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SEISMIC DESIGN AND RETROFIT PROCEDURE FOR TOTAL ACCELERATIONS AND INTER-STORY DRIFTS REDUCTION OF BUILDINGS WITH PROTECTIVE SYSTEMS.

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ABSTRACT

This paper presents a practical analysis based approach for the design of retrofitting of structures by weakening and damping. Alternatively, the algorithm can be used for the design of new structures equipped with viscous dampers to result desired levels of inter-story drifts while reducing total accelerations as well. The values of capping forces and damping coefficients serve as design variables. The capping forces are the yield forces in yielding members and the maximum forces in nonlinear elastic members. The physical behavior of nonlinear structures equipped with added viscous dampers is first analyzed and some insight to the level of capping forces and damping effects is gained. This insight is used to formulate simple intuitive criteria for the design that are then used to formulate a design procedure.

Introduction

For many years seismic design was aimed at preventing loss of human life while permitting a heavy damage to structures and their contents in case of a strong ground motion. Recently, focus has been drawn to limiting both structural and nonstructural damage and the concept of performance-based design has gained prominence. This new approach is intended for structures in general and for important structures in particular. Hospitals, power plants and communication centers, for example, are required to function after an earthquake has occurred. Hence, in the design of a hospital for example, damage to the structure and to the sensitive medical equipment it houses should be limited. Since both the structure and nonstructural components such as infill walls, piping, etc. are sensitive to inter-story drifts, those should be reduced to allowable limits. Medical equipment as well as some nonstructural components such as communication equipment, air-conditioning, etc. are sensitive to total accelerations, hence the reduction of total accelerations has recently gained attention as an additional design objective. Byproducts of the reduction of total accelerations are the reduction of base shear and overturning moment. Unfortunately, when ground motions are considered, reduction of inter-story drifts and total accelerations are two competing objectives.

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Although reduction of both drifts and accelerations leads to a conflict, it has been shown that, in the case of retrofitting, a carefully designed addition of viscous dampers can reduce both (Lavan and Dargush 2009). A new concept of weakening some structural connections in addition to the added viscous dampers has been recently proposed (Viti et al. 2006). It was shown to be able to lead to a further reduction in the total accelerations with respect to retrofitting with viscous dampers only (Cimellaro et al. 2009a; Lavan et al. 2008; Lavan and Dargush 2009; Roh and Reinhorn 2008). Roh and Reinhorn also proposed a practical strategy of weakening concrete frames by cutting the longitudinal reinforcement at some of its columns' edges (Roh and Reinhorn 2008; Roh and Reinhorn 2009). Their experimental tests verified the analytical models they proposed and showed a very good behavior of their "rocking column" strategy with a close to nonlinear elastic behavior. That is, the maximum horizontal force taken by the rocking column is capped while almost no damage is observed. The advantageous nonlinear elastic behavior of rocking elements has been also used in other works ((Christopoulos and Filiatrault 2006) and references therein). They added external mechanisms to dissipate energy by means of hysteretic behavior and result in a flag shape hysteretic loop. An additional advantage of the rocking and the flag shape behaviors is the small residual drifts associated with them.

The concept of having a relatively weak structure and adding dampers to control the inter-story drifts can also be applied to new structures. This can be achieved by integrating the design of the structure with that of the added dampers so as to reduce both drifts and accelerations. In that case a nonlinear elastic behavior of the structure is preferable in preventing structural damage while limiting the maximum internal forces and hence the total accelerations.

Many procedures have been proposed for the design and the optimal design of viscous dampers (Dargush and Sant 2005; Gluck et al. 1996; Hwang et al. 2008; Kim et al. 2003; Lavan and Levy 2005; Lavan and Levy 2006a; Lavan and Levy 2006b; Lavan and Levy 2009; Liu et al. 2005; Shukla and Datta 1999; Silvestri and Trombetti 2007; Singh and Moreschi 2001; Takewaki 1997; Zhang and Soong 1992). Most of those approaches, however, are appropriate for use in cases where the retrofitted structure is assumed to behave linearly. This is, of course, not the case when weakening is concerned since the reduction of total accelerations strongly relies on capping the maximum internal forces. The extension of some methodologies that were proposed for linear structures to cases where the structure is nonlinear is not straightforward, not to say impossible. In addition, most of those methodologies were not aimed at limiting total accelerations and may not be easily modified to do so.

