First Middle East Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures
8 – 10 February 2011, Dubai, UAE

SMAR 2011

Streicker Bridge: an on-site SHM laboratory at Princeton University campus

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ABSTRACT: Streicker Bridge is a new pedestrian bridge built at 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 will focus on addressing some general SHM challenges, but it will include specific studies in domain of monitoring approaches, methods, and instrumentation as well. Two fiber-optic sensing technologies are currently 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. The installation of monitoring systems, applied monitoring strategy, comparison between results obtained with the two monitoring systems and comparison of design with monitored stressess generated by post-tensioning are presented.

1 INTRODUCTION

Structural health monitoring (SHM) is a process aimed at providing accurate and in-time information concerning structural health condition and performance. The information obtained from monitoring is used to plan and design maintenance activities, increase safety, verify hypotheses, reduce uncertainty, and widen the knowledge concerning the structure being monitored. SHM helps prevent the adverse social, economic, ecological, and aesthetic impacts that may occur in the case of structural deficiency, and is critical to the emergence of sustainable civil and environmental engineering. In spite of its importance and its promising benefits, SHM is relatively scarcely used on real structures, since an efficient approach for its broader implementation has not been developed.

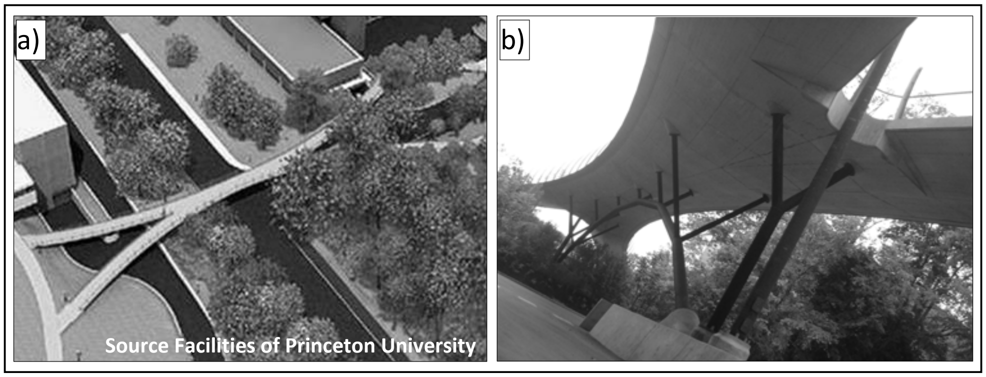
One reason for the scarcity of SHM applications is the current fragmented approach to structural health monitoring at several levels - in research activities, in practical applications, and in education. One example related to research: the studies of next generation SHM systems (sensor and interrogation units) are urgently needed, while the currently-available systems are not systematically employed, and in some cases their monitoring capacities are actually not even fully assessed. Another example is related to practical applications, where SHM methods and data analysis algorithms developed and tested on reduced scale models in laboratories, which neglected real on-site conditions, start to face challenges when implemented on real structures, and consequently lead the bridge managers to abandon the SHM. Finally, there is a bidirectional educational gap between researchers and practitioners – the researchers do not fully understand realistic needs of practitioners (e.g. what types of damage are the most critical or the most widespread), while practitioners are not aware of potentials of various SHM techniques.

SHM Lab at Princeton University instrumented the bridge with various SHM systems, with aim to transforming it into an on-site laboratory for various short- and long-term research and educational purposes. The research will focus on addressing general SHM challenges such as bridging education gap between research and practice, collecting real structural behavior data sets, identifying changes in strain patterns caused by unusual behaviors, and characterizing the SHM contribution to sustainability of built environment. Research in domain of monitoring approaches, methods and instrumentation, and evaluation of life-cycle cost benefits in function of the long-term SHM approaches is planned as well, Glisic & Adriaenssens (2010). A long-term objective of this project is to develop a holistic framework that will transform the current inefficient fragmented approach to SHM and eventually lead to the widespread, comprehensive, and beneficial application of SHM as a tool for optimized bridge management.

The SHM of Streicker Bridge serves as a support to university courses on SHM and several other courses related to structural analysis and design. The bridge represents tangible demonstrator for students and practitioners, and it is open for visits of community members. Initial phase of the project including currently deployed monitoring systems, monitoring strategy, and examples of preliminary results is presented in this paper.

