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State of the Art Review on Bridges Structural Health Monitoring (Applications and Future Trends)

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Abstract

New bridges offer opportunities for developing complete structural health monitoring systems for bridge inspection and condition evaluation of the bridges. Existing bridges provide challenges for applying state-of-the-art in structural health monitoring technologies to determine the current conditions of the structural element, connections and systems, to formulate model for estimating the rate of degradation, and to predict the existing and the future capacities of the structural components and systems. Advanced health monitoring systems may lead to better understanding of structural behavior and significant improvements of design, as well as the reduction of the structural inspection requirements. Great benefits due to the introduction of structural health monitoring are being accepted by owners, managers, bridge engineers, etc. This chapter provides health monitoring applications to bridges in different spots of the world as well as future trends and research needs.

Introduction

Probably, the most advanced applications of health monitoring are developed in the western parts of the world, specifically, in the United States and Canada. In the following sub-sections, the recent applications of health monitoring techniques in North America are presented.

1- APPLICATIONS IN UNITED STATES

Alampalli, et. al. [**Error! Bookmark not defined.**] studied continuous monitoring of two steel bridges over the Conrail mainline tracks in Rochester, N.Y. These bridges were built in 1963. The monitoring system was included as a part of rehabilitation contracts. Altogether five inclinometers, 22 accelerometers, and five strain gauges were installed in these two bridges. All these were connected with to a remote host computer. Natural frequencies, mode shapes, damping ratios, modal assurance criteria, etc. were then computed for use in condition monitoring and assessment.

A long-term ambient vibration survey on the Fred Hartman Bridge in Texas (fig 1) is in progress primarily to monitor stay cable vibration [1]. Other objectives include efforts to better understand the overall wind performance and the modal characteristics of the structure. The bridge site is prone to extreme climate conditions, such as high-speed winds, rain, thunderstorms and temperature changes throughout the test program. The instrumentation system consists of the following components: (1) two three-axis anemometers at the deck level, (2) propeller-vane anemometer at the south tower top, (3) 19 two-axis accelerometers installed on stay cables, (4) 8 displacement transducers installed on stays, (5) 8 strain gauges measuring strains on guide pipes, (6) 4 dampers on various cables, (7) 2 load cells installed on dampers, (8) 5 accelerometers, 4 one-axis and a two axis, installed on the bridge deck (±4g range), (9) 2 rain gauges (0.01’’ resolution), (10) Temperature probe and barometer, (11) 4-pole Bessel filters set to 10 Hertz, and (12) Windows-based Pentium PC with data acquisition and remote communication software.

FIGURE 1 FRED HARTMAN CABLE-STAYED BRIDGE.

All of the instruments were continuously monitored using a remotely interrogated self-triggering system that records files on the basis of exceeding threshold motion and wind levels. The recorded data files contain 5-minute time histories that are sampled at 40 Hertz and are stored on high-capacity removable disks for further processing. Approximately 10,000 trigger files have been recorded during the three years of the test program, and more are continuously being collected. Analyzing such a large number of data files demands the extensive use of automated procedures. However, the use of automated procedures must be carefully controlled to ensure that flawed or questionable data are not blindly processed. The recorded files are initially processed to determine the statistical features of each record. These features include the mean, standard deviation and other higher moments of the data as well as 1-minute average wind speeds, wind directions, accelerations and displacements, all of which are automatically added to a database. The second stage of processing involves the statistical determination of modal parameters by means. Each 5-minute time history is divided into 1-minute sections, which are processed to obtain the power spectrum of deck and stay accelerometers.

One of the primary tasks in this process was the identification of structural frequencies and mode shapes under a wide range of meteorological and operating environments. fig 2 shows the histogram of deck frequencies for modes up to 1 Hz that was obtained using this database. The locations of peaks in this histogram indicate the presence of modal frequencies. The modal frequencies are distributed in specific ranges along the frequency axis. Modes 1 and 2 are first bending modes with in-phase and out-of-phase motions of the decks, respectively. Similarly, modes 3 and 4 are differently phased second bending modes. A distribution of 0.05 Hz in frequencies for these modes, corresponding to 17% and 12% of the mean values respectively, can be seen in these histograms. This range of values suggests that the inherent variability of modal frequencies should be carefully considered in applications, which use modal characteristics.

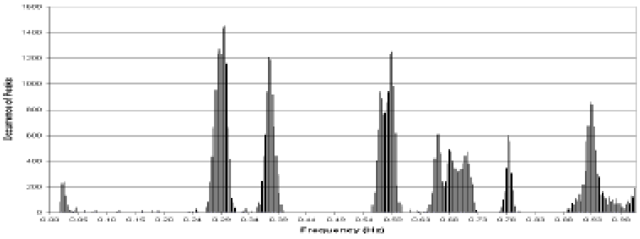


FIGURE 2. HISTOGRAM OF DECK MODES [1].

In a structural identification effort, the frequencies and mode shape estimates have been compared to a finite element (FE) model of the structure, showing reasonable agreement. Another objective was to obtain measurements of these large-amplitude vibrations at full-scale. Numerous events of large-amplitude vibration were recorded before the installation of a vibration mitigation system. As a preliminary analysis of the collected data, statistics were routinely computed for each channel in every record and stored in a relational database to allow for easy analysis of correlations between the various statistical quantities using queries. Observations of the vibration characteristics and their correlation with wind speed, wind direction, and rainfall have been presented using the statistics in this database. The bulk of the large-amplitude responses occur for wind speeds between 16 and 45 km/h; the precise limits vary from stay to stay.

Aktan et. al. [2] implemented a health-monitoring scheme to Commodore Barry Bridge (fig 3 and 4). They reviewed the design and shop drawings for the bridge, inspection reports and relevant reports and documentation for the bridge to identify the state of the structure including its performance and maintenance history. A site visit was also performed to visually examine and verify the condition and locations of any special or complex member and connection details, retrofits to the structure, boundary conditions, and to establish access requirements for any instrumentation work. A three-dimensional FE model of the bridge was, then, constructed to assist with identifying the critical regions and behavior mechanisms of the bridge’s structural systems and to estimate the limits of the forces, strains, tilts, displacements and accelerations that may be necessary to measure. The theoretical model was calibrated through system-identification procedures to permit reliable simulations based on the data from a health monitoring implementation. The data needed for system identification of the bridge and subsequent calibration of the FE model were obtained from controlled experiments conducted on the bridge. These experiments included ambient vibration monitoring of the through truss spans and a controlled load test using heavy cranes.

