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Optimization of force-limiting seismic devices connecting structural subsystems

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ABSTRACT

This paper is focused on the optimum design of an original force-limiting floor anchorage system for the seismic protection of reinforced concrete (RC) dual wall-frame buildings. This protection strategy is based on the interposition of elasto-plastic links between two structural subsystems, namely the lateral force resisting system (LFRS) and the gravity load resisting system (GLRS). The most efficient configuration accounting for the optimal position and mechanical characteristics of the nonlinear devices is obtained numerically by means of a modified constrained differential evolution algorithm. A 12-storey prototype RC dual wall-frame building is considered to demonstrate the effectiveness of the seismic protection strategy.

1. Introduction

The protection of structures in earthquake-prone regions may require the installation of devices for the mitigation of the demand induced by seismic loads, such as active control systems [1], single or multiple passive tuned mass dampers [2–4] or base isolators [5,6]. Throughout the available technologies for seismic protection, passive devices are especially widespread because of their robustness, low manufacturing cost (compared to the cost of the whole building) and easy maintenance. The use of additional mechanical and/or hydro-mechanical devices often needs a design strategy capable of defining the optimal configuration that would ensure an adequate reduction of the seismic demand.

Among the existing strategies for seismic protection, the use of devices for connecting adjacent structures has been investigated in the past decades. In this regard, the use of viscous dampers between two neighboring floors is quite common [7], typically together with a linear spring within a Voigt- or Maxwell-type configuration [8,9]. Other studies consider nonlinear models, such as a friction model [10] or the Bouc–Wen model [11,12]. For what concerns the behavior of the coupled buildings, basically all studies assume shear-type linear elastic and viscously damped systems having one or multiple degrees-of-freedom [8–12]. Existing literature encompasses analytical or semi-analytical approaches as well as numerical procedures based on soft computing techniques. For instance, Zhu and Xu [9] presented closed formulations to estimate the optimal parameters of Maxwell model-defined fluid dampers connecting adjacent structures under white-noise ground excitation. The stochastic equivalent linearization technique was exploited in [13] and an energy performance index is determined by calculating the stochastic response of two interconnected structural systems. In this case, the optimal device is the one that corresponds to the maximum value of the computed performance index. Differently from rigorous analytical approaches, empirical design procedures based on the dynamic characteristics of the structure have the merit of allowing the design of seismic protection strategies by employing a lower computational effort, see for instance [14] for an application to the optimal placement of controllers. On the other hand, multi-objective optimization problems were proposed in [15,16], and a genetic algorithm was considered to find the Pareto optimal solutions. Both studies considered linear elastic shear-type protected systems. Particularly, Uz and Hadi [16] studied the simultaneous minimization of two objective functions, i.e. the maximum relative displacement between two successive floors and the total number of semi-active magnetorheological dampers.

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The dampers were modeled using the Bouc–Wen model and the motion equation was linearized in a stochastic sense. Pareto optimal solutions were calculated via genetic algorithm for two different earthquake records.

The passive seismic protection strategy investigated in this paper is based on the use of energy dissipation devices (nonlinear connectors) to be placed between the lateral force resisting system (LFRS) and the gravity load resisting system (GLRS). This type of protection system is especially intended for mid-rise structures, such as conventional residential buildings, hospitals, schools, laboratories, institutions and commercial buildings. The devices are positioned with their vertical axis lying on the horizontal plane of the corresponding slab, to which they are connected at one edge. On the opposite side, they are fixed to the LFRS. Therefore, the force developed by the device acts on the same plane of the slab to which it is linked. The connection between GLRS and LFRS is initially elastic. Once a predefined horizontal force level is achieved – which could be either the static friction force for friction devices or the yield force for other elasto-plastic devices – the primary transfer mechanism is activated by experiencing a nonlinear behavior, thus starting to dissipate energy through the relative motion between GLRS (e.g., floors system and gravity columns) and LFRS (e.g., cores, shear walls, braced or moment resisting frames). This relative displacement of the floor is controlled and limited by the displacement capacity of the device. After an earthquake, only the connectors that suffered high deformations have to be replaced, without damages to the other structural members of the GLRS (which have to behave elastically under the design displacement of the seismic protection system). In this way, the permanent deformations of the building are removed and the system is brought to its initial configuration. The presence of these seismic devices uncouples the response of shear wall and floors system, and thus it enables the design of the GLRS by mainly referring to the gravity loads. Since the seismic forces carried by buildings originate mostly from the inertia of the floor system, a reduction of the accelerations transmitted between LFRS and GLRS leads to lower demands for the structural elements, thus mitigating structural and non-structural damages.

