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Improved response-spectrum analysis of base-isolated buildings: A substructure-based response spectrum method

D. De Domenico*, G. Falsone, G. Ricciardi

Department of Engineering, University of Messina, 98166 Messina, Italy

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ABSTRACT

Unsatisfactory numerical predictions may result from applying the classical modal analysis in conjunction with the response-spectrum-method (RSM) to nonclassically-damped systems such as base-isolated buildings. This inaccuracy is highlighted by comparing the conventional RSM outcomes with results from nonlinear time-history analyses consistent with that given spectrum. Indeed, some underlying assumptions of the conventional RSM are not really appropriate for base-isolated buildings, thus only approximate results are obtained, whereas either a complex-value modal analysis or the direct integration of the equations of motion should be undertaken to follow an exact approach to this problem. In an attempt to overcome the limitations of the conventional RSM as well as the mathematical difficulties and computational cost of the exact approach, in this paper an improved response-spectrum analysis procedure for base-isolated buildings is elaborated. Based upon the substructure approach, this procedure makes use of novel response spectra that quantify the effects of the base-isolation-system (BIS) to the superstructure while accounting for the dynamic interaction between BIS and superstructure. The developed procedure improves the conventional RSM in two aspects: (1) the seismic response of the base-isolated building is computed by applying the modal analysis to the superstructure only, which is typically considered as a classically damped system, rather than to the overall structure having nonclassical damping; (2) the BIS can potentially be modeled as a nonlinear subsystem with its actual hysteretic characteristics. The effectiveness of the proposed procedure and the improvements over the conventional RSM are scrutinized against time-history analyses with Monte Carlo simulated spectrum-compatible accelerograms.

1. Introduction

The strategy of seismic isolation has been increasingly adopted in earthquake-prone regions to mitigate or reduce damage potential due to the shaking ground [1,2]. Basically, some types of supports (typically, laminated rubber bearings or sliding elements) having low lateral stiffness and equipped with some inherent (viscous, hysteretic or frictional) damping mechanism are interposed between the superstructure and the foundation so as to decouple the building structure from the ground motion. The lengthening of the first-mode period combined with the damping features of the BIS, which provides additional energy dissipation, considerably reduce the earthquake-induced forces in the superstructure to such level that practically no damage will occur [3–5]. Consequently, the building can be designed to remain in the elastic range.

While in conventional structural analysis an equivalent viscous damping ratio $\zeta_s = 5\%$ is usually assumed, thus implying that some degree of structural and nonstructural damage will occur during a strong ground motion, the aforementioned reduction of the expected damage in the superstructure justifies the adoption of a lower value of the damping ratio, say $\zeta_s = 2\%$. On the other hand, the BIS generally possesses an equivalent viscous damping ratio of about $\zeta_b \approx 10$–40%. When the difference in damping between the two substructures attains such very high values, the equations of motion in the modal subspace are far from being uncoupled, which is due to the (non-negligible) off-diagonal terms of the damping matrix. Strictly speaking, the BI building is a *nonclassically damped system* [6], its natural modes of vibration are not real-valued, consequently a complex modal analysis should be undertaken to correctly assess the structural response (unless direct integration of the equations of motion in the nodal coordinates is performed). Nevertheless, in the framework of the response-spectrum analysis, the base-isolated structure is often treated as a classically damped system, i.e., with modal equations decoupled and the off-diagonal terms of the modal damping matrix ignored, at least to obtain some preliminary estimates of the structural response. In this paper we will refer to this approach as "*the conventional response-spectrum-method* (RSM)".

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* Corresponding author.
E-mail address: dario.dedomenico@unime.it (D. De Domenico).

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In the simplified, conventional RSM, neglecting the off-diagonal terms in the modal damping matrix may lead to wrong structural response evaluations, especially when the non-classical damping nature of the system is pronounced [7]. The modal equations may still be uncoupled, but in a complex (not real) subspace. Therefore, a more appropriate response-spectrum-analysis (RSA) procedure would require the solution of a complex eigenvalue problem that incorporates the damping matrix, thus implying a *complex mode superposition approach*, see the pioneering works [8,9] and the subsequent applications and enhanced variants proposed by researchers in the last few decades [10–16]. Of particular relevance to the present paper, this complex-mode procedure was used for the analysis of base-isolated structures [17,18]. It is worth noting that two response spectra are necessary to deal with nonclassically damped systems, as the seismic response of these systems depends not only on modal displacements (which requires the pseudo-acceleration response spectrum like in classically damped systems), but also on modal velocities (which needs an additional, relative velocity response spectrum [19,20], or the cosine spectrum [21], or again the more widely adopted pseudo-velocity response spectrum [22,23]), which further complicates the analysis. Additionally, besides being computationally more expensive, the complex modal analysis would make the engineer lose the physical insight and the intuitive grasp of the system's behavior. This is why in engineering practice a real-value RSA procedure for base-isolated buildings that is as simple as the conventional RSM but more accurate than this procedure would be highly desirable, at least to capture, in a simplified manner and under some reasonable assumptions, preliminary estimates of the system response, to be checked subsequently via more sophisticated nonlinear response history analysis (RHA).

