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Vibration analysis and structural identification of a curved multi-span viaduct

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A B S T R A C T

This work continues a line of research aimed at the development of a dynamically based monitoring program of bridges in the area of Friuli Venezia Giulia, Italy. The main infrastructure of the survey program is the curved 15-span post-tensioned concrete viaduct considered in this paper. The viaduct consists of three continuous girders separated by expansion joints and supported on piers by means of elastomeric seismic isolators. Output-only vibration tests under traffic loads were carried out to extract the dynamic parameters of the first vibration modes of the structure. The experimental characteristics were compared with those predicted by a preliminary finite-element model. The properties of vibration modes with prevailing amplitudes along the radial and circumferential direction of the viaduct were described with poor precision. This disagreement required the calibration of the finite-element model through a tuning procedure based on modal data. In particular, the experience has shown that the dynamic behavior of the viaduct is strongly influenced by the mechanical properties of the bearing devices supporting the deck superstructures. The calibrated finite-element model can be used as a baseline model for future monitoring and condition assessment programs on this typology of infrastructures.

1. Introduction

The load-bearing capacity of a bridge and its structural behavior under traffic or seismic excitation can be evaluated using well-established modeling methods aided by computing facilities of great capability. However, to ensure reliable results, numerical models must be calibrated with accurate information on the material properties and structural components. This aspect is particularly relevant for those structural details which are difficult to describe analytically, such as the constraints between structural members, the boundary conditions and the soil–structure interaction.

Among the tools available today for structural investigation, dynamic techniques play an important role from several points of view. Particularly, by measuring the structural response, they allow us to identify the main parameters governing the dynamic behavior of a bridge, namely natural frequencies, mode shapes and damping factors. This information is usually obtained by means of ambient vibration tests using operational identification methods. Ambient measurements generally are less effective than harmonically forced tests, but their use does not require any additive equipment and do not affect the exercise of the bridge. Moreover, since they can be easily repeated, measurement of a high number of points is easily feasible

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Notation

$A_{kl}^{(r)}$	residual term between nodes k and l, for mode r
$\mathbf{C}$	global damping matrix
$\mathbf{f}$	forcing or input vector
$H_{kl}(\omega)$	frequency response function between excitation point l and measured point k
K	shearing elastic stiffness of seismic isolators
$\mathbf{K}$	global stiffness matrix
$\mathbf{M}$	global mass matrix
m_r	mass-normalization factor for the rth vibration mode
p_r	undamped circular frequency for mode r
p_{rd}	damped circular frequency for mode r
s_r	rth pole of a dynamic system
$\mathbf{S}_{ff}(\omega)$	power spectral density matrix of the input $\mathbf{f}$
$\mathbf{S}_{uu}(\omega)$	power spectral density matrix of the output $\mathbf{u}$
t	time variable
$\mathbf{u}$	nodal vector displacements of the output
$u_k^{(r)}$	kth component of the rth mode shape
Δ	frequency estimation error
ω	frequency variable
ξ_r	rth damping factor

even with a small number of available sensors. In addition, recent advances on signal processing techniques applied to output-only measurements allow us to obtain accurate and reliable modal parameters' estimates.

Dynamic data collected during an experiment are important per se, since they constitute a signature of the structural behavior of the bridge. However, this information becomes more effective and can provide more meaningful results when it used to improve a finite element model of the bridge [21,1,12,20,35]. The problem of how to improve the analytical model from dynamic measurements is the main purpose of a branch of structural dynamics called structural identification. Basically, the goal is to extract information from the experimental data and use it to modify inertia/stiffness parameters or geometrical properties of the numerical model to obtain better agreement between numerical and test results [19,2]. Damage identification is another important goal of non-destructive dynamic testing. Repeated tests over time allow us to reconstruct the evolution of modal quantities and can indicate the emergence of possible damage occurring during the bridge's lifetime. Sometimes the change in modal parameters is directly interpreted in order to provide quantitative estimates of the level of residual safety [47,44,4,10,48,9,46,11,36,39,14]. In other situations, suitable indexes related to modal quantities are introduced to express the level of damage [30,31]. Some of these indexes are model independent, but the contribution of a suitable mechanical model can improve the quality of the results. Several accurate investigations have been developed in the last two decades on damage detection on bridges [18,49,27,29,13,51,15,16]. The results are not always very satisfactory and they start to be effective only for high level of damage. The possibility to reach good results depends on many factors, such as reliable experimental results, a suitable quantities of sensors and well positioned with respect to unknown damage location, not influent ambient conditions. The availability of a baseline undamaged configuration of the bridge to which refer the possible decay of structural properties and the effect of temperature on variability of modal parameters are further important points of the analysis [32].

Model updating and damage identification methods based on dynamic data have a common root. They lead to inverse problems in vibration. Indeed, in these applications one wishes to determine some mechanical properties of a system or to improve the description of some structural component 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 dynamics [22,23]. Hence, concerns typical of inverse problems arise, such as high nonlinearity, non-uniqueness or non-continuous dependence of the solution on the data. When identification techniques are applied to the study of real-world bridges, 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 [43,17,28,37,38,34]. To overcome these obstacles, standard procedures do not often suffice and specific approaches must be applied to tackle the intrinsic nature of the identification problem, using ad hoc experimental, theoretical and numerical methods.

This paper continues a line of research developed in collaboration with Autovie Venete S.p.A., the company that manages most of the highway networks of the Friuli Venezia Giulia (Italy). The long-term objective of the project is to define a periodic health condition monitoring of bridge structures based on dynamic measurements to ensure that the structures provide continuous and safe service. This request is of particular importance in Friuli Venezia Giulia owing to the high level of seismic activity present in this area and the fast increase in the volume traffic loads registered in the last two decades.

The first stage of the project was aimed at the development and application of dynamic methods for the structural characterization of bridges. To this aim, a certain number of bridges belonging to the most representative and common typologies of the Friuli Venezia Giulia highway network were selected for dynamic monitoring, structural evaluation, and damage assessment purposes. The main objective of this paper is to present the results of an application of structural identification based on dynamic data on a curved 15-span post-tensioned concrete viaduct. The viaduct is the main infrastructure recently built in the new highway line A28 connecting the cities of Pordenone and Conegliano. It consists of three continuous girders separated by expansion joints and supported on piers by means of elastomeric seismic isolators. Output-only vibration tests under traffic loads were conducted to extract the dynamic parameters of the first vibration modes of the structure. One of the purposes of the experimental campaign was to evaluate the effectiveness of the special