Instrumented Monitoring and Nondestructive Evaluation of Highway Bridges

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Abstract

Non-destructive evaluation technologies of a rigorous and objective nature are sought to quantitatively identify and evaluate the condition or health of highway structures. A global bridge evaluation methodology is under development based upon the structural identification concept, employing modal testing and instrumented monitoring as its principal experimental tools. The test results are transformed to modal flexibility, which has been demonstrated to be a conceptual, quantitative, comprehensive, and damage-sensitive signature. Three test sites are currently being tested, monitored, and studied in order to classify their similar bridge-type-specific behavior mechanisms. Practical, type-specific procedures for instrumented monitoring and nondestructive evaluation can then be developed for the whole group or type of highway bridges.

Introduction

Since the early 1980's, many federal agencies and several universities contributed to our current awareness of the problems related to civil infrastructure systems. We now recognize that the performance of these systems has a significant impact on the nation's gross domestic product (GDP). The Federal Highway Administration (FHWA) estimates that 45% of the bridge inventory is currently deficient due to either structural or traffic inadequacy and that this has lead to a ninety billion dollar backlog of needed maintenance [Federal 1993]. Our future quality of life will be severely impacted due to the current lack of infrastructure performance unless innovations can be introduced in financing and management of the infrastructure (including organizational effectiveness) and in technologies for objective condition assessment, reliability evaluation and renewal engineering.

Subjective or inaccurate condition assessment has been identified as the most critical technical barrier to effective infrastructure management [Clinton 1993]. For example, since 1971, conditions of highway bridges are typically expressed in terms of subjective indices which are based on visual inspections alone [AASHTO 1983 and 1989]. The difficulties of visually inspecting and evaluating an aging constructed facility accurately and completely, even when this may be conducted by experienced engineers, are well-known [Federal 1993]. Non-destructive evaluation (NDE) technologies of a rigorous and

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objective nature are sought to quantitatively identify and evaluate the "global" condition or health of highway structures based upon appropriate signatures or indices which need to be established by research.

The UCII researchers have developed a global condition assessment technique which addresses the conceptualization and measurement of several unknowns for bridges, which include:

- A lack of quantitative knowledge on the as-built state parameters (e.g., initial stresses, strains and displacements, local and global stiffness) and their variation over time;
- A lack of clear and quantitative definitions for the performance parameters (e.g., functionality, serviceability, safety, lifecycle cost, etc.) and relationships between the state and performance parameters;
- A lack of a clear and complete understanding of the phenomena which influence the state-of-force in a bridge; which lead to changes in state parameters; and/or which lead to a decrease in performance.

The global NDE method presented here is based upon the structural identification concept, employing modal testing and instrumented monitoring as its principal experimental tools. The test results are transformed to modal flexibility, which has been demonstrated to be a quantitative, comprehensive, and damage-sensitive signature [Rubin 1983]. Flexibility also provides a conceptual condition index, since it may be used to conveniently obtain the deflected shapes of a bridge under any loading pattern [Aktan 1993].

Bridge-type-specific behavior mechanisms is an emerging concept for the practical evaluation of the nation's inventory. Based on the principal attributes that influence state and performance, it is possible to rationally classify steel-stringer bridges into several groups of like behavior, each of which can then be represented through a statistical population of bridges [Aktan 1995]. Once the statistical population is rigorously tested and studied, practical, type-specific global condition assessment procedures can then be developed for the whole group. In this manner, they could overcome the myth that *"every bridge is a different and unique structure"*. The ongoing research projects are taking advantage of three test sites which are generating information for the international bridge engineering community. The test sites are three-span, steel-girder, RC-deck, composite bridge overpasses located in Cincinnati.

