICKER BRIDGE

Streicker Bridge, located on the Princeton University campus, was completed in the spring of 2010 (see Figure 1). The bridge is 104 meters long and crosses Washington Road. Streicker Bridge has a main span and four approach legs. Structurally, the main span is a deck-stiffened arch, thus the deck mainly carries bending moments and only secondary moments are expected in the columns. The legs are curved continuous girders supported by steel columns. The legs are horizontally curved and the shape of the main span follows this curvature, resulting in a varying main span cross section. It is minimal at the middle of the deck and maximum where the legs join the main span. The leg cross-section is constant. The arch and columns are weathering steel while the decks are reinforced post-tensioned concrete. The slender and elegant deck-stiffened arch spans

34.75 m, with a deck thickness of only 578 mm and arch diameter of 324 mm. The slender elements and varying deck cross section create a geometrically complex structure, and SHM facilitates comparison of its behavior with numerical models and verification of its performance.

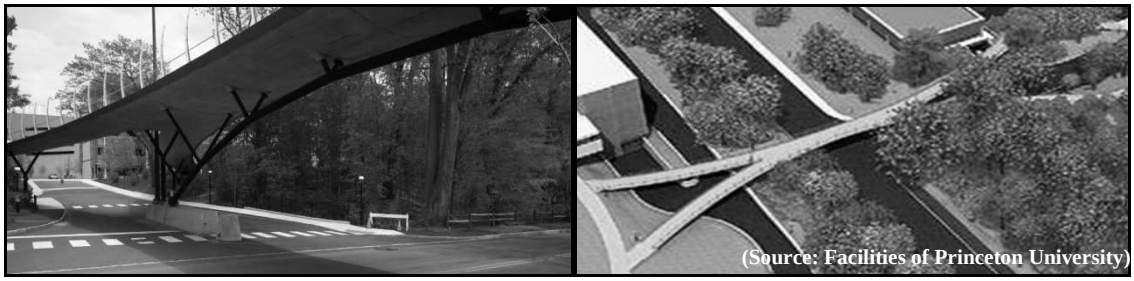



Figure 1. Streicker Bridge. Left: Photograph. Right: Rendering.

The current bridge instrumentation is based on two monitoring approaches. Firstly, global structural monitoring using discrete long-gauge Fiber Bragg-grating (FBG) sensors and secondly, integrity monitoring using distributed sensing based on Brillouin Optical Time Domain Analysis (BOTDA). All the discrete FBG sensors were equipped with a temperature sensor facilitating thermal compensation and temperature monitoring of the concrete.

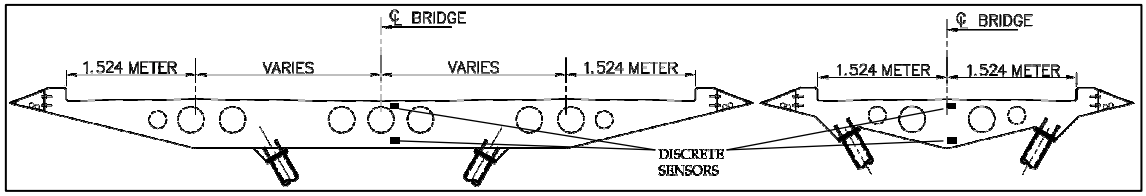



Figure 2. Orientation of a typical pair of sensors within a cross section.

Since the bridge is just about doubly symmetric in plan only half the main span and one of the legs, i.e. the southeast leg is instrumented. Two sensors parallel to the elastic line of the deck are installed close to the axis of symmetry of each cross-section, one sensor at the top and one at the bottom as shown in Figure 2. Parallel sensors are needed in order to capture and distinguish influences of normal force and bending moment. The instrumented area is shown in Figure 3. The gauge length of all the discrete sensors was determined based on principles established by Glisic & Inaudi (2009). The gauge length was chosen to be 60 cm. More can be found about the instrumentation of Streicker Bridge in the literature, i.e. Glisic (2011).

