Development of a Model
Health Monitoring
Guide for Major Bridges

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HEALTH MONITORING OF MAJOR BRIDGES:
An Executive Summary
(Longer Version)

INTRODUCTION:

We define major bridges as those with replacement costs of $50 million or greater; featuring through spans of 300 ft (~100 meters) or longer; with cumulative span lengths of 1000 ft or longer; critical lifelines, monumental structures or those that are essential for the economic vitality of a major urban center. Such bridges require specialized engineering services as they typically fall outside the scope of common bridge codes and guide recommendations.

Health monitoring (HM) is a paradigm that enables an integrated systems approach for a reliable measurement-based understanding of the loading environment of major bridges, and how their structural systems carry their loads as they operate and fulfill their functions. The HM paradigm enables a comprehensive and integrated evaluation of the entire spectrum of performance expected from a major bridge. Management of bridge operations, response to accidents and emergencies, routine inspections, preventive maintenance as well as any major structural repair may be integrated and optimized in a rational manner based on objective, quantitative criteria customized to a specific bridge.

This paper describes the paradigm of health monitoring and how this paradigm may serve as a foundation for the integration of technologies to bring effective solutions to complex infrastructure problems by coordinated multidisciplinary engineering. Writers have accumulated a 30-year expertise on integrated multidisciplinary field research and applications on actual operating or decommissioned infrastructure systems. This document should indicate that experience, which can only be gained by field research, properly complemented by in-depth analytical studies and laboratory testing, is necessary for meaningful advances in the state-of-knowledge in civil engineering. This document includes an example application of health monitoring to a major long-span bridge, conducted through a partnership of the writers and the owner of the facility.

DEFINITIONS: PERFORMANCE, HEALTH, MONITORING, STRUCTURAL ID

The dictionary definition of performance is “the fulfillment of a promise”. In the case of most systems designed and constructed by civil engineers, the heuristic knowledge base comprising the foundation of standard codes and specifications has been associated with certain minimum performance expectations.

The health monitoring concept permits a more comprehensive and quantitative description of performance covering the entire spectrum of limit-states and events that may govern throughout the lifecycle of a bridge (Table 1).

We note that the nomenclature of Table 1 slightly differs from the nomenclature in the Commentary of the AASHTO LRFD Code. For example the AASHTO Code considers fatigue as a distinct limit state, and lumps the Safety and Stability at Failure, and, Safety
at Conditional Limit States into a single “EXTREME EVENT LIMIT STATES,” defined as “the structural survival of a bridge during a major earthquake or flood, or when collided by a vessel, vehicle or ice flow possibly under scoured conditions.” Table 1, however, classifies fatigue as an event within the “safety and stability of failure” limit state and differentiates between destructive events that have very different return periods. For example, earthquakes that may govern the design of a bridge at a highly seismic region in the Western US should be considered in a different context than the earthquakes that are anticipated in the Central and Eastern US and which are associated with much greater return periods. Finally, Table 1 provides a comprehensive and integrated view of all of the performance limit-states including utility and functionality.

A critical issue related to the definition of performance is the formulation of objective, quantitative criteria for each limit-event, and then finding appropriate tests, measurements and simulation methods for assuring that the desired performance criteria will be met and any limits will not be exceeded during the lifecycle of a bridge. The health monitoring concept promises to provide data and information for various types of bridges to serve for formulating objective performance indices. The importance of crisp and quantitative indices for assuring performance is evident as the performance limit-states and the corresponding limit-events serve as critical foundations for performance-based design and evaluation, and for emerging innovative contract delivery mechanisms such as design-build, design-build-operate, etc.

**Table 1. Performance Limit States, Limit-Events and Return Period**

<table>
<thead>
<tr>
<th>Utility and Functionality</th>
<th>Serviceability and Durability</th>
<th>Safety and Stability of Failure</th>
<th>Safety at Conditional Limit States</th>
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<tr>
<td>Environmental and Social Impacts</td>
<td>Large Deformations</td>
<td>Excessive Movements/Settlements</td>
<td>Events: Central-NE Earthquake</td>
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<td>Cost (Initial and Life-Cycle)</td>
<td>Large Vibrations</td>
<td>Material Failure (yielding, fatigue, dynamic fracture)</td>
<td>Extreme Flood</td>
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<td>Deterioration</td>
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<td>Feasibility of Construction, Inspection, and Maintenance</td>
<td>Damage</td>
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<tr>
<td>Aesthetics</td>
<td>Lack of Durability</td>
<td>Collapse With an Incomplete Mechanism</td>
<td>Terrorism</td>
</tr>
<tr>
<td>Events with the certainty of frequent (0-year) return: maintain safe operations at or close to design capacity</td>
<td>Occasional moderate events with 25-75 year return: minimum disruption to operation and quick repair</td>
<td>Progressive and Dynamic Collapse</td>
<td>Extremely rare catastrophic events with 2500 year return: Minimize casualties and control long-term impacts</td>
</tr>
</tbody>
</table>
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HEALTH

Given the intent of the recent AASHTO LRFD Specifications to provide a probabilistic basis to loads and resistances, it is proposed to define the health of a bridge as “the system reliability to possess adequate capacity against any probable demand that may be imposed on it in its lifecycle and in conjunction with the entire spectrum of limit states in Table 1”. Here we emphasize that system reliability should cover the entire spectrum of limit states and events in Table 1 and not just “structural safety” as is commonly assumed.

HEALTH MONITORING

Health monitoring is defined as tracking of any aspect of a bridge’s health by reliably measured data and analytical simulations in conjunction with heuristic experience so that we may describe the current and expected future performance of the bridge for all the critical limit-events. In this manner we may prepare for any mechanism that may adversely affect performance in a pro-active manner (in conjunction with “an ounce of prevention is better than a pound of cure”). We may mitigate the circumstances that increase the possibility of incidents and accidents that impact operational safety, as well as the mechanisms that may affect long-term structural performance. For example, we may detect incipient fatigue cracking or infiltration of chlorides into concrete before the onset of corrosion and mitigate their progress by effective preventive maintenance.

Although many experimental and analytical technologies have long been applied by bridge engineers and particularly a number of sophisticated nondestructive evaluation technologies have become available for localized evaluation of material conditions, health monitoring provides a common frame-work for the appropriate selection, integrated application, and interpreting the results of any group of technologies for maximum reliability and investment payoff.

The single most important distinction of health monitoring from a typical in-depth bridge evaluation and testing application is in the minimum standards that are required for analytical modeling for reliable simulations, and how the measurements, loads and tests are designed and implemented in conjunction with the guidance of analytical simulations.

STRUCTURAL IDENTIFICATION

The integration of analytical modeling and experiments for calibration and verification of the analytical model for reliable simulations is termed structural identification. Structural identification serves the starting point and remains as the core concept for health monitoring. The structural identification principle guides bridge engineers in the determination of minimum required amount of the best possible measurements to be collected so that a structure may be accurately and completely characterized for reliable simulations.

The relation between structural identification and health monitoring may therefore be summarized as follows: In the case of structural serviceability and safety, health monitoring consists of a series of structural identification applications providing snapshots along the lifecycle of a bridge, these snapshots may be connected along time.
by continuously monitoring the critical loading effects and the corresponding bridge responses. In this manner, any event that may slowly or abruptly create a significant change in the force and deformation states and that may cause damage to the bridge is recognized in a timely manner and appropriate management decisions may be taken.

In the case of operational management and safety, i.e. ITS and the integration of maintenance management with operations, we need continuous monitoring, in real-time, of weather conditions and their effect on the road surface and driving conditions, traffic volume, speed and composition, toll collection, any incidents, enforcements and any maintenance that may be taking place on the bridge. The integration of operation and structural monitoring offers the greatest promise in enhancing all aspects of bridge performance by an integrated management of the bridge as an asset.

HEALTH MONITORING TOOLS AND APPLICATION SCENARIOS

Given the innovative and ambitious objectives of the health monitoring paradigm, it is important to classify the associated technology tools and possible application scenarios. The technology tools are classified as those that are experimental (i.e. for data collection), analytical and information as outlined in the following:

![Image of technology tools]

Integration of these three classes of technologies is not a common capability except in the case of some of the national laboratories under DOE or DOD, major defense contractors and a few universities. Currently, many major bridge consultants have excellent analytical capabilities, however experimental expertise is typically provided by various sub-consultants. On the other hand, complex systems problems cannot be effectively solved by a linear, process-oriented approach. For health monitoring to deliver its promise, a closely coordinated integration of all of the critical experimental, analytical
and information technology by a multi-disciplinary team is strongly recommended. The example provided in the following and in relation to a long-span bridge further illustrates the level of integration that is essential for success in leveraging advanced technology.

