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TOWARDS REALISTIC MINIMUM-COST SEISMIC RETROFITTING OF 3D IRREGULAR FRAMES USING VISCOUS DAMPERS OF A LIMITED NUMBER OF SIZE GROUPS

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ABSTRACT

A new formulation for performance-based optimal seismic retrofitting using a limited number of sizes of viscous dampers is first presented. The problem formulation addresses costs that are related to both the topology and the sizes of the dampers, thus it presents a step forward to a more realistic definition of this optimization problem: a new cost function, the objective function in the optimization problem, is set down. Constraints are assigned to inter-story drifts at the peripheries. Then important results regarding two 3D irregular frames, obtained through a genetic algorithm, are presented. These examples will establish important benchmarks for other, more efficient, methods to be developed.

INTRODUCTION

Recent earthquakes (e.g. Northridge 1994, Kobe 1995, Christchurch 2011) have shown that prevention of loss of human lives should not be the only criterion for structural aseismic design. Nowadays, limiting damage due to earthquakes is becoming more and more desired. This statement holds for both new and existing buildings.

The structural and nonstructural damage of existing buildings could be efficiently reduced by using energy dissipation devices (see e.g. Soong and Dargush 1997; Christopoulos et al. 2006; Takewaki 2011). Among those, viscous dampers have been shown to be very effective in reducing various seismic responses. This is particularly true in the case of retrofitting due to the out-of-phase effect that may eliminate the need for foundation and columns strengthening (Constantinou and Symans 1992; Lavan 2012).

Design and optimal design methods for the seismic retrofitting of frame structures using viscous dampers have been proposed in the literature for both 2D (see e.g. Whittle et al. 2012 and references therein) and 3D (e.g. Lavan and Levy 2006; Levy and Lavan 2006; García et al. 2007; Aguirre et al. 2013) structures.

Most of the abovementioned approaches adopt continuous design variables typically corresponding to damping coefficients of the dampers. Furthermore, at each potential location the damping coefficient is usually taken independent of the damping coefficients in other potential locations. This results

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in designs consisting of a wide variety of different dampers. Hence, in order to characterize a practical damper distribution, some rounding and grouping of the dampers to only a few size groups is required. While, practically, this approach may provide reasonable designs in the majority of cases, there is no guarantee that these would be optimal in a formal sense.

Methodologies have also been proposed for the design and optimal design of dampers using discrete values for the damping coefficients (e.g. Zhang and Soong 1992; Agrawal and Yang 1999; Dargush and Sant 2005; Lavan and Dargush 2009; Kanno 2013). While presenting an important step towards making the designs attained practical, each of these methodologies makes use of predetermined parameters for the damping: either the dampers' sizes; the damping increment; the number of dampers; or a combination of those. The values adopted for those parameters may have a considerable effect on the optimal solution attained. Furthermore, the resulting optimization problems consisting of integer variables are relatively difficult to solve compared to problems with continuous variables. This poses a limit on the number of variables (damper locations and sizes) that can be considered.

Lavan and Amir (2014) presented an optimization formulation that overcomes these limitations and an associated methodology for its solution. In their approach dampers of similar properties, which were taken as continuous variables and were determined by the optimization algorithm and not a-priori, were optimally allocated by the algorithm. Their objective function minimized the direct cost of manufacturing the dampers. Constraints were adopted to limit the interstory drifts of the peripheral frames while those were evaluated under a suite of realistic ground motions.

This paper formulates and solves an optimization problem that is an enhanced, more realistic, version of that solved in Lavan and Amir (2014). The optimization problem will be formulated through continuous and discrete variables and the objective function will combine a few components. The first component represents the cost associated with removal of existing non-structural components; the cost of labour required for connecting the damper to the existing structural elements; and the interference with everyday activity. The second component, as in Lavan and Amir (2014), represents the direct cost of manufacturing the dampers themselves. Finally the third component represents the cost associated with the design and testing of the prototype damper of each size group. The first and third components of the cost function present another step towards an optimization problem formulation that adequately represents reality. Thus, a design attained using this methodology could be adopted in practice, tuning the cost function according to each particular case.

PROBLEM FORMULATION

This papers addresses the optimization problem of minimizing the realistic cost of seismic retrofitting using added damping in potential locations for dampers. This problem is subjected to a constraint on the maximum inter-story drift for a frame excited by a realistic ground motion. The optimization methodology consists in minimizing a realistic cost function. The variables adopted to represent the damping coefficient for each size group of dampers are continuous, while the existence of a damper in a potential location of the frame and its belonging to a particular size group of dampers are expressed through discrete variables. Here we refer to two possible size groups of dampers, but in general the approach presented can be extended to more size groups of dampers.

