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A novel stochastic linearization framework for seismic demand estimation of hysteretic MDOF systems subject to linear response spectra

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ABSTRACT

This paper proposes a novel computationally economical stochastic dynamics framework to estimate the peak inelastic response of yielding structures modelled as nonlinear multi degree-of-freedom (DOF) systems subject to a given linear response spectrum defined for different damping ratios. This is accomplished without undertaking nonlinear response history analyses (RHA) or, to this effect, constructing an ensemble of spectrally matched seismic accelerograms. The proposed approach relies on statistical linearization and enforces pertinent statistical conditions to decompose the inelastic *d*-DOF system into *d* linear single DOF oscillators with effective linear properties (ELPs): natural frequency and damping ratio. Each such oscillator is subject to a different stationary random process compatible with the excitation response spectrum with damping ratio equal to the oscillator effective critical damping ratio. This equality is achieved through a small number of iterations to a pre-specified tolerance, while peak inelastic response estimates for all DOFs of interest are obtained by utilization of the excitation response spectrum in conjunction with the ELPs. The applicability of the proposed framework is numerically illustrated using a 3-storey Bouc-Wen hysteretic frame structure exposed to the Eurocode 8 elastic response spectrum. Nonlinear RHA involving a large ensemble of non-stationary Eurocode 8 spectrum compatible accelerograms is conducted to assess the accuracy of the proposed approach in a Monte Carlo-based context. The novel feature of iterative matching between the excitation response spectrum damping ratio and the ELP damping ratio enforces the required compatibility in the damping properties of the effective linear oscillators and the imposed elastic response spectra. It is found that this latter feature reduces drastically the error of the estimates (i.e., by an order of magnitude) obtained by a non-iterative application of the framework.

1. Introduction

Practical design and assessment of structures for earthquake resistance commonly involves defining the seismic action through uniform hazard spectra (UHS) derived from probabilistic seismic hazard analysis based on ground motion prediction equations for spectral acceleration [1]. UHS provide the peak seismic response of linear viscously damped single-degree-of-freedom (SDOF) oscillators having a pre-specified probability to be exceeded in a given time period as a function of the natural period, *T*. They are developed for a nominal critical viscous damping ratio ζ_o, usually taken equal to 5%, and are complemented by damping adjustment factors [2] which reduce linear spectral ordinates in case a higher damping level from the nominal one needs to be adopted. Still, the vast majority of (ordinary) structures are expected to yield under the design seismic action since seismic codes and National regulatory agencies allow for structures to resist severe earthquakes through ductile behavior to achieve cost-effective design for reduced strength [3]. In this setting, the problem of estimating the peak *inelastic* response (i.e., seismic demand) for structures modelled

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as multi-degree-of-freedom (MDOF) systems subject to smooth *linear* response UHS arises naturally in code-compliant seismic structural design and assessment.

For any particular structure, this problem can be addressed through nonlinear response history analyses (RHA) applied to pertinent inelastic MDOF finite element (FE) models for a number of seismic ground motion records (GMs), whose average response spectrum matches (i.e., is in close agreement with) the linear UHS within a certain range of natural periods centered at the fundamental structural natural period [4]. In this respect, putting the need for dependable inelastic FE modelling aside, code-compliant nonlinear RHA requires considering artificial UHS compatible accelerograms [5], and/or judicial GM selection from large databanks of recorded accelerograms which are further scaled/modified to match a given linear UHS [6]. Such steps necessitate specialized software, are subject to subjective preferences and experience, and are cumbersome for everyday seismic design (or assessment) of ordinary structures. Further, nonlinear RHA is computationally demanding itself, especially if a sufficiently large number of GMs are considered in the analysis to reduce the variability of peak inelastic response data observed [7] when only the minimum number of GMs allowed by current seismic codes (typically 7 pairs or less) is used [8].

In view of the above challenges, seismic codes and guidelines [9–12] favor the use of simplified methodologies for routine seismic design and assessment involving less demanding structural analysis steps compared to nonlinear RHA. In particular, the long-standing force-based seismic design methodology utilizes modal response spectrum-based analyses applied to linear MDOF FE models in conjunction with modal combination rules without requiring explicit structural seismic performance assessment [3]. Further, displacement-based seismic design and assessment methodologies supporting modern performance-based earthquake engineering utilize nonlinear static (pushover) analyses applied to MDOF FE models to derive detailed pushover curves. Structural capacity is then quantified through surrogate inelastic SDOF oscillators characterized by idealized backbone capacity curves fitted to the detailed pushover curves [13–16 and references therein]. In this context, design *seismic demand* is specified by *scaling the linear UHS ordinates* through modification factors derived by considering the peak seismic response of inelastic SDOF oscillators following idealized force-deformation hysteretic relationships, commonly following bilinear hardening backbone curves, to safeguard general applicability. Specifically, UHS ordinates are scaled by strength modification (or behavior) factors, *R*, in the traditional force-based design approach to derive constant-ductility inelastic spectra [17]. These spectra provide seismic design forces compatible with a pre-determined ductility μ (ratio of peak inelastic over yielding deformation) expected under the design seismic action. Initiated by the work of Veletsos and Newmark [18], *R* factors are specified through R-μ-T relationships (e.g., [19]) derived by application of nonlinear RHA to inelastic viscously damped SDOF oscillators with initial (pre-yield) natural period *T* and damping ratio ζ_o for large ensembles of judicially selected GMs [20]. Despite the availability of R-μ-T relationships for several different hysteretic force-deformation laws, codes of practice adopt *R* values pertaining to elastic perfectly-plastic SDOF oscillators known to yield conservative results for design purposes [21,22].

