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Optimal design of nonlinear viscous dampers for frame structures

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ABSTRACT

It is well-known that in order to decrease displacements and accelerations in a frame structure during earthquakes, purely viscous dampers can be effectively employed, allowing for a remarkable dissipation of seismic input energy. The design of such devices, however, is still an open issue, since it is often carried out by means of inefficient trial-and-error procedures, or simplified analytical approaches which do not guarantee the optimal exploitation of the dampers. This work investigates the use of an optimisation-based approach for the design of nonlinear purely viscous dampers, aimed at improving the seismic behaviour of frame structures. The potential and the flexibility of the method are shown through an illustrative example displaying how different structural requirements (limitation or minimisation of inter-storey drifts and/or forces transferred by the devices) can be easily taken into account by means of a suitable formulation of a constrained optimisation problem.

1. Introduction

Purely viscous dampers are devices that can be used in bracing systems to dissipate large part of input seismic energy [1,2]. They consist of a cylinder, filled with a silicone fluid inside which a piston slides, allowing the device to produce a force $F = c{\cdot}sign(\dot{u}){\cdot}|\dot{u}|^{\alpha}$, where c is the damping constant characteristic of the device, $\dot{u}$ is the velocity between the two device ends and α is an exponent typical of the device type.

Optimisation of linear viscous damper systems (i.e. $\alpha = 1$) has been widely studied in the literature (see for instance [3–5]). In comparison, nonlinear devices have been investigated in less works, due to inherent difficulties in the analytical formulation. In [6], a simplified procedure for damper design aimed at a given target in terms of displacement reduction factor was developed. Reference [7] proposes a practical method for optimum design of non-linear oil dampers with relief mechanism. A comprehensive probabilistic design methodology considering life-cycle cost criteria together with uncertainty in structural response and earthquake loading is proposed in [8].

Most of these methods rely on simplified assumptions that may limit their use, i.e. very specific objectives, reduction of the structure to simpler SDOF systems, linearization of damper behaviour, limitation of design variables. However, any designer knows that objectives and constraints are often given by the specific problem at hand, and thus a flexible procedure which can be adapted to the case under study may be more desirable than more efficient yet problem-dependent methodologies. In this work, an optimisation-based approach to the design of nonlinear viscous dampers for seismic retrofitting of frame structures is investigated. Different objectives and constraints are proposed to show the flexibility of the methodology, and comparisons with state-of-the-art methods of the literature are provided.

2. Design of nonlinear dampers

A general approach to the design of nonlinear dampers, overcoming the difficulties given by the strong nonlinearity of the equations of motion, can be based on mathematical optimisation. According to this approach, an objective function $\omega(\boldsymbol{p})$ is minimised, with $\boldsymbol{p}$ design variables, under n inequality constraints g_i, and m equality constraints h_j. To solve the problem, in the scientific literature metaheuristic methods have proved effective when traditional methods as Simplex or Karush – Kuhn – Tucker theorem are not applicable. Among them, Genetic Algorithms (GA) [9] are well-established in the technical literature and have been used in this work. They are mathematical models based on the analogy with natural evolutionary processes, and operate on a population of design alternatives (individuals), initially dispersed in the parameter space. During the evolution, due to specific GA operators as selection, crossover and mutation, the population improves its average fitness and converges towards the optimum. The process stops after a pre-fixed number of generations. The optimisation process was implemented in the software TOSCA (acronym for *Tool for Optimisation in Structural and Civil engineering Analyses*), developed at the University of Trieste [10].

The evaluation of the k-th individual entails the following steps:

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Table 1
Analysis performed.

Analysis	α	Number of device types	Objective	Constraint
1	0.3	6	$\sum_{i=1}^{6}(\eta_i(\boldsymbol{p})-\bar{\eta})^2$	–
2	0.15	6	$\sum_{i=1}^{6}(\eta_i(\boldsymbol{p})-\bar{\eta})^2$	–
3	0.15	2	$\sum_{i=1}^{6}(\eta_i(\boldsymbol{p})-\bar{\eta})^2$	–
4	0.15	2	$\sum_{i=1}^{6}(F_i(\boldsymbol{p}))^2$	$0.45\leq\eta_i(\boldsymbol{p})\leq 0.55$
5	0.15	2	$\sum_{i=1}^{6}\left(\frac{\delta_{ij}(\boldsymbol{p})}{h_i}-0.004\right)^2$	–

1. A finite element (FE) of the structure equipped with the damper system identified by $\boldsymbol{p}^k$ is generated within the FE code ABAQUS [11];
2. Nonlinear dynamic analyses of the structure under a pre-defined set of N ground motions are performed;
3. Relevant outputs of the analysis are extracted:
   – maximum interstorey drift for each ground motion j and each floor i, $\delta_{ij}(\boldsymbol{p}^k)$;
   – average drift for each floor $\delta_{i,avg}(\boldsymbol{p}^k)=\frac{1}{N}\sum_{j=1}^{N}\delta_{ij}(\boldsymbol{p}^k)$;
   – reduction factor for each floor $\eta_i(\boldsymbol{p}^k)=\frac{\delta_{i,avg}(\boldsymbol{p}^k)}{\delta_{i,avg}(\xi=0.05)}$ with respect to the bare frame (with inherent classical damping $\xi=0.05$);
   – maximum force F_i developed by the dampers at each floor.
4. The outputs are combined into the objective and the constraints.

