COSSAN Case Study

Reliability-based optimization of non linear viscous dampers

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Summary and Key Finding

Vicous damper are dissipative devices aiming at reducing the dynamic response of structures or systems in case of a seismic event.
In this study the optimal properties of non-linear viscous dampers are computed by means of a reliability-based optimization approach.
After careful analysis, a number of conclusions have been reached:

1. **Non-linear viscous dampers allow reaching a lower total costs** by maintaining the same performance level of the linear case.
2. **The optimal damping coefficient decreases for increasing values of the exponent** α.
3. **Reliability-based design optimization** provides reliable solution which accounts for inherent uncertainties in the seismic input definition.

Figure 1: Buddhist HQ (Taipei, Taiwan) equipped with viscous dampers

1 Problem Description

1.1 Viscous dampers

Energy dissipation devices are widely employed to improve the performance of structural systems under earthquake input. In particular, the use of viscous dampers represents a valuable and cost-effective solution to achieve a structural performance enhancement [Christopoulos et al., 2006, Dargush and Soong, 1997, Takewaki, 2011]. This work introduces a novel and rigorous approach that allows to explicitly consider the variability of the intensity and characteristics of the seismic input [Atkinson and Silva, 2000] in designing the optimal viscous constant and velocity exponent of the dampers based on performance-based criteria [Altieri et al., 2017]. The optimal solution allows controlling the probability of structural failure, while minimizing the damper cost, related to the sum of the damper forces. A 3-storey steel moment-resisting building frame (Figure 2) is considered to illustrate the application of the proposed design methodology and to evaluate and compare the performances that can be achieved with different damper nonlinearity levels.

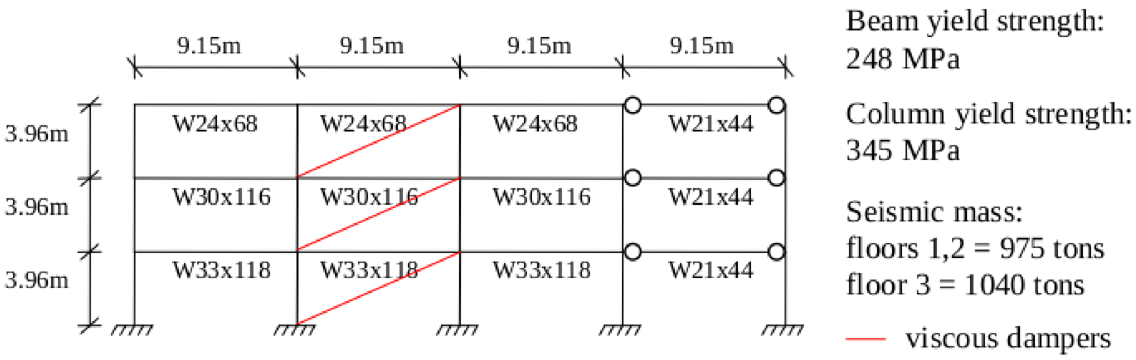

Figure 2: Structural model description and properties

2 Analysis

2.1 Problem formulation

The design of the dampers is an inverse reliability problem aiming at finding the values of the design variables $\mathbf{x}^*$ such that the system meets a pre-fixed performance level. This problem can be cast in the form of a Reliability-based design optimization (RBDO) problem [Patelli and De Angelis, 2012], aiming at identifying the optimal damper properties which minimize the dampers cost while satisfying the stochastic constraints on the probability of exceeding a prescribed global damage level. Finally, additional constraints are needed to ensure that the values assumed by the design variables are physically admissible.
In the problem at hand, the design variables and the objective function depend on the damper constitutive law:

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

where v represents the relative inter-storey velocity, C_d the damping coefficient and α the parameter that describes the nonlinearity of the damper response.
In particular, the design variables are the the coefficients C_d of the dampers to be added to the building frame at each floor. These are collected in the vector $\mathbf{x} = [C_{d,1} C_{d,2} \cdots C_{d,N_d}]^T$.The velocity exponent α is kept fixed, and the optimization process is repeated for different values of α.
In this study, the objective function is expressed as a function of the sum of the maximum forces observed

in the dampers $\Xi = \sum_{i=1}^{N_d} f_{d,i}$, where N_d is the total number of added dampers.
The structure is assumed to fail if the maximum inter-storey drift among the various storeys Δ exceeds a given limit related to the building damage $\bar{\delta}$. The same limit $\bar{P}$ assumed for the sum of the damper forces is considered for the probability of exceedance of the drifts $P_\Delta(\bar{\delta}, \mathbf{x}) = P[\Delta \geq \bar{\delta} | \mathbf{x}]$.
By limiting the inter-storey drifts, also the strokes in the dampers are indirectly controlled. The RBDO problem can be mathematically formalized as follows:

$$\begin{aligned} &\text{min}\phi(\mathbf{x}) \\ &x \\ &\text{subject to:} \\ &c(\mathbf{x}) \leq 0 \qquad (i = 1, 2, ..., m) \\ &P_\Delta(\bar{\delta}, \mathbf{x}) - \bar{P} \leq 0 \end{aligned} \tag{2}$$

$c(\mathbf{x}) \leq 0$ = (linear and/or nonlinear) deterministic constraints specifying the feasible domain of the damper properties.

2.2 Numerical simulation

The optimal solution allows controlling the probability of structural failure, while minimizing the damper cost, related to the sum of the damper forces. The optimization problem solution is efficiently sought via the constrained optimization by linear approximation (COBYLA) method, while Subset Simulation is employed in the reliability analysis at each iteration of the optimization process (Figure 3).

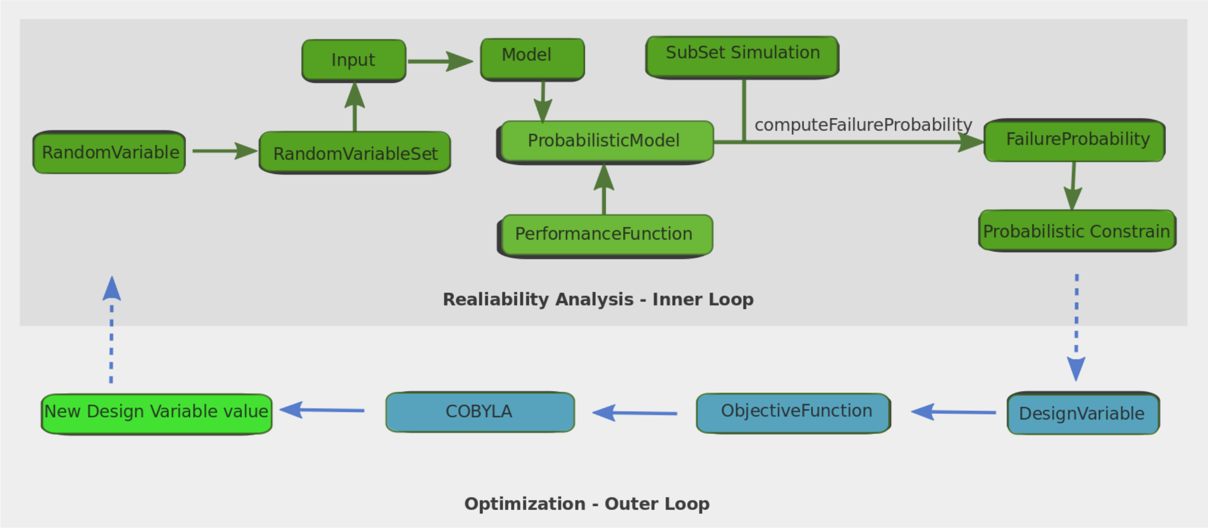

Figure 3: Logical structure of the OpenCossan code

2.3 Results

Figure 4 shows the values of both the optimal solution $\mathbf{x}^* = C_d^*$ and the corresponding objective function $\phi(\mathbf{x}^*)$ obtained for different exponents α . It can be observed how the use of non-linear dampers allows to reduce the maximum forces in the dampers, leading to a more economical solution. In fact, the value of $\phi(\mathbf{x}^*)$ in the case $\alpha = 0.3$ is about 70% lower than the linear case.

