OBJECTIVE GLOBAL CONDITION ASSESSMENT

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ABSTRACT. *The problem of objective global condition assessment is the transformation of the traditional process of subjective rating and evaluation to one which objectively incorporates all the past, present and future systems and properties which affect performance, into a more meaningful expression for the global health of a structure. The two fundamental concepts which provide the basis for this transformation are structural reliability and structural identification. Moreover, by utilizing actual operating or decommissioned facilities as test-specimens in conjunction with laboratory and analytical-numerical-computational support for the research, and interacting with practicing engineers, a reasonable check and balance is maintained between academic imagination and vision, the current state-of-the-art research tools, and the actual states of engineering education and practice. The two basic and distinct experimental approaches offering the greatest promise for feasibly generating objective and detailed information about the mechanical characteristics and loading mechanisms of an operating structure are dynamic testing and instrumented monitoring.*

1. PROBLEM DEFINITION

Ensuring adequate performance of civil infrastructure systems (CIS) is critical to a variety of national interests [1]. Even during disasters, we cannot accept a lack of safety during the lifetime of a structure. We require the designed serviceability to be maintained under current and future demands. Economic growth has been closely linked to improving the serviceability of CIS. The National Science Foundation (NSF) targets intelligent CIS as a means of improving performance in a cost effective manner. Research initiatives in condition assessment, deterioration science, renewal engineering, organizational effectiveness, intelligent materials and systems, and structural control have been launched by the NSF. Of these problems, subjective or inaccurate condition assessment has been indicated as the most critical technical barrier to effective CIS management by the federal administration [2].

The current engineering practice for condition assessment has been influenced by the National Bridge Inspection program enacted following the 1967 collapse of the Silver Bridge over the Ohio River. Today, condition assessment of bridges are conducted visually and bridge conditions are described by subjective indices. Bridges are then typically rated by the same idealized models and procedures used for their design. A similar approach has been adopted by the Army Corps of Engineers in inspecting and evaluating the river facilities under their jurisdiction. We further note many similarities in the evaluation of earthquake vulnerability for constructed facilities.

Figure 1 shows a Bridge Inspection Report form used by Ohio DOT. This form guides an inspector to assign ratings (between 1-4) to various elements of a bridge, and then appraise the condition of major components, such as the deck, superstructure, or substructure, by assigning a condition index (0-9). A general appraisal index (0-9) is also assigned to the complete bridge which is used in evaluating permits and maintenance management. The problem of objective global condition assessment is the transformation of this subjective rating and evaluation process to one which objectively incorporates all the past, present and future systems and bridge properties that affect performance, into a more meaningful expression for the global health of a bridge. The objective information generated during global condition assessment will pave the way to effective maintenance and optimum renewal. More specific definitions for objective global condition assessment and related terms have been formulated by the authors [3].

2. BACKGROUND

The authors started their research on objective global condition assessment a decade ago. They formed a multi-disciplinary group including structural engineering, engineering mechanics, mechanical engineering, electrical and computer engineering, materials science and design. They also developed close partnerships with local, state and federal government agencies and industry. A decade of interactions between these partners led to a common language and a sound understanding of the problem. The problem is a complex multi-systems identification and integration issue, as outlined in Figure 2. Even without a full grasp of the global problem, one may envision formulating basic research for various aspects of the problem, such as developing a local nondestructive test technique, or instrumenting a certain bridge without a structural identification plan. However, developing a global understanding of the problem maximizes the benefit-to-cost ratio of the research, permits formulation of an appropriate scope commensurate with the challenges of the problem, and permits the research team to seek mechanisms for an appropriate level of funding so that the required scope can be effectively undertaken.

The authors designed a research strategy that recognizes the true scope and the technical challenges of the problem. They first focused on the nondestructive and destructive testing and characterization of numerous concrete, steel and composite bridge types. The team came to recognize the ***generic*** loading and behavior mechanisms, as affected by the super-structural system, sub-structure system, foundation and so-called non-structural details, which are exhibited by different bridge structural types such as beam-slab bridges, truss-bridges, or other abutment, pier and foundation types. In this manner, they could overcome the myth that ***"every bridge is a different and unique structure"***. A similar understanding is used in medical and biological sciences, and permits applying a small set of principles to an ***apparently*** unrelated population. Moreover, by utilizing actual operating or decommissioned facilities as test-specimens in conjunction with laboratory and analytical-numerical-computational support for the research, and interacting with practicing engineers, a reasonable check and balance is maintained between academic imagination and vision, the current state-of-the-art research tools, and the actual states of engineering education and practice [3].

