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Assessment of optimal design methods of viscous dampers

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Abstract

Viscous dampers are often used for seismic protection and performance enhancement of building frames. The optimal design of such devices requires the modelling and propagation of the uncertainties related to the earthquake hazard. Different approaches are available for the seismic input characterisation and for the probabilistic response evaluation.

This work analyzes the effect of different characterizations of the seismic input and of the response evaluation on the design of dampers for building frames. The seismic input is represented as a stochastic process and the optimal damper properties are found via a reliability-based design procedure aiming at controlling the frame performance while limiting the damper cost.

Two simplified approaches are used to design the viscous damper of a multi-storey steel frame and the design results are compared with those obtained by considering a rigorous design approach resorting to advanced simulations for the response assessment. The first methodology evaluates the response through a prefixed probabilistic demand model, while the second approach considers the average response for a given hazard level only. The comparison allows to evaluate and quantify the effect of the seismic input uncertainty treatment on the system and damper performances.

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Keywords: Viscous dampers; stochastic seismic input; earthquake hazard; structural optimisation

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1. Introduction

The modelling and propagation of the uncertainties related to the earthquake hazard is an important issue in the seismic assessment and design of structures. Different models are available for the seismic input characterisation and for the probabilistic response evaluation. The model choice might have a significant effect on the design of structural components.

Viscous dampers are passive control devices which have proven to allow reaching satisfactory levels of protection of structures under earthquake input [1,2]. Deterministic methodologies for the design of viscous dampers for a single seismic intensity level have already been proposed [3,4] but a robust optimal solution should involve reliability studies considering different intensity levels and their relevant occurrence probability [5].

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In [6] a reliability-based methodology has been proposed for the optimal design of viscous damper properties. The methodology is based on a stochastic representation of the seismic input and it aims at identifying the damper viscous constants that minimize the dampers cost (related to the sum of the damper forces) while limiting the probability of exceeding a prefixed inter-storey drift ratio for the frame. The probabilistic response assessement is based on Subset Simulation, which provides an efficient mean for estimating the stocastich quantities involved in the objective function and probabilistic constraint.

Although the proposed design methodology employs an efficient and advanced simulation method for the reliabilty analyses [7,8], it is computationally expensive and it cannot be employed for design practice. For this reason, in this paper two alternative approaches are proposed and analyzed, which permit to reduce the computational cost of the reliability analyses. The first approach involves a response probabilistic model, which is built via linear regressions [9]. The second approach considers a single level of the seismic hazard for the generation of a prefixed set of seismic inputs to consider during each optimisation loop.

The proposed design methodologies are embedded into the Matlab toolbox OpenCossan [10] , which is connected to the opensource software Opensees [11] for the dynamic analysis.

2. Problem definition

The optimal solution of the viscous dampers design problem is evaluated inside the domain of the feasible configurations that respect a specific constraint on the structural performances. In particular, the performance of the structural system is assumed to be controlled by the maximum inter-storey drift among the various storeys (δ), for which a maximum permissible level δ_{max} is given

The viscous dampers are described by the following constitutive law, providing a relation between the damper force f_d and the velocity at the dampers ends $\dot{u}$:

$$f_d(\dot{u}) = C_d|\dot{u}|^{\alpha} \cdot sign(\dot{u}) \tag{1}$$

where C_d represents the damping constant and α the damper exponent that controls the non-linearity of the damper response. Small values of α are preferable in order to reduce f_d for high intensity earthquakes [4].

The damping constants at the different building storeys, collected in the vector $\mathbf{x}$, are the design variables of the optimisation problem while α is kept constant during the optimisation process. The objective function $\phi(x)$ is estimated in different ways in relation to the specific methodology adopted, but it is always related to the sum of the damper forces θ.

3. Semplificated Approaches

The next two sections describe the two different design approaches proposed in this study. A full description of the reliability-based optimisation problem and of its solution based on Subset simulation is given in [6].

3.1. Linear fitting

This method simplifies the problem of the computation of the exceedance probabilities of δ and θ during the design life time T_L by employing a conditional IM-based approach [5] and by fixing a priori a probabilistic seismic demand model. The simplified probabilistic model proposed provides a description of the nonlinear relation between the response of the generic engineering demand parameter of interest EDP and the seismic intensity level IM [9] that in this study are assumed equal to the inter-storey drift and the spectral acceleration S_a respectively.

