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EVOLUTIONARY ASEISMIC DESIGN AND RETROFIT OF PASSIVELY DAMPED IRREGULAR STRUCTURES

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SUMMARY

In this paper, we develop a parallel genetic algorithm-based approach for discrete optimal design of passively damped structural systems within an uncertain seismic environment. The primary structure may contain metallic yielding dampers, viscous fluid dampers or viscoelastic solid dampers of various sizes, distributed throughout the building. For each candidate design, a series of nonlinear transient dynamic analyses are conducted within a spatially-distributed seismic environment consistent with the USGS Gutenberg-Richter model for eastern North America. A graphical user interface also is created to enable visual display of evolving designs and to interactively interrogate the design database. Several examples are considered to elucidate the methodology and to assess the potential benefits of the evolutionary approach for seismic design and retrofit. While this methodology is sufficiently general to consider a broad range of structural systems, here the emphasis is placed on steel frame buildings with structural irregularities.

INTRODUCTION

Passive energy dissipation systems are now widely used for the seismic control of civil engineering structures and a wide variety of device types are available, including metallic yielding dampers, friction dampers, viscous fluid dampers and viscoelastic dampers (e.g., Soong [1]; Constantinou [2]). While the introduction of these passive energy dissipation concepts and systems presents the structural engineer with considerable freedom in aseismic design and retrofit, further guidance may be needed to help direct the design process. In order to address this issue, several simplified design procedures have been in

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development over the past decade (e.g., FEMA [3-6]). These procedures are oriented mostly toward the design of simple uniform structures. Alternatively, one may attempt to develop new computational approaches that can provide insight into seismic performance, as well as design guidance both for simple structural systems and for more complicated irregular structures.

Here we adopt this latter approach and continue our development of an evolutionary approach for aseismic design and retrofit with special focus on irregular structures. Previous research on the application of genetic algorithms to passively damped structures includes the work by Singh [7-9] and Dargush [10-14]. In particular, we extend the latter approach by introducing a parallel genetic algorithm for the discrete optimal design of passively damped structures within an uncertain seismic environment. The primary irregular structure 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 USGS database for eastern North America (Frankel [15, 16]) and the synthetic ground motion generation algorithm developed by Papageorgiou [17] 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 is also created to enable a visual display of the evolving designs and to provide a means to interactively interrogate the database. Several examples are examined in order to elucidate the methodology and to assess the potential benefits of the approach for aseismic design of irregular structures.

COMPUTATIONAL FRAMEWORK

Overview

In this section, we provide an overview of the proposed computational approach for aseismic design and retrofit. The following subsections include a narrative description of the basic formulations and algorithms employed for structural modeling, geophysical modeling and design evolution. More specific details on the structural model and evolutionary methodology can be found in Dargush [13, 14].

Structural Model

For non-uniform structures, a nonlinear transient dynamic analysis is often needed in order to assess the performance of a given design or retrofit option. In the present work, we employ a lumped parameter representation for both the primary structure and passive elements.

The behavior of the primary structure and metallic dampers is represented by a two-surface plasticity model written directly in force-displacement space (Constantinou [2]). For this model, two distinct, but nested, yield surfaces are defined in one-dimensional force space. The inner or loading surface separates the elastic and inelastic response regimes. This is characterized by its center and radius represented by a back-force F_α and inner yield force F_y^L, respectively. Meanwhile, the outer or bounding surface, which completely contains the smaller inner surface, is always centered at the origin of force space with radius equal to a variable outer yield force F_y^B. Translation of the inner surface corresponds to kinematic hardening, while expansion of the outer surface produces isotropic hardening. A total of six model parameters must be specified, including the stiffness k, inner yield force F_y^L, initial outer yield force F_{y0}^B, and hardening parameters h_0^B, h_1^B and r.

Viscous dampers are represented as purely linear Newtonian devices, with force proportional to velocity. In a physical sense, this implies that the bracing elements, used to incorporate the viscous dampers into the structural system, are infinitely rigid compared to the stiffness of the primary structure. In some cases, it may be more appropriate to consider more sophisticated models as discussed in Constantinou [2], however only purely viscous models are utilized here.

The viscoelastic dampers are modeled as nonlinear rate-dependent devices based upon a thermally-sensitive generalized Maxwell model. This model is written as a set of coupled first-order ordinary differential equations for the damper force, temperature, intrinsic time and Maxwell element internal variables. This thermally-sensitive viscoelastic model is able to account for the typical softening that occurs at elevated ambient temperatures and also as the damper temperature increases during seismic excitation.