Design variables and functions definitions

In this section we introduce and define some variables that have an important role in the present formulation. The damping coefficient for each potential location is contained in the vector $\tilde{\mathbf{c}}_d$. This vector is defined as follows:

$$\tilde{\mathbf{c}}_d = \bar{c}_d \mathbf{x}_1^{odd}(y_1 + (y_2 - y_1)\mathbf{x}_2^{odd}) + \bar{c}_d \mathbf{x}_1^{even}(y_1 + (y_2 - y_1)\mathbf{x}_2^{even}). \tag{1}$$

The number of potential locations for dampers is denoted N_d and is defined a priori; in each position we allow the algorithm to allocate 0, 1 or 2 dampers, choosing between 1 or 2 sizes of dampers. $\mathbf{x}_1$ is a vector with dimension $2N_d \times 1$ and it is defined as follows: $\mathbf{x}_1^{odd} = [\mathbf{x}_1(1) \quad \mathbf{x}_1(3) \quad \mathbf{x}_1(5) \quad \ldots]^T$ and $\mathbf{x}_1^{even} = [\mathbf{x}_1(2) \quad \mathbf{x}_1(4) \quad \mathbf{x}_1(6) \quad \ldots]^T$; similarly for $\mathbf{x}_2$. In the vector $\mathbf{x}_1^{odd}$ a value of 0 in the *i-th* position will mean that the 1^{st} damper out of 2 in the $\frac{i+1}{2}th$ location in the frame does not exist. On the other hand a value of 1 will mean that it exists. In the vector $\mathbf{x}_2^{odd}$ a value of 0 in the *i-th* position will mean that the 1^{st} damper out of two in the $\frac{i+1}{2}th$ location in the frame, if it exists, belongs to the 1^{st} size group, while a value of 1 will mean that it belongs to the 2^{nd} size group. The same properties apply to the *i-th* element of $\mathbf{x}_1^{even}$ and of $\mathbf{x}_2^{even}$ that relate to the 2^{nd} damper in the $\frac{i}{2}th$ location in the frame.

The damping coefficient related to the dampers of the 1^{st} or 2^{nd} size group will be given by the variables $y_1^L \leq y_1 \leq y_1^U$ and $y_2^L \leq y_2 \leq y_2^U$. Essentially the continuous variables y_1 and y_2 are scaling factors of a damping reference coefficient $\bar{c}_d$. It means that in the case of 2 size groups of dampers we will have the following two damping coefficients for the two size groups:

$$\bar{c}_1 = y_1 \bar{c}_d, \quad \bar{c}_2 = y_2 \bar{c}_d. \tag{2}$$

$\bar{c}_d$ is the maximum damping coefficient to be potentially adopted and it is defined by the user. Through a proper matrix transformation, which depends on the geometry of the structure, the vector $\tilde{\mathbf{c}}_d$ defines the added damping matrix $\mathbf{C}_d$.

Objective function

One of the main aims of this research work is to propose an optimization approach for minimizing a realistic formulation of the cost due to the added damping in a structure. The cost function, which is the objective function in the optimization problem, is composed of three components: $J = J_1 + J_2 + J_3$.

The first component, J_1, represents the cost due to the number of bays in which dampers are installed. This cost considers all the aspects of preparing the structure for the damper installation and the architectural constraint that this installation will represent. Moreover, in case of retrofitting, the removal of existing nonstructural components is also considered. We allow the algorithm to allocate as many as two dampers in each potential location, and it will be more expensive to allocate the 1^{st} damper in an empty potential location than to allocate the 2^{nd} damper in a location in which already exist the 1^{st} damper.

In formulating J_2, the cost of a single fluid viscous damper is a function of the peak force it is designed for and its stroke (maximum elongation). In practice the dampers of a same size group are designed to have the same properties, hence a size group of damper is designed to take the peak stroke expected in the most elongated damper of the same size group. The peak stroke are strongly correlated with the peak inter-story drift, that are constrained in our problem formulation; this is why dampers strokes are not considered in the cost formulation. Each size group of dampers is also designed for the peak force of the most loaded damper of that size group. Therefore, this peak force should be considered in the cost. Assuming a dominant mode behavior, the velocity in the damper in the location j is proportional to $\omega_1 d_j$, where ω_1 is the dominant frequency and d_j is the envelope peak drift at the location j. Experience shows that usually dampers are located where the drifts reach their allowable values, that are known values. Thus the maximum velocities are known in advance. This is why minimizing the damping coefficient is equivalent to minimizing the peak force of the most loaded damper of a particular size group. The number of dampers of each size group has also a considerable effects on the cost. Thus the component J_2 of the cost mimics the maximum envelope peak force in the damper of any given size group as it is multiplied by the number of dampers of that size group.

The third component of the cost, J_3, goes along with modern seismic codes, that require to test a prototype of each size group of damper so as to verify its force-velocity behavior. Hence, the number of different damper size groups has to be minimized. The third and last component of the objective function, J_3, refers to the variety of damper size groups.

