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Dynamic testing of a damaged bridge

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ABSTRACT

In this paper the results of a campaign of dynamic tests carried out on an existing reinforced concrete single-span bridge subjected to increasing levels of damage are presented. The deck structure 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 modal parameters of the lower vibration modes were estimated from frequency response measurements obtained under harmonic excitation. The variation of natural frequencies shows an anomalous increase in the transition from one intermediate configuration to the next damage configurations. Changes in vibration modes are appreciable from the earliest level of damage. In particular, changes in modal curvature of lower modes do provide indication on the damage location.

1. Introduction

Non-destructive vibrational methods are frequently used as diagnostic tool to detect damage in structures [23,33]. Repeated tests over time can indicate the emergence of possible damage occurring during the structure lifetime and provide quantitative estimates of the level of residual safety.

Structural damage is often thought as a decay of the mechanical properties of the structure and it is represented by a decrease of stiffness. Accordingly, a common way to solve inverse problems posed in structural diagnostics is to determine the change in the stiffness coefficient caused by the damage such that a given set of natural frequencies are closest in some least square sense to those found experimentally, see, for example [27,22,7,5,43,40,38] for detailed studies on beam structures. A method based on the rank-ordering of the modes according to the fractional eigenfrequency changes was proposed in [1] to detect cracks in beams. Assuming that the damage configuration is a perturbation of the undamaged one, it was shown in [31,13,14] that natural frequency shifts and antiresonant frequency shifts induced by the damage contain information on certain generalized Fourier coefficients of the unknown stiffness variation.

Mode shapes have also been used, even in conjunction with frequency data, to detect damage [36]. Pandey et al. demonstrated in [35] that changes in the curvature of mode shapes may be useful for damage detection in beams. Gladwell and Morassi [21] and Dilena and Morassi [11] show that the direction by which nodal points of vibration modes of beams under longitudinal or bending vibration move can be used for predicting the location of a single, concentrated damage. Caddemi et al. proposed in [3] a method for identification of multiple cracks in bending beams from a suitable set of mode shape amplitudes.

One of the main difficulties connected with the use of above vibrational methods lies in the small sensitivity of the dynamic parameters to damage. This is an intrinsic feature of structural diagnostics based on dynamic data. It represents a source of important indeterminacy, such as the strong dependence of the results of identification on the experimental errors and on the accuracy of the structural model that is chosen to interpret measurements. These facts are nowadays

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Nomenclature

A_i	constants
$A_{kl}^{(r)}$	residual term between nodes k and l, for mode r
B_i	constants
$\mathbf{C}$	global damping matrix
E_c	Young's modulus of the concrete
f_δ	spline function
$H_{kl}(i\omega)$	frequency response function between excitation point l and measured point k
J	objective function to be minimized
$\mathbf{K}$	global stiffness matrix
K_i	constants
L	span length
m_r	modal mass for mode r
$\mathbf{M}$	global mass matrix
M_{kl}	kl-components of the mass matrix $\mathbf{M}$
p_r	undamped circular frequency for mode r
p_{rd}	damped circular frequency for mode r
s_r	rth pole of a dynamic system
t	time variable
$\mathbf{u}$	nodal vector displacements
$u_k^{(r)}$	kth component of the rth mode shape
γ	volume mass density
δ	decomposition of the interval [0,L]
ω	frequency variable
ξ_r	damping factor for mode r

quite well known for simple structural systems, such as beams or frames [10,32], but still are not completely clarified for more complicated structures. As a consequence, when diagnostic techniques are applied to the study of real-world civil engineering systems, such as in situ bridges, serious obstacles arise, owing to the uncertainty about the modeling and the presence of measurement errors. Incomplete experimental data and unexpected effects due to changes in environmental and operational conditions are also important points of the analysis.

It is probably because of these difficulties that, so far, a limited number of studies have investigated the effect of damage on modal parameters of full-scale bridges and have developed suitable strategies for damage identification. Furthermore, a critical review of the literature on this topic 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. The reasons for these uncertainties are undoubtedly due to the peculiar structural behavior of each construction and to the difficulty to have standard approaches to structural modeling of bridges. Some authors agree that changes in natural frequencies are measurable and do provide some indication of the structural modifications [25,37]. The experience of other researchers is different. The papers [42,18] reported that natural frequencies could not reliably identify the location and level of damage. Also changes in mode shapes have been judged some times poor indicators of damage. However, from several studies emerged that mode shapes are the best indicators of where the damage is occurring [37,28]. In particular, the ability to identify damage by mode shapes turns out to be improved by applying suitable damage identification techniques, such as those based on reconstruction of modal flexibility matrix [42,6], determination of modal curvature [44,9], identification of the stiffness coefficients via model updating techniques [41,45]. Overall, several aspects remain to be clarified such as those connected with the effect of environmental conditions on the dynamic behavior of a bridge and the possibility of using dynamic data within on-line structural health monitoring programs [8,24,26,2,20].

The main objective of this paper is to present the results of a campaign of dynamic tests carried out on a concrete single-span bridge in the Municipality of Dogna (Friuli, Italy). The bridge structure consists of a slab supported by three longitudinal beams simply supported at the ends. The structural typology is simple, but at the same time rather common in the Friuli Region and, in general, even in Northern Italy. Harmonically forced tests were conducted to evaluate the variation of the modal parameters of lower vibration modes after imposing artificial, increasing levels of damage. The damage is represented by a series of notches made on a lateral beam to simulate the effect of concentrated damage caused, for instance, by the impact of an object carried by the water during a flood. Changes in modal parameters as a result of structural deterioration are documented and discussed. In the second part of the paper, changes in curvature of the lower vibration modes are used to identify the location of the damage.

2. Description of the bridge

Dogna Bridge is a four-span, single-lane concrete bridge. The bridge lies over the River Fella and connects the two villages Crivera and Valdogna (Dogna) in the Friuli Venezia Giulia, a region located in the North East of Italy. The length of each span is 16.0 m and the lane is about 4 m width. A general view of the bridge is shown in Fig. 1. The bridge deck is formed by a reinforced concrete (RC) slab 0.18 m in thickness, supported by three longitudinal RC beams of rectangular cross-section 0.35×1.20 m. 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 of rectangular cross-section 0.3×0.7 m. Each pier is a RC wall approximately of 1.5 m thickness, 4.5 m depth, and around 3.6 m height. Each abutment consists of a RC wall 1.00 m in thickness. Pier and abutments were built on cast-in-place concrete piles of 1.0 m in diameter and 18.0 m in length. Dynamic tests were carried out from April 2 to April 11 2008 on the right span shown in Fig. 1. This span (denoted as Dogna Bridge in what follows) 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 in thickness was also removed before testing, see Fig. 2.