The two fundamental concepts which provide the basis for the authors' research on global objective condition assessment are "***structural reliability***" and "***structural identification***":

Structural Reliability:

To permit cost-effective maintenance, condition assessment cannot simply be a replacement of the visual inspection index with a corresponding number (0-9) from a diagnostic experiment. The most appropriate objective index or set of indices for expressing the "global condition or the state of-health" must be determined. The best candidate for this is "structural reliability". However, the evaluation of structural reliability should be approached as a conceptual structural engineering problem as opposed to a theoretical problem dealing with the mathematics of complex probability density functions.

We need to evaluate structural reliability by estimating the actual capacities and demands at different limit-states, based on an understanding of the actual loading environment and behavior mechanisms of a structure. In this regard we should be considering two different reliability indices for the serviceability and ultimate limit states for the same structure. The state-of-practice in bridge engineering, based on 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 10-20 years. While we blame increased traffic volume for many bridge problems, the authors' evidence is that the impacts of traffic on bridge serviceability are ***negligible!*** Therefore, we do need separate reliability indices for serviceability, which is the real problem for the large majority of bridges, and for safety, which is a problem mainly for areas affected by a high probability of natural disasters.

Structural Identification (St-Id):

The most definitive manner of generating objective information about a structure is by structural identification. A broad definition for St-Id follows from Figure 3: The art of analytically conceptualizing, modeling, and designing experiments for measuring and quantifying structural behavior, and the phenomena affecting it, as a basis for subsequent engineering decisions. St-Id can serve to identify phenomena that are not yet clearly understood, or it can even be extended to the identification of interactions between legal, political, economical, and technical issues. Examples: Identifying interaction between orthogonal phenomena in building response; or, interaction between the performance of civil infrastructure sub-systems, such as bridges, pavement, traffic, public, and departments of transportation.

