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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.

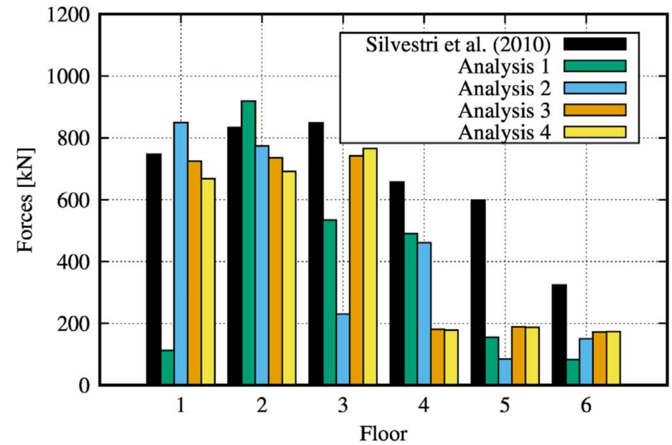

Fig. 2. Maximum forces transferred by the dampers.

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 40×60 cm^2 section, while the columns have square section with dimension equal to 60 cm for the first two floors, 50 cm for

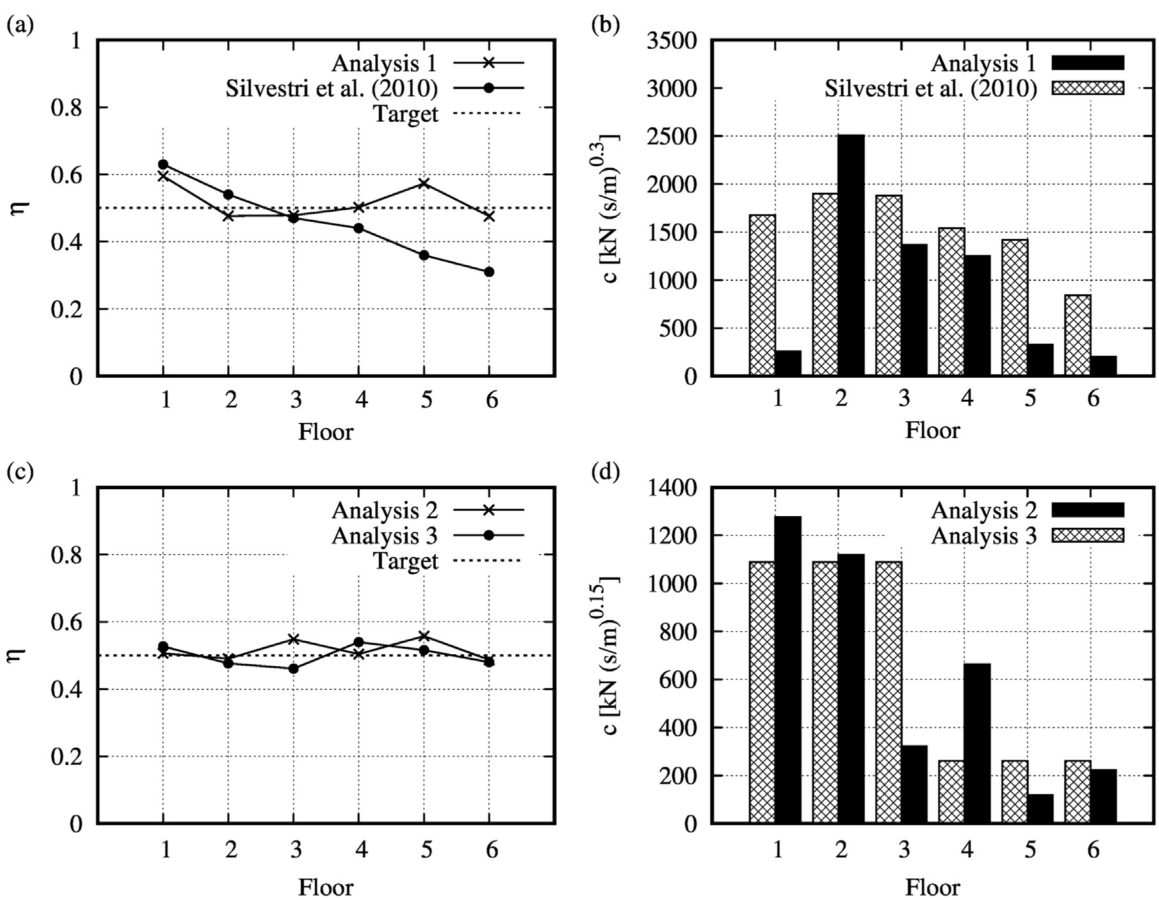

Fig. 1. Comparison between Analysis 1 and reference [6] in terms of: (a) reduction factor, and (b) damping constants; comparison between Analysis2 and 3 in terms of: (c) reduction factor, and (d) damping constants.