APPLICATION SCENARIOS AND BENEFITS OF HEALTH MONITORING

The application scenarios may be classified as:

(a) Implementations to major bridges, further classified as “new” or “existing” construction;

(b) Implementations to large numbers of existing common short-and-medium span bridges. In the case of recurring short-span bridges that share similar materials, conceptual designs and construction and maintenance parameters, we may take advantage of statistical sampling techniques and fleet monitoring and management strategies;

(c) Integrated structural and operational health and security monitoring, i.e. using health monitoring to address the structural engineering aspects, intelligent transportation systems (ITS) aspects, and risk, security and emergency management aspects of major bridge through one integrated platform;

(d) Implementations to new bridges constructed of new materials or systems or processes that are not yet fully codified (e.g. fiber-reinforced polymer composites, high-performance concretes or steels). We also consider implementations in the realm of research such as data and knowledge generation in this category.

APPLICATIONS TO NEW VERSUS EXISTING BRIDGES

The distinction between implementation to new as opposed to existing bridges is that the former provides an opportunity for measuring:

(a) The precise geometry of the as-constructed system before commissioning;

(b) Material properties (chemical and physical properties of aggregate, cement and any additives, mix properties, curing conditions, strains and temperatures, in-situ properties such as porosity following curing, initial micro-cracking and any cracking, etc);

(c) The flexibility coefficients, frequencies, mode shapes, damping coefficients;

(d) The transient and any trapped intrinsic forces at the critical regions of a bridge system during its fabrication, erection and construction.

Many consultants, contractors and owners do not consider the documentation of the as-constructed materials and structural characteristics as an important contract delivery requirement even in the case of bridges that may cost $500 Million or higher. Given that the measurement and documentation of the as-constructed properties of materials and structural systems both serve as an excellent quality control vehicle, and that they are also essential for a performance-based contract delivery, it is strongly recommended
that such documentation is considered as a contract delivery requirement for at least significant projects.

Monitoring of the material and structural properties in the course of construction by objective and effective measurement technologies and their thorough documentation, together with the environmental conditions affecting the construction, would serve as an excellent “baseline” for making future assessments and management decisions along the lifecycle of a bridge.

In the case of health monitoring of existing bridges, instrumentation and measurement opportunities are somewhat more limited and certain information about the initial forces and the previous loading history cannot be reliably measured. However, in spite of these limitations it is still possible to collect a wealth of data and information that offers a great payoff potential for enhancing any aspect of the performance and effective management of the bridge.

**BENEFITS OF APPLICATIONS TO MAJOR NEW BRIDGES**

Monitoring, measuring and documenting the initial state of force and as-constructed properties of a new bridge requires a stepwise instrumentation and event-based data-collection process as the critical elements of a bridge go through their relevant fabrication, erection and construction stages. Health monitoring applications to major new bridges may offer the following benefits:

(a) Many of the major new bridges advance the frontiers of past practice and incorporate novel and pioneering designs and unusual requirements and specifications for materials, erection and construction processes. The control of geometry, material properties and construction process, especially when segmental construction with complex erection or launching or cantilevering and/or post-tensioning processes are involved may be greatly enhanced by properly designed monitoring. In the case of extremely demanding structural geometry and/or construction environments, active feedback control during erection and construction may be necessary as demonstrated during the construction of the Honshu-Shikoku bridges in Japan. Monitoring for feedback is an essential component of any control process, whether it is closed-loop intelligent structural control or if a human closes the loop.

(b) Monitoring may help to manage safety risks during construction, as incomplete structural systems may be especially vulnerable when exposed to accidents and hazards. There are cases when major bridges experienced typhoons or earthquakes during construction, and monitoring provided information for quickly responding to changes in condition and geometry of the incomplete structural systems.

(c) Design of instrumentation and of data acquisition for monitoring the fabrication and construction process is best accomplished before the construction drawings and specifications are finalized. In fact it is highly desirable to integrate monitoring directly into the design specifications. In this manner, the validity of the assumptions made during design calculations regarding the forces, reactions, displacements and drifts that a structure is expected to experience during its construction can be checked and confirmed. If the measurements indicate a need to modify the erection and construction, appropriate steps may be taken in a
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Monitoring may therefore help to mitigate the uncertainty and unforeseen circumstances affecting contract delivery. The risk of constructing a structure with undesirably high intrinsic forces, deformations and any other initial defects may be controlled. In addition, the design of fabrication and construction monitoring before the start of construction may serve as an excellent measure for checking and mitigating any inconsistency, omission or errors in the fabrication and construction drawings as these may cause significant delays in project completion if they happen to be discovered later after the start of construction.

(d) Major construction projects that are in the vicinity of and involving complex interactions with existing structures and the environment (both the built and natural environments) have been delayed due to non-engineering challenges. Monitoring of large construction projects together with their impacts on the built and natural environments have been used as a measure for mitigating possible claims as in the case of the Central Artery Project in Boston.

(e) Inspections, maintenance, repairs and retrofit of major bridges may typically cost upwards of many tens of millions of dollars and in some cases well over $100’s of millions of dollars for critical, monumental bridges over their lifecycle. There is evidence that visual biannual inspections of major bridges cost significantly while restricting operations for many months. Yet these inspections may miss many of the early initial signs of deterioration and damage even at locations that may be visible, as there are natural limitations to the ability of even experienced human eyes to scan thousands of members and connections that have large dimensions in the order of hundreds of feet.

Instrumented health monitoring integrating analytical, experimental and information technologies is an excellent complement to visual inspection directing the experienced inspectors to the critical areas where sensors and analyses indicate circumstances that may warrant close attention. By the same token, if the measurements indicate various redundant sub-systems of a bridge to be negligibly stressed, these systems may not require an in-depth inspection. For example, in the case of bridges that are equipped with energy dissipating dampers for vibration control, instrumented monitoring of a selected number of dampers may serve as a means for reducing the effort required for inspecting every single damper.

The cost of implementing instrumented health monitoring on a major long-span bridge today, even if such a system may need to employ over a hundred sensors, may still be accomplished with a budget that is not necessarily more than the cost of a couple of in-depth inspections of the bridge. Further, the cost of an integrated operational and structural health monitoring system implementation to a major bridge is not necessarily more than the cost of just an ITS implementation to a major bridge. We note that a recent ITS implementation to the George Washington Bridge has been reported to have cost about $50 Million and such a system could have incorporated structural health monitoring with only a marginal increase for a multiple-fold increase in the payoff.

Given the payoff potential offered by the opportunity of measuring and tracking the as-constructed properties by recently developed health monitoring technologies requiring an insignificant fraction of the inspection and maintenance costs, the implementation of health monitoring during the design process should be a welcome opportunity in terms of the expected payoff. A pro-active management of health, i.e. diagnosing and mitigating the circumstances that may eventually lead to deterioration, damage and/or unsafe operation in a timely manner, so that costly replacements, rehabilitation or retrofit may be avoided or delayed by effective preventive maintenance, is too important a paradigm to
ignore in view of potential payoff for protecting and enhancing the performance of major investments upwards of tens of millions of dollars.

APPLICATIONS TO EXISTING MAJOR BRIDGES

Many of the benefits that have been discussed above related to health monitoring implementations to new construction would remain valid for implementations to existing major bridges. However, given the current state of bridge engineering research, technology development and related implementations, the most compelling argument for health monitoring applications may be made in the case of existing major bridges that exhibit premature aging, distresses and performance problems. Secondary to this would be implementations to bridges that have aged beyond their anticipated design lifecycles.

For example, a number of landmark bridges in the urban centers along the North and Mid-Atlantic region have aged beyond their expected lifecycle, yet they remain as critical and irreplaceable links for the sustenance of regional commerce and the economic vitality of large metropolitan areas. Bridges such as the Brooklyn Bridge in New York and the Benjamin Franklin Bridge in Philadelphia also serve as monumental landmarks that have to be preserved at any cost. However, whether the conventional approaches to the inspection and maintenance management of such major bridges are proving cost-effective (and in fact, just effective), especially after their aging, has become a valid question.