For any given design or retrofit option s within the set of possible structures S, the properties for the lumped parameter primary structure and passive element models must be defined at each story. The resulting equations of motion for the n-story passively damped structure are written in state-space form and then solved, along with the applicable constitutive models, using an explicit, adaptive step-size Runge-Kutta method (Press [18]).

Geophysical Model

With the structural models defined, we next examine the approach taken to model the seismic environment. One possibility, of course, is to define a small set of historical or synthetic ground motions and attempt to find the best structural design for this set. However, this approach may introduce a bias, particularly if the set is developed with a specific structural frequency in mind. Instead, here we employ the USGS Gutenberg-Richter seismicity database for eastern North America (Frankel [15, 16]) and generate as many ground motions as necessary to evaluate proposed structural design and retrofit options.

Following the USGS model, the entire geographical region of eastern North America is subdivided into bins, with each bin representing 0.1 degrees of longitude and latitude. The USGS database then provides Gutenberg-Richter parameters a and b for each bin such that N the number of earthquakes per year of magnitude greater than or equal to M can be written as $\log N = a - bM$. We simulate the seismic environment by running Poisson processes in each bin to determine first arrival times T of significant events that may occur during the intended life cycle T_l of the structure. Figure 1 defines the approach used for n_e environmental realizations of an individual structure s. Once magnitude M and epicentral distance R are established for a significant event, the ground motion generation algorithm defined by Papageorgiou [17] is used to produce an appropriate synthetic accelerogram.

Loop over n_e environmental realizations for structure s
- Loop over active bins of environmental realization e
  - Run Poisson process to determine first arrival time T of significant earthquake
  - If $T \le T_l$, then
    - Determine earthquake magnitude from scaling law and precise location assuming uniform distribution within bin
    - Analyze structure and determine damage
  - Continue to evolve time within bin, until $T > T_l$

Figure 1: USGS Model Implementation

Evolutionary Methodology

In this section, we provide a brief overview of a proposed evolutionary methodology for aseismic design and retrofit. The primary objective is to develop an automated system that can evolve robust designs under uncertain seismic environments. The work of Holland [19, 20] on complex adaptive systems and genetic algorithms provides the basis. Figure 2 depicts the overall evolutionary approach, borrowing terminology from biological systems. Design involves a sequence of generations within a sequence of eras. In each generation, a population of individual structures $s \in S$ is defined and evaluated in response to ground motions that are realized in association with an environment $e \in E$. Cost and structural performance are used to evaluate the fitness of each structure in the population. Then the individual structures compete for survival within the uncertain environment. The fitness values, along with random genetic operators modeling selection, crossover and mutation processes, define the makeup of the next generation of structures. While, in the present implementation, generations must be processed sequentially, evaluations within a generation can be performed in parallel. Furthermore multiple simulations with different initial seeds can be run simultaneously in a massively parallel computing environment.

