13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1600

DESIGN OPTIMIZATION OF PASSIVE DEVICES IN MULTI-DEGREE OF FREEDOM STRUCTURES

Daisuke ASAHINA[1], John E. BOLANDER[2], and Stefano BERTON[3]

SUMMARY

Passive energy dissipation devices are effective in reducing structural response to earthquake and wind loadings. However, the optimal sizing and distribution of such devices within multi-degree of freedom structures is not evident. This paper reports on the development of a genetic algorithm (GA) based approach for distributing a finite quantity of passive devices within two- and three-dimensional frame structures subjected to base excitation. Linear viscous dampers (LVD) are used, yet the approach is general with respect to damper type. Significant reductions in intra-story drift and absolute accelerations are obtained relative to the uniform placement and Monte Carlo assignment of dampers. The dependence of optimal damper distribution on excitation frequency is reaffirmed through examples involving harmonic (first and second mode) and earthquake loadings. As a step toward effective damper placement within large complex systems, the design population is periodically surveyed to identify and trim unnecessary material from the genetic representation of the structures. This systematic reduction of the design variable space is effective in seeking optimal solutions.

INTRODUCTION

Passive energy dissipative devices have been used to reduce the response of buildings to wind and earthquake loadings. Examples of such devices include viscoelastic dampers, friction dampers and fluid viscous dampers. The advantages of adding such damping devices are well known, based on data from physical testing, analytical and numerical modeling, and the monitoring of actual building performance. However, practical, comprehensive guidelines for the design of such systems in civil structures are still being developed [1].

When passive devices are used in multi-degree of freedom (MDOF) systems, such as multi-story buildings, the sizing and relative placement of the passive devices within the structure becomes an optimization problem. In recent years, several approaches have been proposed to determine optimal damper placement in multi-story buildings. Because passive devices are activated by intra-story displacements (and/or velocities), most of the procedures base their optimization techniques on the evaluation of the maximum intra-story displacements. Examples of such procedures include the Sequential Search Algorithm [2] and

[1] Grad. Student, Oceanic Architecture & Engng., Nihon Univ., Chiba, Japan. Email: dasahina39@yahoo.co.jp
[2] Assoc. Prof., Civil & Environ. Engng., Univ. of California, Davis, CA, USA. Email: jebolander@ucdavis.edu
[3] Post-Doctoral Researcher, Civil Engng., Kyushu Univ., Fukuoka, Japan. Email: sberton@doc.kyushu-u.ac.jp

the Simplified Sequential Search Algorithm [3]. In these two approaches, an index related to intra-story displacement is determined from the structural response to an input ground motion. At each sequential step of the algorithms, an additional damper is introduced in the story where the index has a maximum value and the damping properties of the structure are updated. The procedures stop when all available dampers have been placed into the structure. The resulting distribution of dampers is significantly more effective in reducing structural response relative to a uniform distribution of the same quantity of damping over the building height. Another important finding is that the optimal distribution of dampers can be highly dependent on the frequency characteristics of the input excitations. A further example is the approach proposed by Takewaki [4]. In this case, the optimization is based on the minimization of the amplitude of the transfer function of the intra-story displacements evaluated at the fundamental period of the structure.

In this paper, a Genetic Algorithm (GA) is used to size and position dampers in 2-D and 3-D multi-story shear-frame structures. Based on assignments and rules that mimic the processes of natural selection, the GA seeks to minimize a performance index (derived from intra-story displacements) for a given input ground motion. The first application of GAs to optimizing damper placement was in the area of active control [5]. GAs have been used to optimize the control parameters of a tuned mass damper [6] and to optimally place dampers in shear-frame structures [7]. Here, too, significant reductions in various response quantities are realized by the GA selection of damper sizes and locations. The general approach described in this paper is similar to that presented in reference 7, although there are some significant differences in the analysis objectives and implementation, as noted within the paper. Although linear viscous dampers (LVD) are distributed within example structures, the optimization procedure is general in that it is not restricted to a given damper type. The resulting displacements are compared with those obtained from a uniform distribution of the same amount of damping material. In particular, a novel approach is used to systematically reduce the design variable space during the course of genetic adaptation. This is in an effort to improve the performance of GAs when applied to distributing dampers within large, complex structures.