In the last several years, workshops bringing owners, consultants and academics together discussed this issue and concluded that there are too many limitations and shortcomings in the current approaches to inspection, evaluation, maintenance, rehab and retrofit of existing major bridges. Moreover, the cost and operational impacts of the common inspection and maintenance practices have also reached very high and objectionable levels, and given the lack of assurance of their effectiveness, we should expect the bridge owners, consultants and contractors to be ready to embrace innovative paradigms that promise cost-effective and measurement-based objective approaches to solving the problems of aging major bridges.

We note that the single most pressing challenge in solving performance problems such as objectionable movements and geometry changes, displacements, vibrations and visible signs of aging, deterioration, distress and damage to materials, elements and connections is to first clearly identify any root causes and determine the most effective and compatible renewal technology based on mitigating the root cause. In most cases, monitoring over an extended time may be a necessity for definitively identifying the root cause(s) and mechanisms leading to symptoms of deterioration or damage.

In the case of major bridges identified as lacking sufficient system reliability due to the construction details or techniques that have been recognized as undesirable, the challenge would be in designing a retrofit that would indeed provide a significant enhancement of the system reliability while not adversely impacting any of the existing elements, and one that can be safely and feasibly constructed.

Most retrofits are designed and constructed with great uncertainty regarding the as-is condition of a structure and how the retrofit would be affecting the performance of existing systems that will remain in place. There is a conspicuous lack of established and/or codified guidelines for retrofit design, and most designers follow exactly the same analysis methods and thought processes that are followed in new design for the design
and construction of retrofit. Health monitoring of a retrofit candidate for a sufficient period before the design of retrofit and continued monitoring through and following retrofit offers especially important advantages and benefits to the owners of bridges that require retrofit.

APPLICATIONS TO POPULATIONS OF COMMON BRIDGES

Applications of advanced technology to common bridges are currently driven by concerns over their structural condition and performance, and often when a performance problem is identified during a visual inspection. For example, there is an increasing interest in the use of load testing for load capacity rating of posted bridges, following a National Cooperative Highway Research Program (NCHRP) project that led to a Manual for Load Testing. However, there is also remaining concerns that applications of load testing as per the new AASHTO Manual may fall short of a complete understanding of a bridge’s load resisting mechanisms and cannot assure that the load capacity estimated by the test will be maintained over several years following a test.

As it has been discussed earlier, unless load testing is planned, designed and executed in the context of structural identification, integrated with sufficient analytical insight and adequate instrumentation, it may not be possible to understand why a bridge exhibits a greater load capacity than what has been estimated from rating analysis. It is necessary to identify any secondary elements and/or mechanisms that may be enhancing the load distribution and resistance, and it is necessary to insure that the elements and/or mechanisms leading to a higher load capacity can be counted on over the expected lifecycle of the test bridge under all probable loading conditions. Further, before increasing the rating of a bridge, sufficient redundancy for system reliability should be verified and undesirable failure modes should be ruled out. These require reliable analytical modeling and simulations. All of these concerns point to the need to conduct load testing as a component of a comprehensive health monitoring program and not just as an isolated application.

In addition to concerns over insufficient load rating typically leading to posting, there are other incentives for health monitoring applications to existing common bridges as a management strategy discussed in the following.

FLEET HEALTH MONITORING OF LARGE BRIDGE POPULATIONS

Fleet-monitoring strategies inspired from the manner aircraft fleets are maintained and managed may help bridge engineers to boldly rethink and restructure the problem of bridge condition assessment and management. Experienced bridge engineers inspect and make decisions about condition and maintenance of a bridge by taking advantage of the heuristics they accumulate from past efforts on similar bridges. However, in recording data for the National Bridge Inventory (NBI) and in the analysis of data for management decisions, we may not be fully and systematically capitalizing on the common threads in the performance and behavior of bridge types such as the steel-stringer, prestressed concrete, steel-truss, etc that comprise large populations within each state as well as across states and jurisdictions.

The science of statistical sampling, applied in conjunction with structural identification
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and health monitoring, would permit to group bridges into populations whose critical loading and behaviors, i.e. the mechanisms that control their serviceability, load capacity and failure modes, may be expressed in terms of only a small number of statistically independent parameters. In this manner, we may represent a large population of, say, several thousands of reinforced concrete deck on steel-girders bridges that were designed and constructed within a decade, in terms of a statistical sample of “a few dozen” from their population.

To take advantage of fleet strategies for bridge management, each bridge in the National bridge Inventory (NBI) would not be considered as a unique structure and inspected, recorded, maintained and managed in a bridge-specific manner. The bridges in the NBI that have similar geometry, materials, design and construction history and behavior similarities would be categorized into groups represented by statistical samples for their in-depth evaluation and analyses. For example, the reinforced concrete deck-on-steel girder bridges may be classified into a number of groups (analogous to fleets) that have comparable system-reliability and load capacity rating, governed by only a very limited number of design, construction, location and maintenance-related parameters. Naturally, sub-structural and foundation characteristics will also be as important as the super-structure details in sampling the statistically representative group of bridges.

Such an approach may permit an authority with an inventory of ten-thousand steel-stringer bridges to classify these into, say, ten fleets of a thousand bridges each, and represent each fleet by a statistical sample of, say, fifty bridges, depending on the statistically independent parameters that govern the load capacity rating and other concerns that are taken into consideration for bridge management. The fifty bridges making up a sample would be rigorously inspected and tested by expert bridge engineers in a few years, creating a sufficient amount of data and insight for their management in the decades to come. In this manner, it is possible to take maximum advantage of the bridge-type specific heuristics that has been accumulated in the few, experienced engineer-experts that are available in the country, and integrate this with the advanced technological tools that offer reliable and measurement-based determination of serviceability and load capacity.

Once a “bridge fleet” is re-qualified by objective data based on an in-depth study of its representative statistical population, and an objectively measurable indicator of health that may be measured by a practical experiment (such as obtaining a deflection basin along a bridge by a falling weight deflectometer test) is developed and calibrated to “take the pulse of any bridge within the fleet,” it would then be possible to formulate a rational and effective approach for the condition assessment and optimum management of the fleet.

INTEGRATED OPERATIONAL AND STRUCTURAL HEALTH WITH SECURITY MONITORING

Integrating structural health, operational health and security monitoring is a concept that makes great sense as it embodies an integrative, systems approach to various closely related, interactive concerns of bridge owners that are currently being addressed in a highly fracticious and therefore a less than optimal manner. If we monitor a bridge structure over any period of time it becomes clear that the load effects due to the natural environmental influences (temperature changes, radiation, chemical agents, long-term changes in soil and water, etc) are often as significant if not more significant than the load effects due to traffic. The environmental conditions and their affect on the bridge
structure (ice on the structure, high wind inducing vibrations, etc) directly impact the operational decisions and safety. Routine operational decisions such as toll schedules, speed limits, lane allocations, safety during inspections, maintenance, etc influence the live load environment significantly. Any incidents or accidents are critical in their impact on operational safety and security and may directly affect structural health such as in the case of a vehicle impact on a structural element and/or fire. In case a cascading of incidents or a manmade hazard affects the structure and create a crisis requiring emergency management, clearly all of the structural, environmental, operational and organizational elements of bridge/infrastructure management are also intertwined.

Given the complex and highly integrated meta-systems nature of the natural-environmental, structural, operational and organizational systems that affect bridge performance at all critical limit-states, it is obvious that there are great benefits in integrating all of these systems through health monitoring. If the same health monitoring system senses and displays, in real-time, both the environmental, operating and structural conditions of a bridge and enables on-line communication between any and all of the organizational elements, and also permits access to all and any legacy data or information that may be needed for effective operational and emergency management, then we would have reaped all the benefits of technology and a systems engineering approach to the problem of management. In addition, we may benefit from great similarities and synergy between security surveillance, operational monitoring and structural health monitoring.

