Engineering Structures 126 (2016) 571–585

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

A bridge safety monitoring system for prestressed composite box-girder bridges with corrugated steel webs based on in-situ loading experiments and a long-term monitoring database

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ARTICLE INFO

Article history:
Received 4 October 2015
Revised 2 August 2016
Accepted 3 August 2016
Available online 17 August 2016

Keywords:
Bridge monitoring system
In-situ experiment
Long-term monitoring
Warning threshold
Critical threshold

ABSTRACT

In order to reduce the self-weight of Highway No. 4 in the Taichung living circle in Taiwan, a corrugated steel web, with a span of 145 m, is used to replace the conventional concrete web. To appraise the structural safety and operating conditions of a prestressed composite box-girder bridge with a corrugated steel web, which is the first bridge of its kind in Taiwan, a bridge monitoring system is developed based on in-situ experiments, numerical modeling, and long-term monitoring. In order to determine the initial static and dynamic behaviors of a real bridge, a series of experiments are first carried out on a newly-constructed bridge. Before entering service, a bridge is subjected to forced vibration experiments and static loading experiments to establish its initial condition. In this study, a numerical model of the bridge is constructed based on the finite element method. The results of the structural analysis are compared with experimental data, and the two sets of results are found to show good agreement. Moreover, thermometers, strain gages, displacement gages, and inclinometers are installed on the bridge to measure changes in the physical quantities, and the monitored temperature gradient profile over a year is fed back to the numerical model for further analysis. Results have indicated that the in-situ linear variable differential transformer (LVDT) and inclinometer monitoring data can be effectively simulated by the numerical model. Finally, based on the material properties, numerical model, and long-term monitoring data from inclinometers, the safety threshold of the bridge is determined to provide a useful reference for bridge management agencies. Prediction of the extreme inclination angles by the Generalized Extreme Value Distribution (GEVD) method for the 50-year life cycle of the monitored bridge also falls within the envelopes of the warning and critical thresholds, which support the long-term safety of bridges.

1. Introduction

Conventionally, bridge management has mostly been based on regular visual inspections or idealized numerical models with a simplified analysis. Such methods conduct assessments on the basis of possibly damaged members and the region in which the structure is located. They often result in increased human resources costs and underestimation of on-site safety [1,2]. In recent years, bridge health monitoring has gradually become an important topic in bridge engineering. Monitoring data are obtained by properly arranging bridge monitoring devices, and the data can be used in evaluating the reliability of a structure, updating the numerical model, and examining safety conditions at observation points [3–6], thus offering comprehensive bridge information such as deformation and stress. Depending on the assessment requirements, different types of data acquisition devices such as accelerometers, smart total stations, velocity meters, and ground penetrating radars can be used. These devices can measure physical changes without causing any damage to the bridge. The measuring devices should be chosen appropriately to reflect the practical conditions [7,8].

With regard to long-term monitoring, devices that are commonly seen on-site are thermometers, strain gages, displacement

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http://dx.doi.org/10.1016/j.engstruct.2016.08.006
0141-0296/

gages, and inclinometers. Through measured physical quantities, structural behaviors, and abnormalities, the operating conditions and structural safety of a bridge can be better understood. The collected data can also serve as a reference for bridge maintenance and repair [9]. Moreover, long-term monitoring can also facilitate increased accuracy in prediction of the remaining life of the bridge and provide guidance for the design of bridges in the future [10,11].

The fundamental frequency and structural mode of a bridge in the operating phase are affected by the environment. As a result, a safety assessment of a bridge can be performed by measuring the frequency through ambient or indirect approach [12,13]; however, the measured frequency and structural mode only represent the condition of the entire bridge, and it is difficult to recognize local damage. As the amount of change in bridge expansion joints is mainly affected by the ambient temperature, a bridge safety monitoring system can be established by the maximum allowable change in the expansion joints and the corresponding temperature. The displacement in expansion joints in the safe state can be determined based on long-term monitoring data. When in-situ monitoring data deviate from the predetermined range, an abnormal alarm is triggered [14–16]. Kulprapha and Warnitchai proposed a numerical model considering the contribution of ambient loading, temperature gradient distribution, concrete strain, and reinforcement stress. Compared to the database measured from in-situ experiment, compatible result can be achieved [17]. The member force and temperature profile of a full-size rein-forced box girder was monitored [18]. Based on the proposed empirical formula for maximum temperature gradient and average temperature, the member force of the structure can be reliably estimated.