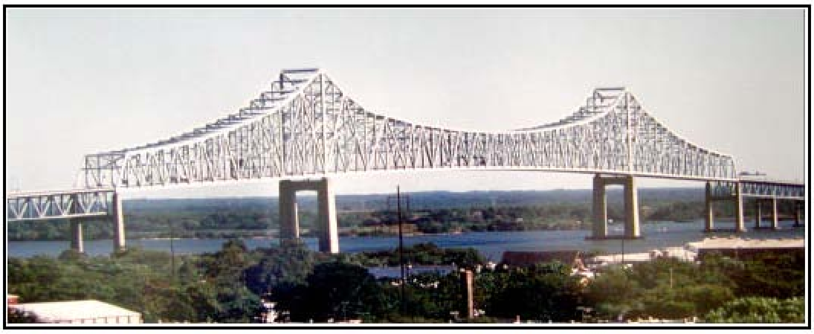


FIGURE 3. COMMODORE BARRY BRIDGE THROUGH-TRUSS STRUCTURE.

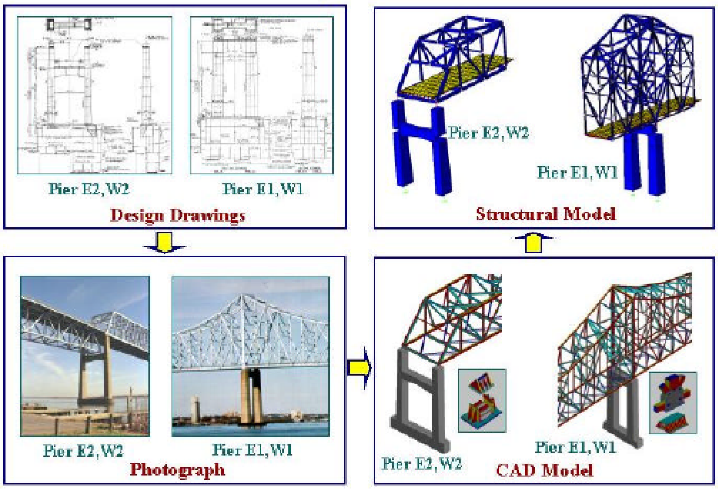


FIGURE 4. 3D ANALYTICAL MODELING OF THE BRIDGE SUBSTRUCTURE.

The obvious and less understood phenomena that would be monitored for a successful and long-term health monitoring implementation were determined. It is important to recognize the possible impacts of humidity, wind, temperature, radiation, long-term movements, tilts, slips and settlements on the intrinsic strains and forces. Non-linearity and boundary and continuity conditions and energy-dissipation mechanisms were recognized in the design of the health monitoring system. The sensing-and-data acquisition systems for the measurements were selected based on the phenomena needing measurement. The individual sensor and data acquisition components were selected from a number of proven off-the-shelf sensors, signal conditioning and data acquisition systems based on their physical, electrical and thermodynamic behavior data. It is imperative that these data were verified through calibration studies to permit reliable interpretation of the acquired measurements. The Commodore Barry Bridge health monitoring system integrated streaming digital video images that monitor the traffic moving over critical areas of the bridge and temperature, displacement, tilt, strain and acceleration measurements.

Being connected to a local area network, the Commodore Barry Bridge health monitoring system permits a combination of continuous, event-based and time-based programmable as well as manually controlled on-line data acquisition modes. Video cameras, wind, temperature, radiation and humidity measurement, vibrating-wire based displacement, tilt and strain measurement and the high-bandwidth strain, displacement and acceleration sensors for high-speed responses are interrogated by a dedicated data acquisition system. Wireless operation is a simple step from the copper-optical fiber network communication mode. 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 timed or event-based triggered modes. For example, the system might be triggered to acquire and archive data from a subset of the complete sensor suite on the bridge during the morning and evening rush hours when traffic levels on the bridge are highest, at midnight when traffic levels are very low, when the wind speed reaches a certain threshold value, or when a heavily-loaded truck is detected by the weigh-in-motion system. 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 more reliably established the bounds of normality and possible indications or precursors of anomalies in operation or structural behavior.

The architecture of the information systems that have been designed in conjunction with the health monitoring system for the Commodore Barry Bridge is schematized in fig 5. Aktan [2] commented that the data quality assurance, processing and archival represent the major information technology related challenge in regards to health monitoring of a major bridge, as, there are many possible sources of error and uncertainty that can affect the reliability of sensing and data acquisition in the field. Therefore, the authors suggested carrying out controlled tests as a means of calibrating both the analytical models. They assured the importance of integrating heuristic knowledge for interpreting and assuring the quality of data, redundancy requirements in the application of sensors, integration of different types of sensors and measurement systems, calibration of the health monitoring system in the field by controlled testing, and, justifying the output of any sensor based on the physics of the measured phenomena are techniques for data quality assurance.

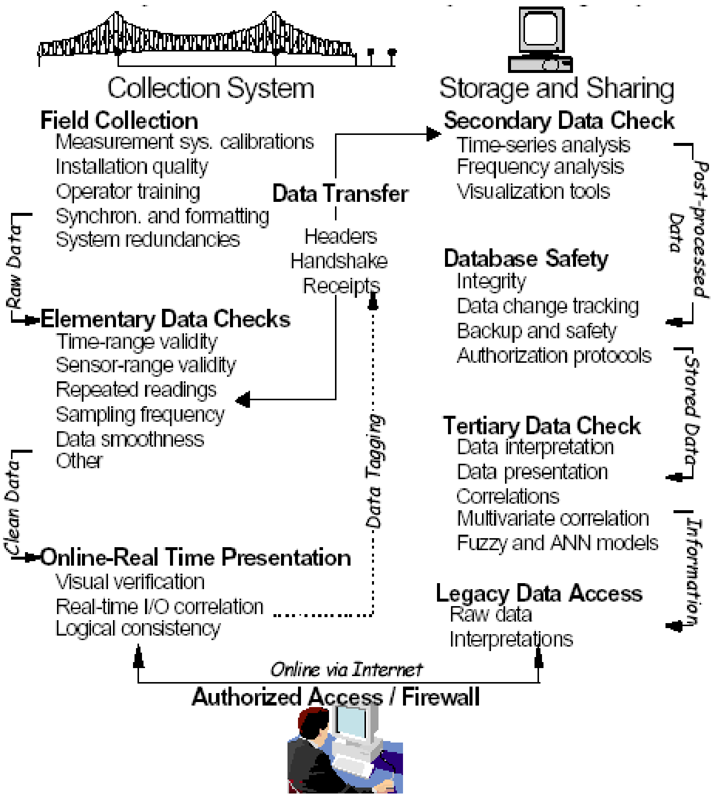


FIGURE 5. INFORMATION GENERATION FROM ACQUIRED DATA [2].

