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ABSTRACT: The Indian River Inlet Bridge is under construction in southern Delaware, U.S. The bridge carries Route 1 over the Indian River Inlet, which is a tidal canal that connects the Indian River Bay to the Atlantic Ocean. The canal experiences very strong tidal flows twice a day, which has precipitated the development of two large scour pits near the piers of the existing bridge. The scour pits have put the existing bridge, which is otherwise in good condition, in jeopardy of potential failure. The new bridge is a 1750 ft long cable stayed design, and uses a combination of pre-cast and cast in place reinforced concrete. It is nearly 3 times as long as the existing bridge and has no supporting elements in the inlet. In an effort to allow for improved long-term maintenance and management of this significant infrastructure, a comprehensive structural health monitoring (SHM) system is being installed on the bridge. An all fiber-optic based design was selected for the SHM system because of its immunity to electrical noise, reduced cabling requirements, and simpler installation. Almost 200 sensors of different types are to be distributed throughout the bridge. The sensor measurements include acceleration, strain, tilt, displacement, temperature, chloride intrusion, and weather conditions. Once completed and operational the system will provide valuable quantitative data to the bridge owner, in an easy to understand and convenient format, so that this valuable infrastructure can be optimally maintained and managed for years to come.

1 INTRODUCTION

The Delaware Department of Transportation is in the process of building a new bridge over the Indian River Inlet. Located along the Atlantic coast in southern Delaware, the Indian River Inlet is a tidal waterway that connects the Atlantic Ocean to the inland bays. The bridge carries State Road 1, which is a vital road to the region, over the inlet. During the summer months the population in the region swells as vacationers travel to the various beach resort towns along the coast. The road and the bridge are vital to the economic livelihood of the region.

The first bridge to be built over the Indian River Inlet was constructed in 1934. It was built of timber and was quickly destroyed by storms. A second bridge was built, but in 1948 collapsed due to ice flows. A third bridge was built in 1952 but was closed in 1962 due to severe storm damage. Its replacement, the existing bridge, was built in 1965. The current bridge is a three-span slab on steel girder design. Increased traffic demand required that a second, parallel bridge be built in the mid 1970's.

The superstructure of the existing bridge is in good condition; however, the bridge suffers from a serious scour problem. The main supporting piers of the present bridge are in the tidal inlet. The manmade jetties, in combination with the twice daily tides, have created a channel with very high flow rates which is threatening to undermine the main supporting piers (Delaware, 2011). Two deep scour pits sit very close to the piers. Bathymetry surveys, as well as in-service monitoring of the pits, are conducted to monitor the location and depth of the pits. Thus while the superstructure of the existing bridge could last perhaps for many more years, the bridge is being replaced because of the scour problem. An aerial view of the inlet and existing bridge is shown in Figure 1. Figure 2 shows an aerial view of the inlet with a contour plot of the bathymetry of the inlet which shows the location of the two piers and the two scour pits.

Figure 1. Aerial view of inlet and existing bridge (www.google.com, 5/21/10)

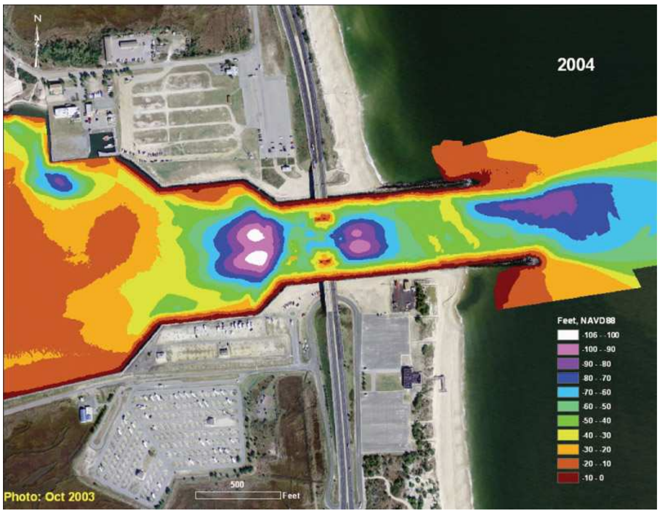

Figure 2. Aerial view of inlet with 2004 bathometry survey overlaid; shows scour pits near the piers of the existing bridge (http://www.deldot.gov/information/projects/indian_river_bridge, 6/28/11)

2 DESCRIPTION OF THE NEW BRIDGE

The new Indian River Inlet Bridge (IRIB) is a cable stayed design, with a main span length of 900 feet and a total length of 1,750 feet. It is a combination of precast and cast-in-place concrete. A typical deck cross-section is 105 feet wide. Four 250 foot tall pylons support the two independent planes of stay cables. The inlet is 300 ft wide at the point of the bridge crossing; however, the pylons are spaced 900 feet apart, taking them well out of the inlet. This aspect of the design will allow for future widening of the inlet, should that be desired. Construction of the bridge began in the fall of 2009 and is expected to be completed by the end of 2011. An artist's rendering of the bridge showing the location of the SHM system sensors is shown in Figure 3.

