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Multiobjective Optimisation Strategy for Seismic Response Control of Buildings using Genetic Algorithm

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Abstract *Multiobjective optimisation by evolutionary algorithms is becoming attractive strategy in several disciplines of engineering. This study employs supplemental damping to improve seismic performance of buildings and exploits the power of genetic algorithm, to strategically place the viscous fluid devices throughout the height of building, and optimise the damping provided by them. Interstorey drift and base shear, which serves as important seismic control parameters, are used as two significant objectives for their simultaneous minimisation. Strong ground motions which have shown excessive damage to buildings in the past are used to analyse their effect on set of five and ten storey buildings and subsequent response control by providing damping devices. Comparison of results shows that genetic algorithms are best suited for multiobjective optimisation in seismic response control.*

Keywords *Multiobjective optimisation, seismic response control, strong motion, energy dissipation devices, genetic algorithm, interstorey drift.*

I. INTRODUCTION

An Earthquake energy management in short duration of real time has been a critical challenge to mankind for its uncertainty and devastating effects. It received serious attention of researchers in last three decades owing to substantial life and infrastructural loss all over the globe. Seismic response control is emerging active field of research, wherein, resilient design of buildings is achieved by absorption or dissipation of earthquake input energy. Technological advancement today has allowed practitioners to implement base isolation and supplemental damping solutions, covering large spectrum of devices and control systems, to protect the buildings from undesired response in seismic event of high magnitude. These measures have permitted structural designers to follow a strategy of achieving desired performance objectives in structures without pushing them into collapse state.

The objective of utilizing energy dissipation devices (EDD) is to reduce critical responses of structure and to mitigate damage or collapse of structures from severe earthquakes by participating in energy dissipation. As a successful application, installation of EDD in a building structure, enables control of the story drift within the required limitation and maintains its desired functions during an earthquake event. Since the first application of EDD in structural engineering took place in 1960s, abundant research work has been conducted to study their material characteristics, mechanism and the behaviour of externally damped structures. With the invention of different types of damping devices and systems, improvement of modelling techniques and development of new computational methodologies, use of these devices has become a mature technology in designing of new structures and retrofitting of existing facilities.

Prevailing technology of EDD systems requires economical utilization due to its expensive manufacturing costs and simultaneously achieve expected high-quality performance and reliability. As a result, structural control with optimization of these systems should become an integrated design approach.

II. PASSIVE CONTROL AND OPTIMISATION STUDIES

The passive energy dissipation systems, such as fluid viscous devices and visco-elastic devices, act as energy sinks and absorb some of the input vibration energy so that less is available to cause deformation of structural elements. Importance of this approach is highlighted and emphasized in several studies ([1],[2],[3],[4]).

Displacement, interstorey drift and base shear serve as important performance indicator of seismic response of buildings. The results of these quantities are useful for assessing, comparing and discussing effectiveness of structural behaviour under any structural control strategy or optimization.

Cheng and Pantelides [5] pioneered an approach in which the locations of active controllers were optimized based on controllability index. The guiding principle underlying the method is that a device/controller is optimally placed when it is located at a position where the relative controllability index defined in terms of weighed modal inter-storey drifts is minimum. Though it was done in the context of active control, the concept was very much applicable for addressing the optimal positioning issues in passive control. Zhang and Soong [6] used an intuitive idea of inserting devices one by one at that location where maximum of inter-storey drifts is found at latest cycle, for renewed properties of structure. This was pioneering extension to the controllability index method to address the issue of locating passive dampers. This procedure was called the Sequential Search Algorithm (SSA), which determined the optimal location index by evaluating the random seismic response of a structure using the transfer matrix method. The mean square values of the inter-story drifts were used as optimal location indices. This approach was further extended by Garcia [7] as simplified sequential search algorithm (SSSA) to optimize the computational efforts.

A new approach of passive damper placement with a algorithms in frequency domain solution pioneered by Takewaki [8],[9] was to minimize the sum of the amplitudes of the transfer functions evaluated at the undamped fundamental natural frequency of the structural system. This work was based on the concepts of inverse problem and optimal criteria based design approaches. However, it still lacks the required convincing in its direct use in practical implementation, owing to the fact that neither the current standards nor the practicing structural engineers are tuned to the frequency domain techniques.

