

Evolutionary Seismic Design and Retrofit with Application to Adjacent Structures

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Summary

Although passive control devices have been widely used for the seismic retrofit of existing structures, current design codes do not provide guidelines for optimizing configuration of dampers or choosing the appropriate device type that may enhance the structure performance or reduce the overall design cost. In this paper, an adaptable and practical optimization methodology for seismic design of adjacent buildings is introduced using Genetic algorithms. Within the overall algorithm, passively damped structural designs evolve toward configurations that satisfy constraints on inter-story drift, absolute floor acceleration, and separation between the adjacent structures while attempting to limit damper cost. It is suggested that the methodology presented in this paper can achieve significant improvements in determination of the optimum distribution, number, and/or size of passive-control devices of known capacity in adjacent buildings and can provide a powerful approach for mitigating potential damage due to pounding.

Introduction

Over the past decades, pounding between adjacent buildings has been observed during most major urban earthquakes (Filiatrault A. et al. 1994; Kasai and Maison, 1997). A sufficient separation between the structures would avoid the structural pounding; however, for metropolitan cities located in regions of high seismic activity, the need to maximize use of land has lead to inadequate separation often resulting in pounding of adjacent structures during a strong earthquake. Intensive study has been carried out on mitigation techniques of structural pounding hazards by applying different structural models and using various models of collisions (Anagnostopoulos 1995; Lopez Garcia 2004). Seismic design of adjacent buildings, retrofitted with passive-control devices, is one of the suggested pounding mitigation methods and is reasonably applicable to optimization techniques. Location, type, size, and number of dampers can be design variables when considering an optimized seismic design of adjacent buildings. The model of searching in a large design space, theoretically formed by combining all possible values of the design variables, may be difficult to formalize mathematically or expensive to compute. Therefore, recently, tracing a path through increasingly "better" designs has become a realistic perspective for many researchers. Genetic algorithms (GAs), which were originally developed by Holland (1975), are one of the efficient search algorithms based on the evolutionary theory of "survival of the fittest". GAs have the robustness and the capability to perform well over a wide range of problems. Thus, many researchers (Furuya et al. 1998, Singh and Moreschi 2002; Dargush and Sant 2005) used GAs for the optimum seismic design of structures. In this paper, the evolutionary seismic design and retrofit approach defined in Dargush and Sant (2005) is extended for adjacent structures. With minimum cost and maximum functionality objectives, a

general computational framework that promotes evolution of robust seismic design and retrofit of adjacent structures subjected to fixed seismic environments is developed.

Seismic Design Procedure

A uniaxial version of a two-surface cyclic plasticity model (Chopra and Dargush 1994) is implemented for the nonlinear transient dynamic analysis with an explicit state-space approach for the primary structures and metallic yielding dampers. Primary structures simplified by lumped parameter models may contain a number of metallic yielding dampers, viscoelastic solid dampers and/or viscous fluid dampers. A coupled thermo-viscoelastic Maxwell model is used for viscoelastic dampers. Additionally, viscous fluid dampers are modeled as strictly linear Newtonian devices. Details on the mathematical models employed for passive energy dissipation devices can be found in Dargush and Soong (1995), Constantinou et al. (1998).

Seismic environment is characterized in a manner consistent with the Multidisciplinary Center for Earthquake Engineering Research (MCEER) Northridge Earthquake ensemble (2% PE in 50 years) (Filiatrault and Wanitkorkul 2005). Eight ground motion records are used for the fixed seismic environment analysis. The peak ground acceleration (PGA), the peak ground velocity (PVG), the peak ground displacement (PGD) amplitudes, and the period corresponding to the intersection of the constant spectral acceleration and constant spectral velocity branches of a 5% damped elastic spectrum, $T_{V/A}$ values of these eight ground motion records are listed in Table 1 and Figure 1 shows the 5% damped spectrum of the records of Table 1.