The generality of the approach lies in the possibility of formulating the optimisation problem in several ways, depending on the objective functions and the constraints. Different possibilities are shown in the applicative example.

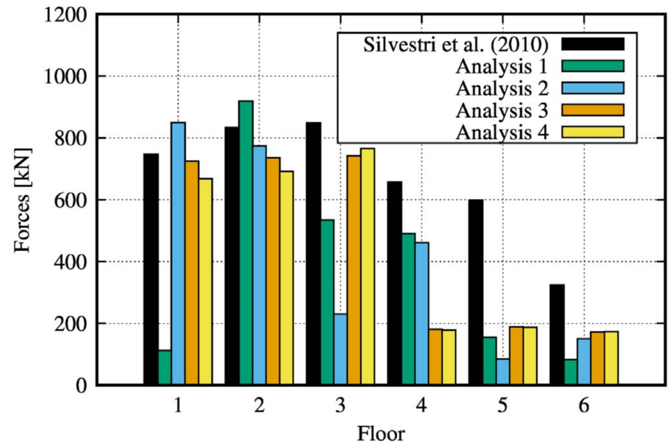

Fig. 2. Maximum forces transferred by the dampers.

3. Applicative example

3.1. Description of the structure

To assess the methodology, the example reported in [6] will be considered. The structure is a reinforced concrete (RC) frame consisting of 6 floors and 4 bays, with interstorey height 3.5 m and bay span 6 m. The beams have $40\times60\ \mathrm{cm}^2$ section, while the columns have square section with dimension equal to 60 cm for the first two floors, 50 cm for

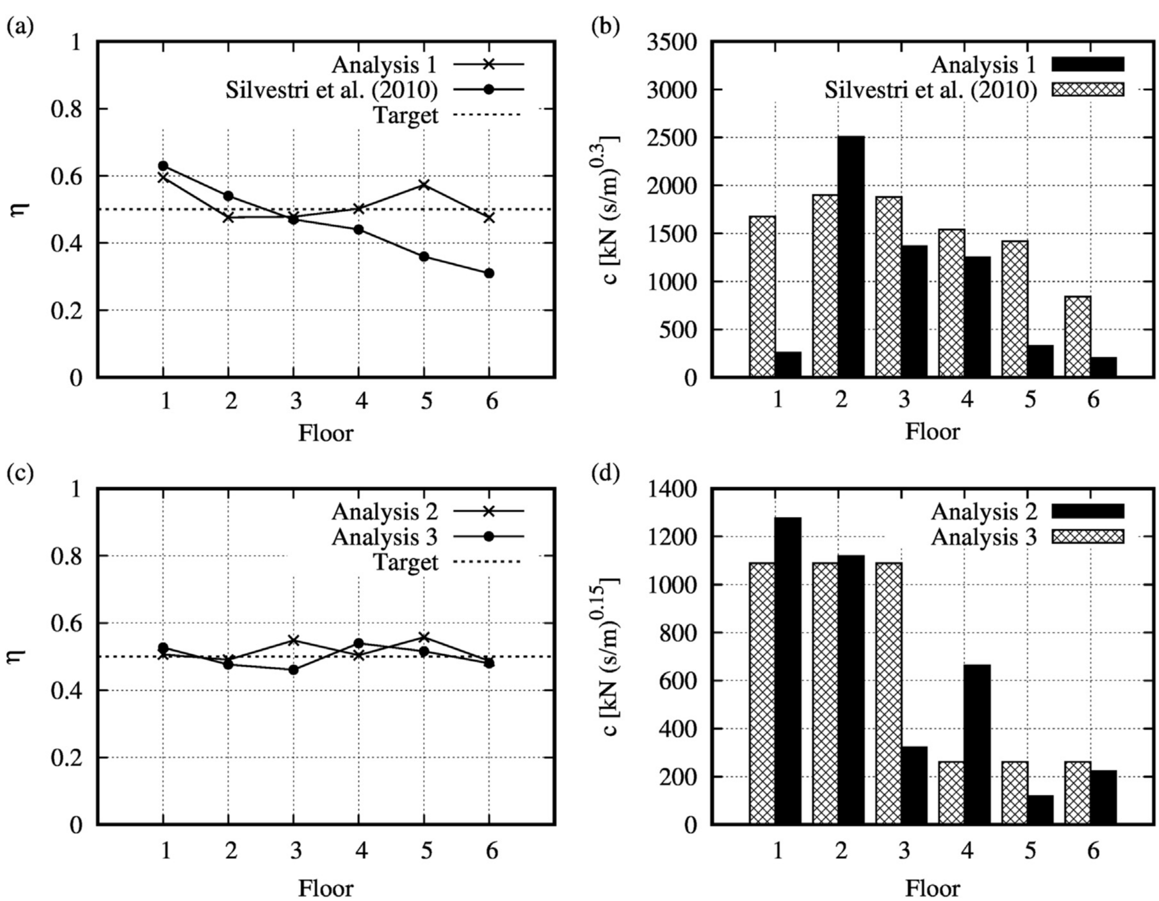

Fig. 1. Comparison between Analysis 1 and reference [6] in terms of: (a) reduction factor, and (b) damping constants; comparison between Analysis2 and 3 in terms of: (c) reduction factor, and (d) damping constants.