In an attempt to overcome the limitations of the conventional RSM while at the same time preserving the simplicity and the attractive features of a real-value response-spectrum approach, the aim of this paper is to present an improved, real-value RSA procedure for base-isolated buildings. The key idea of the proposed procedure stems from the *substructure approach* wherein the primary system is the (linear) superstructure and the secondary system is the (potentially nonlinear) BIS. The two subsystems interact with each other due to the inertia forces of the BIS to the superstructure as well as the feedback of the superstructure to the BIS. Strictly speaking, such feedback would depend upon all the natural vibration modes of the superstructure, which characterize the actual nonclassical damping nature of the system. However, in most practical cases little error is made by truncating to the first mode, which is the main assumption made in the proposed procedure. In particular, from the overall set of *m* coupled modal equations (with *m* being a reasonable number of modes of vibration, up to a given cut-off frequency, that contribute to the structural response in a significant manner), a group of just *two equations* are extracted to characterize the first-mode response while accounting for the coupling terms between first mode and BIS but neglecting the higher-order-mode feedback contributions. In a similar fashion, a group of just *three equations* are extracted to evaluate the response of a generic higher-order mode of vibration, retaining the first-mode equation and BIS equation in addition to the jth modal equation of the analyzed modal oscillator. Substructuring the equations of motion suggests to denominate this procedure a "*substructure-based response-spectrum-method* (SB-RSM)".

For the practical application of the proposed SB-RSM, a family of novel response spectra are constructed by averaging the peak values of the response obtained via direct integration of the equations of motion, for given dynamic properties of BIS and superstructure. Once such novel response spectra are constructed, the remainder of the proposed RSA procedure turns out to be nothing but a conventional RSM applied to the fixed-base structure only. Indeed, the presence of the isolation system and the coupling effects due to the nonclassical damping nature of the system are *a priori* incorporated in the definition of the above response spectra and one can straightforwardly deal with the superstructure as a classically damped system. Therefore, conventional combination rules for classically damped systems may be adopted, see e.g. [24], thus avoiding the need of introducing *ad hoc* cross-correlation coefficients specifically developed for nonclassically damped systems, e.g. [19,25–27].

The novelty and main advantage of this procedure over both the conventional RSM and the complex-mode-superposition approach is that the nonclassical damping nature of the system is taken into account without the evaluation of complex eigenmodes, which is possible by resorting to a substructure approach. Two main differences as compared to the conventional RSM are recognized: (1) the substructure approach makes it possible to apply the classical modal analysis to the superstructure only, which is typically considered as a classically damped system, rather than to the overall structure having nonclassical damping; (2) while the superstructure can reasonably be modeled as a linear subsystem (owing to the reduction of the expected structural damage induced by the base isolation), linearizing the BIS behavior may or may not be acceptable in practice. We propose a formulation in which incorporating a nonlinear model of the BIS does not imply any extra computational cost as compared to the linearized behavior. Potentialities and limitations of the proposed SB-RSM procedure are scrutinized by a few simple numerical applications. Comparison with (averaged) results from nonlinear RHA with Monte Carlo simulated spectrum-compatible accelerograms has shown remarkable improvements of the proposed formulation over the conventional RSM, especially with increasing (nonclassical) coupling of the modal equations.

2. Conventional RSM for base-isolated buildings

Before proceeding with the formulation of the proposed RSA procedure, it is worth summarizing the basic steps of the conventional implementation of the RSM for base-isolated buildings. To this aim, first the equations of motion are briefly summarized and expressed in a format that will be useful for the next derivations, then the steps of the conventional RSM are carefully analyzed, underlining assumptions and limitations of this technique when applied to BI structures.

2.1. Equations of motion of a base-isolated building

Let us consider a planar *n*-story building as sketched in Fig. 1, which is base-isolated and subject to the horizontal ground acceleration $\ddot{u}_g(t)$. Following a typical approach to this problem, a preliminary *static condensation method* has already been applied to the structure in order to eliminate the (zero-mass) rotational degrees of freedom (DOFs). Consequently, with axial deformations in structural elements neglected, the mass of the *n*-story frame depicted in Fig. 1 is lumped at the floor level, with m_j denoting the mass at the *j*th floor associated with the *j*th translational DOF, while c_j and k_j denote the viscous damping coefficient and the condensed (lateral) stiffness term at the *j*th floor. As a result, the superstructure has *n* dynamic DOFs, represented by the displacements of the *n* stories relative to the BIS (cf. again Fig. 1) which are collected in the array $\mathbf{u}_s^T(t) = [u_1(t),u_2(t),...,u_n(t)]^T$. Note that the above assumptions do not necessarily imply that a one-bay shear frame is being analyzed since the rotational DOFs may be calculated once the translational u_j DOFs are determined. On the other hand, the BIS is represented by an additional single degree of freedom (SDOF) system (i.e., the displacement $u_b(t)$ relative to the ground) having mass m_b and interconnected to the superstructure. For the sake of generality and as better clarified in the following Section 3, two schematic models of the hysteretic BIS behavior are postulated in Fig. 1(a): (1) an equivalent linearized behavior, featured by a combination of a spring and a dashpot element whose stiffness and viscous damping coefficients are denoted as k_{eff} and c_{eff}, respectively (adopting a common terminology of most building codes [28,29], the subscript eff stands for an *effective* variable that is the linearized counterpart of an intrinsically nonlinear variable); (2) a more realistic rigid-plastic behavior, characterized by a