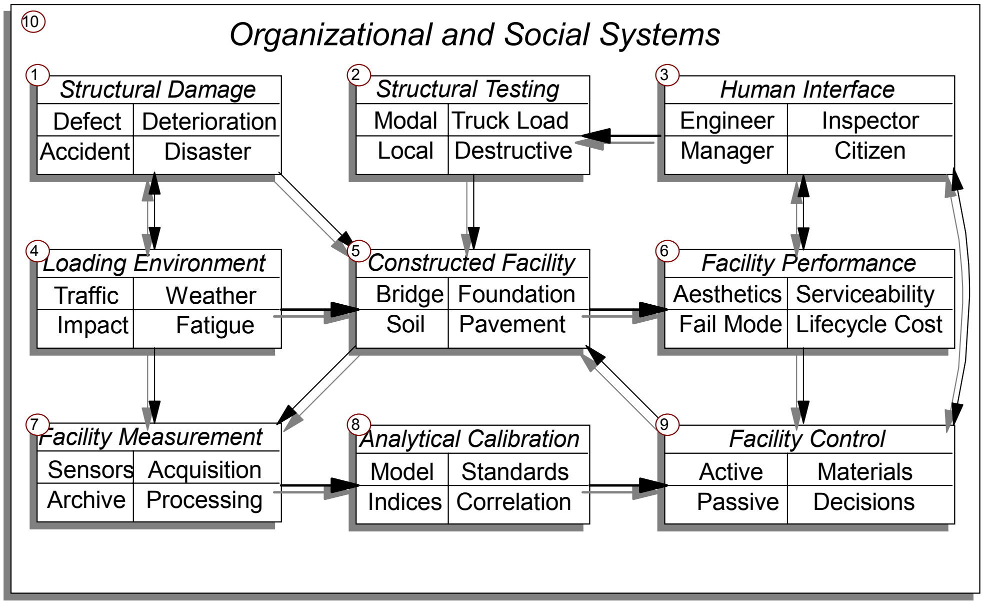
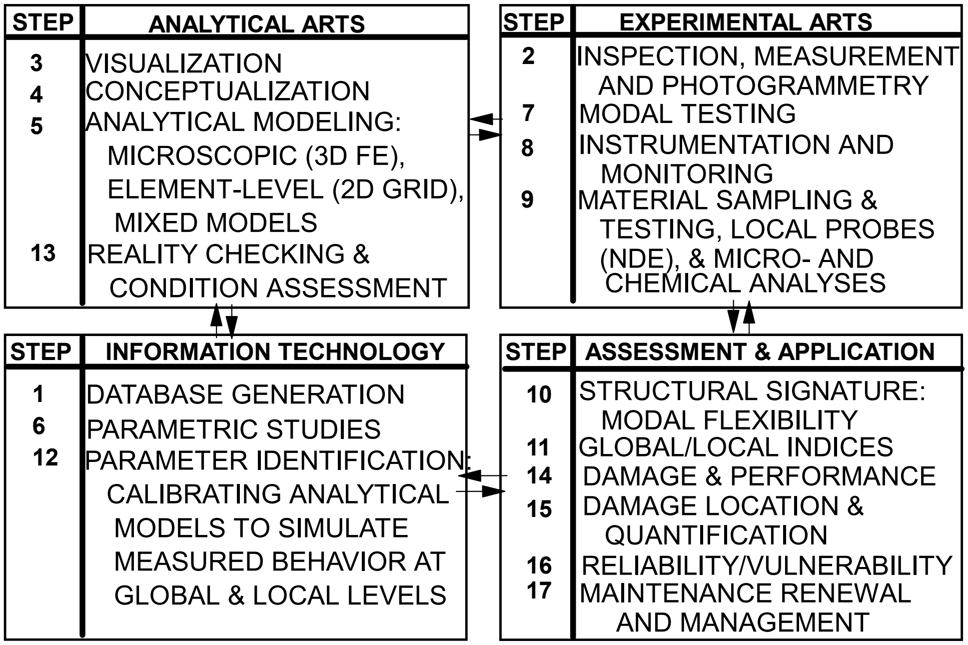


Figure 2. Multi-System Conceptualization of Intelligent Infrastructure



STEP	ANALYTICAL ARTS
3	VISUALIZATION
4	CONCEPTUALIZATION
5	ANALYTICAL MODELING: MICROSCOPIC (3D FE), ELEMENT-LEVEL (2D GRID), MIXED MODELS
13	REALITY CHECKING & CONDITION ASSESSMENT

STEP	EXPERIMENTAL ARTS
2	INSPECTION, MEASUREMENT AND PHOTOGRAMMETRY
7	MODAL TESTING
8	INSTRUMENTATION AND MONITORING
9	MATERIAL SAMPLING & TESTING, LOCAL PROBES (NDE), & MICRO- AND CHEMICAL ANALYSES

STEP	INFORMATION TECHNOLOGY
1	DATABASE GENERATION
6	PARAMETRIC STUDIES
12	PARAMETER IDENTIFICATION: CALIBRATING ANALYTICAL MODELS TO SIMULATE MEASURED BEHAVIOR AT GLOBAL & LOCAL LEVELS

STEP	ASSESSMENT & APPLICATION
10	STRUCTURAL SIGNATURE: MODAL FLEXIBILITY
11	GLOBAL/LOCAL INDICES
14	DAMAGE & PERFORMANCE
15	DAMAGE LOCATION & QUANTIFICATION
16	RELIABILITY/VULNERABILITY
17	MAINTENANCE RENEWAL AND MANAGEMENT

Figure 3. Bridge Structural Identification and Condition Assessment Methodology

Figure 3 summarizes the structural-identification methodology which has been developed to serve as a CIS condition assessment research and application procedure. The principal experimental technologies and tools which have been explored, developed and validated by the researchers are indicated. The two basic and distinct experimental approaches offering the greatest promise for feasibly generating objective and detailed information about the mechanical characteristics and loading mechanisms of an operating structure are ***dynamic testing and instrumented monitoring***.

