Instrumentation of the US Grant Bridge for Monitoring of Fabrication, Erection, In-Service Behavior, and to Support Management, Maintenance, and Inspection

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Project Background

The replacement of the US Grant Bridge over the Ohio River in Portsmouth, OH, was initiated by the Ohio Department of Transportation (ODOT) in 2001 when the original bridge was closed and demolished, and its substitute opened on October 16, 2006. The new structure consists of 9 spans, including a 875’ main span crossing the Ohio River, for an overall bridge length of 2,155’. The design of this replacement structure is a steel cable stay design with steel girders and floor-beams supporting a post-tensioned concrete deck system nearly 65’ wide carrying one lane of traffic in each direction. Each of the two main pylons/support towers are 288’ above the waterline and the main span deck sits more than 85’ above the Ohio River. The design calls for a radial arrangement of a system of 32 cables of seven-wire strands with anchorages at both deck (floor-beam web) and pylon. The combination of epoxy-coating, grout filling, and outer tubing provides protection for the all-important structural cabling suspension system from both weather and corrosion. Ironically, however, these same features make it impossible to gain direct access to either the cables or the interior of the anchorages which, in turn, presents special challenges for inspection and rehabilitation of these critical bridge components on bridges of this type.

It was envisioned that the long-term behavior of the new US Grant Bridge and any associated changes in its structural condition could be best understood with the aid of a longitudinal study beginning during bridge construction, one that includes instrumented monitoring of both construction/erection and in-service phases of the life of this bridge. Such an approach, integrated with traditional bridge management techniques, would help lead to a safe and economical realization of the 100-year design life of this structure. A health monitoring system for the bridge would be designed, planned, and implemented, 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 would be based upon the predicted stresses and rating factors using the analytical data provided by the designer. Bridge Plans Addendum and Construction Contract Bid Documents would be developed to document the monitor design and its requirements during construction.

Study Objectives

The project sought to identify an appropriate instrumentation and field testing program to support management of the US Grant Bridge. This program augments the traditional visual inspection program to provide objective, quantitative data for use by ODOT in assessing the status of the structure. It was anticipated that the instrumentation plan will be designed to allow researchers and ODOT officials capture key aspects of the behavior of the bridge during both the fabrication and erection phase as well as during in-service use.

Key variables that were monitored include:

- Weather conditions (i.e., temperature, precipitation, and wind direction and velocity).
- Cable acceleration in response to thermal, wind and traffic loads, in order to characterize vibration levels and mechanisms. Loads and stresses were calculated in order to ensure proper tensioning and positioning.
- Acceleration of selected deck sections in response to thermal, wind, and traffic load to compare with the designed frequencies of its movement, and to resolve any coupling with the stay movements themselves.
- Longitudinal stress of selected exterior girder and deck sections, particularly at abutments, pylons, and mid-span (high moment regions), in response to thermal, wind, and traffic load. These were used to monitor stress levels as compared to the design values and movement of the neutral axis of the section, and to obtain information on the integrity of the designed level of composite action.
- Thermal cross section of exterior girders and decking sections, over time, to resolve the environmental responses and internal strains of the structural components, and separate them from traffic responses.

A schedule of regular and automated monitoring, controlled truckload tests, and ambient cable vibration studies were also developed for the purposes of structural identification. The monitor and controlled tests/studies utilized installed sensor suites, and yielded the necessary information for comparison with design values as well as to calibrate finite element models of the structure. Such models were useful in determining the bridge response, globally, and interpolating responses at locations where gages were not mounted, developing trend lines for bridge response over time to understand long term behavior of structural systems, and provide a response-prediction tool which can be used for rating and issuance of overload permits, etc.

In the initial phase, proper arrangements were made with the construction contractor for necessary on-site assistance in installing gages to monitor the bridge’s response to construction loadings (responses accumulated through erection, etc). Subsequently, environmental loadings (from wind, temperature, etc) and traffic/in-service loadings were employed, after construction, without requiring the need for contractor assistance. All instrumentations were operated by a computer-controlled, digital data-acquisition system located on-site, and accessible tele-remotely via direct modern/telephone connection. The goal was to achieve a high degree of monitoring intelligence so that the system would be user friendly and would alert ODOT officials of anomalous structural events.
Description of Work

UCII researchers prioritized the many possible events of concern that may occur throughout the construction and service of this bridge, and winnowed the critical sections down to only five due to budget constraints. Existing design calculations and erection analyses were used to specifically identify the five critical sections to instrument, test, and monitor these variables during the life of the bridge. Allowable stress rating of the exterior girder section identified three minima of concern for the bottom flange in terms of positive moment and three for the cast-in-place (CIP) joint/decking above the girder in terms of negative moment. There was three of each, corresponding to each span of the structure. They do not necessarily coincide with each other, due to the very nature of a stayed structure and its staged construction; however, the middle and Ohio spans are proximate.

