Optimal Placement of Supplemental Dampers in Seismic Design of Structures

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ABSTRACT: *The optimal locations for a given number of fluid viscous dampers (FVDs) in a 3-D 10-storey model shear building, with or without eccentricities are investigated. A general approach for finding optimal placement of supplemental dampers in structural systems with arbitrary degree of complexity in configuration has been proposed. To seek the optimal location of dampers, a linear combination of maximum inter-storey drift and maximum base shear of the damped structure normalised by their respective undamped counterparts has been taken as the objective function. The effect of soil-structure interaction on maximum response reduction and also on the optimal placement of dampers is studied for various degrees of soil compliance. It is found that the supplemental dampers are more effective in reducing the seismic response of a symmetric building and its effectiveness reduces as either plan irregularity, or soil compliance increases.*

Keywords: Non-classical damping; Optimisation; Response spectrum method; Soil-structure interaction; Supplemental damping

1. Introduction

In conventional design practise, ordinary structures are proportioned to respond elastically only for a fraction of the estimated seismic forces and are especially detailed to dissipate a substantial portion of input seismic energy by means of inelastic deformations. These inelastic deformations inevitably lead to a reduction in the effective stiffness of structural members, and thereby, of the entire structural system. Though it is possible to design a structure to remain elastic even for a very severe (and rare) earthquake, such a design is not an economically viable solution for ordinary structures considering very low probability of the event. Further, some existing structures might also be required to withstand higher seismic forces than that accounted for in the original design due to enhancement in seismicity of a region in the subsequent revisions of design codes. It is generally expedient and economical to retrofit the structures instead of constructing them anew. One of the popular seismic retrofitting measures is the installation of supplemental dampers. Several different types of dampers are available, such as, viscous, visco-elastic, friction, metallic yielding, rheological, etc. These devices act as energy sinks to dissipate the input seismic energy thereby reducing the seismic demand on the structural members. However, an indiscriminate spatial distribution of dissipation devices in the structure may not necessarily lead to a substantial reduction in the seismic response. The effectiveness of a damper in reducing the structural response depends on the extent of its participation in response of structure to the external excitation. Keeping in view the damper costs and its effectiveness in reducing the response of structure, it is necessary to optimise the damper location and their numbers to improve the seismic performance of the structure.

The problem of optimal location and design of response control devices in structural system has been addressed by many in the recent past. Rao et al [16] studied the optimal location of actuators in an actively controlled structure in the framework of zero-one optimisation problem with a constraint on the number of actuators. An optimisation scheme based on genetic algorithm was developed to solve this zero-one optimisation problem. The maximisation of energy dissipated by an active controller was used as the objective function. Gluck et al [4] optimised the performance cost function that produces the most suitable damper configuration of visco-elastic dampers. They used optimal linear control approach to determine the constant coefficients for damping devices. They found that single mode approach was suitable for a tall structure subjected to earthquake loadings, for which the first mode was governing. Wu et al [24] evaluated the optimal locations of viscoelastic dampers required in a torsionally coupled building to achieve minimum translational and rotational response due to torsion. They used transfer function matrix method to construct the objective function and found that excessive amount of damping does not always result in better structural performance. It was also revealed that the optimal locations for damping devices correspond to the positions where the relative displacements were largest. Takewaki [21] investigated the optimal damper placement to minimise the sum of amplitudes of the transfer functions evaluated at the undamped natural frequency of a structural system subjected to the constraints on the sum of the damping coefficients of added dampers. The optimal locations of dampers in a uniform shear building were found to correspond to those locations where inter-storey drifts were maximum. Shukla and Datta [17] determined the optimal location of visco-elastic dampers with the help of a controllability index, defined as the measure of structural response to the earthquake excitation. The root mean square (r.m.s.) value of inter-storey drift was taken as the performance index. They used a sequential method for optimal positioning assuming that a damper is said to be optimally located if it is placed at a location where displacement response of the uncontrolled structure is maximum. Takewaki et al [22] used the steepest direction search technique to optimise the visco-elastic damper locations. The transfer function amplitudes of local inter-storey drifts evaluated at the undamped fundamental natural frequency of a 3-*D* shear building, were minimised subject to the constraint on the sum of the damper capacities. They concluded that the optimal placement increases the lower mode damping ratio more effectively than uniform placement and that the increase in number of additional dampers does not always reduce the structural response. Zhang and Soong [25] developed a sequential procedure to optimise the locations of linear visco-elastic dampers in a symmetric building based on the assumption that a damper is optimally placed at a particular location in which the relative displacement of the uncontrolled system is maximum. They found that addition of each damper modified the response of the structure and optimum damper locations varied with excitation. Singh and Moreschi [19] employed a gradient-based approach for optimal placement of visco-elastic dampers in a symmetric structure. The r.m.s. value of inter-storey drifts was taken as performance index with a constraint to minimise the difference between the summation of coefficients of added dampers and total amount of damping distributed throughout the building and found that 40% reduction in the objective function was achieved with 37 dampers in a 24-storey building. Subsequently, Singh and Moreschi [20] used genetic algorithm to optimise the visco-elastic damper locations with maximum floor acceleration and maximum storey drift as performance indices and found that same number of dampers were required to achieve nearly same percentage of reduction in the floor acceleration and storey drift. In another study, Moreschi and Singh [13] studied the optimal design of yielding metallic dampers and friction dampers and found that optimal damping parameters were different for various storeys.

