Effect of The Optimal Number of Metallic Dampers on The Seismic Response of Frame Structures

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SUMMARY:
This paper addresses the questions of the number of Metallic dampers and the selection of their physical parameters via optimization techniques. The effectiveness of metallic dampers in introducing damping in a structure is a function of several variables, including their number, their location in the structure, and their physical properties. This study applies a genetic algorithm (GA) to obtain a proper number of the damper blades in each story of the building. The desired performance is defined in terms of several different forms of performance functions such as inter-story drift and base shear.

Keywords: genetic algorithm, energy dissipation devices, metallic dampers, optimization

1. INTRODUCTION

The usefulness of supplementary energy dissipation devices is now quite well-known in the earthquake structural engineering community for reducing the earthquake-induced response of structural systems. In particular, passive Metallic dampers have been the dominate choice of engineers. There are many reasons of dominance of metallic dampers within the earthquake engineering community. For example, since these protective systems are separated from the main structure, they act as structural fuses that can be replaced after a severe seismic event occurs if damaged. These devices exhibit stable hysteretic behavior, they are insensitive to thermal effects, and extremely reliable. The suitability of such damping elements for retrofitting existing structures as well as the construction of new ones is confirmed and advocated by several researchers. Yielding devices have been installed as part of seismic retrofit projects in concrete and steel buildings.

In contrast to active or semi active control devices, passive control devices do not require an external power source for their operation. However, since the mechanical properties of passive control devices cannot be altered to accommodate changing conditions during an earthquake, the selection of the type of control devices and the assignment of their number and location within the structure must be given particular attention.

In other hands, Dampers are known to rehabilitate the seismic response of the structures but the locations, numbers and the sizes of dampers in the structure need to be well defined by engineers and scientists. Tsuji and Nakamura introduced an algorithm for the optimum sets of story stiffness coefficients and damping coefficients of the dampers of an elastic planar shear building with viscous dampers. Takewaki proposed a systematic procedure for finding the optimal damper placement based on minimization of the sum of amplitudes of the transfer function of the interstorey drift at the undamped natural circular frequency of a structural system under a constraint on the sum of the damping coefficients of added dampers. Takewaki and Yoshitomi presented how to affect optimal dampers distribution and the lowest mode damping ratio due to variations support member stiffness of dampers. Shukla and Datta studied how to obtain optimally placed VEDs in the frequency domain using spectral analysis for narrow and broad band stationary random ground motions. Takewaki suggested a critical excitation approach by employing a stochastic response index as the objective function was maximized. Takewaki presented the optimal damper placement for a planar building frame using a minimum transfer function. Singh and Moreschi used a gradient-based optimization approach to solve the optimal damper distribution problem.

Yang, Lin, Kim and Agrawal presented two optimal design methodologies for passive added dampers based on active control theories. One approach was based on the H2 performance of the structure whereas the other approach was based on the $H\infty$ performance. Agrawal and Yang, Yang et al. and Hwang et al. used active control theories to determine damper allocations. Ji-Hun et al. studied a gradient-based simultaneous optimization procedure for both VEDs and supporting braces added in a structure. They showed that the size of the supporting brace could be reduced without significant increase in the size of VEDs by the simultaneous optimization procedure.

Among those who have examined the application of genetic algorithms for damper location selection, Furuya, Hamazaki and Fujita attempted to identify a suitable distribution of dampers for vibration control of a 40-story building subjected to various seismic excitations and with consideration given to economical issues while Singh and Moreschi determined both the optimal number and optimal distribution of dampers for seismic response control of a 10-story linear building structure. The results of Singh and Moreschi demonstrated that the number of dampers required using an optimal distribution is significantly less than that required when a uniform distribution is utilized.