GENETIC ALGORITHM REPRESENTATION OF PASSIVELY DAMPED STRUCTURES

GAs optimize functional relationships by mimicking the processes of natural selection [8]. The concepts and basic procedures of GAs are well-documented, so that only details specific to the damper distribution problem are described in this paper. Figure 1 shows a multi-story shear-frame structure with LVDs inserted between neighboring floor levels. The structure is regarded as an individual within a population of such structures. Individuals are distinguished by differences in their genetic makeup. The structure is represented by a chromosome, which is composed of multiple genes. In this case, gene i is a fixed-length binary string representation of the LVD coefficient, c_{di}, assigned to story i in the structure (Fig. 1).

A population of such individuals is generated by randomly assigning the bit values within each chromosome. The optimization problem can be stated as the minimization of a performance index, δ, which is a function of the problem variables, **c**:

$$\text{minimize} \qquad \delta = f(\mathbf{c}) \tag{1}$$

$$\text{subject to} \qquad c_{dT} = \sum_{i=1}^{n} c_{di} \tag{2}$$

Here, **c** is the vector of LVD coefficients and n is the total number of damper locations. According to Eq. 2, the total amount of damping material, c_{dT}, is constant for each individual.

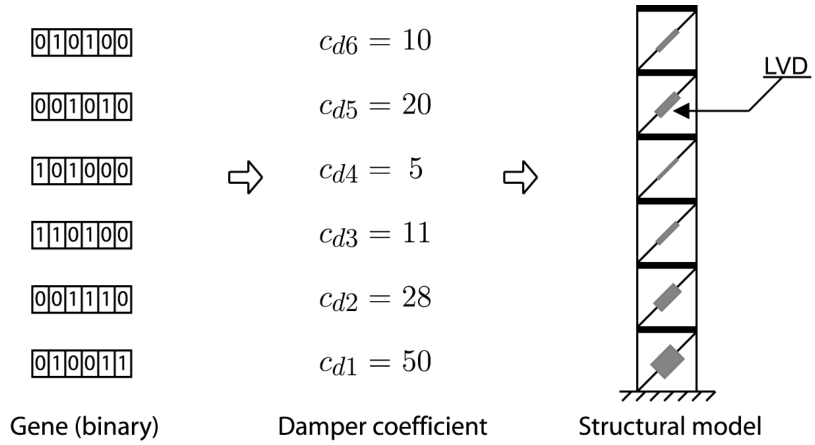

Figure 1: Genotype to phenotype (LVD coefficient) conversion

The three major components of evolution (i.e. selection, reproduction, and variation) are treated in a conventional manner, as described in Goldberg [8]. To produce a new generation, pairs of individuals in the current generation exchange genetic material using an ordinary, single-point cross-over scheme. Optimality is sought by allowing the fittest individuals (i.e. those that best minimize the performance index) to participate more frequently in this mating process. Roulette wheel selection and elitist selection (i.e. the best individual is copied into the next generation) schemes are used here. The possibility of variation through mutation is simulated by randomly inverting bits within the individual chromosomes. The probability of random bit inversion is controlled and kept low.

The development of optimization routines is driven by the need to improve performance, while minimizing the various costs associated with damper use within new construction and for retrofit of existing structures. Besides the cost of the dampers themselves, there are significant costs associated with damper installation and possible obstruction of view. In this paper, it is assumed that the size of the damper (i.e. damping coefficient) is the primary factor influencing cost. Thus, the cost of adding dampers is fixed by c_{dT}, so the objective becomes how to make best use of that resource. In this work, practically continuous distributions of c_{di} can be obtained over the building height due to the high bit resolution of each phenotype.

GENETIC ADAPTATION AND REGENERATION

For practical applications, the damping coefficient associated with a given location would be constrained by commercially available damper sizes and the costs associated with installation. Installation and basic costs would preclude the use of very small dampers, such as that indicated in the 4th story of the structure in Fig. 1, for example. There is a threshold for damping coefficient, below which it is not economical to install dampers. When allocating finite resources amongst the various design options, such non-viable options should be avoided.

