EVOLUTIONARY ASEISMIC DESIGN AND RETROFIT OF BUILDINGS

Seda Dogruel[1], Gary F. Dargush[2], and Mark L. Green[3]

ABSTRACT

Over the past decade, passive energy dissipation systems have provided an increasingly attractive approach for the seismic retrofit of existing structures, as well as, for the design of new seismically resistant structures. Many different types of passive devices have been developed and general design guidelines have been prepared. However, the choice between the device types for a specific application often is not clear, particularly when consideration must be given to the performance of non-structural components. For example, in general, are rate-independent devices and rate-dependent devices equally beneficial, or are there circumstances in which one of these two categories is preferable? Furthermore, regardless of device type selection, the designer also is faced with the complex issue of effective device distribution.

In this paper, we present a genetic algorithm based methodology to address these aspects of aseismic design within the context of steel frame buildings. The primary structure is represented in terms of a nonlinear two-surface plasticity lumped parameter model. Meanwhile, the available passive device types include rate-independent metallic plate dampers, along with rate-dependent viscous fluid dampers and solid viscoelastic dampers. In order to capture more accurately the dynamic response, these devices are also represented by nonlinear models. The seismic environment is characterized either in terms of a fixed set of specified ground motions or by utilizing synthetic signals generated from geophysical models that simulate the actual uncertain seismicity of the site. Within the overall algorithm, passively damped structural designs evolve toward configurations that satisfy constraints on inter-story drift and absolute acceleration, while attempting to limit damper cost. For adjacent buildings, a separation constraint also may be included to alleviate structural pounding. Besides providing an overview of the simulation algorithm, the paper includes a number of illustrative examples to highlight the benefits of the proposed computational design approach.

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passive energy dissipation, structural control, optimization, genetic algorithms

INTRODUCTION

Energy dissipation devices are recently becoming more widespread in the seismic control of civil engineering structures and a large variety of device types are available, including metallic yielding dampers, friction dampers, viscous fluid dampers and viscoelastic dampers (e.g., Soong and Dargush 1997, Constantinou et al. 1998). While the structural design is modernized with the introduction of these passive energy dissipation systems, many questions also naturally arise. Other than the concept of arranging and designing the members of a structure in order to provide sufficient safety and allow efficient construction, cost and feasibility are the other objectives of the engineer in the design of structures. Within the perspective of passive energy dissipation devices, the possible questions, which might be raised, can vary from performance and durability issues to concerns related to distribution, selection of the proper size and type of passive device. At a given site, are there advantages to one particular type of passive device? Should devices be distributed uniformly throughout the height of a uniform structure? Is it beneficial to include both rate-dependent and rate-independent devices in a single structure? What damper distribution should be employed for irregular structures?

Structural design optimization methodologies have been investigated for the past two decades and continue for the development of design guidelines and procedures for passive energy dissipation systems. Many researchers have suggested different schemes for optimal design of energy dissipation devices, such as the optimal sequential search algorithm, control theory method, single point substitution method, steepest directions search algorithms, genetic algorithms (Furuya and Hamazaki 1998, Singh and Moreschi 2000, Dargush, Green and et al. 2002), and general optimization methods (Takewaki 2000, Wu et al. 1997). Furuya et al. (1998) examined the application of genetic algorithms (GA) for damper distribution. In particular, they attempted to establish a suitable combination of dampers for structural response control of a 40-story building under a specified wind excitation, along with some economical considerations. More recently, Singh and Moreschi (2000) studied both the optimal number and optimal distribution of dampers for seismic response control of a 10-story building. The results of Singh and Moreschi (2000) showed that the number of dampers needed using an optimal distribution is considerably less than that needed when a uniform distribution is employed.