A pre-fixed set of 100 accelerograms of different intensity is generated from the stochastic earthquake model by using Latin Hypercube Sampling. A structural analysis is then performed for each record, thus obtaining a collection of responses forming a ”cloud” of EDP samples. A linear seismic demand model is then fitted in the bilogarithmic plane to express the relationship between the EDP values and the IM values. It is widely employed in seismic engineering for its simplicity and because it leads to a close form estimate of the seismic risk. This model has the form:

$$ln(EDP|IM = im) = ln(a) + bln(im) + \epsilon \tag{2}$$

where the values of a, b are derived by linear regression, and ϵ is the total error which is assumed to be normally distributed with zero mean and standard deviation β. The total error represents the lack of fit [9,12].
The probability distribution of $EDP|IM$ is Lognormal and the exceedance probability $P_{EDP}(edp|x)$ for a given set of damper design properties **x** can be evaluated via the closed-form expression as [13]:

$$P_{EDP,T_L}(edp|x) = 1 - exp(-\lambda \cdot P_{EDP}(edp|x) \cdot T_L) \tag{3}$$

where λ denotes the mean annual frequency of seismic events of any intensity and T_L is the design lifetime.
The objective function is defined in this method as the value of the sum of the damper forces θ such that the probability of exceedance is equal to a predefined level $\overline{P}$. The reliability constraint on the other hand ensures that the probability of the maximum inter-storey drift δ exceeds the limit δ_{max} does not exceed $\overline{P}$.

3.2. Single hazard level

This methodology is based on the same approach used in design codes, since the response in terms of δ and θ are evaluated by considering only a single seismic hazard level. In particular, assuming a target value of hazard equal to $\overline{P}$, the corresponding IM, denoted to as im^*, can be evaluated by solving the following equation:

$$P_{IM,T_L}(im) = 1 - exp(-\lambda \cdot P_{im} \cdot T_L) = \overline{P} \tag{4}$$

where P_{IM} represents the probability of exceedance of IM given a seismic event occurrence.
SubSet Simulation [7,8] can be employed to generate seismic records characterized by the intensity im^*. Structural analyses are then performed for the different records and the results in terms of δ and θ are averaged. At each iteration of the optimisation loop the same set of accelerograms can be used to evaluate the mean structural response. The objective function then corresponds to $\phi(x) = \overline{\xi}(x)$, i.e. the mean value of θ, whereas the constrain corresponds to having the mean $\overline{\delta}$ lower than the limit δ_{max}.

4. Case Study

4.1. Structural system

A 3-storey steel moment-resisting frame equipped with a viscous damper at each level has been considered for the structural analysis. It is a system already employed in several projects to study the performance of retrofit applications involving passive control systems. Some geometric and physical properties describing the system are shown in figure 1. Further information can be found in [14].

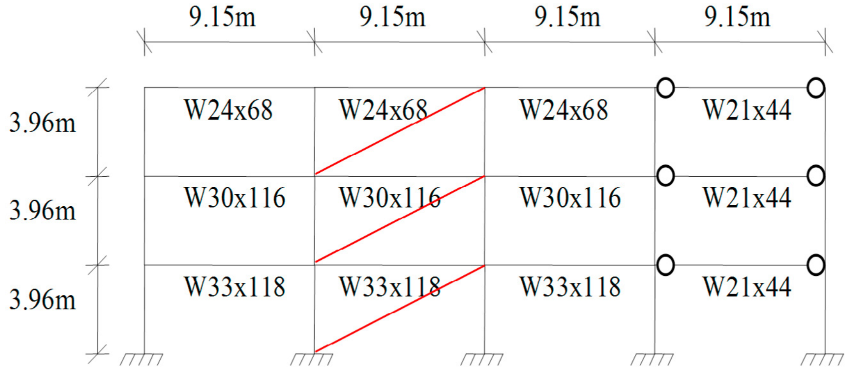

Fig. 1. Structural system considered for the case study

4.2. Stocastic earthquake model

A point-source stochastic ground motion model is employed to describe the seismic input. This model is defined by the moment magnitude M and source-to-site (hypocentral) distance R of the seismic source, together with the ground motion radiation spectrum $A(f; M, r)$ and the time envelope function $e(t; M, r)$.
The uncertainty of M is modelled by the truncated Gutenberg-Richter law, corresponding to the following probability density function (pdf) of M given an earthquake event:

$$p_M(m) = \frac{\beta e^{-\beta m}}{\beta e^{-\beta m_{min}} - \beta e^{-\beta m_{MAX}}} \qquad m \in [m_{min}, m_{MAX}] \tag{5}$$

