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Intensity measures for the seismic response prediction of mid-rise buildings with hysteretic dampers

J. Donaire-Ávila[a], F. Mollaioli[b], A. Lucchini[b], A. Benavent-Climent[c,*]

[a] Department of Structural Mechanics and Hydraulic Engineering, University of Granada, Spain
[b] Department of Structural and Geotechnical Engineering, Sapienza University of Rome, Italy
[c] Department of Mechanical Engineering, ETSII, Polytechnic University of Madrid, Spain

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ABSTRACT

Dampers are energy-dissipating devices widely applied for new and existing structures in earthquake prone areas. Among the different types of devices, hysteretic dampers are particularly popular due to their simplicity, economy and low cost. Although many studies have focused on ordinary buildings for evaluating the predictive capability of the different intensity measures (IMs), those dedicated to structures with dampers are scarce. The objective of this paper is to evaluate the capability of the most commonly used IMs to predict the seismic response of frame structures with hysteretic dampers, having low-to-moderate height (less than about 12 stories) and low height-to-width aspect ratios (less than approximately 3). To this end, a 6-story reinforced concrete (RC) frame structure designed to fulfill the old Italian seismic codes was retrofitted with hysteretic dampers. The dampers were designed for two different scenarios depending on the distance to the fault (i.e. near and far field ground motions). Two sets of accelerograms, consisting of ordinary and pulse-like near-fault records, are used in the analyses. Modified versions of existing IMs are also proposed, with the intention of improving the correlations between the considered IMs and response quantities.

1. Introduction

In the conceptual framework introduced in Performance-Based Earthquake Engineering, PBEE [1], the characterization of strong ground motion by means of suitable intensity measures (IMs) is a crucial element in the analysis of seismic risk of structures. It is particularly important to define optimal IMs that are capable of describing the probability that a structure would exceed a given limit state, usually represented by an Engineering Demand Parameter (EDP), at a designated site [2,3].

In PBEE, the selection of an optimal IM—an intermediate variable between ground motion hazard and structural demand estimates—for representing ground motion uncertainty is clearly a key issue to be addressed. The use of a specific IM in seismic risk analysis should correspond to the local or global damage of a given structural system. The stronger the correlation between the predicted EDP and the adopted IM, the more precise the result of a probabilistic risk assessment. A number of concepts and quantities can be considered when appraising the suitability of an IM in representing the dominant features of ground shaking. Optimum intensity measures are therefore defined in terms of sufficiency, efficiency, scaling robustness, predictability (through a probabilistic seismic hazard analysis) and practicality [3–5]. The first two of these properties are of particular importance for the present study. Efficiency refers to the total variability of an EDP for a given IM. A highly efficient IM calls for fewer ground motions and numerical analyses to achieve a desired level of confidence in the EDP response. In turn, sufficiency describes the extent to which the IM is statistically independent of ground motion characteristics such as magnitude and distance; that is, sufficiency renders the structural demand measure regardless of the earthquake scenario. Hence, when using a sufficient IM, a comprehensive ground-motion record selection is not needed, though the same accuracy in seismic structural performance estimation is achieved. The two properties may be quantified via statistical analysis of the response of a structure for a given set of records.

Several alternative IMs and their predictive capability have been put forth and evaluated in previous research efforts. It was shown that the optimal IM to be used in the seismic response prediction depends, in general, on the specific type of structure considered, and on the specific response quantity of interest. For buildings, building aggregates and structures, some modifications of the Peak Ground Acceleration (PGA) and Spectral acceleration

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* Corresponding author. Tel.: +34 913 363135.
E-mail address: amadeo.benavent@upm.es (A. Benavent-Climent).

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at the fundamental period, $S_a(T_1)$, have been proposed [3,6,7]. The aim is twofold: to improve the predictive efficiency of the IM for every limit damage state of a given structure, while also accounting for IM computability through a ground-motion hazard analysis without any other prediction equation. Some studies show that good intensity measures can be derived from a vector-valued IM consisting of $S_a(T_1)$ and spectral values at other periods, and of $S_a(T_1)$ and ε (defined as the number of standard deviations by which $\ln S_a(T_1)$ diverges from its predicted mean value as obtained from a ground motion attenuation relationship) [8–10]. For regular structures and buildings where most of the mass participates in the first mode, spectral acceleration (S_a) and/or spectral displacement (S_d) may be the preferred IMs.

Moreover, previous research has demonstrated, that in some cases, $S_a(T_1)$ and related parameters may not be good predictors; spectrum-based scalar IMs (energy- and velocity-derived) are in general better correlated to different deformation EDPs, both for ordinary and pulse-like ground motions [11–13]. The good predictive capabilities of energy-based parameters are linked to the amplitude, frequency content and duration of the motion, as well as the properties of the structure. Energy input spectra can be used to develop IMs that would explicitly account for higher mode influence [8] and the elongation of periods of vibration caused by damage [14]. Recent studies focused on ground motion prediction equations use input energy equivalent velocities [15–17] to overcome the problem of IM computability in ground-motion hazard analysis.