Real-time intelligent control systems are envisioned as providers of surveillance, protection, guidance, enforcement and behavior modification activities to help manage the entire spectrum of performance and health of regional transportation systems and their components. They are ideal assistants to human managers and a virtual protective shield for all the users of a transportation system. These integrated sensing, communication, computation and information management systems therefore have strategic importance for the health security of the nation’s entire civil and engineering infrastructures. Applications such as real-time vehicle identification, e-tolling, behavior imaging, e-enforcement, in-vehicle guidance and optimum path selection, traffic conflict resolution, incident and emergency management, and eventually, even the remote-control of unmanned vehicles are functions that may be integrated within operational and maintenance management of an entire regional highway transportation network by real-time intelligent control systems. Further, these systems would enable the constructed components of a transportation system such as bridges to take full advantage of smart system technologies for structural performance, such as hybrid structural control of vibrations, movements and stresses due to traffic and environmental load effects in addition to monitoring and mitigating any conditions that may create or accentuate deterioration and damage.

The application to the Commodore John Barry Bridge over the Delaware River has been intended to serve as a demonstration of the concept of a real-time on-line integrated operational and structural health monitoring system discussed further in the following.
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HEALTH MONITORING DEMONSTRATION ON THE COMMODORE BARRY BRIDGE

INTRODUCTION AND BACKGROUND

Writers explored the applications of structural identification and health monitoring on a considerable number of steel, prestressed concrete and concrete short-span bridges. After forming a partnership with the Delaware River Port Authority of PA and NJ (DRPA) in 1997 they started exploring the issues related to applying innovative paradigms and advanced technology for assisting the management of major long-span bridges. Their purpose for establishing an academe-government partnership were:

(a) to foster a research Institute capable of providing technology development and integration services that are not yet available in the industry for long-span bridge owners;

(b) to advance the state-of-the-art in structural identification and health monitoring of major constructed infrastructure elements as well as the development and improvement of related technology tools; and,

(c) to advance the state-of-knowledge related to the behavior of large structural systems and the interactions between these systems with their natural-environmental and socio-technical systems.

In 2000 Modjeski and Masters were invited to join the partnership as a representative of the consulting industry so that the immediate practical value from the research could be better realized. In this manner, all of the known critical elements of an academe-industry-government partnership for infrastructure research and advanced technology applications came together to explore how we can advance the engineering and management of major long-span highway bridges and similar constructed infrastructure systems.

Since the Drexel Intelligent Infrastructure Institute and DRPA partnership initiated in 1997, the writers have partnered with additional government agencies (such as FHWA and PADOT) as well as numerous industries and academic institutions, in an effort to further enhance the education, research and the practice of engineering and management of large infrastructure systems (www.di3.drexel.edu).

OBJECTIVES AND SCOPE OF THE PROJECT

The Drexel and DRPA partnership focused their efforts on the Commodore John Barry Bridge (CBB) which is one of the four major long-span bridges owned and operated by DRPA further described in the following. The general objectives of the research and applications were:

(a) Is it possible to characterize the through-truss structure of the main spans of the bridge in terms of a field-calibrated finite element model such that the movements, deformations, forces and stresses caused by live loads, wind and temperature at the critical regions may be reliably estimated (within a confidence
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(b) What is the current state and future projections of the safety and serviceability performance of the bridge? Is it possible to answer this question with measurement and analysis in a manner that will impress and convince the owner and practicing bridge consultants? For example, there were previous experiences with wind-induced vibrations damaging the truss members. Given these experiences that took place during construction, can we measure how wind is currently affecting the bridge? Is there a concern for fatigue? Are the vibrations of the deck of concern? Does the condition of the concrete deck warrant a concern? Most importantly, can technology integration provide quantitative answers to these questions and help formulate maintenance more effectively than just based on visual inspection and heuristics?

(c) What is the potential of an academe-industry-government partnership for bringing advanced technology solutions to complex infrastructure systems problems and for advancing the practice of large bridge management. What are the requirements for such partnerships and for technology solutions to work? Can we leverage technology, especially information technology, for enhancing the performance and for economical and effective preservation of our major infrastructure systems?

(a) Additional and more specific objectives of the research and applications are described following the introduction to the bridge.

THE COMMODORE JOHN BARRY BRIDGE

The Commodore John Barry Bridge (CBB) (Fig. 2) spans the Delaware River between Chester, Pennsylvania and Bridgeport, New Jersey. The bridge has five traffic lanes and currently serves more than six million vehicles annually, a significant percentage of which is heavy truck traffic. It was opened to traffic in 1974 as the longest cantilever steel truss bridge in the world with a main span length of 1,644 feet and a total bridge length of 13,912 feet. The focus of the study and subsequent discussions are directed to the principal long-span through-truss component shown in Fig. 2.

The sub-structures of the through-truss comprised of four reinforced concrete piers that are shown in the photo in Fig. 2. The piers were constructed on pile foundations in the river bed. The two principal trusses of the through-truss are spaced 72.5 feet apart. Each truss has 73 panel points spaced at 45.7 feet intervals. The top and bottom chords of the trusses are constructed from welded box sections. A combination of welded box and I-sections are used for the vertical and diagonal truss members.

Lateral "wind" bracing is provided by K-bracing at the top and bottom chord levels, and by portal and sway frames located at various panel points throughout the structure. The suspended span of the bridge is connected to the cantilever arms via vertical hangers, which are pinned at their upper and lower extremities. Truss members with axial and rotational releases transition the top and bottom chords between the suspended span and the adjacent cantilever arms. The floor system of the bridge is an 8-inch thick lightweight reinforced concrete deck that is composite with 9 steel beams laterally spaced at 6.9 feet. The beams are continuous over the floor beams in either four span or five span increments. Figs. 3-5 further illustrate various aspects of the structure.
SPECIFIC OBJECTIVES & SCOPE OF THE STUDY ON CBB

The specific objectives of the study follow from the general objectives presented earlier and the following discussion. The through-truss segment of the bridge was constructed with two principal truss systems as shown in the photo in Fig. 2. Since FHWA inspection guidelines labels all bridges with only two primary load carrying systems as “fracture-critical,” it may be argued that CBB would have to be characterized as such.

![Commodore Barry Bridge Through-Truss Structure](image)

However, we have to note that there may be significant differences in the actual system-reliability of various types of through-truss bridges, and many bridges constructed with only two principal vertical trusses may possess an excellent level of system-reliability by virtue of rigidly connected truss elements and horizontal bracing, providing a highly redundant box-like structural system with excellent redistribution and energy dissipation capabilities. Hence, the applied forces and any internal reactions that are released as a result of the yielding or buckling of a truss element may be effectively redistributed to other elements of the primary trusses and/or the lateral bracing systems.

As a result of the cantilever-truss construction of the structural system of CBB, the suspended 822 feet-long central component of the main span is hung from the cantilever arms by four tension elements (Fig. 3, also showing the “dummy” upper-chord element that is equipped with a movement system at the hanger connection). This rendered the suspended central portion of the structure to be non-redundantly supported by the four pin-ended hangers. The hangers, therefore, should certainly be considered as “fracture critical elements” due to a lack of any other primary or secondary mechanism for maintaining equilibrium should a failure of any one of the hangers took place.

A further area of concern in the evaluation of safety related to load-capacity rating. The
stringers carrying the floor-system were considered to be the critical elements for live-load stresses and governed permit-rating. Given this background, the specific objectives of the study were established as:

(a) Evaluation of the actual stresses of the critical elements that governed the structural safety performance: the four hangers and the stringers within the floor system;

(b) Evaluation of the condition of the deck that exhibited widespread cracking and deterioration, and the causes of vibration of the walkway railing along each side of the deck that required frequent repairs and replacement because of vibration related damage. Fig. 4 shows typical deck damage initiating from cracks traversing the entire width of the deck at frequent intervals and deterioration of concrete around the crack mainly due to traffic-induced abrasion;

(c) Evaluation of the stresses of the truss elements that were constructed with an electro-slag welding process that was subsequently discovered to be highly susceptible to cracking, as well as the soundness of the electro-slag welds. An earlier study of the electro-slag welds a decade ago had recommended checking the welds in ten years;

(d) Evaluate the effectiveness and the conditions of approximately 1000 vibration dampers installed on the unbraced truss elements (some dampers are visible in Fig. 3) following damage caused by wind-induced vibrations to welded member connections during the erection of the bridge. These dampers had reached the end of their initially predicted useful lives of 20 years;

We note that the above specific performance concerns are typically addressed by providing contracts to consultants. It is traditional to apply a reductionist approach to performance problems and assign one contract per each perceived problem irrespective of the possible relationships or interactions between a multitude of problems. The consultants would have solicited the help of expert subconsultants for highly specialized testing services such as nondestructive testing, strain-gaging, electron-microscope study, petrographic analysis, etc. as needed, and would have then reported their recommendations to the Authority. The Authority would then have the option of issuing a
contract for construction or fabrication that would provide a corrective action. The DRPA’s engineering staff would have coordinated and provided oversight to each project, and, would have integrated the outcome of different projects.

