COMPDYN 2015
5th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.)
Crete Island, Greece, 25–27 May 2015

SEISMIC LOSS OPTIMIZATION OF FRAME BUILDINGS USING VISCOUS DAMPERS

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Keywords: Gradient optimization, Viscous dampers, Passive control, Sequential linear programming, Earthquake engineering.

Abstract. *The effectiveness of control strategies in achieving the objectives of a performance-based-design is well accepted in the earthquake engineering community. Consequently, various methods have been proposed for optimal design of dampers and their distribution along the building height. Most of the formulated methods concentrate mainly on reducing the responses with no explicit consideration of their long-term economic impact. In this study, an optimization problem is formulated for optimally distributing viscous dampers by minimizing the initial cost subject to a constraint on the total expected seismic loss. An intensity based assessment is used for the computation of the total expected loss. A generic Sequential Linear Programming procedure is employed to solve the formulated optimization problem. Implementation scheme of the optimization procedure is outlined in detail. The efficacy of the proposed procedure is illustrated by applying it on a four story reinforced concrete frame. It has been shown that the optimization procedure results in the optimal quantity and distribution of viscous dampers along the height of the case study building.*

1 INTRODUCTION

Conventional capacity design strategy relies on the philosophy of “dissipation with degradation” as seismic energy is dissipated by inelastic deformation. Due to the reliance of this philosophy on inelastic deformations, this incurs heavy damage to the parent structure making it non-functional after most major seismic events. A more rational approach to reduce damage would be to rely on “dissipation without degradation” rather than “evasion/dissipation” of seismic induced forces by degradation. One way to achieve this is by increasing the amount of effective damping in the system by introducing control strategies. The introduction of control techniques in structural engineering was mainly necessitated due to the growing demand for minimizing damage during a seismic event. Among the different control techniques implemented in structures to reduce seismic responses, application of viscous dampers seems to be more common; especially from a retrofitting perspective. This is mainly attributed to the fact that the damper force is linearly or nonlinearly proportional to velocity and is out of phase from the column displacements. As a result, the columns or foundations are not subjected to additional demand, and may not need to be strengthened [1-3]. This paper is mainly concerned with the seismic performance enhancement of existing frames using viscous dampers.

The main task needed to be addressed by the engineer in the retrofitting design using viscous dampers is to efficiently allocate and size the dampers. This should take into account both the initial cost that needs to be invested and the achievement of the performance objective. Various optimal design methodologies for retrofitting are available in the literature. Many of them primarily address the problem of distributing a given total added damping to achieve the best performance (minimize damage measures). Some of the works in this direction presented very efficient methods [4-12]. Note that in these works the total added damping is predetermined. The algorithms are thus used to determine the optimal positioning of this quantity along the height of the building. In some of these works, approaches to estimate a reasonable total added damping were also proposed.

From a different perspective, Lavan and Levy [13-15] minimized the total added damping subject to a constraint on the performance of the structure (allowable inter-story drifts). They also present a practical analysis/redesign procedure for arriving at the optimal designs exploiting the advantage of the fully stressed characteristics of the optimal solution [16, 17]. While this formulation lends itself to the performance-based-design framework, the allowable inter-story drifts, or performance measures, are determined based on code requirements. These drifts are usually not determined explicitly based on the economic consequences.

In the present paper a novel optimization scheme is developed in which the total initial cost is minimized while explicitly constraining on the total expected loss. One of the ways of measuring the economic consequences can be in terms of expected annual loss which actually corresponds to the economic loss that, on an average, occurs every year in the building [18, 19]. A more simplified version of this measure could be the use of the total expected loss which is actually the loss that the building incurs for a specific intensity of earthquake. In this study this approach of measuring the economic consequences is adopted. The formulated problem thus directly incorporates the economic impact, and the optimization scheme proposed reflects the economic aspect of the response optimization. The parent frame is assumed to remain linear. The framework developed is generic and is easily extendable to nonlinear frames.