These procedures are mostly restricted to linear structural and damper response. On the other hand, Singh and Moreschi (2002), Dargush and Sant (2002, 2005) have considered nonlinear behavior for aseismic design using genetic algorithms. In this paper, we extend the evolutionary aseismic design and retrofit approach defined in Dargush and Sant (2005). This approach provides insight into seismic performance, as well as the reliability of the passive energy dissipation devices and some key factors in order to evaluate costs and benefits. With all of these objectives, we may develop a general computational framework that promotes evolution of robust aseismic design and retrofit of single or adjacent structures subjected to fixed or uncertain seismic environments through the development of a new multi-level genetic algorithm. The base structures may contain a number of metallic yielding dampers, viscous fluid dampers and/or viscoelastic solid dampers over a range of sizes. The seismic environment is characterized in a manner consistent with the MCEER Northridge Ensemble (*2%* PE in *50* years; *25* ground motions) (Filiatrault and Wanitkorkul 2005) and the synthetic ground motion generation algorithm developed by Papageorgiou (2000) is utilized for each realization. In order to estimate seismic performance for each potential design configuration, a series of transient dynamic analyses are conducted utilizing an explicit state-space approach. A graphical user interface also is created to enable a visual display of the evolving designs and to provide a means to interrogate the database. However, these interactive aspects are not addressed in the present paper. Instead, we focus on the results obtained from a number of numerical simulations in order to elucidate the methodology and to assess the potential benefits of the approach for aseismic design in both regular and irregular structures.

COMPUTATIONAL FRAMEWORK

Genetic Algorithms

First found by Holland (1975), genetic algorithms have been widely studied and applied in many fields in engineering. The GA is an adaptive heuristic optimization technique that makes use of a population-based search strategy. The texts by Goldberg (1989) and Mitchell (1996) provide good introductions to the subject. The following sections include a brief description of the basic formulations and algorithms employed for structural modeling, and design evolution. More specific details on the structural model and evolutionary methodology can be found in Dargush and Sant (2005).

Evolutionary Methodology

The primary objective is to develop an automated approach that can identify the optimized design or retrofit of both single and adjacent structures under fixed or uncertain seismic environments. Figure 1 depicts the overall approach for computational aseismic design and retrofit, again utilizing terminology from evolution theory. In the baseline analysis, a population of individual structures is generated from a specified number of iterative generations. Within each generation, each structure is subjected to a specified number of environmental conditions. Whenever the drift, acceleration or separation performance criteria are not met for a given earthquake excitation, a failure occurs. Failure is also possible during other seismic events for that individual within the current generation. This approach tends to promote the development of more robust structures. The design process involves a sequence of generations. In each generation j for $j = 0, 1, 2, \ldots, n_g$ the population of n_p structures is defined and evaluated. The design of each structure s is encoded by a binary string of length N_l. Thus, the space of possible structures S has $N_s = 2^{N_1}$ members. We assume, in general, that there may be uncertainty in the structural system, the seismic environment, and the economics. Consequently, as indicated in Figure 1, each evaluation involves the realization of the structure and appropriate ground motions. The fitness values, along with random genetic operators modeling selection, crossover, and mutation processes, define the makeup of the next generation of structures.