We can now introduce the expressions of the three different components of the cost function, that is our objective function. The first component of the cost is defined as follows:

$$J_1 = \mathbf{x}_1^T \mathbf{C}_{mont} \tag{3}$$

where $\mathbf{x}_1$ is a vector $2N_d \times 1$ and $\mathbf{C}_{mont}$ is a $2N_d \times 1$ vector in which every *i-th* component is a cost component related to the *i-th* component of $\mathbf{x}_1$. The vector $\mathbf{C}_{mont}$ it is defined as follows:

$$\mathbf{C}_{mont} = D(\mathbf{C}_{m1}) \begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \\ \vdots \end{bmatrix} + D(\mathbf{C}_{m2}) \begin{bmatrix} 0 \\ 1 + (1.5 + \frac{C_{m1}}{C_{m2}})(1 - \mathbf{x}_1(1)) \\ 0 \\ 1 + (1.5 + \frac{C_{m1}}{C_{m2}})(1 - \mathbf{x}_1(3)) \\ \vdots \end{bmatrix} \tag{4}$$

D is a matrix operator that transforms a vector into a diagonal matrix (similar to the "diag" function in MATLAB); $\mathbf{C}_{m1}$ represent the specific cost of installation of the first damper in a bay; its dimensions are $2N_d \times 1$ and it has N_d elements different from 0. $\mathbf{C}_{m2}$ represent the cost for each bay of adding the second damper assuming the first damper is already installed at that location; its dimensions are $2N_d \times 1$ and it has N_d elements different from 0. Both $\mathbf{C}_{m1}$ and $\mathbf{C}_{m2}$ are vectors defined by the user. Since $\mathbf{C}_{m1}(i) \geq \mathbf{C}_{m2}(j)$ $\forall i$ and $\forall j$, we can observe that the algorithm will find cheaper to install a damper in a location in which a damper is already installed than to put a damper in an empty potential location. The vector that multiplies $D(\mathbf{C}_{m2})$ is defined so that it will be more expensive to allocate firstly the 2^{nd} damper in an empty location than to allocate the 1^{st} one in the same position: referring to the $\frac{i+1}{2}$ location, in the first case the cost will be $\mathbf{C}_{m1}(i) + 2.5 \times \mathbf{C}_{m2}(i+1)$ while in the second just $\mathbf{C}_{m1}(i)$.

The J_2 component is defined as follows:

$$J_2 = \bar{c}_d \mathbf{x}_1^T (y_1 \mathbf{1} + (y_2 - y_1)\mathbf{x}_2) \tag{5}$$

$\mathbf{x}_1$ and $\mathbf{x}_2$ are vectors of dimensions $2N_d \times 1$ whose meaning has been already defined. The vector $\mathbf{1}$ is a constant vector $2N_d \times 1$ containing in every position the value 1.

J_3 is defined as follows:

$$J_3 = C_{type} \left[sgn(\mathbf{x}_1^T \mathbf{x}_2) + sgn(\mathbf{x}_1^T (\mathbf{1} - \mathbf{x}_2)) \right] \tag{6}$$

where $\mathbf{x}_1$, $\mathbf{x}_2$ and $\mathbf{1}$ have been already introduced above, and C_{type} is a scalar defined by the user that gives to J_3 the desired weight in the total cost J, according to the order of magnitude of J_1 and J_2. The function *sgn* is the sign function:

$$sgn(x) = \begin{cases} +1 & for \quad x > 0 \\ 0 & for \quad x = 0\,; \\ -1 & for \quad x < 0 \end{cases} \tag{7}$$

in our formulation last option is not possible thanks to the variables definition. We observe that:

- in case of all dampers of the 1^{st} size J_3 will be equal to $C_{type} \times [0+1]$;
- in case of all dampers of the 2^{nd} size J_3 will be equal to $C_{type} \times [1+0]$;
- in case of dampers both of the 1^{st} and 2^{nd} size J_3 will be equal to $C_{type} \times [1+1]$.

Performance index

We are now considering the retrofitting of a generic structure using added dampers. The damage due to earthquakes can be divided in structural and nonstructural. Inter-story drifts, ductility demands in the plastic hinges of structural elements and hysteric energy dissipated in these plastic hinges are the responses that indicate structural damage. Ductility demands are strongly associated to the peak inter-story drifts. The contribution of hysteric energy to common damage measures is relatively small in most cases. Thus inter-story drifts serve as an appropriate measure of structural damage. Limiting the drifts also allows to ensure a linear behavior, if feasible, of the structure. This can be assured including in the formulation of the optimization problem such limitation. Moreover, when retrofitting using added dampers, some structures may be brought to behave linearly under the design earthquakes, and in these cases structural damage is not expected but nonstructural damage is to be controlled. For many non-structural components the main cause for damage is the peak inter-story drift they experience; hence inter-story drifts are constrained here to allowable values.

The maximal inter-story drift normalized by the allowable value is chosen as the local performance index for the 2D frames, which is defined as

$$d_{c,i} = \max(d_i(t)/d_{all,i}). \tag{8}$$

Here $d_i(t)$ is the *i-th* inter-story drift and $d_{all,i}$ is the maximum allowable value of $d_i(t)$. For 3D structures $d_i(t)$ refers to an inter-story drift of a peripheral frame. The $d_i(t)$ performance indexes are evaluated through the equations of motion of a linear dynamic viscously damped system, given by:

$$\begin{aligned}&\mathbf{M}\ddot{\mathbf{u}}(t) + [\mathbf{C} + \mathbf{C}_d(\tilde{\mathbf{c}}_d)]\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) = -\mathbf{M}\mathbf{e}a_g(t) \quad \forall t\\ &\mathbf{u}(0) = 0, \quad \dot{\mathbf{u}}(0) = 0\end{aligned} \tag{9}$$