2 PROBLEM FORMULATION

When the optimization is used for strengthening existing buildings using viscous dampers, the stiffness and the mass of the building to be retrofitted are known (and do not vary for different combinations of the damper amount and configuration). Therefore the initial cost in the case of enhancing seismic performance with viscous dampers can be assumed as the cost of added dampers and their installation. A component based loss computation methodology is adopted for calculating the total expected loss. As the parent frame is assumed to remain linear after retrofitting, the computed loss is due to non-structural component damage only. In this study, seismic losses due to downtime and injury are not accounted for; thereby resulting in underestimation of the benefits of optimal intervention.

2.1 Linear frame

In this paper, it is assumed that a linear analysis reasonably predicts the behavior of the damped frame. This does not necessarily require a strict linear behavior of the structure. Nonetheless, a strict linear behavior can be ensured by limiting the damage to drift sensitive components in a prescriptive manner by specifying an allowable/acceptable total expected loss.

2.1.1. Equations of motion

The equations of motion of the linear frame with added dampers are given as,

$$\begin{aligned}&\mathbf{M}\ddot{\mathbf{u}}(t)+\left[\mathbf{C}+\mathbf{C}_{damper}(\mathbf{c}_d)\right]\dot{\mathbf{u}}(t)+\mathbf{K}\mathbf{u}(t)=-\mathbf{M}\mathbf{i}\ddot{\mathbf{u}}_g(t)\\&\mathbf{u}(0)=0;\dot{\mathbf{u}}(0)=0\end{aligned} \tag{1}$$

In eq. (1), **M** represents the mass matrix and **K** represents the stiffness matrix; in the case of a linear frame both the matrices remain constant. Similarly, **C** represents the inherent damping matrix, $\mathbf{C}_{damper}(\mathbf{c}_d)$ is the added supplemental damping matrix, $\mathbf{c}_d$ is the added damping vector, **i** represents the ground motion directional vector, $\ddot{\mathbf{u}}(t)$,$\dot{\mathbf{u}}(t)$and $\mathbf{u}(t)$ represent the relative acceleration, relative velocity and relative displacement, and $\ddot{\mathbf{u}}_g(t)$ represents the acceleration due to gravity.

2.2 Loss computation

In classical detail loss assessment framework, the expected annual loss or the loss expected over a period of time is computed as [18, 19],

$$E[L_T]=\frac{1-e^{-\lambda t}}{\lambda}\int_0^{\infty}E[L_T\mid IM]dv(IM) \tag{2}$$

where $E[L_T]$ is the expected annual loss, λ is the discount rate (to convert the future loss to net present value), t is the period for which the rate is applied, $E[L_T\mid IM]$ is the expected loss conditioned on the intensity measure *IM*, and *v(IM)* is the mean annual rate of exceedance of the intensity measure. As this study aims to present the optimization methodology, the expected loss is computed only at a single value of intensity measure. Hence, the computed loss is independent of period *t*; thereby making eq. (2) not readily usable. Hence, in the present study, the total expected loss in no-collapse scenario conditioned on the mean engineering demand parameter ($\overline{EDP}$) which in turn is conditioned on the selected intensity measure $(IM_1)$is used and is assumed to be [18],

$$E\left[L_T \mid NC,\overline{EDP}_{IM_1}\right]=\sum_{j=1}^{N} a_j\left(E\left[L_j \mid NC,\overline{EDP}_{IM_1}\right]\right) \tag{3}$$

Over here, a_j is the cost of a new j^{th} component and *NC* refers to no-collapse state, *N* refers to the number of components. Eq. (3) is period independent and $\overline{EDP}$ is computed for the specific intensity measure $\left(IM_1\right)$. As dampers are added into the structure and the structure is assumed to behave linearly, collapse probability can be argued to be zero. Hence, only the no-collapse state is used for estimating loss in this paper.