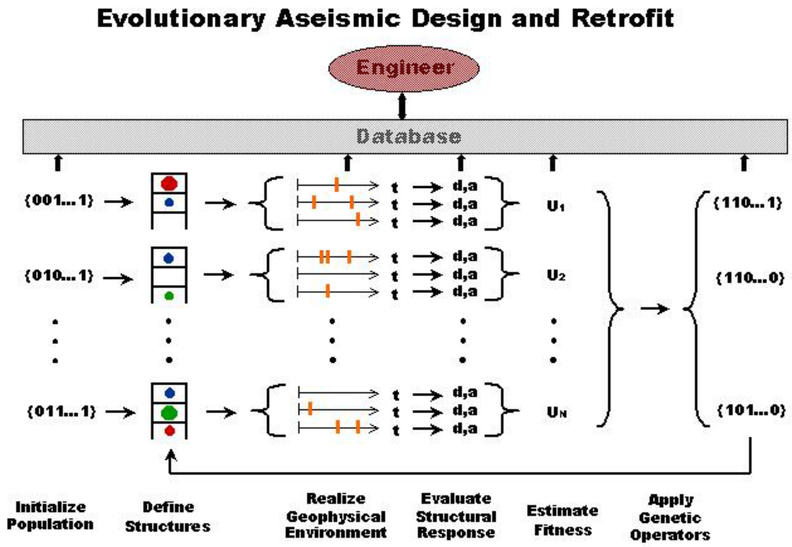


Figure 1. Overall framework

Structural Models

A uni-axial version of a two-surface cyclic plasticity model (Tseng and Lee 1983, Banerjee et al. 1987, Chopra et al. 1998) is implemented for the nonlinear transient dynamic finite element analysis of the structures. Additionally in this research, the same two-surface plasticity model has been applied for metallic dampers. A coupled thermoviscoelastic Maxwell model with inelastic heat generation is used for viscoelastic dampers. Meanwhile, the viscous dampers are modeled as strictly linear Newtonian devices, with force proportional to velocity. Further information on the mathematical models that are employed for passive energy dissipation devices can be found in Dargush and Soong (1995), Constantinou et al. (1998), and Dargush and Sant (2005). Typically, interstory drift, story acceleration and, in some cases, a separation constraint between adjacent buildings are used to evaluate performance and potential damage. Realized costs, along with these performance measures, are then employed to determine fitness value of the design.

Computational Simulations

We will consider a series of examples involving steel frame structures with various retrofit possibilities, in order to illustrate the methodology clearly, rather than to provide guidance for specific design situations. The structures are simplified as lumped parameter models. In order to set the stage for those investigations, the present section details the generic formulations and properties employed in the simulations. Fitness U of each structure based upon the following form:

$$U = B - C - D$$

where B, C, and D are random variables representing the economic benefit derived from the structure, the cost of passive dampers and the damage cost associated with the seismic environment.

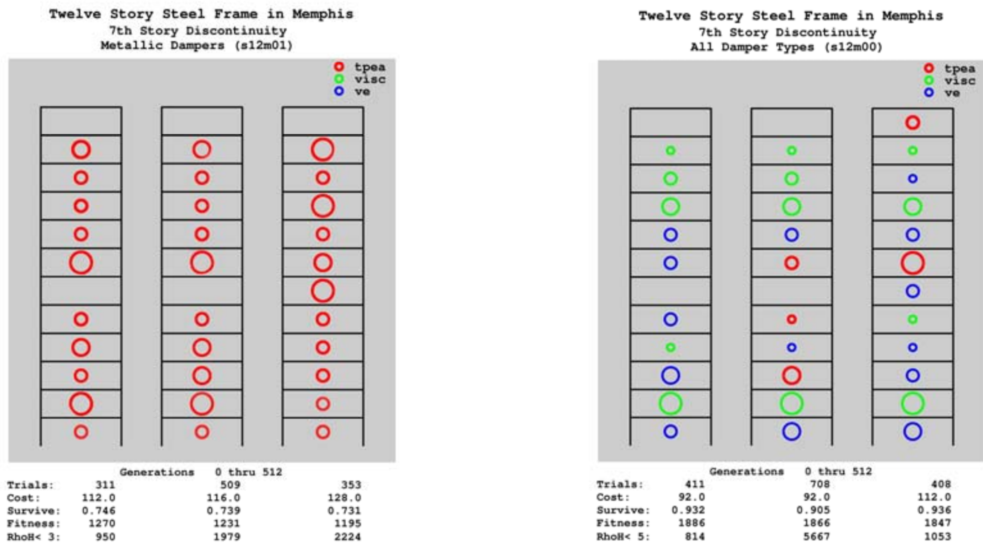
Twelve Story Steel Frame with Discontinuity

