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Issues in Instrumented Bridge Health Monitoring

Surveillance de l'état de santé de ponts par capteurs

Brückenzustandsüberwachung mit Instrumenten

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SUMMARY

A market survey and laboratory evaluation identified the most promising sensors and data acquisition systems for infrastructure application. A pilot monitor was implemented on a steel-stringer bridge in Cincinnati for traffic and environmental monitoring. This research improved understanding of the actual loading environment and the corresponding res-ponses of a highway bridge. Instrumented monitoring is expected to complement inspec-tion methods, provide an objective measure of the state-of-health, and alert bridge officials to deterioration or failure.

RÉSUMÉ

Une étude de marché et une évaluation en laboratoire ont évalué les capteurs et les systèmes d'acquisition de données les plus prometteurs en matière de surveillance d'infrastructure de ponts. Un appareil prototype de surveillance a été installé sur un pont métallique à Cincinnati pour mesurer le trafic et les conditions d'environnement. Ce projet a permis d'améliorer la connaissance de la charge réelle et du comportement correspondant du pont. La surveillance avec ce type d'instrumentation devrait compléter les méthodes d'inspection, permettre une mesure objective de l'état de santé du pont et alarmer les responsables du pont en cas de détérioration ou de panne.

ZUSAMMENFASSUNG

Eine Marktstudie und Laborauswertungen identifizierten die vielversprechendsten Sensor- und Datenerfassungssysteme für Überwachung der Brückeninfrastruktur. Ein Bildschirm wurde in eine Stahlbrücke bei Cincinnati eingebaut um Verkehrs- und Umwelt-einflüsse zu beobachten. Diese Untersuchung ergab ein tieferes Verständnis für die Belastungen und das damit verbundene Verhalten der Brücke. Diese Art der Überwachung soll ergänzend zu anderen Möglichkeiten gesehen werden. Sie soll eine objektive Messung des Bauwerkzustandes gestatten und so die Brückenverantwortlichen bei Verschlechterungen oder Versagen alarmieren.

1. PROBLEM STATEMENT

There are two significant reasons why we should be interested in instrumented bridge monitoring. The first reason is to improve our understanding of the actual loading environment and the corresponding bridge responses. With this knowledge, better design, construction and maintenance practices can be initiated. The second reason is to explore whether the information from monitoring may properly complement the current practice of bridge inspections, in order to provide an objective measurement of the state of-health or reliability of the bridge.

This research project aimed at exploring in two phases the multi-disciplinary issues and advancement of the state-of-knowledge in instrumented monitoring of highway bridges. The first phase necessitated a rigorous investigation of commercially available hardware for the bridge monitor in terms of cost, laboratory verification, field accuracy, and useful lifetime. In the second phase, the initial design of the monitor system optimized the installation of the scaffolding and wireway framework; the number, location, and positioning of selected high-speed and long-term strain gages on steel girders; and, the installation of a weather station on a typical three-span steel-stringer bridge in Cincinnati (HAM-42-0992). An integrated multi-disciplinary team of electrical and civil engineers was fully utilized to tackle the challenging research, optimal design, and analytical interpretation of the necessary components of the bridge monitor. For example, a civil engineer used finite-element modeling and cross-sectional analysis to define the optimal sensor types and positions for the bridge monitor, while an electrical engineer designed an accurate data acquisition system for these sensors based upon application-specific signal conditioning and hardware selection.

2. PHASE 1: MARKET SURVEY AND LAB VERIFICATION

The first phase of this research necessitated a rigorous investigation of commercially available hardware for the bridge monitor in terms of cost, laboratory verification, field accuracy, and useful lifetime (Fig. 1). One has to consider reliability in terms of the measured quantity and the interpretation of that quantity. A response that is measured by a sensor and data acquisition system will be composed of five components: (a) Transducer assembly errors (e.g., self-response of the transducer and the attachment assembly as a mini-structure); (b) Instrument/data acquisition variance errors (e.g., spurious readings or noise due to electromagnetic interference); (c) Instrument/data acquisition bias errors (e.g., drift or changes in calibration due to an impact or temperature effects); (d) Apparent structural response (e.g., unrestrained temperature strains and rigid-body displacements as well as rotations caused by settlements, temperature, creep, or shrinkage); and, (e) Structural response associated with stress and force. The logistics for longterm continuous monitoring include the careful decomposition of a sensor reading into the above components, and the resulting reliability of each.