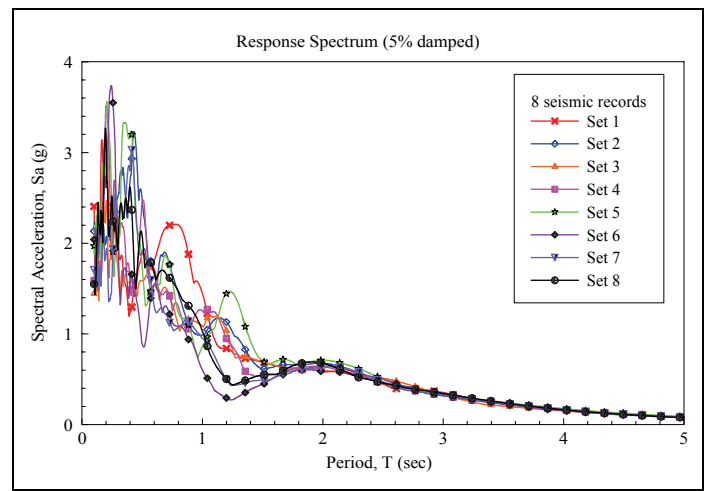


Figure 1. 5% damped spectrum of the records of Table 1

Table 1. Eight ground motion records from MCEER Northridge earthquake ensemble

	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8
PGA [g]	1.25	0.94	0.79	0.79	0.97	0.85	0.82	0.86
PDV [m/sec]	0.83	0.93	0.99	0.96	0.98	0.69	0.97	1.03
PGD [m]	1.00	0.44	0.48	0.45	0.40	0.40	0.71	0.65
$T_{V/A}$ [sec]	0.33	0.49	0.63	0.61	0.50	0.40	0.59	0.60

Performance Based Evolutionary Optimization

This study develops an automated performance based design algorithm that can identify the optimized design or retrofit of both single and adjacent structures under fixed seismic environments. Figure 2 illustrates the overall process of constructing the GA string representation generated for a pair of adjacent steel frame structures. GA starts with a set of initial pair of structural designs that are generated from an exhaustive combination of different damper sizes and/or types. Within each generation, each structure is subjected to a specified number of seismic environmental conditions and evaluated to determine the degree to which the objective is satisfied and to what extent design constraints are violated. Violation is also possible during other seismic events for that individual within the current generation. Consequently, as shown in Figure 2, 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 framework of the next generation of structures.

Objective Criteria: Minimum damage to the structure under seismic loading is certainly the most desirable performance criteria for the seismic design or retrofit of structures. In order to quantify the damage to the structure, the relationship between validation of design constraints and degree of damage should be established. Not satisfying the drift or acceleration or separation design constraints for a given earthquake excitation, is assumed to directly lead to design failure. Thus, the degree of damage to a structure can be formulized with the use of survival rate that the proposed design realized (i.e., the ratio of earthquake survivals to total number of earthquake attempts). As well as minimizing the damage to structure, minimizing the overall structural cost is another significant design objective. The mathematical formulation of a meaningful cost definition is achieved by using relative realized cost and size values for dampers, assuming that the cost of any type of damper is proportional to its size. The foregoing two performance criteria, concerning overall structural cost and structural damage are combined into a single objective function, which is defined as fitness function, f , for each structure. The fitness function f (also called the utility function) to be maximized is formulated in Equation 1 as follows:

$$f = \left(\frac{B - C}{B} \right) \left(1 - \frac{D}{B} \right)^r \quad (1)$$

where B, C , and D are variables representing the economic benefit derived from the structure, the cost of passive-control devices, the damage to structure associated with the seismic environment

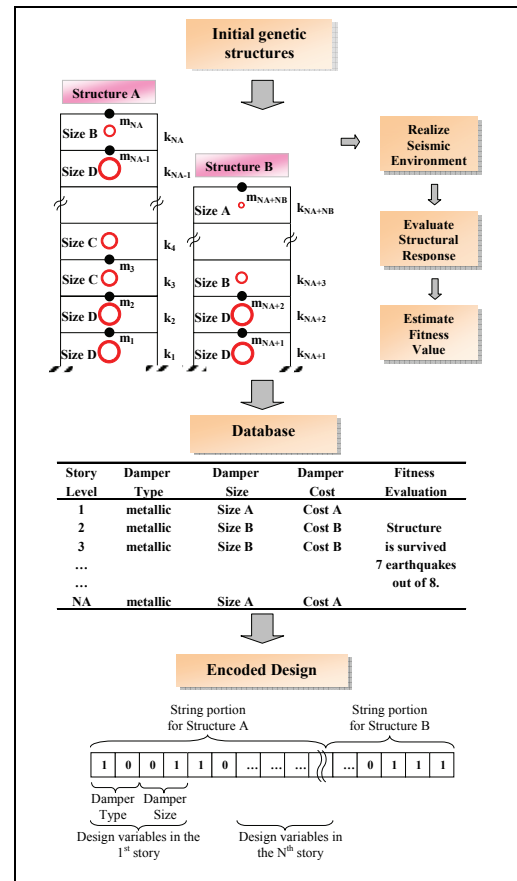


Figure 2. Overall framework of evolutionary methodology

respectively. Additionally, the fitness function is also dependent on the risk aversion index r , which is introduced for risk-based decision making in engineering. In order to reflect the realistic evaluation of economic costs and benefits involving risk, the risk aversion index r accounts for the willingness of spending proportionally more either to avoid larger losses or to reduce epistemic uncertainties involved in the structural system, the seismic environment, and the economics.