The Kentucky span is not a coincidence due to its large negative moment occurring near the end of construction when the bridge is weighed down and tied at the abutment in order to achieve the desired vertical profile for the structure. The ratings were also important because they enabled the identification of sections which may actually be classified as "cracked" (according to the designer) or non-composite. Note that the ratings for the pre-cast deck panels are also considered, which includes the post-tensioning to considerably improve the rating over the CIP joint/decking.

Finite Element Model

A three dimensional model, able to represent the real bridge geometry accurately, as well as having the ability to simulate symmetrical and unsymmetrical loading, was needed. Two finite element analysis packages were used depending on the desired response. The initial part of the research was conducted using SAP2000 version 7.44 (and version 10.0 later on) and the latter part of the study was conducted in ABAQUS, owing to limitations of SAP2000 to handle the involved complexities of the problem.

Construction Loads

A significant amount of effort was expended in this project to measure, record, and interpret the behavior of the steel framing and composite concrete decking system during construction. This included monitoring the induced stresses and strains, where and when they occurred, and investigating causative effects. The main components of the framing system, namely the edge girders and the cast-in-place concrete strip directly above them, were comprehensively instrumented and continuously monitored during the construction of the bridge. Instrumented monitoring commenced immediately before the segment was erected onto the bridge, through any temporary stressing or profiling with the stays or post-tensioning strands, placement of the precast concrete deck panels, during the concrete pour and curing of the cast-in-place strips, and as other segments were installed on either side of its respective tower, throughout most stages of its construction and into (and beyond) service on October 16, 2006. Note that for most of the instrumented segments there is relative agreement between measured and estimated values.

Stay Vibration

At the end of construction, several rounds of field experiments were conducted to investigate the ability to estimate cable tensions using vibration-based measurements. Because the configuration of cable stays prevents direct measurement of the internal wire strands that comprise the stay, these measurements have been made by measuring the motion at the sheath. Based on the series of experiments, it has been shown that accurate tension estimates could still be made by measuring cable motion at the sheath even with the cable cross-ties in place.
Truckload Testing Results

ODOT provided four tandem-axle dump trucks to conduct static and moving truck load tests at the end of construction (2006), after initial repairs at the Kentucky abutment (2009), and after the installation of exterior pulldowns (2012). Upstream and downstream edge girders have comparable response to truckload; however, the thermal response for some gages (e.g., web) dwarfs the liveload response. Composite action is clearly evident in all test results, with a greater slope in the strain profile and hence large effective deck width than predicted by analysis. Lane load results control over the truckload results and are used as the liveload response in the rating analysis of the structure. Measured results are slightly less than the conservative predictions of the design analysis, with two exceptions at the middle span and Kentucky abutment. These locations should be especially observed during inspection for unexpected signs of distress.

Pulldown Instrumentation and Testing

Additional instrumentation was installed at the Kentucky abutment (KYA) to monitor and track changes in its state of stress during and beyond the pending retrofit at that location. Vibrating wire gages were to be installed on both of the new upstream and downstream pull downs and at the abutment wall near KYA. Just as there was consistent behavior for the strain gages on the exterior girders over time, the strand and tilt meters show daily and seasonal cycles with very little drift over their deployment. The results provide a liveload benchmark of the pulldown sensor package for future reference, and allow some rating analysis for the pulldowns themselves (found to be 2.0 under static truckload).

Structural Analysis and Load Rating

An inventory HS25 rating using both the allowable stress and load factor methods was formulated for both the composite and noncomposite or cracked case for each section as defined by the stations used by both the designer and the erection engineer. Each section was analyzed by each method at the bottom flange, top flange, cast-in-place (CIP) decking immediately above the edge girder, and for the deck panel adjacent to the edge girder which is to include the effect of the post tensioning (PT) force reported by the erection engineer. In addition, each of these members was analyzed under both the positive and negative liveload moment reported by the designer.

Many of the sections have a bottom flange whose dimensions are such that the section will fail the compression flange check for compact and even braced sections. Many of the sections have lateral bracing (e.g., floorbeams) which does not meet the specification for the compression flange of a compact nor even a braced section. Without some guidance from the designer, we reduced the ultimate moment for negative moment regions to the yield limit state due to this concern. Accordingly, we calculated both the measured (RF = 1.11) and designed (RF = 1.13) load factor rating at the instrumented sections of the US Grant bridge. This inventory rating was formulated using the measured deadload and superimposed deadload (DL) from the vibrating wire strain gages, both with and without the measured liveload (LL) response from the moving truckload tests, for the instrumented sections at the End of Construction (EOC) in October, 2006. For the same stations, an inventory rating was formulated using the analytical estimates of the erected deadload (version 3) and the design liveload by the designer for comparison. The measured load factor rating remained about the same (RF = 1.18) based upon field measurements of both deadload and liveload; however, the critical location switched from the center span to the Kentucky abutment due to the field restoration of the pulldowns.