Recently, Main and Krenk [10] have developed an approximate solution for the complex eigenvalue problem resulting from free vibration of structures with supplemental damping. The approximate solution for frequencies is developed as an interpolation between the results of two limiting real eigenvalue problems. These results are then used to determine the best location for dampers from examination of undamped mode shapes of the structure so as to get maximum relative displacement between the two ends of the viscous damper(s). Marko et al [11] studied the influence of different types of dampers embedded into the cut-outs of shear walls in buildings on the seismic behaviour. About 40% reduction in tip deflection was reported and it was found that the most effective position in the building differed for different types of dampers. In another study, genetic algorithm was used for optimal distribution of dampers in a 20-storey building seeking minimisation of a norm of the linear transfer function [23]. It was observed that the optimal damper locations vary significantly depending on the objective function used for optimisation. However, most of the dampers tend to be concentrated in lowermost and uppermost storeys. The effect of supplemental viscous damping on seismic response of asymmetric-plan one-storey buildings has also been studied and it was found that the asymmetric distributions of supplemental damping are more effective in reducing seismic response compared to the symmetric distributions [5, 9].

While all of the above mentioned studies refer to optimisation of supplemental damping/controlling devices for installation in a structural system, the problems considered were mostly open-ended, and no limit was imposed on the available number of dampers. However, due to budgetary constraints, it is quite possible that only a limited number of dampers are available, or the seismic retrofit itself may be taken up in a phased manner. Moreover, none of the above mentioned studies consider the effect of dynamic soil-structure interaction and plan-asymmetry on the optimal placement of dampers in structural systems with several degrees of freedoms. In this study, the effect of soil compliance on the optimal placement of a pre-specified number of dampers for seismic response reduction of a 10-storey symmetric/asymmetric example building has been considered. The ground motion is characterised by the 5% damping design response spectrum specified in Indian Standard Criteria for Earthquake Resistant Design of Structures IS-1893:2002 (Part 1) [1]. The response spectrum method for non-classically damped systems has been used for the computation of seismic response [18].

