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Optimal assessment and location of tuned mass dampers for seismic response control of a plan-asymmetrical building

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Abstract. A bi-directional tuned mass damper (BTMD) in which a mass connected by two translational springs and two viscous dampers in two orthogonal directions has been introduced to control coupled lateral and torsional vibrations of asymmetric building. An efficient control strategy has been presented in this context to control displacements as well as acceleration responses of asymmetric buildings having asymmetry in both plan and elevation. The building is idealized as a simplified 3D model with two translational and a rotational degrees of freedom for each floor. The principles of rigid body transformation have been incorporated to account for eccentricity between center of mass and center of rigidity. The effective and robust design of BTMD for controlling the vibrations in structures has been presented. The redundancy of optimum design has been checked. Non dominated sorting genetic algorithm (NSGA) has been used for tuning optimum stages and locations of BTMDs and its parameters for control of vibration of seismically excited buildings. The optimal locations have been observed to be reasonably compact and practically implementable.

Keywords: bi-directional tuned mass damper; genetic algorithm; Pareto optimization; passive control; asymmetric building; rigid body transformations.

1. Introduction

Asymmetry in the structures has always been a principal cause of structural failure in every major earthquake. There are numerous observations of damages caused by excessive torsional response in particularly irregular buildings (both in plan and elevation). The torsion-induced failures have been especially terrible for multi-storey buildings because torsional response changes the uniform translational seismic floor displacements and causes concentration of demand in elements at the perimeter of the building. This often leads to failure of the over-loaded elements, which in turn initiates progressive collapse of the building.

To protect civil structures from significant damage, the response reduction of civil structures under such severe earthquakes has become an important topic in structural engineering. During the last three decades, significant efforts have been made to apply control methodology to civil structures

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for enhancing structural safety against natural hazards. In this study, BTMDs have been used to control the torsional as well as lateral floor displacements and accelerations.

A reasonable amount of research work has been reported in the literature, where tuned mass dampers and other related methodologies were used to control the vibration of structures. Xu and Igusa (1992) studied the dynamic characteristics of a system supporting multiple subsystems with closely spaced frequencies. They demonstrated the use of such subsystem as a means of passive control to large structures. Yamaguchi and Harnpornchai (1993) studied the fundamental characteristics and performance of multiple tuned mass dampers (MTMDs) with distributed natural frequencies for controlling response of the harmonically forced structures. The investigation was carried out analytically with the parameters of the covering frequency range of MTMDs, the damping ratio of each tuned mass damper (TMD) and the total number of TMDs. The effectiveness and robustness of MTMDs were also studied. Abe and Fujino (1994) analytically studied characteristics and efficiency of MTMD-structure system consisting of a large number of small oscillators with natural frequencies distributed around the natural frequency of the first mode of the structure. Joshi and Jangid (1997) studied the optimum parameters of the MTMD system for base-excited structure. The criterion selected for optimality was the minimization of the root mean square (rms) displacement of the main structure. The base excitation was modeled as a stationary white noise random process. Jangid and Datta (1997) investigated the dynamic behaviour of a simple torsionally coupled system with MTMDs with uniformly distributed frequencies. It was shown that the effectiveness of MTMDs in controlling the lateral response, modelled as a broad-band stationary random process, of the torsionally coupled system decreased with the increase in the degree of asymmetry. Jangid (1999) investigated optimum parameters of Multiple Tuned Mass Dampers (MTMD) for an undamped system to harmonic base excitation using a numerical searching technique. The criteria selected for the optimality is the minimization of steady-state displacement response of the main system. Li (2000) fabricated MTMD by keeping the stiffness, damping constant and varying the mass of dampers. The structure was represented by its mode-generalized system in the specific vibration mode being controlled using the mode reduced-order method. It was found that the current optimum MTMD was more effective than the other optimum MTMD fabricated by keeping the mass constant and varying the stiffness and damping coefficient and the optimum single TMD with equal mass. Li (2002) conducted a study to search for the most preferable MTMD, which performed better and could be easily fabricated from various combinations of the stiffness, mass, damping coefficient and damping ratio in the MTMD and the optimum parameters were obtained based on the minimization of the maximum value of the displacement dynamic magnification factor (DDMF) and that of the acceleration dynamic magnification factor (ADMF) of the structure. Chen and Wu (2003) designed and fabricated several mass dampers to suppress the seismic responses of a 1/4 th scale three-storey building structure. Experimental results indicated that the multiple damper systems was substantially superior to a single tuned mass damper in mitigating the floor accelerations even though the multiple dampers were sub-optimal in terms of tuning frequency, damping and placement. Li and Qu (2006) adopted MTMD with identical stiffness and damping coefficient but with different mass for suppressing translational and torsional responses of a simplified 2DOF structure, representing general asymmetric structures subject to ground motions. Rana and Soong (1998) summarized the results of parametric study performed to enhance the understanding of some important characteristics of TMD. The effect of detuning on some of the TMD parameters on the performance is studied using steady state harmonic excitation analysis and time history analysis. Hadi and Arfiadi (1998) discussed the optimum design of TMD for seismically excited building considering the structure as a multi degree freedom system. GA was used to find optimum value of TMD parameters. Sarbjeet and Datta (1998) studied the seismic response of shear frame model of tall buildings with the help of active mass dampers (AMD). A control study based on a free forward and backward gain algorithm (an open-closed loop) was presented for the control of structural displacement response under random ground motion. Chen and Wu (2001) studied about multistage and multimode tuned mass dampers. Several optimal location indices were defined based on intuitive reasoning and a sequential procedure was proposed for practical design and placement of the dampers in seismically excited building structures. Park and Reed (2001) extended the results of many previous investigations to examine the performance of uniformly and linearly distributed multiple mass dampers, respectively under El Centro earthquake motion. A method to design multiple tuned mass dampers for minimizing excessive vibration of structures were developed by Hoang and Warnitchai (2004) using a numerical optimizer. The method has been used to design MTMD for SDOF structures subjected to wide-band excitation. Multiple active-passive tuned mass dampers (MAPTMD) consisting of many active-passive tuned mass dampers with a uniform distribution of natural frequencies were proposed by Li (2002) for attenuating undesirable oscillation of structures under the ground excitation. MAPTMD was observed to render high robustness and better effectiveness than a single APTMD, particularly when large active control force was required. The process of a damper in improving a structure's ability to dissipate the earthquake's input energy was studied by Wong and Chee (2003). Singh *et al*. (2002) presented an approach for optimum design of tuned mass dampers for response control of torsional building system subjected to bi-directional seismic inputs. For a fixed number of dampers and fixed location, optimal damper parameters were obtained using GA. Ahlawat and Ramaswamy (2003) discussed multiobjective optimal design of an absorber system for torsionally coupled seismically excited buildings. This absorber system consists of four TMDs arranged in such a way that the system can control the torsional mode of vibration effectively in addition to the flexure modes. GA was used to arrive at optimal damper parameters. The eccentricities of the building were evaluated for the purpose of analysis, which would be computationally involved. In the present study the effect of asymmetry has been taken care of by rigid body transformations. Desu *et al.* (2006). proposed a coupled tuned mass damper (CTMD), where a mass is connected by translational springs and viscous dampers in an eccentric manner to control coupled lateral and torsional vibrations of asymmetric building.