As a related problem, it is useful to remove the design variables that are not functional in the optimization process, in order to raise the efficiency of the GA. In this paper, the genetic representation of the design problem is regenerated several times during the optimization process. Regeneration involves reducing the design space by trimming non-functional genes off the individual chromosomes and reinitializing the resulting population of structures [9]. It is important to look at the average values rather than the current optimal, since decisions based on the current optimal might remove important components in competing strategies. Since the average values rarely go to zero, some threshold value ε is necessary to define non-functionality.

$$\epsilon = \alpha \ c_{dT} \tag{3}$$

where α is an adjustable parameter.

STRUCTURAL MODEL

In this paper, LVDs are distributed within shear-frame structures subjected to ground excitation. To determine the vector of floor displacements, **x**, a response history analysis is performed [10]. This involves solving the following MDOF equation set for each individual within a current generation:

$$\mathbf{M\ddot{x}} + (\mathbf{C} + \mathbf{C_d})\mathbf{\dot{x}} + \mathbf{Kx} = -\mathbf{M1y}(t) \tag{4}$$

where **M**, **C**, and **K** are the mass, damping, and stiffness matrices, respectively, of the bare structure; and **y** is the vector of ground accelerations. The dots over the vector of floor displacements indicate derivatives with respect to time. For the sequential numbering of stories and their associated degrees of freedom, the damping coefficient matrix for the LVDs has the following banded form:

$$\mathbf{C_d} = \begin{bmatrix} c_{d1} + c_{d2} & -c_{d2} & \cdots & 0 & 0 \\ & c_{d2} + c_{d3} & \cdots & 0 & 0 \\ & & \ddots & \vdots & \vdots \\ & & & c_{d(n-1)} + c_{dn} & -c_{dn} \\ \text{SYM} & & & & c_{dn} \end{bmatrix} \tag{5}$$

where c_{di} is the damping coefficient for story i. In this paper, the damping associated with the bare system is neglected (i.e. **C = 0**) to focus on the effects of supplemental damping. The resisting elements in each story are assumed to remain linearly elastic. In practice, structural response to moderate loading can often be controlled within the elastic range through the effective use of supplemental damping.

GA APPLICATION – PLANAR FRAMES

In this section, an idealized 20-story building is retrofitted with LVDs and analyzed for different input motions. An equal amount of mass (2.0×10^5 kg) is lumped at each floor level and each story has the same lateral stiffness (3.0×10^3 kN/cm). The 1st and 2nd natural periods of this shear building are 2.12 and 0.71 sec, respectively. The total amount of damping material available to the optimization process is $c_{dT} = 3\times10^2$ kN sec/cm. In building applications, LVD are normally used in brace configurations and activated by a component of the structural displacement. Relative displacements within a story are also closely related to potential damage. Thus, the performance index used by the GA is based on intra-story displacements for the following numerical simulations.

Harmonic base excitation

As a first step toward evaluating the effectiveness of the GA approach in distributing dampers, the planar frame structure is subjected to harmonic base excitations. The frequencies of the input motions correspond to the 1st and 2nd natural modes of vibration of the structure. Both motions have a displacement half-amplitude of 10 cm. The mode shapes of the structure are known, so it is possible to verify some aspects of the program operation, since dampers should be positioned where relative displacements are larger.

Figures 2 and 3 show the relative displacement envelopes and the distribution of LVD coefficients for the 1st and 2nd mode excitations, respectively. The LVD coefficients, c_{di}, have been normalized by the total amount of damping material, c_{dT}. For these two optimizations, each design population consisted of 200 individuals and the GA was applied for up to 500 generations. The resulting damper distributions vary smoothly over the building height and agree with the modal displacement patterns. As shown in previous studies [7,11], the optimal distribution of dampers depends strongly on the frequency characteristics of the input motion.

Figure 4 illustrates convergence of the best individual within the design population to the optimal result (for the mode 2 case shown in Fig. 3). The almost periodic, abrupt increases in the performance index δ are associated with the trimming of specific design variables from every chromosome in the design population and the subsequent re-initialization of the design population (i.e. random bit assignment). The criteria for trimming design variables is expressed by Eq. 3, where $\alpha = 0.01$ for this case. In addition, the regeneration process is considered only when the current population exhibits asymptotic behavior in its convergence to a local optimum. That is, regeneration is performed when the change in the performance index over a set number of generations is less than a threshold value.