The first step towards the optimal weakening and damping was taken as the design of optimal locations for softening structural connections and added dampers Cimellaro and Reinhorn 2006; Gluck et al. 1996). Here, the design variables are associated with the stiffness of the connections rather than their strength. On the other hand, only a few design methodologies using the new concept of added damping and weakening structural connections, or the integrated design approach, have appeared in the literature (Cimellaro et al. 2009; Lavan et al. 2008; Lavan and Dargush 2009). Those methodologies rely on control theory, optimization theory or both and may not be easily integrated in practical design process.

This paper presents an analysis based approach for the design of retrofitting of structures by weakening and damping. Alternatively, the algorithm can be used for the design of new structures equipped with viscous dampers to result desired levels of inter-story drifts while reducing total accelerations as well. The values of capping forces and damping coefficients serve as design variables. The capping forces are the yield forces in yielding members and the maximum forces in nonlinear elastic members. The physical behavior of nonlinear structures equipped with added viscous dampers is first analyzed and some insight to the strength and damping effects is gained. This insight is used to formulate simple intuitive criteria for the design that are then used to formulate a design procedure.

Behavior of nonlinear structures with high damping (SDOF)

The concept of a nonlinear structure with high damping will now be demonstrated through the SDOF system of Figure 1a that is subjected to ground acceleration. A free body diagram of the mass in an un-damped structure is presented in Figure 1b. The equation of motion of this structure is given by:

$$m\ddot{u}(t) + f(t) = -m\ddot{u}_g(t) \tag{1}$$

where m=system mass; u=roof displacement relative to the base; f=column shear force; $\ddot{u}_g$=ground acceleration; t=time and a dot represents a derivative with respect to time. This equation can also be formulated as

$$m\ddot{u}^t(t) = -f(t) \tag{2}$$

where $\ddot{u}^t$=total acceleration of the mass. This equation implies that the total acceleration of the mass is equal to the negative total shear force in the columns, f, divided by the mass, or $\ddot{u}^t(t) = -f(t)/m$. Hence, since the size of the mass is dictated by other considerations, the maximum value of the shear force in time dictates the total acceleration and is the key variable in controlling it. Limiting the maximal shear force, and hence the maximum total acceleration, could be done by controlling the story capping force of new structures, or by weakening the columns in existing structures, as shown in Figure 1c. In this case of nonlinear behavior of the shear force, the maximum value of the total acceleration is independent of the ground motion input, assuming the maximum force the system can take has been reached. Experience shows, however, that weakening the columns will lead to an increase in the inter-story drifts, which is in contrast to the desired reduction of drifts. Hence, viscous dampers, which are effective in reducing inter-story drifts, can be added. The addition of damping leads to the following equation of motion:

$$m\ddot{u}^t(t) = -(c\dot{u}(t) + f(t)) \tag{3}$$

where c=damping coefficient. That is, the shear force is now the sum of the total force in the columns and in the added damper. At first sight an increase in the maximum shear force, and hence in the total acceleration, might be suspected due to the addition of the damper. In many cases, however, this is not the case due to the out-of-phase velocity based damping forces. Since the maximum of the damping force and the maximum of the restoring force do not occur at the same time (Constantinou and Symans 1992), only a minor increase in acceleration is resulted.

The last statement becomes less valid as the damping force increases with respect to the restoring force. In the limit where the damping force is larger than the hysteretic force, or, the magnitude of weakening is too large, damping forces actually dictate the maximum total shear force and hence the maximum accelerations. Hence, for an effective design of a SDOF system it is suggested to limit the capping force not to be smaller than the maximum damping force.

