Bridge instrumentation for long term structural health monitoring

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ABSTRACT: Advances in structural analysis, instrumentation, data management, and reporting make it feasible to reconsider alternate approaches for bridge design. A new procedure can incorporate development of a “baseline” bridge model that can be used for structural health monitoring (SHM) of the bridge over its lifetime. Regular and effective use of SHM for bridges can provide more objective data on bridge conditions over time and lead to improved maintenance for more efficient use of limited resources. This approach has great promise at a time of aging infrastructure and limited funds for maintenance and repair.

This paper presents a new procedure for bridge design and load rating that incorporates the development of a long term SHM system which will lead to more efficient and effective bridge maintenance and management. A baseline finite element model that represents the actual 3D system behavior of the bridge is presented as a part of the designer’s submittal requirement. Such a calibrated model captures the design intelligence envisioned by the original designers. For this project, a continuous three span composite steel stringer bridge in Barre, Massachusetts was used as a pilot bridge. During construction, a monitoring system was installed in order to capture the locked in stresses that occur in the girders during construction, prior to being fully loaded. Once construction was completed a static load test was conducted to provide data that could be compared to the baseline model for verification. It is intended to use the collected test data during and after construction for finite element model updating using PARIS, a parameter estimation program that was developed at Tufts University. There are several benefits to the bridge owner of having a structural model that reflects the actual bridge 3D system behavior that can be used for load rating and overload permitting.

This paper presents a collaborative research project currently funded by the Partnership for Innovation and the CAREER programs at the National Science Foundation to develop a framework for bridge condition assessment integrating instrumentation and structural modeling for highway bridge decision-making and management.

1 INTRODUCTION

1.1 Current state of affairs: Why the time is right?

The 1956 Interstate Highway Program expanded the U.S. highway system to include over 500,000 bridges. This unprecedented period of infrastructure construction was arguably the greatest single coordinated building effort (Gifford, 2006). There was no monitoring or condition assessment component included in this initial design and building effort. After 50 years of service, many bridges are approaching the end of their design life, and require repair or replacement. From a perspective of infrastructure system performance and management, the situation is critical (Chase, 2006). A modern society cannot function with inadequate infrastructure, and thus the U.S. faces a monumental task of repair and reconstruction. Travel on this system increased by 38% from 1990 to 2004 while capacity grew 6%, according to TRIP (The Road Information Project). TRIP predicts interstate travel will increase an additional 60% by 2026 (Copeland, 2006). According to the American Association of State Highway and Transportation Officials (AASHTO) Bridging the Gap report, 12% of U.S. bridges are functionally obsolete, while 13% are rated as structurally deficient (AASHTO, 2008).

The structural health and condition of in-service bridges is typically assessed through visual inspection and nondestructive testing & evaluation (NDT/NDE) conducted on a pre-set maintenance schedule. Highway bridges in the U.S. require inspection at least every two years. The results of manual inspections are, to a degree subjective, and the data is limited due to the frequency of inspections.

Recent advancements in technology have made bridge structure instrumentation more feasible (Cubillo et al, 2006). FIFWA envisions sensing and measurement capabilities fully integrated into the design, construction, and operation of the bridge of the future (ISHMII, 2004). Even with the advances in technology, it is still not practical to install SHM for bridges. The basic concept is clouded by errors introduced by bridge modeling, instrumentation per-
formance and interpretation, data management, and other sources of error.

In January 2008, the National Science Foundation (NSF) selected a team of researchers from Tufts University, the University of New Hampshire, Fay Spofford & Thorndike, and Geocomp Inc. to participate in a project, “Whatever Happened to Long Term Bridge Design?”. The goals of the project include evaluation of bridge design procedures to facilitate long term monitoring and development of structural health monitoring systems. To help achieve these goals, the research team, working in cooperation with highway departments in New England, proposed to develop a “baseline” analytical model of a highway bridge. This model would be as close as possible to a “perfect” analytical representation of the bridge structure, in contrast to the typical AASHTO analysis model with its appropriately conservative assumptions and element-based approach. The baseline model will be updated with collected field data from the sensors installed on the bridge during construction. The comparison between analytical predictions and collected field data will facilitate the evaluation of bridge performance over its design life. This research will advance the development of procedures for deployment of a structural health monitoring program for bridges, leading to better and more cost-effective bridge maintenance and management programs.

