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Executive Summary Report

Instrumentation of the Maumee River Crossing

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Project Background

This project has focused on the instrumentation, monitoring and testing of the main span unit of the VGCS, one of Ohio's first long-span, cable-stayed bridges and one of only a few dozen such bridges in service in the nation. This effort looked at five main areas: (1) health monitoring; assessment of the changes in force distribution and bridge condition during erection and early service, (2) verification of design assumptions during erection, (3) investigation of the unique design features which have been incorporated into the VGCS, (4) investigation into the unique erection features and sequencing which will be used during its construction, and (5) investigation of stay cable vibration which is a general, unresolved issue for bridges of this type.

Study Objectives

The purpose of this and associated documents is to outline the completed scientific study, which happened to consist primarily of two phases. The first phase (Nims, 2002), contracted at the District level, included the initial structural analysis, modeling, instrumentation package design for the monitor, and casting into the segments of the embedded sensors. The goal of this first phase was to capture the critical instrumentation issues associated with this construction project and to develop a detailed instrumentation and testing in close consultation with ODOT officials, bridge designers, and construction contractors.

The second phase (Helmicki, 2003), contracted through Central Office, included permanent instrumentation operated through a computer controlled, digital data acquisition system located on-site and accessible tele-remotely via direct fiber optic internet connection, field calibration of a main span finite element model using truckload and modal field tests; verification of various design assumptions and erection load conditions; creation of a database of measurements for use as a supplement to the designer's maintenance manual to provide guidance for conducting future maintenance, and determination of vibration performance of stay cable damping system under wind and rain-induced excitation.

The goal of the second phase was to finish the monitor installation begun in the first phase, establish a baseline concept of structural behavior and performance by utilizing a combination of field tests and ambient monitoring, capturing the overall structural concept by calibration of the finite element models, and finally benchmarking the condition of the structure by comparison of the above with its design values.

Description of Work

A health monitoring system for the bridge was designed, planned, and implemented for the Veteran's Glass City Skyway bridge, with data collection and archival throughout its construction and ultimately an automated, user-friendly interface on a dedicated website. The primary criteria for selecting the instrumented segments were the predicted stresses and rating factors using the analytical data provided by the designer. A total of 64 vibrating wire strain gages were installed in eight segments at four cross sections to monitor the long-term behavior of this bridge. Data from these gages has been collected since the casting date of each segment. A method of assembling the time line was developed, a Matlab program was written to combine the strain time history line for the data of one strain gage, and the experimental stresses were compared to analytical stresses calculated by the contractor.

An extensive component of the project involved the use and development of analytical and FE models of the structure for a variety of reasons. Keeping in mind that the instrumentation suite employed for VGCS is a sparse one, it was decided to progressively calibrate the model; that is, make changes to the model parameters such as stiffness and support conditions so that the model output correlates well with the measured data even for intermediate stages of construction. This was done to instill confidence in the use of the model as a maintenance tool.

By checking the gages at the same elevation located in the same longitudinal position, the assumption of a two dimensional model, where there is little bending about the vertical axis was verified. Based on this verification, information from one top and bottom gage in each cross section is concluded to be representative for the local load condition.

The next step was using the strain gage data to derive experimental stress time histories to compare them to the construction finite element analyses. To calculate converted stress time histories, the initial strain and modulus of elasticity are required. The initial strain for each gage can be obtained from the strain time history on the casting date. The modulus of elasticity can be assumed to be a constant because the construction procedure did not take too long time and thus influence the modulus of elasticity much.

Above all, this work supplied a convincing confirmation of both the accuracy of the gage monitoring process and the finite element analysis used in the design and construction of the VGCS.

The following actions are recommended for further data review:

- The modulus of elasticity as a time dependent coefficient should be studied in the future to generate a more accurate experimental stress time history line for a long time comparison and prediction.

- The continuous database of collected strain needs to be updated to the current time. Based on this database, the long-term monitoring, the future load condition prediction, and load rating can be correlated with the contractor's or another model.

- The zero strain estimate for each strain gage is inherently uncertain. The method of determining the zero strain should be more fully developed to minimize the uncertainty

- Other factors, such as temperature and geometry, which could influence the reduction of the strain gage data needs to be studied in the future to get a more accurate result.

Towards this goal, temperature gradients in the VGCS were studied with two main goals: to preliminarily assess if the bridge behaves as the AASHTO Code predicts, and to lay the foundation for future studies of temperature gradients. Plots of the positive temperature gradients were fairly consistent for most of the collected data. This consistency was in the shape of the gradient, while the actual temperatures varied. It was found by inspecting the plots that the actual gradients follow and typically fall within the design gradient. Plots of the negative temperature gradients were not as consistent as the positive temperature gradients, however, they were still insightful. Plots for two of the eight months of negative temperature gradients followed the general idea of the top slab being colder than the bottom slab, while the other six months actually were positive temperature gradients, indicating that negative temperature gradients never occurred during those months.

In addition to the temperature analysis, certain local aspects or features of the structure were directly instrumented and investigated throughout this project in order to validate certain design estimates/behavior and to use this knowledge in the FE model.

During the first phase of this project, a delta frame was also instrumented and monitored. A sparse array of instrumentation concentrated in areas of high strain was used to resolve uncertainties in modeling of a complex element of a cable stayed bridge. After calibration, the element model was used to verify that there was no cracking before service. This conclusion was also supported by the visual inspection of the delta frame done during construction. Finally, the calibrated model of the element can be placed confidently in a model of the overall bridge.

Two research studies focused on investigating the concentration of strain in the bottom slab by comparing the deadload and liveload results of the experimental data to the analysis results provided by the design engineer.

