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Parametric study on acceleration-based design of low-rise base isolated systems

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ABSTRACT

The dynamic response of a series of base isolated systems subjected to ground motions that were recorded in firm soils of the Mexican Pacific Coast was estimated in order to evaluate the influence of the structural properties of these systems in their floor acceleration demands. While the super-structures were assumed to remain elastic and to exhibit 2% of critical damping, the isolation systems were assumed to exhibit linear behavior with viscous damping ranging from 10% to 30% of critical damping. The different damping levels assigned to the super-structures and isolation systems were taken into account through a non-classical damping approach. After identifying in general terms the structural properties of the systems that are able to better control their floor acceleration demands, it is concluded that flexible isolation systems with low levels of damping coupled with stiff super-structures result in substantial reductions of the participation of upper modes to the global dynamic response of isolated structures. Within this context, an equivalent single-degree-of-freedom system that can be used within an acceleration-based format to conceive base isolation systems is formulated, and implications for its practical use discussed.

1. Introduction

The excessive losses derived from the unsatisfactory seismic performance of buildings designed according to worldwide accepted standard practice has created discomfort in the community of structural engineering. This has gained particular importance since the unacceptably high material and socio-economic losses that have resulted from the excessive damage suffered by nonstructural systems and acceleration-sensitive contents during recent worldwide seismic events (Northridge 1994, Kobe 1995, Taiwan 1999, Sichuan 2008, Chile 2010). The level of loss has highlighted the need to: (A) establish design criteria distinct from that specified in current building codes; and (B) develop innovative design approaches that can explicitly control the level of damage and losses suffered by buildings that are built in high seismicity zones. In remarkable contrast with the past, the performance of modern buildings should transcend the prevention of catastrophic structural failure during severe seismic events, in such a manner that they satisfy the multiple and complex socio-economic needs of modern human societies. This implies that structural as well as nonstructural damage should be explicitly controlled.

The main objective of performance-based formats is to promote the design of earthquake-resistant structures that are able to control their dynamic response within thresholds associated to well-defined damage levels. Currently, the most used design response parameter to achieve adequate seismic performance is the maximum lateral displacement/drift demand [31,8,37,32]. Nevertheless, under some circumstances, there are other demands that should be controlled to achieve adequate overall seismic performance [48,45,9]. For instance, acceleration-sensitive contents in facilities that allocate museums, healthcare facilities and manufacturing facilities represent a large percentage of the cost of the building [36,46,30]. The nature of the dynamic response of some nonstructural components implies controlling their velocity and acceleration demands to reach an adequate seismic performance.

Villaverde [48] provides a detailed classification of equipment and nonstructural components, and offers an interesting discussion on the social and financial need to control their seismic damage. Within this context, equipment and nonstructural components can be defined as those *housed or attached to the floors, roof and walls of a building that are not part of the main or intended load-bearing structural system, but may also be subjected to large seismic forces and must depend on their own structural characteristics to resist these forces*.

Recent studies suggest that the estimation of acceleration demands for nonstructural components on fixed-based buildings depends on several variables, in such a manner that the formulation of rational design methods rapidly becomes too complicated

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for practical application. Among other things, acceleration demands depend on the: (A) type of structural system and the variation of its mass and structural properties along the height; (B) height of the building and location of the nonstructural component along the height; and (C) interaction that occurs between the dynamic and mechanic characteristics of the structural system and the frequency and energy content of the ground motion [27,19,48,9,30,41,11]. Within this context, current design approaches exhibit some shortcomings: (A) oversimplification and underestimation during the quantification of acceleration demands; and (B) the use of a design approach in which the nonstructural components are revised and their supports designed after the seismic design of the main lateral load carrying system is carried out. The supports and anchors of nonstructural components are designed so that they are able to withstand without collapse, toppling and shifting the acceleration demands imposed on them by the design ground motion [9]. Within this black-box approach, no effort is carried out to control the dynamic response of sensitive and valuable contents housed within some nonstructural components.

In highly refined facilities, such as hospitals and high-tech manufacturing facilities, a black-box design approach may easily result in loss of operation and unacceptable damage on sensitive equipment and contents, in such a manner that methodologies should be developed for the conception and preliminary design of structural systems that are capable of controlling the acceleration demands on the building. On one hand, a growing effort is being devoted to the analytical, field and experimental study of acceleration-sensitive nonstructural components [28,12,24,38,21]. This has led to the formulation of vulnerability functions and design recommendations aimed at establishing acceleration thresholds associated to various limit states of different type of nonstructural components.