2 STREICKER BRIDGE

The Streicker Bridge is a new pedestrian bridge currently being constructed at Princeton University. The bridge is 104 meters (300 ft) long and crosses Washington Road, connecting the Ellipse Walk near the Carl Icahn Laboratory to a new plaza being constructed as part of the new Chemistry Building. Funded by Princeton alumnus John Streicker (class of 1964), the bridge was designed by Swiss engineer Christian Menn in collaboration with the HNTB architecture and engineering firm, whose lead engineers for the project were Princeton alumni Theodore Zoli (class of 1988) and Ryan Woodward (class of 2002). Turner Construction Company was the main contractor and university’s Office of Design and Construction was the supervisor. The bridge rendering and photograph are shown in Figure 1.



Source Facilities of Princeton University

Figure 1. Rendering (a), and photograph (b) of Streicker Bridge.

2.1 Description

The Streicker Bridge has a main span and four approaching legs. Structurally, the main span is a deck-stiffened arch and 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. The arch and columns are weathering steel while the main deck and legs is reinforced post-tensioned concrete. The slender and elegant deck-stiffened arch represents an efficient solution to bridge the span of 34.75 m (114 feet) keeping the deck thickness of only 578 mm (22.75 inches) and arch diameter of 324 mm (12.75 inches).

2.2 *Significance*

Besides its primary aim, to provide and facilitate safe pedestrian crossing over the Washington Road, the bridge has strong symbolic and aesthetic significance. Taking into account its scientific, social, and symbolic measures, Billington (1983), the Streicker Bridge can be considered as a piece of structural art. Created as a part of Princeton University's Natural Sciences neighborhood, the bridge connects the Icahn Laboratory (Lewis-Sigler Institute for Integrative Genomics) and new neuroscience and psychology building (under construction) on the west with Jadwin Hall (physics), Fine Hall (mathematics), new Chemistry building, and Lewis library on the east. The bridge will "stand as a tangible symbol of the cross-disciplinary collaborations that are central to scientific research and teaching today", (President Tilghman in News at Princeton 2006). The bridge's "X" shape in plane symbolizes these cross-disciplinary collaborations, and the arch itself represents the south entrance gate to Campus.

3 STRUCTURAL HEALTH MONITORING OF STREICKER BRIDGE

3.1 *Instrumentation*

At the present stage the bridge instrumentation is based on two monitoring approaches: global structural monitoring using deformation sensors, and integrity monitoring. The first approach deals with long-gauge Fiber Bragg-grating (FBG) sensors, while the second approach deals with distributed fiber-optic sensing based on Brillouin Optical Time Domain Analysis (BOTDA).

Taking into account that the main aims of monitoring are related to research and education, not all the components of the bridge were instrumented. Assuming symmetry and similarity in structural performance, it was decided to equip only half of the main span and only one approaching ramp, i.e. south-east leg with sensors.

The fiber optic technologies were used in this initial project phase because they have proven durability and feature very good long term stability and insensitiveness to external environmental and man-made influences, Measures (2001). In the future the other monitoring systems and other approaches will be applied. The sensor network design is based on fiber-optic methods using loose structural analysis approach, Glisic & Inaudi (2007). The total number of the sensors was determined as a trade-off between the performance and the cost.

3.2 *Main span*

The main span of the bridge is a deck-stiffened arch and, thus the bending moments created by loads are mainly carried by the deck and only secondary moments are expected in columns. The deck is symmetric with respect to both vertical planes and it can be divided in seven segment delimited by columns P3 to P10, see Figure 2. Due to symmetry only east half of the main span is equipped with discrete long-gage FBG sensors as shown in Figures 2 and 3.

In deck-stiffened arch bridge important bending moments are located in cross-sections above the columns, while the moment variation along each segment is less dramatic. That is why it was decided to equip the cross-sections above columns P7, P8, P9 and P10 with sensors, and only mid-spans between columns P6 and P7, and P8 and P9. Two sensors parallel to elastic line of the deck are installed close to axis of symmetry of each cross-section, one sensor at top and one at bottom of the cross-section as shown in Figure 3. Parallel sensors are needed in order to capture and distinguish influences of normal force and bending moment.

