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Response simulation of hybrid base isolation systems under earthquake excitation

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ABSTRACT

In the present work, we investigate the response of a hybrid base isolation system under earthquake excitation. The physical parameters of the hybrid base isolation system are identified from dynamic tests performed during a parallel project involving two residential buildings in the town of Solarino, Sicily, using the well-established optimization procedure ‘covariance matrix adaptation-evolution strategy’ as dynamic identification algorithm in the time domain. The base isolation system consists of high damping rubber bearings and low friction sliding bearings. Two separate models are employed for the numerical simulation of the high damping rubber bearing component, namely a bilinear system and a trilinear system, both in parallel with a linear viscous damper. In addition, a linear Coulomb friction model is used to describe the behavior of the low friction sliding bearing system. Analytical solutions are provided, in compact form, for all possible phases of motion of the hybrid base isolation system under earthquake excitation. A series of numerical simulations are carried out to highlight the behavior of the considered hybrid base isolation system under different excitation and site conditions.

1. Introduction

According to the literature, the use of base isolation was first recommended in 1909 and thereon it has gradually developed into a full-fledged industry for the seismic protection of infrastructure in earthquake prone regions [1]. At the turn of the century, two four-story reinforced concrete buildings were seismically retrofitted by hybrid base isolation systems (HBIS), in the small town of Solarino in eastern Sicily. The HBIS consists of 12 high damping rubber bearings (HDRB) and 13 low friction sliding bearings (LFSB). Hybrid base isolation systems have been used extensively in Japan [2] and continue to be used. Their popularity derives essentially from the low cost of LFSB compared to any type of rubber bearing carrying a similar weight. For this reason, small diameter LFSB are placed under central columns carrying heavy loads, while HDRB are placed under corner or perimeter columns usually carrying smaller loads [3]. The same philosophy was applied in the design of the isolation system of the Solarino buildings. The LFSB used in the Solarino project are of the classical polytetrafluoroethylene (PTFE)-(stainless-steel) flat-sliding-interface kind, used extensively and successfully in bridge supports all around the world. A new LFSB technology, also used in Japan for hybrid base isolation systems, incorporates the cross-linear bearings (CLB) manufactured by the THK corporation [4,5].

Descriptions of the Solarino buildings and of the retrofitting system may be found in [6,7]. Static and dynamic tests were performed on one of the two buildings and are described in [8]. The static tests were used for the identification of the static friction force and residual displacement after unloading. The dynamic tests were in the form of free vibration following static application and instantaneous release of an initial displacement close to the design one. Free vibration tests are appealing as they can be performed at any time during the life of a building and with moderate economic effort [9]. The model used to describe the HDRB system is either a bilinear system (BLS) or a trilinear system (TLS), in parallel with a linear viscous damper (LVD). The LFSB system is modeled by a linear Coulomb friction model (LCFM), of which the constant Coulomb friction model (CCFM) is a special case. Simulations using the BLS and the LCFM were performed in [10], using an analytical solution, and in [11] via a numerical procedure based on constrained optimization. The first objective of the present work is to identify the best models and best set of parameters for the description of the seismic behavior of HBIS from full scale free vibration tests as the ones performed on the Solarino building. The covariance matrix adaptation evolution strategy (CMA-ES), a powerful stochastic optimization method belonging to the class of evolutionary strategies (ES), is used as the core algorithm of the

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identification procedure [12]. The dynamic identification procedure is based on finding the set of model parameters that give the best match between the experimentally measured response and the response predicted by the models. The second objective of the present paper is to provide an analytical solution, not yet available in the literature, for the model including the TLS. This solution is developed for both free vibration and earthquake excitation. The final goal is to assess the performance of the identified Solarino buildings under earthquake excitations. A set of 27 normalized acceleration records are considered and the response under each record evaluated. The records that produce an unexpected response are singled out and their characteristics are investigated in an effort to explain the observed behavior. For a description of the acronyms used throughout the paper the reader is referred to Table 1.

2. Dynamic identification procedures for the Solarino HBIS

Several mechanical models, and various dynamic identification techniques, have been used in previous identification studies of the Solarino HBIS. In [13], the HDRB component of the isolation system was modeled by a linear spring in parallel with a viscous damper, while a CCFM was used to model the LFSD. The dynamic identification procedure was carried out in the frequency domain using the least squares method. Of course, a linear model is generally not appropriate to capture the behavior of a nonlinear system. Therefore, in following studies, more sophisticated models were considered and different identification procedures were implemented in the time domain.