This paper focuses on the application of a genetic algorithm for identifying optimal number of blades of Metallic dampers that will provide the largest structural response reduction of a 10-story nonlinear benchmark building subject to seismic loading. The distribution of the metallic dampers within the buildings is optimized under the constraint that the number of damper's blades and their properties are known parameters. The search space of the optimization is the possible stories in which dampers can be placed. An integer optimization is therefore utilized within the genetic algorithm process. The inter-story drift as the objective function is considered in the optimization process such that the optimal numbers of damper are dependent on the dynamic characteristics of both the building and ground motions. Simulation results of the nonlinear building model subjected to earthquakes are presented which illustrate the effectiveness of each damper distribution strategy. Also, depending on the objective function used, the optimal numbers of damper can vary significantly.

2. YIELDING METALLIC DAMPERS

Triangular-plate Added Damping and Stiffness (TADAS) dampers have been implemented to enhance structural performance by reducing seismically induced structural damage and particularly suitable for the retrofit of existing structures as well as the construction of new ones. TADAS is a variation of ADAS consisting of triangular plate elements that are made to deform as cantilever beams. Fig. 1 depicts the typical configuration of these devices. Because of their shapes, the metal plates in these devices experience uniform flexural strains along their length. Thus when the strain reaches the yield level, yielding occurs over their entire volume. During cyclic deformations, the metal plates are subjected to hysteretic mechanism and the plastification of these plates consumes a substantial portion of the structural vibration energy. Moreover, the additional stiffness introduce by the metallic elements increase the lateral strength of the building, with the consequent reduction in deformations and damage in the main structural members.

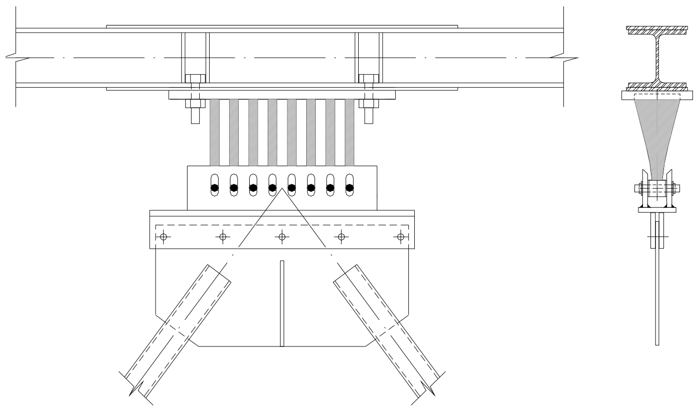

Figure 1. Triangular-plate Added Damping and Stiffness (TADAS) and typical configuration

It is noted that in contrast to the viscoelastic devices, the cyclic response of yielding metallic devices is strongly nonlinear accompanied of abrupt changes in element stiffness due to the loading, unloading and reloading of yielded elements. The introduction of these devices in a structure will render it to behave nonlinearly, even if the other structural elements are designed to remain linear. Here in this study, it is assumed that the structural elements and the braces that support these devices remain linear when they are subjected to the design level earthquake.

3. GENETIC ALGORITHM

A genetic algorithm is a stochastic search algorithm based on the mechanics of natural selection and population genetics. In this optimization method, information about the problem, such as variable parameters, is coded into a genetic string known as a chromosome. Each of these chromosomes has an associated fitness value, which is usually determined by the cost function to be maximized or minimized. Each chromosome contains sub-strings known as genes, which contribute in different ways to the fitness of the chromosome. The genetic algorithm proceeds by taking a population, which is comprised of different chromosomes and generating a new population or generation by combining features of chromosomes with the highest fitness values. The aim of the algorithm is to produce chromosomes with increasing fitness, and to increase the average fitness of each successive generation. Only the fittest chromosomes pass to successive generations.

The genetic algorithm uses three basic operations: selection, cross-over and mutation. Selection is the process of choosing the fittest string from the current population for use in further reproductive operations to yield fitter generations. Cross-over is the process whereby new chromosomes are generated from existing individuals by cutting each old string (chromosome) at a random location (cross-over point) and replacing the tail of one string with that of the other. Mutation is a random process whereby values of element(s) with in a genetic string are changed. In a binary string, mutation is the random changing of 1's to 0's and vice versa. Mutation ensures genetic diversity within the population by producing strings that contain new material and are therefore not totally derived from the previous generation. This operation therefore helps to prevent the Genetic Algorithm from being trapped in a local minimum. Fig. 2 shows the cross-over and mutation operations.