The sources of errors and uncertainties in the strain measurement system may have their origins in the gage itself, the measurement circuit or in other portions of the instrument, such as power supply, amplifier, analog-to-digital converter, etc. To make certain that static characteristics of instruments such as repeatability, linearity, accuracy, hysteresis, sensitivity as well as instrument gage factor, fall within the published tolerances which the manufacturer provides, the sensors are individually calibrated by measurement-system scaling techniques in the laboratory. This requires the input of a series of known displacements by utilizing the micrometer. The calibrator used reads directly in ten-thousandths of an inch over one inch range. Calibration was performed with three cycles of extensions and retractions, over the useable and application ranges for each instrument. The researchers tried to simulate the field test system with respect to data acquisition settings, cable length, and connections, that will be used in actual bridge monitoring and testing. This allowed the error of entire system to be measured.

For weldable foil and vibrating wire strain gages, a simply supported structural steel rolled W6x20 beam was loaded to induce constant moment along the span and used as a calibration structure. The beam was tested in the elastic range, by applying two concentrated loads 34.5" apart, creating stresses up to 140 MPa at the flanges at the midspan. To obtain redundancy, more than one sample of the same kind of gages were placed at the spots that would yield the same reading. A finite element analysis of the beam was calibrated based on the measured mid-point deflection of the beam. Longterm and shortterm monitoring were performed on this calibration beam and strain readings of various gage clusters were compared with FE analysis results.

Long-term reliability of sensor clusters and data acquisition hardware were evaluated with respect to temperature, humidity, and ultraviolet radiation. The QUV Accelerated Weathering Tester is a laboratory simulation of the damaging forces of weather, for the purpose of predicting the durability of certain transducers exposed to the outdoor environment. Cyclic environmental tests of sensors mounted on free moving steel plates were conducted with controlled heat, humidity, and UV radiation. For simulation of freezing winter conditions, a simply supported structural steel profile beam was instrumented and placed in a freezer, to serve as a calibration structure. These weathering tests were monitored over long-term (weeks) in order to estimate gage reliability. Static and dynamic temperature tests were conducted to measure the apparent effect on sensor readings. There were many problems discovered with these tests and, in some cases, resulted in the modification of vendor literature or even gage design.

After the tests, it was concluded that the smaller Geokon Vibrating Wire models (VK 4100 and 4150) were not adequate due to their extreme sensitivity to installation and to hysteresis observed during load testing. Although Hitec Products foil gages performed well under load testing, they showed erratic reading when bathed with moisture in the Weathering Tester. Also contrary to vendor specifications, the full bridge strain gages showed considerable response to temperature. During the calibration process and the beam tests, it was observed that the accuracy and resolution of the Tokyo Sokki Kenkyujo clip gages were not suitable for the bridge monitoring under service loads. Further, the vendor's specification of gage factor was found to be in error by a magnitude of ten.

The Optim MEGADAC was chosen for data acquisition due to its proven performance and accuracy in past research experiments. Lab testing and analysis related to electronic acquisition of data included, electrical I/O calibration, cable shielding and losses, surge protection, proper grounding, filter and gain selection, minimum sample frequency, and software optimization. The selected Tokyo Sokki Kenkyujo AWC-8B is a weldable strain gage especially designed for use in harsh environments and longterm measurement. The gage is constructed of a strain element enclosed in a stainless steel tube, a metal carrier base for spot-welding, and an integral shielded 3-wire system. The selected vibrating wire Geokon VSM-4001 strain gage with thermistor revealed a rugged, dependable gage which exhibited unparalleled thermal compensation in our laboratory tests. The advantage of vibrating wire technology over the traditional resistance strain gage is in the use of a frequency, rather than a voltage, output from the sensor. This factor, coupled with rugged steel design and hermetically sealed construction, results in excellent long-term zero stability.

For all kinds of gages, installation plays an important role in accurate and reliable data collection. During the lab studies, it was seen that improper installation can cause errors resulting in no data reading at all as well as misreading that can lead the researcher to erroneous conclusions. Several different installation techniques ranging from industrial magnets to various epoxy applications were evaluated for outdoor testing. The ones selected for the next phase of the project were spot welding for foil strain gages and 3M Scotch-Weld epoxy for the VSM-4001 gages.

