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SYSTEM RELIABILITY-BASED STRUCTURAL HEALTH MONITORING WITH FEM SIMULATION

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Abstract

Current bridge inspection and assessment techniques are becoming inadequate and outdated for the aging bridge inventory in the United States. Structural Health Monitoring (SHM) approaches provide opportunities for objective condition assessment of existing structures for overcoming the setbacks caused by customary visual inspection methods. Objective and dependable data collection integrated with reliability analysis tools can lead to development innovative bridge management systems. While structural health monitoring offers promise for the condition assessment problem, the decision-making process is to be supported by stochastic analysis of the bridge failure modes and uncertainties associated with the random variables, limit states, and sensor data. In the paper, the authors focus on steel movable bridges for the implementation of the basic framework of the SHM system with reliability analysis. The objective of this paper is to develop a framework for reliability-based structural health monitoring of the movable bridges to improve bridge management practices, while addressing common problems specific to these type of bridges. This paper presents the identified maintenance problems, finite element model development along with the critical structural elements and components, and a plan for the instrumentation based on a movable bridge.

INTRODUCTION

Structural Health Monitoring (SHM)

Visual inspection is the routine method for inspecting structures for damage. However, this method has some inherent drawbacks, the first of which is that the damage must have progressed far enough to be visually observable. Second, through visual inspection only the extent of damage is assessed based on subjective criteria. A study conducted by the Federal Highway Administration's NDE Center on the accuracy of visual inspection of short-to-medium span bridges concluded that at least 56% of the bridges given an average condition rating were done incorrectly (1). Even if the damage is successfully identified, the final problem facing the engineer is accurately assessing its effect on the overall health of the structure (2). Visual inspection also requires much time and effort, and may overlook locations of limited and/or no accessibility. Therefore, more advanced condition assessment methods using sensor measurements and analysis techniques based on statistical and reliability methods should be implemented into bridge management practice (3). Structural Health Monitoring (SHM) applications are well developed and becoming even more widespread, by providing accurate measurement of structural parameters. Reliability analyses provide life-cycle condition prediction based on probabilistic techniques, incorporating the uncertainties, and deterioration effects. Therefore, reliability assessment should be based on SHM data, which should in turn be based on the requirements of a reliability analysis.

Reliability Methods based on SHM

There is a need for integrating SHM and reliability analysis as a framework composed of a comprehensive SHM application used for probabilistic analysis of system and component reliability for efficient bridge management and decision-making. Integrating reliability analysis in a SHM framework is a tool to achieve a comprehensive and advanced bridge management practice (3).

Current SHM technology is capable of providing rapid or even real-time condition assessment of structures. Accurate and comprehensive data is produced, which greatly eliminates the uncertainties involved in the traditional structural appraisal methods. Better accuracy means improved operational safety, as well as instant notification of unexpected distress. These tools should be complemented with probabilistic structural analysis approaches for evaluation and estimation of uncertainties, and determination of structural system reliability based on SHM data. These advances in bridge condition assessment will lead to higher level management practices by performance projections, accurate project/network level cost-benefit evaluation, and life-cycle cost analysis for maintenance optimization and decision making.

CASE STUDY ON MOVABLE BRIDGE

A movable bridge is a structure which has been designed to have two alternative positions and which can be moved back and forth between those positions in a controlled manner. The primary purpose of movable bridges is to allow conflicting flows of traffic to pass through a crossing point or to move traffic across a waterway. The movable bridge may allow access for waterborne, rail, land vehicle or pedestrian traffic. It is often considered as a viable alternative to a high fixed bridge over the waterway, however, also presents significant drawbacks and problems (4, 5). In certain cases, where aesthetics and dimensional constraints dominate the design, movable bridges constitute the best choice.

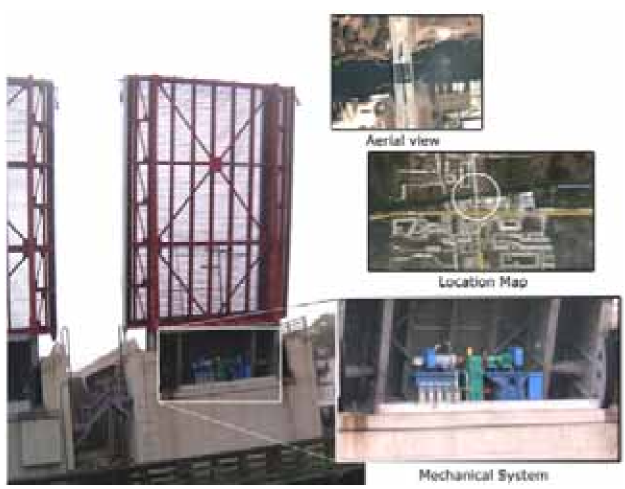

Figure 1: Representative Movable Bridge

Based on the analysis of inspection reports, common problems and average characteristics, and interaction with Florida Department of Transportation (FDOT) structures and maintenance engineers, a bascule type is selected for detailed investigation, considering its type, span length, age, opening frequency, type of traffic and accessibility.