**Fig. 4 Deterioration of Lightweight Concrete Deck and View of Railing**

We further note that at 28 years of age as a “young” bridge, the CBB has been inspected more a dozen times, and about a half of these inspections would be “in-depth”. These visual inspections required by law may typically cost around $0.5-1 Million, require several months to complete at an added cost of significant disruption to operations. The Authority maintained a policy of rotating the consultants that provided bridge inspection services rather than maintaining in-house equipment and staff for inspections or retaining one primary consultant for providing this service on a long-term basis. Although the inspections are valuable, whether any one of the above areas of specific performance concern could have been effectively and conclusively addressed by visual inspection is also questionable.

The design and construction drawings and all previous consultant reports were archived by the Authority in hard-copy form. These were made available to the researchers. Conditions for access to the bridge depended on stringent safety training, and the research personnel took special training that involved the application of rock-climbing safety techniques to accessing the remote locations of the bridge.

**HEALTH MONITORING WORK-PLAN**

Researchers have been working with the DRPA engineers since 1998 and most of the issues which made up the general objectives and all of the specific concerns are near resolution. The research work-plan was designed to accomplish the integration of experimental, analytical and information technologies within a coherent health monitoring approach:

(a) Conceptualizing the structural systems of the bridge, including the full recognition of the natural-environmental and the socio-technical systems that impact the bridge performance. The researchers had to understand the organizational
structure of the Authority and interact with various layers of administrators, engineers, safety and maintenance personnel as well as consultants that are involved with both operational and engineering decisions impacting the bridge.

Conceptualizing the structural systems was accomplished by reviewing the design calculations and drawings as well as fabrication and construction drawings as these were reconciled with the actual structure by numerous visits. Heuristic insight of a rare class of a deeply experienced bridge structural engineer, Mr. Martin Burke Jr. (who has since retired) was solicited. Mr. Burke studied the drawings and visited the bridge with the researchers providing deep insight on the typical performance problems of major cantilever bridges and what to expect from the CBB. A number of fatigue-sensitive details were identified and prioritized for scrutiny.

The researchers further conceptualized the 3D geometry of the piers, supports, structural systems and components, connections, force-releases and the movement mechanisms by virtually reconstructing the entire structure in 3D CAD. At the culmination of this stage, the 3D CAD was transformed into a finite element model of the bridge and numerous analyses were conducted. Analysis results were correlated with the results from the initial design calculations and load-rating calculations.

As an example, Fig. 5 shows how the global geometric attributes of the structure and of the floor system (the shell elements modeling the concrete deck are not shown) were modeled by reconciling the 2D plans, photographs taken during visits to the bridge and 3D CAD. Similar comparisons of drawings, photographs, 3D CAD and the FE model were prepared for every critical region and detail of the structure such as the typical connections, bearings, member force releases, the movement systems, etc. In this manner, the FE model was developed and verified to represent all the critical physical details of the as-constructed structure as completely and accurately as possible.

(b) Various experimental studies were conducted on the bridge:

1. The operating vibrations were monitored at the tower regions, the mid-span and in the vicinity of the hangers. Approximately 16 accelerometers were used to simultaneously capture the traffic-induced vibrations and their attenuations or amplification through the deck, the railing, the floor system and the trusses. Frequency-domain transformations and cross-correlations revealed the dominant input vibrations occurred at a frequency band of 5-15 Hz and with an amplitude of about 0.25 g at the deck, attenuating to an amplitude of 0.06 g at the truss lower-chord.

Impact-modal analysis of several railing elements revealed that the railing fundamental frequency in the lateral and vertical directions was about the same, 10 Hz, and this coincided with the frequency of the input excitation. The coupled lateral-vertical resonance of the railing elements caused extensive damage to the railing;

In conjunction with the ambient monitoring of the vibrations, various stringers and the girders of the floor system were instrumented and the operating strains were monitored under traffic. The stringers were observed to experience the largest tensile strains under traffic, corresponding to about 3-6 Ksi peak stresses at various locations. A composite behavior of the stringers with the lightweight concrete deck was evident from the measured strain profiles along the depth of the stringer sections under traffic.
Fig. 5a Conceptualizing and 3D Analytical Modeling of the Substructure - Superstructure
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Floor System

Fig. 5b Conceptualizing and 3D Analytical Modeling of the Floor System

Although it is certain that many interacting mechanisms are involved in causing the observed cracking and deterioration of the lightweight concrete deck, the traffic-induced vibrations were considered sufficiently critical as these aggravated the distress and at least negatively impacted the effectiveness of any local patch repair. Various options for controlling deck vibrations exist. Increasing the mass of the deck and separating its frequency band from that of the input excitation, or making modifications to the structural connection details between the stringers and the floor girders, or adding artificial damping material to the stringers, as well as possible combinations of all of these options are promising alternatives. Naturally, simulations by a field-calibrated analytical model would be critical for evaluating these alternative solutions to the problem of deck vibration. Further, when the Authority considers it appropriate to replace the deck in the future, it is recommended to consider prefabricated post-tensioned reinforced concrete segments as opposed to cast-in-place concrete. Recent applications of prefabricated segmental post-tensioned deck elements on the Van Der Zee Bridge in New York have enabled replacement with almost no impact on traffic.

2. Various vibration dampers on truss members were tested in the field by monitoring the vibrations of the dampers and of the truss members before and after removing the dampers. Some of the dampers on the bridge were replaced by spares and the removed dampers were brought from the field into the laboratory for in-depth testing of their mechanical, materials and dynamic characteristics. Dampers were found to have been well-tuned to the member frequencies for optimum energy dissipation. The chemical and physical properties of the neoprene material was investigated further by cutting samples for chemical analysis. Results did not reveal any deterioration.
Fig. 6 shows the photograph of a truss member equipped with several dampers. Note that the protective cover has been removed from one damper. A second photograph shows a close up view of the damper instrumented by two accelerometers. The time-histograms of member and damper acceleration responses in the same figure indicate that acceleration amplitudes that were about 0.15 g without the dampers are being reduced to about 0.06 g with the dampers. The importance of the dampers in controlling operating vibrations was therefore clear from these results from monitoring. Although the damper and member vibrations are yet to be monitored under sufficiently high wind that would cause wind-induced excitation of a member, it is clear that the dampers are highly effective and critical for controlling truss vibrations.

Results of material tests conducted on the damper material and experiences of the earliest users of similar material indicated that the dampers should have a useful life of at least 50 years if controlled by the durability of neoprene. Five different dampers representing different damper mass configurations were identified for continuous monitoring of their acceleration responses together with the truss elements, and a visual inspection schedule was designed so that the mechanical conditions of every damper and its attachment to the truss would have been evaluated at least once a decade.

3. Nondestructive evaluation of the critical welds. Electro-slag welds that were identified as critical and were previously tested in 1997 were re-evaluated by ultra-sonic and dye-penetration testing. No changes were observed in the conditions of any of the defects that were identified a decade ago. In addition, the welds on the critical hangers
fabricated from A514 steel were tested and these were established to be in excellent shape. Monitoring of the traffic-induced strains of the truss members by strain gages intermittently over several months indicated live load stress amplitudes were within only 1 Ksi in the members with critical electro-slag welds and within 3 Ksi in the hangers.

4. Instrumentation and continuous monitoring of both the intrinsic and transient (live-load) strains in the hangers, various chord elements and of the wind linkages for more than a year in conjunction with video images of traffic, wind and temperature. Wind was measured at the tower and midspan of the bridge by four ultrasonic sensors. Fig. 7 shows the schematics of the 77 sensors providing 115 channels of data.

The data permitted an understanding and quantification of the loading influences creating intrinsic and transient stresses along with the stresses. Such an extensive and long-term data collection about the wind, temperature and live-load environment together with the corresponding strains provided a unique insight into the relative significance of the load effects and the challenges of health monitoring based on continuous and long-term data collection.