In support of the NSF project, the Town of Barre, Massachusetts, in coordination with the Massachusetts Highway Department, granted the research team access to Bridge #B-02-012, Vernon Avenue over the Ware River in Barre, Massachusetts. The research project includes the development of a structural baseline model of the bridge, instrumentation plan and monitoring program.

1.2 Current state of the art of bridge design and structural health monitoring

Current design methods explicitly account for “opening day” conditions. The bridge design code specifies rigorous, mathematical treatment of initial state requirements. Long term requirements such as future inspection, corrosion, and reconstruction are not generally treated as part of the rigorous design matrix approach. These issues are either dealt with subjectively by the design code or not at all. As a result, long term issues are dealt with over the bridge’s life without the benefit of a rigorous design approach prior to construction. This can lead to a “reactive” mode by the responsibility of the over-taxed bridge management team. In the current design process, the design essentially ends at opening day. The analysis and decision-making process that comprises the initial design is completed and filed away, often in a format that is difficult for subsequent interpretation and use.

Prior to developing an integrated framework for structural condition assessment, the current bridge design paradigm must be adjusted to more rigorously account for long term conditions. In current AASHTO design practices, bridges are designed on an elemental basis. Each bridge component is treated separately, with analysis providing enveloped moments and forces representing a maximum limit state for the component. This approach is appropriately conservative and suitable for design. But it does not provide a realistic analytical representation of the bridge structure. Without such a realistic model, a SHM could not be employed.

This research project includes the development of a “baseline” structural model. The baseline model is an analytical model accounting for the full system behavior of the structure, as opposed to the traditional elemental approach which envelopes loads and conditions to individually evaluate bridge structural components. Incorporation of a baseline model into long-term bridge management would provide a useful tool for design verification (Myroll et al., 2001), condition assessment, long-term structural health monitoring and potential rehabilitation (Feng et al., 2004) using collected data from instruments deployed during construction. Repair and rehabilitations needs make it imperative that long-term conditions be better considered in the design process.

Current technology for data management and field sensors make it increasingly feasible to design new bridges more rigorously for long term conditions and performance.

1.3 Closing the design loop

The process of bridge design today, regardless of the method of project procurement, is for a designer to prepare a set of construction documents which include drawings, specifications, calculations, and special reports. In a design-bid-build project, typical of U.S. public works construction, these construction documents are included in the bid documents. On the day of delivery, the analytical process largely stops, i.e. it is considered “complete”. The graphic drawings may be updated to form an as-built set of documents. However, unless there is an extreme variation between design conditions and as-built field conditions, usually the analysis and design calculations are not updated. So in most projects, there is no feedback mechanism between what was designed and how it performed. This is essential information that the original designer usually never receives.

In the past, design calculations were prepared manually. The calculations represent documentation of the analytical design process that formed the decision making basis for the nature of the bridge: what type of beams, what size deck, and so on. Many state departments of transportation (DOTs) have vast storage sites full of calculation files. Some organiza-
tions have used data processing methods to better record the information. The design calculations could be submitted in the form of a “baseline” model accompanied by a prescribed, transparent documentation. Such a baseline model would be invaluable to future maintenance and evaluation of the bridge. Engineers could use the model to more easily and accurately perform load rating of the bridge and evaluate its structural health.

NDT data can be used to verify design assumptions and the data is available for revisiting analytical models and updating, for the purpose of using them for future structural evaluation. Structural parameter estimation can serve as a platform for the correlation between the “baseline” model and NDT data. One of the problems facing bridges owners is the large amount of structural health monitoring data that is collected for each instrumented bridge (Cuelho, 2006). This “baseline” model will provide bridge owners a platform to translate the collected field data into decision-making information that is directly related to the components of the bridge structure.