Critical structural elements were identified as the deck, girder, and transverse beams from the inspection reports. Development of a finite element model (FEM) helped to determine the locations and types of extreme stresses over these members by performing load simulations. The results obtained from the finite element analyses were used for investigating damage scenarios and determining instrumentation locations.

The bridge model was formed by two bascule girders, connected in the transverse direction by W27×102 floor beams. Six W16×36 girders span between the floor beams, holding the deck and transferring the loads to the floor beams and bascule girders.

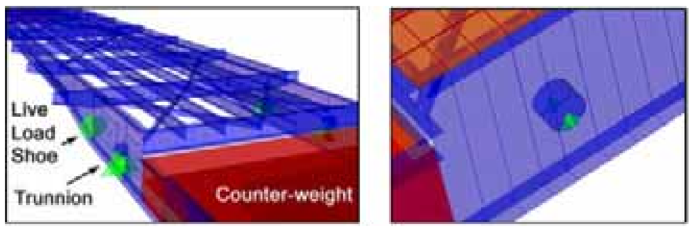

Figure 2: Finite Element Model Views

Florida Department of Transportation is using Bascule Bridge Balance Tests (6) for evaluating the balance state and to verify the functioning of the shaft-gear-trunnion system. The test is performed by mounting strain sensors on the main drive shafts to obtain the torsional shear strain, which are used to calculate the torque during opening and closing of the leaves, recorded in conjunction with the opening angle, obtained by a tiltmeter near the trunnion. The average torque (AVT) changes with the horizontal distance between the trunnion and center of gravity, thus, it is a cosine curve. The positive region of this plot indicates unbalance towards the leaf side, and the negative region corresponds to unbalance towards the counter-weight (heel) side.

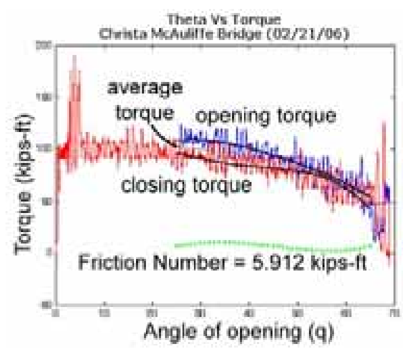

Figure 3: Balance Test Results for the Representative Movable Bridge

The most recent balance test for the Christa McAuliffe Bridge was analyzed to obtain the location of the center of gravity with respect to the trunnion. A single leaf of the bridge model was analyzed in the closed position right at the onset of opening, when there is no reaction from the live load shoe, the counter weigh, or the other span, and the weight of the bridge is balanced by the driving torque at the trunnion. Therefore, the counter-weight was modified in the model until the same trunnion torque is obtained in the model, establishing the same center of gravity position obtained through the balance tests.

LOAD RATING AND RELIABILITY ANALYSIS

Movable Bridge Load Rating

Load rating of the movable bridge was calculated following the AASHTO Guide . Bending capacity, including lateral torsional buckling effect, and shear capacity were calculated as deterministic values. Critical positions of the standard (HS-20) truck load were used to obtain the maximum live load moment and shear. The sections selected for load rating are the joints at the floor beams.

Table 1: Load Ratings

Location	Load	
	Inventory	Operating
FB-2	0.979	1.269
FB-3	2.072	2.686
FB-4	2.524	3.272

Moving Load Simulation and System Reliability

The finite element model was used to simulate a standard AASHTO HS-20 truck traveling over the bridge. The truck load was applied as joint loads, with 12.5-in increments, which corresponds to about 0.015s steps for a truck traveling at 50 mph. This simulation was expected to provide the structural reliability of the bridge, and also simulate the sensor readings during a moving load for using in data-based reliability assessment.

System reliability can be modeled with certain assumptions, which is assembling the failure limit states as parallel or series links after determining the failure modes (7, 8). Evaluation of a system model is performed by first reducing the parallel components. Parallel and series models of the movable bridge structural components were constructed according to the most general structural failure mechanisms. The main components of the system were the main girder bending failure state, main girder shear failure state, and the moment failure of the transverse beams. The main girder failure states were assumed as the failure condition at any of the monitored sections. These sections, however, are not completely independent, therefore cannot be modeled as acting in series. Accounting for the correlation of the failure modes at these sections, two bounding cases were considered. The first case assumes no correlation between the failure of monitored sections, and the second case assumes full correlation. The system model is shown in Figure 4, which illustrates the lower bounding case.