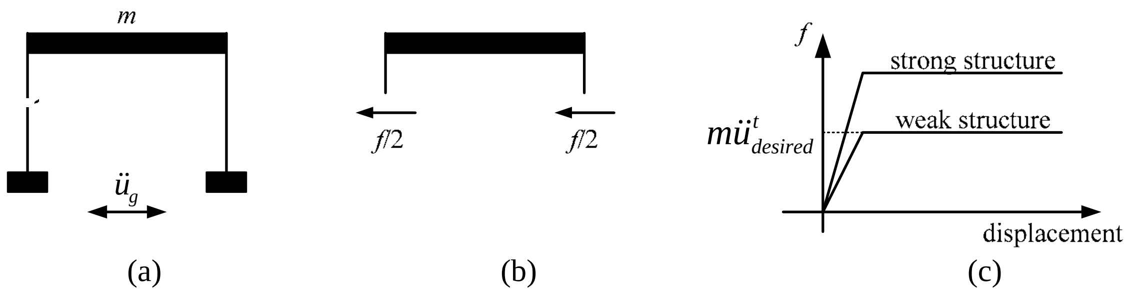


Figure 1. SDOF frame: a) description, b) free body diagram of the mass, and c) strength reduction effect.

Problem formulation (MDOF)

The problem formulation for a Multi-Degree of Freedom (MDOF) structure is comprised of finding the damping coefficients of the added dampers and the capping forces of the different stories. The main objective in the design is limiting the envelope peak interstory drifts while achieving additional reduction in the envelope peak floor total accelerations. Those responses are computed based on the equations of motion for a given ensemble of ground accelerations.

Equations of motion

The general equations of motion of a structure excited by an earthquake and equipped with added linear viscous dampers can be written as:

$$\begin{aligned} &\mathbf{M}\ddot{\mathbf{x}}(t)+[\mathbf{C}+\mathbf{C}_{\mathrm{d}}]\dot{\mathbf{x}}(t)+\mathbf{B}_{\mathrm{fx}}\mathbf{f}_{\mathrm{s}}(t)=-\mathbf{M}\cdot\mathbf{e}\cdot\mathbf{a}_{\mathrm{g}}(t)\;;\mathbf{x}(0)=\mathbf{0},\dot{\mathbf{x}}(0)=\mathbf{0} \\ &\dot{\mathbf{f}}_{\mathrm{s}}(t)=\mathbf{f}(\dot{\mathbf{x}}(t),\mathbf{f}_{\mathrm{s}}(t))\;;\mathbf{f}_{\mathrm{s}}(0)=\mathbf{0} \end{aligned} \qquad (4)$$

where $\mathbf{x}$ = displacements vector of the degrees of freedom (DOFs); $\mathbf{M}$ = mass matrix; $\mathbf{C}$ = inherent damping matrix; $\mathbf{f}_{\mathrm{s}}$ = restoring forces vector; $\mathbf{B}_{\mathrm{fx}}$ =transformation matrix that transforms the restoring forces from their local coordinates to the global coordinates; $\mathbf{e}$ = excitation direction matrix with zero/one entries; $\mathbf{a}_{\mathrm{g}}(t)$=ground motion acceleration vector; $\mathbf{f}$= a given function that represents the hysteretic rule; and $\mathbf{C}_{\mathrm{d}}$= added damping matrix whose entries are functions of the damping coefficients of the added dampers.

Design variables

Using the weak structure with added damping concept for new structures, or the damping and weakening approach for existing ones, the engineer has the freedom of choosing values for the damping coefficients of the added dampers and for the capping forces of structural members.

Of course, practice often assigns constraints on those values. In addition, their coupling with other structural properties such as stiffness should be considered. That is, a change in stiffness may need to be considered with the change of capping force, depending on the weakening technique chosen.