2 CASE STUDY: VERNON AVENUE BRIDGE IN BARRE, MASSACHUSETTS

2.1 Bridge properties

Vernon Avenue over the Ware River in Barre, Massachusetts was constructed during the summer of 2009 and opened to traffic in September, 2009. Owned by the Town of Barre, the bridge was designed by Fay, Spofford & Thorndike and constructed by ET&L Corporation. Design and construction work was administered under the procedures and guidelines of the Massachusetts Highway Department. This bridge is a 150 foot, three-span continuous bridge, as shown in Figure 1. It is comprised of a concrete deck supported by six steel girders. This three-span continuous bridge spans the Ware River which flows at a maximum depth of approximately 10 feet. The eight inch (203.2 mm) concrete deck was cast-in-place (CIP) during a single continuous pour. The construction included seven diaphragms along the length of the bridge and a Town of Barre water line running underneath the bridge deck.

Capturing the behavior of this bridge required an extensive instrumentation plan with various types of sensors, data acquisition boxes, data transfer devices, and data storage devices. This instrumentation plan was deployed during the construction process to be able to capture the full strain history of the bridge. The instrumentation of the Vernon Ave Bridge will also serve as a guide for future instrumentation projects and will examine the need for redundant instrumentation locations.

The instrumentation plan of the Vernon Ave Bridge includes 100 strain gauges, 36 girder thermistors, 30 concrete thermistors, 16 bi-axial tiltmeters, and 16 uni-axial accelerometers at 13 stations across the span of the bridge, as shown in Figure 2. These data sets will be collected using iSite® data acquisition boxes provided by GeoComp, INC.

2.2 Instrumentation details

Strain sensors and thermistors are distributed along the length of each girder on both sides of the web with the exception of the exterior girders, which only have instrumentation on the interior face, Figure 3 shows the instrumentation for Girder 3, which is typical for all interior girders. Each girder was fabricated in two parts with a splice located just off the north pier. All iSite® boxes were clustered on the south end of the girders for ease of access to a power supply.

Each station was selected to provide maximum information relating to the bridge performance. A detailed structural model and engineering judgment were used to predict the location of inflection for static deflections, induced by a truck load, see Figure 4. These locations were selected by the research team and then reviewed by the bridge designers and management team. It was vital to get the input from all parties related to the life-cycle of the bridge in order to maximize the future benefit of this instrumentation plan.

The strain sensors were manufactured by Omega technologies. The strain gauges and thermistors were installed at the steel fabricator yard in Lancaster, Pennsylvania of High Steel, INC., a sub-consultant to ET&L. The installation was done after steel fabrication was complete and prior to delivery to the construction site. Each gauge was environmentally protected and the wires were wrapped for transportation. The concrete thermistors were tied to the reinforcing bars prior to the deck pour. The tiltmeters and accelerometers were installed at the bridge site after girder erection and deck casting but prior to commissioning.

3 DATA COLLECTION AND LOAD TESTING DURING CONSTRUCTION AND BEYOND

Long term monitoring and recording of measurements from instrumentation were performed remotely, with wireless transmission of data from on-site DAQ boxes to a receiver in Boxborough, Massachusetts. The girders were instrumented prior to erection, in order to capture the initial strain values as the bridge girders were erected prior to the concrete deck pour. Data was collected periodically at key milestones during construction.
The first milestone was the continuous concrete deck pour. A set of data was collected prior to the concrete pour when the only load on the girders was the metal pans and steel reinforcing bars. The concrete pour was the first major data collection however there were times during the rebar cage installation where strain values were taken. Since the concrete deck was poured, data has been continuously collected every 5 minutes to capture the onset of composite action and initial strain values of the bridge as a whole.

A benefit of establishing baseline values for strain readings prior to the concrete pour is that the girders are behaving in an elemental manner. At this point in the construction the concrete has not cured and therefore is not acting compositively with the girders. The girders are still acting as single elements and not acting together with the deck and experiencing system behavior. With the baseline strain value defined, then the change in strain, if any, during the curing of the concrete deck can be more easily determined. As the concrete deck is poured the girders will deflect independently of one another and strains will increase. As the concrete begins to cure it will engage the girders and composite action will begin. It is important to understand that the transition from non-composite to composite behavior occurs while the girders are in a deflected state. The initial strains due to the dead load of the concrete are locked into the girders. If only changes in strain are looked at, the initial locked in strains that are developed prior to composite action are neglected and the actual strains in the girders will be underestimated.