where $\mathbf{u}$ is the displacement vector of the degrees of freedom; $\mathbf{M}$ is the mass matrix, $\mathbf{K}$ is the stiffness matrix, $\mathbf{C}$ is the inherent damping matrix, $\tilde{\mathbf{c}}_d$ is the added damping vector, $\mathbf{C}_d$ is the supplemental damping matrix, $\mathbf{e}$ is the location vector that defines the location of the excitation, and a_g is the ground acceleration. There is a linear relation between the displacements $\mathbf{u}$ and the inter-story drifts $\mathbf{d}$. In fact $\mathbf{d}(t) = \mathbf{H}\mathbf{u}(t)$, where $\mathbf{H}$ is a transformation matrix. The present formulation can be extended to the analysis of non linear structures and the algorithm considered herein can easily manage such extension.

Optimization problem

The optimization problem is now formulated. We focus on design with up to two damper size groups, even though the methodology can accommodate any number of damper and potential locations. Formally, this optimization problem can be stated as follows:

$$\begin{aligned}
&\min_{\mathbf{x}_1,\mathbf{x}_2,\mathbf{y}} \quad J = J_1 + J_2 + J_3\\
\text{s. t.:}\quad & d_{c,i} = \max_t(|d_i(t)/d_{all,i})|) \le 1 \quad \forall t, \forall i = 1,\dots,N_{drifts}\\
& x_{1,k} = \{0,1\} \quad k = 1,\dots,2N_d\\
& x_{2,k} = \{0,1\} \quad k = 1,\dots,2N_d\\
& 0 \le y_1^L \le y_1 \le y_1^U \le y_2^L\\
& y_1^U \le y_2^L \le y_2 \le y_2^U \le 1\\
\text{with}\quad & \mathbf{M}\ddot{\mathbf{u}}(t) + [\mathbf{C} + \mathbf{C}_d(\tilde{\mathbf{c}}_d)]\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) = -\mathbf{M}\mathbf{e}a_g(t) \quad \forall t, \quad \forall a_g(t) \in \mathscr{E}\\
& \mathbf{u}(0) = 0, \quad \dot{\mathbf{u}}(0) = 0
\end{aligned}$$

where $\mathscr{E}$ is an ensemble of ground motions that in general can be considered, N_{drifts} is the number of drifts constrained, y_1^L, y_1^U, y_2^L, y_2^U are user-defined bounds. For optimizing the distribution and size of a single damper size group, only the $\mathbf{x}_1$ and y_1 variables are necessary, thus it can be seen as a particular case of the two-dampers size groups optimization.

COMPUTATIONAL SCHEME

The problem that we are analyzing is characterized by mixed discrete and continuous variables, and in general this kind of problem will be a non-convex one. The algorithm chosen to solve it is a genetic algorithm (GA). As a matter of fact a GA is an effective tool, in most cases it can find the global optimum solution with a high probability (Rao 2009). GAs are based on the principles of natural genetics and natural selection. The basic elements of natural genetics – reproduction, crossover and mutation- are used in the genetic search procedure. GAs differ from the traditional methods of optimization in some aspects. Several points are used as candidate solutions, thus GAs are less likely to get stuck in local optima. GAs use only the values of the objective function and constraints, this means that the derivatives are not used in the process. Moreover GAs are search methods naturally applicable for solving discrete and continuous problems. The features mentioned above explain the reasons why a GA is a powerful tool in solving our problem; a GA is effective in finding a global optimum with a very high probability exploring the whole domain of the problem.

NUMERICAL EXAMPLES

In this section we present two examples, demonstrating the effectiveness of the optimization approach proposed in this paper. In particular we want to focus our attention on the realistic formulation proposed thanks to the innovative objective function, thus preparing important benchmarks for further developments on this subject.

We assume 5% of critical damping for the first two modes in order to construct the Rayleigh damping matrix of the structures. The algorithm used for optimization is a built-in Genetic Algorithm in the MATLAB library. The optimization process automatically stops when one of the following conditions is verified: the number of generations reaches the limit value of generations "*Generations*"; the weighted average change in the fitness function value over "*StallGenLimit*" is less than "*TolFun*". For numerical experiments a parallel-processor MATLAB code was executed on a standard PC with a 2.50 GHz Intel®Core™2 Quad Processor.

Example 1: Eight-story three bay by three bay asymmetric structure

With the following example we want to prove the capability of the methodology to work efficiently with a large number of potential damper locations in a realistic structure. In fact we first consider a classical example of an asymmetric reinforced concrete frame introduced by Tso and Yao (1994). This example was studied in Lavan and Levy (2006) where an optimal continuous damping was found; Lavan and Amir (2014) solved the same problem this time finding a discrete optimal damping distribution. A plan and two sections of the structure analyzed are given Fig.1. The dashed lines represent beams and columns that are part of the structure analyzed in this example. The column sizes are $0.5m \times 0.5m$ in frames 1 and 2; $0.7m \times 0.7m$ in frames 3 and 4. The beam sizes are $0.4m \times 0.6m$ and the floor mass is uniformly distributed with a magnitude of $0.75[ton/m^2]$. The optimization was performed considering initially only one size group of dampers ($J = J_1 + J_2 + J_3$, where J_3 is constant and equal to C_{type}) and then two size groups of dampers ($J = J_1 + J_2 + J_3$). The methodology is capable to manage more than two size groups of dampers.