Design Variables: The design variables are chosen to be the type of the passive control devices, the size of the passive control devices, and the cost of the passive-control devices. Therefore, there are four basic relative cost values (cost 1, 2, 3, 4) and their associated relative size values (size 1, 2, 3, 4) for each type of passive control devices including metallic yielding dampers, viscoelastic solid dampers, and viscous fluid dampers (e.g., the cost 1 for the size 1 viscoelastic solid damper).

Design Constraints: The primary constraints are considered to be interstory drift constraint, absolute floor acceleration constraint, and in design of adjacent structures, separation constraint in order to evaluate performance and potential damage. The allowable interstory drift is taken as 1.5% of the height of the story of the buildings (FEMA-450 2003) and the allowable absolute floor acceleration is taken to be equal to $1.5g$. Separation limit is calculated as 2.25% of the height of the story of the buildings by adopting the square root of the sum of the squares rule of the two lateral displacements of adjacent buildings (IBC 2003). Then, the performance of structural response reduction is expressed in terms of reduction in the maximum interstory drift, the maximum absolute floor acceleration and the maximum relative displacement between adjacent structures.

Computational Simulations

A series of design examples, involving a pair of undamped adjacent steel frame structures (Building A and Building B), with various retrofit possibilities are selected as an example to examine the competence of the proposed GA based automated design methodology for configuring passive-control devices in the adjacent buildings, rather than to provide guidance for specific design situations. Building A is a twelve-story, 51.2 m. height steel frame structure with discontinuity and Building B is a five-story, 17.8 m. height steel frame structure. For computational efficiency, these buildings are simplified into a system of lumped masses connected by means of springs representing the lateral stiffness of the structure. Additionally, the lumped parameter two-surface cyclic plasticity model mentioned previously is employed to represent the hysteretic behavior of the primary structures. Within this idealized model, the values of k_i , W_i , F_i^{yl} , and F_i^{yb} , representing lateral stiffness, weight, yield force on the inner loading surface, and yield force on the outer loading surface for the i^{th} story, are shown in Table 2 for Building A and Building B. The parameters listed in Table 2 are selected as $k = 172843$ kN/m, $W = 1717$ kN, $F^{yl} = 1718.8$ kN, and $F^{yb} = 5156.4$ kN. The mass and stiffness distribution of Building A is non-uniform, unlike Building B. The corresponding first natural periods for Building A and Building B are 1.5 and 0.9 seconds, respectively. The maximum structure benefit and the risk aversion index are set at $B = 2000$ and $r = 2$, respectively.

Table 2. Basic dynamic properties of the adjacent building models

	Story stiffness [kN/in]	Story weight [kN]	Yield force (inner surface) [kN]	Yield force (outer surface) [kN]
Building A	$k_1 = \dots = k_8 = k$	$W_1 = \dots = W_8 = 1.5W$	$F_1^{jL} = \dots = F_8^{jL} = 1.5F^{jL}$	$F_1^{jB} = \dots = F_8^{jB} = 2F^{jB}$
	$k_9 = k_{10} = 0.75k$	$W_9 = \dots = W_{12} = W$	$F_9^{jL} = F_{10}^{jL} = 1.12F^{jL}$	$F_9^{jB} = F_{10}^{jB} = 1.5F^{jB}$
	$k_{11} = k_{12} = 0.5k$		$F_{11}^{jL} = F_{12}^{jL} = 0.75F^{jL}$	$F_{11}^{jB} = F_{12}^{jB} = F^{jB}$
Building B	$k_1 = \dots = k_5 = 1.12k$	$W_1 = \dots = W_5 = 1.8W$	$F_1^{jL} = \dots = F_5^{jL} = 2F^{jL}$	$F_1^{jB} = \dots = F_5^{jB} = 6F^{jB}$