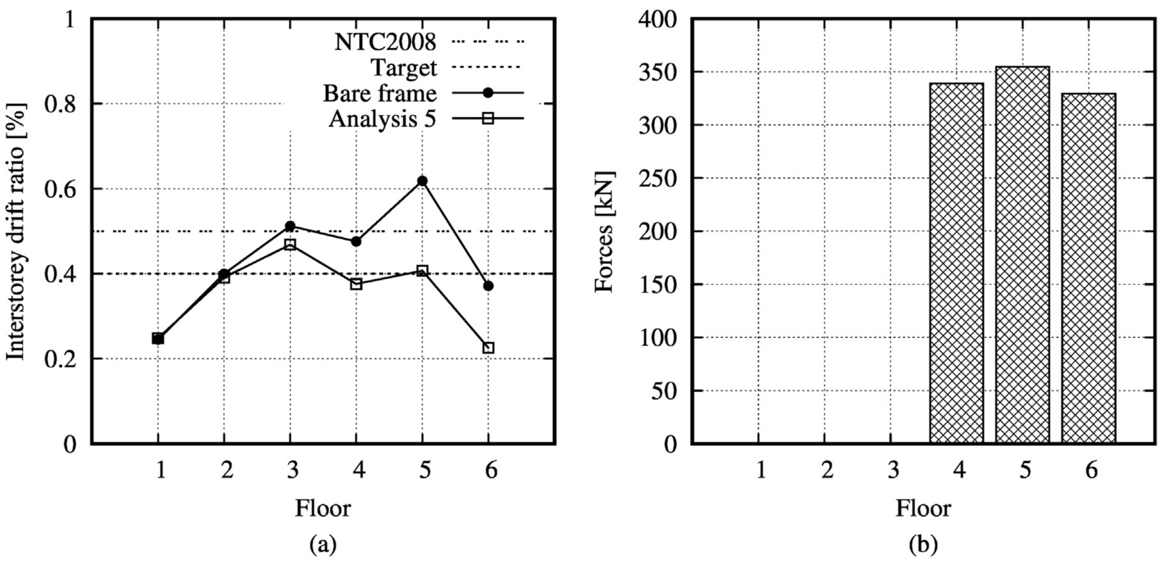

Fig. 3. Results of Analysis 4: (a) interstorey drift ratios, and (b) maximum forces in the dampers.

third and fourth floor, 40 cm for the last two floors. At each floor a mass equal to 130 t is applied in addition to the self-weight, evaluated from a density $\gamma = 25\,\text{kN/m}^3$. The Young modulus is assumed equal to $E_c = 3{\cdot}10^4\,\text{N/mm}^2$; the structure is fixed at the base. The dampers are placed at all floors at the second bay, in diagonal position.

The RC elements (beams and columns) are modelled in ABAQUS as isotropic elastic beam elements B32, having the mechanical properties of the gross section without considering the steel reinforcement. As the design of the dampers will be based on the control of damage limit state (DLS), a linearly elastic approximation can be accepted to model the structure. This is the same assumption utilised in [6]. More realistic nonlinear representations (as that based on the fibre approach studied in [12]) should be used in case of design for Near Collapse Limit State.

The concentrated mass at each node is added as *MASS element having mass proportional damping equal to 0.6142, corresponding to a 5% structural damping. Each mass accounts for the structural self-weight and the additional loads. The fundamental period of the structure, evaluated by means of modal analysis, is 1.023 s. Each viscous damper is represented by a DASHPOTA element with nonlinear behaviour defined in the input file by a force-velocity linear-wise law. This law is evaluated starting from the value assumed by the damping constant c and the exponent α.

For each of $N = 10$ natural ground motions, a direct-integration dynamic analyses (keyword *DYNAMIC) was performed. Hilber-Hughes-Taylor time integration, with parameters $\alpha = -0.05$, $\beta = 0.28$ and $\gamma = 0.55$ and automatic time increment was utilised [13]. The natural ground motions considered for the analyses are described in the reference [6], but not reported here for the sake of brevity. For more realistic design, ground motion selection could be based on matching design spectra prescribed by building codes.