Thus, it is observed from the literature survey that a good number of studies were carried out to arrive at optimal damper parameters for effective control of dynamically excited structures. Various parameters like frequency ratio, mass ratio and damping ratio were varied to understand the dynamic characteristics of TMDs and their applicability in structural response control. However, it has been realized that use of optimization methods are necessary for finding optimum design parameters of a control system. It has been observed that very few studies are available using multiple search technique like genetic algorithms to arrive at optimal design parameters of TMD. The asymmetric structures considered in previous studies were having asymmetry in the structural elements only, where footprint of the structure was taken as rectangular. For such a case the eccentricity of the structure will be small in comparison with the structures having asymmetry in plan. Thus there is still need of considerable work for studying the suitability of TMD and the evaluation of optimal parameters for seismic response control of irregular buildings. Further there is a need of efficient procedure for modeling of combined building and damper systems, where fixing and orientation of damper *a priori* is not possible, particularly for asymmetric buildings. It is also important that the appropriate stage (floor level) of damper be evaluated for optimum control of displacement as well as acceleration.

In the present study, a new arrangement of TMD, termed as bi-directional tuned mass damper (BTMD) has been introduced for controlling response of asymmetric building having asymmetry in both plan and elevation. The performance of the damper for controlling response of asymmetric buildings subjected to biaxial ground motion has been evaluated. The asymmetric building has been analyzed as 3D shear framed building using rigid body transformations. The key parameters of dampers such as spring stiffness, damping coefficient of dashpots, the magnitude of tuned mass, stage of each TMD and its location in plan are obtained for optimum control of displacement as well as acceleration of a seven storeyed asymmetric building subjected to seismic excitation. An effective and robust control of responses due to seismic excitation of an asymmetric building has been attained. The optimal location of dampers has also been obtained with a good deal of compactness.

2. Modeling of asymmetric building

An asymmetric building has been reduced to a system with a master node at each floor level with several slave nodes corresponding to the nodal points of the structure. The asymmetric building has been modeled as 3D shear framed building with three degrees of freedom at each floor level considered at the master node. These degrees of freedom correspond to the translations along x and y directions and rotation about the axis normal to the slab surface. The slab in a building structure is

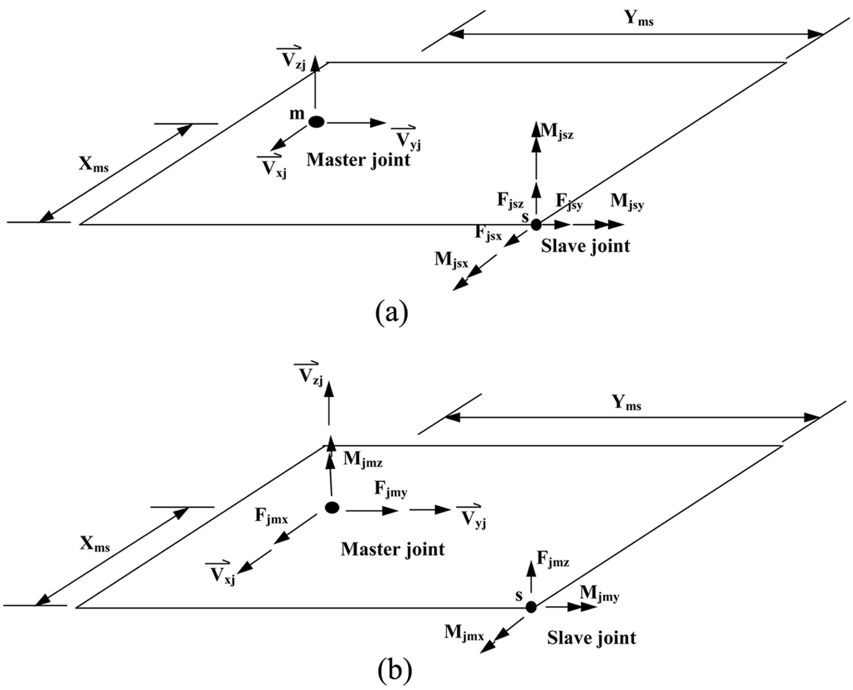

Fig. 1 Force transformation of a floor slab; (a) master and slave joints at floor plane, (b) force transformation

very stiff in the plane of floor; but is flexible out of plane. Thus a floor slab can be considered as a rigid body for in plane forces and a *planar constraint* is used to treat the floor slabs as rigid diaphragms. The three forces, F_{jsx}, F_{jsy} and M_{jsz} at slave joints as shown in Fig. 1(a) can be related to the forces F_{jmx}, F_{jmy} and M_{jmz} at master joint as shown in Fig. 1(b) by Eq. (1). Similarly, the slave nodes displacements can be constrained to the master node displacement as defined by Eq. (2). Consequently, the total degrees of freedom in a structure are considerably reduced. The model adopted for study is capable of handling different eccentricities at different floor levels.

Force transformation between master and slave nodes can be expressed as

$$\begin{Bmatrix} F_{jmx} \\ F_{jmy} \\ F_{jmz} \\ M_{jmx} \\ M_{jmy} \\ M_{jmz} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ -Y_{ms} & X_{ms} & 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} F_{jsx} \\ F_{jsy} \\ F_{jsz} \\ M_{jsx} \\ M_{jsy} \\ M_{jsz} \end{Bmatrix}$$

$$\{F_{jm}\} = [T_{ms}]\{F_{js}\} \tag{1}$$

Similarly, displacement transformation between master and slave nodes can be expressed as

$$\{\delta_{js}\} = [T_{ms}]^T\{\delta_{jm}\} \tag{2}$$

where, $\{F_{jm}\}$ is force vector at master nodes
$[T_{ms}]$ is constraint matrix
$\{F_{js}\}$ is force vector at slave nodes
$\{\delta_{js}\}$ is displacement vector at slave nodes
$\{\delta_{jm}\}$ is displacement vector at master nodes

X_{ms} and Y_{ms} are the distances between master and slave node as shown in Fig. 1(a)

The equilibrium equation at any slave joint may be written as

$$\{F_{js}\} = [K_{js}]\{\delta_{js}\} \tag{3}$$

Eq. (1) may be rewritten as

$$\{F_{js}\} = [T_{ms}]^{-1}\{F_{jm}\} \tag{4}$$

Substituting Eqs. (2) and (3) in Eq. (4)

$$[T_{ms}]^{-1}\{F_{jm}\} = [K_{js}][T_{ms}]^T\{\delta_{jm}\} \tag{5}$$

$$\{F_{jm}\} = [T_{ms}][K_{js}][T_{ms}]^T\{\delta_{jm}\} \tag{6}$$

Hence, stiffness matrix at master joint is

$$[K_{jm}] = [T_{ms}][K_{js}][T_{ms}]^T \tag{7}$$

Most of the researchers have used simplified 3D model by calculating center of mass and center of stiffness at each floor level. However, the process is very tedious in actual practice, particularly for buildings, which are highly asymmetric in plan and elevation. In this present study, torsional response of structure has been estimated with out explicitly calculating the centre of mass and stiffness. The effect of eccentricity has been taken care by the internal master slave transformations (rigid body transformations).