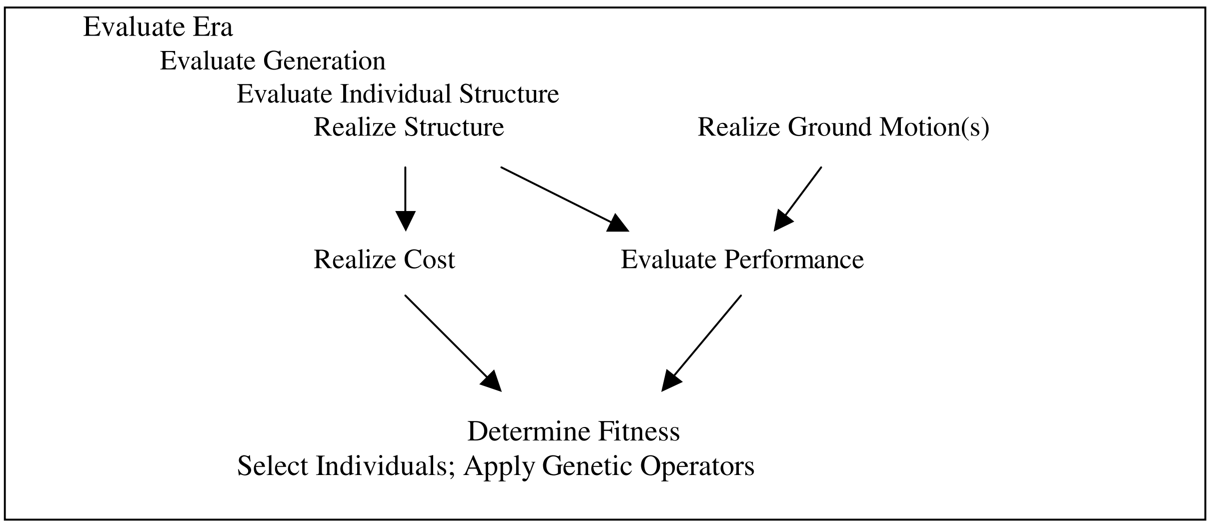


Figure 2: Evolutionary Methodology

In our present system, performance is judged by conducting nonlinear transient dynamic analyses, as described above, for ground motions that are consistent with the USGS seismicity model. The structural analysis utilizes an explicit state-space transient dynamics research code (tda), while the implementation of the genetic algorithm controlling the design evolution is accomplished within Sugal (Hunter [21]).

For illustrative purposes, we will now consider an example of a twelve-story steel frame retrofit with passive energy dissipators. Assume that three different types of dampers are available: metallic plate dampers, linear viscous dampers, and viscoelastic dampers. For each type, four different sizes are possible. Consequently, a 48-bit genetic code is employed to completely specify the dampers used in each story of any particular structure $s \in S$, where for this problem, the set S of attainable structures contains roughly 2^{48} members. Thus, there are over one hundred trillion possible structures.

In some situations, the use of multiple damper types in a single structure may be beneficial. However, it is unlikely that a structure with all three types (i.e., metallic, viscous and viscoelastic) represents a practical design option. In order to restrict the number of distinct damper types, techniques related to gene repair or fitness penalization can be utilized. Instead, we introduce the following recessive gene concept. The chromosome representing each new structure is formed by the standard genetic operations of selection, crossover and mutation. The resulting binary string represents the structural genotype. However, the actual structural design or phenotype is established by first determining the dominant damper type(s) present in the string. Afterwards the binary string is re-interpreted to convert recessive damper types into dominant ones of the same size. This technique constrains the design space in an appropriate manner, while preserving the diversity of the chromosomes. Results from several simulations will be shown in the next section to illustrate this new approach.

Additional details concerning the relative cost, performance and fitness definition must be specified. For example, in order to establish acceptable performance, we establish the parameters ϕ and β to set limits on interstory drift Δ_i and story acceleration a_i for each story i in relation to the story height H and gravitational acceleration g, respectively. Seismic performance of the structure under a given ground motion is acceptable only if $\Delta_i \le \phi H$ and $a_i \le \beta g$ for $i = 1,2,...,n$. Further details can be found in Dargush [10-14].

COMPUTATIONAL SIMULATIONS

Introduction

We now consider a series of examples involving steel frame structures with various retrofit possibilities. The primary purpose of these simulations is to illustrate the methodology, rather than to provide guidance for specific design situations. In each example, a number of parameters must be specified to control the genetic algorithm. Unless otherwise noted, the replacement rate is 50% at each generation. One-point crossover is always activated to form the new structures, followed by random bit mutations with a frequency of 1/24 per bit. Furthermore, the number of generations is set at $n_g = 128$, with $n_p = 32$ structures in the population and $n_e = 128$ environmental realizations per structure at each generation. A life cycle $T_l = 100\,\text{yrs}$ is assumed. Meanwhile, the fitness U of each structure is estimated by using the relationship $U = (n_e^+ / n_e) B_{\max} - C$, where n_e^+ represents the number of successful environmental realizations for the structure, $B_{\max}$ is the maximum benefit obtained from structure and C is the damper cost.

Twelve Story Steel Frame with Discontinuity

As a first example, we continue with the twelve-story structure discussed in the previous section. Let W_i and k_i represent the i th story weight and stiffness, respectively. The baseline steel frame model has story weights $W_1 = ... = W_6 = W$, $W_7 = W_8 = 3W/4$, $W_9 = ... = W_{12} = W/2$ and stiffness $k_1 = ... = k_6 = k$, $k_7 = ... = k_{12} = k/4$. 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 0.5Hz and 1.10Hz. Additionally, the lumped parameter two-surface cyclic plasticity model discussed 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. Then, $F_{y1}^L = ... = F_{y6}^L = 0.20W$, $F_{y7}^L = ... = F_{y12}^L = 0.05W$. The maximum structure benefit is set at $B_{\max} = 2000$. Damper costs vary from 4 to 20 units depending on size.