3.2. Analyses

For the structure described at Section 3.1, five different analyses were carried out, differing from one another for the value assumed by the exponent α, the placement of the devices in height and the objective function. They are summarised in Table 1. Except for case 1 in which the exponent $\alpha = 0.3$ was considered for a direct comparison with [6], in all other cases it was set as $\alpha = 0.15$, as proposed for most devices in the market. The variation ranges for the damping constants c_i was set as $[0,\ 3000\ \text{kN(s/m)}^{\alpha}]$.

In analyses 1–3, the objective is to minimise the squared differences between the real reduction factors for each floor and the target $\overline{\eta} = 0.5$; analysis 4 has the objective of minimising the maximum forces transferred by the dampers, with the constraint of $\eta_i(\boldsymbol{p})$ being sufficiently close to the target; analysis 5 minimises the differences between the interstorey drifts and a limit (0.4%) slightly less than that imposed by the Italian standard NTC2008 [14] for RC buildings with partition walls rigidly connected to the structure (0.5%).

30 generations of 30 individuals, the first of which generated by the Sobol algorithm, were utilised in the search for the optimum. Stochastic Universal Sampling, with linear ranking and scaling pressure equal to 1.6 was used as selection operator, while Blend-α crossover with $\alpha = 2.0$ and probability equal to 0.85 and aleatory mutation with probability equal to 0.005 were responsible of the creation of the evolving populations.

3.3. Main results

In Fig. 1a-b, the results in terms of reduction factors and damping constants obtained in [6] and in Analysis 1 are compared. It can be seen that the optimised solution is much closer to the prefixed target $\overline{\eta} = 0.5$, especially when comparing the top floors. This is achieved by increasing the constant of one damper (at the second floor) and decreasing the others.

One of the strength points of the procedure is the possibility of embedding constraints which are usually encountered in practice. For instance, the coefficient $\alpha = 0.15$ is more common than 0.30 for the devices in the market [15], and it usual practice to use a limited number of damper types as the design and the production cost of six different dampers would be too high compared to the simplicity of the structure under study. Fig. 3c-d show the comparison between Analysis 2 and 3, which differ on the number of damper types only. It is noticeable that the level of fidelity to the target is very similar, and thus a procedure as that proposed herein may be effectively employed for the design of the damper setup even in presence of practical constraints.

When designing a damper system, it is important to limit the forces transferred to the existing structure, as too high actions may imply costly retrofitting interventions. This is the aim of Analysis 4, where the objective is the minimisation of the forces acting on the structure, while maintaining a reasonable adherence to the reduction factor target. In Fig. 2 the forces transferred by the devices are plotted. The results for analyses 3 and 4 are almost indistinguishable, with small differences at the lower floors, with analysis 3 giving smaller forces. At floors 2, 5, 6 the forces for analyses 2, 3 and 4 are comparable; conversely, at the first floor, the maximum force in analysis 2 is greater than that determined by using the procedure developed in [6]. The maximum differences are noticeable at the intermediate floors: while at floor 3 a clear reduction in force is attained in analysis 2, this does not happen at the floor 4, where it is much greater than that obtained when only two types of dampers are utilised.

Analysis 5 provided the following results in terms of damping constants: $c_1 = 0$ for the first three floors; and $c_2 = 434$ kN(s/m)$^{0.15}$ for the last three floors. The most interesting aspect emerging from the results of analysis 5 is related to the distribution of the dampers along the height: at the first three floors an optimal design would not require any viscous damper (null damping constants). This is due to the fact that in this floors the normative limitations for interstorey drift are mainly satisfied by the bare frame (Fig. 3a). The most important consequence deriving from this design is that while in previous cases the concentrated forces transmitted by the dampers could be significant (700–800 kN), in case 5 they are null, as no dampers are applied, and those at the last floors are rather limited (less than 400 kN, Fig. 3b).

4. Conclusions

In this work, a methodology for the design of nonlinear dampers for seismic retrofitting of existing frames or for newly designed structures is described. The procedure is based on an optimal-design paradigm, in which the best configuration for the dampers is sought by considering pre-defined objectives and constraints. The process is managed by an optimisation software utilising Genetic Algorithms. Through a simple example taken from the literature, it is showed how this type of approach based on the optimisation of the structural response has great potential and flexibility. In fact, it allows one to consider a wide range of possibilities both in the input variables (number and characteristics of the devices) and objectives (interstorey drifts, forces transmitted by the dampers, etc).

Future works will focus on the extension of the method to ULS design by means of more accurate representation of nonlinear behaviour of the RC members and to 3D structures and loadings. Multi-objective optimisation will also be investigated.

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