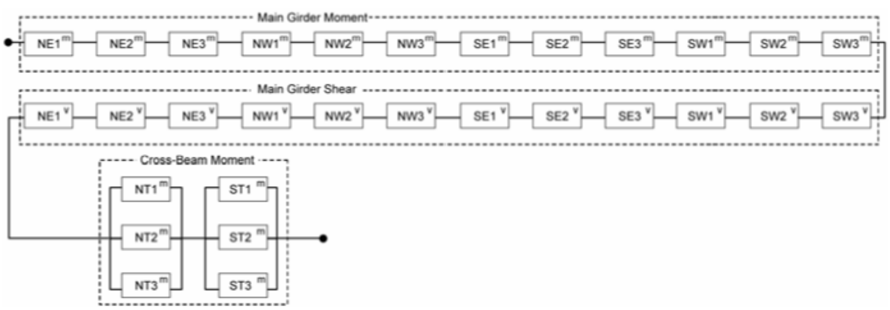

Figure 4: Movable Bridge System Reliability Model with Parallel/Series Assembly (Lower Bound)

The system reliability was first calculated according to the same load case with the load rating calculations. Results of the finite element analysis were used to generate the input variables, and the reliability index was obtained as 3.24 for the lower bound, and as 3.37 for the upper bound case.

Reliability analysis was performed for the moving load case, where a single standard truck is simulated crossing the bridge. The results for each position of the truck were obtained from the finite element simulation and processed by the component and system reliability algorithms developed in MATLAB. The result of the system reliability analysis is plotted in Figure 5, for elastic moment capacity. The horizontal axis is the truck position, which can also be regarded as time. The vertical axis shows the reliability index, which changes according to the position of the truck. The minimum reliability index was calculated as 5.79 when the middle axle of the truck arrives at the midspan. The calculated reliability is relatively high, since the simulation uses a single truck crossing the bridge without lane loads or additional load cases, and for a single instant in time, instead of the life span.

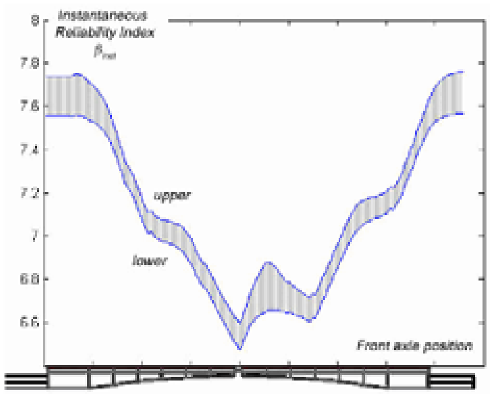

Figure 5: System Reliability under a Single Moving Truck

Safety indices based on component or system reliability can be evaluated with much higher accuracy and confidence over long term throughout the monitoring process. Component-based monitoring data should be assessed to evaluate the reliability index of each monitored structural component, and deterioration with time. Components to be instrumented should be carefully selected, as well as the parameters to monitor.

Using SHM techniques makes it possible to retrieve information about the status of individual elements of a bridge. Since every component requires unique maintenance work, maintenance operations can be scheduled more specifically and efficiently. Also, once individual deterioration and maintenance models are available for each critical node, a system reliability analysis can be conducted within the bridge components, in order to determine the most critical ones. Structural condition state and reliability are to be determined from component data. Reliability of the structural system depends on reliability of its components. If there is no redundancy, the weakest link will determine the overall reliability. The presence of redundant members makes it necessary to perform a system reliability analysis, modeling the structure as parallel and/or series combinations of the components (9, 10).

IMPLICATION TO SHM

A monitoring plan is investigated that follows the reliability analysis approach, by assigning the considered limit state locations as monitoring targets. Measurements will be the strain on the top, bottom, and center of the girder web, indicating the realization of the yielding limit state due to flexure, and shear limit state due to web buckling. The limit states calculated from the analyzed data and other statistical parameters will be combined in the previously described parallel/series assembly to obtain the system reliability.

