Journal of Constructional Steel Research 72 (2012) 179–191

Contents lists available at SciVerse ScienceDirect

Journal of Constructional Steel Research

Evaluation of a strain monitoring system for existing steel railway bridges

Bruno J. Afonso Costa [a,*], Joaquim A. Figueiras [b]

[a] LABEST, Faculdade de Engenharia, Universidade da Beira Interior, Edifício II das Engenharias, Calçada Fonte do Lameiro, 6200-001 Covilhã, Portugal
[b] LABEST, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal

ARTICLE INFO

Article history:
Received 19 December 2010
Accepted 16 December 2011
Available online 14 January 2012

Keywords:
Steel railway bridge
Field testing
In-service evaluation
Strain monitoring
Electric and fiber optic sensors

ABSTRACT

The old steel bridges that integrate the existing railway lines are structures built with materials that are no longer used and whose knowledge has being lost over the years, often presenting severe problems of deterioration and subjected to loading environments very different from those for which they were designed. In this context, adequate strain monitoring is a crucial tool in supporting the behavior characterization and safety assessment of these structures.

This article presents and discusses the monitoring systems installed in the Trezói Bridge, within a research project aimed at developing and applying procedures for evaluation of the structural integrity of steel railway bridges. The field observations of the structural behavior were accomplished by using two different types of sensors: electric and fiber optic strain sensors. The electric monitoring system was designed and installed on the bridge to supply the experimental data for the research project, while the fiber optic monitoring system was firstly applied to evaluate the reliability of the former and to check its efficiency, and secondly to provide some redundancy of the measurements at critical locations. The obtained results are analyzed to characterize the bridge behavior and the capabilities and limitations of both types of sensors to acquire the relevant data for the bridge service condition and fatigue assessment are discussed, namely in what concerns the ability to accurately capture the static and dynamic components of the structural response and the frequency content of interest.

1. Introduction

1.1. Economic context

Bridges are fundamental elements for building transportation networks but also play a decisive role in their operationality, efficiency, cost-effectiveness and longevity. These aspects are even more significant when it comes to rail networks. The electrified network comes up as the best natural option to transport goods and passengers since it is less dependent on non-renewable energy sources which became a mandatory issue to account for in developed countries. On the other hand, the recent guidelines for environmental protection related with human consumption and waste production, are based on three concepts: reduction, reuse and recycling. In this perspective, bridges can and should be seen as products used by modern societies, and therefore maintenance, rehabilitation, strengthening and upgrading of existing structures should be preferred to their decommissioning and replacement.

1.2. Key problems concerning aging in-service railway bridges

At the present time, old railway bridges are being subjected to live loads very different from the ones established in their original design. Not only the traffic flow has increased but also the characteristics of the crossing vehicles are diverse and their operating speed and axle loads are higher [1,2]. Thus, the need for reliable and updated data related with current traffic patterns is crucial for any evaluation to be made, in particular the fatigue related one [3].

As it is well known, fatigue in steel structures depends on the stress distribution among their constituent elements under transient loads, mainly those caused by passing vehicles, as well as on its fluctuation in time. These forces induce strain/stress cycles in the material that can lead to fatigue cracks and their propagation at the points where amplitudes reach higher values, typically in connection details. Furthermore, these areas are frequently more prone to material degradation, and consequent cross-section loss, which reduce the load carrying capacity [4].

Accurate evaluation of the structural condition of an element or connection, specially their fatigue resistance, is of great importance for the bridge assessment. Guidelines as part of an integrated fatigue assessment for aging structures are already available, of which the most relevant are AREMA [5], AASHTO [6] and ECCS [7]. These documents draw attention to strain field measurement as a means of collecting reliable data concerning the structure behavior. One of the

* Corresponding author. Tel.: +351 275329722; fax: +351 275329969.
E-mail address: bjac@ubi.pt (B.J.A. Costa).

0143-974X/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jcsr.2011.12.006

most important aspects that distinguishes these structures is the material they are made of, since many of them are more than one hundred years old. The knowledge of its properties is sometimes deficient among most technical actors, especially the youngest [8].

1.3. Monitoring for assessing and management

Until recently, bridge management had been relying mainly on periodic visual inspection, idealized modeling and simple analysis. Evaluation based on structural identification provided by field observation was only an optional action even if the bridge was suspected of being structurally deficient [9]. This conventional procedure often led to incorrect decisions, both in safety and costs. Thus, in the last decade health monitoring has become an integrated tool within several management systems [10,11]. Monitoring data made available by a well designed and implemented observation system can be used for reliability assessment and to update prediction models [12,13], as well as to detect symptoms of any risk to the structure and its users [14]. Moreover, loads acting on the structure may also be measured in order to accurately characterize the loading environment [3].