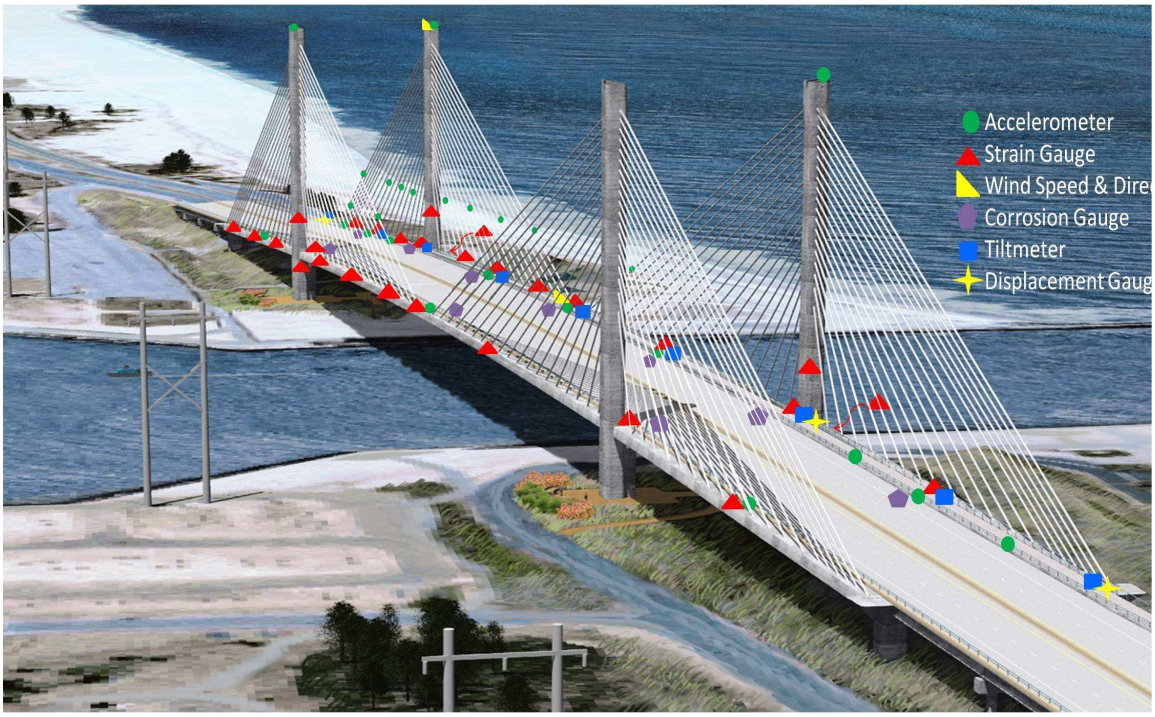

Figure 3. Rendering of the new Indian River Inlet Bridge with details of the SHM shown.

3 THE HEALTH MONITORING SYSTEM

The new bridge has a 100-year design life, and the inspection and maintenance of the bridge during that time will require a substantial investment of time and resources. By installing the SHM system, the owner, the Delaware Department of Transportation (DelDOT) will be able to understand how the as-built bridge is functioning, and through long-term monitoring will be in a better position to efficiently and effectively manage this significant resource.The University of Delaware (UD) Center for Innovative Bridge Engineering (CIBrE) championed the idea of a permanent structural monitoring system for the new bridge. The owner saw the value in having such a monitoring system and decided to make it an integral element of the design/build project. CIBrE was awarded the contract to design and install the SHM system on the bridge during its construction. While the SHM system was not part of the design contract, CIBrE has worked side-by-side with the designer, contractor, and owner to execute the project.

The SHM system is an all fiber-optic based system, with the exception of a few sensor types. The optical system was selected over a conventional analog system because of the immunity to electrical noise, multiple sensors can be placed on a single fiber, and excitation and sensing are completed using a single fiber. Since the majority of the sensors were to be embedded in the concrete, the last two features significantly reduced cabling and conduit requirements of the project, thus simplifying the design and construction of the system. The bridge itself is being built under a design/build contract; thus, the design and construction of the SHM system is by default also design/build. This has presented unique challenges to the team.