Genetic algorithms are used in evolution search methods and have found success in various applications. The algorithm models biological processes to optimize highly complex cost functions. The fundamental concept of genetic algorithms is to perform a systematic random search for the fittest individual through a number of generations of a population. Since genetic algorithms do not require the evaluation of cost function derivatives, they can readily handle highly complex and/or discontinuous problems with a large number of parameters. Moreover, since the algorithm simultaneously searches over a wide sampling of the search space, the solutions can easily escape from a local minimum. A detailed description of genetic algorithms can be found elsewhere. See Goldberg.

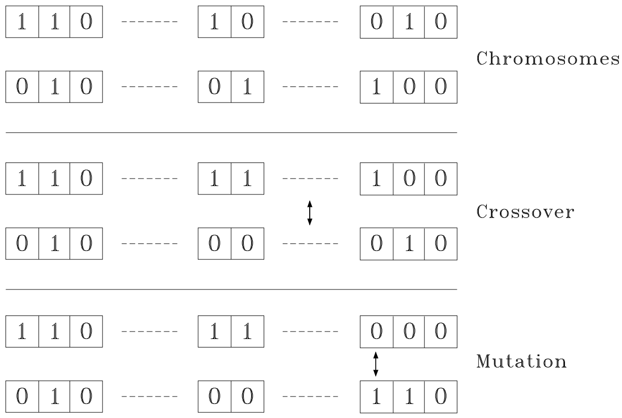

Figure 2. Operations of Genetic Algorithm

3.1. Genetic Algorithm Parameters

The values of the parameters used in the genetic algorithm are given in table 1. The string length is a variable depending on the encoding of the variables of the design problem. The size of the population is chosen to be 30 and the number of generation used in analysis is also 120. These values are considered to be reasonable since convergence is easily optained. The crossover rate is 0.9 and the rate of mutation used for the analysis is 0.1.

Table 1. Genetic Algorithm Parameters Used in Analysis

String Length	Population Size	No. of Generations	Crossover Rate	Mutation Rate
10	30	120	0.9	0.1

4. STRUCTURAL BUILDING MODEL AND ANALYTICAL MODELING OF YIELDING METALLIC DEVICES

The structure is modeled as 10-story planar shear building. In this idealization, the building is considered as a system of masses connected by of linear springs and yielding metallic dampers to represent, respectively, the lateral stiffness and energy dissipation of the structure. Associated to each lumped mass there is one-degree-of freedom defining its displaced position relative to the original equilibrium position. The mass is uniformly distributed, but the mechanical properties of this building are changing during process. A simple bilinear hysteretic forcing model is used to identify the parameters involved in the design of a typical metallic element. Fig (3.a) represents a structural frame bay with an added hysteretic damper. Herein, the combination of a yielding metallic element and the bracing members that support the device is called as the device-brace assembly. The combined lateral stiffness of this assembly is schematically shown in Fig (3.b). This combined stiffness, denoted as k_{bd}, can be obtained by considering the contribution in stiffness k_d due to the metallic device and the stiffness k_b added by the bracing. Since these stiffnesses are connected in series, it follows that :

$$k_{bd} = \frac{1}{\frac{1}{k_b} + \frac{1}{k_d}} \tag{1}$$

The structural fuse concept requires that yield deformation of the damping system, Δ_{ya}, be less than the yield deformation corresponding to the bare frame, Δ_{yf}. Considering the deformation of the device support system, the yield deformation of the added damping system is equal to:

$$\Delta_{ya} = \Delta_{yd}\left(1 + \frac{k_d}{k_s}\right) \tag{2}$$

where Δ_{yd} is the damper yield deformation. k_s is the lateral stiffness of the device support system (which may be optional, depending on whether the device requires to be attached to a support system).