2.3 Optimization problem

The optimization problem is formulated as,

$$min\, J\left(\mathbf{c}_d\right)=\mathbf{c}_d^T\mathbf{1} \tag{4}$$

Subject to:

$$\sum_{i=1}^{N_d}\left(\theta_i\right)\le\Theta_{allowable} \tag{5}$$

Over here θ_i refers to the expected loss at the i^{th} degree of freedom computed based on the maximum peak response. Mathematically θ_i is given as,

$$\left.\begin{array}{l}\theta_i=\chi\left(max\left(abs\left(\mathbf{r}_i\left(t\right)\right)\right)\right)\\ \textit{where } \chi \textit{ represents a function form and } \mathbf{r}_i\left(t\right) \textit{is the response vector}\\ \textit{and satisfies the following equation,}\\ \mathbf{M}\ddot{\mathbf{u}}(t)+\left[\mathbf{C}+\mathbf{C}_{damper}\left(\mathbf{c}_d\right)\right]\dot{\mathbf{u}}(t)+\mathbf{K}\mathbf{u}(t)=-\mathbf{M}\mathbf{r}\ddot{\mathbf{u}}_g\left(t\right)\\ \mathbf{u}(0)=0;\dot{\mathbf{u}}(0)=0\\ 0\le\mathbf{c}_d\end{array}\right\}\forall\ddot{\mathbf{u}}_g\left(t\right) \tag{6}$$

Eq. (5) can be re-written as,

$$\Pi=\frac{\sum_{i=1}^{N_d}\left(\theta_i\right)}{\Theta_{allowable}}\le 1.0 \tag{7}$$

where Π is called the performance index and $\Theta_{allowable}$ is the allowable (i.e. acceptable) total expected loss.

3 OPTIMIZATION ALGORITHM

This section gives stepwise implementation scheme of the optimization procedure. The algorithm employs intensity based assessment for loss computation. A target mean spectrum corresponding to a specific intensity is selected and a suite of ground motion pair is matched to the target spectrum. Following steps are involved in the proposed optimization scheme.

Step 1: Computation of mean responses

Perform linear time domain analysis of the system with an initial amount of damping vector $\mathbf{c}_d$ for all the matched ground motions and compute the mean responses. The initial amount of $\mathbf{c}_d$ vector can be computed using any of the approximate methods available in the literature [20].

Step 2 Evaluation of the total expected loss and performance index Π

Compute the total expected loss and performance index Π by using eqs. (3), (6) and (7). No dispersion is applied in this study to the mean responses obtained and hence the expected total loss can be treated as a deterministic scalar value. In a more generic study the dispersion can also be taken into account within this framework.

Step 3 Computing the gradient of the performance index Π and the objective function *J*

Gradient for the objective function *J* is trivial as it is a direct function of the damping vector $\mathbf{c}_d$ and the sensitivity will return a vector **1.** But the gradient of the performance index Π is not trivial. In this study gradient is derived using the classical finite difference scheme and it is given as below,

$$\frac{\partial \Pi}{\partial c_{dj}} \approx \frac{\Pi_{new} - \Pi}{\Delta c_{dj}} \tag{8}$$

where Π_{new} is the new performance index computed with perturbed $\mathbf{c}_d + \Delta\mathbf{c}_{dj}$ where $\Delta\mathbf{c}_{dj}$ is the perturbed vector with Δc_{dj} at the j^{th} location and zero elsewhere in the vector. Eq. (8) has some limitations especially when applied to large systems as it requires *n+1* analysis for *n* design variables. But as the main intention of this paper is to illustrate the optimization procedure incorporating the loss methodology, finite difference scheme is deemed to be sufficient.

Step 4 Estimating a new guess for the optimal design using Sequential Linear Programming (SLP)

The original optimization problem is given in eqs. (4) and (7) through (6). This is a nonlinear programming problem. SLP is chosen to solve this problem as other nonlinear schemes require the estimation of Hessian matrices which can pose serious difficulties in the vicinity of the optimum solution. So linearizing the objective function given by eq. (4) at the i^{th} iteration gives,

$$J^i(\mathbf{c}_d) = J(\mathbf{c}_d^i) + \{\nabla_{\mathbf{c}_d} J(\mathbf{c}_d^i)\}(\Delta\mathbf{c}_d^i) \tag{9}$$

and linearizing the constraint at the i^{th} iteration satisfying eq. (6) is given as,

$$\Pi^i(\mathbf{c}_d) = \Pi(\mathbf{c}_d^i) + \{\nabla_{\mathbf{c}_d} \Pi(\mathbf{c}_d^i)\}(\Delta\mathbf{c}_d^i) \tag{10}$$