Instrumented Monitoring of a Bridge in Service

A 10-year old bridge, HAM-42-0992, has been subject to structural identification by modal analysis, following which it was instrumented with a monitoring system to record the environmental and truck-load inputs and the system responses. Bridge temperatures, strains, rotations, displacements, and accelerations are continuously being measured under a variety of high-speed and low-speed regimes. The monitor has successfully operated for two years and valuable data has been recorded [Hunt 1994 and 1995, Levi 1996]. Several observations were made, including (Figure 1):

1) Traffic loading was most observable at the lower girder flange near the midspans, and the recorded deflection and strain were substantially less than that required of the bridge design; and,

2) Temperature effects were most significant at the bridge supports, especially the integral abutments, and recorded strain over the annual thermal cycle would far exceed that of any recorded truck traffic.

This bridge holds up very well for the traffic load that it was designed to carry; however, the bridge design did not account for the forces of nature in its consideration of lifetime performance. The state-of-practice in bridge engineering, based upon a simplistic and mainly empirical understanding of the interactions between a bridge and nature, has led to a large population of bridges which do not have a safety problem while requiring extensive maintenance and rehabilitation in as early as ten to twenty years. While increased traffic volume is blamed for many bridge problems, research evidence indicates that the impact of traffic on bridge serviceability is *negligible* [Aktan 1995].

Lifetime Monitor of a Constructed Bridge

The measurement and documentation of construction and service effects for another bridge, HAM-126-0881L, will permit evaluation of the complete state of force in a bridge over its lifetime, together with the corresponding causative effects or events. A complete sensor suite, including a weigh-in-motion (WIM) roadway scale, was incorporated within the construction plans and drawings. The monitoring system began operation as construction commenced in March, 1995 with the drilled shafts. The foundation and substructure were instrumented with embedded concrete strain gages, welded pile strain gages, inclinometer conduit, soil pressure sensors, and others. Relevant atmospheric effects at the site are monitored with a weather station. Data was collected by weldable foil and vibrating wire strain gage instrumentation of the girders and the cross-braces prior to critical fabrication steps in the shop, and by adding tilt and displacement instruments at subsequent steps of the construction.

Except for painting, construction was concluded in the Fall of 1996 with the pour and cure of the concrete deck. Modal testing and other diagnostic tests under controlled truck-loading will be conducted in the Spring of 1997, so that the baseline mechanical characteristics of the bridge can be established and an accurate finite-element computer model can be developed and calibrated. The calibrated analytical model will then be used to transfer the recorded strain, distortion, inclination, displacement and temperature data into the corresponding stresses, forces and reactions. Since complex time-dependent self-equilibrating effects such as thermal gradients, creep and shrinkage are involved, extensive analysis efforts and nonlinear finite-element analysis expertise are required. Accumulated versus transient stresses and forces will be evaluated by conducting analyses simulating different episodes of causes and effects in the construction and service stages of the bridge and correlating these with the recorded data (Figure 2). Traffic service is expected to commence in the Fall of 1997.

Data acquired through instrumentation will be used to conceptualize less-understood or unknown phenomena that influence bridge performance and to verify design assumptions and rating models. For example, the deck cracking phenomena has significantly influenced the life cycle cost of a bridge. Data relating to the deck construction and the corresponding intrinsic strains and stresses will help to determine if these strains and stresses are the only reasons contributing to the deck cracking phenomena, or whether there are other causative effects that lead to the deterioration of the concrete and of the chemical bond between the concrete deck and the steel grid superstructure. Bridge engineers will be able to evaluate if there are means of mitigating deterioration by adjustments in our current design, construction, inspection, and maintenance operations.

Validation of Tools Via Damage Simulation Project

A decommissioned, 3-span steel-stringer bridge, HAM-561-0683, has served as a test specimen in the latter half of 1996 for the evaluation of different concepts, experimental approaches, algorithms, and hardware/software tools for the detection of various types and levels of induced damage. Damage scenarios have included the simulation of long-term deterioration such as the loosening and/or breaking of connections, fatigue-fracture, dislocated bearing, corrosion and reduction of effective area and inertia of steel members and connections, loss of chemical bond providing composite action, and cracking and delamination of deck concrete.