3. Equation of motion for BTMD-structure system

Bi-directional tuned mass damper (BTMD) has been introduced for the seismic response control of asymmetric building. The BTMD comprises of single mass block connected by two linear springs and two dashpot systems in orthogonal directions. Top view of the BTMD is shown in Fig. 2. It is a compact model of absorber system, which has been used in the present study to control the translational and torsional vibrations of asymmetric structures. Each BTMD is having eight distinct parameters, which are related to the mass, stiffness, damping coefficient and its location in a structure. These parameters are tuned by solving multi-objective optimization problem using genetic algorithm for the best possible control of displacement and acceleration response of a structure.

The BTMD (Fig. 2) has degrees of freedom along both x and y directions with the associated mass (M_t), stiffness (K_x and K_y) and damping values (C_x and C_y). One end of BTMD is fixed to the slave joint on the floor (ith end), while the other end (jth end) with spring-mass-damper system is kept free. The coordinates of the connecting ends of dampers to the structure are guided by genetic algorithm for finding optimum placement of damper system. The equilibrium equation of the BTMD system under floor excitation (Q) may be written as

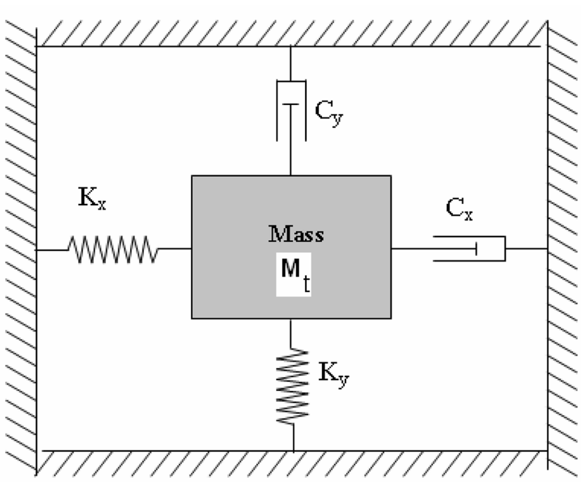

Fig. 2 Bi-directional model of TMD

$$\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & M_t & 0 \\ 0 & 0 & 0 & M_t \end{bmatrix} \begin{Bmatrix} \ddot{x}_i \\ \ddot{y}_i \\ \ddot{x}_j \\ \ddot{y}_j \end{Bmatrix} + \begin{bmatrix} C_x & 0 & -C_x & 0 \\ 0 & C_y & 0 & -C_y \\ -C_x & 0 & C_x & 0 \\ 0 & -C_y & 0 & C_y \end{bmatrix} \begin{Bmatrix} \dot{x}_i \\ \dot{y}_i \\ \dot{x}_j \\ \dot{y}_j \end{Bmatrix} + \begin{bmatrix} K_x & 0 & -K_x & 0 \\ 0 & K_y & 0 & -K_y \\ -K_x & 0 & K_x & 0 \\ 0 & -K_y & 0 & K_y \end{bmatrix} \begin{Bmatrix} x_i \\ y_i \\ x_j \\ y_j \end{Bmatrix} = Q \tag{8}$$

The equilibrium equation of motion of the coupled damper-structure system under seismic excitation is given as

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{p}_{eff} \tag{9}$$

where, **M**, **K** and **C** are the global mass, stiffness and damping matrices of the BTMD-structure system obtained by appropriate placement of BTMD parameters in the overall assembled system.

$\ddot{\mathbf{u}}$, $\dot{\mathbf{u}}$ and $\mathbf{u}$ are the acceleration, velocity and displacement vectors of BTMD-structure system.

$\mathbf{p}_{eff}$ is the force vector due to ground excitation

where
$$\mathbf{p}_{eff} = -\mathbf{M}\mathbf{R}\ddot{\mathbf{u}}_g(t) \tag{10}$$

$\mathbf{R}$ and $\ddot{\mathbf{u}}_g(t)$ are the influence matrix $n \times 2$ and the ground acceleration vector (2×1) respectively, where "n" represents number of degrees of freedom of the BTMD-structure system. The linear dynamic equilibrium Eq. (9) has been solved using Newmarks-β method. Average acceleration has been assumed while solving the equation.

4. Implementing GA for optimization process

In order to use GAs in optimization problems, some parameters of interest in the system to be optimized have to be chosen. These parameters are called design variables. These design variables are represented by some set of strings coded in binary or other codes, which corresponds to the chromosomes of living things. In the present case, an individual design is represented by a binary string of appropriate length incorporating, generally by simple concatenation, the values of all design variables.

$$\text{Design} = \langle y_{p_1}, y_{p_2}, \ldots, y_{p_n} \rangle$$
$$\text{Chromosome} = \langle 10011100\ldots001110 \rangle \tag{11}$$

These strings form the initial population. The variable y_{p_i} is bounded between upper (y_p^u) and lower limits (y_p^l). The decimal value of the design variable can be computed from

$$y_p = y_p^l + \frac{y_p^u - y_p^l}{2^q - 1} \sum_{k=0}^{q} 2^k b_k \tag{12}$$

where q is the string length of binary coded design variable. In the present study, fifteen bits have been taken to code each of the design variables.

The GA has been adopted to solve a multi-objective optimization problem in the present paper. In a typical multiobjective optimization problem, there exists a set of solutions which are superior to the rest of solutions in the search space when all objectives are considered; but are inferior to other solutions in the space in one or more objectives. These solutions are known as Pareto-optimal solutions or nondominated solutions. Since none of the solutions in the nondominated set is absolutely better than any other, any one of them is an acceptable solution. The approach presented by many researchers (Hoang and Warnitchai 2004, Li 2002) were based on a fitness function formulated either as a weighted sum of all objectives or some other form of ranking, which assigns better fitness values to the designs based on their dominance. As the GA starts its search from a number of points (population) in design space and evaluates the entire population in each and every generation, a set of nondominated designs can be formed in each iteration. Non-dominated sorting genetic algorithm (NSGA) (Wong and Chee 2003) has been used in the present study in which six objective functions have been considered. It provides a set of Pareto-optimal designs making efficient use of GA's population-based search. The procedure of NSGA has been given below in an algorithmic form.