A good choice of the ground motion is one for which the ground motion remains an active constraint at the optimal solution during the process. Active means that the excitation caused by a particular ground motion pushes the structure to its limits, or close to them, during all the optimization process more than the other ground motions in the ensemble. In this work, since displacements are constrained, the record with the maximal spectral displacement has been selected. From the LA 10% in 50 years ensemble LA16 has the largest maximal displacement for reasonable values of damping ratios. Hence, the ground motion considered was LA16 acting in the y direction (Lavan and Levy 2006).

16 potential locations for dampers were assigned, as presented in Fig.1; the allowable inter-story

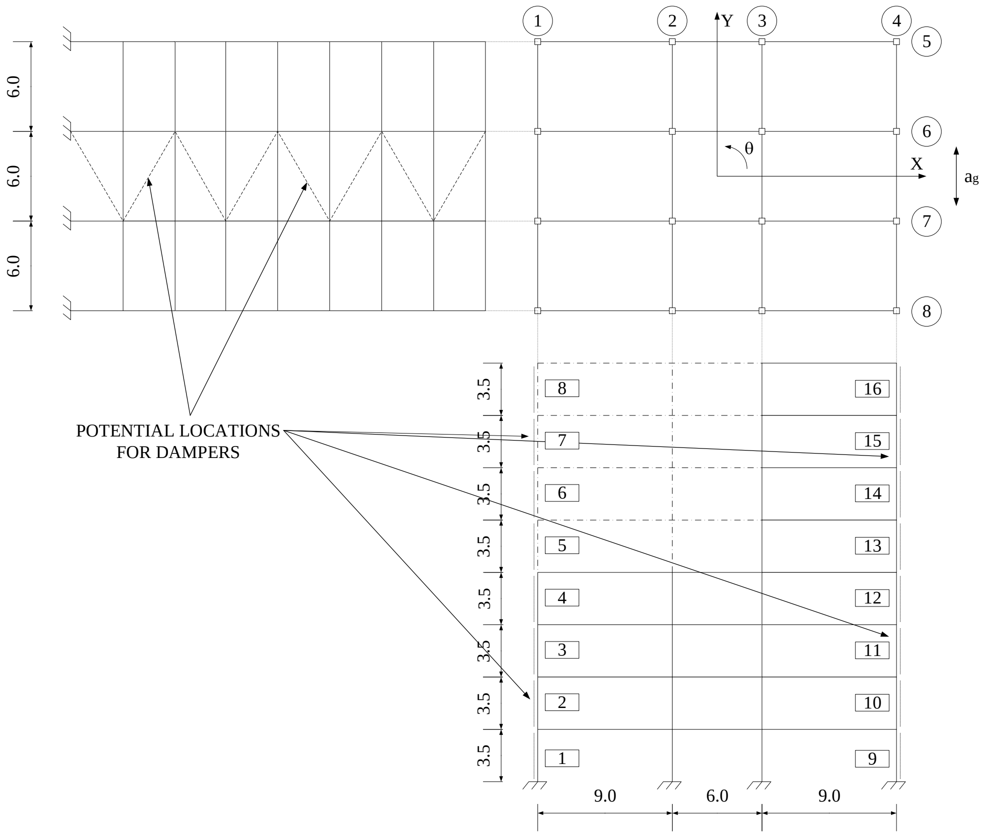

Figure 1: An asymmetric 3D frame structure for examples 1 and 2.

drift was set to $0.035m$. The optimization problem was solved with the following parameters: $C_{m1} = 20000[kNs/m]$, $C_{m2} = 10000[kNs/m]$, maximum nominal damping coefficient $c_d = 50000[kNs/m]$; the scaling factor for the nominal damping coefficient in the optimization that considers only one size group of damper is $0 \leq y_1 \leq 1$, while in the optimization with two size groups of dampers the scaling factors are $0 \leq y_1 \leq 0.5$, $0.5 \leq y_2 \leq 1$ and $C_{type} = 10000[kNs/m]$; population size = 300; maximum number of iteration = 500; to be sure that the algorithm was not badly influenced by local optima 10 different analyses were performed choosing among them the best one.

Considering only one size group of dampers a value of $y_1 = 0.4073$ was obtained, corresponding to an optimized damping coefficient of $\bar{c}_1 = 20366.91[kNs/m]$. The final value of the objective function was $J = 353302.2[kNs/m]$. In Fig.2 is presented the distribution of dampers in the potential locations. In Fig.3 are presented the normalized drifts of the structure with the added damping by the allowable value.

Considering two size groups of dampers the values $y_1 = 0.3236$ and $y_2 = 0.6039$ were obtained, corresponding to an optimized damping coefficient of $\bar{c}_1 = 16180.31[kNs/m]$ for the first size group of dampers, and for the second size group an optimized damping coefficient equals to $\bar{c}_2 = 30197.79[kNs/m]$. The final value of the objective function was $J = 341494.93[kNs/m]$. The chosen locations of the dampers are presented in Fig.4. In Fig.5 are presented the normalized drifts of the structure with the added damping by the allowable value.