The intrinsic value of health monitoring applications especially for operational and emergency management in conjunction with engineering purposes is realized only by the visual display of critical images and data on-line in real-time. A challenge is in the integration and graphical display design of critical data streams so that users and owners may conceptualize phenomena reflected in the measurements in order to make timely decisions. In many cases, on-line data may have to be compared against recent data. Quick on-line access to recent data and analysis engines are needed to take full advantage of real time data. Integrated information management systems providing on-line data acquisition control and data display, data quality assessment, visualization, analysis and archival capabilities are a required element of health monitoring as discussed further in the following. Health monitoring design should involve the owners and engineers in charge of the operations, maintenance and management of the bridge for maximum benefit. User communication, information and alert protocols, and training and maintenance support needs are major challenges related to monitor-user organizational interface design.

Fig 6 illustrates the interface designed for viewing real-time images from the bridge and information from the weigh-in-motion system as well as the weather station. Moreover, the upper left window of this interface permits a user to identify any one of the nearly 500 channels of data from the bridge and view this in real-time together with the images. The possibilities of correlating images and data and further processing for monitoring of various measures of health and performance are striking. More important is the ability to automate detection for immediate and effective response to incidents and to take various proactive measures through smart-signs if adverse driving conditions due to inclement weather and/or roadway conditions maybe emerging.

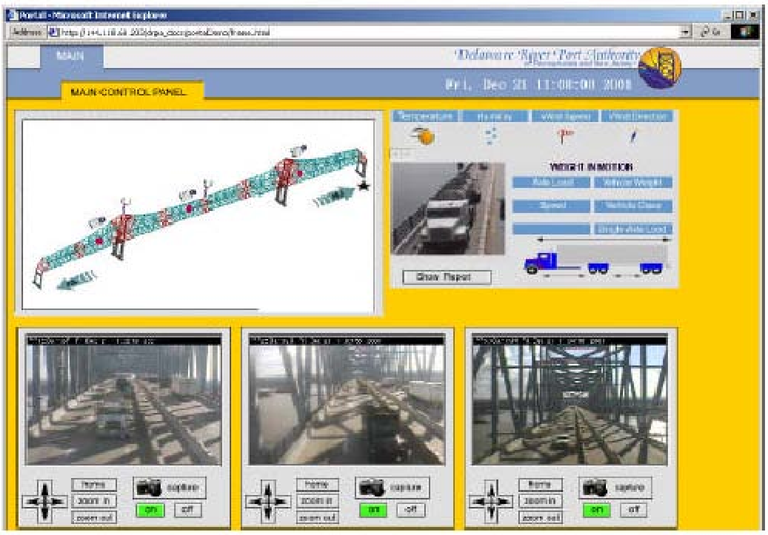


FIGURE 6. REAL TIME REMOTE MONITORING SYSTEM FOR BRIDGES.

2- APPLICATIONS IN CANADA

Mufti [3] summarized the applications of structural health monitoring of Canadian bridge engineering, including fiber-reinforced polymers sensors, remote monitoring, intelligent processing, practical applications in bridge engineering, and technology utilization. Further study and applications are still being conducted now. Mufti noted that remote monitoring techniques have been developed using lasers, fiber optic sensors, and remote data collection and processing. Research has resulted in a software package for monitoring structures, which is currently available to all Intelligent Sensing and Innovative Structures

(ISIS) field monitoring teams. Results of an ISIS Canada research project located at the University of Alberta showed that wireless technology achieves continuous monitoring of structures while reducing the volume of data collected and power consumed, thus increasing the lifespan of instruments. ISIS Canada's University of Alberta research node and Optimum Instruments Inc. have introduced a second generation wireless data logger and radio modem that connects a monitored site to an office. The data logger eliminates the need for permanent site installations, phone hookups, power, and site heating. When combined with new internet management technologies, it also facilitates efficient management of monitoring networks, with minimal overhead costs for data collection and scheduled maintenance. Another research component of ISIS Canada is the development of smart reinforcements and connectors.

Further, Mufti highlighted several projects in which health monitoring concept was applied. The first bridge to be outfitted with FRP tendons and a system of structurally integrated optical sensors for remote monitoring is the Beddington Trail Bridge in Calgary, Alberta, as shown in fig 7. The bridge opened in 1993. Fiber optic Bragg grating strain and temperature sensors were used to monitor structural behavior during construction and under serviceability conditions. The four-channel Bragg grating fiber laser sensing system was developed for this purpose at the University of Toronto Institute for Aerospace Studies. A four-channel Bragg grating fiber laser sensor system was used at different locations along the bridge girders that were pretensioned by the carbon FRP. Each fiber laser was attached to the surface of the tendon to serve as a sensor. The sensors were connected, through a modular system, to a laptop computer used at the construction site to record the measurements at different stages of construction and after completion of the bridge. The optic sensor system measures the absolute strain rather than a strain relative to an initial calibration value similar to the electric resistance strain gauges and mechanical gauges. In 1999, the bridge was tested statically and dynamically to assess the durability of fiber optic sensors. After six years, all FOSs were functioning. This finding validates the view that FOSs are durable and reliable for long-term monitoring.

FIGURE 7. THE BEDDINGTON BRIDGE, CANADA.

Another example is the Portage Creek Bridge, in Victoria, British Columbia built in 1980s. It is a 125m long, three-span steel structure with a reinforced concrete deck supported on two reinforced concrete piers and abutments on steel H piles. The deck has a roadway width of 16 meters with two 1.50-meter sidewalks and aluminum railings. The Portage Creek Bridge is a relatively high-profile bridge that has been classified as Disaster-Route Bridge. However, it was built prior to current seismic design codes and construction practices, and would not resist potential earthquake forces as required by today's standards.