Indeed, the working principle of such protection system is similar to that exploited when coupling adjacent buildings, i.e. it makes use of the fact that dynamic responses of dissimilar systems are different under the same ground motion. Nonetheless, the seismic protection system here considered is somewhat different. Most important, in this study *two subsystems* of *one building* (namely, LFRS and GLRS) are connected each other, against the typical situation that occurs if *two adjacent buildings* are coupled, where *two systems* are connected. The considered seismic protection strategy is best suited for new buildings, even if it represents a feasible choice for the retrofitting of existing RC buildings. Concerning possible issues arising from the installation of the nonlinear connectors, practical problems will be certainly faced when placing these devices within the structural system of an existing RC building, whereas in new buildings the subsystems can be designed so as to best incorporate the connectors. On the other hand, the connection of two adjacent buildings may result quite problematic if they belong to different owners. Hence, eventual disputes are avoided when connecting structural subsystems, because the intervention concerns the same building.

Within this framework, the optimum design of elasto-plastic devices to be placed between GLRS and LFRS is hereafter investigated in order to demonstrate the effectiveness of the seismic protection strategy. Further aspects regarding different mechanical characteristics, improved nonlinear modeling, constructive and technological details of the connectors will be topics of future insights. Differently from the previous studies in similar research areas, this paper considers a realistic structural modeling for both subsystems, whereby the performance under seismic loads is evaluated through nonlinear dynamic analyses. Based on these assumptions, the resulting constrained seismic design optimization problem cannot be solved analytically and, as a consequence, a computer-aided procedure that exploits an advanced differential evolution algorithm has been implemented. The optimization strategy has been developed in `MATLAB` whereas the `OpenSees` platform has been used for nonlinear dynamic analysis. Results for a 12-storey prototype reinforced concrete (RC) dual wall-frame building are discussed at the end of the paper for demonstrating the effectiveness of such seismic protection strategy.

2. Optimum design problem

The seismic performance of the protected building depends on, both, mechanical properties and vertical distribution of the passive devices connecting LFRS and GLRS. Choosing optimal mechanical characteristics and position for such floor connectors is not a straightforward numerical task, as either favorable or unfavorable results can be achieved. The search for favorable links' configurations and properties is hereafter formulated as constrained single-objective optimization problem.

2.1. Formulation

The optimum design problem of this seismic protection strategy aims at minimizing a cost-based objective function under the condition that appropriate constraints (depending on the performance of the protected structural system) are satisfied. Therefore, it is mathematically formulated as single-objective constrained optimization problem:

$$\begin{aligned}&\min_{\mathbf{x}\in\mathcal{D}}\{f(\mathbf{x})\}\\&\quad s.t.\\&\quad g_a(\mathbf{x})\leqslant 0\end{aligned}\tag{1}$$

where $f(\mathbf{x})$ is the objective function, $\mathbf{x}$ is the design vector and $g_a(\mathbf{x})$ are constraints of the optimization problem (with $a = 1,\ldots,NC$). The design vector $\mathbf{x}$ is lower bounded by $\mathbf{x}^l$ and upper bounded by $\mathbf{x}^u$. These bounds define the hyper-rectangle $\mathcal{S}$, that is the total search space of the problem. The best design solution $\mathbf{x}^*$ is the global minimum of the objective function within the feasible domain $\mathcal{D}\subset\mathcal{S}$.

2.2. Design variables

Floor connectors are modeled as elastic-perfectly plastic springs with no supplemental damping. The vector $\mathbf{x}_i = \{x_{i1} \ \ldots \ x_{ij} \ \ldots \ x_{in}\}$ denotes the ith candidate design solution and it includes the stiffness value of each link, which is assumed as a continuous variable. For instance, x_{ij} is the ith candidate stiffness link value at the jth floor. The strength value of each link depends on the selected device, and it can be (linear or nonlinear) function of the stiffness. In doing so, the strength is not considered as a constant value because it depends on the corresponding optimal stiffness value. As the stiffness of the links are the independent design parameters of the optimization problem, the number of dimensions of the search space is restricted to the number of floor levels (whereas it doubles when considering the strength value of each link as an independent design parameter). Although every candidate design solution $\mathbf{x}_i$ is defined through n stiffness values, the building may not have all n possible floor connectors installed. The placement of a link is based on the corresponding design variable value by adapting an idea presented in [17] and recently implemented in [18] to look for the best seismic isolators