Goldberg and Samtani [10] appear to have first suggested the use of genetic algorithms (GA) for structural optimization. They considered the use of a GA to optimize a 10-bar plane truss. Hajela and Lin [11] analysed the potential of GA as function optimizers in the context of structural optimization. He discussed encoding, optimal population size, selection, crossover and mutation over binary alphabets, making an important distinction between random search and genetic search. Rajeev and Khrisnamoorthy [12] used the GA for discrete optimization of generalized trusses.

Lavan et al. [13] and Lavan and Dargush [14] provided a framework for multiobjective optimization methodology in evolutionary computing by GA, to optimize performance of building to given seismic excitation by means of energy dissipation devices. Optimization of interstorey drifts and floor accelerations was demonstrated with Pareto front concept using novel fitness index. Three building were used to demonstrate the methodology and its effectiveness. A 10-storey building with elastic behaviour, five-story regular yielding shear frame that considers strength reduction and added viscous damping as an additional retrofitting approach are considered. Though this work was able to set certain direction to multiobjective optimization with passive devices, it also admitted the shortfalls in the study. Important to mention is, missing comprehensive characterization of the seismic environment which can take into consideration distribution of devices appropriate to meet specific performance objectives for specific seismic hazard level. Secondly, the methodology focuses more on topology optimization which does not address the exact amount of supplemental damping essential for certain objective.

In this study, problems identified in scientific literature discussed above are addressed sufficiently accurately by using elitism strategy. The strong stochastic characteristics of genetic algorithm (GA) allows global optimization and simultaneously handle multiple objectives of competing nature.

III. GENETIC ALGORITHM PROCEDURE

In order to find optimal designs, the GA processes populations of fittest chromosomes, successively replacing one such population with another. The procedures required to achieve this goal and organize the task in systematic but stochastic way are termed as operators in GA. The simplest form of genetic algorithm involves three types of operators: selection, crossover and mutation.

A. Selection (Reproduction)

The Selection or reproduction is usually the first operation which is exerted on population. In this step, a set of chromosomes are selected from the population as parents. Based on the survival of the fittest, to create the better generation, the best and fittest chromosomes must be selected. Selecting the most prospective chromosomes from the current generation, creating several copies of them and finally putting them into the mating pool is the main goal of several selection methods. At the end of the above step, the mating pool is full. A new population is generated from the parent population of the mating pool. A probabilistic based roulette wheel selection strategy is depicted in figure 1.

B. Crossover (Recombination)

Creating minimum two offspring from two parents randomly chosen from mating pool requires a crossover operator. A newly born child inherits genetic information from its parents, similarly the crossover operator exchanges the information in chromosomes at random location/s. The crossover point in chromosomes is known as site. Single-point, two-point, multi-point and uniform crossover are the most common crossover techniques. The crossover operator roughly mimics biological recombination between two single‒chromosome organisms. Figure 2 demonstrates a general crossover operation in binary coded chromosomes. A crossover rate is percentage of recombination from total number of parent population in mating pool. The crossover probability of 80 % to 99 % is used in general.

C. Mutation

This operator randomly flips bits, 0 to 1 and vice versa, in a chromosome. By this operation few individuals of new population are modified (mutated) to mimic the diversification of population in nature. This operation is performed according to a certain mutation rate or probability on a bit by bit basis. The bits of any individual are mutated independently and randomly. It means that the mutation of an individual bit doesn't affect the mutation probability of other bits. In general, 1% to 2% mutation rate is accepted. The mutation operation is explained in figure 3.

D. Computation in GA

This A simple GA works as follows

1. Start with a randomly generated population of even number of chromosomes (candidate solutions to a problem).

2. Calculate the fitness of each candidate chromosome x in the population.

3. Repeat the following steps until same no. of offspring have been created:

di a. Select a pair of parent chromosomes from the current population, the probability of selection being an increasing function of fitness. Selection is generally done "with replacement," meaning that the same chromosome can be selected more than once to become a parent.

b. With chosen probability of crossover called “crossover probability" or "crossover rate", cross over the pair at a randomly chosen section to form two offspring. There are also "multi−point crossover" versions of the GA in which the crossover rate for a pair of parents is the number of points at which a crossover takes place.

c. Mutate the two offspring at each locus with the mutation probability or mutation rate, and place the resulting chromosomes in the new population. If population size is odd, one member from new population can be discarded at random.

4.Replace the current population with the new population.

Each iteration of this process is called a generation. A GA is typically iterated for anywhere from 50 to 500 or more generations. The entire set of generations is called a run. At the end of a run there are often one or more highly fit chromosomes in the population.