The electric based monitoring systems installed in steel railway bridges are prone to present unwanted noise in the signals caused by electromagnetic interferences, due both to the material nature and to the fact that railway lines are electrified [15]. For this reason, the fiber optic based instrumentation for railway steel bridges has being preferred, since immunity of such sensors to this phenomenon is well known [16]. One example of a successful field application is the strain monitoring sub-system based on Fabry–Perot optic sensors deployed on Wuhu Yangtze River Railway Bridge, in China [17]. Costa et al. [11] have also applied an extensive and comprehensive monitoring system to a centenary steel arch bridge, comprising fiber Bragg grating (FBG) sensors, to assist the evaluation of the rehabilitation operations performed on the structure and to appraise its behavior under the new exploitation. A fiber optic monitoring system has been installed on the Tsing Ma Bridge, the world longest road and railway suspension bridge, in order to assess the possibility of using the FBG sensors developed by Chan et al. [18] for structural health monitoring, and Tsamasphyros et al. [19] have implemented a study to investigate the applicability of FBG sensors on a late 19th century steel railway bridge located at Nea Peramos near Athens in Greece.

1.4. Objectives and scope

As mentioned before, the problems concerning the in-service railway steel bridges are in need of urgent attention. European project *Sustainable Bridges* [2] is one recent example that aimed at bringing additional knowledge on this matter. Its ultimate goals were to: i) increase the transport capacity of existing bridges; ii) extend the residual service life of structures; and iii) enhance management, strengthening, and repair systems. At national level, officials are now beginning to be aware of the necessity to develop more extensive programs to deal with specific problems of aging railway infrastructure. Even though some efforts have been addressed to modernize the Portuguese network, several of its structures do not benefit from major interventions for decades, and as a result may not meet the current requirements for railway transportation. In this context, a research project has been performed aimed at developing and applying procedures for assessing the structural integrity of railway steel bridges within the national railway network, taking into consideration fatigue resistance and remaining fatigue life under past, present and expected loading environments.

For this study a bridge was selected as test bed. The structure was opened to the public in the middle of the last century, and is located on the international Beira Alta route, nowadays the principal rail connection of the country to Europe. In a first stage, records of train induced vibrations and data collected by an ambient vibration test were used to validate and update a 3D finite element model of the bridge, thus making possible the simulation of the bridge dynamic behavior and fatigue analysis [20]. The second stage and respective preliminary results are to be presented in this paper. For this stage a monitoring plan was designed and implemented in order to continuously collect steel strain records induced by railway traffic. The established objectives are as follows: i) to characterize the structural behavior, both local and global, and thus to enable the improvement of the numerical model previously developed; ii) to check strain/stress paths and patterns in critical elements and connections; iii) to obtain experimental strain/stress histograms suitable for fatigue analysis; and iv) to gather data concerning the crossing vehicles in terms of speed, moving direction, number of axles and distances between them. To accomplish the outlined goals two parallel monitoring systems were deployed, the first based on electric strain gages (primary) and the second constituted by fiber optic strains sensors (secondary). The sensors were applied to cross sections of bars which experience the higher tensile stress ranges, near the joints and at a quarter and half-length. In addition, rails sections in the vicinity of both abutments, but outside the bridge, were instrumented with strain gages.

The results obtained with both installed systems, electric and fiber optic based systems, are presented and, through their confrontation, some conclusions related to the advantages and disadvantages of each system are drawn, mainly regarding the feasibility of using the primary monitoring system to meet the experimental goals established within the research project. In this paper the monitoring plan and procedures are analyzed and discussed, which includes options related to the installation techniques, sensors, sampling frequency of the signals and observed sections. The quality of the strain readings to support fatigue analysis through the concept of damage accumulation, making use of counting algorithms for strain/stress ranges, is discussed. Finally, the most significant features of the observed structural behavior are pointed out, and the reliability of the traffic data extracted from the adopted instrumentation is evaluated.

2. Test bridge

The bridge is located near the village of Trezói in the center of Portugal, and is in continuous operation since August 20th of 1956. Its construction was accomplished with funds from the Marshall Plan, and took place during the decommissioning and substitution of all bridges in the same route, built by Eiffel House. The new larger structures, including Trezói Bridge, were designed, manufactured and assembled by the German House Fried Krupp [20].

Two inverted Warren truss girders, 5.68 m high and 4.40 m apart between axes, constitute the steel deck of the bridge. Its total length is 126 m, comprising two extreme spans 39 m long and one central span 48 m long. The girders panels are 6.50 m wide in the central span and 6.00 m in the end spans. Two trapezoidal shape trusses acting as piers and two granite masonry abutments transmit the loads carried by the structure to the foundation (see Fig. 1). All connections between the elements are riveted.

The superstructure's bearing supports are made of steel, allowing free rotations in the structure plane (see Fig. 2(a)). At the east abutment the longitudinal displacements are constrained whereas at the west abutment they are permitted to embrace the deformations caused by thermal loads. The connections between the deck and the piers tops are hinged, as well as their connections to the granite masonry bases, therefore behaving as pendula.

The chords and diagonals of the truss girders are formed by double "C-shape" sections, whereas the floorbeams that connect the top of the girders as well as the stringers resting on them are "I" profiles. The verticals are "H-shape" sections and the horizontal bracing of the chords is accomplished with angle bars. Fig. 2(b) shows a typical joint of the truss girders at the bottom chord. The two stringers that carry the live loads are aligned with the rails of the single track.