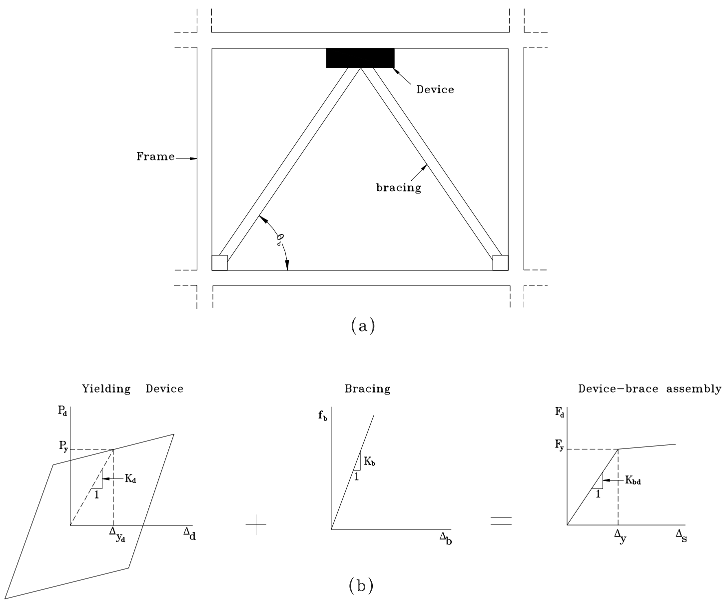

Figure 3. Yielding metallic damper, (a) typical configuration, (b) yielding metallic device, bracing and yielding element parameters

5. PROBLEM DEFINITION

The equations of motion of a building with added damping devices subjected to base motion can be written as:

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) + \sum_{j=1}^{n_l} \mathbf{r}_j n_j P_j(t) = -\mathbf{M}\mathbf{E}\mathbf{f}(t) \tag{3}$$

where M, K and C represent, respectively, the N×N mass, structural stiffness and inherent structural damping matrices, f(t) is an l-dimensional vector representing the seismic excitation, E is a N×l matrix of ground motion influence coefficients, u(t) is the N-dimensional relative displacement vector with respect to the base and a dot over a symbol indicates differentiation with respect to time. The contribution of the force caused by a single damper P_j to a degree of freedom is considered through the influence vector r_j. The number of identical dampers installed at the jth location is denoted by n_j , and n_l is the number of blades for a damper in the structure. Given an energy dissipation device with predetermined mechanical properties, it is of interest to determine the optimal number and locations of such devices to achieve a desired reduction in the structural response. Such a question can be answered by posing this design problem as an optimization problem.

The reduction of a desired response quantity or the performance expected from a structure could be expressed in terms of the desired value of a performance index or function, f( ). In terms of a performance index, the optimal design problem at hand can be stated as

$$\text{minimize}(n) \quad f[\mathbf{R}(\mathbf{n},t)] \tag{4}$$

$$\text{Subject to} \quad \sum_{j=1}^{n_l} n_j = n_b \tag{5}$$

where n is the vector of design variables n_j , n_b is the total number of blades of dampers to be placed in a structure and R(n,t) is the structural response vector such as the floor accelerations, shears, etc. on which the performance function depends. The performance index in Eqn. 4 could be stated in different forms, depending on the objectives of the design. For example, it could be defined in terms of a single response quantity of interest, such as the acceleration of a floor or the base shear or the over turning moment, if the objective is to reduce such a response quantity. It could also be defined in terms of several similar response quantities such as the sums of the squares of the floor accelerations, or the squares of the sums of the inter-story drifts, where the interest would be to reduce these quantities for the entire structure. For the performance-based seismic design of structures, where the structure is expected to perform in a certain desired manner at different levels of excitation intensities, the performance index could take forms that are more complex. For example, it could be defined in terms of the life cycle cost estimates for the building structure, considering different levels and types of hazards a building structure can experience. The objective may be to minimize the life cycle cost by altering the structure design parameters, including the parameters of the protective devices such as dampers and other control devices. We do not intend to go into the details of the formation of these performance indices, but just to indicate that they can take different forms serving different objectives. The forms of performance indices that are chosen in this study are defined later when the numerical results are presented. The primary objective of this study is to obtain the best combination of n_j, that is the number of dampers at locations, such that the performance index of Eqn. 4 is minimized.