The research was designed within the framework of structural identification. The two basic experimental approaches explored were instrumented monitoring and dynamic testing. A monitoring system comprised of temperature, strain, displacement, and acceleration sensors at the critical regions of the test bridge was utilized to record and collect data in several modes: (a) Continuous low-speed monitoring of environmental conditions and bridge responses corresponding to these as well as the damage being induced; (b) high-speed monitoring of responses due to ambient or traffic vibrations; and, the responses under controlled static and crawl-speed truck loading [Levi 1997]. Modal testing was conducted by impact and by forced excitation, using a new generation of hardware and software which have been developed for bridge modal testing based on research at the Structural Dynamics Research Laboratory of the university [Lenett 1997]. Figure 3 illustrates the excellent correlation of the derived and measured flexibility from the two testing methods along a given girder line of the bridge [Catbas 1997]. The testing methods were repeated several times to determine a statistical error bound for the flexibility estimation due to instrumentation, experimental conditions, and analytical techniques. The tests could confidently detect a 10% change in flexibility; however, this change can correspond to significant and observable damage (e.g. loss of bearing, Fig. 3) due to the structural redundancy found in most bridges or it can correspond to the natural variation in flexibility due to seasonal or environmental changes (e.g. backwall resistance to thermal expansion).

The test data and results will be made available to the general bridge research community via the Internet and CD-ROM technologies in 1998. The research and the test-specimen will therefore serve as a national test-bed for global bridge NDE. In this manner, a host of other promising damage indicators for highway bridges may be explored (Table 1). The basic concept is that modal parameters, such as frequencies and mode shapes, are a function of the physical properties of the structure and their dynamic interrelation. Any changes in the measured modal parameters is, therefore, due to some change in the structural properties and is considered as damage. For example, relative frequency changes between different modes have been used in crack detection [Adams 1978, Cawley 1979]. Shifts in the higher-frequency bending modes obtained via local instrumentation, such as strain gages, have been proposed to be more sensitive to the onset of member cracking [Begg 1976]. Stubbs compares the distribution of flexural strain energy, as related to the measured member curvature, of a mode shape along a beam-element before and after damage [Stubbs 1995]. It has been demonstrated that modal flexibility is a damage sensitive index by conducting modal tests on decommissioned concrete and steel highway bridges which were loaded to various damage states [Toksoy 1993, Aktan 1994]. Zhang showed that the uniform load surface and its curvature can provide an accurate and conceptual health index for a structure [Zhang 1993].

Intelligent Health Monitor

Given the synergy of the on-going research and test specimens, the expressed objective for UCII research is the systematic and integrated development of an intelligent health monitor for steel-stringer bridges. While the concept of an intelligent structure is not new, many of the issues which need to be resolved are not all recognized. Further, real-life implementation of well-researched concepts is still a major challenge. The basic issues which are obstructing an intelligent monitor include:

- Limitations in sensor and data-acquisition technologies
- Limitations in state-of-the-art field experimentation
- Uncertainty of actual state and performance properties and quantitative indices
- Uncertainty of natural factors and their potential significance over service loads
- Indices to track changes in state properties due to damage and deterioration
- Optimal integration of human and machine intelligence, specifically:
    - ⇒ Accumulated heuristic know-how and experience on bridge engineering
    - ⇒ Structural testing results and on-line instrumented monitoring data

This research seeks the rational organization and integration of nondestructive evaluation technologies such as proof-load and modal testing, the methods of structural identification, and concepts of reliability and fault detection, each according to its merits, within a system devoted to monitoring the state-of-health of an instrumented structure. This monitoring system may sit resident and on-line at the site of a structure in order to provide continuous assessment of its performance; or, the monitoring system may represent the remote bureau of responsible engineers and inspectors which is the typical practice of the present day. In either case, this system takes a hybrid approach for structural monitoring where emphasis is placed upon the optimum interconnection and interaction of several NDE methods and technologies of merit for the given structure.