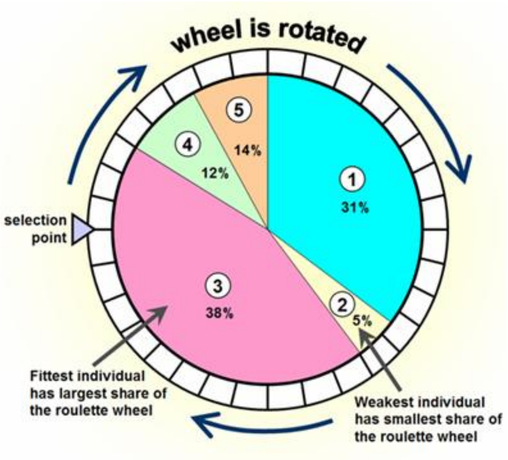

Fig. 1 A Roulette wheel selection strategy
(http//www.edc.ncl.ac.ukhighlight-rhjanuary-2007g02.php)

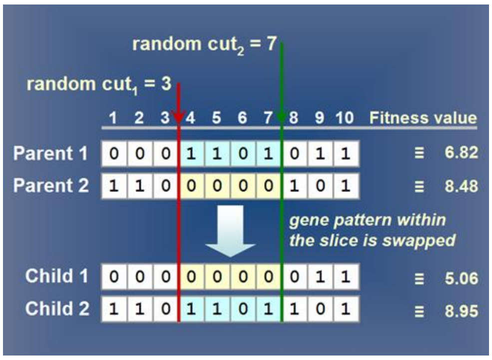

Fig. 2 Crossover operation
(http//www.edc.ncl.ac.ukhighlight-rhjanuary-2007g02.php)

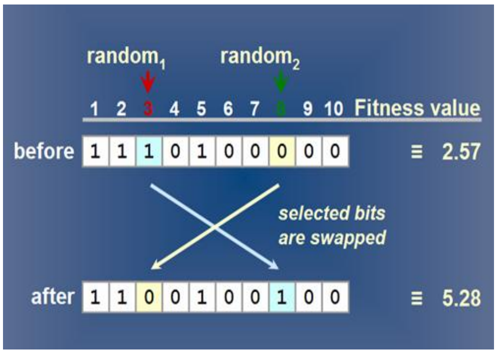

Fig. 3 Mutation operation
(http//www.edc.ncl.ac.ukhighlight-rhjanuary-2007g02.php)

IV. MULTIOBJECTIVE OPTIMISATION PROBLEM AND SEISMIC ANALYSIS

Interstorey drift and base shear serve as two important performance indicators in seismic response analysis of buildings. A close insight shows that these two quantities are mutually related if considered for simultaneous optimization. An excessive reduction of drifts will automatically require corresponding increase in base shear. On the other hand, limiting the base shear to minimum will cause increase in interstorey drifts and total roof displacement of buildings, both of which may cross the limits prescribed by code. Hence, these two quantities are used as simultaneous performance objectives to be handled by GA for multiobjective optimization. The goal of GA chosen in this study is to select the optimized amount of damping and device placement which results in minimizing both base shear and interstorey drifts simultaneously.

Set of 5 storeys and 10 storey buildings are considered for investigation with and without dampers installed. The structural properties of these buildings are chosen in such a way that they provide sufficient range of periods to obtain meaningful results of optimization analysis. In order to compare the performance of optimal solution, a uniform device placement strategy is also followed which minimizes interstorey drifts and base shear both.

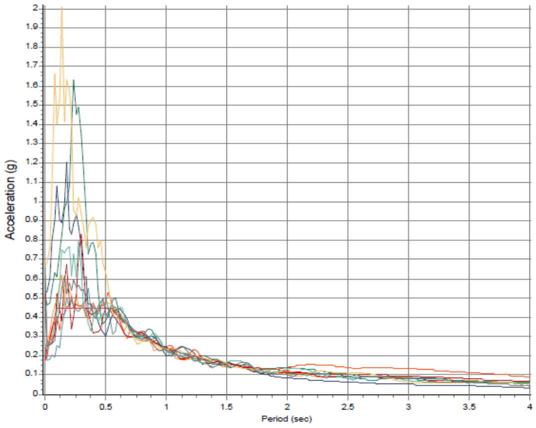

Fig. 4 DBE spectrum matched ground motion time histories (Ref. Table I)

The ground motion chosen for the analysis are as shown in Table I. These motions are selected with magnitude and peak ground acceleration such that they represent sufficient damage in the past. These ground motion are scaled, as shown in figure 4, by the SEISMOMATCH [15] code, which follows a procedure given by Al-Atik and Abramson [16]. The spectral matching is carried out in such a way that, they are period matched for each building under consideration, for design basis earthquake (DBE) response spectrum indicated in IS1893-2002 [17].