The second milestone was a truck load test of the completed bridge conducted on September 3, 2009, see Figure 5. The research team conducted a comprehensive load test using a three axle truck. The test featured 25 separate runs, including two vibration tests. To perform the test, the bridge deck was marked with stop locations. A Lieca® total station with tracking provided continuous information related to the position of the truck along the length and width of the bridge. Truck load paths with stop stations are shown in Figure 6.

The truck was loaded with aggregate, weighing approximately 72 kips (36 tons). There were several non-destructive tests: crawl speed, stopping, moderate speed, ambient temperature, and ambient vibration tests. The truck made 9 passes over the bridge at a crawl speed of 5 MPH and 9 stopping tests (three runs per lane path). Truck position was recorded and time-stamped with the data via a total station. After completion of truck crawl speed tests, the truck made 9 passes (three runs per lane path) over the bridge, stopping at predetermined locations, for about 20 seconds at each point. Truck positions were recorded and time-stamped with the data via a total station. Continuous strain, tilt, acceleration, temperature, and truck location measurements were taken for the duration of the experiments via the instrumentation previously installed on the bridge. Data were collected onsite via a computer connection to the iSite boxes at a rate of 200 Hz.

![New Vernon Ave Bridge](image)

![Instrumented Vernon Ave Bridge](image)

Figure 5: Vernon Avenue Bridge

4 STRUCTURAL MODEL CREATION CONSIDERING SHM AND CONDITION ASSESSMENT

Creating a baseline model for SHM and condition assessment requirements is much different than creating a model for design purposes. For example, boundary conditions, commonly considered as “fixed” or “pinned” in a design model, must be modeled with more accuracy for SHM and condition assessment. Stanton et al (2008) acknowledges that AASHTO design specifications for elastomeric bearing pads are highly conservative and not experimentally verified. The conservative approach is suitable for design, but not helpful in an attempt to model actual bridge performance.

There has been recent research on how to more accurately capture the rotational and axial stiffness for steel reinforced bearing pads, which will be used in the modeling of the Vernon Avenue Bridge (Stanton, 2008). Structural design uses modeling tech-
tiques as an aid in the design process along with the AASHTO code to ensure the safety of the bridge.

At the most basic level of SHM for condition assessment, data collected from the structural response of the bridge is compared with the same measurements taken from a computer based model, and adjustments are made to the computer model to match measured values. Basic design models are inadequate to perform this task since some elements are traditionally omitted such as steel diaphragms, deck reinforcement and bearing pads. Reinforcement in the deck must be included to accurately capture the proper bending and axial behavior exhibited as test loads are applied. All key components influencing structural behavior must be modeled for accurate condition assessment. Advances in analytical modeling make it possible to realistically and economically include many features that are conservatively not evaluated as part of the traditional bridge design process.

4.1 Predictive monitoring-based structural modeling for the Vernon Avenue Bridge

Currently, as part of the NSF research project, there are two types of computer based models being created in order to determine the amount of detail needed in a computer model to accurately capture the structural response of the bridge. The first model is a very detailed finite element model consisting of solid elements representing the concrete deck and shell elements representing the steel girders, see Figure 7(A). The cross section of the bridge was initially drawn in SAP2000® and then extruded along the length of the bridge. Based on previous research, environmental factors such as temperature can significantly affect strain readings taken under different weather conditions (Wipf, 1991). The baseline model includes temperature gradients in order to capture the variation of stresses that develop in members due to changing temperatures. The creation of the baseline model was saved in stages in order to parallel the construction process. This allows the opportunity to calibrate the model throughout the construction process with the end goal being a highly accurate living model that can be used for bridge management. The detailed model is being created to include every detail of the bridge that could possibly be included and modeled using a finite element package, essentially the "perfect" bridge model.