ALGORITHM: **NSGA**

Initialize population;
Compute objective functions (possibly in parallel);
Do *generation*: =1, *number of generations*;
Compute fitness values using non-dominated sorting;
Compute probabilities for each individual to enter tournament;
Repeat
  Select two parents using tournament selection;
  Form two children using crossover;
Until new population is full;
Perform mutations;
Compute objective functions (possibly in parallel);
Copy individuals from the old population according to elitism;
End Do

NSGA varies from simple genetic algorithm only in the way the selection operator works. The crossover and mutation operators remain as usual. The crossover operation consists in taking two selected chromosomes as parents. Then, they are either crossed by using a certain probability value in order to create two new chromosomes (children) or they are directly included into new population. For the binary string in the present study, single point crossover has been used. Mutation is a randomly applied change, which is incorporated to a single gene to simulate copying errors in real organisms. This change is applied with a probability defined by the mutation rate. This operation is performed with the help of a random number in the range of 0 to 1. If the random number is less than the probability of mutation, then the bit under consideration will be switched (i.e., 0 to 1 or 1 to 0). High probability of cross over and low probability of mutation (inversely proportional to population) are considered. The size of initial population is considered such that the population is neither too small causing inadequate supply of building blocks nor it is too large causing wastage of time in processing unnecessary individuals.

Before the selection is performed, the population is ranked on the basis of non-domination. The nondominated individuals present in the population are first identified from the current population. Then, all these individuals are assumed to constitute the first nondominated front in the population and assigned a large dummy fitness value. The same fitness value is assigned to give an equal reproductive potential to all these nondominated individuals. In order to maintain diversity in the population, these classified individuals are then shared with their dummy fitness value. This causes multiple optimal points to co-exist in the population. After sharing, these nondominated individuals are ignored temporarily to process the rest of population in the same way to identify individuals for the second nondominated front. These new set of points are then assigned a new dummy fitness value, which is kept smaller than the minimum shared dummy fitness of the previous front. This process is continued until the entire population is classified into several fronts. The population is then reproduced according to the dummy fitness values. A stochastic remainder proportionate selection has been used in this study (Wong and Chee 2003). Since individuals in the first front

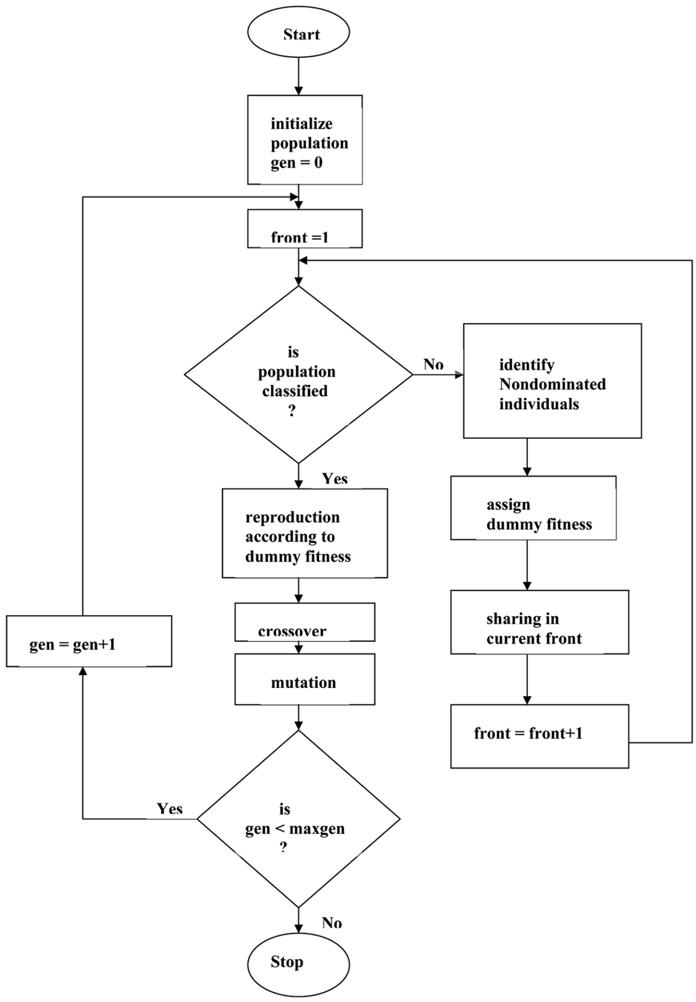

Fig. 3 Flow chart of NSGA

have the maximum fitness value, they always get more copies than the rest of population. This was intended to search for nondominated regions or Pareto-optimal fronts. This results in quick convergence of the population towards nondominated regions and sharing helps to distribute it over the region. Fig. 3 shows the flowchart for implementing GA for the evaluation of optimal tuned mass damper for effective seismic response control of structures.

5. Optimization problem

The formulation of multi-objective optimization problem and related parameters have been discussed in the following subsections.

5.1 Details of objective function and constraints

Six objective functions and six constraints are used in the present problem for controlling floor displacement and acceleration in both x and y directions. The optimization problem to be solved in the present study involves minimization of objective functions.

The six objective functions are given as

$$
\begin{aligned}
f_1 &= \max\left[\max_t\left\{\frac{|x_t(t)|}{x_{\max}}\right\}\right] & f_2 &= \max\left[\max_t\left\{\frac{|y_t(t)|}{y_{\max}}\right\}\right] \\
f_3 &= \max\left[\max_t\left\{\frac{|\theta_{zi}(t)|}{\theta_{z_{\max}}}\right\}\right] & f_4 &= \max\left[\max_t\left\{\frac{|\ddot{x}_t(t)|}{\ddot{x}_{\max}}\right\}\right] \\
f_5 &= \max\left[\max_t\left\{\frac{|\ddot{y}_t(t)|}{\ddot{y}_{\max}}\right\}\right] & f_6 &= \max\left[\max_t\left\{\frac{|\ddot{\theta}_{zt}(t)|}{\ddot{\theta}_{z_{\max}}}\right\}\right]
\end{aligned}
\tag{13}
$$

where, for the structure with control, $x_t(t)$ and $y_t(t)$ are displacements in x and y directions respectively, θ_z is torsional displacement, $\ddot{x}_t(t)$ and $\ddot{y}_t(t)$ are absolute accelerations in x and y directions respectively, and $\ddot{\theta}_z$ is acceleration in θ_z direction, Similarly, for the structure without any control mechanism, $x_{\max}$ and $y_{\max}$ are maximum displacements, $\theta_{z_{\max}}$ is maximum rotation about z axis and $\ddot{x}_{\max}$ and $\ddot{y}_{\max}$ are maximum absolute accelerations in x and y directions respectively, $\ddot{\theta}_{z_{\max}}$ is maximum rotational acceleration about z axis. Maximum displacement, maximum absolute acceleration in x and y direction and maximum rotation are given by

$$
\begin{aligned}
x_{\max} &= \max[\max_t|x_t(t)|]_{unc} & y_{\max} &= \max[\max_t|y_t(t)|]_{unc} \\
\theta_{z_{\max}} &= \max[\max_t|\theta_{tz}(t)|]_{unc} & \ddot{x}_{\max} &= \max[\max_t|\ddot{x}_t(t)|]_{unc} \\
\ddot{y}_{\max} &= \max[\max_t|\ddot{y}_t(t)|]_{unc} & \ddot{\theta}_{z_{\max}} &= \max[\max_t|\ddot{\theta}_{tz}(t)|]_{unc}
\end{aligned}
\tag{14}
$$