As a first example, we start with a twelve-story structure. Let W_i and k_i represent the i^{th} story weight and stiffness, respectively. The baseline steel frame model has story weights $W_1 = \ldots = W_6 = W$, $W_7 = W_8 = 3W/4$, $W_9 = \ldots = W_{12} = W/2$ and stiffness $k_1 = \ldots = k_6 = k$, $k_7 = \ldots = k_{12} = k/4$. Notice that there is a strong discontinuity at the seventh story. The parameters W and k are chosen such that the first two natural frequencies are *2.0*sec and *0.91*sec. Additionally, the lumped parameter two-surface cyclic plasticity model mentioned above is employed to represent the hysteretic behavior of the primary structure. Within that model, let F_{yi}^L represent the yield force on the inner loading surface for the i^{th} story and $F_{y1}^L = \ldots = F_{y6}^L = 0.20W$, $F_{y7}^L = \ldots = F_{y12}^L = 0.05W$. The maximum structure benefit is set at $B_{\max} = 2000$. Damper costs vary from *4* to *20* units depending on size. Very strict limits on interstory drift and story acceleration are imposed.

Assuming that this structure is situated on firm ground in Memphis, TN, it is found that that the baseline design without passive dampers survives less than 30% of the significant earthquakes, according to the definitions for magnitude and distance cut-offs, and the proposed drift and acceleration limits. Using the results from four simultaneous simulations, a number of robust designs is observed when the building is retrofitted with triangular metallic (tpea) dampers only, including those presented in Figure 2a. Here and in all subsequent structural diagrams, the size of the rings denotes damper size, while ring color indicates damper type. It should be that the leftmost design has a significant earthquake survival rate of approximately 75% and a fitness of nearly *1300*.

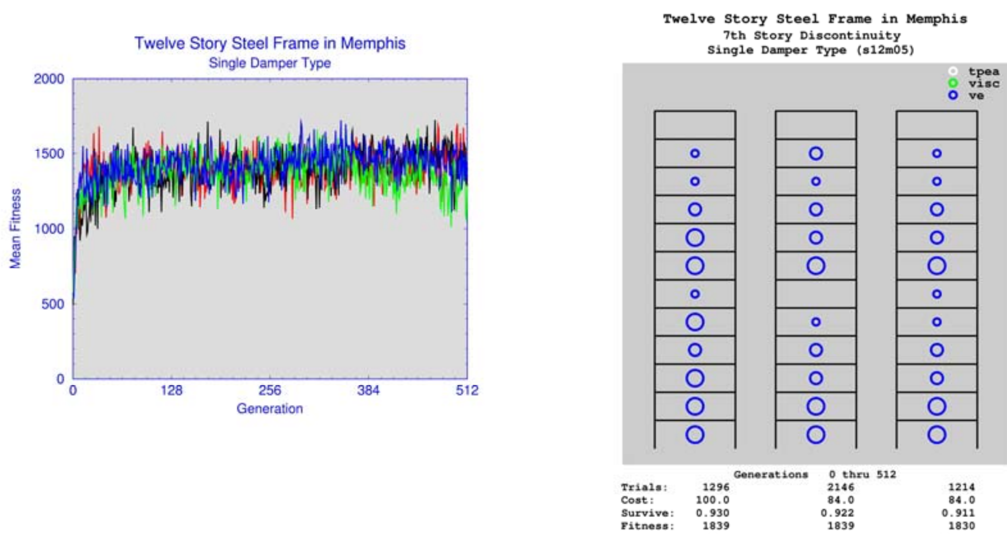
However, in these simulations only metallic dampers were permitted. Next, we expand the design space to permit all three damper types, including metallic (tpea), viscous (visc) and viscoelastic (ve) devices. The results are presented in Figure 2b. Now survival rates have increased to over 90% and the fitness values are well above *1800*. These are clearly more robust designs than those presented in Figure 2a. During each simulation, many design configurations are tested. The structures presented are those designs that appear most frequently in the design pool. These designs typically survive over many generations under variable environments and thus can truly be considered as the most robust structures. Notice also that the evolutionary algorithm apparently recognizes the structural discontinuity at the seventh story and designs accordingly.