Design objectives

Peak interstory drifts are a widely used measure for both structural and nonstructural damage of some nonstructural components. Hence, limiting the peak interstory drift of each story separately is the main objective considered here for design. The peak interstory drift of the story *i* for a given ground motion is given by:

$$d_i = \max_t \left(\left| u_i(t) - u_{i-1}(t) \right| \right) \tag{5}$$

where d_i=peak interstory drift of the story *i* and u_i=displacement history of the floor *i*. Of course, in the case where a design for an ensemble of records is considered, limiting the envelope or mean plus standard deviation of the peak drift of each story could be considered.

An additional measure that has gained attention lately is the peak floor total acceleration. A large total acceleration may cause damage to acceleration sensitive equipment and nonstructural components. In addition, a large total acceleration may cause objects in the structure to move around and hurt occupants. The peak floor total acceleration of the floor *i* for a given ground motion is given by:

$$a_i = \max_t \left(\left| \ddot{u}_i(t) + a_g(t) \right| \right) \tag{6}$$

where $\ddot{u}_i$=peak floor total acceleration of the floor *i*. Again, in the case where a design for an ensemble of records is considered, the envelope or mean plus standard deviation of the peak total acceleration of each floor could be considered as a measure. It should be noted in passing that byproducts of the reduction of total accelerations are the reduction of base shear and overturning moment.

Since inter-story drifts and total accelerations are competing objectives, limiting both to desired values may result no feasible solution. Hence, the main objective in this work is limiting the envelope peak interstory drifts while achieving additional reduction in the envelope peak floor total accelerations. This is done by the computation of appropriate values for the added damping coefficients and the capping forces of structural elements.

Design procedure

Practical design procedures, whether optimal or not, usually rely on analysis tools only. More complex methods that require sophisticated tools and theoretical knowledge do not, in general, naturally integrate into the design process. The practical design procedures vary from the primitive trial and error methods where the engineer executes analysis to an initial design of the structure and makes changes based on his intuition, to more sophisticated analysis/redesign methods where the recurrence relation used in each trial actually targets an optimality criterion and leads to an optimal design. Such optimality criteria for static problems were proposed as early as 1990 (Cilley 1900) and were later shown to actually lead to the optimal design (Levy 1985). For example, simple analysis/redesign schemes have been widely used for the practical design of trusses under static loads. Using this iterative procedure the engineer assumes initial sections for the bars of the truss and performs an analysis. Then, based on the stress in each bar and a predefined recurrence relation the cross section area is modified. A new analysis is then carried out using the new cross sections and so on. In this case the cross section area is the design variable and the stress is the performance index which is constrained to an allowable value. In this traditional scheme the characteristic of the optimal design that is targeted is called Fully Stressed Design (FSD) where all the bars with nonzero area reach their allowable stress and all bars with zero area having strains less than the allowable. Using the analysis/redesign scheme the engineer would use a heavier section in the next iteration where the stress is larger than allowed and a lighter section where the stress is smaller, thus target a FSD. The author proposed a similar technique for minimizing the total added viscous damping in linear framed structures as well as nonlinear shear frames, where constraints were assigned to inter-story drifts and story hysteretic energy, respectively (Levy and Lavan 2006). The recurrence relation that was used is based on a "FSD" characteristic of optimal designs attained by a formal optimization method (Lavan and Levy 2005; Lavan and Levy 2006a; Lavan and Levy 2006b).