Some consideration has been given to seismic aspects as evidenced in the original drawings, although it requires retrofitting to prevent collapse during a seismic event. The service life of the bridge can be increased to 475 years. Most of the bridge is being strengthened by conventional materials and methods. The dynamic analysis of the bridge predicts that the two tall columns of one pier will form plastic hinges under an earthquake. Once these hinges form, additional shear will be attracted by the short columns of Pier. Therefore, it was decided that FRP wraps should be used to strengthen the short columns for shear without increasing the moment capacity. The bridge is instrumented with 16 foil gauges, eight fiber optic sensors and two accelerometers (refer to fig 8). The bridge is being remotely monitored and data is being collected.

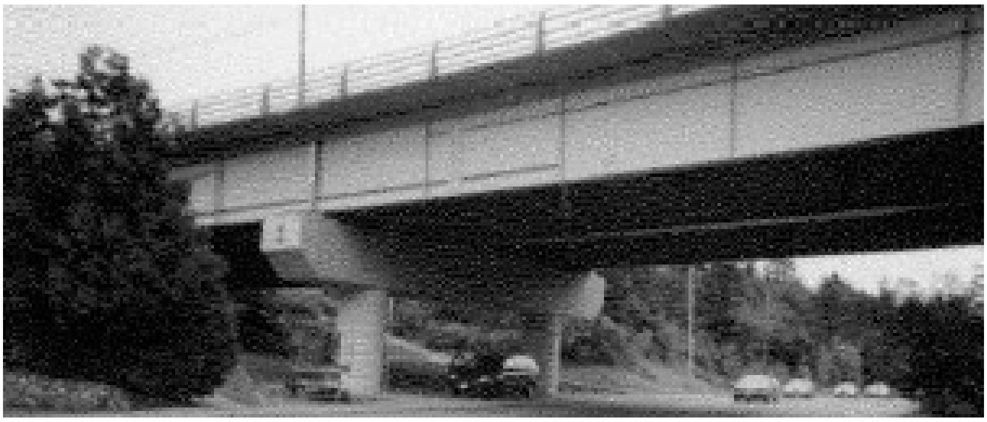


FIGURE 8. PORTAGE CREEK BRIDGE.

3-APPLICATIONS IN MEXICO

Muria-Vila, et al. [4] initiated a monitoring program to study the dynamic properties of Tampico Bridge. The bridge is a cable-stayed one with a total length of 1543 meters and a main span of 360 meter length. Twenty-one servo accelerometers were installed and ambient and pull-back tests were conducted. The resulting frequencies were in good agreement but the damping values were still poorly estimated.

4- APPLICATIONS IN SOUTH AMERICAN

Caicedo et al. [5] reported on the development and implementation of a health monitoring system for the Hormiguero bridge in Colombia, South America (see fig 9). The bridge has obvious signs of deterioration from heavy traffic usage. Additionally, the bridge is in a seismically active region, and the bridge has periodically experienced earthquakes. The bridge was instrumented with accelerometers, and the responses were measured and recorded at the Colombian Southwest Earthquake Observatory. Traffic loads are used to excite the bridge, and the responses are measured.

FIGURE 9. THE HORMIGUERO BRIDGE IN COLOMBIA.

This traffic-induced vibration data was used to determine the natural frequencies and associated motions. A series of twelve tests were conducted on the Hormiguero Bridge. In each test 120 seconds of response data was recorded and two channels of data were obtained. This time length allowed for between one and eight trucks to pass over the bridge in the various tests. In these tests, several mode shapes were identified including, transverse, vertical, torsional modes, as well as modes that appear to be combinations of these motions.

5- APPLICATIONS IN ASIA

Abe, et al. [6] studied the feasibility of health monitoring of a 120 meter span Hakucho Suspension Bridge in Japan by ambient vibration measurement. An identification scheme that made use of cancellation of randomness in data by shaking was employed to use the ambient vibration measurements with high accuracy. Catbas, et al. [7] designed and implemented a long-term continuously operating health monitoring system for the Commodore Barry Bridge. Over 80 channels of different sensor types were installed to collecting data such as temperature, wind speed and direction, strains, acceleration, etc. The authors noted that the extraction of the measured data is very hard work because it is hard to separate changes in vibration signature due to damage form changes, normal usage, changes in boundary conditions, or the release of the connection joints.

Brownjohn et al. [8] conducted an experiment-based structural assessment of a bridge before and after upgrading works including strengthening. Each assessment comprised three separate components: (1) a strain and acceleration monitoring test lasting approximately one month; (2) a full-scale dynamic test carried out in a single day without closing the bridge; and (3) a finite-element model updating to examine and to identify structural parameters and mechanisms. The dynamic testing and the modal analysis were used to identify the vibration properties and the quantification of the effectiveness of the upgrading through the subsequent model updating. Before and after upgrade, similar sets of vibration modes were identified, resembling those of an orthotropic plate with relatively weak transverse bending stiffness. Conversion of bearings from nominal simple supports to nominal full fixity was shown via model updating to be the principal cause of natural frequency increases of up to 50%. The authors concluded that the utility of the combined experimental and analytical process in direct identification of structural properties has been proven, and the procedure can be applied to other structures and their capacity assessments.

6- APPLICATIONS IN EUROPE

Grosso [**Error! Bookmark not defined.**] noted that, while the establishment of common design standards has been the subject of direct actions at the Union level since a long time (Eurocodes), efforts devoted to establishing a reference framework for the management of bridges on the European road network are relatively recent. In the recent years, both long-term and short-term instrumental monitoring are being proposed for bridge evaluation in Europe. Although these techniques are encountering increasing interest among infrastructure owners, extensive application is still lacking. When instrumental monitoring is used, comparison between forecasted and observed behavior becomes a key issue in the determination of global condition indices and in the detection of the insurgence of local damaging. Advanced data processing and modeling techniques are therefore needed. The possibilities offered by modern instrumental monitoring techniques are however offering a wider interpretation of the health monitoring, including the construction phase into the behavioura1 fields that may be investigated by observation. In particular, embedding sensory systems for long-term static monitoring in reinforced concrete structures during construction or retrofitting works may introduce a new type of knowledge into the health monitoring process.

To make an example of the type of information that can be gathered from structural monitoring during construction of a bridge, the case study of the Siggentha1 arch bridge in Switzerland was presented. The Segmental Bridge is a concrete arch bridge with an arch span of 117 m, built over the Limmat river in Baden, Switzerland (see fig 10 for a schematic and a photo of the scaffolding that has been used for arch construction). The arch curve is made of seven segments with inflexion point under the columns supporting the deck and slightly curved in between. The arch construction proceeded in five successive concrete pouring phases, executed symmetrically and starting from the feet. After construction of the arch the scaffolding was removed. The arch has been stabilized by temporary steel towers under the first columns to continue construction of the bridge.

