Mechanical Systems and Signal Processing 25 (2011) 2990–3009

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Dynamic identification of a reinforced concrete damaged bridge

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ARTICLE INFO

Article history:
Received 2 April 2011
Accepted 28 May 2011
Available online 1 July 2011

Keywords:
Dynamic tests
Bridges
Structural identification
Finite element models
Damage localization
Concrete

ABSTRACT

The results of a series of harmonically forced tests carried out on a reinforced concrete single-span bridge subjected to increasing levels of damage are interpreted in this paper. The deck structure of the bridge consists of a slab and three simply supported beams. The damage is represented by a series of notches made on a lateral beam to simulate the effect of incremental concentrated damage. The variation of lower natural frequencies shows an anomalous increase in the transition from one intermediate damage configuration to the next ones. Vibration mode shapes show an appreciable asymmetry in the reference configuration, despite the nominal symmetry of the bridge. A justification of this unexpected dynamic behavior is presented in this paper. The analysis is based on progressive identification of an accurate finite element model of the reference configuration and on reconstruction of damage evolution from natural frequency and vibration mode measurements. Changes in modal curvature of the first two vibration modes evaluated along the main beams are successfully used to identify the location of the damage.

1. Introduction

Damage changes the vibratory behavior of a structure and, therefore, structural diagnostics based on dynamic methods has potentially great importance in engineering applications [3,4,13,14,22]. Recent technological progress has generated extremely accurate and reliable experimental methods, enabling a good estimate of changes in the dynamic behavior of a structural system caused by possible damage. Although experimental techniques are now well-established, the interpretation of measurements still lags somewhat behind. This particularly concerns identification and structural diagnostics by dynamic data due to their nature of inverse problems in vibration [8]. Indeed, in these applications one wishes to determine some mechanical properties of a system on the basis of measurements of its response, in part exchanging the role of the unknowns and data compared to the direct problems of structural analysis. Hence, concerns typical of inverse problems arise, such as non-uniqueness or non-continuous dependence of the solution on the data. When identification techniques are applied to the study of real-world structures, additional obstacles arise given the complexity of structural modeling, the inaccuracy of the analytical models used to interpret experiments, measurement errors and incomplete field data. Furthermore, the results of the theoretical mathematical formulation of problems of identification and diagnostics, given the present state-of-knowledge in the field, focus on quality, while practical needs often require more specific estimates of quantities to be identified.

It is probably because of these difficulties that a limited number of studies have investigated so far the effect of damage on modal parameters of full-scale bridges and have developed suitable strategies for damage identification. Without claim of completeness, here we recall the interesting researches developed in [2,7,9–12,18–21,25]. A critical review of the

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0888-3270/$ - see front matter
doi:10.1016/j.ymssp.2011.05.016

Nomenclature

E_c	Young's modulus of the concrete
f_δ	spline function
f_{err}	objective function to be minimized
K	elastic stiffness
L	span length
p_r	undamped circular frequency for mode r
R_{ck}	cubic strength of concrete
$u_k^{(r)}$	kth component of the rth mode shape
γ	volume mass density
δ	decomposition of the interval $[0,L]$
δ_u, δ_d	multipliers

literature shows that there is still no general consensus among experts on the type of data to be taken as good indicator of damage and also on the effectiveness of a diagnostic method rather than another, see, for example, the Introduction of the paper [5].

The main objective of this paper is to give an interpretation of the results of a campaign of dynamic tests carried out on a reinforced concrete bridge under increasing levels of damage. The bridge deck is formed by a slab supported by three longitudinal beams. Harmonically forced dynamic tests were carried out in the reference configuration and in several damage configurations. The damage states were obtained by cutting the downstream beam by means of a hydraulic saw.

Some important indications emerged from experiments. First, the trend of natural frequencies to the progress of the damage shows an unexpected increase in the transition from one intermediate damage configuration to the next ones. Second, despite the bridge is nominally symmetric, from vibration mode measurements it was possible to detect a structural asymmetry – mainly in transverse direction – of the reference configuration of the bridge.

In the first part of the paper we provide a justification of these two circumstances. The analysis is based on progressive structural identification of reference and damaged configurations from measurements of natural frequencies and vibration modes of the bridge. The second part of the work is addressed to damage localization from mode shape data. In particular, changes in modal curvature of the first two modes evaluated along the main beams were successfully used to identify the location of the damage.

2. Description of the bridge

Dogna Bridge is a four-span one-lane concrete bridge. The length of each span is 16.00 m and the lane is 4.00 m width. Fig. 1 shows the span tested during the experiments and considered in the present research. This span is denoted as Dogna Bridge in what follows. The bridge deck is constituted by a reinforced concrete (RC) slab supported by three longitudinal RC beams. The beams are simply supported at the ends on thin metallic sheets and are connected at the supports, at mid-span and at span quarters with transverse RC diaphragms. Pier and abutment consist of RC walls and are founded on cast-in-place concrete piles.

Construction of the bridge was completed in 1978. The bridge suffered of an exceptional flood of the Fella River on August 31, 2003. At that time, due to the material deposited upstream, the deck structures of the bridge were involved by the flow of the water, see Fig. 2. A visual inspection conducted on the tested span revealed no apparent deterioration on slab and beams, whereas a state of degradation was noticed on support bearing side pier. For reasons of traffic safety, Dogna Bridge was demolished on May 2008 and has been replaced by a new bridge built about 200 m downstream.

3. Damage scenarios and experimental results

The experimental campaign was carried out from April 2 to April 11, 2008. The tested span was made independent of the adjacent span by removing the deck-joint in correspondence of the pier. Moreover, the asphalt overlay of about 0.1 m thickness was also removed before testing. Harmonically forced tests were carried out on the bridge deck in its present condition (*reference* configuration, indicated by R in the following) and in six *damage configurations* D1–D6 obtained by cutting the downstream beam as shown in Fig. 1(c). The sequence of notches was produced by means of a hydraulic saw fitted with a diamond disc.

The experimental layout is shown in Fig. 1(a). An electric vibrodyne was mounted in vertical direction at one fourth of the upstream beam, near the abutment side. Seventeen piezoelectric accelerometers with vertical axis and one horizontal accelerometer were simultaneously used to determine the deck's response to the excitation.

Deck's inertance was measured by means of zoom analysis within narrow neighborhoods of the expected natural frequencies values, see [5] for more details. The frequency resolution ranged from 0.02 for lower modes (up to 15 Hz) to 0.04 Hz for higher modes (15–50 Hz). During the experiments a time harmonic force with maximum amplitude of 15 kN has been used.

The procedure has been applied for the characterization of the reference and all the damaged configurations D1–D6. Dynamic tests were carried out under similar environmental and weather conditions, so that the influence of temperature and humidity on dynamic modal parameters can be considered negligible.