In the heart of analysis/redesign based methods is the strong dependency of each of the local performance indices on the corresponding design variable. For example, in the truss problem the stress in a bar is strongly dependent on its area. In the dynamic problem the inter-story drift strongly depends on the total added damping at the same story. Such a dependency does not exist, however, between the total acceleration of a floor to the strength of the columns above or below it, excluding the top floor. In cases where added damping is also considered, the behavior of the total acceleration and its dependence on the different design variables is even more complex. It is therefore necessary to gain more understanding of the behavior of the problem in order to develop different criteria for the design of capping forces so as to reduce the accelerations. Based on the discussion related to the behavior of a nonlinear SDOF system with high damping above, it is suggested here to design the capping forces in the stories such that the maximum forces exerted on the floors by the restraining system are similar to those exerted by the dampers. Those forces are actually the difference in story shear forces rather than the shear force in a specific story. Hence, at the limiting case where all stories reach their capacity this force equals the difference in the capping shear forces of the stories above and below. As for the damping system, the difference in shear forces should be taken as well. Now, since this requirement holds for all floors, keeping the level of capping shear force equal to that of the maximum damping force in each story is expected to lead to similar peak damping forces and peak restoring forces on the mass as well. It is hence suggested to design the dampers to lead to the allowable drifts while reducing the story capping shear forces to a level similar to the maximum damper forces. This concept is implemented by an iterative process that will now be described in more detail.

In each iteration the dampers are designed based on the inter-story drifts using the recurrence relation

$$c_{d\,i}^{(k+1)} = c_{d\,i}^{(k)} \left(\frac{d_i^{(k)}}{d_i^{all}} \right)^{\frac{1}{q}} \tag{7}$$

where $c_{di}^{(k)}$=damping coefficient of the story i at the iteration k; $d_i^{(k)}$=peak interstory drift of the story i at the iteration k; d_i^{all}=allowable drift of the story i; and q=convergence parameter with a suggested value of 0.5. Based on the previous discussion, the story capping shear forces are designed to be equal to the maximum damper forces. This is targeted by the following relation

$$F_{c\,i}^{(k+1)} = \frac{F_{c\,i}^{(k)} + c_{di}^{(k+1)} v_i^{(k)}}{2} \tag{8}$$

where $F_{ci}^{(k)}$=capping force of the story i at the iteration k and where $v_i^{(k)}$=peak interstory velocity of the story i at the iteration k that is given by

$$v_i^{(k)} = \max_t \left(\left| \dot{u}_i^{(k)}(t) - \dot{u}_{i-1}^{(k)}(t) \right| \right) \tag{9}$$

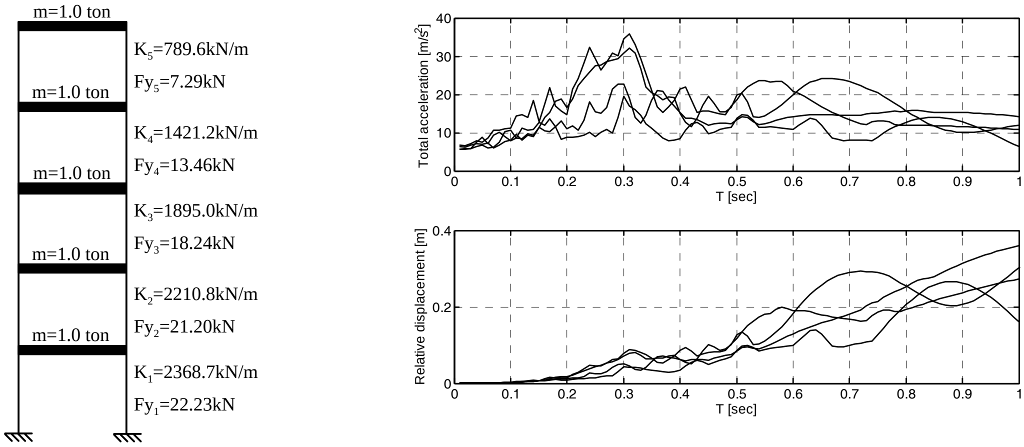
The proposed design procedure is summarized in Table 1.

Table 1. Proposed Design procedure.