For example, unless wind speed and all of the three perpendicular wind directions are measured at a sufficient number of locations within the bridge, it is not possible to correctly characterize the wind environment. Many incidents of high wind were observed within the year. However, the measurements revealed that the mean wind-speed during durations of consistent wind direction for an hour was significantly less than the peak wind speed measured on the bridge during the same duration. Therefore, even when wind speeds of 50-60 mph were measured, the “effective” wind speed was in fact 20 mph or less, and often such an “effective” wind with a consistent direction may not occur at all throughout the entire length of the bridge. At the same time, although such “sporadic” high wind with changing directionality had little impact on the structural stresses and vibrations, it had significant impacts on the operations at the bridge. One conclusion was that a time window of an hour when high speed wind (exceeding 40 mph) may occur consistently in a given direction and throughout the entire length of the bridge may have a return period of a decade or longer.
Fig. 7 Sensor Distribution and Measurement Schematics For Long-Term Monitoring

Temperature changes and solar radiation were observed to be the most significant load effect on the trusses. For example, Fig. 8 shows the annual change in the intrinsic strains of one of the hangers, together with the temperatures recorded during the year. Strains are observed to vary significantly in the order of 6 Ksi or more during days when large temperature changes occur within a short time. An annual seasonal variation of up to 10 Ksi is observed in the intrinsic strains correlating perfectly with the temperature. This is a considerable stress when we consider that calculated dead load stresses varied between 20 Ksi-30 Ksi at most truss members and reached magnitudes of 50 Ksi at the most critically stressed elements.

A closer scrutiny of the measured strain and temperature histograms indicated that the hanger intrinsic strains were affected by the complex movement and force-release systems at and in the vicinity of these members. A distinctly unsymmetric behavior at the long-term strains of the two instrumented hangers was attributed to a difference in the behavior of the movement systems at their respective boundaries on the North and the South trusses. In addition, an out-of-plane behavior was noted in the hangers that were expected to be concentrically loaded due to radiation and temperature changes.
Such observations were of importance as the hangers are the most critical and fracture-critical elements that control the system-reliability. It was clear that the bridge should benefit from a retrofit to enhance system-reliability, however, the issue was how to retrofit the bridge in an effective and safe manner and at acceptable cost, including the impact to operations.

5. Ambient monitoring of the through-trusses was carried out for capturing the global dynamic characteristics of the principal structural system. Ambient monitoring of long-span bridges has been attempted for many years, and it has been demonstrated that it is possible to extract some information about frequencies and mode shapes. However, there has not been any results revealing data on the dynamic properties of a major bridge with a desirable accuracy and completeness within their entire frequency band of interest, especially when the frequencies are less than 1 Hz. Recent work at Tokyo University demonstrated that it is possible to greatly improve the reliability of operating frequencies and mode shapes extracted from ambient vibration monitoring of long-span bridges by using a large number of sensors for simultaneously recording data throughout a bridge at a fine spatial resolution.

The frequencies and mode shapes, if they are reliably captured with a sufficiently fine spatial resolution along a bridge are invaluable for calibrating a finite element model. The dynamic characteristics may also be directly interpreted to gain insight about the
boundary and continuity conditions under operating conditions. In most cases an ambient monitoring test may be the only means for objective measurements to gain insight on the actual global structural mass, stiffness and damping properties of a major bridge. Although there have been cases of testing medium-sized bridges under forced excitation, it is not feasible to excite an entire bridge of CBB's size with a sufficient force amplitude in order to overcome the vibrations caused by ambient influences such as wind and traffic. Other controlled tests such as by truck-loading are useful for measuring local behavior of the floor system, but cannot provide the same level of insight on the global behavior of a bridge.

To maximize the spatial resolution of the mode shapes, one-half of the bridge was instrumented as illustrated in Fig. 9. It is possible to develop multiple instrumentation grids which are then numerically spliced. However, roving the sensors reduces the reliability in the data and the roving option was eliminated. In order to verify that the test instrumentation grid will be adequate and for optimizing the sensor locations, a finite element analysis of the bridge was conducted. Analysis results helped to estimate the fundamental frequencies of the bridge, the frequency band of interest as well as the frequency spacing.

32 PCB Model 393C ICP and 13 PCB Capacitive accelerometers were placed on the main truss using magnets as shown in Fig. 9. Two ICP signal conditioners and a capacity signal conditioner, in conjunction with an Agilent Technologies VXI system with three 16 channel E1432A boards was used for data acquisition. The data sets were collected for 6 minute intervals. For each sensor channel, time and frequency plots are defined using HP DAC Express software. This allowed real time monitoring and quality control of the data both in time and frequency domains as it was acquired.

Time domain data is important for monitoring signal characteristics such as the magnitude of the signals, the level of DC off-set, overloads etc. The voltage ranges can be adjusted during a test to ensure high quality data based on such information. A number of data sets with different sampling rates were collected while time domain and frequency domain responses of all the channels are monitored in real time.
The first six modes identified from post-processing of the ambient monitoring data are compared to the corresponding modes obtained by the analysis of the nominal (uncalibrated) finite element model in Fig. 10. We note that the measured frequencies are consistently higher than the analytical counterparts, and the discrepancy is increasing with higher modes. Assuming that there are no errors in inertia mass, test results are indicating that the structure is considerably stiffer than as it is simulated by the finite element model. Calibration of the finite element model, in the context of “structural identification” is discussed subsequently.

6. Controlled Load Testing By Two 107 Kip Cranes. Fig 11 shows the cranes that were positioned in static configurations as well as crawled along the bridge for this test that required closure of the bridge. The through-truss and two typical approach spans were tested during the two consecutive nights on Nov 16 and 17.

Two 108 Kip cranes were used for loading and 52 high-speed strain gages were used for recording critical member strains during the tests. Both the floor system and the truss responses were captured as the cranes were statically positioned at critical locations. Following this a crane crawled on each of the five lanes throughout the bridge. By conducting the tests between midnight and 4 AM, it was possible to maintain reasonably constant ambient conditions. Fig. 11 shows the influence coefficients obtained for one of the hangers and a lower-chord member at mid-span by crawling the crane along each lane. These influence coefficients may be further normalized by decomposing them into single-axle loads, and these may serve as an excellent index capturing the as-is structural behavior.
Even if different vehicles are used for repeating controlled load tests every several years or after a change in bridge conditions is suspected, changes in the influence coefficients for critical member responses can be detected, serving as an objective condition index. Both the relative values of the influence coefficients obtained for the loading of different lanes, and those obtained as the load resided at different locations along the bridge serve as valuable indicators of the stiffness and load distribution. The load versus strain relations at each location of the load(s) may serve as an independent test for checking the reliability of the finite element model in simulating local strains and therefore member forces under live load. Finally, the stress states that would be measured at critical member cross sections by appropriate instrumentation provide an important understanding of local behavior, such as the level of composite action and the amount of flexure in truss members. For example, measurements by the hanger instrumentation during the loading test indicated unsymmetric bending in these members.
(c) The Calibration Of The Finite Element Model:

The primary purpose for constructing a detailed 3D finite element model of the bridge true to its as-constructed geometry, material and element properties was to conceptualize the bridge and use the model as a tool for properly designing the experiments and the instrumentation described above. However, there are many additional and practical uses of such detailed 3D finite element models that are true to the actual geometry of the structure and capable of simulating local behaviors at the element and connection levels. Both hardware and software for analyzing large structural models have recently become readily available and feasible. At the same time, bridge owners are rightfully cautious in relying on analytical simulation as a management tool, since finite element models may contain many errors, and the analysis results can be misleading and may even offer a false sense of safety. Fig. 10 implies that the nominal finite element model underestimated the global stiffness of the structure by as much as 40% (assuming that the inertia is properly modeled, a 20% discrepancy in frequency would correspond to over 40% discrepancy in stiffness). Obviously, unless a finite element model is properly tested, calibrated and verified, it would not be advisable to make critical decisions based on simulations.

Before calibration, any human errors in input were eliminated by reviewing the results of diagnostic analyses and by systematically checking input data after transforming the input file into a spreadsheet format. In this manner various patterns represented within the data based on symmetry or anti-symmetry could be checked as a means of validating its accuracy. It is important to note that many errors in element properties and connectivity that were not recognized by reviewing the output of the diagnostic analyses were discovered by such a scrutiny of the patterns in the input data.

Calibration process started by a careful analysis of mass and inertia modeling in order to eliminate the uncertainty in this parameter, and leaving only the stiffness-related parameters for adjustment. The impacts of substructure stiffness, boundary conditions of the superstructure (defined by modeling assumptions for the bearings shown in Fig. 5), and the assumptions of continuity or lack of continuity at each of the movement mechanisms at the wind-linkages, hangers and between the cantilevers and the suspended span on the calculated frequencies and mode shapes were investigated.