Moreover, in displacement-based seismic design and assessment UHS compatible inelastic seismic demand is obtained through scaling the UHS ordinates either by displacement modification factors [23], leading to constant-strength inelastic spectra, or by damping adjustment factors leading to heavily damped linear spectra [24,25]. Specifically, displacement modification factors are defined by the ratio of the peak response of an inelastic SDOF oscillator over the peak response of a linear SDOF oscillator under the same design seismic action, having common *T* (pre-yield for the inelastic) natural period and ζ_o damping ratio. These factors are determined either by "inverting" R-μ-T relationships or, directly, through application of RHA for large ensembles of GMs [26] commonly considering bilinear hysteretic SDOF oscillators [27] consistent with capacity curves obtained from pushover analyses of MDOF systems [16]. On the other hand, damping adjustment factors for inelastic seismic demand estimation are derived through linearization techniques seeking to determine an equivalent linear SDOF system (ELS) with effective linear properties (ELPs), natural period $T_{ef} > T$, (or, equivalently, natural frequency $\omega_{ef} = 2\pi/T_{ef}$), and damping ratio $\zeta_{ef} > \zeta_o$, such that its peak response under seismic excitation matches the peak response of an inelastic SDOF oscillator with pre-yield period *T* and damping ζ_o under the same excitation. Early linearization techniques assumed ductility-dependent secant stiffness at maximum displacement to define T_{ef} using the geometry of bilinear force-deformation loops reaching some ductility μ under harmonic excitation (e.g., [24,28]). Then, ductility-dependent ζ_{ef} is defined by enforcing equality criteria between the dissipated energy in the inelastic oscillator and in the ELS (e.g., [29 and references therein]). Nevertheless, secant stiffness-based linearization techniques were found to be deficient for displacement-based design and assessment (e.g., [14,30]). Therefore, numerous alternative linearization approaches yielding larger effective stiffness values from the secant stiffness have been developed for the task based on RHA of inelastic SDOF oscillators for large ensembles of recorded GMs (see e.g., [31,32,33 and references therein]). Some of these linearization approaches apply signal processing tools to the nonlinear response time-histories to define T_{ef} such as Fourier-based peak picking [34] and wavelet analysis [35], while others consider statistical fitting of heavily damped linear response spectra to inelastic spectra (e.g., [25,30,36–38]).

Recently, Giaralis and Spanos [39] established an alternative stochastic dynamics-based framework for code-compliant seismic demand estimation of bilinear hysteretic SDOF oscillators. The latter framework is considerably different from the previously reviewed approaches and does not require undertaking RHA. The steps of this framework, being of particular relevance to this paper, are delineated in Fig. 1(a). They comprise: (I) the derivation of a stationary power spectrum representing a time-limited stationary stochastic process compatible in the median sense with a given linear response spectrum (i.e., an UHS) for ζ_o damping, (II) the application of *statistical linearization* to obtain ELPs (i.e., ω_{ef} and ζ_{ef}) from a viscously damped bilinear SDOF oscillator with pre-yield natural period *T* and damping ζ_o excited by the previously derived power spectrum, and (III) the use of these ELPs in conjunction with the given UHS and damping adjustment factors to estimate the peak inelastic response of the nonlinear oscillator (i.e., inelastic seismic demand for the UHS) through heavily damped spectra. Giaralis and Spanos [39] used the early stochastic averaging technique due to Caughey [40] to derive ω_{ef} and ζ_{ef} whose applicability is limited to relatively mild levels of nonlinear response (see also [41]). Later, Spanos and Giaralis [42] incorporated higher-order statistical linearization techniques in the above framework along with a system order reduction step allowing for treating a wide range of hysteretic force-deformation relationships (e.g., [43]), while enhancing the accuracy of seismic demand estimates compared to nonlinear RHA for UHS compatible GMs.

The above review reveals that current approaches for code-compliant inelastic seismic demand estimation consistent with a linear response spectrum (e.g., a UHS) are solely applicable to idealized inelastic (mostly bilinear) SDOF oscillators. Properties of these oscillators are obtained from capacity curves derived through static inelastic analyses to MDOF structural models which do not account for dynamic energy-dissipation phenomena (i.e., viscous