3. OBJECTIVES AND SCOPE

The researchers are currently using a decommissioned, 3-span steel-girder bridge in Cincinnati as a test-specimen for nondestructive and damage-level tests. The global objective of this research is to evaluate the success of different concepts, experimental approaches, algorithms and hardware/software tools for condition assessment, by detecting various types and levels of damage and repair which will be induced in the decommissioned bridge. The research is designed around the successive application of the St-Id methodology which is shown in Figure 3. The bridge is subjected to a variety of modal tests and instrumented monitoring scenarios including truck-load tests to generate data to help answer the following questions:

1. ***What are the most appropriate condition and damage indices for expressing global health?***

1A. Can indices based on hysteretic response proposed for earthquake damage serve real-life condition assessment applications?
1B. Can more practical linearized (both spatially and temporally) indices serve for condition assessment? Some of the most common linearized condition indices are shown in Table 1**.**
1C. How stationary are different condition indices, i.e. how are different indices affected by natural aging, impact of climate-environmental conditions, unavoidable experimental errors, etc.?
1D. Can we correlate the traditional subjective condition indices for bridges based on visual inspections to any objective one? Can we directly correlate an objective index to the structural reliability of different bridge types, or do we need extensive analytical post-processing to estimate structural reliability?

2. ***Can we find direct relationships between measurable load and response quantities and the global structural condition (Table 1)?***

2A. What are the condition indices which require the minimum analytical and numerical processes on measured data?
2B. What are the sensitivity thresholds of different indices? Which indices can serve for global assessment and quantify the impact of damage on performance?
2C. Are there objective condition indices which are directly measurable and are also sufficiently conceptual for practicing engineers to aid in decision making?

Identification Space	Experimentally Measured Quantities	Indices Derived by Post-Processing Data, No Analytical Model Is Required	Analytically Derived Indices Requiring Structural Identification
Modal model	Input: Impact or Excitation; Output: Acceleration; Input & output in time-domain, FRF, or both	Mode frequencies and damping Disp. Mode Shape Vectors Strain Mode Shape Vectors MAC, COMAC, MSF	Strain energy of a mode shape Curvature distribution of a mode shape
Numerical model: with 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, and 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-level, or FE	Same as in Modal and Numerical	Modal Flexibility Uniform Load Surface (ULS)	Member level and localized structural properties

Table 1: Linearized Structural Damage and Condition Indices

3. ***How can we establish the relationships between microscopic damage indices (such as continuum damage theories based on in-situ material characterizations), local defects (as measured by local probes such as impact-echo), and visual damage and deterioration indices (spall, crack, localized yield, corrosion pitting, etc.) and the global health/reliability techniques such as modal testing and instrumented monitoring?***

3A. How can we reliably diagnose, locate and quantify local damage by measuring a limited number of local or global responses or state parameters?
3B. What are the minimum spatial and temporal resolutions of local and global responses to be measured for reliable condition assessment and reliability evaluation?
3C. Can we take advantage of the synergy which can exist between global and local assessment technologies? Can we develop algorithms for feasible yet accurate and comprehensive condition assessment by employing global and local NDE techniques in conjunction with each other?

4. ***What are the optimum use modes of modal testing and instrumented monitoring for structural identification of constructed facilities?***

4A. How can we maximize the synergy which can be realized by designing and applying both of these experimental techniques in conjunction with their integration by analytical modeling?
4B. How can we streamline the applications of either tool for maximum benefit/cost ratio?
4C. Can parameter identification for different geometric and numerical characterizations in conjunction with system-identification serve for global condition and damage assessment?

5. ***Is it possible to assess condition and damage without a baseline? What are the most critical requirements and particularly the stationarity issues in baseline generation?***

5A. Is it possible to assess the condition of a large population of bridges by generating detailed baselines of statistical samples?
5B. How can we take advantage of type-specific characteristics of bridges in objective condition assessment?

The bridge has been subjected to the following damage conditions (Figure 4):

1. As-is condition of the 40-year old bridge, with extensive deterioration of the deck concrete and extensive corrosion of steel girders and bearings at the abutment regions;
2. Removal and clearing of the expansion joints, auxiliary bumper-plates and cleaning of the bearing plates at the abutments;
3. Removal of one bearing plate at an abutment;
4. Restoration of the bearing plate and welding the bearing plates at the abutments to simulate frozen bearing conditions;
5. Cutting one-half of the lower flange of an interior girder at the middle of an end-span;
6. Cutting the remaining half of the lower flange for a full flange-cut;
7. Cutting the web at the location of the cut flange up to 60% of its height;

The objectives of this and the following papers in this Session are to report preliminary results of the research. The most significant observations are presented in the following.