3. PHASE 2: IMPLEMENTATION OF THE MONITORING SYSTEM

In order to be able to develop a reliable bridge monitoring technique, one should first select a bridge type which would represent large populations such as continuous steel-stringer bridges. The Cross-County Highway Bridge over Reading Road was selected as a typical sample as it has been extensively instrumented, monitored and tested by a multitude of global and local nondestructive techniques in the past. The nondestructive tests conducted for structural identification included modal tests by impact as well as vertical and lateral forced excitation, followed by truck load tests for measuring global and local bridge responses under static loading patterns. The results of these experiments helped to improve an understanding of bridge behavior at the service limit states. A complete and accurate characterization of the as-is structural condition has been related to the structural capacities and structural reliability. Only with this level of understanding can it be possible to determine exactly how many and what types of instruments are needed as a minimum, and where exactly they should be located for the specific bridge type, so that we may confidently interpret the measured responses and have sufficient advance warning for critical changes in the state of an instrumented bridge. Following this type of research, a low-cost instrumented monitoring strategy may be developed and implemented in a large number of bridges.

The two main characteristics of the bridge that need to be captured are the longterm behavior of the bridge under environmental changes and the shortterm behavior of it under traffic loading. In order to capture these behaviors, locations for the baseline sensor set were determined by careful investigation. A finite element analysis was utilized in order to get the optimum sensor locations on the bridge. The general-purpose, FE analysis program SAP90 was employed to analyze the model for sensitivity studies. To find the maximum responses, a moving unit load is used to obtain influence lines of the two middle girders which are considered as critical. The influence lines for several locations are compared. The same kind of analysis is also conducted for the other half of the bridge and the results are found to be compatible with the previous ones. It is concluded that instrumenting only half of the bridge would be sufficient due to symmetrical bridge design with a slight skew. This simplifies installation and reduces cost. The optimum sensor location sections were selected as the abutment, midpoint of the quarterspan, over the pier and midpoint of the midspan. Because the truck traffic is expected most on girder 2, the instrumentation is concentrated on that girder. The other girders are instrumented for control measurements. A finalized first round instrumentation plan can be seen in Fig. 2. The possible deterioration and damage locations were also taken into consideration during design. Because of the limitations of the data acquisition system, the sensor set was limited to 64 gages. The selections of these gages were based on the lab studies done in UCII and former bridge tests done by UCII researchers.

The baseline set is composed of two different gage types: the Geokon VSM-4001 vibrating wire strain gages with thermistor, and the Tokyo Sokki Kenkyujo AWC-8 weldable foil strain gages. The vibrating wire gages are used to capture any strain accumulations due to overall temperature changes, soil pressure changes at the abutments, and differential temperature changes across the width of the bridge. Ten locations have been determined for the placement of the vibrating wires, each having two gages, one at the top flange and one at the bottom flange. They are placed on the outermost girders at the abutments where the maximum responses are expected, as well as on girder two and girder three. The weldable foil strain gages are used to monitor the real-time behavior of the bridge under traffic loads. The data sampling rate of these gages in conjunction with the data acquisition system is sufficient to do real-time monitoring (roughly one kHz). Nine locations with twenty six gages were determined for foil gages. A weather station was also implemented including wind speed, wind direction, temperature, and humidity sensors. It is used to correlate ambient or climatic conditions with readings of the other various gages. Other gages such as tilt meters and DC-LVDTs are planned for future installation.