One lateral sensor is installed above column P7 and in the mid-span between columns P8 and P9 in order to evaluate horizontal bending of the bridge. Although horizontal bending is not expected under dead and live loads it can be created by uneven post-tensioning and by post-tensioning losses. Two additional parallel lateral sensors were installed above column P10 in order to evaluate local influence of loads transferred from the south-east leg of the bridge.

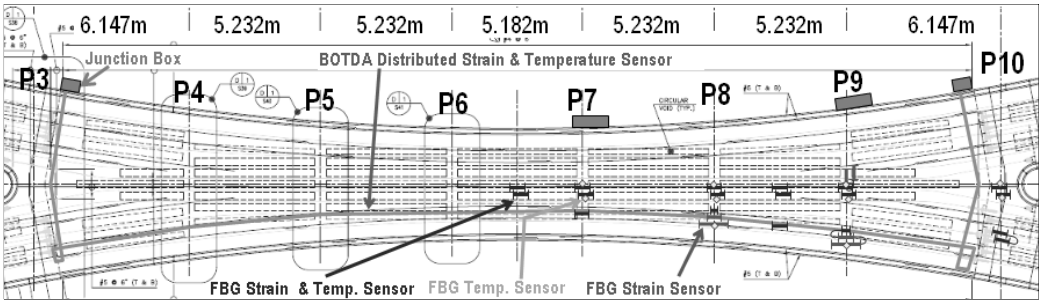


Figure 2. Position of sensors in the main span, plan view.

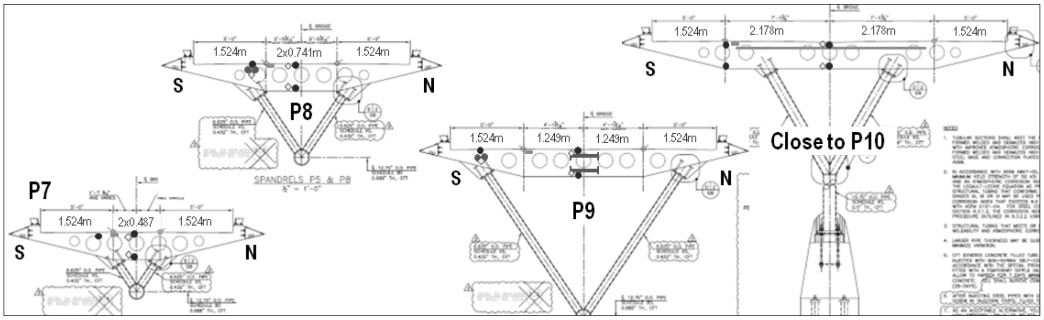


Figure 3. Position of sensors in the cross-sections above columns of the main span.

The width of the cross-section of the main span varies from section to section and it is minimal in the middle of the deck and maximal above the column P10. Column arms span follows the width of the deck cross-section. Due to combined influence of post-tensioning and the dead load, some stresses can occur between the arms of column P9 in direction of cross-section's horizontal axis. That is why additional "in-plane" parallel sensors are installed in cross-section above column P9 (see Figure 3).

The gauge length of all above presented sensors was determined based on principles established by Glisic & Inaudi (2009). In order to limit the relative error of measurement inherent to gauge length it was decided to use sensors of approximately 1/10 of the length of deck segments between the columns. However, to avoid errors due to concentrated loads the gauge length of the sensor should not be smaller than depth of the cross-section, i.e. 57.8 cm (1'-10¾''). Since the length of deck segments between columns varies from 5.2 m (17'-0'', segment P6-P7) to 6.1 m (20'-2'', segment P9-P10) the gauge length of 60 cm is chosen as a good compromise. In order to evaluate the influence of the gauge length to results of measurement, two groups of three sensors with gauge lengths of 30 cm, 60cm and 120 cm were added in cross-section above columns P8 and P9. These sensors are positioned right above the joint, thus in the zone where the strain field in deck is expected to be perturbed by concentrated force transferred from column (see Figures 2 and 3).

