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Optimization of height-wise damper distributions considering practical design issues

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ABSTRACT

This paper discusses the optimal height-wise distribution of supplemental viscous dampers in multistorey building structures. Seismic excitation is modeled as stochastic stationary process and response statistics for linear structural systems are obtained through state-space analysis. For nonlinear damper applications statistical linearization is employed to accommodate a similar, state-space formulation. Emphasis is placed on three practical design issues: (i) realistic quantification of damper upfront cost based on damper force capacity rather than on the damping coefficient; (ii) investigation of bracing configuration schemes anchored at non-consecutive floor levels; and (iii) consideration of the cost of column strengthening required to accommodate the additional axial loads due to the supplemental damping system. Five different cost-based objective functions are defined to address these issues and the impact of each of them on the optimal damper distribution is examined in detail. Adjustments for estimation of peak responses when statistical linearization is used are also discussed. The optimal design problem considers the structural performance as a constraint, requiring that a target vibration suppression be achieved through the damper addition. An extension to a multi-objective design optimization is also discussed, incorporating the vibration suppression level as additional objective. The proposed approach is illustrated considering an actual Chilean 26-storey building subjected to an excitation compatible with the Chilean seismic hazard. Results show that damper distributions optimized considering realistic cost assessments are more efficient (with respect to cost-based design objectives) than distributions optimized considering simplified criteria. It is also demonstrated that consideration of practical issues such as column strengthening and feasible damper force capacity have a considerable influence on the optimal distribution. Finally, results also show that further cost reductions can be achieved with braces anchored at non-consecutive floor levels, and that such reductions are consistent with predictions given by approximate analytical expressions.

1. Introduction

An increasingly popular approach to attenuate the effects of large earthquakes on the built environment consists of equipping structures with passive energy dissipation devices. Among them, fluid viscous dampers are of special relevance; their proven efficacy and modeling simplicity make them an attractive seismic protection device for new and existing buildings [1–3]. The effectiveness of such dampers in reducing the seismic response of multistorey buildings is sensitive to their height-wise distribution [4,5], and a variety of optimization criteria have been proposed in the literature for choosing this distribution. A first group of distribution schemes, such as the uniform, the stiffness proportional, or the storey shear proportional [5,6], distribute the total damping coefficient (i.e., the sum of the damping coefficients of all dampers) according to pre-selected simplified criteria, with the total damping coefficient chosen so that a specific performance is achieved, for example a specific increase of the damping ratio in some chosen mode (typically the fundamental mode). Somewhat more sophisticated alternatives, still belonging to this group, are the storey shear strain energy distribution schemes [7], which have been shown to provide a good compromise between efficiency of damper application and implementation simplicity [6]. In a second group of distribution schemes dampers (representing a portion of the total damping coefficient) are sequentially placed at the location (i.e., storey) where the value of a specific performance index reaches a maximum. Examples are the Sequential Search Algorithm (SSA) [8], the Simplified Sequential Search

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Algorithm [9] and the Energy-Based Sequential Algorithm [10], with performance indexes given by interstorey drift, interstorey velocity, and dissipation rate of elastic strain energy, respectively. Finally, a third group of distribution schemes establish a formal optimization procedure based on some chosen performance objectives, incorporated into the optimal design through proper selection of the objective and constraint functions. For instance, Takewaki [11] derived optimality criteria and proposed an optimization scheme that minimizes the sum of the amplitudes of transfer functions at the undamped fundamental natural frequency. Singh and Moreschi [4] used genetic algorithms to reduce the root mean square response of base shear and floor accelerations. Lavan and Levy [12] proposed an equivalent problem approach to minimize the total damping coefficient needed to keep interstorey drifts within allowable levels and presented a gradient-based solution procedure for an ensemble of ground motions. Gidaris and Taflanidis [13] examined an optimization based on probabilistic life-cycle performance criteria. In the same study they also considered the minimization of the sum of root mean square responses of damper forces constraining interstorey drifts and floor accelerations to target performance levels.

A variety of different performance quantifications were adopted in the aforementioned studies. Performance is frequently described with respect to that of the uncontrolled structure [14,15], i.e., targeting a specific improvement, though frameworks that evaluate globally the favorability of the damper implementation also exist [13,16,17]. Simplified approaches adopt a modal analysis philosophy, emphasizing the damping ratio (or transfer function) at the fundamental mode. Other methodologies use time-history analysis and peak response quantities (interstorey drifts and absolute floor accelerations) to evaluate structural performance, the quantification of which ranges from simple aggregation over an ensemble of ground motions representing future excitations [18] to comprehensive risk analysis through probabilistic frameworks [19] that might even include life-cycle performance considerations [13,20]. Between these two extremes in terms of complexity, i.e. simplified modal analysis and comprehensive time-history analysis, another wide range of approaches evaluate performance using random vibration theory, modeling the seismic excitation as a stationary stochastic process. In this case the response is typically quantified in terms of variance or root mean square (RMS) values, though more advanced quantifications such as first-passage probability have also been suggested [20,21]. In most of these investigations emphasis was placed on linear dampers, though studies that discuss nonlinear damper implementations also exist. When the latter are combined with a stochastic representation of the excitation, statistical linearization techniques are typically adopted [22,23] to simplify the evaluation of the response of interest.