For the first two bridge specimens discussed here, HAM-42-0992 and HAM-126-0881L, an “intelligent” sensor system is planned (Figure 4) which will monitor structural condition and alert officials in case it is decided that the reliability of the structure is reduced to an unacceptable level. At a minimum, the health monitoring systems will be comprised of a collection of sensors and data-acquisition hardware which will act to collect, archive, and possibly telemeter various bridge measurements such as strains, deflections, accelerations, temperature, rotation, and others. These measurements will, in turn, be used by bridge engineers to complement the subjective visual inspections and must be sufficient to characterize the structure’s response to its ambient loading environment in order to assess structural integrity. Detected anomalies may trigger an on-site battery of objective NDE tests which would escalate, as needed, in rigor and detail in order to fully appreciate the extent and magnitude of the defect, deterioration and/or damage (DDD). As a long-range goal, the bridge health monitor may gain an autonomous nature where preliminary decisions regarding bridge health are made on-site, immediate corrective actions (such as closing the bridge to traffic) are made, and communication with a central information and planning system is maintained regularly.

In the Fall of 1997, a demonstration of the prototype bridge health monitor will be given to our sponsors. The prototype (Figure 5) will consist of an on-site continuous Windows-based health monitor which:

- Acquires sensor data at variable sampling speeds,
- Communicates with peripheral devices such as the WIM scale,
- Provides a graphical interface via phone line with a remote engineer,
- Performs simple range and other checks for sensor faults,
- Identifies parameters for a simple mechanical grid model of the bridge,
- Detects any structural degradation or damage via thresholds,
- Has an open architecture for future expansion or connection.

Conclusion and Acknowledgement

As we seek answers to our fundamental questions, we expect to develop practical, streamlined procedures and simple tools for feasibly testing and reliably monitoring large numbers of bridges for serve objective condition assessment. The basic premise of the research is to advance concepts and strategies such as structural dynamics, instrumented monitoring, system identification, failure-mode analysis, statistical sampling, and intelligent systems. This research has been supported by the Ohio Department of Transportation and the Federal Highway Administration.

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Table 1: Some Common Linearized Condition Indices For Constructed Facilities

Identification Space	Experimentally Measured Quantities	Post-Processed Indices, *No Analytical Model Is Required*	Analytically Derived Indices Requiring Structural ID
Modal model	Input: Impact or Excitation; Output: Acceleration; Input and output in time-domain, FRF, or both	Mode frequencies and damping Displacement Mode Shape Vectors Strain Mode Shape Vectors MAC, COMAC, MSF	Strain energy of a mode shape Curvature distribution of a mode shape
Numerical model: w/ assumed forms of M,K,C matrices	Input: None, or as in Modal; and/or known static (truck) loads Output: As in modal, or strains, tilts, displacements	Mode frequencies and damping Mode shapes Global flexibility or stiffness coefficients	Member level properties Parameters derived from stochastic or statistical models
Geometric model: Macro, element or FE forms	Same as in Modal and Numerical	Modal Flexibility Uniform Load Surface (ULS) Other indices directly obtained from modal flexibility	Member level and localized structural properties

Table Definitions:

FRF	Frequency Response Function	MAC	Modal Assurance Criterion	ID	Identification
M	Mass	COMAC	Coordinate Modal Assurance Criterion		
K	Stiffness	MSF	Modal Scaling Factor		
C	Damping	ULS	Uniform Load Surface		
FE	Finite Element				

