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The Structural Health Monitoring System of the Izmit Bay Bridge: overview and SHM-based fatigue assessment

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ABSTRACT: The planned Izmit Bay Bridge, crossing Izmit Bay will be the world's fourth longest suspension bridge upon completion. A lean Structural Health Monitoring System (SHMS) will provide the owner and the operator with important information concerning the structural behaviour and safety as well as information that will assist with operation and maintenance planning. The SHMS will also constitute a valuable tool for investigating and trouble-shooting unforeseen problematic behaviours; rapid reporting of the bridge condition after seismic events or wind storm loadings will provide input for management crew.

The objectives of this paper are to present the SHMS of the new Izmit Bay Bridge and to illustrate the design as well as the challenges and benefits of modern SHMS on long-span bridges. Furthermore, an overview is given to a data-based model for performance assessment and simulation of welded joints in orthotropic steel decks considering pavement temperatures, heavy traffic intensities and monitored strain data, which could be used with the data provided by the SHMS of the Izmit Bay Bridge.

1 INTRODUCTION

The new Izmit Bay Bridge will carry the new Gebze-Orhangazi-Bursa-İzmir motorway across the Sea of Marmara at the Bay of Izmit (Turkey). The bridge will be located between the Diliskelesi peninsula on the north side of the Izmit Bay and the Hersek peninsula on the south side. The new suspension bridge will have a main span of 1550 metres and will be the world's fourth longest suspension bridge upon completion.

The Izmit Bay Bridge will be equipped with a comprehensive Structural Health Monitoring System (SHMS) which will provide the owner and the operator with important information concerning the structural behaviour and safety as well as information that will assist with operation and maintenance planning. As the bridge is located in an active seismic zone, the system will provide input for decision-making via rapid reporting of the bridge condition after seismic events. The system will also constitute a valuable tool for investigating and trouble-shooting unforeseen problematic behaviours, such as wind induced vibrations.

The objectives of the present paper are: firstly, to present the SHMS of the New Izmit Bay Bridge as a case study to illustrate the design, challenges and benefits of modern SHMS on long-span bridges. Secondly, to highlight the problem areas related to long-span suspension bridges and how monitoring can assist for better control and maintenance planning, and thirdly to give an overview of a data-based model for performance assessment and simulation of welded joints in orthotropic steel decks considering multiple sources of monitoring data. Model applications include performance assessment, performance simulation of past and future events and fatigue assessment of welded joints.

2 IZMIT BAY BRIDGE

The Izmit Bay Bridge is a very complex project: the suspension bridge will have a free span of 1550 meters and 566 meters long side spans. The total length of the bridge is about three kilometres and the height of the towers is 250 meters, see Figure 1.

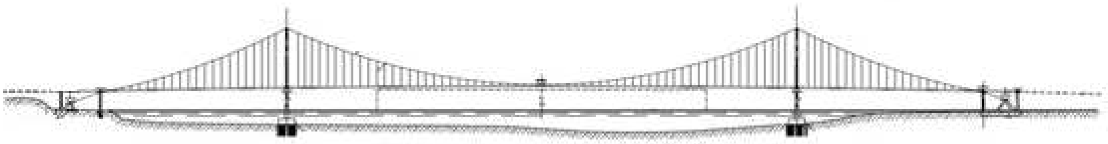

Figure 1. Izmit Bay Bridge, longitudinal view

The bridge girder will be a steel box girder with a stiffened steel plate deck with asphalt surfacing. The main suspension cables will be formed from pre-fabricated parallel wire strands (PPWS). The towers will be of stiffened steel plate construction. The anchorages will be of gravity type and will be supported on spread foundations. The tower foundations will be concrete caissons placed on improved soil.

The Izmit Bay Bridge will be built in one of the most seismically active areas in the world, which places additional demands on the bridge's design. The seismic analyses have been carried out by considering specific time-histories of ground displacements. The bridge will be made earthquake-resistant by building its pylons on a concrete foundation that rests on a large gravel bed so that the pylons can slide in the event of a major earthquake. In this way, the suspension bridge will be partly isolated from the enormous energy released by an earthquake.

3 STRUCTURAL HEALTH MONITORING SYSTEM

3.1 General

The Izmit Bay Bridge will be equipped with a Structural Health Monitoring System (SHMS) for continuous monitoring of ambient conditions, loadings and structural responses. The SHMS will be a sophisticated redundant set-up that will provide the owner and operator a valuable tool for investigating and trouble-shooting unforeseen problematic behaviour such as wind induced vibrations. The SHMS will provide key data from sensors located strategically around the structure (see Table 1 for an overview of the instrumentation). As far as possible, the SHMS will be based on standard components and "on the shelf" software. The basic operation of the system will be as far as practicable automatic, requiring minimal operator input.