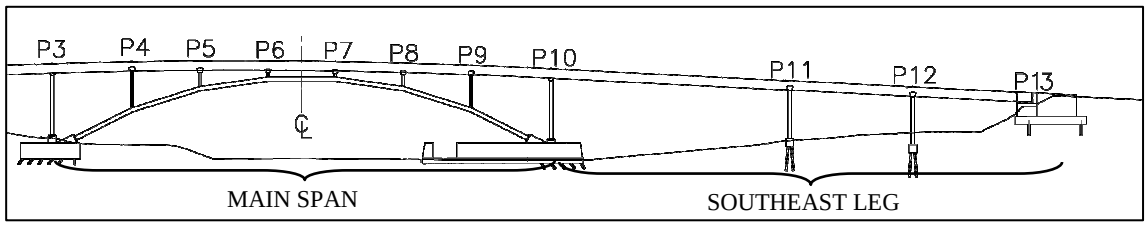



Figure 3. Bridge elevation, one approach ramp (leg) and half the main span are instrumented.

The main span can be divided into seven segments, delimited by columns P3 to P10, see Figure 3. Discrete sensors are located above columns P7, P8, P9 and P10 and at two mid-spans between P6 and P7 (P6h7), and P8 and P9 (P8h9). Two additional parallel

lateral sensors were installed above column P10 in order to evaluate any local influence of loads transferred from the southeast leg of the bridge. Figure 4 shows the location in plan of the main span sensors.

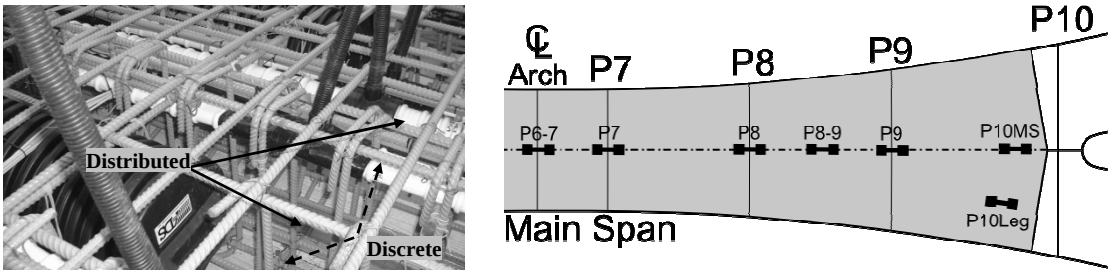



Figure 4. Left: Distributed and discrete sensors installed on reinforcing steel. Right: Plan view of the main span, showing parallel sensor locations.

The southeast leg is fixed to the deck of the main span on one end and simply supported at the other end. The deck consists of three spans shown in Figures 3 and 5. The most highly stressed sections – those above the columns and in the middles of spans – are monitored. In addition, both quarter-span sections of the longest span, P10-P11, are monitored. A distributed sensor (sensing cable), consisting of two strain sensitive and two temperature sensitive optical fibers was installed in the span P10-P11, at the top and at the bottom of the cross-section, parallel to the elastic line of the deck. The distributed sensor was installed close to discrete sensors in order to facilitate direct comparison of the two systems; this can be seen in the left image of Figure 4.

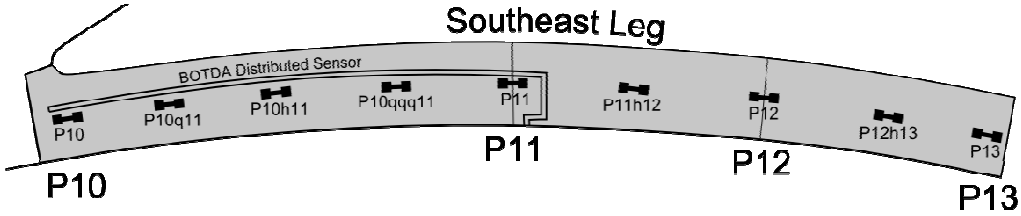



Figure 5. Plan view of the southeast leg, showing parallel and distributed sensor locations.

The condition of Streicker Bridge has been monitored for almost two years. Several observations were made under its very early age, as the concrete hardened and after the post-tensioning. In addition, static and dynamic tests were conducted to identify the structural system and assess the bridge's structural condition. Following is a discussion and results of four aspects of the bridge behavior: early age behavior and post-tensioning, static structural identification, natural frequency study, and behavior under varying thermal conditions. In addition, a comparison between the two deployed systems was made. Detailed analysis of the results would exceed the scope of this paper, thus only an overview with the most important findings is presented, aiming to demonstrate the rich information about structural behavior obtained by SHM.