All the discrete FBG sensors were equipped with temperature sensor necessary for thermal compensation of sensors and temperature monitoring of concrete. In total 24 strain and 28 temperature sensors were installed. One distributed sensor was installed along the full length of the main span as shown in Figure 2, but this sensor was accidentally broken during the pouring of concrete.

3.3 *South-east leg*

The south-east leg of the bridge is a continuous curved girder with constant cross-section. It 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 with lengths as shown in Figure 4. Positions of all the sensors are shown in the same figure.

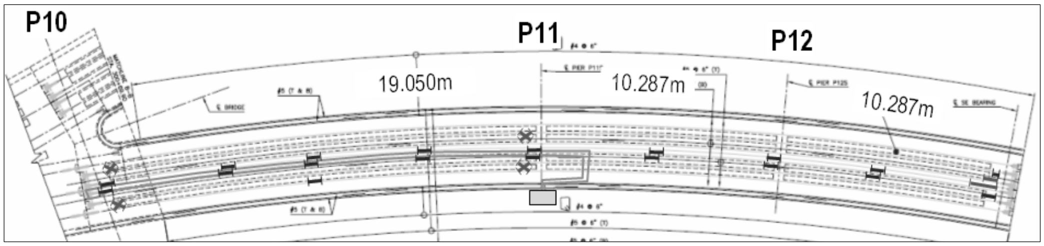


Figure 4. Position of sensors in the south-east leg, plan view.

Pairs of discrete sensors parallel to elastic line were installed close to axis of symmetry in several cross-sections with the purpose of monitoring influences of normal force and bending, similar to as for the main span. The most loaded sections, those above the columns and in middles of spans are monitored. In addition, both quarter-span sections of the longest span, P10-P11, are monitored. One lateral sensor for monitoring horizontal bending is added in the middle of the span P10-P11. The gauge length of sensors is 60 cm, the same as for the main span.

Crossed discrete sensors were placed close to the extremities of the span P10-P11 in order to monitor shear strain and torsion that may occur due to curved shape of the bridge. The gauge length of theses sensors (50 cm) and their angle of inclination (33° to 39°, depending on location) were adapted to dimensions of the cross-section.

Package of three sensors with different gauge-lengths (30 cm, 60 cm, and 120 cm) was installed close to abutment in order to evaluate the influence of the gauge length to measurements in the cross-section close to extremity where concentrated force due to post-tensioning perturbs the strain field. In total 29 strain and 19 temperature FBG sensors were installed.

Distributed sensor (sensing cable), consisting of two strain and two temperature 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 make possible direct comparison of two systems. A position of all the sensors in typical cross-section is shown in Figure 5.

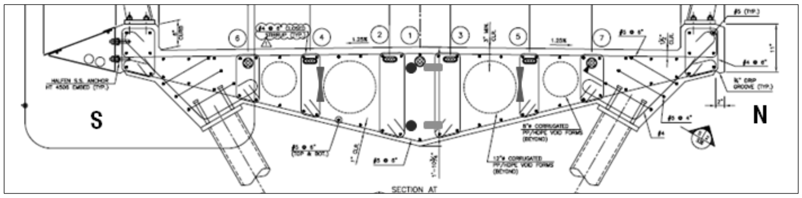


Figure 5. Position of sensors in the cross-section of the south-east leg.

3.4 Installation

The sensors were embedded in concrete during the construction. Installation was performed by undergraduate and graduate students of Princeton University. The pouring of the main span was performed on August 15, 2009, and the pouring of the south-east leg on October 23, 2009. The photographs taken during the installation are shown in Figure 6. Discrete sensors are indicated with white arrows and distributed sensor with black arrows. Distributed sensor in the main span was damaged during the pouring, while all the other sensors function properly.