Currently, a bridge monitoring system often consists of various long-term monitoring devices, which are chosen in accordance with the mechanical characteristics of a bridge. While the static and dynamic responses at sensing points can be obtained, the practical condition of specific bridge members affected by external loadings still cannot be reflected. It is therefore necessary to implement sophisticated numerical models. The reliability of numerical models must be validated by in-situ experiments to support an explicit and reliable bridge monitoring system. Moreover, as the diagnosis results on the same bridge may vary with the site environment and traffic volume, comprehensive monitoring data are required to determine the safety threshold.

A prestressed box girder with corrugated steel webs consists of prestressed concrete, corrugated steel webs, and prestressed tendons. Upon the application of a prestressing force, the web does not carry an axial force due to its special geometry and low axial stiffness. Consequently, the prestressing force is effectively transferred into the top and bottom concrete flanges; this is referred to as the accordion effect [19]. The bending moment and axial force on the girder with corrugated steel webs are carried by the top and bottom concrete flanges, and almost all of the shear force is carried by the webs [20]. Shear buckling mostly contributes to the failure mode of a corrugated steel web. The global shear buckling governs the strength with dense corrugation; otherwise, local shear buckling strength governs. Interactive shear buckling may also occur during the buckling process [21].

By adopting a prestressed composite box-girder bridge with corrugated steel webs, the following advantages can be expected: (1) the self-weight of the bridge can be reduced by replacing a concrete web with a corrugated steel web; (2) the prestressing effect can be enhanced as the majority of the longitudinal prestressing force being carried by the top and bottom concrete flanges due to the small longitudinal stiffness contributed by a corrugated steel web; (3) shrinkage and creep of concrete from temperature effects are reduced; (4) the required web thickness and stiffening reinforcement are reduced due to the large shear strength and shear buckling strength supported by a corrugated steel web; (5) compared to conventional concrete, a corrugated steel web is easier to assemble during construction, eliminating web reinforcements and formwork, thus improving construction efficiency and shortening construction time; and (6) the external prestressing steel cables are easy to replace, offering convenience in bridge maintenance and retrofitting. Due to these benefits, prestressed box girders with corrugated steel webs have gradually become a new trend in the development of bridge structures [22,23]. However, concrete crack and spoiling have been challenges for the durability of the prestressed composite box-girder bridges with corrugated steel webs. Moreover, as regular painting is required by for maintenance, corrosion protection of the connection between steel and concrete should also be specifically considered.

The established finite element models are updated by in-situ experiment or long-term monitoring result. Combination of finite element response surface and genetic algorithm was proposed by Shan et al. to update the model [24]. Design parameters were also optimized based on the static and dynamic experimental data [25]. Ribeiro et al. [26] measured the ambient vibration of a bowstring-arch railway bridge employing accelerometers, and developed a finite element model to perform comparisons. To improve consistency of the numerical model, the Genetic Algorithm (GA) was also applied in parameter optimization. An updating process based on response surface method (RSM) was applied on a practical prestressed concrete bridge [27]. The result has indicated that the finite element can be optimized through the RSM-based method.

The safety and sustainability of a bridge can be largely improved with the support of reasonable estimation of the extreme structural deformation during its whole life cycle. As most bridges are under regular loading patterns, the intervention timing of maintenance can be optimized based on the long-term monitoring database to reduce the life-cycle cost of bridges [15,28,29]. Researches have demonstrated that life prediction of structures using extreme value distribution can be achieved by utilizing the long-term monitoring database for only 1 year.

Considering hydrological requirements for bridges over rivers, a prestressed box girder with corrugated steel webs has been adopted for the first long-span river-crossing bridge in Taiwan. To further understand the real structural behavior, a long-term monitoring system has been established to examine the bridge design and the reliability and accuracy of system parameters. The proposed system can provide a reference for evaluating the effect of temperature, traffic loading, and seismic impact on the bridge structure, thus improving practical techniques in bridge engineering and theoretical analysis.

The paper is organized as follows. The structural components of a prestressed composite box-girder bridge with corrugated steel webs are first described in Section 2. The framework of the bridge monitoring system is also introduced. The proposed forced vibration and static loading experiments, which are conducted to obtain the static and dynamic characteristics of the bridge are presented in Section 3. The numerical model of the bridge based on a finite element method is described in detail in Section 4. As the initial state of the model is determined by the frequency measured in experiments and the static deformation responses, the structural model is further integrated into the bridge monitoring system. In Section 5, monitoring data over an entire year are fed back to the numerical model. The condition of the bridge during a single year is investigated and its safety threshold is established to complete the monitoring system. Through the proposed process, the monitoring data and safety threshold can be used as a basis for future safety assessment. Moreover, the extreme inclination angle of the bridges during their life cycle is estimated based on the long-term monitoring database to reflect the current safety status. Finally, conclusions are drawn.