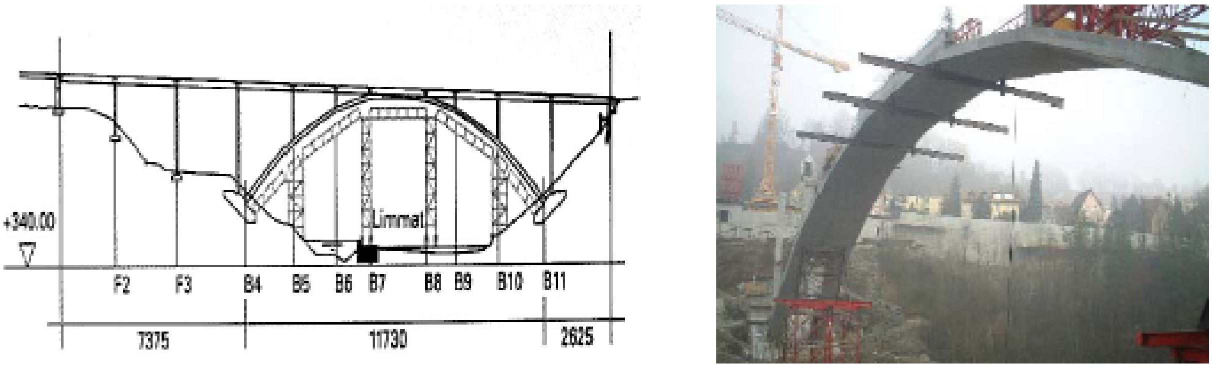


FIGURE 10. SCAFFOLDING DURING ARCH BRIDGE CONSTRUCTION.

A monitoring system composed by two inclinometers, eight temperature sensors, and 58 long-gage (between 3 and 5 meter) fiber optic sensors, placed in pairs at the interior of the arch in order to measure curvatures. From the measurement of curvatures, vertical displacements can be retrieved by double integration. The monitoring system aimed at detecting local concrete deformations, measuring local curvatures in the vertical plane, and reconstructing the perpendicular displacements of the whole arch during the entire life span of the bridge. The sensors have been installed before concrete pouring, for being interpreted with particular interest to the following phases: concreting of the different arch sections, removal of the scaffolding, free standing phase of the arch, installation of the temporary towers, construction of the supporting columns and of the deck, bridge testing, long-term in-service monitoring. Collected results showed that important information on the behavior of the as-built structure may be obtained. The designers were able to compare with a high degree of accuracy the observed behavior of the arch with the computed one. It has to be noticed that by using fiber optic sensors, readings can be obtained in a few minutes for the whole array, and the effect of temperature variation is clearly recognizable and can be easily filtered out for separate analysis by means of signal processing techniques.

Habel et al. [9] reported on a long monitoring of two bridges in Berlin, Germany. The two bridges had to be monitored right from the beginning of construction until commissioning as well as later on for several years, because vertical displacements were expected as a consequence of the construction activities in immediate vicinity and difficult soil conditions. A laser-based system has been upgraded with respect to long-term monitoring and installed in the bridges. The system is tolerant against extraneous light, protected against dust, insensitive to vibration and effects of the environment, e. g. temperature, and harmless for eyes. The source illuminates two sensors at each side, which are fixed above the piers and near the ends of the span, respectively. The sensors which contain a linear array of photodiodes measure the deviation from a straight reference line given by the laser beam. From these deviations the vertical movements at the piers as well as the sag at mid-span can be calculated. In addition, the strains in concrete were measured using two sensor types: resistive strain gages and fiber optic strain gages. Because resistive strain gages are known to have limited long-term stability and because of expected electromagnetic influences, fiber-optic strain sensors have been installed at important locations.

The Danish Bridge Management System is based on data from four different kind of inspections, all described in national codes. The inspection types are all separate activities, but of course with inter-relations between them. The four types are as follows: roadman check, routine inspection, principal inspection and special inspection [10]. The roadman check of bridges is normally performed once a week with the objective of monitoring the whole infrastructure closely in the time between the principal and routine inspections. The check ensures day-to-day traffic safety and serviceability for the road users and contributes considerably to the monitoring system. Bridges are checked for any sudden damage or deterioration such as signs of settlements or displacements, damage on slabs, girders, railings, columns or piers due to impact from traffic, erosion of slopes etc.

Frequent routine inspections are carried out in order to monitor the safety and the day-to-day serviceability of the bridges, for the planning of routine preventive maintenance work for avoiding serious and costly damage development. On the national highway network in Denmark this type of inspection is executed by bridge inspectors at least once a year. The principal inspection is the key activity in monitoring the condition of bridges in the Danish

BMS. All the activities leading to the final choice of a rehabilitation strategy for a damaged bridge are initiated at this stage. The principal inspections are carried out by a highly experienced bridge engineer. The principal inspection is a visual inspection of all visible parts of the bridge. The purpose is to maintain an overview of the general condition of the whole bridge stock, and to reveal significant damage in due time, so that rehabilitation works can be carried out in the optimum way and at the optimum time, taking safety and economic aspects into consideration. Damage which does not require remedial action is not noted in the inspection report, and in any case, the damage is briefly described.

A special inspection will always be carried out before major repair works, including a detailed damage description. Normally, special inspections are initiated at the principal inspection, when the principal inspector is not certain about the cause, the type and extent of damage or the proper rehabilitation method. Special inspections are always carried out by engineers with experience in deterioration mechanisms, bearing capacity, advanced inspection methods and considerable knowledge in the field of rehabilitation design. The special inspection comprises both destructive and nondestructive tests carried out in-situ, as well as laboratory tests on collected samples. Based on the results of these tests, the state of damage is assessed as well as its probable future development, and various rehabilitation strategies are evaluated.

Mangerig et al. [11] measured the vibrational response of a steel glass pedestrian bridge to demonstrate the potential of identifying structural changes from measured ambient data. The mentioned bridge is located in the German Museum in Munich. They noted that the monitoring of structural behavior contained a variety of uncertainties, like technical measurement errors or natural influences. Measurement data over a long period of time allowed a statistical based analysis. In such an analysis, frequency diagram could be drawn, containing e.g. the mean value, the standard deviation and the variance. A modification is identified by recognizing changes or changing trends in the statistic parameters calculated on the base of continuously analyzed and updated measuring results to complete the first phase of damage identification. The second phase is to identify the structural change as damage scenario and to locate it. The authors used numerical models for objective.