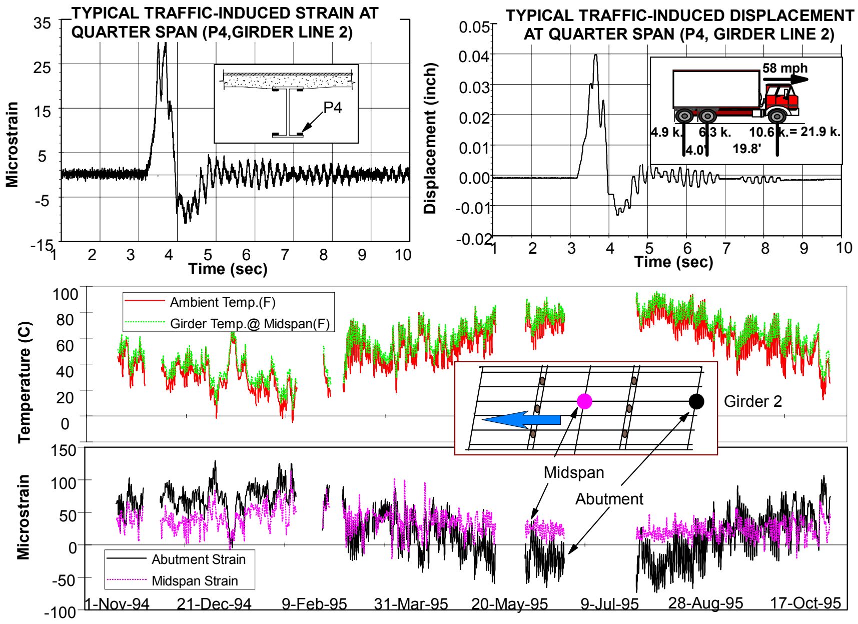

Figure 1. Typical Bridge Responses to Traffic and Long-Term Ambient Input

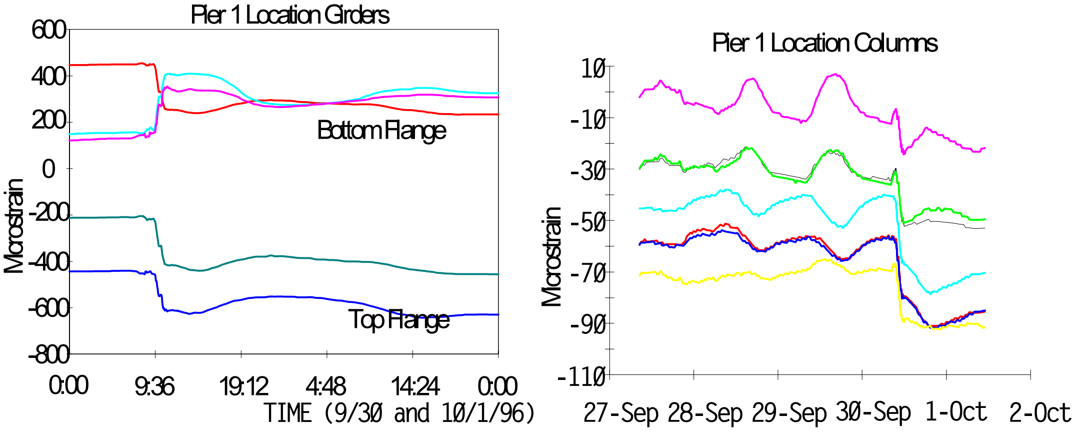

Figure 2. Event-Based Monitoring of Bridge Construction: Deck Installation

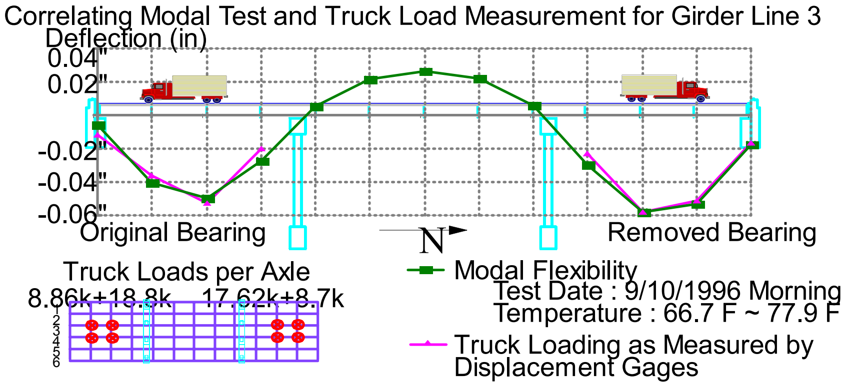