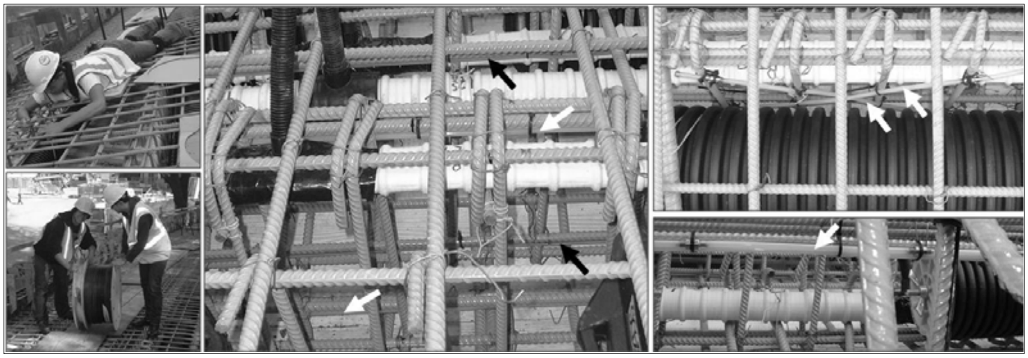


Figure 6. Photograph taken during the installation (from upper left clockwise): student installing the sensors, parallel discrete and distributed sensors installed onto the rebar, crossed sensors, package of three sensors with different gauge lengths, and students installing extension cable.

4 EXAMPLES OF RESULTS

4.1 General

Static monitoring started for the main span approximately 6 hours after the pouring of concrete, while for the south-east leg it started immediately after the pouring. The data was registered with the pace varying from 5 to 15 minutes for discrete FBG sensors, and approximately 1 h for distributed BOTDA sensor. Full presentation of results would exceed the contents of this paper, which is why only the most illustrative findings are presented. Since the project is still in its initial stage, the analysis of the presented results is to be considered as preliminary.

4.2 Early age

The first month of measurement performed on the middle segment of the main span is given in Figure 7a. “P6-7” denotes the sensors installed in the middle of the segment P6-P7 and “P7” denotes the sensors installed in the cross-section above column P7, while “up”, “down” and “lateral” denotes position of the sensors in the cross-section (see Figure 3). Similar notation is used in the other diagrams. Various works and events were successfully detected and they are indicated in Figure 7a: thermal contraction due to hydration process (swelling was not registered since the monitoring started 6 hours after the pouring), post-tensioning, de-centering and removal of the forms. No unusual behaviors were detected in this period.

The early age measurements for middle of the span P10-P11 of the south-east leg are presented in Figure 7b. Thermal swelling and contraction due to hydration process, and the post-tensioning of the deck were detected in indicated in the figure. However, besides these usual behaviors, an unusual event is detected – increase in strain – by all the three sensors. Similar unusual behaviors were noticed in sections close to P10, P11, P11-12, and P12. The nature of this event is still under investigation, but preliminary study indicates the early age cracking as the cause. The unusual strain was rectified in all the sections by the post-tensioning. Further analysis of the detected event represents the topic of a graduate student master thesis.

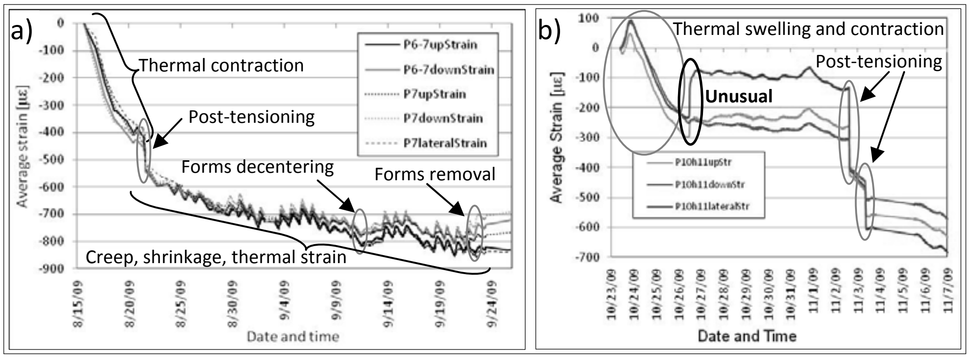


Figure 7. Early age measurement in the main span (a) and the south-east leg (b).

4.3 *Distributed vs. long-gage measurement*

Post-tensioning as measured with distributed sensor is given in Figure 8a. The comparison with long-gauge FBG sensors is shown in the same figure. Two monitoring systems has good agreement in quarter span sections were no unusual behavior occurred. Discrepancy is noticed in the section where the unusual behaviors were detected. This discrepancy is a consequence of one-meter spatial resolution of distributed system, which makes it impossible to detect strain concentrations, unless a special software module is enabled. Unfortunately, this module was not available at the time of measurements. The difference between the distributed and long-gauge sensor measurement in the sections close to P10, P10-P11 and P11 actually corresponds to crack opening. Comparison of two systems is the topic of an undergraduate student senior thesis.

