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Combined primary–secondary system approach to the design of an equipment isolation system with High-Damping Rubber Bearings

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ABSTRACT

Isolating acceleration-sensitive equipment from the motion of the supporting structure represents an effective protection from earthquake damage. In this paper, a passive equipment isolation system composed of High-Damping Rubber Bearings (HDRB) is designed by adopting a coupled approach in which the supporting structure and the isolated equipment are considered as parts of a combined primary–secondary system and analyzed together. This allows for taking into account their dynamic interaction when significant and non-negligible according to the mass ratio and to the frequency ratio. The design methodology is developed by resorting to a reduced-order 2-DOF model of the combined system, a linear visco-elastic constitutive model of the isolation system and to a modal damping constraint depending upon the damping properties of the HDRB and their rubber compound. A 1:5 scale experimental model, consisting of a two-storey steel frame and a heavy block-type mass isolated from the second floor, is subsequently used to exemplify the design methodology and to perform shaking table tests. The dynamic properties of the experimental model are identified and the seismic performance of the equipment isolation system is discussed under a wide selection of seismic inputs, both artificial and natural.

1. Introduction

As recognized due to past and recent severe earthquakes (Northridge, 1994, USA; Kocaeli, 1999, Turkey; L'Aquila, 2009, Italy; Tohoku, 2011, Japan), nonstructural damage may result in serious threats to life safety and in major direct and indirect economic losses. In the worst case of critical facilities (hospitals, government buildings, nuclear power plants, etc.), the failure of equipment strongly impacts on the post-earthquake functionality, causing the loss of essential services or businesses, and may pose a catastrophic risk to the environment or to a large number of people [1].

In view of these considerations, current building codes in high seismicity countries (e.g., United States [2,3], New Zealand [4], Italy [5,6]) have devoted an increasing attention to the development of seismic design requirements, aiming at harmonizing the performance levels between structural and nonstructural components and particularly equipment. Intended to provide, in a form as simple as possible, conservative estimates of the seismic forces, such provisions adopt a static lateral force method that is easy to implement and sufficiently accurate for designing light ordinary equipment in

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ordinary buildings [7–9]. In the presence of heavy equipment or an increased hazard level, specific provisions are still missing and the innovative technologies for the vibration control are a feasible and workable means to preserve integrity and operational continuity [10].

Equipment is generally classified as acceleration-sensitive since prone to damage from inertial loading: correlated failure modes are of two sorts, depending either on the internal damage to vibration sensitive apparatus or on the breakage of restraints and service lines due to sliding/overturning [11]. An effective mitigation strategy consists in implementing an isolation system between the equipment to be protected and its supporting structure, according to one of the following configurations: the isolation of a single equipment item ("equipment isolation systems") [12–14], especially if heavy [15], or of an individual raised floor, on which a group of several items is anchored ("isolated raised-floor systems" or "floor isolation systems") [16–20]. As a result, the absolute accelerations transmitted to equipment are reduced and the damages due to inertial forces are prevented. A variety of passive, semi-active and hybrid isolation systems have been studied to this purpose. Passive systems have been proved to be effective and practical [17–19] although they may suffer from low-frequency resonances, leading to excessive isolator displacements, when subjected to high-amplitude long-period ground motions like near-fault earthquakes [12]. To overcome this drawback, semi-active isolation systems, given as the combination of passive isolators of sliding- or rolling-type with semi-active control devices of various sorts [13,14], have been investigated: while feasible and effective when their control loops are designed properly, semi-active and hybrid systems require, however, an integrated net of sensors and processors that make them more complex than passive systems. Recent studies are therefore seeking to improve the performance of passive systems by exploiting the adaptive behavior inherent in nonlinear isolators [20,21].

In the present paper, the authors deal with a passive equipment isolation system composed of High-Damping Rubber Bearings (HDRB) and develop a design methodology based on a coupled approach in which the supporting structure, or primary subsystem, and the isolated equipment, or secondary subsystem, are considered as parts of a combined primary–secondary system and analyzed together. This allows for taking into account their dynamic interaction, when expected to be significant and non-negligible according to the mass ratio and to the frequency ratio, and to monitor the effects produced on the structural response by the introduction of the equipment isolation system. The methodology is developed by resorting to a reduced-order 2-DOF model of the combined system, a linear visco-elastic constitutive model of the isolation system and to a modal damping constraint depending upon the damping properties of HDRB and their rubber compound. Ground acceleration is modeled as a Gaussian stochastic process with filtered white noise power spectral density.

To exemplify the design methodology by way of an application, a 1:5 scale experimental model, made of a two-storey steel frame and a mass representing a block-type equipment isolated from the second floor, is later considered. The isolated mass is assumed to be more than 1.5 times the structural mass, in order for the experimental study to investigate the dynamic behavior of heavy equipment mounted on light supporting frames, a configuration typically found in industrial plants [15]. Shaking table tests are carried out to identify the dynamic properties of the experimental model and to assess the seismic performance of the equipment isolation system under a wide selection of seismic inputs, both artificial and natural.

2. Modeling assumptions

A frame structure housing a single equipment is considered: in the uncontrolled configuration, the equipment is rigidly fixed to the attachment floor of the supporting structure (Fig. 1(a)); in the controlled configuration, the equipment is isolated from the attachment floor through a passive isolation system (Fig. 1(b)).

2.1. Supporting structure

The supporting structure is a moment-resisting frame with N storeys and satisfying the following assumptions: (a) regularity in plan and in elevation as to lateral stiffness and mass distribution, so that the dynamic analysis can be performed using a planar model and neglecting torsional effects; (b) columns are inextensible; (c) floors are taken as rigid in their own planes and masses are lumped in the center of gravity of each floor; (d) the structure is proportionally damped; (e) the structure is subjected to a single horizontal component of base motion; (f) the structure remains within the elastic limit during the base excitation.

2.2. Equipment

The class of block-type equipment, whose dynamic behavior is essentially the one of rigid body, is considered: a significant portion of mechanical, electrical and electronic items is here comprised, like emergency power electric generators, Uninterruptible Power Supply (UPS) systems, transformers and computer cabinets, to name a few. The following assumptions are made: (a) the equipment is floor-mounted with a single attachment point to the supporting structure; (b) the dynamic interaction between the isolated equipment and the supporting structure is assumed to be non-negligible; (c) among the possible response modes for floor-mounted block-type equipment [22,23], this study is focused on the sliding response and its related failures.