Although several robust designs are presented in Figure 2b, notice that two of the three incorporate all three damper types. However, this is not likely to yield a practical rehabilitation scenario. Next, we constrain the simulations to permit only a single damper type in a given structure. Results are presented in Figure 3b. The left-hand plot Figure 3a displays the evolution of mean fitness for four simulations using different initial seeds. The mean fitness tends to increase rather quickly before hovering around *1500*. The variability is due to the uncertain environment and the on-going need to explore new regions of the design space. The three robust designs presented in Figure 3b again have survival rates above 90% and fitness values significantly over *1800*. Interestingly, viscoelastic (ve) dampers are selected for all of these robust design alternatives.



(a) (b)

Figure 2. Twelve story steel frame in Memphis - robust designs



(a) (b)

Figure 3. Twelve story steel frame with viscoelastic dampers: (a) average fitness; and (b) robust designs

Adjacent Steel Frames: Eight-story steel frame and Five-story steel frame

The proposed methodology for adjacent building retrofit design is illustrated with the pair of structures, involving an eight-story steel frame and a five-story steel frame. Let W_i and k_i represent the i^{th} story weight and story elastic stiffness, respectively. The baseline frame models have following properties.

Eight-story steel frame: The baseline frame model has non-uniform weight and stiffness distribution, such that: $W_1 = \ldots = W_4 = W$, $W_5 = \ldots = W_8 = 0.75W$, $k_1 = \ldots = k_4 = k$, $k_5 = k_6 = 0.75k$, $k_7 = k_8 = 0.50k$, where $W = mg$ and $k = 1.7\bar{k}$. The parameters W and k are chosen to produce fundamental natural period $T_1 = 1.200$ sec. Additionally, the lumped parameter two-surface cyclic plasticity model defined in Dargush and Soong (1995) is employed to represent the hysteretic behaviors of the primary steel structure. Within the model, let F_i^{yL} and F_i^{yB} represent the yield force on the inner loading surface and on the outer loading surface for the i^{th} story, respectively. Here, $F_i^{yL} = 1.5W\, k_i/k$ and $F_i^{yB} = 4F_i^{yL}$. Additionally, the story height of the eight-story steel frame is chosen to be 4.27 m (168 in).

Five-story steel frame: The baseline frame model has uniform story weight and stiffness distribution, such that: $W_1 = \ldots = W_5 = W$, and $k_1 = \ldots = k_5 = k$, where $W = 1.6mg$ and $k = 3.2\bar{k}$. The parameters W and k are chosen to produce fundamental natural period $T_1 = 0.844$ sec. Within the primary structure model, let F_i^{yL} and F_i^{yB} again represent the yield force on the inner loading surface and on the outer loading surface for the i^{th} story, respectively. Here, $F_i^{yL} = 2W$ and $F_i^{yB} = 3F_i^{yL}$. Furthermore, the story height of the five-story steel frame is chosen to be 4.27 m (168 in).

The results of three simulations for this pair of structures are shown in Figures 4, 5 and 6. In Figure 4, the structures are assumed to be well-separated and therefore designed independently. Notice that the design solution survives all *25* of the specified ground motions. On the other hand, the structural design displayed in Figure 5 results from the consideration of the separation constraint for close spacing of the two buildings. Notice that, compared with the Figure 4 structural designs, additional large dampers are incorporated in the preferred solution. Finally, in Figure 6, the simulation assumes that only the eight-story structure is considered for retrofit. Now the passive devices cannot fully protect the building from pounding damage and the optimal system survives only twelve of the specified earthquakes. The optimization problem considering the number, the size, and the position of passive energy dissipation devices in adjacent structures can also be described as a multilevel optimal design model, since multilevel genetic algorithm is a powerful global search technique. However, space limitations prevent a further discussion here.