The following constraints c_i (i = 1 to 6) are used to restrict the search space within the feasible zone of control, where response of the building with control system can occasionally become more than the response of uncontrolled building, particularly during initial generations.

$$c_1 \rightarrow 1 - f_1 \geq 0 \qquad c_2 \rightarrow 1 - f_2 \geq 0 \qquad c_3 \rightarrow 1 - f_3 \geq 0$$
$$c_4 \rightarrow 1 - f_4 \geq 0 \qquad c_5 \rightarrow 1 - f_5 \geq 0 \qquad c_6 \rightarrow 1 - f_6 \geq 0 \tag{15}$$

Further the properties of BTMD like mass, stiffness, damping coefficient and their locations are constrained by upper and lower limits of the design variable.

5.2 Design variable

Each absorber is having eight parameters these are mass (m), two springs constants (k_x and k_y) and two damping coefficients (c_x and c_y), damper position. The damper position has been defined by location of random node (x, y, z). For the purpose of avoiding high computational time requirement, the numbers of BTMDs have been limited to four for the present study.

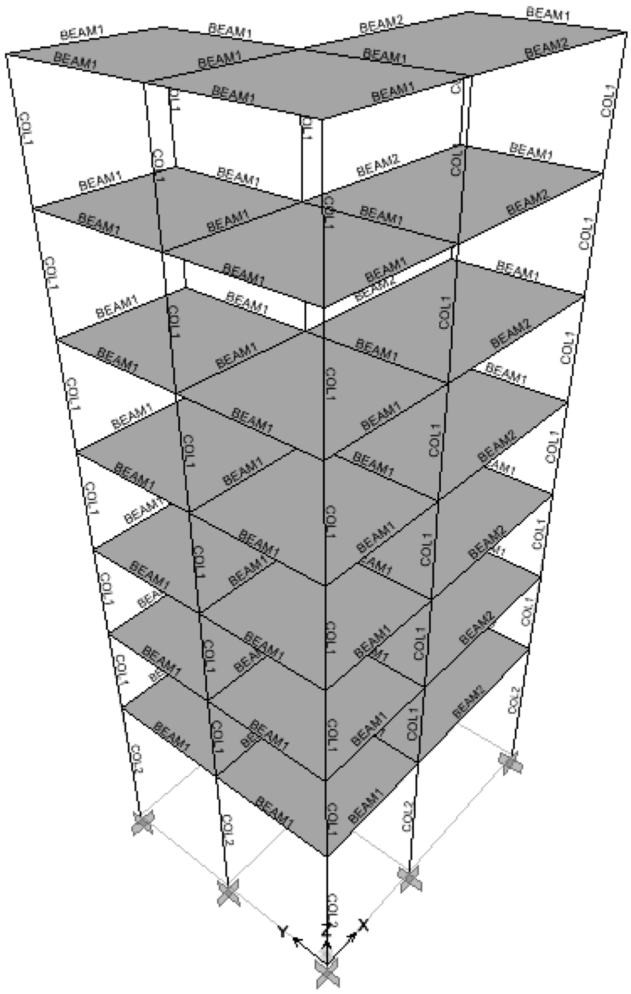

Fig. 4 Building with asymmetry in plan and elevation

6. Numerical study

A seven storey framed building with asymmetry in plan and elevation as shown in Fig. 4 has been considered for the study of seismic response control with MBTMD. The geometric properties of different structural members are given in Table 1. Rayleigh damping has been considered for idealization of structural damping. The damping ratio is taken as 0.05. Two orthogonal components of El Centro 1940 ground motion (El Centro N-S and E-W) are used for bi directional seismic input for the building. The optimum damper parameters and optimum positions of dampers have been found using genetic algorithm.

Six fitness functions as mentioned in Eq. (13) have been considered in order to control maximum displacement, torsion and acceleration in x, y and θ_z directions. The bounds of constraints for damper mass, stiffness, damping coefficients and their locations are given in Table 2. The upper limit of damper mass has been taken as 1% of the structural mass. The optimization procedure selects the values of mass and stiffness of tuned mass dampers along both the transverse directions

Table 1 Geometric properties

Member	Area (sq m)	I_{yy} (m^4)	I_{zz} (m^4)	J (m^4)	I_m (kg-m^2)
BEAM1 (0.25 × 0.35 m)	0.0875	0.000893	0.0004557	0.00102	3.3724
BEAM2 (0.25 × 0.4 m)	0.1	0.001333	0.0005208	0.001273	4.63541
COL1 (0.4 × 0.4 m)	0.16	0.002133	0.0021333	0.0036	10.6667
COL2 (0.5 × 0.5 m)	0.25	0.0052083	0.0052083	0.008789	26.04167

Table 2 Details of design variables

Variables	Upper and lower limits
Tuned mass (m)	10-2700 kg
Translation spring stiffness (k_x, k_y)	1-4000 kN/m
Torsional spring stiffness (k_θ)	1-4000 kN/rad
Damping coefficient of dash pots (c_x, c_y)	1-200 kN s/m
X-ordinate of damper position	0-10 m
Y-ordinate of damper position	0-8 m
Number of floor	0-7

Table 3 Details of genetic parameters

Genetic parameters	Value
Size of population	100
Crossover type	Single point random site
Crossover probability	0.85
Mutation probability	0.0042
Selection	Non-dominated sorting
Random seed	0.854

from within the bounds in such a manner that the tuning is obtained matching the predominant frequencies of the structure for most effective control. All the genetic parameters and operators used in the course of optimization have been listed in Table 3.