When designing earthquake-resistant structures [18,19], the energy input in its relative (E_{Ir}) or absolute form (E_{Ia})—or the respective equivalent velocity form, V_{EIr} or V_{EIa}— would be the reference IMs used to obtain EDP values. For practical purposes, the energy that contributes to damage [19], expressed by an equivalent velocity, V_D, is considered as the IM when designing structures with hysteretic dampers [18,20,21]. This IM takes into account only the energy dissipated by plastic deformations and the vibrational energy. It is usually obtained from empirical equations that provide the ratio V_D/V_{EIr} [22–24].

The present study aims to shed new light on some still unclear aspects of IMs and the seismic response prediction of frame structures with hysteretic dampers that have low-to-moderate height and low height-to-width aspect ratios. For this kind of structures, the contribution of vibration modes higher than the fundamental one, and the contribution of bending beam behavior are both negligible. To date, analyses have involved many different types of buildings [14,25,26], but only a few studies have focused on structures with hysteretic dampers [27–29]. In particular, the objectives set forth here were:

- To investigate the predictive capability of IMs with respect to EDPs related to damage in the hysteretic dampers (dissipated energy by plastic deformations), and more specifically to EDPs that can describe damage in the main frames of the building (maximum inter-story displacement, maximum chord rotation in beams and columns, maximum dissipated energy over all stories by plastic deformations or maximum floor acceleration).
- To evaluate the different predictive capability of the IMs when ordinary or pulse-like near-fault ground motions are applied to the RC frame structure with dampers.

To this end, the response of a building of moderate height and low aspect ratio, having two different hysteretic damper designs, was studied. First, the non-linear dynamic response of the two different structures with hysteretic dampers subjected to two different sets of ground motions (ordinary and pulse-like records) was analyzed. Scalar IMs often used to predict the response of fixed-base buildings were used, together with newly proposed ones. Because of the substantial effort required for their assessment, vector IMs were not used. Spectral derived IMs based on energy concepts were evaluated only in the elastic range. Elastic input energy, and derived parameters, correlate well to the nonlinear response of MDOF structures [13,14]. Parameters based on the inelastic behavior of structures might improve the structural response prediction. However, as our focus was on the probabilistic seismic hazard and risk analyses of structures, using hysteretic-based parameters would have meant developing as many ground motion prediction equations (GMPEs) as the parameters used to characterize the hysteretic behavior of the structure and its particular hysteretic model. Moreover, input energy is held to be an effective tool in seismic design, as it is a very stable parameter that hardly depends on the hysteretic properties of the structure (e.g. see [30]).

2. Case studies

2.1. Studied buildings

The case studies involved a three-bay frame extracted from a 6-story reinforced concrete building with an aspect ratio of $21/18 \approx 1$, hereafter called the main structure (MS), retrofitted with hysteretic dampers. The dampers were installed in parallel at each story level with the MS, forming a “flexible-stiff mixed structure” [19]. The MS constitutes the flexible part and the hysteretic dampers form the stiff part. The MS, designed according to a past code DM 96 [31], is representative of existing ordinary buildings located in a zone of high seismicity (“zone 1” of DM 96 [31]). It is worth emphasizing that the bare frames (i.e. without dampers) were first designed using the old seismic code DM’96, and then this frame underwent seismic upgrading with hysteretic dampers to withstand three levels of seismic hazard associated with earthquakes of moment magnitude ranging between 4.2 and 7.1. A representation of the 6-story reinforced concrete frame with the hysteretic dampers is depicted in Fig. 1, which includes column sections (CS) and beam sections (BS). All the columns of the frame have the same section dimensions. Moreover, all the columns of each story have the same reinforcement. The beams

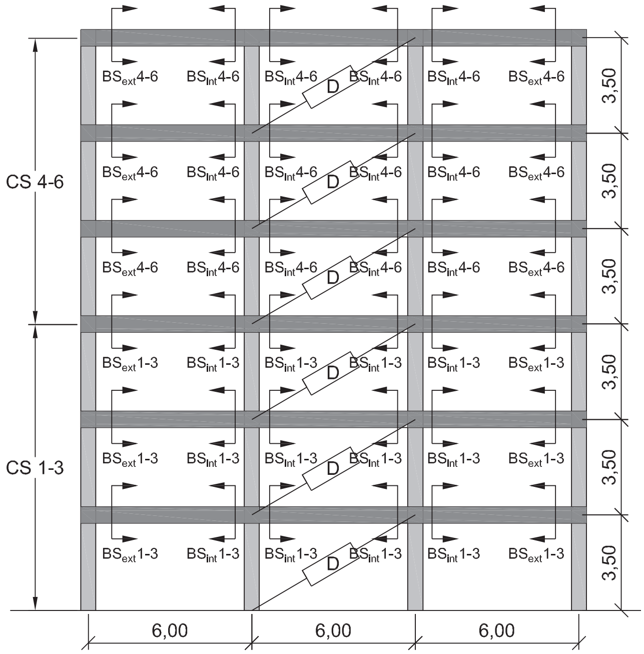

Fig. 1. Schematic representation of the frame structure with hysteretic dampers.