In order to solve eqs. (9) and (10), an additional side constraints of '*move limits'* limiting the damper step size has to be introduced. So the linearized optimization problem for the i^{th} iteration is given as,

$$\left.\begin{array}{l} \min J^{i}(\mathbf{c}_d) \\ \text{Subject to :} \\ \Pi^{i}(\mathbf{c}_d) \leq 1.0 \\ \Delta\mathbf{c}_d^{low} \leq \Delta\mathbf{c}_d^{i} \leq \Delta\mathbf{c}_d^{upper} \end{array}\right\} \forall i \qquad (11)$$

Solving the eq. (11) gives the $\Delta\mathbf{c}_d$ required for the next iteration. Update the damping vector $\mathbf{c}_d$ as,

$$\mathbf{c}_d + \Delta\mathbf{c}_d \qquad (12)$$

Step 5 Check for termination condition

The iteration is terminated if the change in added damper vector $\Delta\mathbf{c}_d$ is less than the tolerance or maximum number of iterations has been reached. Otherwise, update the iteration number as $i=i+1$ and proceed to step 1.0. The optimization algorithm when $\Delta\mathbf{c}_d^{i} \geq \varepsilon_{tolerance}$ is illustrated in Fig. 1.

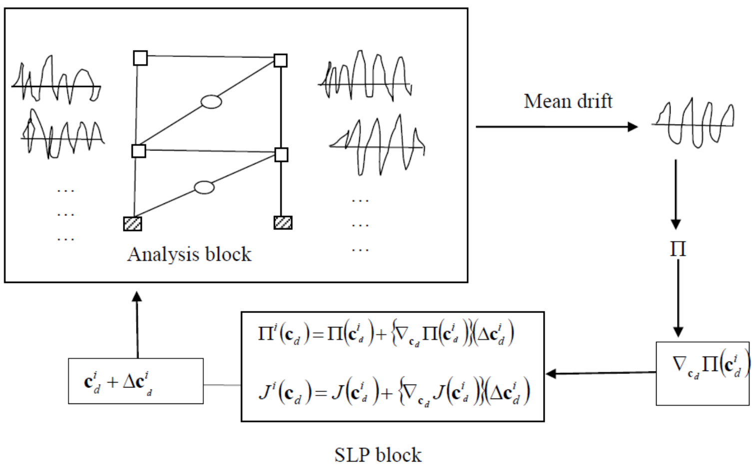


Fig.1 Schematic representation of the optimization procedure for $\Delta\mathbf{c}_d^{i} \geq \varepsilon_{tolerance}$

4 NUMERICAL STUDY

A four story reinforced concrete frame described in [21], designed in accordance with Eurocode 8 (EC8) and Eurocode 2(EC2) is used to illustrate the proposed optimization procedure. The frame is designed for high seismicity assuming a PGA of 0.3g. The details of the frame and the arrangement of the dampers are given in appendix A.

As the whole purpose of this paper is to demonstrate the optimization procedure, a suite of 7 artificial ground motions scaled to match a Eurocode 8 design spectra with PGA adopted as 1.5 times the design PGA is used for the present study. Un-controlled frame analysis has revealed that this level of ground motion intensity can incur inelastic excursions in the parent frame [21]. The allowable expected loss in eq. (5) is computed by assuming an allowable inter-story drift of 0.5% which ensures elastic frame behavior [12]. Only drift sensitive non-structural loss is accounted in the present study. Figs. 2a and 2b illustrate the constraint error and the performance index. As SLP is used, in order to ensure better convergence an adaptive *move limits scheme* had to be introduced. A *move limit* of 1% of the design damping vector is used for the first iteration. This is the reason for the steep slope of the line shown in the plots depicted in Figs. 2a and 2b. An initial *move limit* of 0.1% of the design damping vector is used for the rest of the iterations. In the neighborhood of the optimum the initial *move limit* is adaptively updated for better convergence.