Fig. 5 shows the evolution of optimum solutions with number of generations, where improvements in objective functions with generations are depicted. Solid lines show improvement in displacement control and dotted lines show improvement in acceleration control. It is observed that maximum

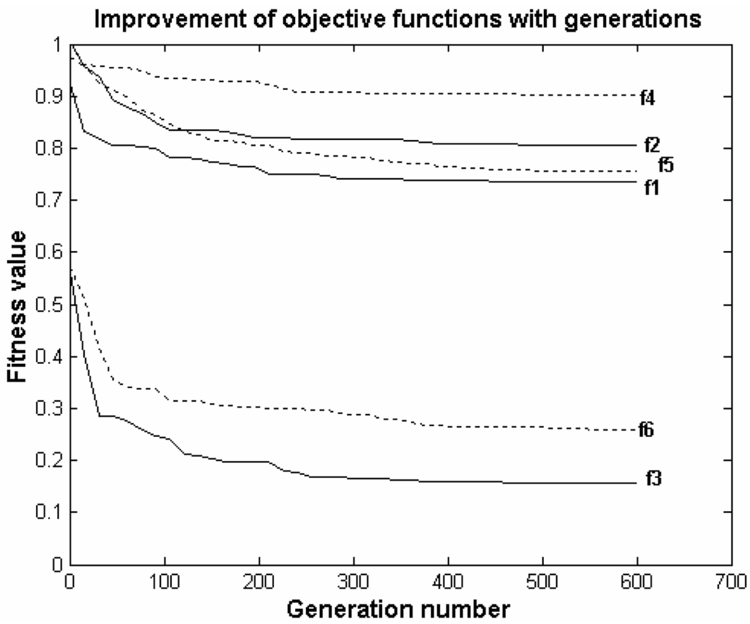

Fig. 5 Improvement of objective functions with generations

Table 4 Details of optimum designs

Design no		m_d (kg)	C_x (KN s/m)	C_y (KN s/m)	K_x (KN/m)	K_y (KN/m)	X (m)	Y (m)	Floor no
1	A	2700	0.406	1.838	317.35	251.21	5.45	2.98	7
	B	2700	92.113	0.005	1379.46	253.16	2.47	7.62	7
	C	2700	8.102	4.331	294.01	276.5	6.75	2.1	7
	D	2700	0.105	0.367	245.38	502.15	4.86	3.64	7
2	A	2700	0.52	8.337	317.35	161.73	9.65	2.95	6
	B	2700	57.796	8.323	455.46	237.6	0.98	7.44	7
	C	2700	7.441	4.545	294.01	276.5	6.75	2.23	7
	D	2700	0.191	2.750	95.59	998.19	4.71	3.73	6
3	A	2700	0.0058	8.386	313.46	253.16	5.61	2.82	6
	B	2700	61.428	4.006	385.43	255.1	1.61	7.31	7
	C	2700	0.225	37.981	294.01	276.5	6.75	3.73	5
	D	2700	0.363	0.938	344.58	692.79	4.71	3.64	7

Table 5 Earthquake records used for Time-History analysis

Number	Site	Year	PGA
1	El Centro	1940	0.313
2	Koyna	1967	0.631
3	Kobe	1995	0.821
4	Northridge	1994	0.828
5	Uttar kashi	1991	0.988
6	Cape mend	1992	1.497
7	Traft	1952	0.179
8	Bhuj	2001	1.038

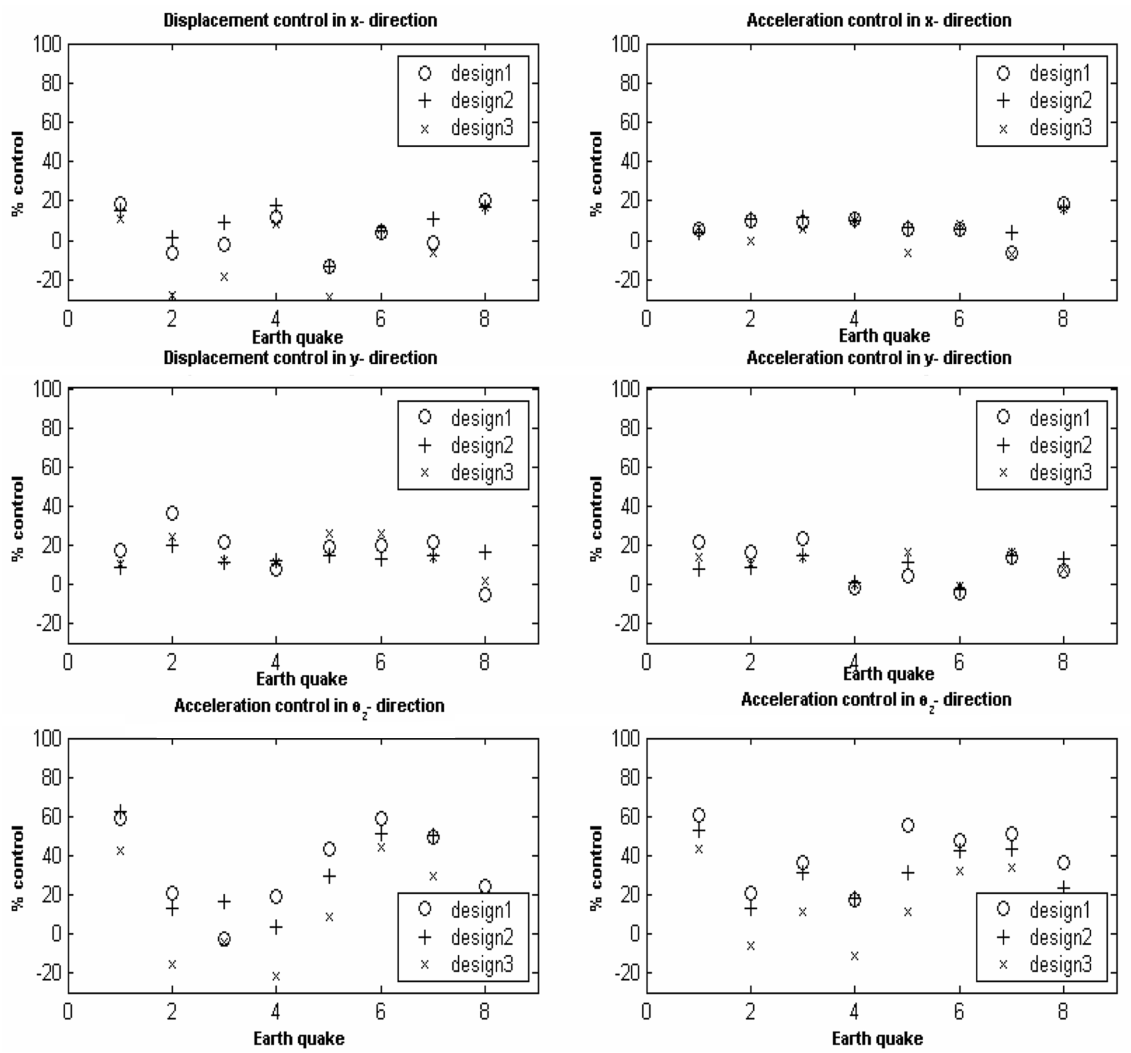

Fig. 6 Percentage reduction in maximum response under different earthquake inputs

possible control on maximum displacement response in x and y directions are 27% and 20% respectively and the control in torsional displacement is 85%. Similarly maximum possible control on maximum acceleration response in x and y directions are 10% and 25% respectively and the control on torsional acceleration in θ_z direction is 75%. It is observed that all the above mentioned percentage control are attainable in individual response direction, while ensuring that the responses corresponding to all other remaining directions are lesser than those of uncontrolled structural responses. A set of non-dominated solutions is obtained at the end of optimization process called as Pareto designs, where each one of them is a possible feasible solution.