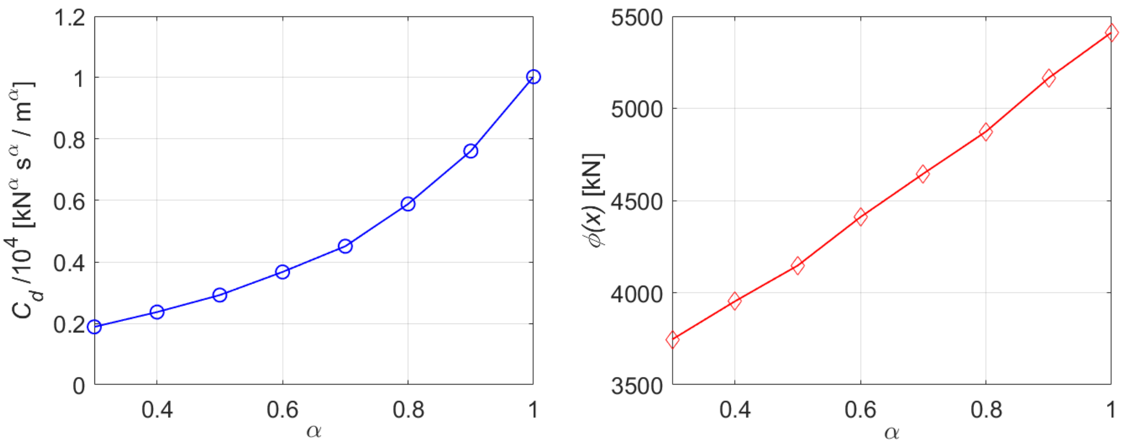

Figure 4: Evolution of the optimal solution in terms of design variable C_d and objective function $\phi(x)$ for different α.

In addition, the case with different dampers at each storey has been analyzed. Figure 5 shows the variation, during the optimization process, of the viscous damping constant at the various storeys, and of the objective function, for the case corresponding to $\alpha = 0.3$. The number of iterations required increases drastically with respect to the uniform damper distribution case. Moreover, the choice of the starting point in the optimization process may also affect the number of iterations.

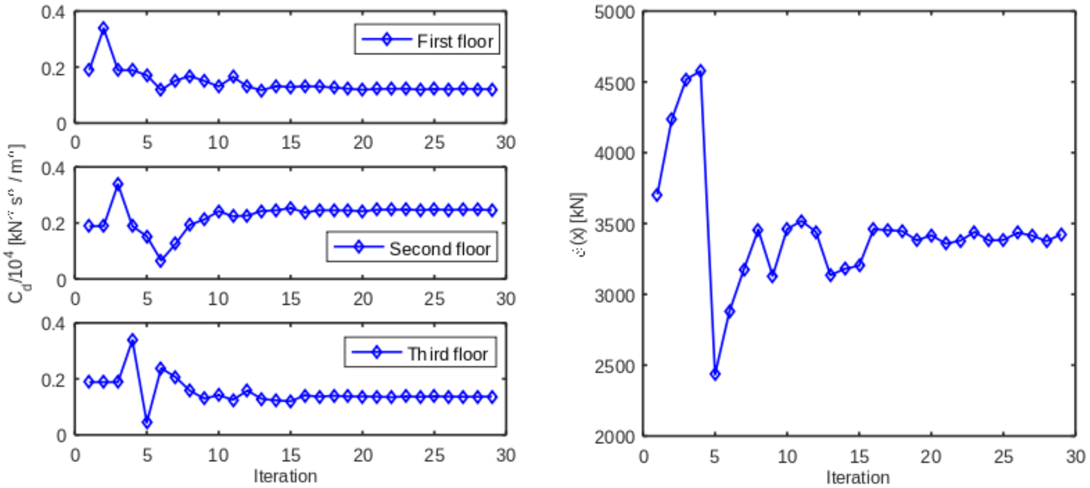

Figure 5: Variation, during the optimization process, of the viscous damping constant at the various storeys and of the objective function, in case of variable damper distribution.

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