During our Project Review with ODOT in 2009, we were asked to report ratings in two distinct fashions: 1) deadload based only upon EOC structural condition (RF = 1.26), and 2) deadload which incorporates both EOC structural condition and any/all other long-term effects and events that were not included within the EOC data (RF = 1.15): seasonal cycle upon the bridge (e.g., thermal, boundary conditions), creep and shrinkage effects on the concrete CIP joint, the initial repairs at the Kentucky
abutment, etc. Of these, the main effect is the seasonal cycle; however, all are actual measured stresses that would constitute a reduction in capacity and lead to the most conservative estimate of the load rating.

In 2010, the designer provided a draft of their Bridge Analysis and Rating Report for the U.S. Grant Bridge to ODOT. A global model of the entire structure was used to calculate the internal demand forces for various structural components of the bridge, including the edge girders, cable stays, deck panels, floor and strut beams. In their rating report, the designer reported that the bridge just barely reached an HS20 inventory rating (RF = 1.0) using Load Factor Method, with the most critical location identified as the West Girder of Segment 15N. Given that our deadloads and liveloads are not sufficiently different to cause such a reduction in our ratings, the reduction must come from capacity.

In 2011, the designer provided a written draft of their Manual for Load Rating and Permits for the U.S. Grant Bridge to ODOT. Most commonly, the segments do not pass the lateral bracing check for a braced noncompact section. Hence, the capacity is reduced to that computed for a partially braced member. Unfortunately, it is not entirely clear as to which reduced capacity of several listed is considered in their rating; so, to be conservative, we assumed the smallest value listed by the designer for a given segment for the capacity of the edge girder segments and subsequent load factor ratings (RF = 1.49). This inventory assessment only considers the marked lanes (and not the two large shoulders) for HS20 lane load and structural deadloads. An operating assessment was made (RF = 1.29) which also included environmental and other long-term deadload effects.

In 2010, the designer redefined the allowable stress for the stay cables as 50% of gross ultimate tensile strength (GUTS) for inventory rating purposes. They list East (or Upstream) Stay 16N as the critical stay with an inventory rating of 1.35, based upon their structural model discussed above. Our stay test results were generally within 10% of those predicted by the erection analysis; hence, our field ratings should be within 10% of those determined by the designer Manual.

**Website Design**

This automated long-term health monitoring system for bridges is highly customizable and modular thus making it possible to add additional gages or other data driven devices. One main reason is the utilization of the existing manufacturer's software in a customized fashion. The most important and potential stopping point for such a system is remote connectivity but with modern devices such as cell phones even fairly remote locations can be connected. The use of open-source software and web standards also 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.

The data collection and warehousing of gage readings means not only can officials do further analysis of the bridges health but a historical archive of bridge performance is recorded. Plotting of strain data for multiple sensors over varying time frames means ODOT and UCII can further analyze the health of certain sections or the bridge as a whole over seasonal changes. 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
The benefits of the overall project were twofold:

1. A database of field measurements, together with structural interpretations, which provide objective information for use as part of the bridge management process specific to this bridge.
2. A deeper understanding of the general behavior and performance of cable-stayed bridges - one that could be used on, and transferred to, other cable-stayed bridges constructed and/or planned in Ohio (e.g. Veterans Glass City Skyway, Pomeroy-Mason, Ironton-Russell, etc).

These would help facilitate the management of this portion of the ODOT bridge inventory, and help make it possible to reach the expected service life of 100 years in an economical manner. Other specific benefits include:

1. Formation of a team with the knowledge and personnel to support ODOT’s efforts in effectively managing cable-stayed bridges.
2. General increase in understanding of the inspection, maintenance, and bridge-management issues associated with cable-stayed bridges by key personnel in Ohio (universities, ODOT and the industry at large).
3. Development of field-ready monitoring strategies, aimed at supporting inspection and maintenance/management activities, and reducing life-cycle costs.
4. Implementation and continued operation of a monitor, using the aforementioned strategies at the US Grant Bridge.
5. Collection and archival of a comprehensive information bank, based on instrumentation and field observations of the US Grant structure, together with recommendations for possible actions to be taken during construction and service.

Recommendations for Implementation of Research Findings

Given the concerns stated above regarding the capacity of the designed structure, UCII recommends regular maintenance and continued monitoring with the designed health monitoring system. In addition, special attention should be directed to the stations mentioned above during visual inspections (specifically, the Kentucky abutment and the middle of the center span). The maintenance manual calls for regular inspection and lift-off tests of select stays in order to check for any changes in their deadload force. Finally, we recommend a regular regimen of truckload tests for comparison with the baseline tests provided herein.