## 2 EARLY AGE BEHAVIOR AND POST-TENSIONING

Data from the southeast leg showed unexpected strain changes in the time histories of several of the sensors. FBG sensors at locations P10h11, P11, and P11h12 all show a

distinct upswing in strain approximately three days after the concrete was poured, with location P10 showing a similar behavior five days later. Figure 6 shows the strain data from these four sensor pairs. This unusual behavior was confirmed by distributed BOTDA system too, Glisic et al. (2011). The strain changes were preliminarily attributed to cracking in the concrete deck. To understand the mechanism of cracks formation, a Finite Element Model (FEM) was created using the analysis program SAP2000. The goal of this analysis was to show that the thermo-mechanical stresses induced in the deck by the heat of hydration were sufficiently large to cause cracking. Due to the low bending stiffness of the tubular steel piers, the deck is practically unrestrained in the axial direction. Thus, thermal stresses in the deck are caused primarily by temperature gradients, which lead to moments in the deck due to the much more significant vertical restraint offered by the piers.

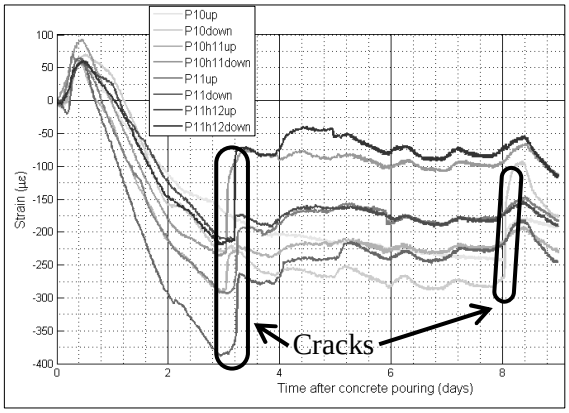



Figure 6. Strain evolution in southeast leg P11, showing cracking.

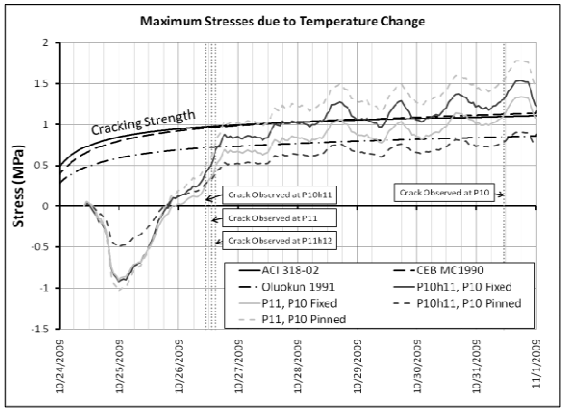



Figure 7. Maximum stress at P10h11 and showing crack formation.

The maximum averaged observed thermal gradient, over the three spans is approximately 19.7°C/m creating a maximum strain between 79με and 91με. This is well within the range of cracking strains for concrete, typically found to be between 60 and 200με, Glisic et al. (2002). As a more detailed analysis, the maximum stress in the deck is compared to the evolving cracking strength of the concrete, as shown in Figure 7. The cracking strength of the concrete is estimated using three different relationships between compressive cylinder strength and tensile strength, Oluokun (1991), ACI (2002), CEB (1993). Size effect is taken into account. The stresses in the deck approach the cracking strength of the concrete on the afternoon of October 26$^{th}$, roughly 3 days after the concrete was poured. This is close to the same time that the sensors observed an unexpected change in strain, as shown in Figure 6. The crack that formed at sensor P10 appears to have been caused by particularly warm weather on the 31$^{st}$.

Finite element analysis has proven that the observed unusual behavior in the early age of the concrete was cracking caused primarily by thermal gradients produced by uneven post-hydration cooling in the deck. Preliminary study shows that these cracks have been effectively closed by the subsequent post-tensioning; further long-term monitoring will show if they have had any lasting effect on the bridge performance.