Wright investigated strain concentrations in the bottom slab of the VGCS caused by the post-tensioning tendons used to hold the delta frames in place. Results of the research monitoring strain levels immediately behind the delta frame tension block following the tensioning of the DF4 tendon indicated that the strain magnitudes attenuated quickly when moving away from the zone of predicted response**.**

Ward studied the transverse bending behavior of the bottom slab by monitoring the slab prior to installation and after the bridge was completed and opened to traffic. Experimental results at a construction stage prior to stressing stay 8 were compared with analysis provided by the designer. Experimental results were higher than predicted by the design engineer, but less than those predicted by the construction engineer. Strains approaching the yield for reinforcement (approximately 2000με) were not observed at any point during construction. Strain magnitudes did not exceed 300με for any of the gages installed on the bottom slab.

In addition, data recorded during live load tests including the crane withdrawal and full scale truckload tests confirms the assertion that dead load bending behavior dominates the transverse bending capacity of the bottom slab. Dead load effects caused by the self-weight of the segments and delta frames are the predominant factor in determining the capacity of the bottom slab in transverse bending of the bottom slab.

A series of two sets of truckload tests was conducted on the structure. These were planned and run with two main goals in mind. One goal was to obtain baseline readings of the bridge so that future load tests could be run and the two sets of data could be compared. Comparing the data sets will be useful when assessing the health of the bridge, as increased levels of strain could indicate a loss of structural integrity such as excessive concrete cracking, or post-tensioning strand deterioration. The other main goal of the truck test was to confirm the Larsa model. By comparing the influence lines with the dynamic loading data, the model was confirmed. This confirmed model can be used in the future to predict stresses, strains or moments for any load configurations for future truck tests. The model could also be calibrated in the future to account for structural deficiencies found during future truck tests. With a model calibrated for structural deficiencies, it would be possible to look at any point in the bridge and determine if there were any sections which were overstressed, or could potentially become overstressed if further deterioration occurred. Thus, the health of the bridge could be monitored over time and structural repairs could be suggested based on any deterioration found either through visual inspection or by increases in strains from a truck load test.

In another aspect of this study, the allowable stress (ASR) load rating method was used to evaluate the inventory load rating factor for analytical and experimental stresses. This work utilized results obtained from both models, long term monitoring results and truckload testing.

Stay vibration tests were also performed during multiple stages of cable erection of the Veteran’s Glass City Skyway Bridge. The stays at VGCS have unique structural characteristics that posed challenges to traditional vibration-based force estimation. Unlike the high density polyethylene sheathing system often incorporated on cable stayed bridges, the relative stiffness of the stainless steel cover pipe prevents the sheath and strands from making contact except at a limited number of locations. The sheath can account for approximately 25% of the total cable mass and its influence needed to be taken into account for accurate estimation of cable tension. After refining the cable force formulation based on field test observations, future vibration-based force estimations can be implemented in lieu of lift-off measurements.

Operational modal tests were also employed for this structure and modal parameter estimates obtained are shown to have comparative results with respect to at least two algorithms. With the help of the available knowledge in terms of the FE model, all the important modes have been estimated properly and compare well with design.

An automated long-term health monitoring system was custom developed for this project. The use of open-source software and web standards makes the system more apt to future customizations and additions. Currently the system consists of the following modules: data collection, data analysis and storage, and the web interface. High speed connectivity allows for more frequent data collection which enables close to real time monitoring of the bridge and conditions like cold weather or icing. This also allows for a close to real time model of the bridge for possible fault detection and warning.

Research Findings & Conclusions

To summarize, based on the discussion above, this project sought to implement and operate an appropriate instrumentation and field testing program to support management of the VGCS through construction and on into its service life. This program augments the traditional visual inspection program to provide objective, quantitative data for use by ODOT in assessing the status of the structure. There is value in continuing to collecting, archive and analyze the strain data from the bridge. The data will give insight into how the bridge is ageing and ascertain that the actual long term behavior is that expected during design.

Implementation Recommendations

The monitor and its website should continue its real-time service for several reasons:

1. Full documentation of the entire project and all the related papers and references. This includes full documentation of the monitor system hardware and software together with a comprehensive listing of the data collected, the frequency of collection, any data post-processing steps necessary, and a standardized set of algorithms/methods/strategies for data interpretation.
2. A continued on-line database which documents the deadload response at the instrumented (and critical) sections of the bridge from initial construction and into service.
3. Future review of the effects and extent of very long-term behavior, such as creep in the concrete or degradation of the post-tensioning reinforcement, at the instrumented locations.
4. User-friendly access to the above.

A regimen of truckload testing could be implemented or, at the least, conducted when concerns develop. This would validate the global safety and integrity of the structure by proving its ability to carry the intended liveload at the instrumented (and critical) sections of the bridge. In addition, changes from the baseline response would be an indicator for damage or deterioration.

A regimen of stay vibration testing could be implemented or, at the least, conducted when concerns develop. This would validate the local integrity and deadload of the stays by measuring its current frequency and comparing it directly with the baseline tests.

The calibrated analytical finite element (FE) model of the main span system is available for a variety of implementations. For example, this model can be used as a tool by the ODOT structural engineers to perform simulation studies for various purposes. In the near term, such a model could be used much like BARS to provide information necessary for overload permit issuance and load rating. In the long term, the model will be available for simulation-based studies in case any damage occurs or repairs or retrofits are needed. Also, the model will be available in the unlikely event that one or more aspects of the performance of the bridge does not turn out as anticipated by the designers (e.g., vibration levels, etc.).

A full set of specifications for highway bridge instrumentation, truckload testing, and real-time monitoring could be formalized and implemented by ODOT as a new section in their Bridge Design Manual or their Construction and Material Specifications Book based upon this and other like projects.