7-BRIDGE INSPECTION AND EVALUATION: A LOOK AHEAD

In the future, bridge health monitoring will focus on the quantitative assessments of bridge performance and conditions rather than visual inspections and condition ratings [12]. A variety of permanent sensors on bridges will collect data at many points. These sensors will be powered by and will report to wireless networks. Data will be analyzed and deterioration will be detected automatically by computer workstations in central locations. When problems arise, engineers will be able to accurately analyze the structural condition and formulate timely corrective strategies. Knowledgeable, experienced engineers are the key to an accurate evaluation of the structural condition. Technology will greatly enhance their ability to make these assessments. Sensors offer definite, unbiased, and quantitative data. These data enable engineers to use high-performance concrete and steel materials along with fiber-reinforced composite materials to increase the service life of bridges. Extensive use of sensors will become possible as advances in the miniaturization of electronic devices, increased availability of wireless communications, and lower costs for devices and communication combine to provide an array of compact, permanent, inexpensive systems.

Measurements of bridge performance will include the detection of changes in chemical and electrical properties of materials related to deterioration, aging in coatings, and changes in service environment or exposure; in addition, the response to loads will be verified periodically. Systems for measuring bridge performance may include · Embedded sensors for measurement of corrosion potential and current, Load cells permanently built into bridge bearings to allow periodic verification of load paths, Interferometry for surface flatness to detect aging in coatings and damage in fiber reinforced composite elements, Embedded fiber-optic sensors for crack detection and strain measurement, Permanent features in substructures for rapid mounting of laser systems for deflection measurements (permanent, dedicated mounting locations allow simple collection and comparison of response signatures), and Radar and infrared sensors housed in overhead bridge lighting and interrogated when weather conditions are favorable.

Because new inspection technologies will detect and measure deterioration in bridges, inspectors will have extensive quantitative data about the condition and performance of structures. Armed with this information, bridge engineers will be able to make better decisions about repairs, to redesign details that will improve durability, and to use specialized repair techniques. The new inspection practices outlined here can be implemented. The sensors and data communication hardware exist. Hardware is costly today, and the long-term durability of sensors has not been established. However, these limitations will be overcome through research, development, and implementation. Computational systems must be further developed to analyze data. Systems must include data interpretation, statistical analysis, evaluation of errors in measurement, identification of bridge conditions based on data, and assessment of structural reliability in its present condition. Recent work in system identification and sensitivity of system response to damage are relevant here. Overarching systems for data analysis and reporting are needed.

8-FUTURE TRENDS

Elgamal et al. are conducting a long-term research program aiming at establishing a health monitoring framework for bridges suitable to the twenty one century [13]. The objectives of this research are to: (1) develop a next generation decision support system to enable governmental agencies to manage efficiently and economically bridge systems (automatic quantitative decision-support system), (2) develop a powerful and innovative Information-Technology-based framework to support and accelerate research in nondestructive structural health monitoring and in the discovery of new physical knowledge in the area of deterioration of civil infrastructure systems, and (3) develop a framework with an open and flexible architecture able to integrate current and future research in the field of structural health monitoring. Eventually, multi scale structural health monitoring techniques will be developed and implemented in the framework.

The authors have the following thoughts about the framework: (1) it must be scalable for simultaneous monitoring of a large group of bridges and very large number of sensors (in the thousands per bridge), (2) it should be able to extend to networks of civil infrastructure systems other than bridges, and (3) it must support two types of infrastructure deterioration: (i) progressive deterioration in time due to environmental effects, and (ii) sudden deterioration due to natural hazards such as earthquakes and hurricanes, man-made disasters and acts of terrorism. In the case of sudden and severe load events, the targeted framework must be able to support rapid and reliable condition assessment of critical civil structures.

Therefore, their research addresses development of: (1) networked sensor arrays, (2) a high-performance database with data cleaning and error checking, data curing, storage and archival, (3) computer vision applications, (4) tools of data analysis and interpretation for real-time data from heterogeneous sensor arrays, (5) visualization allowing flexible and efficient comparison between experimental and numerical simulation data, (6) probabilistic modeling, structural reliability and risk analysis, and (7) computational decision theory.

In order to satisfy these requirements, their research is making use of recent advances in (1) high-performance databases, knowledge-based integration, and advanced query processing, (2) instrumentation and wireless networking, (3) computer vision and related feature extraction algorithms, and (4) data mining, model-free and model-based advanced data analysis, and visualization. An integrated system based on the knowledge discovery hierarchy represented in fig 11 is being built to achieve the above-mentioned objectives. This system integrates all tasks from sensor configuration, data acquisition and control, to decision-making and resources allocation. In the following is a brief preview of the efforts and challenges.

8-1DATABASE RESEARCH

The complexity of data sources (including real-time sensor and video streams, and the output of physics-based and statistical models), and the need to perform advanced real-time and off-line analyses (often requiring the integration of real-time sensor data with simulation model output) necessitates a scaleable high-performance computational infrastructure. New technologies are being employed in the development of a high-performance data management, analysis and interpretation system for civil infrastructure monitoring. This system will integrate sensors, databases, modeling, analysis, visualization and simulation tools, and provide access to various application interfaces (e.g., reliability and risk assessment, event response) through a secure portal.

8-2SENSOR NETWORK

A significantly new research challenge is the need to integrate multiple sensor outputs to develop local and global health state indicator variables that need to be queried and monitored by the system. The indicators may be defined as user-specified aggregates over instantaneous values of several data streams, over pre-computed aggregates covering one or more sensors. The sensor network consists of a dense network of heterogeneous sensors. In addition, the network must be easy to deploy, scalable-allowing for progressive deployment over time, and must allow for local processing and filtering of data, remote data collection, accessibility and control. Using a wireless communication technology will accelerate the extensive deployment of sensor technology.

