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Effects of seismic sequences on structures with hysteretic or damped dissipative behaviour

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ABSTRACT

Repeated seismic events strongly affect the building capacity in earthquake-prone regions, as its resilience, intended as the capacity of a system to quickly revert to a fully operational state after a damage due to a significant event, depends on the ability to withstand cumulated damage. This paper investigates the effects of repeated seismic sequences on structures characterized by different hysteretic behaviour. To this aim, non-linear single-degree-of-freedom (SDOF) systems were subjected to ten recorded seismic sequences taken from literature. The elasto-plastic and pivot hysteresis rules were analysed first, considering both hardening and softening behaviour. From each analysis, the inelastic spectrum of the seismic sequence was computed for different ductility levels, and the ductility demand was calculated and compared with the values for an only seismic event. It was shown that the effect of seismic sequences is quite significant, and a reduction of the behaviour factor from 15% for bilinear with hardening and pivot hysteretic rules to 35% for elasto-plastic systems with high ductility should be adopted in design to increase the seismic resilience. The use of linear and non-linear viscous dampers was also analysed in SDOF systems subjected to seismic sequences, demonstrating the effectiveness of this mitigation measure. Nonlinear viscous dampers with an initial friction force were found to dramatically reduce the acceleration and displacement demand, although it cannot avoid residual displacements at the end of the seismic events, and can be recommended for structures with short vibration periods. Nonlinear and linear dampers have the advantage of allowing full recentring of the structure at the end of the seismic events, thus significantly improving resilience.

1. Introduction

The seismic design of a structure is usually performed for a given reference spectrum, which represents the effect of an expected earthquake ground motion on a single-degree-of-freedom (SDOF) system equivalent to a base-fixed structure. Such assumption, included in the most widespread design codes such as Eurocode 8 [1], does not account for the possibility of a main-shock/after-shock sequence.

Multiple earthquakes may occur in the same region and within short time due to the complexity of fault systems. The time span between subsequent earthquakes may not be sufficient to retrofit the damaged structure, leading to accumulation of inelastic deformation in the building. Such an accumulation of plastic deformation over time has to be taken into account in the seismic design of the structure.

Several papers on the effects of repeated ground motions on structures can be found in literature. One of earliest investigation on this topic was carried out by Mahin [2], who highlighted the influence of earthquake duration and aftershocks on structures that exhibit softening. Ascheim and Black [3] focused on the estimation of the maximum deformation demand on existing structures. A stiffness degrading single degree of freedom (SDOF) system was used to demonstrate that the effect of unloading and reloading stiffnesses at the cycles nearest the peak displacement are crucial when determining the inelastic spectrum for seismic sequences. Ibarra et al. [4] explored the influence of strength and stiffness deterioration of various hysteretic models, while the influence of strong motion duration was investigated in [5].

A subsequent investigation carried out by Amadio et al. [6] on non-linear elasto-plastic (EPP) SDOF systems showed that significant damage is accumulated in the system after each event during a seismic sequence. Such inelastic deformations were found to be even larger when considering a multi-degree-of-freedom (MDOF) structure, for

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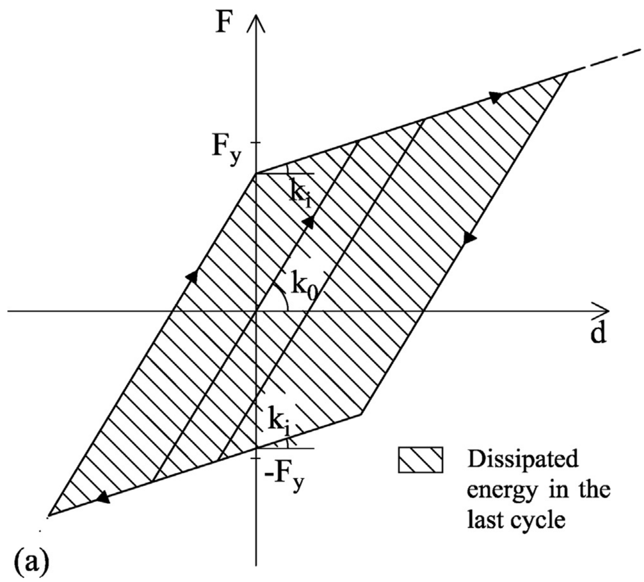

Fig. 1. Dissipated energy in the last cycle for elasto-plastic with hardening (a) and symmetric pivot hysteresis rule (b) used to characterize non-linear SDOF systems.