This example was also analyzed with an incremented cost parameter C_{type} considering two potential size groups of dampers. This time the value of C_{type} was $30000[kNs/m]$ and the algorithm converged to the expected solution presented in Fig.2 and Fig.3, that is choosing the same size group and the same damping coefficient for all the dampers ($\bar{c}_1 = 20366.91[kNs/m]$). The final cost is analogue to the one size group solution presented above, just shifted according to the increment of C_{type}, $J = 373302.2[kNs/m]$. Nevertheless, further investigations are still needed to explore fully the behavior of this particular case.

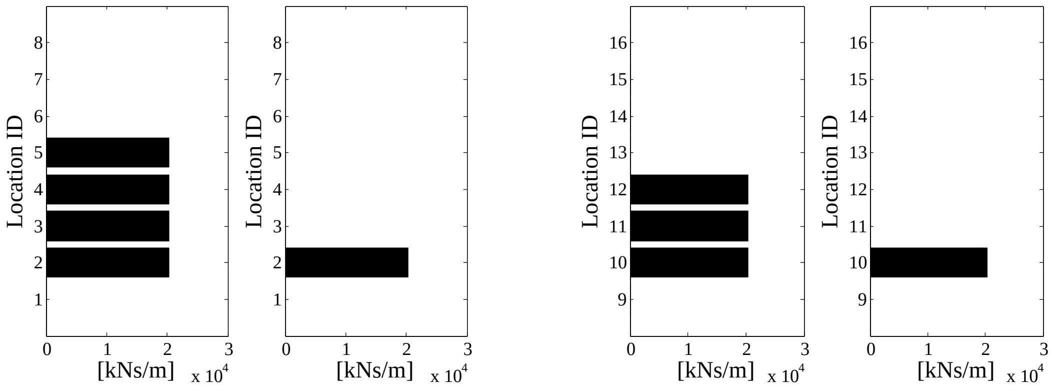

Figure 2: 1^{st} and 2^{nd} damper for each location in 1^{st} ex. considering 1 size group of damper.

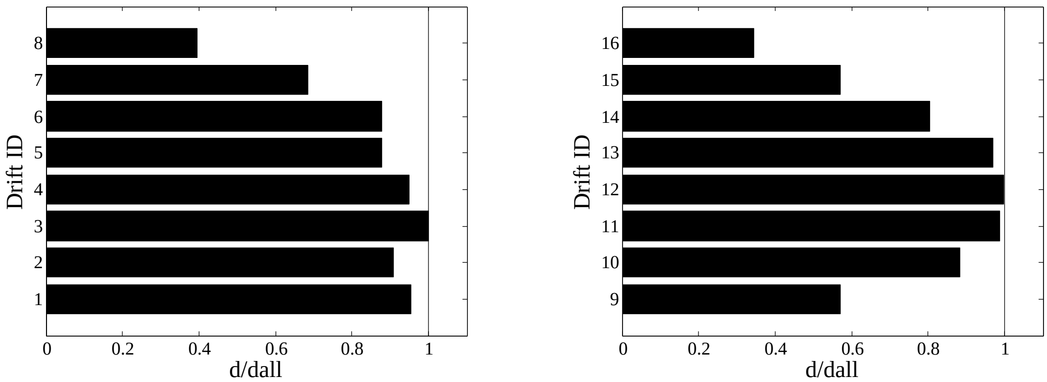

Figure 3: Drifts distribution in 1^{st} ex. considering 1 size group of damper.

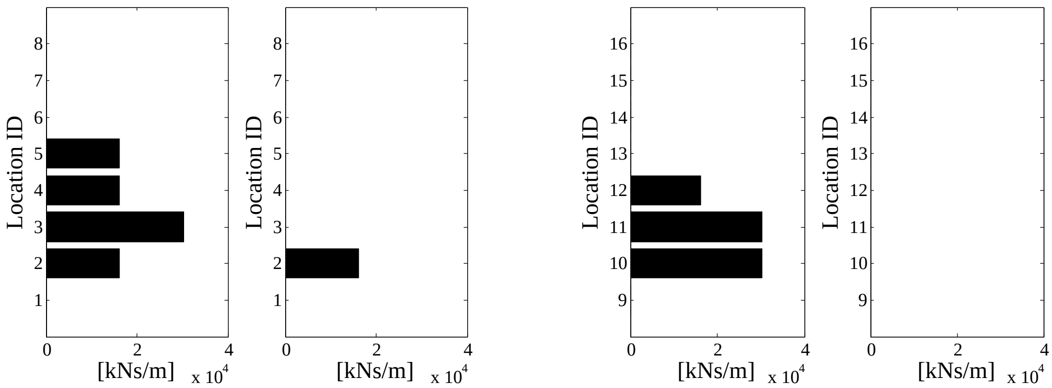

Figure 4: 1^{st} and 2^{nd} damper for each location in 1^{st} ex. considering 2 size groups of dampers.