4. PRELIMINARY RESULTS AND OBSERVATIONS

A. The 40-year old test specimen, which exhibited extensive deterioration, served to demonstrate the difficulties in linearized structural identification of an actual aged constructed facility.

The boundary and continuity conditions and material properties were highly variant, and could not be established with confidence, in spite of extensive effort by the test team. Changes in the ambient conditions strongly influenced the dynamic properties. Temperature changes, in conjunction with other ambient conditions such as cloud cover, humidity, direction of temperature change, etc. were observed to affect bridge boundary conditions significantly. This was aggravated by the design and current condition of the bridge bearings at the abutments and at the piers. Only after physically cleaning and clarifying the contacts between the bridge superstructure, the roadway and the substructure, it was possible to test and capture the state properties of the bridge.

B. Modal analysis was proven again as the most powerful experimental technique for measuring global state properties of a bridge.

However, modal analysis was also proven to require extremely stringent experimental and post-processing standards for successful applications to bridges, particularly if the objective is generating modal flexibility as a global condition index. In spite of the difficulties discussed below, it was possible to design and execute modal tests and post-process the data successfully, and generate meaningful modal flexibility. Details are given in the following papers.

Of many different forms of modal testing, multi-reference impact testing was found to be the most suitable for bridge testing, particularly for bridges with frequencies higher than 4 Hz. Since this type of test could be applied in increments using different grids at different times on the bridge, it was possible to mitigate non-stationarity of the structure. While the bridge mechanical characteristics may shift over a matter of hours depending on the temperature changes, each individual test could be conducted within an hour or so such that the bridge could remain close to a stationary state during the execution of each test. This was found to be an essential requirement in order to be able to post-process the tests meaningfully.

Strict standards in the calibration and installation of the accelerometers and the signal-conditioning and data-acquisition hardware were found to be another critical requirement. Slight de-bonding of an accelerometer was found to introduce very subtle errors at mid-range frequencies; these errors were extremely difficult if at all possible to detect just by reviewing the data. No test should be conducted without a careful physical check of each sensor after installation. If a test continues more than several hours, it is necessary to intermittently check the complete hardware system including the sensors. Many components of test hardware were discovered to be affected by changes in ambient conditions just like the bridge itself. For this reason, it is recommended to prepare a small mechanical specimen at the bridge as an ancillary calibration structure with well-established properties; intermittently, conduct tests on this structure to check for changes in the hardware and software settings. The PCB 393C accelerometers, their installation standards, the TMS impact or drop-hammer, and the HP 3566A Paragon data-acquisition system in conjunction with the HP GUI-DUC impact-test software performed adequately within the 4-50 Hz. frequency band, which applies to a great majority of bridges.

Successful post-processing of the bridge modal test data was discovered to pose major difficulties, particularly if the objective is accurate condition assessment by using flexibility and not just capturing a number of mode shapes and frequencies. Powerful post-processing packages such as I-DEAS, X-MODAL, and LMS exist; however, none of these packages were designed for test data from a bridge which shifted its dynamic properties in the course of a test. Compounding this problem was very high coupling of vertical as well as lateral modes in a critical band. Furthermore, the bridge deck was highly deteriorated and covered by an asphalt overlay. This attenuated the impacts and affected the clarity of the phase responses, in different manners in both the immediate vicinity and the distant points of the test grid. While reciprocity and linearity appeared to be reasonably satisfied over the critical frequency band of interest, slight phasing or complexity was sufficient to introduce significant uncertainty in the experimental data during post-processing.