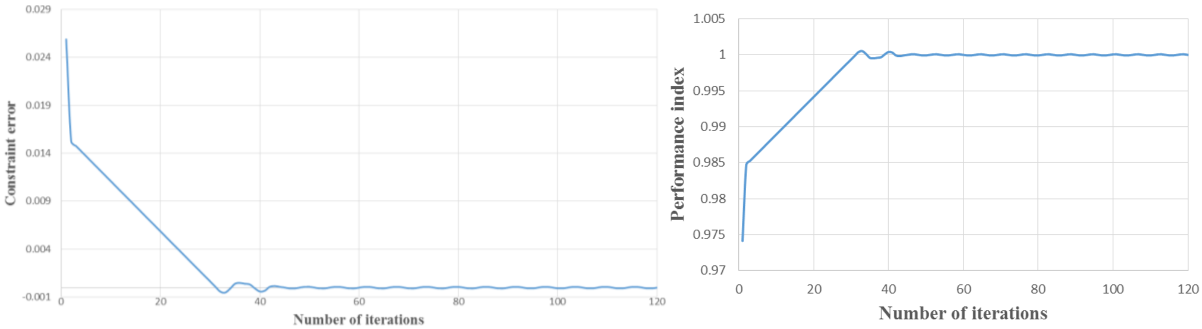


Fig. 2 (a) Constraint error plot, (b) Performance index plot, illustrating convergence to optimum.

Fig. 3 gives the optimum distribution of the damping coefficients along the height of the building. The initial uniformly distributed total damping vector used in this study for starting the optimization procedure is 101.92 kN-sec/m.

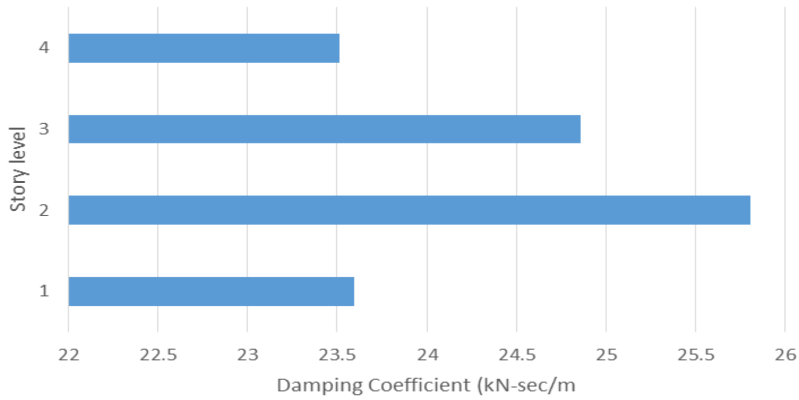


Fig. 3 Optimum damper distribution

The present optimization problem is formulated in such a way that the total expected loss of the building is less than a certain allowable value. In this study *no story level constraints* on the expected loss is considered. So in order to understand the localized effect of the distribution of dampers achieved in Fig. 3 a disaggregation of the total expected loss per story is also conducted.

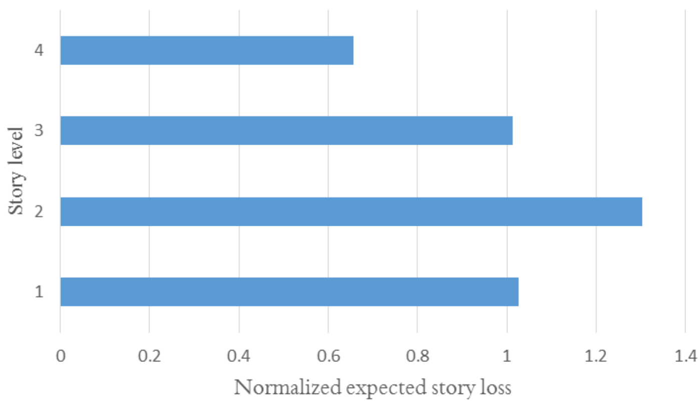


Fig. 4 Disaggregation of the expected loss per story

Fig. 4 shows the story level expected normalized losses. Normalized loss is obtained by dividing the computed story level loss to the allowable story level loss. In a realistic scenario, the allowable loss at story level should be determined based on the performance criterion to be satisfied for the story. Since Fig. 4 is plotted simply to understand the distribution of the expected loss per story, the allowable value of the loss at story level is assumed to be obtained by dividing the total allowable value by the number of stories. From Fig. 4 it could be clearly seen that with the optimum damper distribution shown in Fig. 3, the second story loss exceeds the assumed allowable limit. *This is to be expected as no story level constraint on the expected loss is applied in the optimization procedure*. Fig. 4 suggests that in the present study if we had adopted a constraint on the allowable story level loss limit in addition to the constraint on the total allowable expected loss, more damping would have to be allocated to the second story. But, as the total expected loss is of more concern for engineers and other stakeholders only this is considered as the constraint in the present study. However, if desired the story level constraints can be easily added by specifying the allowable story loss based on the specific requirements of the building. This gives more flexibility in the algorithm and allows the functional requirements of different stories of the building to be accounted for.

