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Dynamic testing and parameter identification of a base-isolated bridge

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ABSTRACT

In this paper the results of a campaign of harmonically forced vibration tests conducted on a two-span post-tensioned reinforced concrete bridge with deck supported on six elastomeric isolators are presented and discussed. The bridge is built in an area of the Friuli Venezia Giulia Region (Northern Italy) having high level of seismic activity. Dynamic measurements are used to update a preliminary finite element model of the bridge. The accurate estimate of the shearing stiffness of the isolators constitutes an important issue of the updating process, both for the evaluation of the dynamic response in service or under seismic actions, and for the evaluation of possible changes in the structural behavior as a result of degradation of the elastomeric bearings. An identification procedure based on experimental data and analytical models of increasing complexity is proposed to estimate the stiffness of the isolation devices and, ultimately, to determine an accurate numerical model of the bridge.

1. Introduction

In recent years base isolation has become an increasingly applied structural design technique to protect bridges from severe earthquakes. Main goal of base isolation is to produce a substantial decoupling of the superstructure from the substructure resting on the shaking ground, minimizing the internal state of stress during an earthquake by increasing the period of the structure and by acting as energy dissipation device [1]. This structural solution also has the benefit of giving better distribution of the seismic forces between the various elevation supports elements.

The use of base isolation techniques was initially confined to large bridges. However, as a result of the imposition of more severe national seismic codes and of refined seismic zoning, in several countries, such as in Italy, base isolation solution has been applied recently even to small and medium-size bridges. In this paper we present and discuss the results of an experimental/analytical study of the dynamic behavior of a reinforced concrete post-tensioned bridge, having two spans of 37.50 m each, with a single continuous deck supported on six elastomeric isolators. The bridge was built in the Municipality of Dogna, in an area of the Friuli Venezia Giulia Region (Northern Italy) having high level of seismic activity (Richter magnitude around 6.5, corresponding to a peak ground acceleration $a_g = 0.35$ g). The infrastructure replaces an existing bridge positioned about 100 m upstream that was found to be hydraulically as well as structurally deficient during the exceptional flood of August 2003. As part of the works to restore the river's hydraulic regime, the new bridge reduces occupation of the river bed owing to a structure having a single pier located in an area where the river was widest. The positioning in the mountain environment required a slender and low-impact structural solution, coupled with an adequate seismic resistance. A preliminary analysis showed that the construction of a traditional bridge having fixed or unidirectional bearings on abutments and on the pier would have resulted in high state of stress and insurmountable execution cost. Therefore, the designers opted for the construction of a base-isolated bridge [2].

In May 2007 the bridge underwent an extensive series of harmonic forced-vibration tests with low levels of excitation for determining the dynamic characteristics of the lower vibration modes.

One of the purposes of the investigation was to verify the reliability of numerical models to describe the measured dynamic behavior of Dogna bridge. It is a well known fact that dynamic data (namely, natural frequencies, mode shapes, and damping factors) can provide meaningful results if they are used to improve a finite element model of the bridge, enabling, for example, to estimate mechanical properties of the materials and description of boundary conditions, see, for example, [3–11]. In the past decade, there have been several experimental research papers regarding the dynamic behavior of isolated bridges. In [12] the authors proposed a system identification method based on strong motion records for the determination, first, of bridge-pier-pile-foundation system

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Notation

A	area of the pier cross-section
$A_{kl}^{(r)}$	residual term between nodes k and l, for mode r
$\mathbf{C}$	global damping matrix
E_c	Young's modulus of the concrete
$\mathbf{f}$	forcing or input vector
G_x, G_y	shear moduli of seismic isolator
h	thickness of the seismic isolator
H	pier height
$H_{kl}(\omega)$	frequency response function between excitation point l and measured point k
I	moment of inertia of the cross-section of the deck
I_x	moment of inertia of the cross-section of the pier
J	error function
K_a	shearing elastic stiffness of the two seismic isolators on the abutment
$K_x,\ K_y,\ K_z$	shearing elastic stiffness of seismic isolators in transverse, longitudinal and vertical direction, respectively
$K_x^{pier},\ K_y^{pier}$	elastic stiffness of the pier in transverse and longitudinal direction, respectively
K_φ	rotational elastic stiffness of seismic isolators in shell FE model
$\mathbf{K}$	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
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
γ	volume mass density
ω	frequency variable
ξ_r	rth damping factor
χ	shear factor
ν	Poisson coefficient