After understanding the impact of various assumptions on boundary and continuity conditions on the dynamic properties, the pier stiffnesses were increased substantially, and all the movement mechanisms were fixed before the model dynamic properties approached the measured properties. After a sufficiently close correlation was obtained between the measured and simulated global dynamic properties, the strains at the critical elements obtained during the controlled load testing were used for local calibration of the floor system element and connection stiffnesses. When a fully-composite behavior of the deck and the stringers, and full continuity between the stringers and the deck were simulated, the root-mean-square (RMS) of the error between measured and simulated strains at 20 measurement locations were reduced from 55% to 24%. The assumptions on global and local stiffness and continuity brought the RMS of the errors in the first six frequencies from 28% to 1.5%. Hence, the model was considered to be sufficiently calibrated. Fig. 12 shows the correlation between measured and simulated dynamic properties after the global and local calibration of the finite element model. Both the frequencies and especially the characteristics of the simulated mode shapes indicate an excellent correlation with their measured counterparts.
An important implication from the FE model calibration studies relates to the apparent fixity at the movement mechanisms including the sliding bearings shown in Fig. 5 supporting the ends of the cantilever trusses at the outer piers. We note that ambient monitoring data analysis is based on the assumption that the structure remains stationary, observable and reasonably linear in the course of monitoring. Data collected during monitoring at a large number of six-minute time-windows over several weeks covered periods of different levels of traffic-induced vibration, various wind environments and temperature ranges. All data was averaged to represent an effective composite of various structural states and behaviors throughout the course of the monitoring, therefore in effect smearing all nonlinearity and non-stationarity and effectively linearizing the structure. Hence, although many of the movement mechanisms are measured to in fact intermittently activate by slipping, the effective stiffness of the bridge averaged over a period of several weeks corresponded to the frozen condition of the movement systems.

### (d) Real-Time Integrated Surveillance and Control Systems

Integrated sensing, communication and computation systems are envisioned to have strategic importance especially for the security of the nation's civil and engineering infrastructures. Real-time Integrated Surveillance and Control Systems (RISCS) are envisioned to serve as decision support systems for large-scale problems, on-line...
advisors for middle-scale problems, and rapid interference tools for a multiplicity of small-scale problems where no procrastination is allowed. The defense establishment has been taking advantage of RISCS-like systems for planning and for battle while there has not been a civilian application especially oriented towards the management of a regional transportation infrastructure system especially in case of an emergency.

RISCS can serve as virtual shields protecting the functionality and health of regional transportation networks and other critical infrastructure systems. Such a function requires the collection of multi-modal, multi-bandwidth and multi-scale data throughout a regional transportation network and processing of the data to identify system components including traffic together with the environmental, constructed and organizational components of the meta-system. In addition, decisions about any real-time or delayed actions are required for safety and optimum functionality, and if so, various control loops at different resolutions should be activated to execute the appropriate decisions. Data collection and processing, interpretation and decision-making, and executing multi-loop, multi-resolution control in real-time require learning-based, decision-theoretic intelligent agents.

The experience of September 11, 2001 indicated the need for real-time data and information management systems that provide timely information to emergency managers regarding the conditions of critical infrastructure following disasters. Integrated information and communication systems that take advantage of a GIS platform have been proposed for emergency management. Health-monitoring systems that integrate real-time sensing, communication and computation together with data and information management have been envisioned for long-span bridges, tunnels and entire regional transportation networks in the realm of next generation’s intelligent transportation systems. Such future health monitoring systems for intelligent transportation networks will collect satellite, aircraft and land-based images and data on weather, traffic, roadway and structural responses, integrate and display the data for on-line, real-time viewing by qualified officials for guiding the public, respond to incidents, support enforcement, and, integrate management.

Given the above incentives, researchers and the Authority decided to take advantage of integrated information systems and explore whether such a system could be developed for the CBB. It was envisioned that the system will permit officials and engineers to access, review and analyze legacy and recent data and information in addition to real-time data. It was desired to explore the issues and challenges in the integration of a large volume of real-time data with many simultaneous modalities, such as satellite images and on-ground streaming-video of traffic and roadway conditions, weigh-in-motion information and critical structural responses including temperatures, accelerations, displacements, tilts and strains.

For health monitoring purposes, intermittent and continuous data should be sufficient to evaluate, in real-time, any critical changes in operational safety due to incidents and weather, and structural reliability due to aging, deterioration, damage due to accidents or overloads, discussed further in the following. The convergence between ITS, transportation health monitoring systems and the real-time damage assessment and emergency response systems envisioned by emergency managers and the disaster mitigation research community are obvious.
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Description of the CBB Real Time Monitor (RISCs) System:

The sensing components of the monitor system, developed by adding on to the instrumentation that was already installed on the bridge and by hardening the entire sensing and data acquisition system for durability over a reasonable lifecycle of a decade with minimum maintenance are summarized in Figure 13. The areas and the mechanisms affecting the bridge that are instrumented, providing 485 channels of on-line data in real-time through an integration of security surveillance, operations and maintenance monitoring in one technological leap are indicated in the figure.

An internet T1 connection was installed for access to the system, which, in its current form is able to integrate the senses of “vision”, “touch” and “hearing”. Vision is in the form of streaming digital video images that monitor the traffic moving over critical areas of the bridge. Touch is in the form of temperature, displacement, tilt, strain and acceleration measurements distributed as shown in Figure 13. Hearing is through the ultra-sonic sensors sensing wind speed and direction. It is possible to envision smell and taste, especially for the detection of explosives that may be carried in vehicles, chemical substances infiltrating into concrete, corrosion and any micro-cracking due to fatigue.

The sensing system is interrogated over a local area network, the architecture of which is illustrated in Figure 14 which further depicts how the various data acquisition system components are distributed and networked along the bridge. The data acquisition systems are controlled, synchronized and integrated by software developed in Labview. Wind, temperature, radiation and humidity interrogation is done with a Handar data acquisition system, vibrating-wire based displacement, tilt and strain sensors capture variations in the intrinsic responses over the long-term and are interrogated by a Campbell data acquisition system, and the cameras are controlled by a Sony EVI system. The high-bandwidth strain, displacement and acceleration sensors for high-
speed responses captured over short time increments are interrogated by a Megadac system.

There have been many applications of Interned-based monitoring. The distinction of the system installed on the CBB is its integrative aspects. Any additional sensors and data acquisition systems based on any operational principle (electrical, mechanical, optical, chemical and combinations) and over any bandwidth, may be integrated into the current system over the network as long as they provide digital electronic output. Wireless operation is a simple step from the current copper-optical fiber network communication mode. In the current system, an operator may take control anytime. However, the system is designed to operate in a programmed mode in which the inputs due to weather and traffic, and the entire set of vibrating-wire sensors are continuously interrogated at low frequency. The high-frequency sensors operate on time or event-based triggered modes. For example, rush hour, midnight, high-wind or an overweight truck may trigger data from a subset suite of sensors to be acquired and archived. The frequency and duration of data and image collection, their processing, evaluation and dismissal, archival, presentation to a manager and/or alarm protocols will be eventually transformed to intelligent agents after researchers can establish the bounds of normal structural behavior patterns and possible indications as well as precursors of anomalies.

The architecture of the information systems that have been designed in conjunction with the monitor is schematized in Figure 15. The basic building blocks of the health and performance monitoring system outlined in Figs. 13-15 are therefore:

(a) sensing, data acquisition and control;
(b) data processing and information management;
(c) human and organizational interfacing for adoption as a management tool. The data and information processing challenges are very much influenced by the necessity of providing a user-friendly, intuitive and secure interface and proper training for the human operators that is in fact the key for organizational acceptance and adoption. The latter is naturally the true measure of success of any technological innovation.
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Internet Portal Interface For The CBB RISCS:

The front page of the Internet portal interface that has been designed for the CBB RISCS System is shown in Fig. 16. This portal permits an authorized viewer to observe real-time streaming digital video images that cover the critical areas of the bridge, together with information about the weather conditions including wind speed and direction at various locations of the bridge. It is important that the cameras may be controlled remotely and individual photographs may be captured and archived as desired, with just a couple of clicks, a major advance over analog video-taping of images.