The second model was developed using the BrIM in SAP2000® for the detailed geometry of the bridge, and then the BrIM is turned off, and additions are made to change from the design based model into a monitoring based model. The common elements that will be involved in bridge modeling, such as Vernon Avenue Bridge, are beam elements to represent the girders and support piers, shell and/or brick elements to represent the deck, see Figure 7(B), and spring elements to represent the boundary conditions.

Since appropriately modeled boundary conditions is essential to obtaining an accurate bridge response, a comparative study was done to determine which method of modeling the elastomeric bearing pads would best capture the behavior measured in the field. The first method used the rotational and axial stiffness coefficients obtained from formulas by Stanton et al (2008). These stiffness coefficients were used to model the bearing pad as a series of translational and rotational springs, replacing the typical pin or roller support.

![A Detailed Finite Element Model](image)

![B BrIM Global Model](image)

Figure 7: Vernon Avenue Bridge Modeled in SAP2000®

A second method employed the results of material tests from the actual bearing pad lot used on the Vernon Avenue Bridge, specifically an unconfined compression test. The elastic modulus of the composite pad was obtained from the results of this test, and a finite element model of an equivalent homogeneous pad was created. From the model, the rotational and axial stiffness coefficients were obtained for use as rotational and axial spring stiffnesses in the model. From this comparison of the two bridge models, researchers will be able to create a matrix that shows the time used to create both models and how the different models were able to predict the behavior of the actual bridge structure. This entire process differs from the element by element typical design process of a bridge, however design based modeling is becoming more popular. The researchers feel that this gives a better insight into bridge behavior because the bridge is analyzed by modeling the complete structural system which accounts for the behavior of the deck and its interactions with bridge girders, as opposed to analyzing each gird as an individual beam.

Strain data from the pour is in the initial stages of being processed, however, as shown in Figure 8, a brief look at the September 2009 load test data looks very promising. This graph shows the strain in strain
gauge 13, which is located just before the south pier on girder 2. The truck stops can easily be seen in the data as the flat portions of the graph. The graph also shows results from the model for the loading conditions at each stop location. This is a preliminary model, just showing that without any updating, the magnitudes of measured strain match those obtained from the model.

Model updating relates measured data to the analytical model, giving validity to both the analytical model and the measured test data. The difference between the design parameters and the estimated parameters reveals the condition change in the structure. Using a discrete FEM, the structural parameter estimates reveal not only damage location but also damage severity. Parameter estimation helps determine the current load rating of an in-service bridge accounting for any loss in stiffness during its life. It can also be used to predict the remaining life of in-service structures given current loading conditions.

5 CONCLUSION AND FUTURE WORK

The Vernon Avenue Bridge is a three span, composite concrete deck and steel girder bridge. The structural models created for this project are a meaningful base for the evaluation of the collected data. Each phase of data was used to refine the structural sub-system prior to combining them for the overall system behavior. These models are more comprehensive than a structural design analytical model. Not only must the model capture the geometric and section properties, connection characteristics and boundary conditions but also all of the loading influences on the bridge. When measured structural response is required to match a predictive model, typical structural modeling methods fail short. Changing from a design model to a condition assessment model for use with a structural health monitoring programs would provide bridge managers an in-depth understanding of structural behavior through the in-service life of the bridge with relatively little effort.

The SHM and condition assessment program being developed for the Vernon Avenue Bridge will be used by the research team as a benchmark example showing the process can provide useful information for asset allocation, and be fairly simple using an established framework.

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REFERENCES


Figure 1: Typical Profile of the Vernon Avenue Bridge

Figure 2: Plan View of Vernon Avenue Bridge with Instrumentation Station

△ Strain Gauge ■ Thermistors ○ Bi-Axial Accelerometer ▶ Bi-Axial Tiltmeter

Figure 3: Selection of Strain Gauge Locations Diagram for Instrumentation Plan for Girder 3 of the Vernon Ave Bridge
Figure 4: Selection of Strain Gauge Locations Diagram Using Predicted Deflected Shape for Girder 3

Figure 6: Vernon Avenue Bridge with Truck Load Paths and Stop Stations

Figure 8: Strain Gauge SG-13 Measured Results from September 2009 Load Test as Compared with Initial Computer Model