and, second, for the identification of structural parameters of two base-isolated bridges in Japan. In a subsequent paper [13], it was pointed out that structural details, such as the presence of transverse side-stoppers near the isolation bearings, can significantly alter the response of a bridge under earthquake. In [14,15], the results of a permanent monitoring system installed on several isolated bridges in Chile were presented and used to reconstruct the dynamic characteristics from ambient-traffic vibrations and seismic motions. Analytical models with different degrees of complexity were developed to reproduce the recorded dynamic response of the bridges. A dynamic identification of an isolated highway bridge in Turkey based on ambient vibration measurements was presented in [16].

Another important purpose of the present research was to define a baseline model of the bridge for future investigation of diagnostic character. This issue is of great importance for the company who manages the local highway network. In fact, a long-term plan of maintenance of the bridge cannot neglect possible changes of performances experienced by the bearing devices [17]. Even though their response characteristics variations have been the goal of research at material and device level, it is essential to develop procedures for monitoring the device functionality in service. In addition, it should be noticed that the periodic removal of isolators from bridge for a laboratory test campaign appears a not feasible approach, due to high economical impact, particularly since traffic interruption is required. There are other limitations of this approach due to need of quantifying the effects of possible degradation of the bearing device in terms of the impact on the overall structural behavior of the bridge. Therefore, a more reliable approach is to test periodically the response of the bridge with devices in service, to localize and quantify global response changes as generated by local degradation of conventional structural elements as well as by isolation devices. Most of the diagnostic methods for damage detection in bridges, in fact, are based on a comparison between the structural response of the actual – possibly damaged – state and that associate to a reference (say, undamaged) configuration of the bridge, see, for example, [18–25]. It follows that, in order to be able to give a proper interpretation of the damage-induced changes on the dynamic characteristics of the construction, it is crucial to have at disposal an accurate knowledge of the undamaged configuration of the bridge, and this was another important goal of the present study.

It can be seen from the above analysis of the literature that studies about dynamic testing, finite element analysis and structural identification of base isolated bridges of small and medium size dimensions are not numerous, in spite of their increasing use in several countries, such as Italy, with excellent results under strong seismic motions. In this paper, harmonically forced tests are performed and dynamic characteristics of the Dogna bridge are extracted via Experimental Modal Analysis techniques. An accurate finite element model of the bridge is created and finite element model updating is carried out to reduce the discrepancies between analytical and experimental dynamic characteristics. In particular, an analytical procedure based on mechanical models of increasing complexity and natural frequency data is developed and applied for estimating the stiffness of the isolators in small deformation regime. The accuracy of the finite element model has been also checked under high-level stress/deformation states corresponding to those induced under static truck load tests.

2. Description of the bridge

Dogna bridge is a continuous two span, two-lane solid slab post-tensioned reinforced concrete (RC) bridge. The main features and the basic dimensions of the structure are shown in Fig. 1.

Each of the two spans has a length of 37.5 m. A single pier is present at mid-span. The pier is a RC wall of 2.4 m thickness, 4.0 m depth, and about 10 m height. The abutments consist of vertical RC walls. At the inner support, the deck is continuous, and it is simply supported by two multi-directional cylindrical elastomeric bearings on each abutment and on the pier, see Fig. 2. The bearing is an elastomeric isolator of 1200 mm diameter, made up of alternating layers of steel laminates and hot-vulcanized rubber. This type of isolator, SI-N-1200/112, is produced by FIP Industriale. For large shear strain, i.e., $\gamma = 1$ (where γ is the ratio between the maximum displacement and the thickness of the specimen in a cyclic shear test at 0.5 Hz), "normal" compound is characterized by dynamic shear modulus $G_{din} = 0.8$ MPa and equivalent viscous damping coefficient $\xi = 10$–15%.

The soil profile consists of a uniform deposit of dense gravel of medium size, with small percentages of silt in the superficial layer. The foundation soil is classified as category B according to the Italian Seismic Code [26] (average shear-wave velocity $V_{s,30}$ between 0