Out of total set of Pareto optimal solutions, three different solutions have been picked up which are having different distribution of damper stage as shown in Table 4. The details of design parameters of three designs as selected are given in Table 4. The selection of this three design has been made using different indices like radial distance of pareto optimal designs in pareto displacement space and in pareto acceleration space and further based on both mean and standard deviation of spread of each pareto optimal design in percentage control for eight different ground motions as mentioned in Table 5.

The set of tuned parameters from the three selected designs (Table 4), which have been obtained corresponding to El Centro N-S and E-W are further examined under different ground motions in order to verify the robustness of the optimal design. It has been observed from Fig. 6 that the performance of Design-3 is comparatively poorer than both Design-1 and Design-2. Further, both Design-1 and Design-2 is observed to be effective and robust in controlling both displacement and acceleration of floors. Thus, it is observed that the tuned optimal design parameters as obtained could work well in controlling the seismic response of the building under a manifold of different ground motions.

Table 6 Table for showing redundancy of the design

	% Control of Maximum displacement in x-direction	% Control of Maximum displacement in y-direction	% Control of Maximum displacement in θ_z-direction	% control of Maximum acceleration in x-direction	% Control of Maximum acceleration in y-direction	% Control of Maximum acceleration in θ_z-direction
A&B&C&D	14	8	61	4	7	52
A&B&C	16	8	61	3	6	50
B&C&D	5	6	40	1	6	39
C&D&A	12	6	35	5	6	27
D&A&B	13	4	52	3	5	42
A&B	14	4	49	2	3	39
B&C	6	6	43	0	4	36
C&D	3	4	25	1	5	14
D&A	9	1	30	4	4	19
A	10	2	24	3	0	16
B	2	1	18	−1	1	24
C	4	2	18	1	1	11
D	−1	−2	−2	0	3	5

Redundancy, which is defined as the ability of the system to be effective when one or more of the dampers do not function has been studied by considering Design-2. It has been observed from Table 6 that the system is redundant in controlling displacement as well as acceleration of floor slabs when any one two or three out of four dampers in the design do not function.

Further, the path traced by the master node at roof level corresponding to Design-2 and subjected to El Centro ground motion has been shown in Fig. 7, where thick line shows uncontrolled response and dashed line shows controlled response. It can be observed from Fig. 7 that over the duration of ground motion the path traced by master node under controlled condition is well within that of uncontrolled motion of master node.

An interesting advantage of the adopted BTMDs have been observed over conventional TMD (spring-mass-dashpot system) used in (Sarbjeet and Dutta 1998, Chen and Wu 2001). While using the conventional TMD in (Sarbjeet and Dutta 1998, Chen and Wu 2001), asymmetric building with a rectangular footprint was considered. Four dampers were considered with pre fixed orientation and GA was used to find their exact location. The pre-fixing of orientation was possible due to the availability of rectangular plan. The problem, which has been studied in the present paper, does not provide any scope for prefixed orientation due to asymmetry in plan. Treating the location of each of the damper as variable in 3-D space, genetic search has been carried out using both BTMD and conventional TMD as adopted for the seven storeyed asymmetric building. While the magnitude of effective control obtained is approximately of the same order, the interesting advantage as visualized can be appreciated form Fig. 8(a) and Fig. 8(b). Fig. 8(a) shows the pareto optimal locations of four conventional TMDs and Fig. 8(b) shows the pareto optimal locations of four BTMDs. It is clearly observed that the optimum locations of BTMDs are much more comprehensive in comparison to that of conventional TMDs. Thus this advantage of compactness will invariably help in practical usage of BTMDs for seismic response control of buildings.