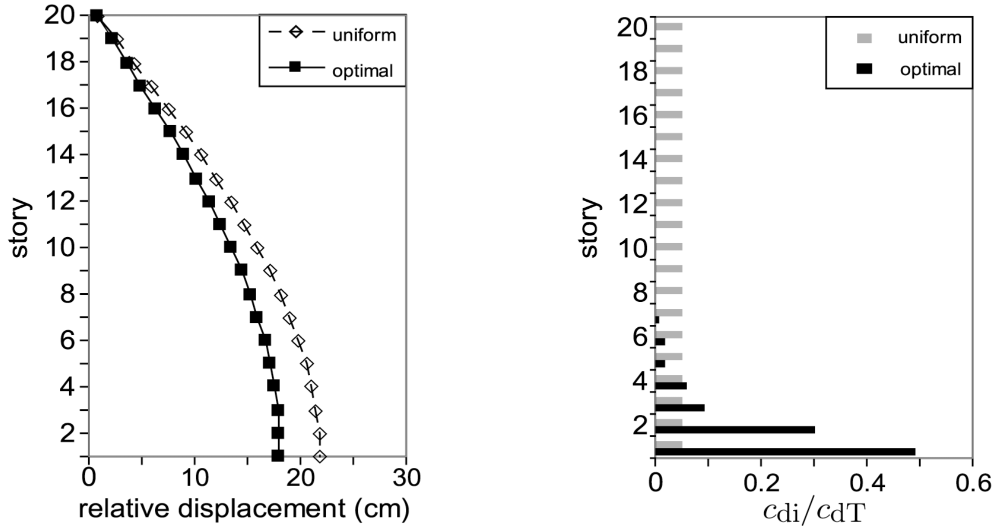

Figure 2: Relative displacements and LVD coefficients for harmonic base excitation (mode 1)

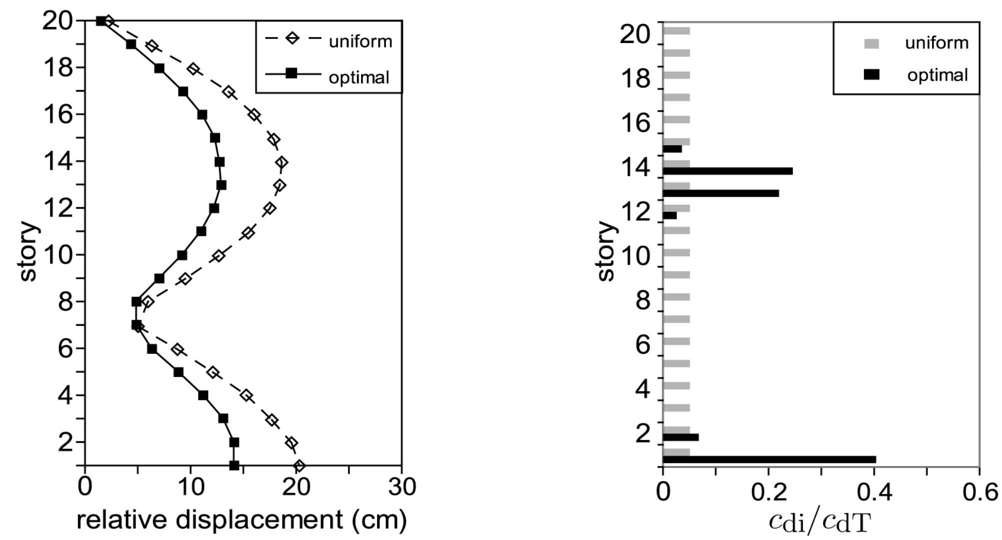

Figure 3: Relative displacements and LVD coefficients for harmonic base excitation (mode 2)