2. Modelling and Dynamic Analysis

A 10-storey shear building with a single bay as shown in Figure (1) has been considered for the study. In case of asymmetric buildings, it is assumed that the eccentricities at all floor levels are identical. The model has three degrees of freedom at each floor, namely, two orthogonal translations in the horizontal plane and a rotation about the vertical axis passing through the centre of mass (*CM*). It is further assumed that the dampers can be placed as diagonal braces along any of the building face at any floor. Thus, the damper location can be uniquely defined by a combination of the face (North, South, East, or West) and storey level identifiers. This notation has a practical advantage in the formulation of optimisation problem as discussed in the next section. Physical parameters of the example symmetric building, considered in the analysis are given in Table (1).

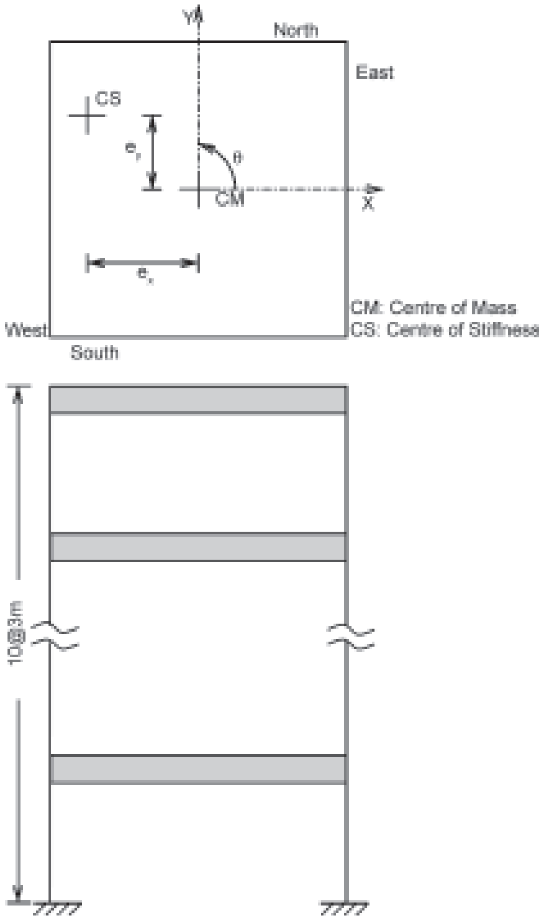

Figure 1. Schematic diagram of the example building.

Table 1. Parameters of example symmetric building.

Parameter	Numeric Value
Column Section	0.3m x 0.3m
Column Height	3.0m
Floor Thickness	0.15m
Plan Dimensions	3.0m x 3.0m
Supplemental Dampers' Coefficient	1.55e+5Ns/m
Native Damping in the Structure	5% in All Modes

A bi-directional excitation by ground acceleration, characterised by the 5% damping design spectrum shown in Figure (2), has been considered. The spectral ordinates for other damping ratios are obtained by scaling the spectrum for 5% damping with appropriate factors as specified in IS-1893:2002 (Part 1) and are given in Table (2). The zero period acceleration (*ZPA*) has been assumed to be 0.12g for the purpose of numerical calculations. This value of *ZPA* corresponds to the design basis ground motion level for the National Capital Region, Delhi.

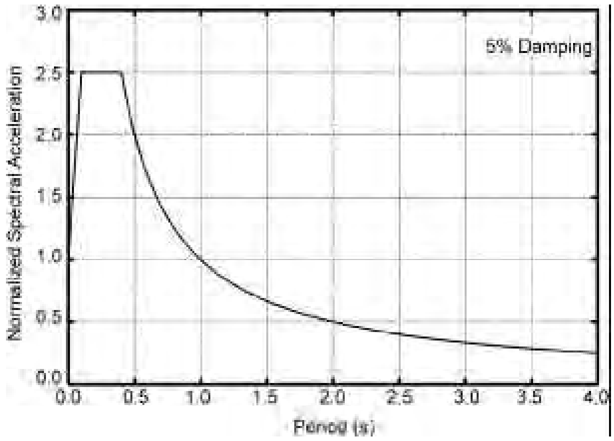

Figure 2. Standard spectral shape of IS-1893:2002 (Part 1) for 5% damping.