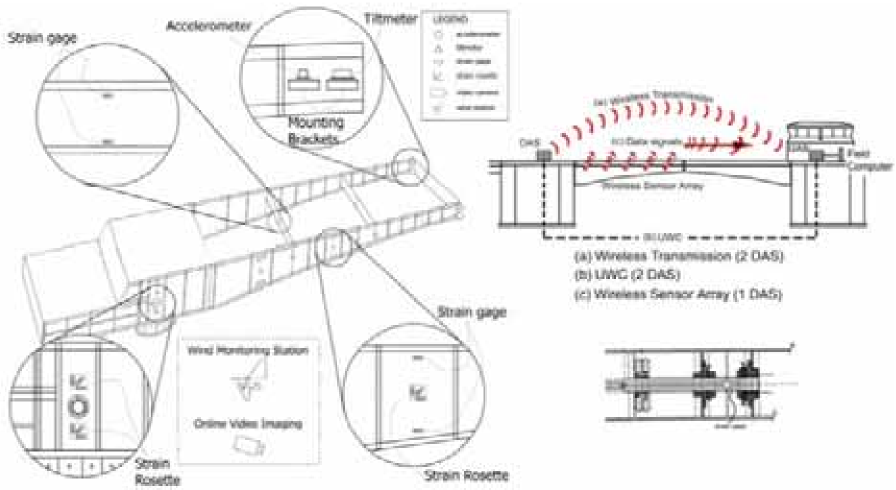

Figure 6: Instrumentation Plan for the Structural System

The instrumentation plan also includes other types of measurements such as span vibration, rotation, and monitoring of mechanical components, but those are not within the scope of the current paper.

The measurements obtained from the permanent or long-term sensor array have to be incorporated into a structural reliability approach. This has tremendous benefits. The most prominent is the advancement of SHM data evaluation into a higher level. The collected data not only will provide a finite element model calibration to yield more accurate load ratings, but also a probabilistic assessment of the structure. Reliability approach will provide the holistic condition state of the structure, future condition prediction, and optimization for most efficient maintenance scheduling.

CONCLUSIONS

The bridge management profession is in crucial need of more accurate, reliable, practical and efficient condition assessment methods, as well as advanced methods to tie the data to asset management functions. The missing link between SHM and bridge management practice will be eventually established by the following or similar scheme;

1. Permanent sensor arrays continuously taking measurements on critical locations/components of the structure.
2. Data collection system that receives the data in real time and transfers to the processing unit, which can be an internal component of the data acquisition system or a computer system at the field.
3. Primary processing of data to extract the necessary information and filter out the useless data. Required information is sent and logged on to a main terminal.
4. The information is stored, managed and shared centrally. Here is where management functions are established. The reliability of the components and the system is developed, condition prediction functions are generated, and maintenance action plans are prepared.
5. Decision makers or other users also connect to the terminal to manage multiple structures in their inventory according to advanced cost-benefit analyses, and disseminating the work orders over the same platform to the maintenance group.
6. During extreme conditions or unexpected failures, or even detected security threats, flags of different levels are triggered from the site to directly alert the emergency response teams, for emergency maintenance/repair, traffic control/diversion, or emergency response.

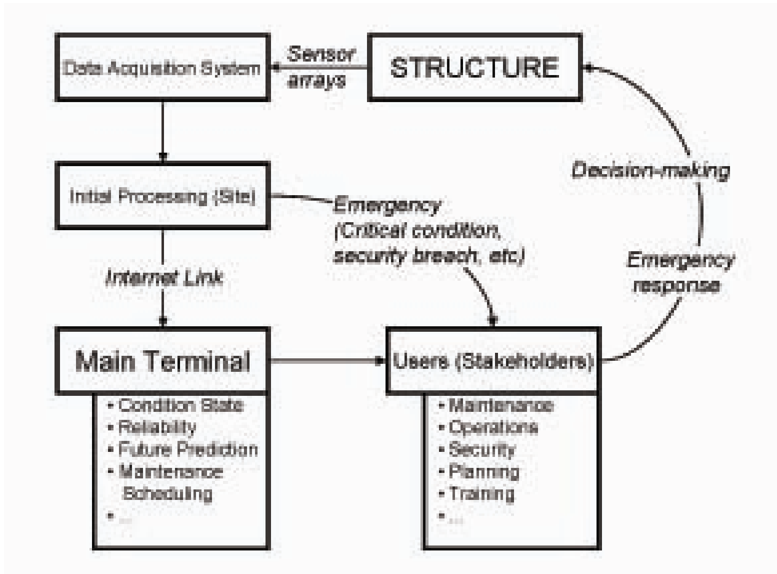

Figure 7: Operation Scheme of Integrated Bridge Management Systems

The current state-of-the art in SHM technology and reliability methods is sufficient for the realization of an integrated approach as described. What is needed is the vision and motivation for advancing the practice further. The progress towards this target, which will be achieved eventually, can be accelerated by intensive studies for successful demonstrations and presentation of the results to gain more support.

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