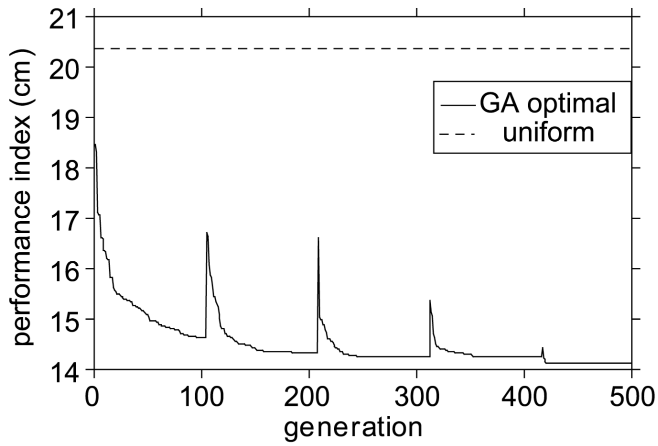

Figure 4: Evolution of performance index for harmonic base excitation (mode 2)

For the small problem size considered here, the need for this systematic reduction in the design variable space is not evident. A conventional GA approach (that operates on the complete set of design variables) produces optimal performance indices similar to those obtained here. One difference is that, when using a conventional approach, non-zero damper assignments generally appear over the building height and the damper distributions exhibit local variations that do not correspond to the modal displacement pattern. For comparison, the performance index associated with a uniform distribution of dampers is also indicated in Fig. 4. For this case, a Monte Carlo approach to assigning the damper distribution (i.e. the best design from the first generation of the GA approach) outperforms the uniform assignment of dampers.

Earthquake loading

The 1940 NS El Centro (PGA = 0.313g) and 1995 Kobe (PGA = 0.599g) ground motion records define the input motions considered here. Figures 5 and 6 show the resulting relative displacement envelopes and the distribution of the LVD coefficients for these two ground motions, respectively. Relative to the uniform placement of dampers, the GA placement of dampers reduces the structural response, although the degree of reduction is not as dramatic as for the modal excitations. A Fast Fourier Transform analysis of the ground motions indicated peaks in the frequency spectra at 1.17 Hz for the El Centro record and 2.93 Hz for the Kobe record. It is therefore not surprising that the GA placement of dampers for the El Centro and Kobe motions resemble those obtained for the 1st and 2nd mode excitations, respectively. Unlike the results from harmonic base excitation, however, the structural response and damper distribution are not smooth over the height of the structure.

GA APPLICATION – 3D FRAMES

For most cases, an accurate representation of structural response to ground motions requires a three-dimensional modeling of the structure. In this section, the GA approach is used to optimally distribute FVD material within models of three-dimensional shear-frame structures, such as the one shown in Fig. 7. The dynamic equations of equilibrium correspond to Eq 4, where the matrix and vector quantities are expanded and modified to account for the additional degrees of freedom per floor and their coupling [10,12]. Also, $\mathbf{C_d}$ in Eq 5 takes a different form for the three-dimensional case. The GA properties are the same as before, except that now each story can accept damping material in any of the four openings defined by the vertical elements and the floors. The number of design variables is therefore $n = 4s$, where s is the number of stories.