where $\beta = ln(10)b$ is a parameter related to the number of the expected earthquakes per annum with magnitude exceeding m . More precisely, it is assumed that the occurrence of an event with $M > m$ is a Poisson process with exceedance frequency $\lambda(m) = 10^{a-bm}$ and no event is expected for $M > m_{MAX}$. It is also assumed that no significant response is observed for $M < m_{min}$. The corresponding mean annual frequency of a seismic event is $\lambda = \lambda_M(m_{min}) - \lambda_M(m_{MAX}) = 10^{a-bm_{min}} - 10^{a-bm_{max}}$. For the uncertainty in event location, earthquakes of magnitude between M_{min} and M_{max} are assumed to occur equally likely in a circular area of radius r_{max} centered at the site where the structure is situated. This leads to a triangular pdf for the epicentral distance R confined to the interval $[0, r_{max}]$:

$$f_R(r) = \begin{cases} 2r/r_{max}^2 & r \in [0, r_{max}] \\ 0 & otherwise \end{cases} \tag{6}$$

The procedure used to obtain simulated accelerograms starts from the modulation in the time domain of a white noise $w(t)$ through the function $e(t; M, r)$, i.e. $z(t) = w(t) \cdot e(t; M, r)$. The normilized Fourier transform $\bar{z(t)}$ is then multiplied by the ground motion radiation spectrum $A(f; M, r)$ and finally, the artificial accelerogram is provided by the inverse Fourier transform of $\bar{z(t)} \cdot A(f; M, r)$.

4.3. Results

This sections shows the results of the proposed design methodologies obtained by considering a target probability $\overline{P} = 10\%$ in the design life time T_L of 50 years. The viscous damping constants are assumed uniformly distributed at the various storeys, i.e., a scalar design variable C_d is considered.
Figure 2 reports the samples of the response in terms of maximum inter-storey drift and sum of the damper forces obtained thanks the first proposed approach for $C_d = 8000kN^\alpha s^\alpha/m^\alpha$ and $\alpha = 1$. In the same figure the fitted probabilistic demand model is reported. Figure 3 reports the corresponding estimates of the risk of exceedance of the maximum allowed inter-storey drift and the complementary comulative density function CCDF of the damper forces for the objective function evaluation.

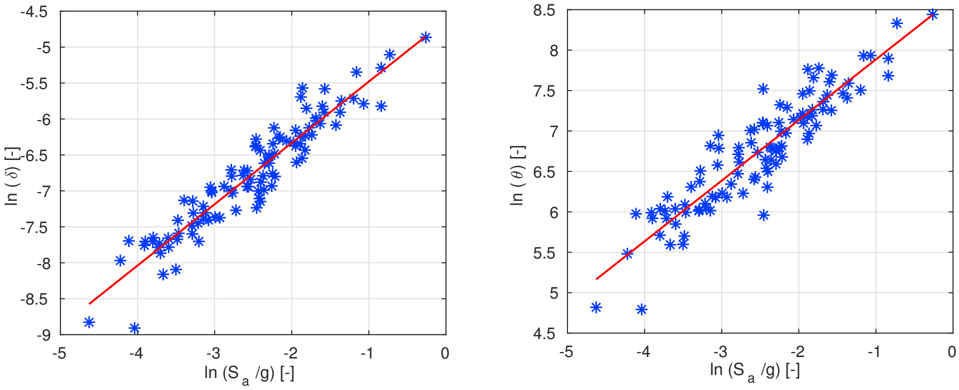

Fig. 2. Linear regressions of the maximum inter-storey drift (a) and the damper forces (b) over a set of 100 seismic inputs with spectral acceleration Sa_i

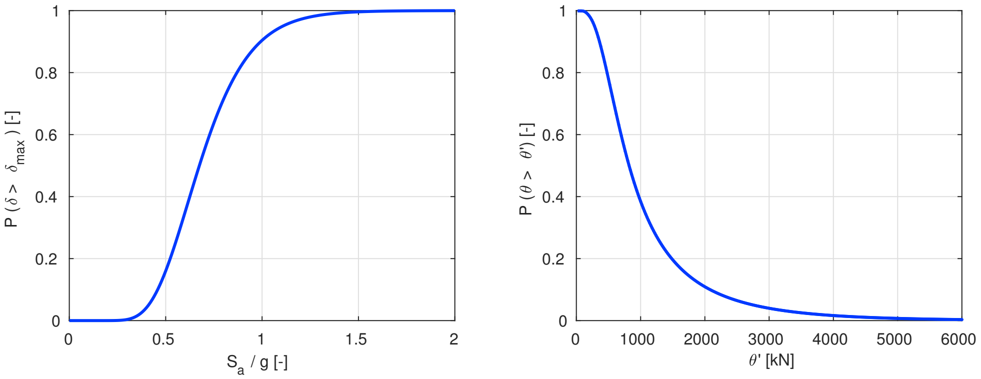

Fig. 3. Probability of exceedance of δ_{max} for a given spectral acceleration (a),$CCDF$ of the damper forces(b)