In order to quantify results and demonstrate the usefulness of multiobjective optimization the viscous fluid dampers (FVD) are used as EDD.

V. STRUCTURE AND DEVICE MODELING

A. Viscous fluid dampers (FVD)

The generalized characteristic relation of FVD is stated as

$$\mathbf{F(t) = c_d |\dot{x}|^{\alpha} sgn(\dot{x})} \qquad (1)$$

Where x with dot over head is relative velocity across ends of device. $\mathbf{c_d}$ is a generalized damping coefficient and α may take values in the range of about 0.25 to 2. That is, the damper may exhibit nonlinear viscous behaviour (the case a α= 1 is that of a linear device and appropriate for earthquake analysis). The force-displacement hysteresis relation indicating energy dissipation characteristics of such devices is as shown in figure 5.

B. Buildings modelling

Two set of reinforced concrete (RCC) buildings are considered in this study to determine the efficacy of optimization algorithm. First set of building models consists of six number of 5 storey buildings and the other set consists of six number of 10 storey buildings. These buildings are designed sing ETAB® software as per IS1893-2002 and IS456-2000 [18]. An imposed load of 3kN/m2 and normal brickwork masonry in the walls is used with height of each storey 3.2m. One of principal direction (Y) is deliberately designed to violate drift criteria for the purpose of evaluating amount of damping and subsequent optimization. The plan layout of each set is as shown in figure 6.

TABLE I

Ground motions used for analysis.

Ground motion	**Station or Site**	**Magnitude (Richter)**	**PGA (g)**
Elcentro Earthquake, 1940	Elcentro Array #9	6.9	0.348
West Washington Earthquake, 1965	Olympia	6.7	0.279
Koyana Dam, Earthquake, 1967	Koyana 1A Gallery	6.5	0.487
Uttarkashi Earthquake, 1991	Bhatwari	6.8	0.246
North Ridge Earthquake, 1994	San Bernardino	6.7	0.582
Park Field Earthquake, 1982	San Luis Obisbo	6.2	0.354
Imperial Valley Earthquake, 1940	Imperial Valley Irrigation district, California	6.9	0.214

Table II
Seismic response results of multiobjective analysis and saving in damping [5 storey]

Building.	Ground motion	Building status	Inter-storey drift ratio [Actual on Limiting] (Unsafe if >1)	Base shear as fraction of seismic weight of building.	Total damp. value (kN/m/s)	% Saving in dampi-ng
A1	W. Washington	I	1.086	0.398	NA	
		II	1.000	0.367	1833	
		III	0.957	0.353	1223	36.71
		IV	0.946	0.348	1454	24.75
A2	Elcentro	I	1.128	0.340	NA	
		II	1.000	0.306	5718	
		III	0.950	0.304	3971	35.10
		IV	0.960	0.297	4465	27.01
A3	Uttarkashi	I	1.129	0.295	NA	
		II	1.000	0.269	7868	
		III	0.903	0.262	5352	31.97
		IV	0.900	0.258	6779	13.84
A4	Uttarkashi	I	1.265	0.281	NA	
		II	1.000	0.230	10624	
		III	0.898	0.221	7643	34.25
		IV	0.881	0.219	8363	28.06
A5	Park Field	I	1.330	0.258	NA	
		II	1.000	0.198	9041	
		III	0.938	0.186	6412	36.14
		IV	0.927	0.184	6703	33.24
A6	Uttarkashi	I	1.404	0.255	NA	
		II	1.000	0.191	15721	
		III	0.914	0.182	10275	42.02
		IV	0.848	0.166	14991	15.40
I-Bare Frame II-Uniform Damping III-Optimal plan-1 IV-Optimal plan 2						