While different post-processing packages did produce numerous modes, these were not reliable. The assumption of complex modes due to nonlinear damping seems to better agree with the circumstances; however, post-processing based on this assumption led to unreliable modes which were extremely damped. The software mistook the nonstationarity shifts in the bridge properties as damping, and produced unreliable modes in the regions of frequency band which had highly coupled modes. Successful post-processing was possible only by using the less-sophisticated algorithm CMIF which incorporated the real-modes assumption. Post-processing the same experimental data by different experts using different software produced different results. A post-processing algorithm which recognizes the typical anomalies in modal test data, but also incorporates strict quality checks and calibration with benchmark structures is needed for universal applications of this technology. ***A very important conclusion is that it is not sufficient to verify the success of the experiment by just looking at mode shapes and frequencies; the derived modal flexibility must be physically realizable.***

C. Modal flexibility was shown to be an excellent objective kernel index or signature for assessing bridge condition.

Depending on the spatial properties of the test grid and the frequency band which can be reliably captured during a test, modal flexibility successfully served for both a global and an element-level local condition assessment. The advantage of modal flexibility, even when only two girder-lines could be tested at a time, was that it permitted the experimental evaluation of individual girder deflections under uniform nodal load, obtained without any analytical characterization or numerical assumption. These deflected shapes provide a conceptual index of girder condition, termed as the “bridge girder condition indicator” (***BGCI***). While other load patterns may be applied to generate girder deflections which are more sensitive to local damage, the uniform load pattern permitted the most reliable index since this index was affected the least by modal truncation and experimental errors.

The BGCI successfully revealed the relative stiffness of different girders at different spans, removal and restoration of a bearing, and a flange-cut at a girder cross-section. The latter is a very local damage, and was detected with the least confidence (Figure 5). However, the damage indicator did point out to a change at the correct location, and work is in progress to evaluate derivative indices such as curvature changes along the affected girder. One may conclude that the BGCI reliably and conceptually locates and quantifies the direction and amount of change at a local deflection node in the case of more than 10% change. The flange-cut produced less than 10% difference in deflections and, although it was clearly revealed by the damage indicator, the amount of change cannot be confidently quantified. Experimental and conceptual uncertainties related to linearized damage detection do not permit confident damage assessment via flexibility when deflection changes are less than 10%.

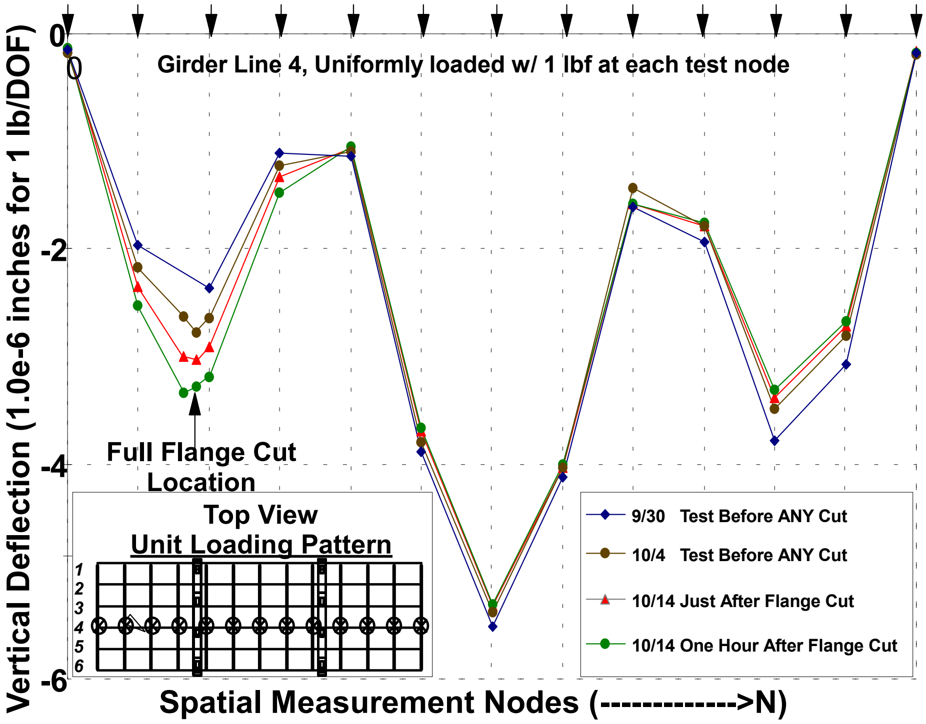


Figure 5. Bridge Girder Condition Index Before/After Flange Cut

D. Instrumented monitoring was found to be a great complement to modal analysis but not a replacement.

The bridge was instrumented extensively and continuously monitored. The local strains and temperatures at the boundaries and the spans, support movements, tilts and deflections were extensively monitored. In addition, extensive truck-load tests were conducted under many different load configurations.