Assume that this baseline structure is situated on firm ground in Memphis, TN and consider retrofit with metallic (tpea) dampers only. Using the results from eight simultaneous simulations, we find a number of robust designs, including those presented in Fig. 3a. Here and in all subsequent structural diagrams, the size of the rings denotes damper size, while ring color indicates damper type. Notice 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 Fig. 3b. Now survival rates have increased to over 92% and the fitness values are well above 1800. These are clearly more robust designs than those presented in Fig. 3a. Of course, 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 that, particularly in Fig. 3b, the evolutionary algorithm recognizes the structural discontinuity at the seventh story and accordingly selects larger dampers in that vicinity.

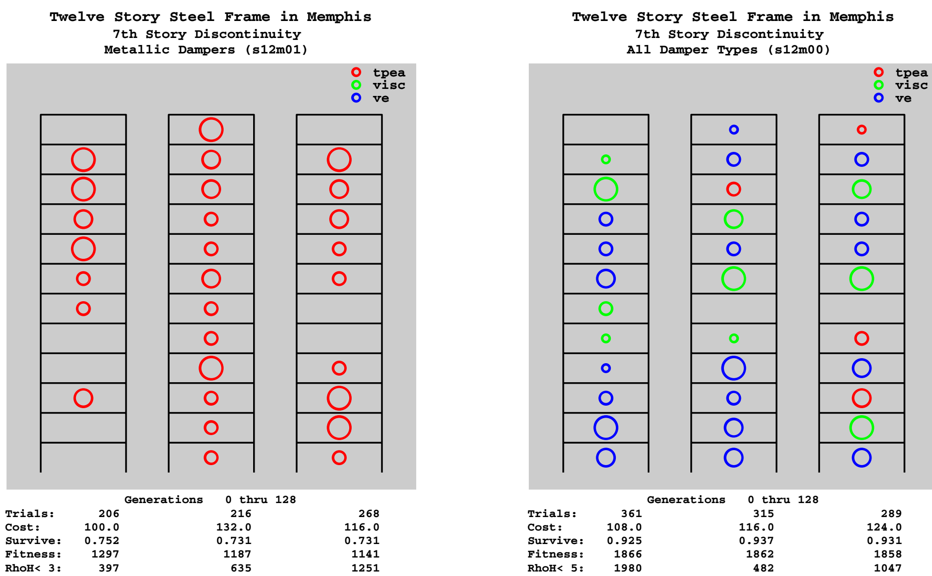


Figure 3: Twelve Story Steel Frame in Memphis, a) Metallic only, b) All damper types

Although several robust designs are presented in Fig. 3b, notice that two of the three incorporate all three damper types. As discussed previously, this is not likely to yield a practical rehabilitation scenario. Next we constrain the simulations to permit a maximum of only two damper types in a given structure. Results are presented in Fig. 4. The left-hand plot Fig. 4a displays the evolution of mean fitness for eight simulations using different initial seeds. The mean fitness tends to increase rather quickly before hovering around 1400. 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 Fig. 4b again have survival rates above 92% and fitness values significantly over 1800. Only viscous (visc) and viscoelastic (ve) dampers are selected for these designs.

When we further restrict the design space to permit only a single damper type within a given structure, the results presented in Fig. 5 were obtained. Again, very similar levels of fitness and survival rates are found for the robust structures, which are dominated by retrofit strategies that incorporate viscoelastic (ve) dampers.