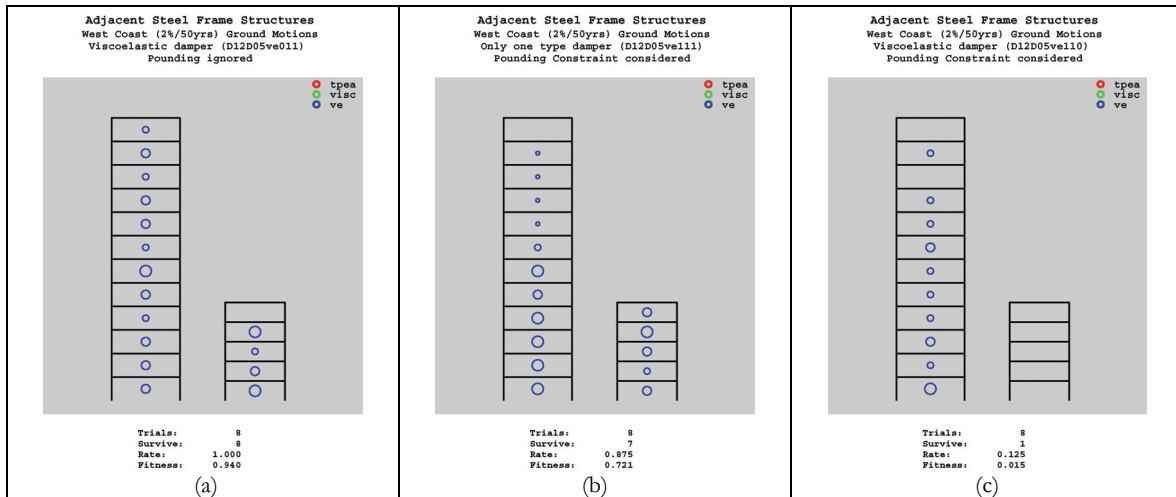


Figure 3. Twelve-story and five-story steel frames with viscoelastic dampers - robust designs with pounding (a) ignored (b) considered (c) considered but only Building A retrofitted

The seismic responses of adjacent structures, the maximum interstory drift and absolute floor acceleration, without or with passive-control devices are shown in Figure 4 and Figure 5, respectively. The maximum interstory drifts (resulted from eight different ground motions) with different passive-control device configurations are plotted in Figure 4. This figure shows that, if the dampers are uniformly distributed, the maximum interstory drift of Building A at story level eleven cannot satisfy allowable drift limit, whereas, with the proposed optimization procedure, the structural

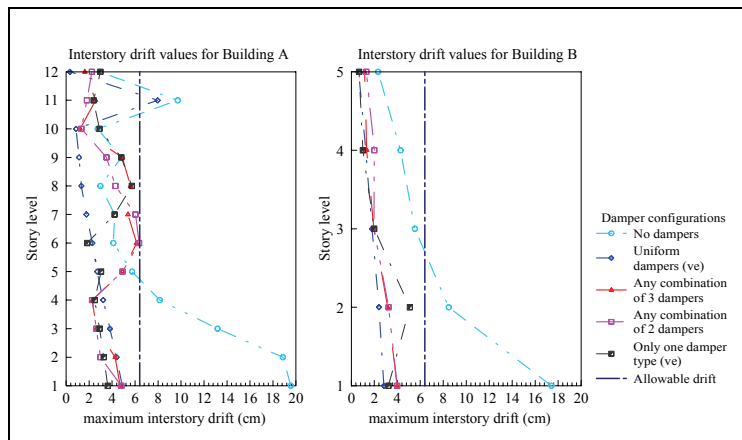


Figure 4. Maximum interstory drifts with different damper configurations

response in terms of interstory drift can

be reduced at 80% for both of the adjacent buildings, with other damper configurations. If the other seismic response, absolute floor acceleration is considered as an optimization criteria, the proposed methodology results in different values that are plotted in Figure 5. The figure shows that maximum absolute floor acceleration occurs at the ninth story of Building A. The optimization methodology can achieve a 60% reduction in absolute floor acceleration of this story level, when all three damper types are permitted for the retrofit. Note that starting from uniform to other damper configurations, accelerations are nearly same for Building A and Building B.