The SHMS will be a stand-alone system that, in function, will operate independently of other operation systems of the Supervisory Control and Data Acquisition (SCADA) system. The SHMS will display live data and triggered alert data to assist the bridge operation and maintenance. The SHMS will store data in a database which can be accessed by other applications of the SCADA system. Data will be received from on-site sensors on a real time basis as part of the SHMS data acquisition network as well as from other components of the

SCADA system. The output of the SHMS will be controlled by the SCADA, but eventually also by remote control by internet from other locations.

Table 1. Overview of sensors for the permanent SHMS

TYPE OF INSTRUMENTATION	NUMBER OF SENSORS
Weather Station	4
Steel temperature sensor	84
Pavement surface temperature	6
Main cable surface temperature sensor	6
Hanger temperature sensor	6
Air temperature	3
Weigh in Motion (WIM) station	2
Road wear	1 system
Triaxial accelerometer	17
Biaxial accelerometer	32
Fibre optic strain sensor	160
Sonic distance sensor	8
Static inclinometer	3
Dynamic inclinometer	2
Humidity sensor: external	16
Load measuring pin	2
Global Positioning System GPS)	8
Force Transducer (LVDT)	12
Monostrand load cell	8
Rain gauge	2
Pyranometer	4
Total sum of sensors	**386**

3.2 Key objectives of the SHMS

The Structural Health Monitoring System of the Izmit Bay Bridge is designed to fulfil the following objectives:

- Systematic evaluation of the operation of the bridge in order to assess if significant contributions to the overall risk of damage can be associated with failure of specific structural elements. The ranking of structural elements is based upon analysis of the design. Automatic monitoring of these elements will supply the operator with necessary information or alarms to shut down the operation before severe consequences emerge.
- Early identification of degradation mechanisms and rates may be essential to an effective planning of operation and maintenance, because structural degradation and wear do not always develop at a constant rate. The structural monitoring system will supply the responsible authorities with quantified information on structural states to assist in formulating, on a rational basis, a systematic approach to schedule periodic inspections.

- Verification of the design assumptions and/or structural response to stochastic loads. To achieve this, the system will be operational from before the opening of the bridge.
- Because periodic phenomena that are unacceptable to the structure can occur, such as wind-induced vibrations of the longest hangers, the system will include a portable data acquisition unit with an appropriate number of sensors in order to provide enough data for understanding unexpected responses and trouble shooting.

3.3 Future expansion

The SHMS will be developed in such a way that future expansions or rearrangements can be easily facilitated. The modularized system architecture, including file architecture, will provide a high degree of flexibility where modules can be added, removed or rearranged. The system hardware architecture will have the functionality of National Instruments cRio system or similar. The SHMS software will be developed taking into consideration the provision of flexibility for future expansion or rearrangement. The Data Acquisition Unit (DAU) hardware will also be developed for expansion, for example by the provision of free slots for additional data acquisition cards. Each DAU will be capable of receiving all sensor types that are included in the SHMS at completion

4 CHALLENGES WITH SUSPENSION BRIDGES

4.1 General

Suspension bridges are flexible structures that allow large span widths, which can be adopted in places where it is difficult to construct other type of bridges. Nevertheless, building and operating a large bridge structure in a seismic environment sets high demands on both the construction and the operation period of the bridge. Yet, suspension bridges have proven their adaptability in seismic zones and the world's largest suspension bridge Akashi Kaikyo in Japan is located in an active seismic zone and survived an earthquake of magnitude 7.2 during its construction period in 1995, Yasuda et al. (2000). Suspension bridges may sway and their flexibility helps to withstand earthquakes better than bridges with a more rigid construction. The large displacements that those structures experience during seismic events require very detailed analysis.

Other complicated issues related to suspension bridges are maintenance aspects of the main cable, hanger vibrations, settlement of the anchor blocks and tower foundations as well as fatigue of welded joints in orthotropic bridge decks. There is also a risk for overloaded vehicles. This has been confirmed by a number of recent projects with much higher traffic intensities than predicted, especially for heavy vehicles.

The following paragraph presents an overview of some of the abovementioned issues and how the SHMS of the Izmit Bay Bridge will contribute to detect and assess them.

4.2 Hanger vibrations

Some experiences show that there is risk for hanger vibrations for the longest hangers in suspension bridges. Large amplitude hanger cable vibrations were observed at the Great Belt East Bridge in Denmark, Egede & Laursen (2007). Analysis of vibration data recorded by means of a structural monitoring system and by visual observation of the bridge were performed in order to identify the cause of the vibration and to evaluate the risk of fatigue failure in the hanger cables. Various mitigation measures were installed for testing in order to identify an optimal method for reducing the hanger cable vibrations with the object to ensure infinite fatigue capacity.