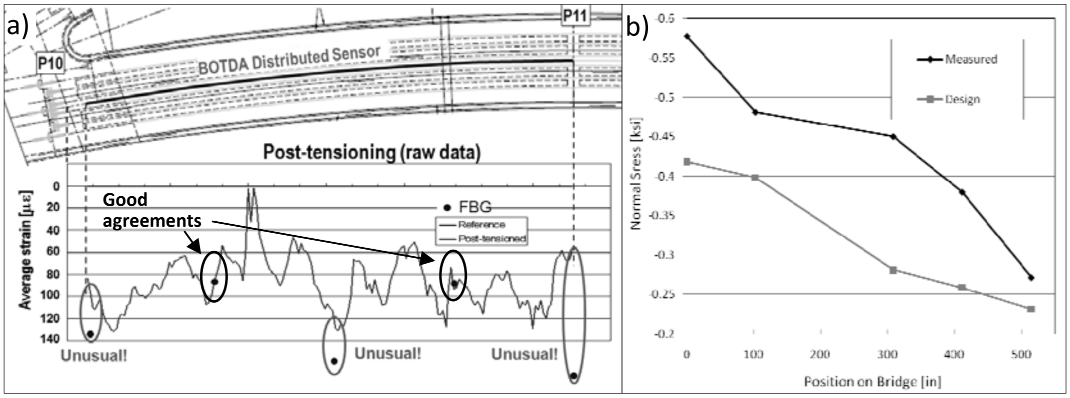


Figure 8: Comparison between distributed and long-gauge sensor measurements (a) and comparison between design and measured stresses in the cross-sections centroids of the main span (b), Liew (2010).

4.4 *Analysis of post-tensioning of the main span*

Based on measurements, the actual post-tensioning stresses are calculated and compared with design as shown in Figure 8b. 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 bigger loads. The comparison between design and measurement, which is only partially presented here, is an outcome of an undergraduate student senior thesis, Liew (2010).

5 CONCLUSIONS

The Streicker Bridge at Princeton Campus, is transformed in 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. The project is in its initial phase and SHM will be upgraded with other monitoring systems. The preliminary results of monitoring provided with rich information concerning the bridge and the monitoring systems.

Important phases of bridge life were registered including early age deformation, pre-stressing, and removal of the forms. Unusual behaviors were detected in several sections of the south-east leg, and based on preliminary analysis they are attributed to the early age cracking. Post-tensioning closed the cracks successfully. The post-tension stresses in concrete were evaluated based on measurements and compared with design. The comparison shows higher stresses than designed, indicating smaller post-tensioned losses and better performance of the bridge.

Comparison between two monitoring systems was successful and at locations where no unusual behaviors were detected the agreement between the systems was within the error of measurements. At locations where unusual behaviors occurred a discrepancy between the systems were observed due to one-meter spatial resolution of distributed monitoring system.

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

6 ACKNOWLEDGEMENTS

This project has been realized with great help, and kind collaboration of several professionals and companies. We would like to thank Steve Hancock and Turner Construction Company; Ryan Woodward and Ted Zoli, HNTB Corporation; Dong Lee and A.G. Construction Corporation; Steven Mancini and Timothy R. Wintermute, Vollers Excavating & Construction, Inc.; SMARTEC SA, Switzerland; Micron Optics, Inc., Atlanta, GA. In addition the following personnel, departments, and offices from Princeton University supported and helped realization of the project: Geoffrey Gettelfinger, James P. Wallace, Miles Hersey, Paul Prucnal, Yanhua Deng, Mable Fok; Faculty and staff of Department of Civil and Environmental Engineering and our students: Maryanne Wachter, Jessica Hsu, George Lederman, Jeremy Chen, Kenneth Liew, Chienchuan Chen, Allison Halpern, David Hubbell, Morgan Neal, Daniel Reynolds, Konstantinos Bakis, and Daniel Schiffner.

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