Instrumented monitoring provided local response data which cannot be obtained by any other experimental technique. However, a complete interpretation of the local response data was extremely difficult, and in fact was possible only by the conceptual help provided by modal analysis results. Global responses under truck loading do offer a conceptual evaluation, however, experimental uncertainties were not any less than those affecting the modal analysis results. The detail of global information from an instrumented monitoring application can never reach the detail provided by a modal test. However, instrumented monitoring was observed to offer many advantages as a follow-up monitoring technique once a comprehensive condition assessment plan is carried out by incorporating modal testing and instrumented monitoring together. Instrumented monitoring, especially a truck-load test, can also provide an independent check on the reliability of modal analysis results.

We note additional implications of the truck-load tests on this and other bridges. If a 40-year old bridge with extensive material deterioration (and rated 4 by visual inspection) has local responses under truck-load which correspond to L/5600 Deflection and 5.3 ksi Maximum incremental stress for the legal truck-load of 72 kips, while the incremental stresses induced by daily temperature changes exceed live-load stresses, and if various forms of local damage including bearing removal did not adversely affect the stresses and stability so that a safety concern arose, and if a super-load which exceeds 10 times the legal load does not cause distress to three similar bridges of various ages, geometry and design, why are so many of these bridges performing inadequately in the serviceability limit state? Can we review the fundamentals of our bridge design and evaluation in a new light based on the results of this research? Can we formulate simple, economical but effective measures which mitigate deck concrete distress requiring expensive replacement? Obviously, we are not designing for the actual critical demands in the case of steel-stringer bridge serviceability!

E. Analytical studies with a finite element (FE) model was essential support for the success of modal testing and instrumented monitoring.

Analytical modeling of the bridge, particularly representing the boundary and continuity conditions properly, was a challenge. Close-range photogrammetry, reverse CAD and visualization software such as auto-CAD and 3D studio were useful tools which helped conceptualize the critical features of the bridge. Further studies are needed before we can understand the promise and limitations of using parameter identification as a tool for condition assessment. However, it is clear that St-Id is essential for correctly designing research and applications for objective condition assessment.

F. Research has clearly demonstrated to the authors that no experimental tool can completely replace visual inspection by an experienced engineer for condition assessment.

Visual inspection has to remain an integral component of any objective condition assessment. St-Id by modal analysis and instrumented monitoring should be considered as research tools for developing more practical experiments in order to: (a) complement condition assessment of important bridges which are suspected to have hidden deterioration or damage; (b) develop practical instrumented monitoring techniques such as with passive sensors in order to provide an alarm in the case of damage due to accidents, or, to indicate that it is appropriate to defer visual inspection in the case of healthy bridges with conditions which have not changed since the last inspection. In this manner experienced inspectors may focus on bridges which are known to have problems.

5. CONCLUSION

Structural identification by modal analysis and instrumented monitoring should further remain as a potent tool in the case of: intelligent infrastructure applications; construction with new materials such as FRP composites applications; long-span, monumental, and/or critical lifeline structures which require continuous health-monitoring; and, historic structures which require preservation design. Perhaps the most important need for structural identification applications today is rationalizing the manner in which we design, inspect, evaluate, maintain and renew bridges and other components of the civil infrastructure system.

6. REFERENCES

1. **National Science Foundation**
   Civil infrastructure systems research: Strategic issues,
   Report of the Civil Infrastructure Systems (CIS) Task Group, National Science Foundation, 1993.

2. **Clinton, W., President, and Gore, A. Vice President**
   Technology For America's Economic Growth, A New Direction To Build Economic Strength,
   Inaugural Address to the Nation, February, 1993.

3. **Aktan, A.E., Farhey, D.N., Brown, D.L., Dalal, V., Helmicki, A., Hunt, V., and Shelley, S.**
   Condition Assessment for Bridge Management, Journal of Infrastructure Systems, ASCE, September, 1996.