Table 2. Multiplying factors for obtaining spectral ordinates for other damping ratios.

Damping Ratio (%)	0	2	5	7	10	15	20	25	30
Scaling Factor	3.20	1.40	1.00	0.90	0.80	0.70	0.60	0.55	0.50

To study the effect of compliant soils on the response of a system, and hence on optimal location of dampers, the following parameters for soil-foundation system are assumed:

i. Poisson ratio for the soil medium is 0.3.
ii. Flexibility of the soil, as reflected by the shear wave velocity, v_s is varied from 300*m/s* to 2000*m/s*, which roughly corresponds to variation between stiff soil to hard rock [2].
iii. The footing is assumed to be rigid, circular with radius 1.2*m* and depth 0.25*m* and without embedment.

The analytical model for building with soil-structure interaction effects is similar to one developed for the rigid base structure except that three additional degrees of freedom (translations and rotation of the base mat) enter into the formulation. The inertia of the base mat contributes to the global inertia matrix at the foundation level and the soil stiffness, characterised by the soil springs, contribute to the global stiffness matrix. The parameters for soil springs and dampers have been derived from the approximate impedance functions given by Pais and Kausel [14] evaluated at the first mode frequency of the structure. Only the inertial interaction effects are considered in this study as the effects of kinematic interaction can be accounted for in the process of defining the foundation input motion [8].

3. Problem Formulation

The equation of motion for the example building with, or without added damping devices subjected to a base motion can be given as:

$$M\ddot{u} + C\dot{u} + Ku = -MR\ddot{u}_g \quad (1)$$

where, M, C, and K denote the inertia/mass, damping, and stiffness matrix respectively; u represents the vector of floor displacements relative to the base; the superposed dots indicate time derivatives; R is the matrix of rigid body influence coefficients; and $\ddot{u}_g$ is the vector of instantaneous ground acceleration components in each of the two orthogonal directions in the horizontal plane. The global mass, damping and stiffness matrices are assembled from the contributions from local matrices for each floor level. The formulation of these structural property matrices follows along the similar lines as given by Hejal and Chopra [6-7]. The damping matrix is a function of the location of the supplemental dampers in the structure and these locations are so selected that the maximum reduction in the objective function occurs. The inherent damping in the building is assumed to be 5% in all modes of vibrations. Accordingly, an appropriate damping matrix can be generated by using the undamped mode shapes, modal mass and modal damping of the structure [3]. This classical damping matrix is then augmented with the damping due to supplemental dampers and the soil compliance in the case of soil-structure interaction model. Due to these additional damping contribution, the system damping matrix can no longer be diagonalised by the use of undamped mode shapes. Therefore, the response spectrum method for the analysis of non-classically damped structures using the damped mode shapes has been used in this study [18].

The damped mode shapes are obtained by first converting the second-order free vibration equation into a first-order equation in state-space. Thus, in state-space formulation, the equation of motion is given as:

$$\begin{bmatrix} 0 & M \\ M & C \end{bmatrix}\begin{pmatrix} \ddot{u} \\ \dot{u} \end{pmatrix} + \begin{bmatrix} -M & 0 \\ 0 & K \end{bmatrix}\begin{pmatrix} \dot{u} \\ u \end{pmatrix} = \begin{pmatrix} 0 \\ -MR\ddot{u}_g \end{pmatrix}$$
$$\text{or, } A\dot{v} + Bv = f \quad (2)$$

where, $v = [\dot{u}, u]^T$ is the state vector. The associated free-vibration problem is given by the homogeneous form of Eq. (2) as:

$$p_i A\phi_i + B\phi_i = 0 \quad (3)$$

for the i^{th} normal mode. Here, p_i and ϕ_i denote the complex eigenvalue (with negative real part) and corresponding complex eigenvector for the i^{th} mode respectively. The pair of complex conjugate eigenvalues of the first-order system are related to the undamped natural frequency and modal damping ratio of the associated second-order system by the following relations [12]:

$$\omega_i = \left(a_i^2 + b_i^2\right)^{0.5} \quad \text{and} \quad \zeta_i = \frac{-a_i}{\omega_i} \tag{4}$$

where, a_i and b_i denote the real and imaginary parts of the complex eigenvalue p_i , respectively. Once the complex eigenvalues and eigenvectors are computed, the response spectrum method for non-classically damped systems can be used to compute the desired response quantity.