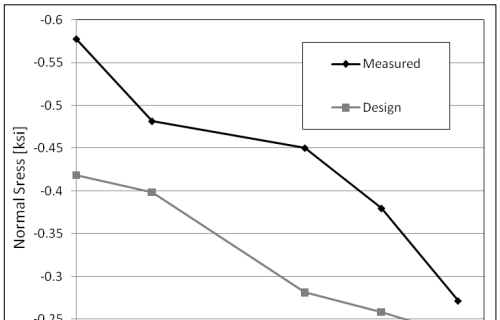
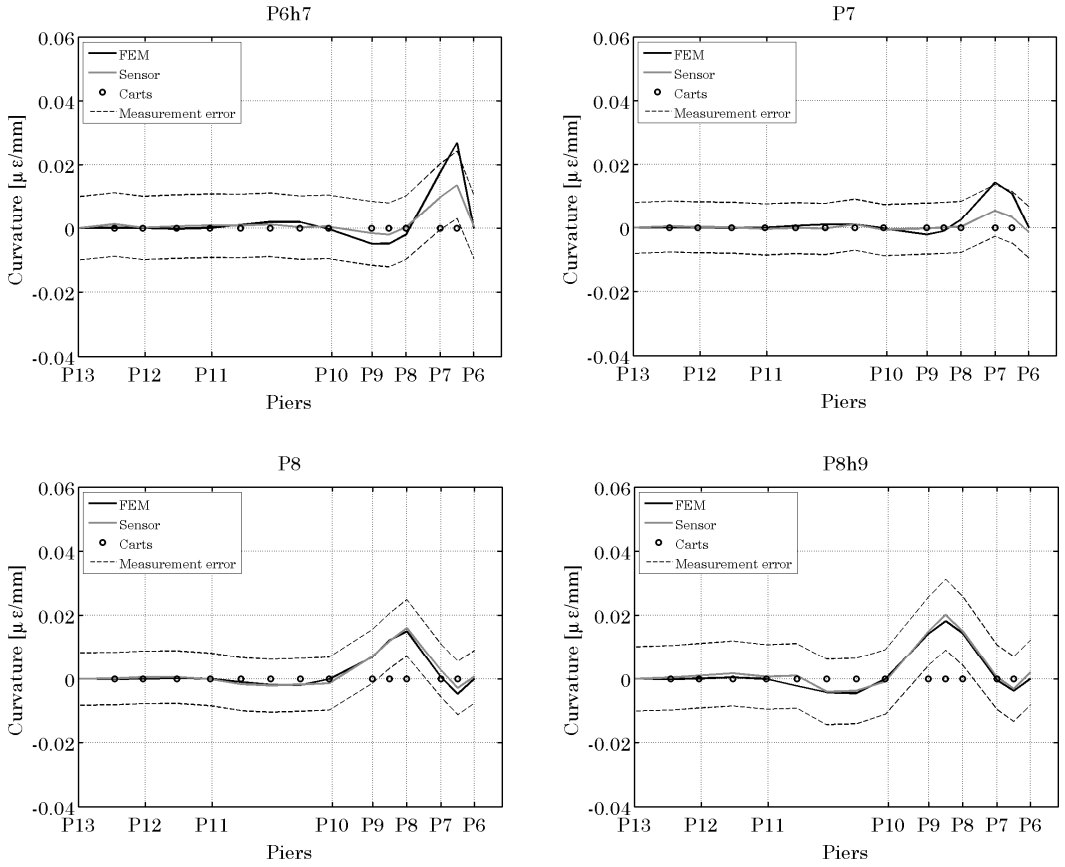


Figure 8. Comparison between design and measured stresses along the main span, Liew (2010).

For the main span, based on measurements, the actual post-tensioning stresses are calculated and compared with design as shown in Figure 8, Liew (2010). The measurements show that in reality, post-tensioning losses are likely to be smaller than expected. This is a positive finding as with more compression, the deck can support greater loads.

## 3 STATIC STRUCTURAL IDENTIFICATION

In order to assess the structural performance, and create and verify numerical models, a static test was performed on the bridge on March 18, 2011. The results of the test and the FEM analysis are shown for eight locations in Figure 9. The error limits are shown in the same figure.