A weigh-in-motion (WIM) system (that is scheduled for installation during July, 2002) will provide pertinent information about vehicles that are of interest. The vehicles may be selected by the scale through triggering, or by an operator as all vehicles entering the bridge through the toll booths are viewed through another camera. Truck tolls are based on weight, and the WIM offers a mechanism for independently checking the weight of selected vehicles, detecting those vehicles that are overweight or those that do not declare their true weight for toll. It follows that WIM in conjunction with the RISCS enables pro-active enforcement and enhances revenue collection.

Figure 15  Data Quality Assessment and Information Generation from Acquired Data
Fig. 16 Internet Portal for Interfacing With the CBB RISCS System

The Internet portal interface further permits an engineer to view, in real-time, the bridge movements and reactions to trucks and to the environment. Any one of the 485 channels of data may be viewed by appropriate graphical interfaces while continuing to observe the traffic and the weather that provide the loading influences, as shown in Fig. 17 for one of the hangers. Just as real-time data is viewable, it is also possible to retrieve any legacy data or archived documentation for immediate viewing through the Internet portal. An Internet retrievable data-base was created for archiving the legacy data and information about the bridge, including all of the design and construction plans, selected portions of the inspection reports and photographs. A second data-base was created for archiving the data and images from the RISCS system for health monitoring. These data-bases and their Internet access represent state-of-art distributed information management applications, enabling any required data/information to be accessed and interrogated through the portal.

The implications of the experiences with the RISCS system installed on the CBB are significant for the future management of CBB. The system may be envisioned as an intelligent telescope, capable of viewing, responding to and archiving any event of significance along a several mile long system, without a need for operator interfacing. In this respect the system represents the embodiment of an ideal Intelligent Transportation System, which can automatically detect incidents and accidents, collect toll and enforce traffic rules by communications with the drivers through smart signs along the roadway or through in-vehicle communication and navigation systems.
Fig. 17  Real-Time Synchronized Hanger Strain Data and Live Load Imaging

Another feature of the RISCS system is the continuous surveillance and real-time data, information and communication capabilities that are invaluable to security and emergency managers in the case of emergencies. Naturally, the system would need to be hardened and redundant communication modes such as radio and micro-wave in addition to wired Internet would need to be incorporated for surviving disasters. As the system is capable of detecting structural distresses following any disaster in real-time, it may serve as a sentry and perhaps help eliminate some of the casualties that are caused by not immediately alerting the traffic following a bridge collapse.

IMPLICATIONS FOR CBB AND FOR BRIDGE MANAGEMENT OF THE FUTURE

The health monitoring paradigm has been defined and described, potential benefits from its various application modes are suggested and an ongoing application to a major long-span bridge has been summarized.

Implications for CBB and for DRPA:

It is the opinion of the writers that health monitoring applications to the CBB have provided a rare wealth of data and information about the loading mechanisms and behavior of the bridge, such as documenting the dynamic frequency band of the input excitation and how this creates near-resonance with various elements of the floor system. An in-depth intuitive understanding and quantitative documentation of the loading effects of wind, temperature and traffic as well as the corresponding strains and forces was possible. The conditions of the critical electro-slag welds and the vibration dampers,
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and their expected performance in the next decades have been established with confidence.

The two areas of special concern for the bridge owner have been the deterioration of the deck concrete and the lack of system-reliability due to the fracture critical hangers. Data collected on vibration levels of the deck, of the truss, and how dampers on truss elements are effectively reducing the vibration of these elements should be useful for making decisions regarding the serviceability of the deck. This data, in conjunction with the calibrated finite element model of the bridge representing the deck and the floor system and their relation with the truss in detail, are sufficient for evaluating alternatives for the replacement or modification of the deck.

About a year ago, the Authority has issued a contract for hydro-demolition of the deteriorated areas and patching these with a new material that is claimed to have excellent bonding characteristics. This operation, as would be expected, has had a significant impact on the operations as two of the five lanes at a time are blocked for maintenance. However, once this operation is complete, it may be an excellent time to add a 2 inch riding surface on the deck for both reducing the vibrations and for helping confine the patches. At this time, the hangers would have been retrofit as discussed in the following, and there should not be a concern in relation to adding to the dead load.

The Authority has issued a contract for the design and installation of retrofit on the four hangers. The retrofit concept is simply “post-tensioning” each of the hangers by four rods, tensioning the rods in increments and in sequence so that about half the tension carried by the hanger is taken over by the rods. Naturally, there are many installation and long-term maintenance issues that require careful analysis, however, the system has already been applied to a number of major cantilever truss bridges in the area without any incident. At the same time, given the significant levels of intrinsic force variation in the hangers, their state of unsymmetric bending, and the complexity of their boundary conditions at the truss connections, require that a careful monitoring of the state-of-stress in the hangers and in the post-tensioning rods be carried out during and following installation.

Clearly, the RISCS system will offer a great value to the Authority for ensuring that the hanger retrofit is successfully being installed and remains functioning within the parameters that have been considered in their design. The researchers will be monitoring the post-tensioning rod and hanger strain profiles in real-time as the installation takes place and this data will also be made available to the engineers, designer and the contractor in real-time. Considering that the hanger element that is being compressed is extremely slender, and that it is already under unsymmetric multi-axial bending, compressing this element sequentially by four rods to relieve its “calculated” tensile force by 50% is naturally a very challenging operation analogous to surgery. Additionally, whether the force in the rods remain constant, or what would happen if a rod relaxed and lost its tension are issues that require a careful analysis and require that the hangers and the rods are monitored continuously.

Following a successful application of the hanger retrofit, the stresses in the hangers should not remain a cause for concern and the deck vibrations may then be easily resolved by adding additional weight and reducing the frequency band of the floor system. Naturally, a careful analysis of alternatives and possibly adding auxiliary damping measures to the stringers would be highly recommended. Once the near-resonance of the floor-system under traffic is mitigated, and once the WIM system provides a control of overweight trucks, we should expect that the Authority will obtain at least a decade of successful performance from the existing deck. Naturally, the RISCS
system will enable the collection and analysis of data over a sufficient length of time for an accurate understanding and modeling of the bridge-specific live-loading of CBB, as well as for an accurate characterization of the impact of fatigue on the lifecycle of various bridge elements.

In terms of the potential of the RISCS system for an integrated structural, operational and security monitoring, this will remain as a future opportunity. The Authority is currently investing into an ITS Management Center that will serve as a central node for all transportation management within the DRPA infrastructure, extending over four major bridges, various port and multi-modal facilities and many miles of highways that connect them. The CBB RISCS System would serve as a reasonable measure of what could be accomplished in the realm of ITS at this time, and it may even be extended to include all of the Authority’s assets.

Following five years of intensive involvement with the Authority, the writers are of the opinion that the partnership has been of immense value as an experiment, evidenced by what has been accomplished as a demonstration project. In addition, the value of exposure and continued learning that implicitly and naturally takes place when academe, government and industry come together as partners, cannot be over-emphasized. The writers have always acknowledged the great value of the partnership for their learning and understanding of reality. Given time, all of the partners will recognize and acknowledge that the investment into such partnerships pay off as long as each side respects what the others are bringing into partnership. We may safely state that the CBB has now become one of the most extensively researched, understood and documented major bridges in the world, and the research and technology demonstration described here will serve to improve its management and performance for the remainder of its lifecycle.

Implications for Bridge and Transportation System Management of the Future:

Writers believe that this executive summary strongly articulates and demonstrates the need for an integrated systems approach to technology development and for the leveraging of technology in order to make a difference in how we manage major bridges. Integrated systems approach requires that we correctly identify, measure and understand and then incorporate in any management decision the interactions between natural, socio-technical and constructed systems that govern the performance of all infrastructure components and systems.

Currently the organizational structures of most government agencies, industry and academe are highly fragmented. For example, in many state departments of transportation there are significant divides between structural and transportation bureaus, and although there may be several management systems in place for traffic, pavement and bridges these remain detached. Especially, bridge and ITS engineering communities and respective industries appear to have very different constituents. The writers hope that this Executive Summary convincingly articulates and demonstrates the necessity for an integrated approach to improve performance by effectively leveraging technology. Any success in the described demonstration project in this summary is completely a result of closely coordinated, integrated, multi-disciplinary research conducted directly in the field with support from the laboratory and the computer.