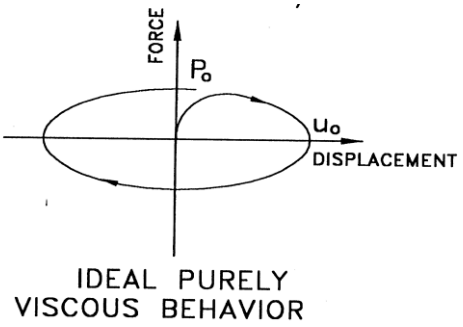

Fig. 5 Fluid viscous damper (FVD) ideal hysteresis loop

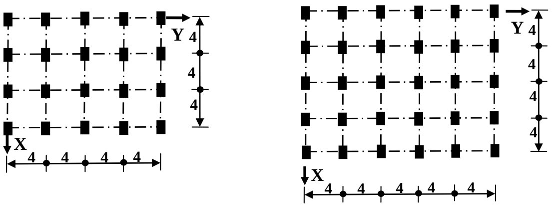

Fig. 6 Plan of 5 storey(left) and 10 storey (right) buildings

VI. MULTIOBJECTIVE OPTIMISATION RESULTS AND DISCUSSION

As discussed earlier, genetic algorithm implementing elitism procedure is developed in this study and implemented to verify the effect of objective priorities on drift and shear control of buildings. Two different strategies are investigated. In the first strategy (optimal plan-1) the priority was set for shear rather than drift, accordingly weightage of shear control was set to 80% and drift control to 20%. In second strategy (optimal plan-2) the priority was reversed i.e. drift at 80% and shear at 20%. With these considerations, in this study, results are discussed for multiobjective optimization.

The 5 and 10 storey buildings were subjected to one of these excitations which could match the level of shaking due to DBE response spectrum at fundamental time period of building under consideration.

Table II shows results for 5 storey buildings and Table III shows results for 10 storey buildings with and without FVD.

As seen from Table II and III, there is good amount of reduction in drift and shear due to supplemental damping strategies of uniform and optimal. It can also be observed that the percentage saving in damping due to optimal plans is quite substantial. The effect of objective priority choice is also very clear from magnitudes of shear and drift. Even minor increase in one requirement (e.g. more drift reduction) can cause large effect on other objective (base shear). This shows the power of multiobjective algorithms over mono-objective optimal strategies. So, a designer can have a choice to obtain specific control as per his priority or choice by setting weightages in the algorithm accordingly.

Table III
Seismic response results of multiobjective analysis and saving in damping [10 storey]

Building.	Ground motion	Building status	Inter-storey drift ratio [Actual on Limiting] (Unsafe if >1)	Base shear as fraction of seismic weight of building.	Total damp. value (kN/m/s)	% Saving in damping
B1	Imperial Valley	I	1.084	0.221	NA	
		II	1.000	0.211	16758	
		III	0.973	0.208	10345	38.27
		IV	0.963	0.207	11264	32.78
B2	Koyana	I	1.166	0.203	NA	
		II	1.000	0.183	28817	
		III	0.936	0.169	19471	32.43
		IV	0.933	0.169	21168	26.55
B3	Imperial Valley	I	1.119	0.158	NA	
		II	1.000	0.144	34915	
		III	0.956	0.144	20783	40.48
		IV	0.975	0.139	24322	30.34
B4	Koyana	I	1.366	0.1641	NA	
		II	1.000	0.1465	54701	
		III	1.000	0.1296	34842	36.31
		IV	1.000	0.1294	37813	30.87
B5	Imperial Valley	I	1.291	0.1338	NA	
		II	1.000	0.1084	67120	
		III	0.964	0.1064	45660	31.97
		IV	0.970	0.1024	50004	25.50
B6	Northridge	I	1.552	0.1466	NA	
		II	1.018	0.1283	97632	
		III	1.003	0.1143	58918	39.65
		IV	1.000	0.1170	59532	39.02

I-Bare Frame II-Uniform Damping
III-Optimal plan-1 IV-Optimal plan 2

VII. CONCLUDING REMARKS

This study has developed multiobjective genetic algorithm to study the mutual effect of drift control and shear control which serves as competing objectives and results of all analyses are examined in detail. The objective of achieving seismic response control in desired manner is verified through important criteria of maximum interstorey drifts and maximum base shear. Analysis results of 5 and 10 storey buildings with and without providing supplemental damping by FVD are compared. To verify the efficacy of optimal control genetic algorithm developed in this study, responses and damping distribution are compared with that of uniform damping.

Comparison of results shows that genetic algorithms are best suited for multiobjective optimisation in seismic response control. The multiobjective strategies provide clear scenario and more power in decision making process, so that designer can set and achieve goals as per his priorities.

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Bldg.	Ground motion	Building status with damping category.	Interstorey drift ratio [Actual on Limiting] (Unsafe if >1)	Base shear as fraction of seismic weight of building.	Total damping value (kN/m/s)	% Saving in damping
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