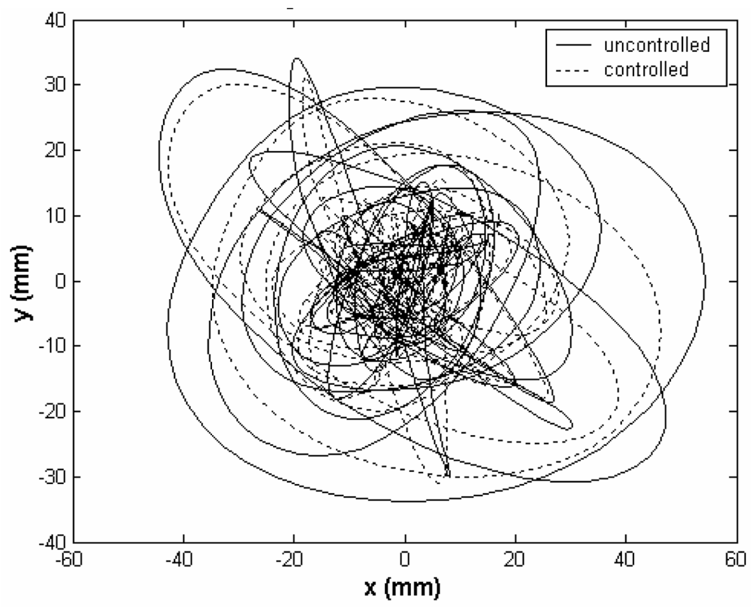

Fig. 7 Path traced by the master node at roof level

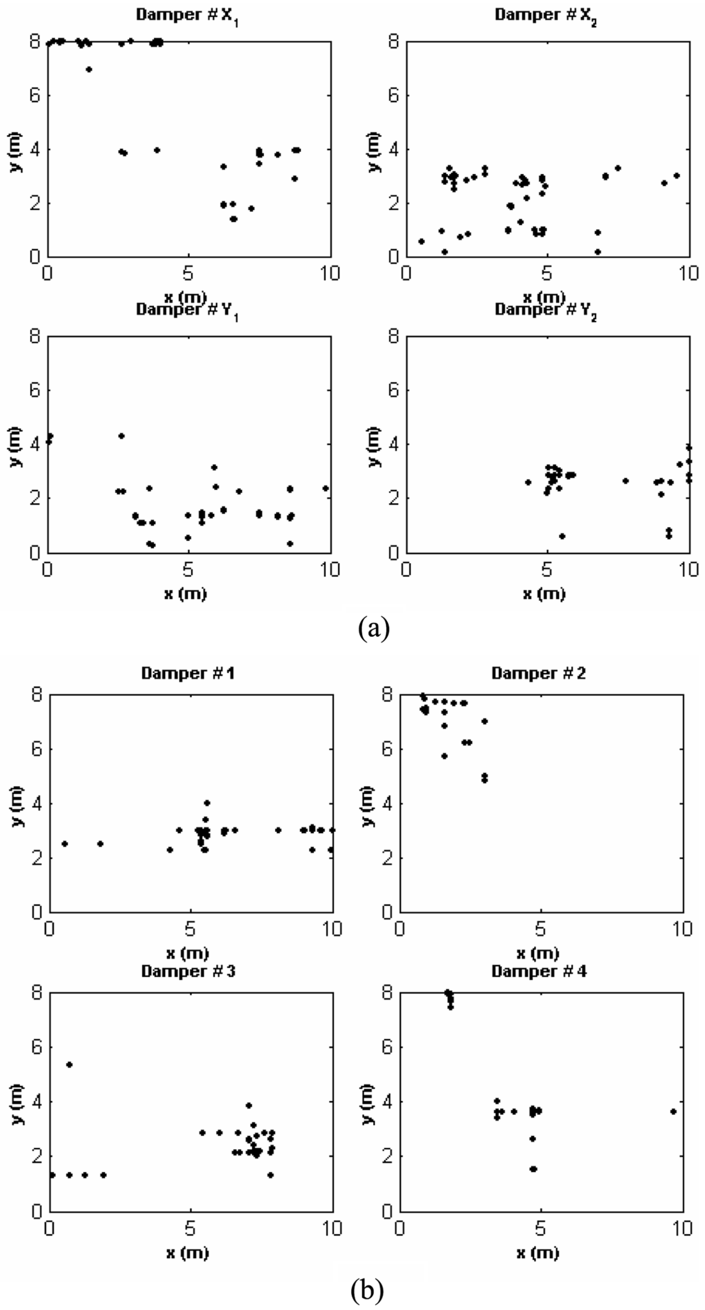

Fig. 8 Different optimal location of TMDs. (a) Conventional TMDs, (b) Bi-directional TMDs

7. Conclusions

Studies have been carried out on the response control of asymmetric buildings using newly introduced BTMDs. Nondominated sorting genetic algorithm has been used to solve six multiobjective optimization problem, which provides multiple Pareto-optimal solutions simultaneously. The BTMDs with distributed stages have been observed to be effective and robust in response control. The BTMDs also provide desired redundancy in the event of non-functioning of any of the dampers during seismic event. The optimum locations of BTMDs as obtained are observed to be far more compact than those using conventional TMDs.

Thus the methodology adopted in present study has been observed to provide quite satisfactory performance for the evaluation of optimal parameters for effective, robust and redundant design of a multi-stage BTMDs, which can easily be used for practical implementation.

Reference

Abe, M. and Fujino, Y. (1994), "Dynamic characteristics of multiple tuned mass dampers and some design formulas", *Earthq. Eng. Struct. Dyn.,* **23**, 813-835.

Ahlawat, A.S. and Ramaswamy, A. (2003), "Multi-objective optimal absorber system for torsionally coupled seismically excited structures", *Eng. Struct.,* **25**, 941-950.

Chen, G. and Wu, J. (2001), "Optimal placement of multiple tune mass dampers for seismic structures", *J. Struct. Eng.*, ASCE, **127**(9), 1054-1062.

Chen, G. and Wu, J. (2003), "Experimental study on multiple tuned mass dampers to reduce seismic responses of a three-storey building structure", *Earthq. Eng. Struct. Dyn.*, **32**, 793-810.

Desu, N.B., Deb, S.K. and Dutta, A. (2006), "Coupled tuned mass dampers for control of coupled vibrations in asymmetric building", *J. Struct. Control Health Monitoring,* **13**, 897-916.

Fonseca, C.M. and Fleming, P.J. (1993), "Genetic algorithms for multi-objective optimization: Formulation, discussion and generalization", *Proc. of the Fifth Int. Conf. on Genetic Algorithms,* Los Altos, (CA): University of Illinois at Urbana-Champaign, Morgan Kauman.

Hajela, P. and Lin, C.Y. (1992), "Genetic search strategies in multi-criterion optimal design", *Struct. Optimization*, **4**, 99-107.

Hoang, N. and Warnitchai, P. (2004), "Design of multiple tuned mass dampers by using a numerical optimizer", *Earthq. Eng. Struct. Dyn.*, **34**, 125-144.

Jangid, R.S. (1999), "Optimum multiple tuned mass dampers for base-excited undamped system", *Earthq. Eng. Struct. Dyn.*, **28**, 1041-1049.

Jangid, R.S. and Datta, T.K. (1997), "Performance of multiple tuned mass dampers for torsionally coupled system", *Earthq. Eng. Struct. Dyn.*, **26**, 307-317.

Joshi, A.S. and Jangid, R.S. (1997), "Optimum parameters of multiple tuned mass dampers for base excited damped systems", *J. Sound Vib.*, **202**(5), 657-667.

Li, C. (2000), "Performance of multiple tuned mass dampers for attenuating undesirable oscillations of structures under the ground acceleration", *Earthq. Eng. Struct. Dyn.*, **29**, 1405-1421.

Li, C. (2002), "Multiple active-passive tuned mass dampers for structures under ground excitation", *Earthq. Eng. Struct. Dyn.*, **32**, 949-964.

Li, C. (2002), "Optimum multiple tuned mass dampers for structures under the ground acceleration based on DDMF and ADMF", *Earthq. Eng. Struct. Dyn.,* **31**, 897-919.

Li, C. and Qu, W. (2006), "Optimum properties of multiple tuned mass dampers for reduction of translational and torsional response of structures subject to ground acceleration", *Eng. Struct.,* **28**, 472-494.

Muhammad, N.S. Hadi and Arfiadi, Y. (1998), "Optimum design of absorber for MDOF structures", *J. Struct. Eng.*, ASCE, **124**(11), 1272-1280.

Park, J. and Reed, D. (2001), "Analysis of uniformly distributed mass dampers under harmonic and earthquake excitation", *Eng. Struct.,* **23**, 802-814.

Rana, R. and Soong, T.T. (1998), "Parametric study and simplified design of tuned mass dampers", *Eng. Struct.,* **20**, 193-204.

Sarbjeet, S. and Dutta, T.K. (1998), "Open-closed-loop linear control of building frames under seismic

excitation", *J. Struct. Eng.*, ASCE, **124**(1), 43-51.
Singh, M.P., Singh, S. and Moreschi, L.M. (2002), "Tuned mass dampers for response control of torsional buildings", *Earthq. Eng. Struct. Dyn.*, **31**, 749-769.
Srinivas, N. and Deb, K. (1993), "Multiobjective. Optimization using non-dominated sorting in genetic algorithms", *Technical Report*, Department of Mechanical Engineering, Indian Institute of Technology, Kanpur, India.
Wong, K.K.F. and Chee, Y.L. (2003), "Energy dissipation of tuned mass dampers during earthquake excitations", *Struct. Design Tall Special Build.,* **12**,105-121.
Xu, K. and Igusa, T. (1992), "Dynamic characteristics of multiple substructures with closely spaced frequencies", *Earthq. Eng. Struct. Dyn.,* **21**, 1059-1070.
Yamaguchi, H. and Harnpornchai, N. (1993), "Fundamental characteristics of multiple tuned mass dampers for suppressing harmonically forced oscillations", *Earthq. Eng. Struct. Dyn.*, **22**, 51-61.