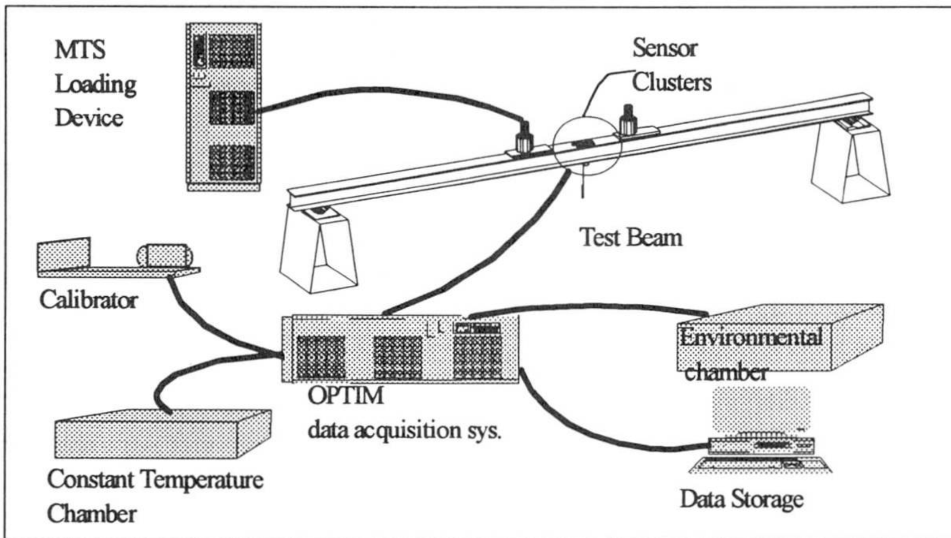

Fig. 1 Schematics of the measurement system scaling for developing a bridge monitoring system.