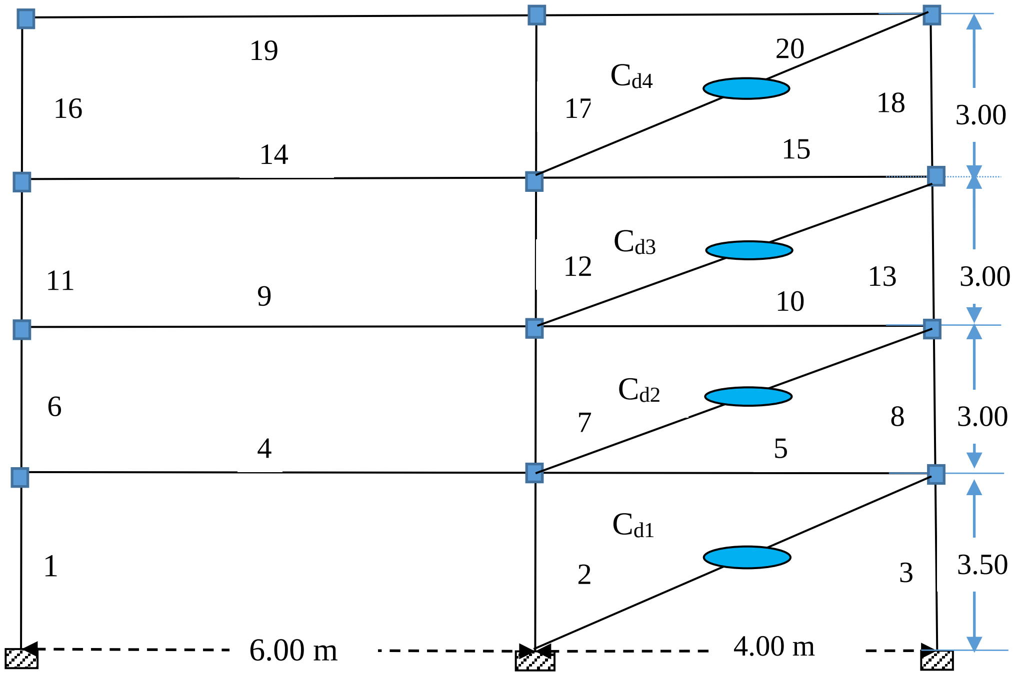
5 CONCLUSIONS

A gradient based sequential linear programming (SLP) optimization methodology is adopted to optimally quantify and optimally position added viscous dampers in multi-story frames. The optimization problem addressed is to minimize the amount of added damping subject to a constraint on the total expected seismic loss. Details of the optimization algorithm is presented and its application is illustrated using a four story reinforced concrete frame subjected to a suite of ground motions scaled to a specific target spectra. It is shown that the proposed procedure is capable of arriving at an optimal quantity of dampers and also simultaneously optimally distributes the dampers along the height of the building.

ACKNOWLEDGEMENTS

The first author gratefully acknowledges the support provided for this research by the NZ Earthquake Commission (EQC) in the form of postgraduate research scholarship.

APPENDIX A: DETAILS OF THE FOUR STORY FRAME



C_{di} refers to added dampers and $i=1....4$

Material Property

Dynamic Young's modulus $=3.5\times10^{10}\ N/m^2$

Geometric Properties

Member number	Width of the member (mm)	Depth of the member(mm)
1,6,11,16,17,12,7,2,3,8,13,18	450	450
4,5,9,10,14,15,19,20	300	450

Nodal Mass

Floor level	Mass per node (kg)
1st floor	29800
2nd -4th floor	29500

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