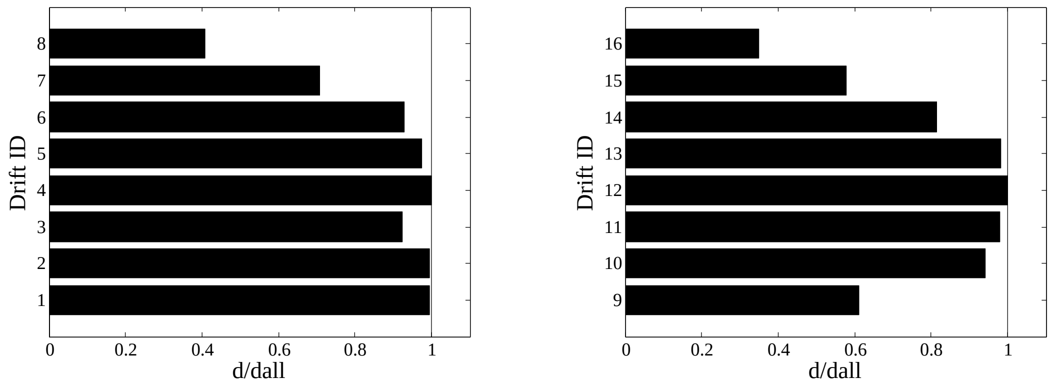

Figure 5: Drifts distribution in 1st ex. considering 2 size groups of dampers.

Example 2: Eight-story three bay by three bay setback frame structure

The second example uses the 8-story 3-bay by 3-bay setback frame introduced by Tso and Yao (1994). Here the topology is that of Example 1 (Fig.1) without the beams and columns marked by dotted lines while retaining the physical properties. Also this example was studied in Lavan and Levy (2006) where an optimal continuous damping was found; Lavan and Amir (2014) solved the same problem this time finding a discrete optimal damping distribution. Again, optimal designs were attained considering a floor mass uniformly distributed with a value of $0.75[ton/m^2]$ and 5% of critical damping was used to construct a Rayleigh damping matrix. Also in this case, between the records of LA 10% in 50 years, LA16 was found to have the largest displacement, hence it was chosen as the record for the ground motion acting in the y direction. This example was studied considering initially only one size group of damper ($J = J_1 + J_2 + J_3$, where J_3 is constant and equal to C_{type}) and then two size groups of dampers ($J = J_1 + J_2 + J_3$), allowing 16 potential locations in analogy with the previous example. The allowable inter-story drift was set to $0.035m$ and the optimization problem was solved with the same set of parameters of the previous example.

Considering only one size group of damper a value of $y_1 = 0.3762$ was obtained, corresponding to an optimized damping coefficient of $\bar{c}_1 = 18807.84[kNs/m]$. The final value of the objective function was $J = 155231.35[kNs/m]$. The chosen locations of the dampers are presented in Fig.6. In Fig.7 are presented the normalized drifts of the structure with the added damping by the allowable value.

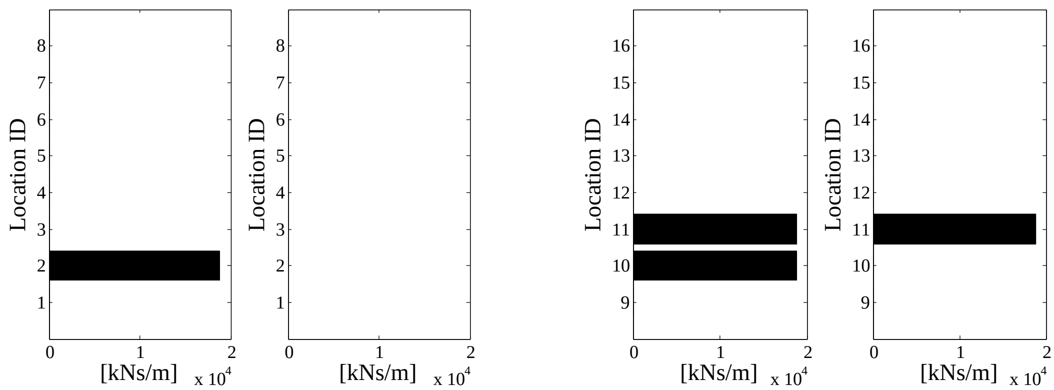

Figure 6: 1st and 2nd damper for each location in 2nd ex. considering 1 size group of damper.

Considering two size groups of damper the values $y_1 = 0.3043$ and $y_2 = 0.5488$ were obtained, corresponding to an optimized damping coefficient of $\bar{c}_1 = 15216.99[kNs/m]$ for the first size group of dampers, and for the second size group an optimized damping coefficient equals to $\bar{c}_2 = 27437.92[kNs/m]$.