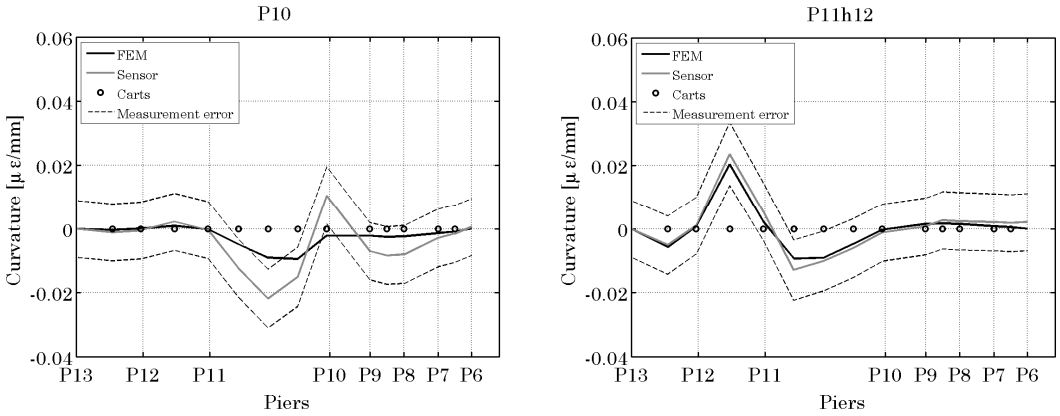



Figure 9. Influence lines at eight different locations when four golf carts stop at 13 points.

Four golf carts, each approximately 9 kN, were used as a moving static load. The carts were positioned at 13 different locations along the bridge and measurements were taken. Influence lines were created for 16 locations based on measurements. Analysis was performed using created FEM and compared with the test results (see Figure 9). Four point loads were moved over the bridge model and the curvature calculated at the sensor locations. The Young's modulus in the FEM was calibrated based on the SHM, resulting in a good quantitative agreement. The black circles indicate the location of the carts as measurements were taken. The measured values and the FEM are in good agreement for most locations. Discrepancy was found where the leg joins the main span, at P10. There the stiffness seems to be lower than expected. This behavior may be explained as consequence of the crack observed at early age, but further study is needed to confirm this. Unexpected behavior was also detected at the center of the main span, but this time the deck is stiffer than predicted by the model. This can be explained by a higher Young's modulus than used in the FEM, higher post-tensioning force, and stronger interaction with the arch, which is due to exceptionally short columns connecting the deck and the span at that location. Further study is needed to identify exact causes for higher stiffness in the middle of the main span.

## 4 NATURAL FREQUENCY STUDY

The monitoring system was used to study the dynamic behavior of Streicker Bridge as well. The goal was to experimentally determine the natural frequencies of the bridge and compare them with the frequencies calculated by the FEM. The first two natural frequencies calculated with FEM are 3.22 Hz and 3.92 Hz.

This study is based on the principle that the natural frequencies of a bridge can be determined with classical tests such as a shaker test or an impact test that introduce free vibrations in the structure. Nevertheless, by exciting the structure with ambient vibrations, the frequencies found would be approximately equal to the natural frequencies of the bridge with the advantage of the simplicity of the tests. The test was made with 5 people running at different random frequencies on the P10-11 span for a short period of time (30 seconds). The natural frequencies were calculated from the strain sensor measurements performed with 250 Hz frequency. Fast Fourier Transform (FFT) was used to extract the natural frequencies of the bridge. Figure 10 shows the FFT of the strain sensor P10h11down located at the bottom of the cross-section of the

mid-span P10-11 of the southeast leg. Considering only the sampling frequency and the duration of the measurements the expected error of the FFT is 0.06 Hz; this does not include any other measurement errors generated by the monitoring system.

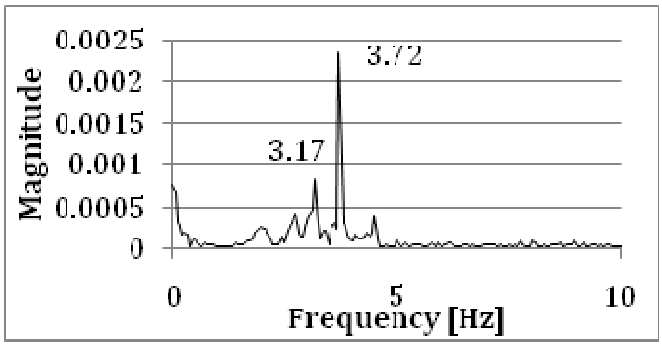



Figure 10. FFT of strain sensor and the first two natural frequencies.

