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Structural health monitoring and reliability estimation: Long span truss bridge application with environmental monitoring data

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Abstract

The main objective of this study is to present the reliability estimation studies for the main truss components as well as the entire structural system of a long span truss bridge which is the longest in its category in the USA. It is possible to assess the safety level of a long span bridge by using a probabilistic approach in terms of its component and system reliability indices. However, most of the older long span bridges were designed based on allowable stress design and it is not possible to quantify their reliability. The reliability analysis in this study is based on the distributions estimated for dead, live and wind loads. The bridge was also subjected to long term structural health monitoring where large amount of input and response data have been collected. Analysis of the long term monitoring data revealed distinct structural behavior in terms of patterns and magnitudes under various external loading effects. As an example, it is shown that the structural responses due to temperature are not very easy to conceptualize and subsequently model using conventional analysis methods. In order to explore the effects of temperature on the structure and to include the long term monitoring data in reliability estimation, temperature-induced responses are also incorporated in the analysis. It is seen that the responses due to temperature have a significant effect on the overall system reliability.

Keywords: Structural health monitoring (SHM); Reliability; Long span bridge; Finite element analysis

1. Introduction

1.1. Background

As civil infrastructure systems age, the concern for economically sustainable maintenance practices is increasing. In addition, it is important to understand the safety and serviceability performance of critical infrastructure components. Long span bridges are critical links within transportation networks. Most of the older long span bridges were designed based on allowable stress design and it is not possible to quantify the reliability of structural components as well as the entire structure. By quantifying the reliability of a long span bridge, it is possible to assess the safety level using a probabilistic approach. This will allow optimum maintenance strategies and will help in designing more crucial repair and retrofit applications. Imai and Frangopol [1] presented an approach and application of reliability-based assessment on suspension bridges where they evaluated the reliability of elements such as main cable, hanger ropes and stiffening girders. This probability-based information about the component and system reliability indices generated in this study is valuable to bridge owners for decision making. While the theory of reliability is well-established, the formulation and assumptions for the distribution of the random variables, current condition and behavior of existing structure greatly impact the final reliability estimation. Novel sensing technologies can be employed to have better approximations and more accurate models. Consequently, several approaches and tech-

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niques are being investigated to make better decisions about the condition and safety of the deteriorating infrastructure for safe and effective performance. For example, advanced sensors and monitoring technologies are available to obtain the structural response data much more accurately and conveniently. Structural Health Monitoring (SHM) can be defined as tracking the responses of a structure along with inputs, if possible, over a sufficiently long duration to determine anomalies, to detect deterioration and to identify damage for decision making [5]. Interest in Structural Health Monitoring (SHM) has been increasing over the last 20 years especially due to the need to objectively manage civil infrastructure systems all around the world. At the same time, probabilistic structural analysis methods, condition indicators and optimization tools are being developed for bridge capacity estimation, predict future performance and balance rehabilitation and budget. However, there are very few successful real-life examples on the use of novel algorithms and structural health monitoring (SHM) with advanced sensing technologies for objective evaluation of structural condition and reliability for decision making. While it is reasonable to expect better accuracy in reliability estimates through measurements, it should be stated that the long term monitoring of a component and/or a system may reveal characteristics even beyond the understanding of an experienced engineer. These characteristics constitute epistemic uncertainty which is related to lack of full knowledge as to how structural systems behave and also related to approximate models that may not fully represent real-life behavior of constructed facilities. This is a major challenge in making decisions for serviceability, safety, operation and maintenance. These types of phenomena can be observed only from long term measurements that can provide sufficient data for history and cause of these behaviors. Therefore, one of the most critical issues in assessing the condition of existing civil structures is identification and minimization of the uncertainties associated with critical structural responses and analytical approaches. This can be achieved by means of improved models and experimental data. The contributors to uncertainty in civil structural systems are discussed by Moon and Aktan [2]. The types of uncertainties are discussed extensively by Ang and De Leon [3] and will be summarized later in this paper as well. Real-time data obtained by means of structural health monitoring systems can be used to reduce some of the uncertainties in the assessment of existing structures. As a result, sensing and information technologies, which have shown tremendous advances recently, can provide critical data if integrated with structural reliability methods. So far, these different approaches have mostly been progressing independently. However, the need to integrate and further develop novel approaches is becoming more obvious and crucial.

This paper is aimed to serve as a complement to a previous study on reliability estimation of long span suspension bridges [1] and demonstrates the reliability estimation application on the longest truss bridge in the USA. The writers demonstrate that advanced techniques for structural monitoring, modeling and reliability analysis can be integrated to yield findings that may not be obtained otherwise. The environmental inputs to the long span bridge as well as the responses of the bridge exhibit unique characteristics which would have remained as a major uncertainty if they had not been measured over a long term. The structural reliability indices without and with the monitoring data are computed and compared indicating how temperature-induced responses can impact the estimation.

1.2. Types and sources of uncertainty

In determining the condition and safety of an existing structure, applied load effects and capacity of the structure must be estimated and/or analytically predicted. The randomness or inherent variability associated with the load effects as well as with the capacity of the structure would constitute uncertainties.

Traditional deterministic civil engineering design approach is already challenged by the obvious need to model and incorporate the uncertainties involved in all natural phenomena related to the resistance parameters and load effects. Briefly, uncertainty can be categorized into two groups, aleatory and epistemic [3]. Aleatory uncertainty represents the inherent randomness of natural occurrences governed by probabilistic models. On the other hand, epistemic uncertainty is the uncertainty due to lack of complete knowledge, such as insufficient data, inaccuracies in measurement, inadequate models, and so on. For example, the inherent variabilities of random environmental forces and mechanical properties of structural materials constitute aleatory uncertainty. The idealization of loading, modeling of structure and the structural responses to environmental loading contribute to the additional uncertainty of the epistemic type [4].

Even with perfect knowledge and understanding of physical occurrences, aleatory uncertainty will remain, since it is the inherent randomness, therefore, it cannot be eliminated or reduced, but quantified through risk analysis. However, increased knowledge and accuracy of information decrease the epistemic uncertainty, making the predictions more reliable. For example, the long term monitoring of the environmental effects provide data to quantify the aleatory randomness. On the contrary the structural responses due to these environmental effects need to be considered for epistemic uncertainty.

The authors have observed that especially responses of civil structures to environmental effects are very challenging. For example, temperature-induced stresses on long span bridges have been observed to create responses that are very difficult to model due to unexpectedly high levels of stress as well as the bending type of behavior of truss elements [5]. Predictions with incomplete models that cannot accurately represent environmental effects will have epistemic uncertainty. In this paper, the writers also show that this can be minimized by using actual data obtained from an SHM system applied to a long span bridge. More specifically, the effects of temperature-induced stresses on critical elements and on the overall system reliability are shown on the truss bridge.

1.3. Objectives of the current study

The main objective of this study is to present the reliability estimation studies for all main truss components as well as the