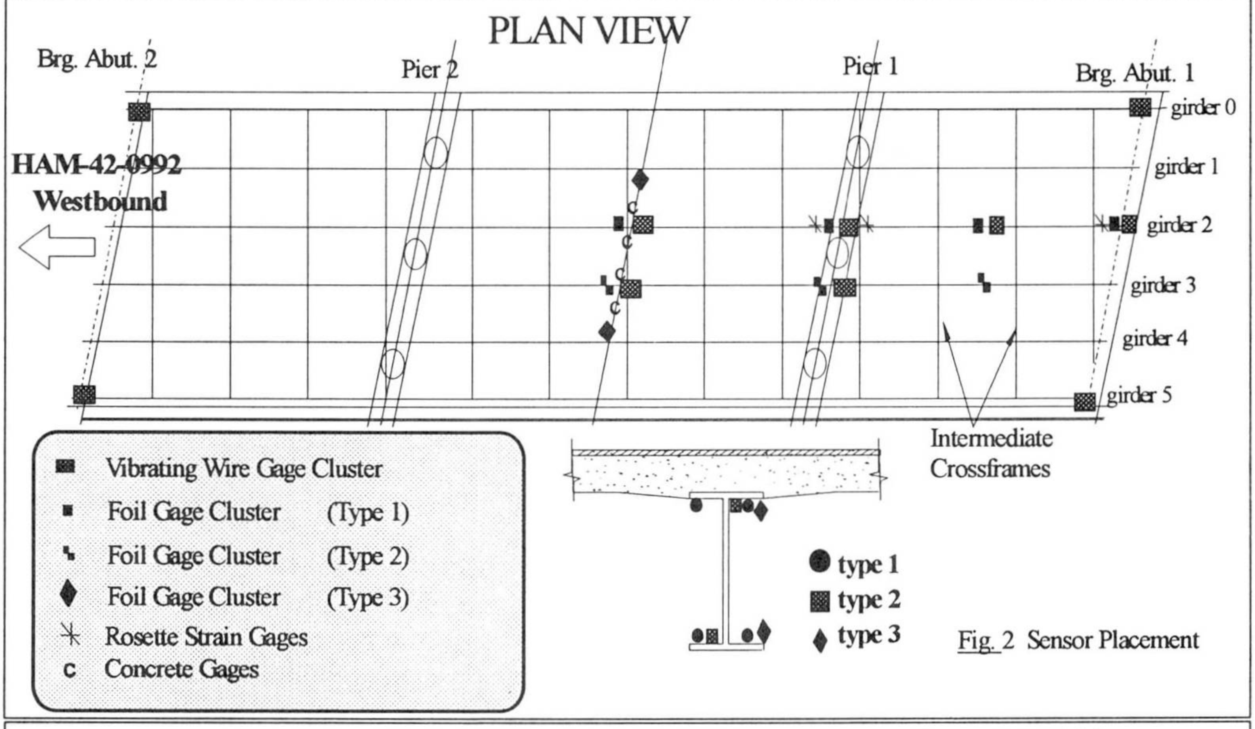

Fig. 2 Sensor Placement

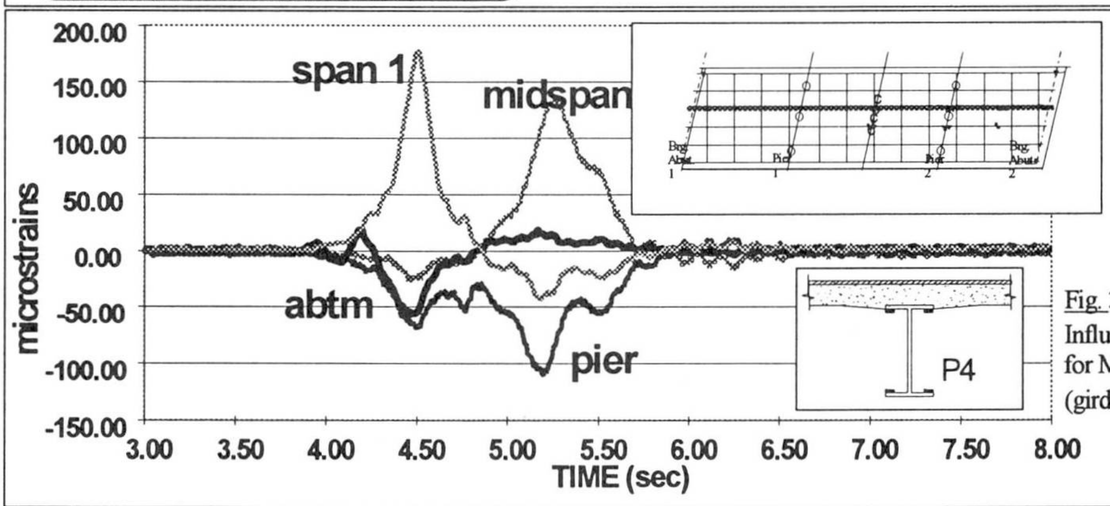

Fig. 3 Real-Time Influence Lines for Moving Truck (girder 2 @ P4)

One may consider the following scenarios for instrumenting a bridge for measuring global and/or local responses: *(a) Instrumenting an existing bridge for intermittently measuring any changes which may occur in the global geometry for health monitoring; (b) Instrumenting an existing bridge for measuring incremental global and/or local responses under static or dynamic loads over a shortterm (in the order of seconds to hours),* such as in weigh-in-motion or in diagnostic testing for bridge rating; *(c) Instrumenting an existing bridge for measuring incremental global and/or local responses under static or dynamic loads over longterm (in the order of months to years); and (d) Instrumenting a bridge through fabrication and construction for measuring the absolute local and global responses over a longterm (months to years).* The first three kinds of testing are being performed on Cross County Highway Bridge over Reading Road (HAM-42-0992).

A "Static Loading Test" is used for measuring responses due to controlled loading and for calibration of the finite element and section analysis models. The load distribution in both the longitudinal and transverse directions are immediately apparent from the field results. The location of the neutral axis is monitored during the entire loading sequence and is useful for determining the degree of composite action that the structure exhibits. The measured strains indicated a nearly fully-composite action, even though the bridge was designed as a non-composite bridge, since the top flange of the girder was embedded into the deck. Since the 3-D FE model of the bridge had been calibrated to closely simulate all the critical response mechanisms, it was used for analytical comparison with the experimental strains of the girders. "High-Speed Dynamic Test" is used for measuring bridge responses due to moving traffic and conducting an on-line bridge rating. A section capacity analysis was performed considering different limit states. Transform equations were written to calculate the rating factors based on the strain readings obtained from the monitor. These calculated factors can allow an instant appreciation of the bridge's health. A "Long-Term Environmental Test" is used for longterm monitoring of thermal and environmental effects on the bridge. Strain and temperature readings at all girder locations are monitored continuously at one-second/gage intervals for capturing their distributions across the bridge with ambient temperature changes. Successful monitoring over three months (Nov. 94-Jan 95) has been achieved. The strains captured by the monitor indicate significant stress cumulation (~14 MPa.) close to abutment due to a ambient temperature change of 20^0C.

The fourth test *Instrumenting a bridge through fabrication and construction for measuring the responses over a longterm* will be pursued in the third phase of the research. This would be the greatest challenge in instrumented monitoring, as there has not been any previous effort to instrument and monitor the responses of a stringer bridge from construction through service and with the objective to synthesize the absolute state-of-stress.

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