

Yang Deng · Aiqun Li

Structural Health Monitoring for Suspension Bridges

Interpretation of Field Measurements



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Preface

The Motivation for This Book

The past decades have witnessed the emergence of applying structural health monitoring (SHM) system to monitor and evaluate the healthy condition of civil infrastructures. China also has made great progresses in bridge SHM with the rapid and large-scale construction of transportation networks. During the past two decades, hundreds of SHM systems have been established for long-span bridges, especially suspension bridges.

The main motivation of this book stems from the observation that although many sensing techniques and data analysis methods have been deployed, some real requirements in SHM of suspension bridges have not been fully addressed. Most of newly built suspension bridges in China have been instrumented with hundreds of sensors to collect information of loads and structural responses. However, the massive data produced by the costly SHM systems usually does not receive enough analysis. Second, the structural behavior of the suspension bridges is pretty complicated due to complex configuration and in-service loading conditions. The comprehensive and reasonable understanding of structural behaviors and performance of the suspension bridges call for deep and enough interpretation on multi-source measurements by using both modern signal process techniques and conventional structural theories.

In this book, we present our 10-year research achievements in field measurement interpretation for the suspension bridges. Some frameworks are especially designed to address the unique requirements of SHM applications for suspension bridges. We share our experiences and findings by stepping from sensing technique selection and data processing to performance assessment for the long-span suspension bridges.

What This Book is About

This book provides comprehensive coverage and detailed insights into the interpretation of field measurements of using SHM for the suspension bridges. The readers can benefit from this book in sensing technique selection, data processing, and performance assessment. In particular, this book helps the readers to develop the frameworks of field measurement interpretation when they face massive and multisource monitoring information from the SHM of long-span bridges. Therefore, it can be seen as a practical guide as well as a textbook for the reader:

- To establish the measurement interpretation frameworks in domain-specific SHM applications for the suspension bridges.
- To learn about the new insights of structural performance and behaviors of the suspension bridges from the authors' practice and experience of SHM for the long-span suspension bridges.

How This Book is Organized

This book is divided into five parts.

The first part includes Chaps. 1 “Temperature Action Monitoring of Main Girder” and 2 “Bridge-Site Extreme Wind Prediction”. This part presents the monitoring results of two important environmental actions for long-span suspension bridges, including temperature action and bridge-site wind. Bridge designers can learn from this part to improve the potential bridge design.

The second part consists of Chaps. 3 “Measurement-Based Damage Detection for Expansion Joints” and 4 “Modal Frequency-Based Structural Damage Detection”. Damage detection is one of the main topics in SHM. However, the structural responses or inherent features of the suspension bridges are not sensitive to the local structural damages. The changes of damage detection indices caused by structural damages are easily masked by the environmental effects. This part provides a series of systematic frameworks to eliminate or minimize the environmental effects on the damage detection indices for the suspension bridges.

The third part is made up of Chaps. 5 “Fatigue Monitoring of Welded Details” and 6 “Fatigue Reliability Analysis for Welded Details”. Fully-welded fleet steel box girders have been widely applied in suspension bridges because of light self-weight and favorable aerodynamic performance. Long-term stress monitoring provides more accurate fatigue investigation methodology for the welded details of in-service steel box girders. The frameworks of long-term stress measurement interpretation and fatigue reliability assessment are presented in this part.

The fourth part is composed of Chaps. 7 “Vertical Deflection Monitoring of Main Girder” and 8 “Serviceability Assessment Based on Deflection Measurements”. The profile of suspension bridge is one of the main concerns for

both bridge designers and managers. In this part, an advanced deflection sensing system has been developed for in-service profile tracking of the suspension bridges. A serviceability assessment framework is presented for in-service suspension bridges by incorporation deflection measurements with the theories of extreme value and system reliability.

The last part consists of Chaps. 9 “Tension Force Monitoring of Main Cable” and 10 “WIM-based Fatigue Performance Investigation of Hangers”. Main cables and hangers, which form the cable system, are the most critical members in the suspension bridges. Tension force of the main cable and fatigue performance of the hangers are the key concerns for the load-carrying capacity of suspension bridges. In this part, the safety assessment frameworks for main cables and hanger are presented by using the long-term measurements.

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Part 1

Chapter 1

Temperature Action Monitoring of Main Girder

1.1 Introduction

Since the first adoption on the Severn Bridge, streamlined flat steel box girders have been widely applied in long-span bridge designs because of light self-weight and favorable aerodynamic characteristics [1–3]. Currently, the maximum main spans of suspension and cable-stayed bridges with streamlined flat steel box girders have reached 1650 m (the Xihoumen Bridge, width-to-depth ratio = 11.0) and 1104 m (the Russky Island Bridge, width-to-depth ratio = 9.2), respectively [4, 5]. Long-span steel box girder bridges bring challenges to both designers and constructors, such as aerodynamic stability, fatigue crack, and construction control [3, 6, 7]. Recent field investigations on bridges with flat steel box girders suggested that temperature distribution should receive more attention [8–12]. During the past years, there have been a few investigations about the effects of temperature, such as those on fatigue damage [8], modal frequencies [10], vertical deflection [12], and displacements of expansion joints [9–11]. All these studies suggested that the temperature effect on bridges with flat steel box girders is important and complex. A comprehensive understanding of temperature characteristics of flat steel box girders is of great importance to not only new bridge design and construction but also lifetime performance evaluation and maintenance of existing bridges.