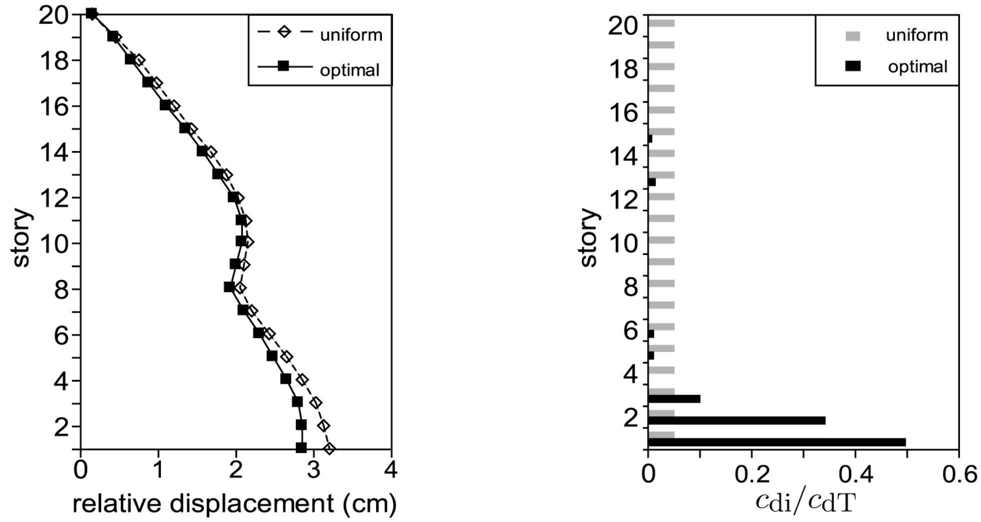

Figure 5: Relative displacements and LVD coefficients for El Centro record

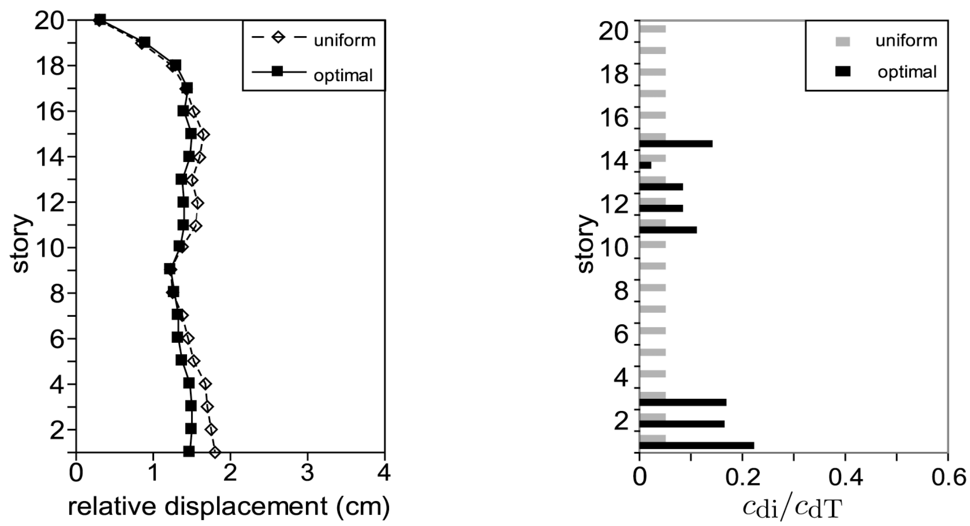

Figure 6: Relative displacements and LVD coefficients for Kobe record

For the example considered here, n = 40. The rigid floors have plan dimensions of 10x10 m and a mass of 2.0×10^5 kg is lumped at the centroid of each floor area. The shear stiffness of each column (in each principal direction) is $k_x = k_y = 3.0 \times 10^3$ kN/cm. There is no eccentricity between the centers of mass and stiffness, so that the effects of installing dampers the structure can be seen more clearly. The total damping coefficient $c_{dT} = 3 \times 10^2$ kN sec/cm. The transverse bending modes of vibration have first and second period values of 1.09 and 0.36 sec, respectively. The torsional modes of vibration have natural period values of 0.63 and 0.21 sec, respectively. Although three degrees of freedom are defined for each floor, the loading considered here is directed along one of the principal directions. Furthermore, the base input motion is harmonic with a period equal to that of the second mode of vibration in transverse flexure. This simple loading case was chosen as a first step in interpreting the effects of damper placement and the capabilities of the GA approach applied to three-dimensional structures. The performance index δ, used for determining the design fitness, is the maximum shear displacement experienced within the set of building columns during the loading history. The shear displacements will generally have x- and y-direction components due to torsional motion induced by the non-symmetric placement of dampers.