The unconstrained optimisation problem is now formulated as:

$$\text{Minimise } f(x) = \frac{V_b}{V_{bu}} + \frac{D}{D_u} \tag{5}$$

where, $f(x)$ is the objective function to be minimised, and x is the vector of design variables. In the present case, the locations of a specified number of dampers in the structural system form the design variables. The objective function for the minimisation problem is considered to be a linear combination of normalised maximum base shear V_b, and normalised maximum storey drift D. The factors V_{bu} and D_u denote the maximum base shear and maximum storey drift in the structure without any supplemental dampers. This composite objective function has been considered to incorporate the strength as well as serviceability criteria in the design optimisation problem.

4. Optimisation Technique

The optimisation process involves the search for the best location for a damper in the structure. In this regard, an automated system of modification of the system damping matrix following the placement of a damper in a trial position is necessary for a computer assisted solution. This can be easily achieved by using a 2- dimensional damper location matrix with four rows and 10 columns for the example building under consideration, wherein the row index corresponds to the face of the building (North, South, East, or West) and the column index corresponds to the building storey level. Each element of this damper location matrix is designated by either '0', or '1' as suggested by Rao et al [16]. The presence of numeral '0' at a particular location in damper location matrix denotes absence of the damper in that location and '1' indicates its presence. A sample format of the damper location matrix for the example building is shown in Table (3), which corresponds to the placement of dampers in north face of the building on first and fourth storey and on the west face on second storey.

Table 3. A sample format of the damper location matrix.

Face	Storey Level									
	1	2	3	4	5	6	7	8	9	10
North	1	0	0	1	0	0	0	0	0	0
South	0	0	0	0	0	0	0	0	0	0
East	0	0	0	0	0	0	0	0	0	0
West	0	1	0	0	0	0	0	0	0	0

Since the set of design variables for the optimisation problem now consists of patterns of discrete values of '0' and '1' as in Table (3), none of the gradient-based approaches can be used. Accordingly, a pattern search algorithm needs to be used to search for the best locations for a given number of dampers. In this study, the method of Hooke and Jeeves [15] has been adopted for its simplicity and ease of programming. This method consists of essentially two steps, namely, (i) exploratory move: exploring the objective function variation with changes in the local neighbourhood of the current pattern to determine the most favourable direction for function minimisation, and (ii) pattern move: a line-search for the maximum step that can be taken in the favourable direction as identified by the exploratory move in the first step (see [15] for details). In the present context, the exploratory move involves iterative placement of dampers at the feasible locations and investigating the variation in objective function. The optimal location for a damper is one for which the objective function is minimum of all searched patterns. The pattern move is redundant in the present formulation as the exploratory move adequately identifies the best location for a damper. Starting from a pattern of all zeros corresponding to the absence of any supplemental damper, once the best possible location has been identified for a damper, the pattern of damper location matrix is preserved. In the next cycle for the search of best location of the next damper, only those locations are considered to be feasible which have a '0' entry in the previously preserved damper location matrix. This cycle is repeated until either the given number of dampers or available feasible locations have been exhausted.