8-3COMPUTER VISION

Visualization is often the first step in data exploration. Visualizations of sensor measurements, features extracted from measurements and simulation results provide visual interpretations of infrastructure status and behavior. It is anticipated that computer vision will become a primary and routine sensing technique within any health-monitoring framework. As a novel aspect of current research, a load database extracted from video data is being created. For video data, the database will record the types and positions of load objects at specific time instants (e.g., cars and trucks crossing a bridge). It will be converted to a load, which will return for each array element of the structure an estimated load at the time instant. In this context, many cameras and potentially different types of video sensors are involved.

8-4DAMAGE DETECTION AND DATA ANALYSIS

This research includes tasks aimed at evaluating, calibrating and applying several promising approaches for detecting small structural changes or anomalies and quantifying their effects all the way up to the decision making process. These approaches include the following: (1) damage detection on the basis of influence coefficients using a time-domain identification procedure to detect structural changes, (2) damage detection using neural networks, and (3) structural health monitoring using statistical pattern recognition.

The research is expected to lead to a flexible integrated framework for condition assessment and damage detection under normal operating conditions. In addition, it will also be beneficial in providing rapid response (in virtually real time) due to sudden dynamic loads or terrorist acts. For bridges, such a computer-based framework is thought to be a necessity.

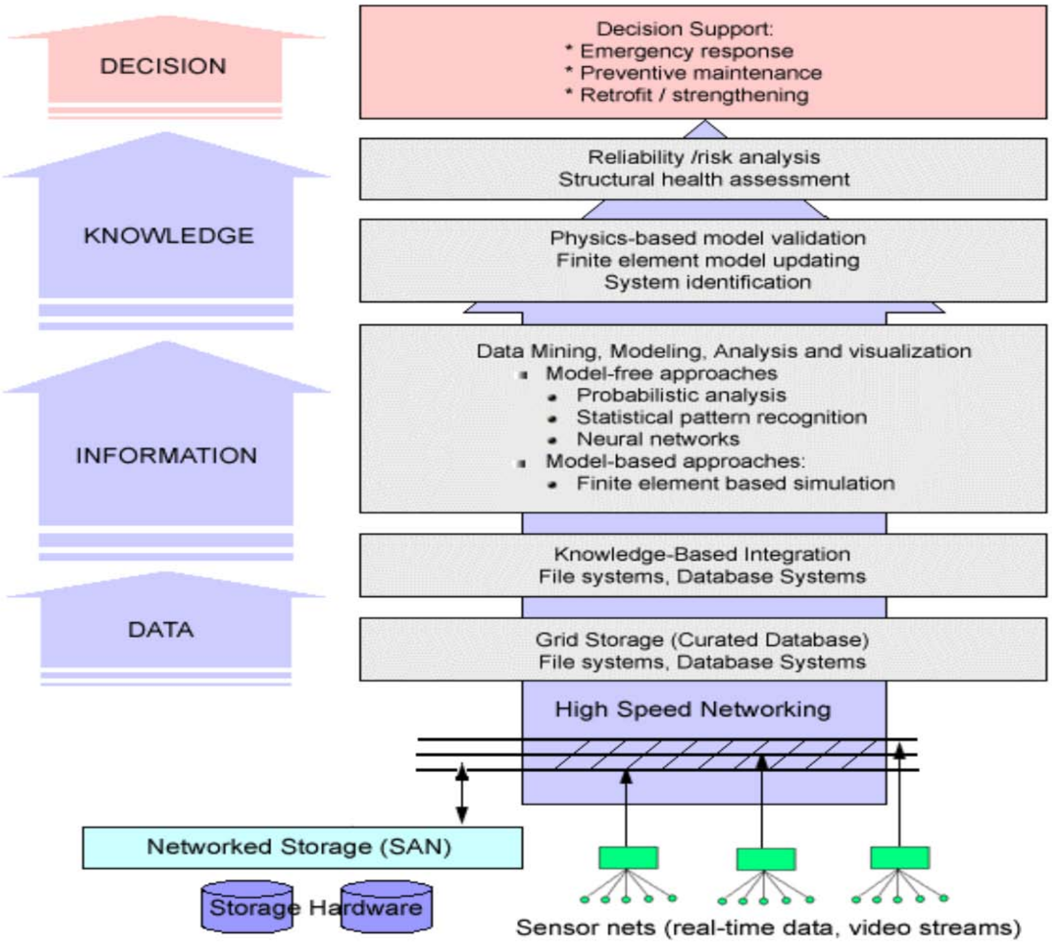
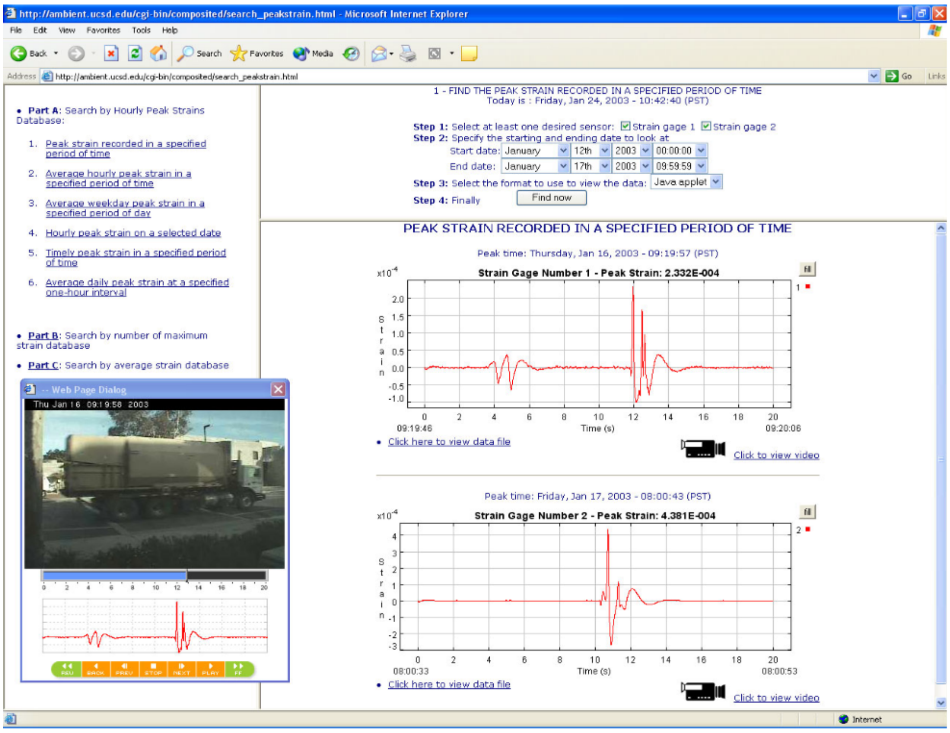


FIGURE 11. KNOWLEDGE DISCOVERY HIERARCHY.