In order to avoid similar problems, biaxial accelerometers will be placed at the Izmit Bay Bridge at the four longest hanger cables of each side of both towers in order to monitor wind induced vibrations. Sockets for portable accelerometers will be additionally supplied to six hangers on each side of the permanently instrumented hangers and on both towers hereby prepared for temporary monitoring by the portable Data Acquisition System (DAS) upon visual observations. Hanger forces will also be monitored with a few load measuring pins and some LVDT force transducers.

4.3 Fatigue issues of the orthotropic deck

Orthotropic steel decks can present fatigue issues at welded joints, MacKenzie et al. (2012), the assessment of which is a complex task due to their intricate geometry, the stochastic nature of the traffic load and various temperature effects, including the temperature-driven composite effect between the pavement and the steel deck, which influences the load transfer from the vehicle axles to the substructure and has an impact on the strains to which the fatigue critical details are subjected, Kolstein (2004). This has motivated the use of sensors, Guo et al. (2008), to better capture the actual performance of such elements and improve the remaining fatigue life estimates.

The Bosporus Bridge showed fatigue damage cracking of the orthotropic deck shortly after construction, MacKenzie et al. (2012), and the Great Belt Bridge shows that the experienced traffic intensity is much greater than expected, Bitsch et al. (2010). In order to assess steel deck fatigue issues on the Izmit Bay Bridge, a system that includes several cross sections with strain and temperature sensors on the steel deck and in the pavement is completed with a Weight in Motion (WIM) system for both directions so that all traffic on the bridge is taken into calculations.

5 PERFORMANCE ASSESSMENT AND SIMULATION OF WELDED JOINTS

One of the main challenges related with modern SHMS, is how to make an effective use of the high amounts of data provided by those systems. In this regard, the SHMS of the Izmit Bay Bridge will carry out automatic data evaluation algorithms for each of the different monitored response types. For seismic responses, this will be in the form of a comparison between spectral analyses of the monitored signals with design spectrums. The response spectrums will be calculated considering the monitored time-series of accelerations of the ground during a seismic event. Time-series belonging to a seismic event are those whose values are above predefined seismic thresholds. The benefit of comparing design and calculated spectrums is to evaluate the safety of the bridge immediately after a seismic event to decide whether the bridge can be opened to the traffic or it has to be closed and schedule special inspections. Other responses, such as cable vibrations, displacements at articulations, etc. will be tackled following simple statistical approaches.

In the following sections, a new data-based approach for performance assessment and simulation of the monitored welded joints of the orthotropic deck is presented, which is aimed at enhancing the outputs from monitoring data thus leading to advanced performance assessments.

5.1 Motivation

In many monitoring-based approaches for fatigue assessment of orthotropic steel decks, attention is exclusively paid to the final strain response, without giving sufficient attention to the underlying factors that combine in producing the monitored strain, for example pavement temperatures and traffic load. This can be an important drawback, because failure to quantify this combined effect makes it impossible to compare monitoring outcomes obtained at different times under different ambient and loading conditions. This limits the possibility of actually performing local SHM by extracting health-related features from the monitored signals.

5.2 Strain-related performance indicator

In order to characterize the performance of a monitored joint, recorded strains are first transformed into stresses by assuming a linear elastic behaviour of the steel. Then, a performance indicator D at time t is defined as:

$$D(t)=\sum_{i=1}^{N}(\Delta\sigma_i)^3 \quad (1)$$

Where $\Delta\sigma i$ is the ith stress range out of the N calculated using the rainflow counting algorithm within the tth monitored hour.

D captures the effect of the traffic load and the local characteristics of the steel deck-pavement system. Moreover, it reflects the effect of the different uncertainties, mainly related to the traffic load. On top of that, D can be regarded as a conservative estimate of fatigue damage under a SN approach, considering a single-slopped SN fatigue curve and a fatigue parameter m equal to 3 for many typical fatigue details.

5.3 Data-based predictive model

In order to overcome current limitations and make proper use of monitoring campaigns, a multiple regression model is proposed to link the strain-related performance indicator D(t) presented in equation 1 with the main fatigue drivers in orthotropic decks, namely concomitant pavement temperatures T(t) and concomitant heavy traffic levels B(t) at hour t:

$$D(t)=B(t)\cdot\left(\theta_0+\theta_1\cdot T(t)+\theta_2\cdot T(t)^2+\theta_3\cdot T(t)^3\right)+\varepsilon \qquad (2)$$

Where θ are the model parameters, B(t) the number of heavy vehicles that cross the monitored joint during the tth hour, T(t) the concomitant hourly-averaged pavement temperature and ε the model error. D is assumed to be directly proportional to the number of heavy vehicles, which is a hypothesis that has been found to lead to reasonable fatigue estimates based on previous experience, Laursen et al. (2008). The temperature-driven composite pavement-deck interaction is hereby captured by a 3rd degree polynomial, Farreras et al (2013a).