Within performance-based seismic engineering, a natural complement for the formulation of design acceleration thresholds is the definition of a design methodology that allows the determination of structural properties for a building that are able to control its acceleration demands. An option to reduce acceleration demands on nonstructural components is to allow plastic behavior on the main structural system or to provide it with added viscous damping [44,2,30,49,35,26]. An efficient alternative in terms of acceleration reduction is to provide energy dissipation capability directly to the nonstructural component [1,23,49]. Nevertheless, in terms of effective and efficient overall acceleration control, there is ample analytical, experimental and field evidence that base isolation is the best option [22,10,28,14,47,29]. In spite of their potential for acceleration control, the design of the properties of base isolation systems and of their super-structures is usually based on strength or displacement-based formats [34,37]. Accelerations demands, if at all, are estimated as a byproduct of the design procedure, and this may lead to several design iterations when acceleration demands on nonstructural components need to be explicitly controlled.

Previous research has been aimed at characterizing the maximum absolute floor accelerations on base isolated super-structures [25,6,7]. Although these studies have concluded that floor accelerations can be significantly reduced through increasing the lateral stiffness of the super-structure relative to that of the base isolation system, there is still a need to directly quantify the acceleration demands at the content level, and to establish simple design methodologies that, according to the type of content and its socio-economic and cultural importance, can explicitly formulate a capacity–demand acceleration approach to damage control. Within one such methodology, the structural engineer needs to establish first, the design lateral absolute acceleration threshold at the floor level as a function of that allowed in the acceleration-sensitive contents; and second, design values for the global structural properties of the base-isolation system and its super-structure in such a way that the building is able to control its global an local dynamic response within such threshold. The methodology should also be simple and conceptually robust, in such a manner that the engineer can easily explore several design options and the use of different base isolation systems in the preliminary phases of a design project.

This paper evaluates the influence of the structural properties of elastic base isolated systems in the absolute floor acceleration demands and their respective floor spectra, and through the integration of the results that it presents, discusses the basis for an acceleration-based format for the conception and preliminary design of base isolation systems that are capable of controlling the acceleration demands at the content level. The paper focuses on elastic and viscously damped base isolation systems subjected to intense ground motions recorded at firm soil sites located in the Mexican Pacific Coast.

2. Dynamics of base-isolated systems

The base isolated systems under consideration contemplate an elastic super-structure consisting of a series of masses (one per story), connected through elastic shear springs that condense the lateral stiffness at the inter-story level. The values of lateral stiffness, reactive mass and damping were considered constant along the entire height of the super-structure. In this sense, the stick models represent low-rise structures with a lateral behavior dominated by global shear deformations in such a manner that they are not sensitive to overturning effects and the vertical component of the ground motion. While several authors have used similar considerations to model low-rise base isolated super-structures [25,6]; Alhan and Sürmeli [7] have shown the pertinence of using this type of model for elastic super-structures with linear base isolation systems.

For the isolation systems, an elastic model with viscous damping was considered. It should be mentioned that this type of modeling is appropriate for normal and high damping rubber bearing isolators, or rubber bearing isolators complemented with viscous damping devices [25,42,13]; and that current analysis tools provide reasonable modeling of the global and local dynamic behavior of actual base isolated structures [22,34,47].

The equation of motion for an isolated system, such as that shown schematically in Fig. 1, can be formulated as [34]:

$$M^* \ddot{v}^* + C^* \dot{v}^* + K^* v^* = -M^* r^* \ddot{u}_g \quad (1)$$

where M^*, C^* and K^* are the mass, damping and lateral stiffness matrices of the isolated system, respectively; v^* is an array of

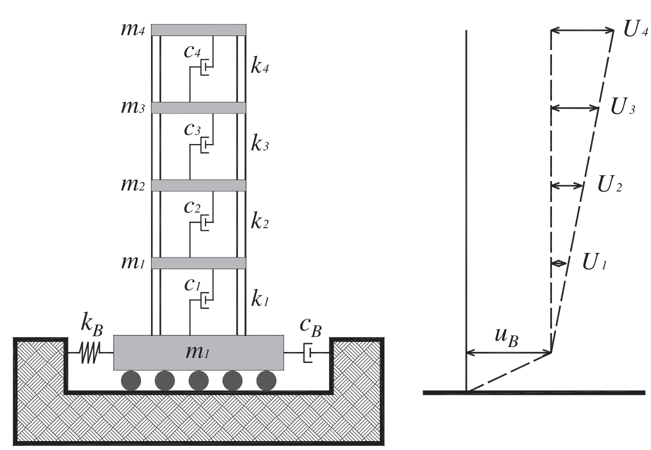

Fig. 1. Shear model of four-story structure with linear base isolation system.