CONCLUSIONS

Over the past decade, passive energy dissipation systems have become a remarkable technology for aseismic design and retrofit of both single and adjacent structures. Although several different design approaches are presently under development, here we present a

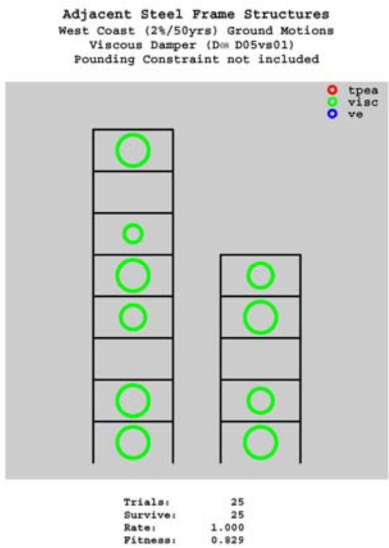


Figure 4. Adjacent steel frames: Pounding constraint not included

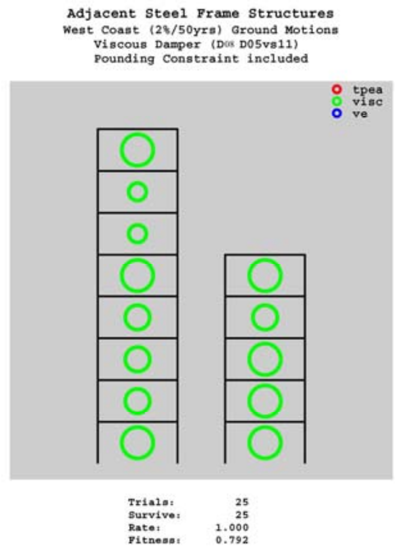


Figure 5. Adjacent steel frames: Pounding constraint included

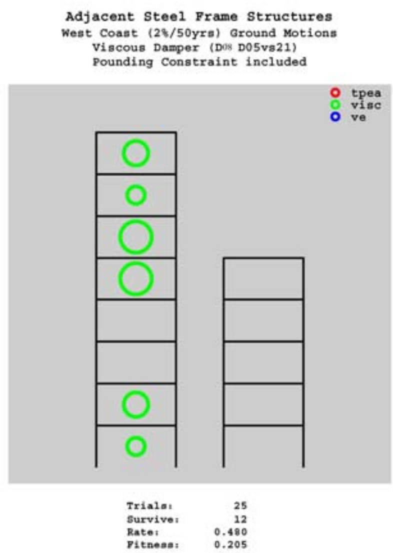


Figure 6. Adjacent steel frames: Pounding constraint not included (only 8-story building is retrofitted)

computational framework based upon evolutionary algorithms that has considerable potential, especially for irregular structures. In this paper, it is verified that the proposed methodology that includes the specific models for the passive-control devices; and allows arbitrary structure models (arbitrary story number, story height, story mass) and arbitrary distribution of the dampers, appears suitable for design analysis to determine optimal damper specification (parameters, damper size, and costs). In numerous case studies, the system is able to discover robust designs in an uncertain seismic environment. A number of examples illustrating the performance of the algorithm have been presented in this paper. The overall evolutionary framework is quite general and can easily accommodate improved geophysical, structural, damage and even socioeconomic models, as these become available. In addition, the algorithms scale well with increasing problem size and are naturally parallel. Consequently, continued development of the methodology appears to be beneficial, particularly in light of the anticipated concurrent advancement of massively parallel computing hardware and grid computing technologies.

Furthermore, the extensions of the evolutionary approach to multi-hazard structural design and retrofit are clearly feasible. Beyond the engineering concerns, there are also many associated issues. For example, what are the socioeconomic consequences of various retrofit strategies? What degree of protection is appropriate? How much risk is acceptable for a building owner? How does the performance of this structure affect the disaster-resiliency of the community? The evolutionary methods presented here may provide an effective framework in which to study some of these issues as well.

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