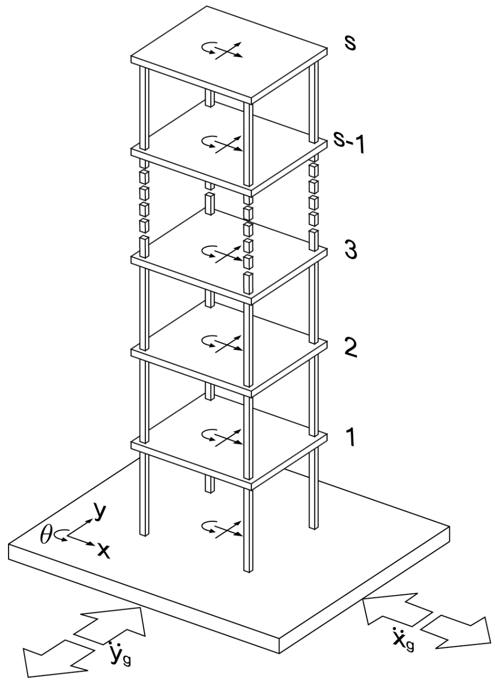

Figure 7: Three-dimensional structural model

Figure 8 shows the development of the performance index through several cycles of reducing the design variable space and random re-initialization. In this case, the Monte Carlo assignment of the damper distribution provides larger performance indices relative to a uniform distribution, even though the same population sizes are used as for the two-dimensional case. This result occurs due to the increased number of design variables and the introduction of rotations in the structural response.

The distributions of LVD coefficients, for both uniform and GA placement, are shown in Fig. 9. The magnitudes of the LVD coefficients are indicated by the scaling of damper sizes in the figure. For the y-direction input motion considered here, nearly all of the damping units aligned in the x-direction are small or have been removed during the regeneration processes. The overall distribution of damping material is similar to that obtained for second mode excitation of the two-dimensional structure (Fig. 3). Remarkably, the GA approach provides a nearly symmetric distribution of dampers about the direction of loading, thus reducing torsional effects.