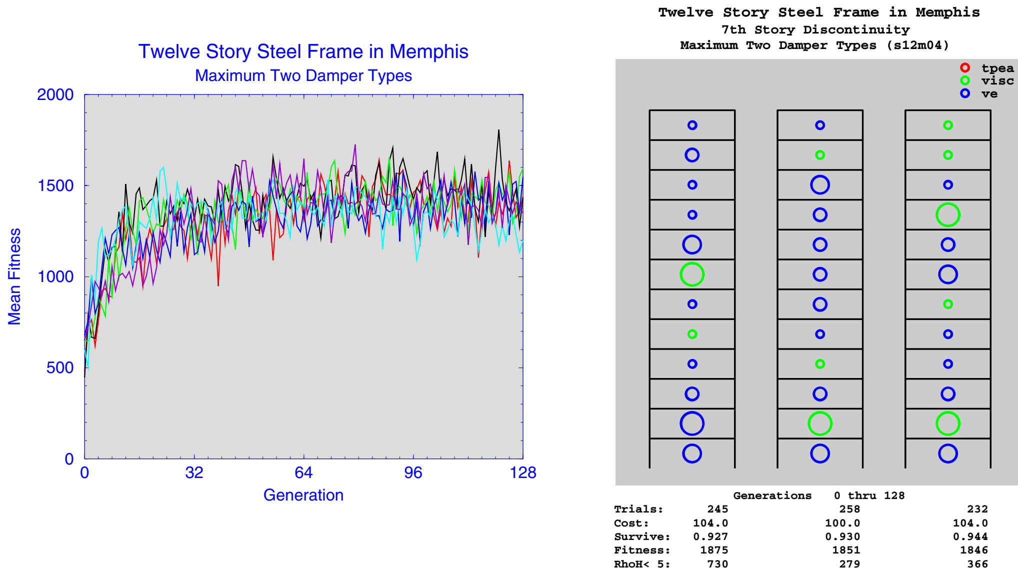


Figure 4: Twelve Story Steel Frame in Memphis, Maximum Two Damper Types, a) Fitness evolution, b) Robust structures

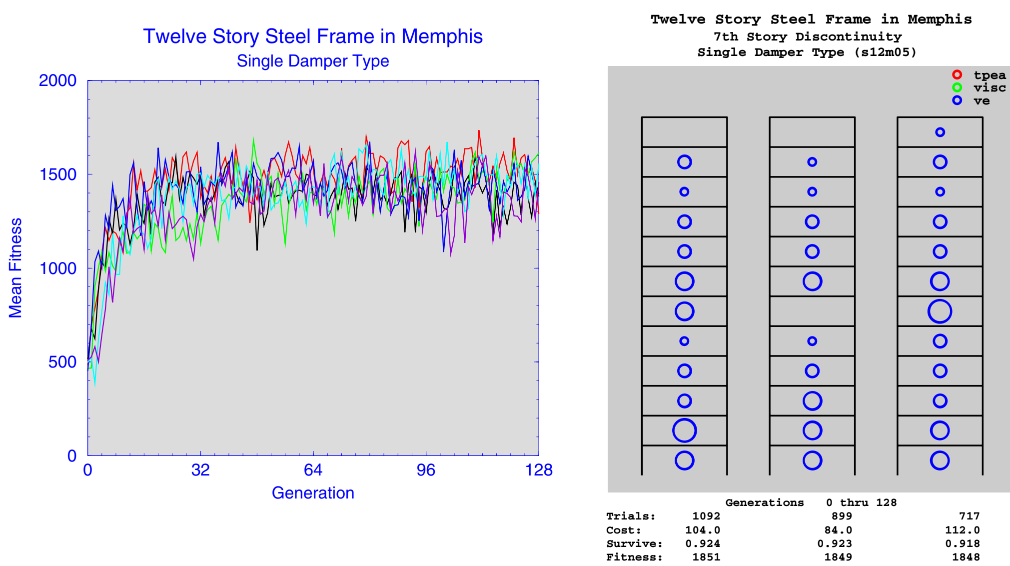


Figure 5: Twelve Story Steel Frame in Memphis, Maximum One Damper Type, a) Fitness evolution, b) Robust structures

Finally, we move this same primary structure to Buffalo, NY and perform simulations while permitting only a single damper type. Robust designs are provided in Fig. 6. Notice that smaller dampers are now selected. Consequently, somewhat lower survival rates are obtained during significant seismic events. However, the fitness values have increased because the seismic environment is less severe in Buffalo compared to the New Madrid area surrounding Memphis.

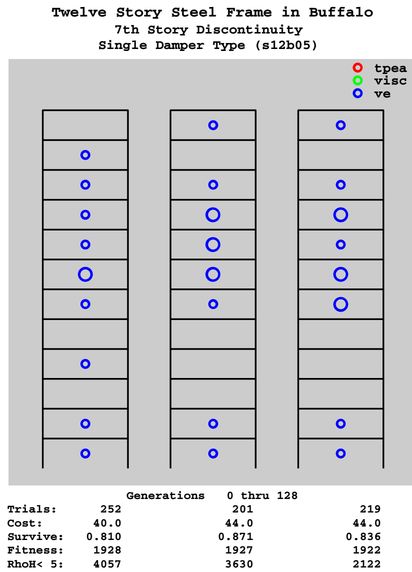
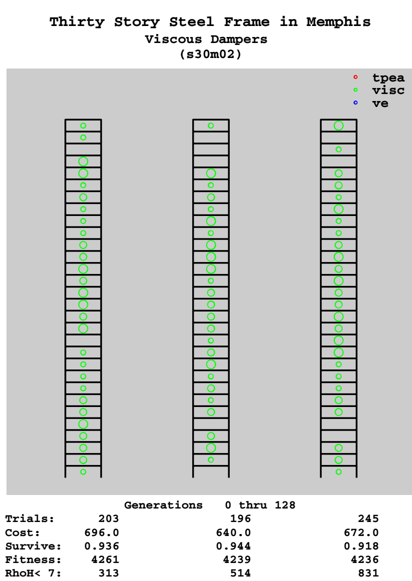