Figure 3. Flexibility Correlation of NDE Test and Instrumented Monitoring

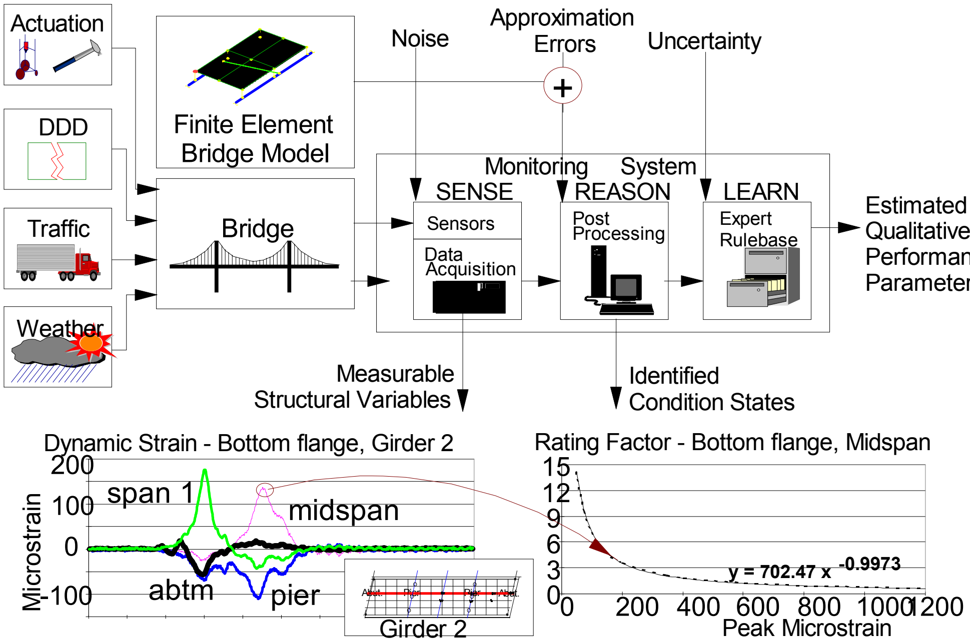

Figure 4. Monitoring Strategy for the Intelligent Bridge of the Future

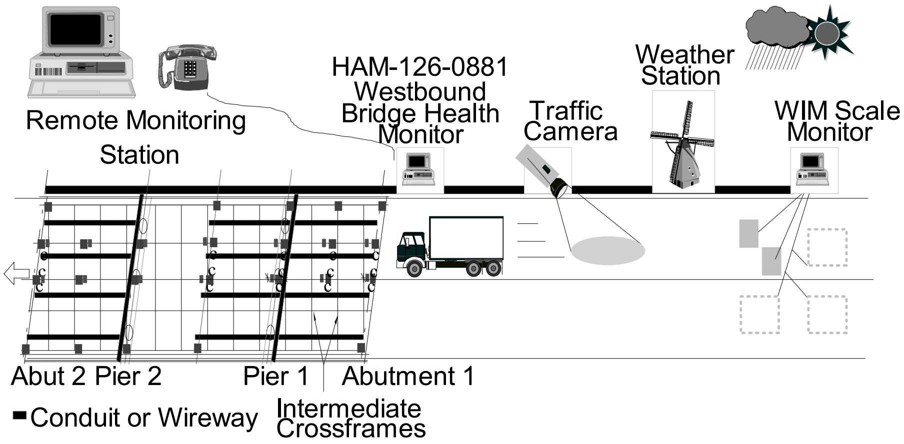

Figure 5. On-Site, Continuous Health Monitor of an Instrumented Highway Bridge