The obtained natural frequencies of 3.17 Hz and 3.72 Hz are very close to the ones calculated by the FEM (3.22 Hz and 3.92 Hz). This indicates that the FEM is able to capture the dynamic behavior of the bridge. The difference between the FEM and measurements can be explained by random errors of the monitoring system and changes in the bridge's frequencies due to the mass of people exciting the bridge, damping, and the influence of environmental conditions. Since this is an initial FEM, further fine-tuning needs to be performed based on future tests conducted at different temperatures.

## 5 BEHAVIOR UNDER VARYING THERMAL CONDITIONS

In Section 3 it is shown that the thermal gradients can generate high stresses in the bridge. The influence of thermal gradient to the deck's structural behavior is further studied in this section.

The thermal expansion coefficient of concrete was determined from measurements to be between 11 and 13 με/°C, thus the value of 12 με/°C is adopted in this study. Next, the thermal strain is determined at each sensor location by multiplying the thermal expansion coefficient with the temperature change. The total strain measured by sensors consists mainly of four components: elastic strain, thermal strain, creep, and shrinkage. Assuming that in short term the last two can be neglected, the elastic strain was calculated by subtraction of thermal strain from the total strain. The stress is calculated as the product of strain and Young modulus (determined from measurements to be 39 GPa). Finally, the bending moment is calculated using the stresses determined at two locations in each cross-section and geometrical properties of the cross-section (moment of inertia and positions of the sensors).

The result is presented in Figure 11. An important preliminary conclusion of this study is that the bending moment that arises at the cross section in the mid-span P10h11 from a temperature gradient of 7°C has the same order of magnitude as the bending moment generated by a static load of 5 tons placed at the same location, which is more than the load of maintenance vehicles (4.5 tons) for which the bridge is designed. The bending moment induced by thermal gradients vanishes once the temperatures at the top and bottom of the cross-section become equal (see Figure 11).

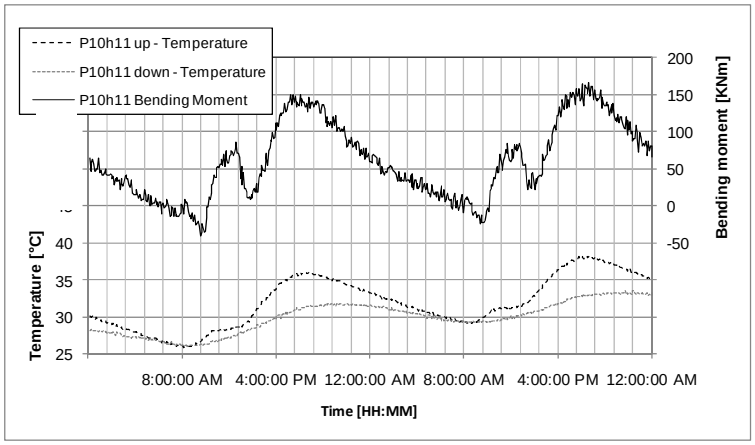



Figure 11. Temperature changes at the top and bottom of the cross section and bending moment variations.

## 6 CONCLUSIONS

Streicker Bridge at the Princeton Campus has been transformed into an on-site laboratory for various research and educational purposes. Currently implemented monitoring systems allow for global structural monitoring using discrete FBG long-gauge deformation and temperature sensors and integrity monitoring using BOTDA distributed deformation and temperature sensors. Important phases of bridge life were registered including early age deformation and post-tensioning. A two-year overview of the project is presented.

The SHM helped understand the real structural behavior and identify some critical points in the bridge's life. The monitoring system detected thermally generated cracking during the early age, but also helped verify that cracks are closed after post-tensioning, and allowed for comparison between design and applied post-tensioning force. Static structural identification and dynamic study helped to build a reliable FEM model of the bridge. The results showed that the thermal gradients in the bridge can generate bending moments in the order of magnitude of designed point loads. In general, the SHM confirmed that the bridge is in very good condition.

The selected monitoring strategy was suitable for the monitoring of Streicker Bridge, which features complex geometry. The selected monitoring systems were able to capture the main features related to the real structural behavior of the bridge (e.g. early age cracking, post-tensioning etc.).

Undergraduate and graduate students were involved in various phases of the project including installation, measurements, and data analysis. The project generates material for an undergraduate and a graduate course at Princeton University and is a central topic of several senior, master, and Ph.D. theses.

## 7 ACKNOWLEDGEMENTS

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