The fiber-optic supplier on the project is Cleveland Electric Laboratories (CEL) and Chandler Monitoring Systems (CMS). The system is being installed as a joint effort between UD-CIBrE and CEL/CMS. The SHM system includes four main components, (1) sensors, (2) interrogator and computer control system, (3) cabling and conduit, and (4) command and control system.

3.1 Description of the sensors

The bridge is equipped with 195 sensors. The exact type, number, and locations are listed in Table 1. The breakdown of each type was based on (1) the expected value of the data and its correlation to the long-term performance of the bridge, (2) durability of the sensors, (3) redundancy of measurements, (4) future maintenance of the system, (5) ease of installation, and (6) budget. Considering all of these factors, a final total and distribution of sensors was arrived at. The sensor positions were determined using engineering judgment and knowledge of how the bridge would behave under various loads. Although a formal investigation of the optimal location for each sensor was not carried out, the final locations are considered, based on engineering judgment, to be the most critical for the bridge.

Table 1. Sensor measurements

Quantity	Measurement	Locations
70	strain	Pylons, edge girders, deck
70	temperature	Pylon, edge girders, deck (integral with all strain measurements)
27	acceleration	Deck, top of pylons, selected stay-cables
9	inclination	Deck
3	displacement	Expansion joints
2	Wind speed and direction	Top of one pylon, deck level mid-span
16	Chloride	Deck (10 conventional and 6 fiber-optic)

All of the sensors are optical sensors, with the exception of the chloride sensors embedded in the deck and the two anemometers.

Acceleration measurements form the backbone of the monitoring system for measuring the dynamic response of the bridge. Biaxial accelerometers are located at the top of three of the pylons. These accelerometers will serve to monitor the longitudinal, transverse, and torsional accelerations of the pylons. Accelerometers are located primarily along the east side of the deck to measure deck accelerations; a few are also located on the west side. The combination of uniaxial accelerometers and some biaxial accelerometers will allow for the estimation of the vertical, torsional, and transverse modes of vibration of the deck. Biaxial accelerometers are located on 11 of the stay cables. The stay accelerometers serve three purposes: (1) estimating the tensile load in the stay cable based on the fundamental period (Ceballos and Prato, 2008), (2) monitoring for wind/rain induced vibration and (3) to characterize and monitor the damping in the stay. Used in combination, the 27 acceleration measurements will allow for estimating the global natural frequencies, mode shapes, and damping of the bridge.

The inclination of the deck will be measured at nine locations. Displacements at the three expansion joints will be measured directly using fiber-optic displacement sensors. The maximum expected displacement due to thermal variations of the bridge is 18 inches.

Three of the four pylons are instrumented with strain sensors and accelerometers. The instrumented pylon cross-sections contain four strain gauges located at the centerline of each of the 4 pylon walls. All of the strain gages used in the bridge have a gage length of 10 in. A photograph of an installed strain sensor is shown in Figure 4. With gauges at two different elevations in three of the four pylons, the axial force and bi-axial bending moments at two different elevations can be determined for those pylons.

The strain sensor being used is automatically temperature compensated: a fiber-optic temperature sensor, integral to the strain sensor, measures the instantaneous temperature of the gage and through software post-processing, makes the necessary correction. However, the temperature at the sensor is also recorded. Therefore, the thermal effect on the structure can also be assessed.

The instrumented deck segments have strain gauges located at the top and bottom of the two edge girders. The placement of the strain gauges in the tensile and compressive regions of the cross-sections allow for the estimation of the axial force and bending moment in the cross-section. The strain data will serve to estimate the thermal effects on the structure, indirect loss of post-tensioning, stay cable stress losses, and loading effects under static loads and extreme events.

Figure 4. Photograph showing a fiber-optic strain sensor mounted to rebar

To monitor the egress of chloride into the deck, chloride sensors are being installed at 10 locations in the deck. Since a fiber-optic chloride sensor with a proven track record was not available at the time the system was being designed, the decision was made to use conventional galvanic chloride ladder type sensors in the deck. These will be read using a hand-held reader from various access points along the deck. A prototype fiber-optic chloride sensor is being installed in 6 locations next to the galvanic sensors. The optical sensors will be verified against the galvanic ladder sensors.

Wind speed and direction will be measured at two locations on the bridge, at the top of one of the pylons and at deck level at mid-span. The two anemometers are conventional analog based sensors; however, optical convertors will be used so that the wind speed and direction can be read and integrated directly into the optical measurement system.