instance a moment-resisting steel frame as showed in [7]. Loulelis et al. [8] investigated steel frames too, using recorded seismic sequences and evidencing the variation in damage indexes and in ductility demand. Damage indexes were also used in [9] to probe the effects of structural pounding in repeated seismic events. Li et al. [10] studied the fragility of steel buildings when subjected to mainshock-aftershock sequences, finding a lesser seismic capacity at collapse. Another study carried out by Di Sarno [11] pointed out the need to account for the inelastic deformations accumulated in reinforced concrete (RC) structures during previous seismic events when developing design codes for structural assessment. Raghunandan et al. [12] referred the investigation on effects of aftershocks in RC structures to the US guidelines to classify damaged buildings. Moustafa and Takewaki studied the effects of the characteristics of recorded ground motions on structures through a damage index [13]. Hatzigeorgiou and Beskos [14] investigated the inelastic displacement ratios with multiple earthquakes, and concluded that the seismic displacement demand increases in an inelastic system subjected to repeated earthquake ground motions.

Two different design strategies are possible in earthquake-prone regions: (i) to accept a certain amount of structural damage after the design seismic event, or (ii) to equip the building with special devices such as dampers or isolators to either absorb part of earthquake input energy or to increase the natural vibration periods of the isolated structure in the spectrum region characterized by low accelerations. This last option is particularly suitable when the design seismic action is high, and the structure is rigid. Others strategies like rocking systems (characterized by a ring-shape hysteresis law) and self-centring isolation devices are also worth of attention.

A recent study conducted by Guo and Christopoulos [15] focused on a direct-performance based procedure to retrofit structures using supplemental dampers. The great interest for such solutions is justified by their cost-effectiveness, more evident in buildings with increasing number of floors [16]. A suitable alternative is represented by Buckling-Restrained Braces (BRB), well investigated by Di Sarno and Elnashai in [17]. Wanitkorkul and Filiatrault [18] studied the effects of passive supplemental damping in steel buildings, with the aim to ease the selection of the dampers, highlighting also the higher convenience in adopting a supplemental damping system instead of hysteretic damping. Kasai et al. [19] developed a comparison on the effectiveness of hysteretic and viscous-elastic systems. In such papers, however, the use of the dampers was aimed to a classic seismic design, with no consideration of seismic sequences. Finally, Zhai et al. [20–22] developed a series of interesting studies in damage levels and spectra, aftershocks effects and ductility demand on SDOF systems using a large number of sequences, categorized upon the aftershock intensity relatively to the mainshock.

In this paper, non-linear SDOF systems with Elasto-Plastic (EP) and modified pivot (PIV) hysteretic rules [23] are investigated under

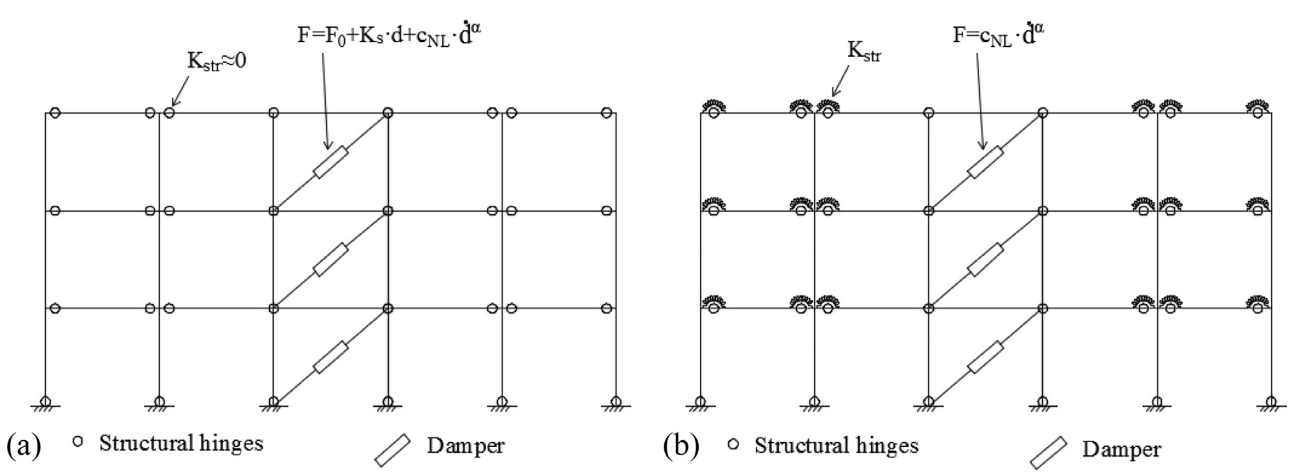

Fig. 2. Structures equipped with dampers: the restoring force can be provided by the dampers (a) or by the structure itself (b).

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