6. NUMERICAL EXAMPLE

The structural seismic responses with or without optimum damper distribution are shown in Fig. 4, 5. The plotted responses are the maximum inter-story drift, number of blades and story shear at each floor. These figures show that optimization of added damping can reduce the structural response under lateral loads. Fig. 4 shows the optimized device configuration (number of blades) based on the drift performance index. According to FEMA 356, the maximum inter story drift is equal to 1.5% height of story.

The left plot (Fig. 4a) is the number of blades distribution for metallic dampers along the building stories. The right plot (Fig. 4b) is the maximum inter story drift in performance point at each story with the original uniform configuration and the optimized configuration. The figure shows that, given the same damper devices, optimization using genetic algorithm (GA) can optimize the structural response with respect to inter story drift about 1.5% height of stories. The optimized damper configuration has more dampers in the lower stories of the building.

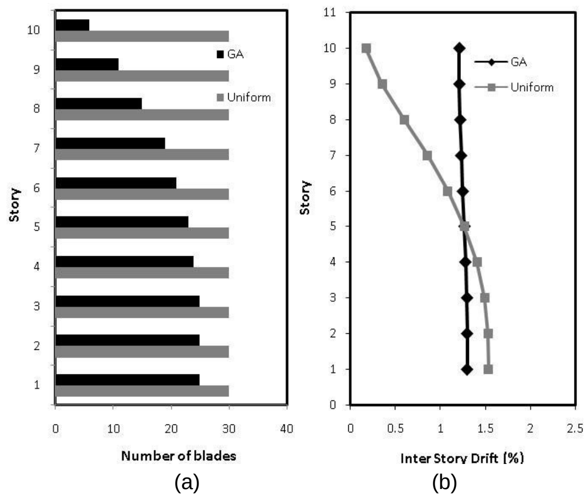

Figure 4. Optimized device configuration for inter-story drift

When the performance index is taken as the inter story drift, the optimization result for story shear at each floor is plotted in Fig. 5. This figure compares reduced story shears in performance point in the optimized configuration with original uniform configuration. After optimization, the base shear has reduced about 27%.

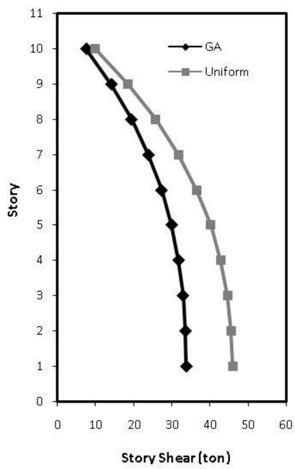

Figure 5. Comparison of response quantities in both cases of optimized and uniform distribution of blades

7. CONCLUSIONS

The paper demonstrates the use of a genetic algorithm approach for optimal design of passive dampers for building structures. The study employs the yielding metallic dampers for the dissipation of energy. The genetic approach is used to calculate the required number of a given capacity dampers and their optimal numbers in a building to achieve a desired reduction in the response. For a given location of dampers, the approach can find optimal distribution of blades to achieve the maximum reduction in a desired response. The response reduction performance could be expressed in terms of a reduction in a chosen response quantity such as base shear, inter-story drift or floor acceleration. It could also be defined in terms of a performance function, depending upon several response quantities. The approach is flexible inasmuch as it can work with any performance function as long as it can be numerically calculated. Numerical results are reported for a shear building model installed with one type of damping devices (TADAS) and one form of performance index.

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