Unlike conventional analog sensors which require a voltage excitation and are read by a data acquisition system (analog-to-digital convertor), fiber-optic sensors are “excited” and also “acquired” by an interrogator. Two Micron Optics model SM130 interrogators will be used for this purpose. The interrogators are controlled by a single industrial microcomputer. The interrogators and control system will be located in a climate controlled enclosure/cabinet located under one of the approach spans. The system will be remotely accessed through a secure connection.

The main multi-fiber backbone of the system will be routed from the communications enclosure through a conduit located in a barrier on the deck. This is the only conduit that will be needed - all other fiber-optic cable will be directly embedded in the concrete, except where it is routed to surface mounted sensors. Junction boxes will be located along the deck where sensor cables will be spliced to the main fiber cable.

3.2 Command and Control of the Monitoring System

Control and interrogation of the system will be through a web based interface. The raw data will be stored locally and then periodically downloaded to computers at DelDOT/CIBrE for further processing and permanent archival. A graphical user interface will provide easy access to all of the sensor setup, control parameters, and reporting options.

The SHM system will operate 24/7. During that time two basic types of data will be collected: “monitor” data and “event” data. Monitor data is a short 5 to 10 second average, recorded once an hour or every few hours. The monitor data will be used quantify the very slow, gradual variations in the bridge that occur. These can be due to daily or seasonal thermal variations or slow degradation due to environmental effects or sustained load.

Event recording will normally be automatically triggered by one, or a combination of sensors that exceed a defined threshold, such as wind speed exceeding a certain level, or strain response exceeding a certain level. Event data will be recorded at a relatively high frequency (200 Hz) and will be used to monitor the bridge response during infrequent “high intensity” dynamic events, i.e., such as during high winds or when a heavy vehicle crosses the bridge.

3.3 Security System

Security is a concern today with any major infrastructure. An added advantage of the fiber-optic monitoring system is the ease with which a real time security system can be implemented. Cameras and sensor pads can be added and become just another type of sensor on the optical network. An integral fiber-optic security system is being installed on the IRIB.

4 REPORTING

The primary function of the SHM system is to provide quantitative data on the response of the bridge over time that can be used by DelDOT's Bridge Management group to better manage and maintain the structure. The data will be continually collected; results will be summarized and reported in Monthly Reports and more detailed Yearly Reports.

Monthly Report – will consist primarily of data tables. These would include: statistical summary of the monitor data for all sensors for the previous month, statistical summary of the event data captured for all sensors for the previous month, and comparison of maximum measured values (event and monitor) to design values. Identification of measurements that are (1) out of their expected range or (2) suggest a possible change in the behavior/condition of the bridge.

Yearly Report – will consist of data tables, graphs, and analysis and discussion of the findings. These would include: statistical summary of the monitor data for all sensors for the previous year, statistical summary of the event data captured for all sensors for the previous year, comparison of maximum recorded values (event and monitor) to design values, analysis of trends over time, analysis and discussion of results from a controlled load test and comparison to the baseline controlled load test results, interpretation and discussion of measurements that are (1) out of their expected range or (2) suggest a possible change in the behavior/condition of the bridge.

The SHM system will also be setup to provide automatic warnings and alerts to DelDOT and UD, through email and text alerts, if a sensor or sensors exceeds a specified threshold.

5 PROGRESS TO DATE

At the time of writing 70% of the sensors or the embedded fiber for surface mounted sensors has been installed. As the project is a design/build, the design and installation of the SHM system has also, in many ways, been a design build. Some of the installations are similar, thus once the process is established it can be repeated. However, with each new section of the bridge comes new challenges and hurdles to overcome. The CIBrE team has gained valuable experience from the project. The installation has not in any way affected the construction schedule of the bridge. The installation of the SHM system is on-track with the bridge construction schedule and is within budget.

6 CONCLUSIONS

A state-of-the-art structural health monitoring system is being installed on the new Indian River Inlet Bridge in Delaware. The all fiber-optic system is designed to provide quantitative data on the response of the bridge for many years to come. The data will become part of the inspection record of the bridge, and will be used to better manage and maintain this significant resource for the state. To the best of the author's knowledge, this is the first comprehensive SHM system of its kind to be installed on a new cable supported bridge in the United States. In that regard it will also serve as a test bed for other SHM systems and other bridges around the country.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

Ceballos, M.A., and Prato, C.A., 2008. Determination of the axial force on stay cables accounting for their bending stiffness and rotational end restraints by free vibration tests, Journal of Sound and Vibration, Vol. 317, pp. 127–141

Delaware Department of Transportation Report, "Purpose and Need," 2011, http://www.deldot.gov/information/projects/indian_river_bridge/index.shtml