Current bridge design specifications around the world provide little information about temperature actions on flat steel box girders. British Standard Institution (BSI) [13] specified the vertical temperature difference of trapezoidal steel box girders, which is known to be very different from that of flat steel box girders. Due to larger width-to-depth ratio, the transverse temperature difference of a flat steel box girder is usually more remarkable than that of trapezoidal one and the temperature gradients in both vertical and transverse directions are needed. Some studies have identified related limitations in current design specifications. Zhang et al. [14] found that the vertical temperature difference was larger than the values provided by BSI [13] for a flat steel box girder without pavement (width-to-depth ratio = 11.8) through

heat-transfer analysis. Kim et al. [15] also used heat-transfer analysis to investigate the temperature distribution of a flat steel box girder (width-to-depth ratio = 11) during construction. Despite its importance, transverse temperature difference was not covered in existing studies due to the limited available data.

Besides, the bridge designers typically prefer that when the girders finally join together during construction stage, the actual effective temperature of the girder can be as close as possible to the reference effective temperature specified during the design stage. However, in the construction stage, it is very hard to obtain reliable information about the temperature spatial distribution information around the cross section and in turn the actual effective temperature of the girder due to the lack of sensors. Hence, ambient air temperature was often used instead in engineering practice to be checked against the reference effective temperature to decide the best time to join the girders. Apparently, ambient air temperature, despite its convenience to be measured, is different from the actual effective temperature. Using ambient air temperature as the actual effective temperature certainly causes discrepancy between the actual bridge and the original design. It thus becomes critical to appropriately transform an easily accessible ambient temperature during construction to an accurate effective temperature for deciding the best time of the final girder assembly. Chang and Im [16] presented a linear correlation model of effective temperature and ambient air temperature for a composite box-girder bridge in Republic of Korea. For flat streamlined steel box girders, the studies on relationship of ambient temperature and effective temperature have been rarely reported.

During the past decade, development of structural health monitoring system (SHMS) offers a great opportunity to provide valuable long-term data to enable an in-depth study of flat steel box girder's temperature distribution. Lucas et al. [17] statistically analyzed the effective temperature and thermal gradient of a steel box girder bridge based on 3-year monitoring data and the transverse temperature difference was not yet covered. Ding et al. [18] and Ding and Wang [19] investigated the transverse temperature differences but the vertical temperature gradient was not included due to the lack of sensors. Zhou et al. [20] investigated the vertical and transversal temperature differences of a steel box-girder suspension bridge and both measured and numerical results showed that the transverse temperature variation across the streamlined girder was significant. Ni et al. [21] also used 1-year (Year 1999) temperature data of the Ting Kau Bridge to predict the maximum and minimum effective temperature. As summarized above, SHMS-based approach opens a new door to understanding the mechanism, predicting possible damages of existing structures, and further improving the design guidelines of new structures.

This chapter proposes a comprehensive approach to study the temperature actions on flat steel box girders of long-span bridges with SHMS techniques and includes strategically placing sensors, collecting, and processing the SHMS data, and gaining comprehensive understanding of the temperature distribution on flat steel box girders. Specifically, the SHMS data is used to (1) establish a mapping relation between effective temperature with ambient air temperature, offering a convenient way to provide key information for joining bridge girders during the construction stage; (2) characterize time-dependent cyclic variation of effective temperature of bridge gird-

ers for performance assessment of some critical components of a long-span bridge; and (3) apply extreme value analysis to provide characteristic values of temperature actions including effective temperature and temperature gradients in both vertical and transverse directions.

1.2 The NSB Description and Instrumentation

The Nanxi Suspension Bridge (NSB), which was open to traffic in 2012, is in the Sichuan province of China with a main span of 820 m. The main girder of the NSB is a streamlined flat steel box girder with the dimensions shown in Fig. 1.1: the girder width is 29.7 m and the height is 3 m (width-to-depth ratio is nearly 10). The widths of the top and bottom plates are 28.1 and 22.7 m, respectively, and the thickness of the pavement is 67 mm. It is worth to mention that this type of flat box girders is popular on long-span bridges and an incomplete list of bridges using similar girders includes Zhanjiang Bay Bridge [3], Runyang Suspension Bridge [7], Jiangyin Bridge [22], and Sutong Bridge [23]. Therefore, the technology as proposed and demonstrated on this bridge and the detailed observations are representative for many long-span bridges using flat box girders. An SHMS was installed on the prototype bridge and the bridge has been continuously monitored since 2013 [12]. The temperature monitoring system was designed to measure the temperature distribution. The sensor placing strategy is as follows: (1) only the middle section of the main span was selected to place the sensors as some previous studies have revealed that the difference of temperature distributions along the span is negligible [18]; (2) 15 Pt-resistance temperature sensors were installed on the inner surface of the middle section (Fig. 1.1). The positions of sensors were arranged strategically to cover the temperature distribution around the cross section to the greatest extent. 5 sensors (ST1 to ST5) were placed on the top plate and another 5 sensors (ST10 to ST14) were placed on the bottom plate. 1.5 sensors (ST6 to ST9 and ST15) were placed on the web plate. The arrangement can allow comprehensive coverage of the temperature distribution in both transverse and vertical directions; (3) To link the ambient air temperature and the structural temperature of flat steel box girder, a temperature sensor was placed on the deck of the middle section to measure the ambient air temperature. Note that ST3 is under the middle barrier and the locations of ST1 and ST5 are near the side barriers. The barriers above the pavement were designed to be hollow without obstructing the solar radiation to the pavement.