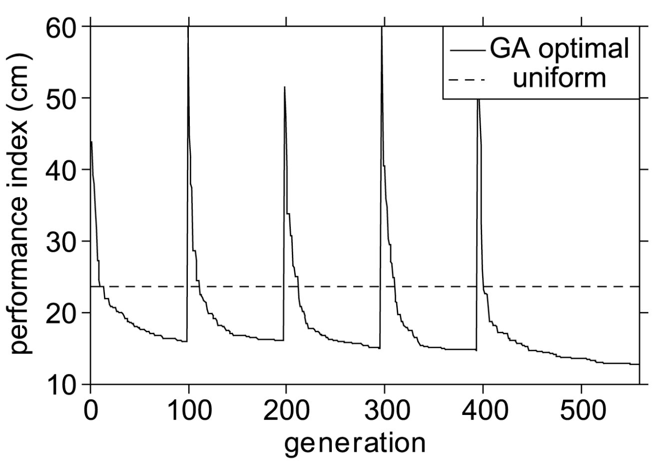

Figure 8: Evolution of performance index for 3-d model

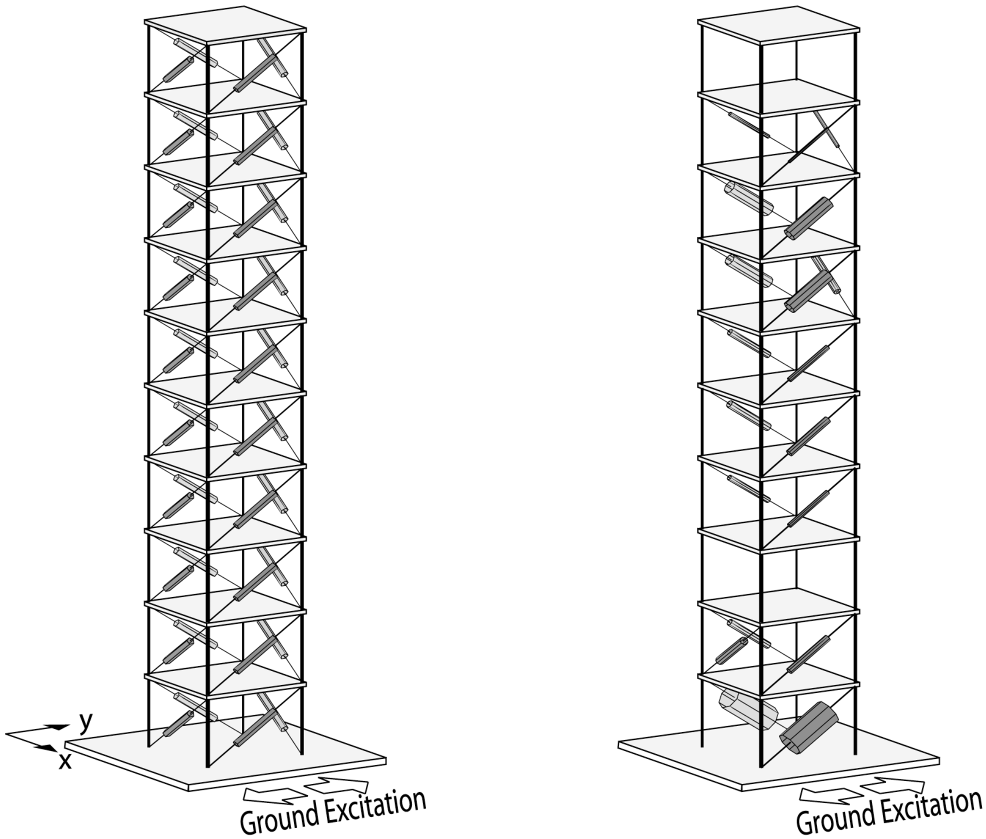

Figure 9: Uniform and GA optimal distributions of dampers for 3-d shear-frame structure

CONCLUSIONS

This paper reports on the development of a GA based approach for distributing a finite quantity of passive devices within two- and three-dimensional frame structures subjected to base excitation. Linear viscous dampers (LVD) are used, yet the approach is general with respect to damper type. Unlike conventional GA that use a static set of design variables, the number of design variables is reduced during the optimization process. Decisions to contract the design variable space are based on surveys of the design population, where the functionality of each specific damping unit is taken into consideration. Upon reducing the number of design variables, a new population is initialized with random values and the optimization continues. Due to the small number of design variables considered in the example problems, the use of this regeneration process did not appreciably affect the optimal performance indices, relative to those obtained using a conventional GA approach. However, the distributions of LVD coefficients better reflected the relative displacement patterns. By using the regeneration approach, the GA approach was able to symmetrically place dampers in three-dimensional shear-frame structures to avoid torsional motions. Simple structural geometries and loading conditions have been considered here to study the basic operations of this approach. It is anticipated that the systematic reduction of the design variable space will be effective in seeking optimal solutions within larger, more complex structures.

REFERENCES

1. Whittaker AS, Constantinou MC, Ramirez OM, Johnson MW, Chrysostomou CZ. "Equivalent lateral force and modal analysis procedures of the 2000 NEHRP provisions for building with damping systems." Earthquake Spectra 2003; 19(4): 959-980.

2. Zhang R-H, Soong TT. “Seismic design of viscoelastic dampers for structural applications.” J. Struct. Engng., ASCE, 1992; 118(5): 1375-1392.
3. Lopez Garcia D. “A simple method for the design of optimal damper configurations in MDOF structures.” Earthquake Spectra 2001; 17(3): 387-398.
4. Takewaki I, “Optimal damper placement for minimum transfer functions” Earthquake Engng. Struct. Dyn. 1997; 26: 1113-1124.
5. Rao SS, Pan T-S, Venkayya VB. “Optimal placement of actuators in actively controlled structures using genetic algorithms.” AIAA J. 1991; 29(6): 942-943.
6. Hadi, MNS, Arfiadi Y. “Optimum design of absorber for MDOF structures.” J. Struct. Engrg. 1998; 124(11): 1272-1280.
7. Singh MP, Moreschi LM. “Optimal placement of dampers for passive response control.” Earthquake Engng. Struct. Dyn. 2002; 31: 955-976.
8. Goldberg DE. “Genetic algorithms in search, optimization and machine learning.” Addison-Wesley Publishing Co., Inc., Reading, Mass, 1989.
9. Bolander JE, Kobashi Y, and Kintzel J. “Structural optimization through genetic adaptation and regeneration.” OPTI 95 - The Fourth International Conference on Computer Aided Optimum Design of Structures, Computational Mechanics Publications, 1995: 85-92.
10. Chopra AK. “Dynamics of structures. Theory and Applications to Earthquake Engineering (2^{nd} edn).” Prentice-Hall: Upper Saddle River, NJ, 2001.
11. Shukla AK, Datta TK. “Optimal use of viscoelastic dampers in building frames for seismic force.” J. Struct. Engrg., 1999; 125(4): 401-409.
12. Shibata A. “Recent developments in the analysis of earthquake resistant structures.” Morikita Press. 2003.