Figure 6: Twelve Story Steel Frame in Buffalo, Maximum One Damper Type

Thirty Story Steel Frame

For the next example, we consider a thirty-story steel frame with discontinuities at every sixth story along the height. The fundamental period is 4s. We again assume that the structure is located in Memphis, TN on firm ground. The maximum total benefit is $B_{max} = 5000$ and damper costs range from 8 to 40 units. Robust designs are shown in Fig. 7 for two sets of simulations. Figure 7a presents results for the case when only viscous dampers are available, while in Fig. 7b all dampers are permissible but each design is limited to a single type.



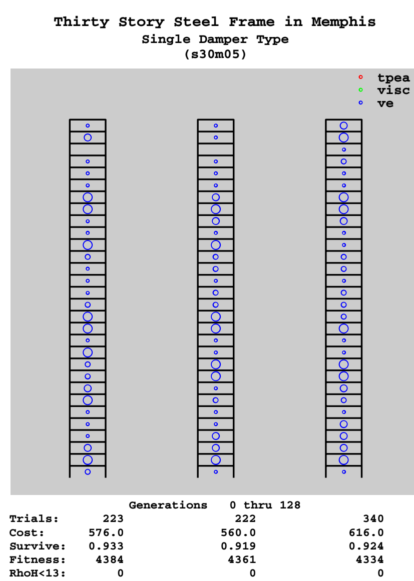


Figure 7: Thirty Story Steel Frame in Memphis, a) Viscous only, b) Single damper type

Notice that the robust designs all have survival rates of greater than 90% and fitnesses above 4200. The fitness values in Fig. 7b for the single damper designs are slightly higher than those obtained with strictly viscous dampers only.

Uniform Eight Story Steel Frame

In all of the previous examples, the robust designs resulting from the simulations specified dampers in many of the stories. For a final example, we consider a uniform eight-story structure with metallic dampers as the only retrofit option. In this case, the robust designs obtained after $n_g = 512$ generations are shown in Fig. 8. Notice here that the predominant design option includes no dampers.

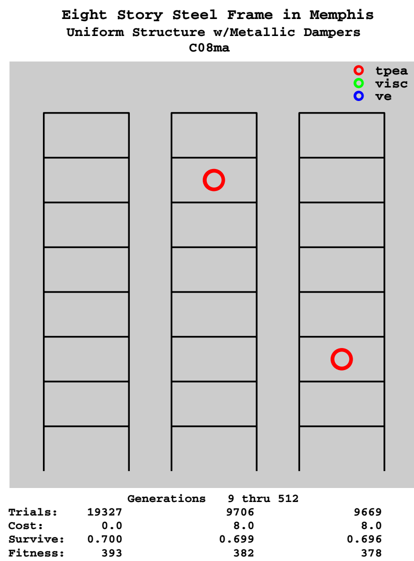


Figure 8: Eight Story Steel Frame in Memphis with Metallic Dampers Only

CONCLUSIONS

Over the past decade, passive energy dissipation has become an attractive technology for seismic design and retrofit of structural systems. Although several different design approaches are currently under development, here we present a computational approach based upon evolutionary algorithms that has significant potential, especially for irregular structures. In numerous case studies, the system is able to discover robust designs in an uncertain seismic environment. In addition, the algorithms scale favorably with increasing problem size and are naturally parallel. Consequently, continued development of the methodology appears to be warranted, particularly in light of the anticipated concurrent advancement of massively parallel computing hardware.

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 socioeconomic issues. For example, does the structure contribute to the disaster-resiliency of the community? What degree of protection is adequate? How much risk is acceptable? The evolutionary methods presented here may provide an effective framework in which to study some of these issues as well.

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