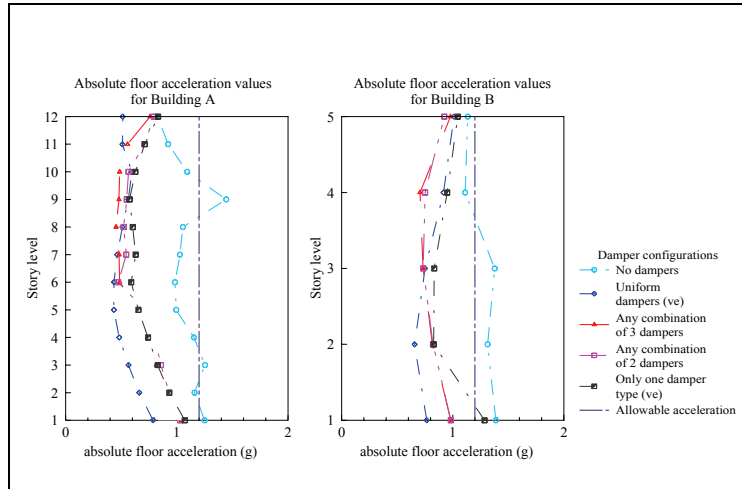


Figure 5. Absolute floor accelerations with different damper configurations

Conclusions

This paper presented a new evolutionary optimization methodology for passively controlled adjacent structures under pounding risk, based on cost and damage objectives. The method's capability of discovering robust designs was examined using a pair of adjacent structures as an example. Computational simulations of this example clearly showed that the optimal choice of the number, size, type, and distribution of the passive-control devices for the retrofit of adjacent structures often differs when potential pounding risk is ignored. The retrofit problem is complicated by the fact that, adjacent buildings usually belong to different owners, and retrofitting only one of the adjacent buildings might not be sufficient to mitigate the pounding risk.

This study is a significant attempt to encourage further research efforts that incorporate consideration of retrofitting issues of adjacent buildings under pounding risk into the structural optimization model so that the design results can be more likely applicable for a real world structural engineering practice. One of the characteristics of evolutionary algorithm appealing to researchers is its effectiveness and adaptability in handling uncertainties and nonlinearities. Because of these strengths, it is advantageous to implement the methodology to improved geophysical, structural, and even socioeconomic models. Consequently, in view of the current structural control technology, which has promising ability to provide protection to structures against multi-hazard dynamic loads, such as strong earthquakes, high winds, and/or blast loading, it is recommended that high priority of further research is given to the extension of the evolutionary algorithm to multi-hazard structural design. Research in this area, which is still in its early years, will certainly result in the enhancement of human safety and structural performance against damage by multi-hazard events.

Acknowledgement

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References

- Anagnostopoulos S.A. (1995): Earthquake induced pounding: State of the art. Proceedings of 10th European Conference on Earthquake Engineering, 2. 897-905.
- Chopra, M.B., and Dargush, G.F. (1994): Development of BEM for Thermoplasticity. *International Journal of Solid and Structures*, 31 (12/13), 1635-1656.
- Constantinou, M.C., Soong, T.T., and Dargush, G.F. (1998): Passive Energy Dissipation Systems for Structural Design and Retrofit. *Monograph No.1*, Multidisciplinary Center for Earthquake Engineering Research, The State University of New York at Buffalo, Buffalo, NY.
- Dargush, G.F., and Soong, T.T. (1995): Behavior of Metallic Plate Dampers in Seismic Passive Energy Dissipation Systems. *Earthquake Spectra*, 11 (4), 545-568.
- Dargush, G.F., and Sant, R.S. (2005): Evolutionary Aseismic Design and Retrofit with Passive Energy Dissipation. *Earthquake Engineering and Structural Dynamics*, 34, 1601-1626.
- Filiatrault, A., Cervantes, M., Folz, B., and Prion, H. (1994): Pounding of Buildings during earthquakes: a Canadian perspective. *Canadian Journal of Civil Engineering*; 21 (2), 251-265.
- Filiatrault, A., and Wanitkorkul, A. (2005): Simulation of Strong Ground Motions for Seismic Fragility Evaluation of Nonstructural Components in Hospitals. *Technical Report MCEER-05-0005*, Multidisciplinary Center for Earthquake Engineering Research, The State University of New York at Buffalo, Buffalo, NY.
- FEMA 450 (2003): *NEHRP Recommended Provisions and Commentary for Seismic Regulations for New Buildings and Other Structures*. Building Seismic Safety Council for the Federal Emergency Management Agency, Washington, DC.
- Furuya, O., Hamazaki, H., and Fujita, S. (1998): Study on proper distribution of storey-installation type damper for vibration control of slender structures using genetic algorithm. *Proc., 1998 ASME/JSME Joint Pressure Vessels and Piping Conf.*, Vol. 364, San Diego, 297-304.
- Holland, J.H. (1975): *Adaptation in Natural and Artificial Systems*. University of Michigan Press: Ann Arbor, MI.
- IBC (2003): *International Building Code*. International Code Council, Falls Church, VA, 2003.
- Kasai, K., and Maison, B.F. (1997): Building pounding damage during the 1989 Loma Prieta earthquake. *Engineering Structures*, 19 (3), 195-207

Lopez Garcia D., (2004). Separation Distance Necessary to Prevent Seismic Pounding Between Adjacent Structures. *Ph.D. Dissertation*, University at Buffalo, The State University of New York at Buffalo, Buffalo, NY.

Singh, M.P., and Moreschi, L.M. (2002): Optimal placement of dampers for passive response control. *Earthquake Engineering and Structural Dynamics*, 31 (4), 955-976.