Stage 1	Assume starting values for the added dampers and capping forces.
Stage 2	Perform a nonlinear time history analysis, using the current added damping vector and capping forces by solving the equation of motion (Equation 4) and evaluate the inter-story drifts and velocities as well as total accelerations based on Equations 5, 9 and 6, respectively. In case of an ensemble of ground motions envelope or mean plus standard deviation values could be considered for each story.
Stage 3	Redesign the added damping vector and the capping force vector using Equations 7 and 8 respectively.
Stage 4	Return to Stage 2 if the changes in the objective function or in the damping vector and capping forces for two subsequent iterations is not sufficiently small.

Example

Although the proposed methodology is not claimed to lead to optimal results it is interesting to compare its designs to those attained by optimization schemes. Hence the 5 story yielding shear frame of Figure 2a, originally presented by Lavan and Dargush (2009) is adopted. As in Lavan and Dargush (2009) an elastic perfectly plastic hysteretic rule is assumed and the ground motion ensemble considered is comprised of the LA13, LA14, LA16 and LA17 ground motions (see (Somerville et al. 1997)). Response spectral values of those ground motions are plotted in Figure 2b. Lavan and Dargush (2009) made use of Genetic Algorithms (GA) to find the Pareto front for the case of minimizing both maximum envelope peak inter-story drifts of all stories and maximum envelope peak total accelerations of all floors. In a nonformal sense, each design on the Pareto front is optimal in the sense that there is no possible design for which the value of one of the objectives is smaller while the value of the other objective is not larger. Since the proposed methodology is not a multi-objective optimization scheme different designs are attained by solving the problem for different values of d_i^{all}.



(a) (b)

Figure 2. a) Five story shear frame, and b) response spectral values of the ground motions.

The total accelerations versus inter-story drifts for the attained designs are presented in Figure 3. Also presented is the Pareto front attained by the GA approach. The plotted drifts and accelerations are normalized by 0.1m and 2.5g, respectively, as in Lavan and Dargush (2009).

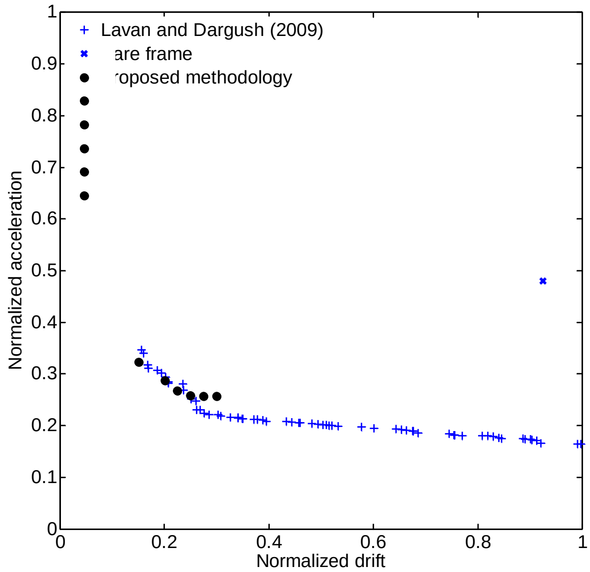


Figure 3. Pareto fronts attained by the GA approach and by the proposed methodology.

As can be seen the proposed scheme leads to very close results to those attained by the GA approach when it comes to small drifts. In fact, it seems to lead to better reductions in both inter-story drifts and total accelerations at some points. The author suspects that this can be attributed to the fact that using the proposed approach a continuous range of values is considered for the damping and the weakening sizes while in the GA approach a discrete set of values was considered. Furthermore, in the GA approach the size of dampers is limited by the maximum size considered while the proposed approach did not consider an upper bound. Nonetheless, the results are very encouraging since the proposed methodology leads to close results to those attained by the GA approach in the range of interest.

Conclusions

A practical, analysis based, design methodology for weakening and damping buildings was presented. The methodology is also applicable for the design of new structures equipped with viscous dampers. It is aimed at limiting the maximum envelope peak inter-story drift of all stories while reducing envelope peak total accelerations of the floors. The method shows a very fast convergence while leading to equal drifts of all storied while a close to uniform total acceleration pattern is observed.

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