The results obtained by considering the design method employing linear fitting for the response assessment are reported in the figure 4 for the cases corresponding to α = 0.3,0.6 and 1. In this case it can be seen that the optimal values of the objective function decrease of about 41% going from α=0.6 to α=0.3 while a reduction of only 23% has been evaluated from α=1 to α=0.6. Considering that the other methodologies have shown a more steady tendency in the objective function evolution, this aspect can be a clue of a not perfect fitting for higher values of non-linearity.
The second approach optimises the viscous dampers properties over a preselected set of seismic inputs. In particular, the value of im^* corresponding to the risk of exceedance of 10% in 50 yrs is 0.6g.
Figure 4 shows a comparison between the optimal configurations provided by the different methodologies. In general the maximum gap reached in terms of C_{opt} is equal to 28%. Differently, the optimal objective functions are more affected by the strategy used during the problem resolution.
The optimum values of C_d are validated against those obtained from a "full" RBO analysis computed by carrying out a complete reliability analysis for each optimisation loop, in particular for α close to the linear case the results provided by the first approach tend to coincide with those obtained by using a complete RBO.

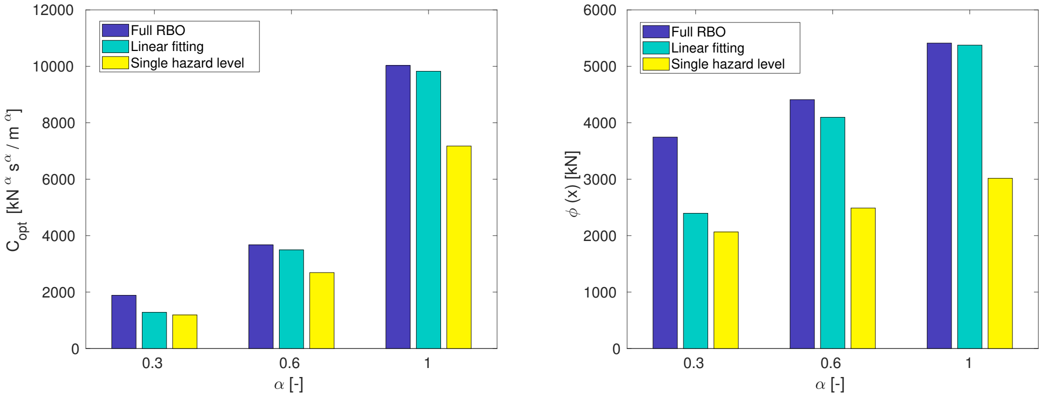

Fig. 4. Results comparison

4.4. Computational costs

During the computational stage the use of some HPC techniques appeared necessary, in particular all the analyses have been carried out by parallelizing the code on a cluster of 31 CPUs. A complete RBO process, for one single value of the exponent α, involves an average of 10 reliability analyses for a total of about 7000 samples of the structural model response.

The first proposed methodology, considering always the same 100 seismic records, attains the optimal solution after around 8 iterations for a total of 800 simulations.

The second approximated approach, considering only one value of the seismic hazard, is very light in computational terms. It needs of about 7 iterations to converge to the optimal solution, no reliability analysis are employed and only 20 structural analysis are required for each loop for a total of 140 simulations.

5. Conclusions

Two approximate methodologies for the optimal design of viscous dampers have been presented in this study. The approaches allow controlling the maximum inter-storey drift by reducing at the same time the total damper forces applied to the viscous dampers that are known to be proportional to the total cost of the dampers. The first approximated approach allows a reduction in the number of simulations during the reliability analysis thanks to the implementation of a probabilistic model that exploits a linear regressions of the structural response vs. the seismic input intensity to calculate the input vector for the optimisation step.

The second methodology presented optimises the system by considering a single level of the seismic hazard during the input selection, and by studying the structural performances always over the same pre-defined set of accelerograms. This methodology is the least computational expensive due to the reduced number of structural analyses required for each optimisation loop.

Although a complete reliability based optimisation allows a more accurate design solution which ensures more strictly the performance objectives, the approximate approaches yield results relatively close in terms of optimal design at a fraction of the total computational cost. The obtain results show that for increasing values of the dampers nonlinearity both the damping viscous constant (i.e., design variable) and the objective function decrease. Thus, dampers with higher nonlinearity levels perform better than linear dampers. Further analyses involving structural systems other than the one investigated in this paper are however needed to generalize the obtained results.

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