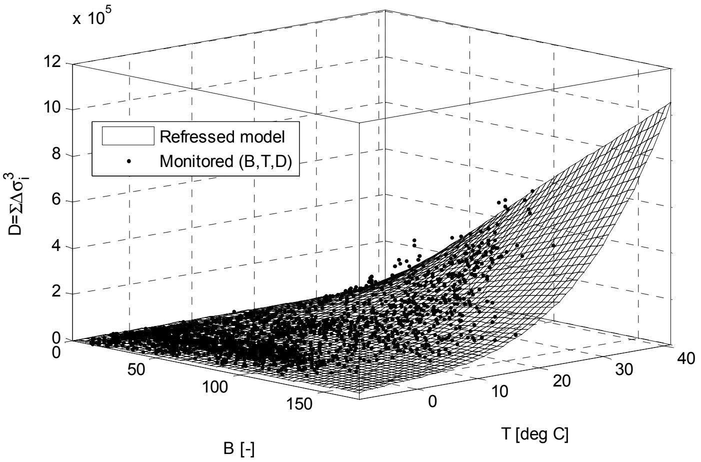

Figure 2. Regressed model from a monitored joint from the Great Belt Bridge (Denmark).

Model parameters are regressed using the set of available monitoring outcomes (B,T,D) by multiple linear regression following the least squares method.

When regressing model

parameters, it is critical to input varying sets of data in terms of temperatures, to capture effectively the composite action effect. Figure 2 presents the regressed model for a particular monitored joint of the Great Belt Bridge (Denmark).

Model parameters characterize the combined effect of the heavy traffic load and the pavement temperature on the induced stresses, as well as the local structural performance in the instrumented weld. In principle, changes in any of the above elements should be reflected in the set of model parameters. Hence, they can be seen as a set of health-related features to perform local Structural Health Monitoring (SHM).

Further details about the model development and model applications can be found in Farreras et al (2013a) and Farreras et al (2013b).

5.4 Model applications

Model applications include performance assessment with complete monitoring data, which is achieved by comparing monitored profiles of D with model-based simulations. This can be used to detect time-varying effects and unexpected responses caused, for example, by overloaded vehicles or to detect some pavement degradation. Moreover, this can flag situations requiring management actions and highlights the benefit of monitoring as a support tool for infrastructure management.

Furthermore, the proposed model can be used for performance simulation of future/past events by predicting profiles of D using historical or simulated data concerning pavement temperatures and traffic levels. Since D can be seen as a conservative estimate of SN fatigue damage, model simulations can be used as well to obtain SHM-based updated estimates of remaining fatigue life. This is of utmost importance to assess reliably the expected fatigue life of the deck, consider potential service life extensions or schedule proactive maintenance actions.

All in all, the proposed approach enhances current monitoring-based approaches in orthotropic decks, provides a framework in which to use effectively the multiple outcomes provided by modern SHMS, increases data robustness and facilitates data visualization.

As SHM data become more widely available, it is essential to demonstrate their effectiveness in enhancing our ability to use performance indicators in support of management decisions during the lifespan of the bridge.

6 CONCLUDING REMARKS

Building and operating a suspension bridge with a free span of 1550 meters in one of the most seismically active areas in the world is challenging. In order to avoid problems, a comprehensive study over challenges related to suspension bridges was done and a straight forward SHMS is designed to secure safe and economic use of the bridge.

The SHMS for Izmit Bay Bridge is designed to be reasonable but comprehensive based on a lean approach covering the most important issues like: environmental conditions, loading conditions, extreme conditions and challenging issues related to suspension bridges. Both the construction period as well as the operation period is considered. The system is also designed for future modifications, expansions or changes. The system ensures that base line information will be provided for all important ambient loads and responses.

It is highlighted that one of the main challenges associated with current SHM approaches is how to make effective use of the large amounts of data provided by modern systems. In this regard, an overview of a data-based model for performance assessment and simulation of welded joints in orthotropic decks has been given. The approach consists of linking a strain-related performance indicator with concomitant hourly pavement temperatures and heavy traffic levels, by means of a multiple linear regression model. Model applications include performance assessment and simulation, as well as fatigue assessment. The proposed approach enhances current monitoring-based approaches in orthotropic decks, provides a framework in which to use the multiple outcomes provided by modern SHMS, such as the one of the Izmit Bay Bridge, increases data robustness and facilitates data visualization.

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