This study investigates the optimal height-wise distribution of viscous dampers in multistorey structures emphasizing design considerations that are relevant in practical applications but have not been yet fully explored in past studies. While many of these considerations are of general relevance, focus is placed here on Chilean reinforced concrete multistorey buildings. Since intent is to address practical applications, a damper distribution approach appropriate for such a setting is adopted, avoiding unnecessary modeling complexity that might reduce the applicability, for example need to examine a small only number of devices [13] (i.e. have a small only number of design variables in the design optimization to accommodate for the complexity stemming from the adoption of complex models for describing structural performance). This is facilitated by modeling structural performance through stationary response statistics. Within this context, the main topics addressed are: the cost of the supplemental dampers, the bracing characteristics of the damping system, and the forces on structural members due to the supplemental damping system.

Regarding the first aforementioned topic, though the importance of explicitly incorporating the upfront damper cost has been demonstrated in studies relying on advanced numerical modeling of structural behavior [13,24,25], this cost is commonly ignored, or is only approximately addressed in simplified design frameworks like the one considered here. In these latter cases usually the total damping coefficient is considered as proxy for damper cost [4]. This proxy, though, does not adequately describe damper cost since the latter has a close connection to the damper force capacity [27].

In terms of bracing schemes, emphasis has been placed solely on configurations where bracing terminals are anchored at consecutive (i.e., adjacent) floor levels. Such approach might not be suitable, though, for stiff buildings where interstorey velocities might not be large enough for efficient energy dissipation through supplemental viscous dampers [28]. This is typically the case of Chilean residential buildings where the lateral force resisting system is made up of stiff reinforced concrete members. While studies have shown the efficacy of bracing schemes that amplify the interstorey displacement between adjacent floor levels [28], very few researches have examined in detail supplemental dampers attached to braces connecting non-consecutive (i.e., non-adjacent) floor levels. Among researchers that mention this issue, study [29] showed that, under the constraint of total supplemental damping (i.e., the sum of the damping coefficients), optimal distributions that include dampers attached to non-consecutive floor levels are more efficient (in terms of response reduction) than optimal distributions of dampers attached only to consecutive floor levels, but they did not provide a comprehensive theoretical framework for analysis/design. As such there is a need for a comprehensive evaluation/comparison of the benefits such a bracing scheme can provide. Such a comparison can provide a rational basis to choose a non-consecutive bracing scheme over a consecutive scheme in cases where such choice is possible (adoptions of non-consecutive bracing schemes are typically result of other constraints, not necessarily of a rational comparison between alternatives). It should be pointed out that existing implementations in Chilean residential and office RC buildings [30] indicate that application of non-consecutive bracing schemes, though not common, do not face insoluble architectural (or other) constraints.

Finally, the additional force demands imposed by supplemental devices on structural members have been widely discussed in the literature but are consistently ignored in height-wise damper optimization. Symans and Constantinou [31] showed that, despite the reduction of interstorey drifts and inelastic deformations, supplemental devices might induce significant axial forces in columns and introduce local failures (for example due to buckling). This issue is usually ignored in design when the supplemental dampers are viscous devices because their peak forces are presumably out of phase with the peak forces imposed by the seismic excitation (i.e., restoring forces related to displacement response). However, such assumption might not be entirely true because of damper nonlinearity, bracing flexibility, structure nonlinearity [32] and damper and/or bracing inclination [33], among other reasons. Moreover, even assuming that the out-of-phase idealization is true, force demands on structural members during the interim phase between force and displacement peaks might still be significant [34]. This issue is especially critical in high-rise buildings [32] where forces on the columns at the bottom of the building are large. Recent experimental studies [35,36] have validated some of these concerns, showing that steel moment resisting frames equipped with viscous dampers have a unique failure mode (different from the one of the bare frame) characterized by a soft storey mechanism where plastic hinges develop at the ends of columns due to the high axial force demands imposed by the supplemental dampers. Furthermore, axial forces on columns due to the addition of supplemental dampers were found to be a key issue in the seismic retrofit of tall buildings [37]. All these remarks indicate that the actual cost of a supplemental damping system should also include possible strengthening of structural members, especially columns. This issue was only partially addressed by Lavan [15], who proposed a formulation in which allowable stresses on structural members can be accounted for as an optimization constraint, but neither the minimization of stresses due to supplemental dampers