In [9], the HDRB component of the HBIS was modeled by a bilinear system and the LFSD component by a constant Coulomb friction model. As in the previous study, the least squares method was again used as the dynamic identification technique. While on one hand the results showed that the mechanical models used were quite reliable, on the other hand they pointed out plenty room for improvement both in terms of modeling and identification techniques.

In following identification studies of the Solarino HBIS, attention was given to evolution strategies [14]. Several of these were tested on the problem at hand and the CMA-ES [15] turned out to be the most efficient, by several orders of magnitude, in terms of solution fitness. In [16], the CMA-ES was used in lieu of the least squares method as dynamic identification technique and a linear Coulomb friction model (LCFM) replaced the previously used CCFM. Improvement in the identified parameters of the single degree of freedom base isolation system was attributed mainly to the use of the CMA-ES but, to some degree, also to the LCFM.

In [17], a trilinear system was used to model the HDRB component of the Solarino HBIS. An even better match was obtained in this case between experimental and simulated response. Moreover, the slope of the force–displacement relationship of the HDRB component of the HBIS was seen to monotonically decrease with increasing displacement amplitudes. However, it was always positive at the displacement levels considered in the Solarino tests.

The most recent identification studies connected to the Solarino HBIS project involve the use of a fractional derivative Zener model connected in parallel with a LVD to model the HDRB component [18]. This work includes a comparative study of four models for the simulation of HDRB, namely a fractional derivative Zener model, a standard Zener model, a BLS and a TLS. The results obtained demonstrated that, although the fractional derivative Zener model is an improved version of Zener model, it is still not quite as accurate as either TLS or BLS models.

Table 1
Acronyms.

BLS	Bilinear system
CCFM	Constant Coulomb friction model
CLB	Cross-linear bearing
CMA-ES	Covariance matrix adaptation-evolution strategy
ES	Evolution strategy
HBIS	Hybrid base isolation system
HDRB	High damping rubber bearing
LCFM	Linear Coulomb friction model
LFSB	Low friction sliding bearing
LVD	Linear viscous damper
PTFE	Polytetrafluoroethylene
TLS	Trilinear system

3. Physical model description

As shown in Fig. 1(b), the physical model of the HBIS considered in the present paper is composed of three independent systems acting in parallel, namely (i) a trilinear/bilinear system, (ii) a linear viscous damper, modeling the HDRB isolators, an (iii) a linear Coulomb friction model describing the behavior of the LFSB isolators. The LVD also accounts for any additional energy dissipation not accounted for by the TLS and the LCFM, for instance energy dissipated in the superstructure. The parallel system just described is attached to the total mass of the building, resulting in a single degree of freedom system. The fact that such a system is suitable for the simulation of the dynamic behavior of base isolation systems is demonstrated in the literature [9,19].

A novelty in the present work is the introduction of a trilinear system to model the behavior of the HDRB. As shown in Fig. 2(a), the constitutive behavior of the TLS may be described by five parameters, namely (i) the elastic stiffness k_0, (ii) the first post-yielding stiffness k_1, (iii) the second post-yielding stiffness k_2, (iv) the second yielding displacement u_3, and (v) the force at zero displacement F_2 [17]. By setting $k_2 = k_1$, and realizing that u_3 is no

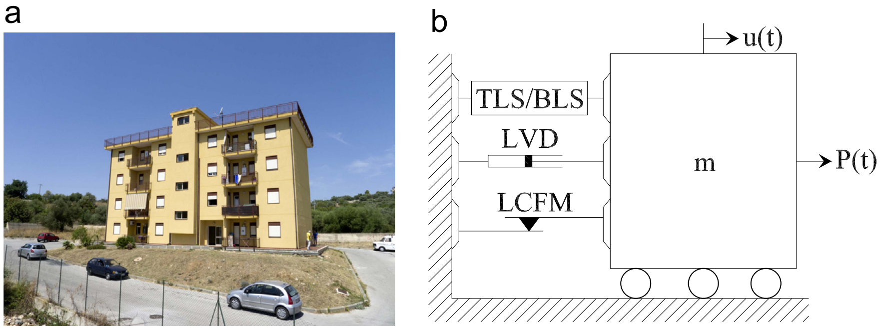

Fig. 1. (a) Solarino building and (b) single degree of freedom base isolation system.