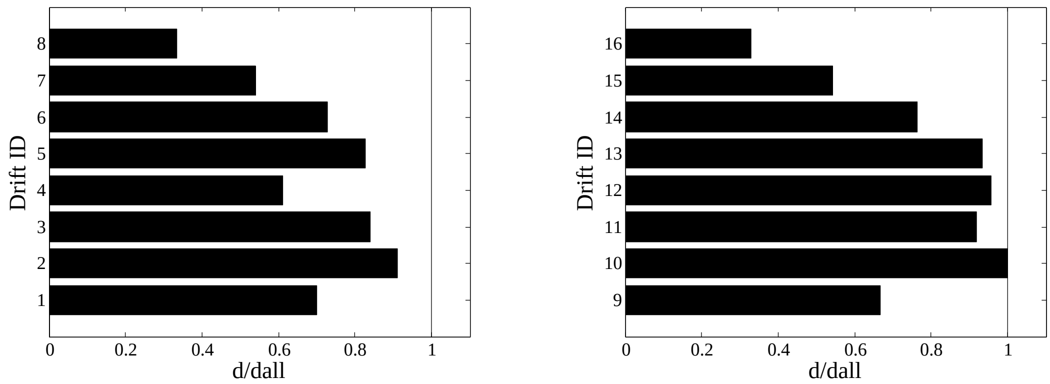

Figure 7: Drifts distribution in 2^{nd} ex. considering 1 size group of damper.

The final value of the objective function was $J = 150092.85[kNs/m]$. The chosen locations of the dampers are presented in Fig.8. In Fig.9 are presented the normalized drifts of the structure with the added damping by the allowable value.

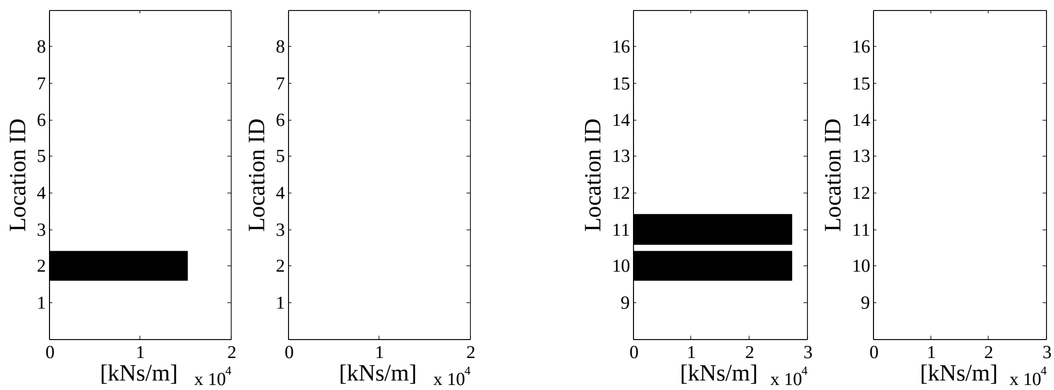

Figure 8: 1^{st} and 2^{nd} damper for each location in 2^{nd} ex. considering 2 size groups of dampers.

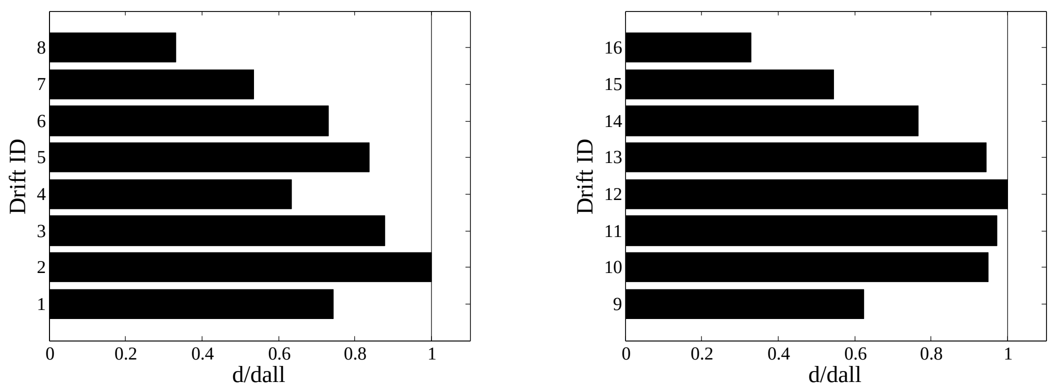

Figure 9: Drifts distribution in 2^{nd} ex. considering 2 size groups of dampers.

CONCLUSIONS

In this paper an innovative formulation for optimal sizing and allocation of viscous dampers was presented. The novelty lies in its cost function, that here plays the role of the objective function in the optimization problem. In fact it mimics the retrofitting cost considering: the architectural obstruction caused by the dampers into the structure; the sum, for all sizes of dampers, of the number of dampers of the given size times the peak force expected in the most loaded damper of that size; and the variety of size groups of dampers involved in the seismic retrofitting. Constraints were assigned on peak inter-story drifts of each story of each peripheral frame separately. These were computed based on a given realistic ground motion. Various effective optimization approaches have been developed recently for minimizing seismic retrofitting costs. The formulation presented herein provides a significant contribution to these efforts. Important results have been achieved, showing the reliability and effectiveness of genetic algorithms in achieving economical solutions when the optimization problem formulated in this paper is applied to realistic 3D irregular frames. Moreover important benchmarks have been produced, assuring solid references for further developments on the subject.

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