A pilot on-line continuous monitoring effort is available. This effort integrates some basic elements of an automated on-line continuous monitoring framework for bridge systems (fig 12). Data from motion sensors and associated video signals are retrieved in real-time, over the Internet on a 24 hours, 7 days a week basis. Video feature extraction has been performed on the recorded video (see fig 13) to generate load estimates. Using data fusion, the extracted features (area, length, height, and speed of traffic), and the sensor data (recorded strains) are a basis for data mining and system identification.



1 - FIND THE PEAK STRAIN RECORDED IN A SPECIFIED PERIOD OF TIME
Today is : Friday, Jan 24, 2003 - 10:42:40 (PST)

- **Part A**: Search by Hourly Peak Strains Database:
  1. Peak strain recorded in a specified period of time
  2. Average hourly peak strain in a specified period of time
  3. Average weekday peak strain in a specified period of day
  4. Hourly peak strain on a selected date
  5. Timely peak strain in a specified period of time
  6. Average daily peak strain at a specified one-hour interval
- **Part B**: Search by number of maximum strain database
- **Part C**: Search by average strain database

Step 1: Select at least one desired sensor: ☑ Strain gage 1 ☑ Strain gage 2
Step 2: Specify the starting and ending date to look at
Start date: January 12th 2003 00:00:00
End date: January 17th 2003 09:59:59
Step 3: Select the format to use to view the data: Java applet
Step 4: Finally [Find now]

PEAK STRAIN RECORDED IN A SPECIFIED PERIOD OF TIME

Peak time: Thursday, Jan 16, 2003 - 09:19:57 (PST)
Strain Gage Number 1 - Peak Strain: 2.332E-004
- Click here to view data file

Click to view video

Peak time: Friday, Jan 17, 2003 - 08:00:43 (PST)
Strain Gage Number 2 - Peak Strain: 4.381E-004
- Click here to view data file

Click to view video

FIGURE 12. SAMPLE OF REAL-TIME DATA COLLECTION AND ANALYSIS.

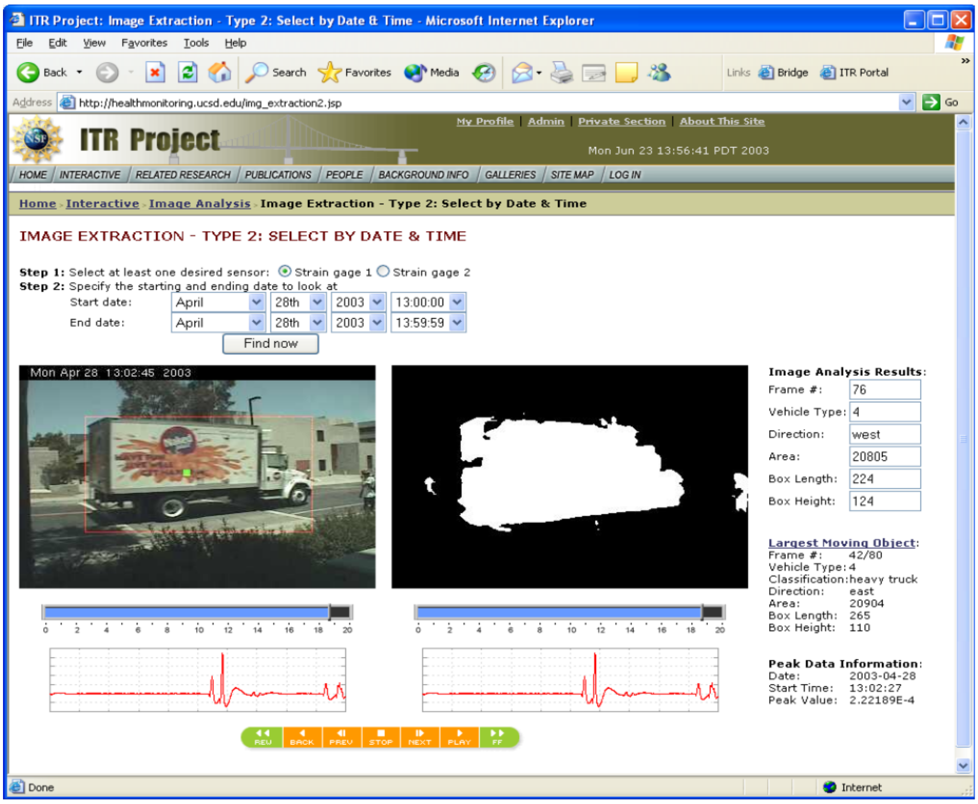


IMAGE EXTRACTION - TYPE 2: SELECT BY DATE & TIME

Step 1: Select at least one desired sensor: ● Strain gage 1 ○ Strain gage 2
Step 2: Specify the starting and ending date to look at
Start date: April 28th 2003 13:00:00
End date: April 28th 2003 13:59:59
[Find now]

Image Analysis Results:
Frame #: 76
Vehicle Type: 4
Direction: west
Area: 20805
Box Length: 224
Box Height: 124

Largest Moving Object:
Frame #: 42/80
Vehicle Type: 4
Classification: heavy truck
Direction: east
Area: 20904
Box Length: 265
Box Height: 110

Peak Data Information:
Date: 2003-04-28
Start Time: 13:02:27
Peak Value: 2.22189E-4

FIGURE 13. SAMPLE OF DATA COLLECTION DEPICTING INTEGRATION OF TIME-SYNCHRONIZED SENSOR DATA AND VIDEO.

9 - *CONCLUSIONS*

1. The evaluation of serviceability and load-carrying capacity for existing highway bridges based on the damage identification and reliability theory should be studied. It is very important for the load rating, condition assessment, and decision making of repair, strengthening, and rehabilitation of existing highway bridges.
2. Information techniques and systems are needed to integrate field, theoretical and laboratory research for solving large system identification and condition assessments problems.
3. New and innovative construction materials will enhance the strength and durability of the infrastructure system in the twenty-first century.
4. Testing and evaluation methodologies need to be developed specific for characterization of newer and high performance materials.
5. Advanced condition monitoring technologies will enable detection of cracks, onset of failure, extent of degradation, and location of damaged zones in structural elements.

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