5. Results and Discussion

A 10-storey example shear building with different sub-soil conditions is considered to investigate the optimal location of a number of fluid viscous dampers to achieve maximum reduction in the composite objective function comprising of a linear combination of normalised maximum base shear and normalised maximum drift. Four different types of plan configurations, namely, (i) symmetric, (ii) asymmetric with $e_x = 5\%L$, (iii) asymmetric with $e_y = 7.5\%L$, and (iv) asymmetric with $e_x = 5\%L$ and $e_y = 7.5\%L$ have been considered to study their effect on the response reduction and optimal location of dampers. Here, L refers to the maximum plan dimension of the building. These plan eccentricities are schematically shown in Figure (1). The excitation is characterised by the 5% damping design spectrum as shown in Figure (2) with $0.12g$ *ZPA* and scaling coefficients given in Table (2) to determine spectral ordinates at other damping levels.

6. Modal Parameters

The first five distinct natural frequencies of example buildings, with different eccentricities, for the two extreme case of sub-soil conditions considered in the study are compared in Table (4). These natural frequencies are computed from the complex eigenvalues of the first-order system as in Eq. (4). The computed frequencies of the example building are consistent with the established trend of increase with increasing eccentricity and decrease with increasing soil compliance.

Next, the effect of supplemental dampers on the modal damping ratios in buildings with different eccentricities and soil conditions is explored. These results correspond to the optimal layout of supplemental dampers as determined by minimisation of the composite objective function. The variation of modal damping ratios with the number of supplemental dampers is shown in Figure (3) for the fixed base condition and in Figure (4) for the soft soil condition with shear wave velocity (v_s) being $300 m/s$. In these figures, the first row corresponds to the results for symmetric building, and the other three rows correspond to the building configurations with different eccentricities, namely, $e_x = 5\%L$ for the second row, $e_y = 7.5\%L$ for the third row, and $e_x = 5\%L$ and $e_y = 7.5\%L$ for the last row. Further, the plots in the first column correspond to the first mode of vibration of buildings and second column shows the variation in the second mode of vibration, and the third column corresponds to the third mode properties. The modal damping in the first mode of fixed base case tends to saturate quickly as seen by the flattening of modal damping ratio curve with respect to the addition of dampers. This behaviour is broadly in concurrence with the observations of Wu et al [24] and Takewaki et al [22]. However, with addition of more dampers, the damping in higher modes increases appreciably as the damping in lower modes tends to saturate. This might be a consequence of the placement of dampers in locations which contribute significantly to the higher modes of vibration. It may also be inferred from these figures that the modal damping increases with soil flexibility in each of the first three modes for all plan configurations and for different number of supplemental dampers. Further, the enhancement in modal damping with addition of supplemental dampers is found to decrease with increasing plan eccentricity in the building. Also, this enhancement in modal damping is greater in lower mode in comparison to the higher modes in fixed base building and this difference becomes more perceptible as the plan eccentricity increases. For example, there is a difference of about 5% in the modal damping in first and third mode of fixed base asymmetric building with eccentricities in both directions. With increase in soil flexibility, the difference in increase in modal damping due to addition of dampers is maximum in the case of symmetric building and this difference decreases with the increase in plan eccentricity.

Table 4. First five natural frequencies (in rad/s) of sample buildings for different eccentricities and soil types.

Mode	Symmetric		$e_x = 5\%L$, $e_y = 0$		$e_x = 0$, $e_y = 7.5\%L$		$e_x = 5\%L$, $e_y = 7.5\%L$	
	Fixed	$v_s =$ 300m/s	Fixed	$v_s =$ 300m/s	Fixed	$v_s =$ 300m/s	Fixed	$v_s =$ 300m/s
1	5.87	2.32	5.92	2.34	5.96	2.35	6.01	2.89
2	12.79	8.89	12.79	8.91	12.79	8.91	13.48	8.96
3	22.15	15.15	22.76	15.17	32.61	26.21	33.03	26.46
4	38.09	30.72	38.08	31.03	38.08	32.42	40.15	32.89
5	62.54	43.34	62.53	49.76	69.53	55.12	69.54	57.02

7. Optimal Damper Location Matrix

The pattern of best locations for dampers in the

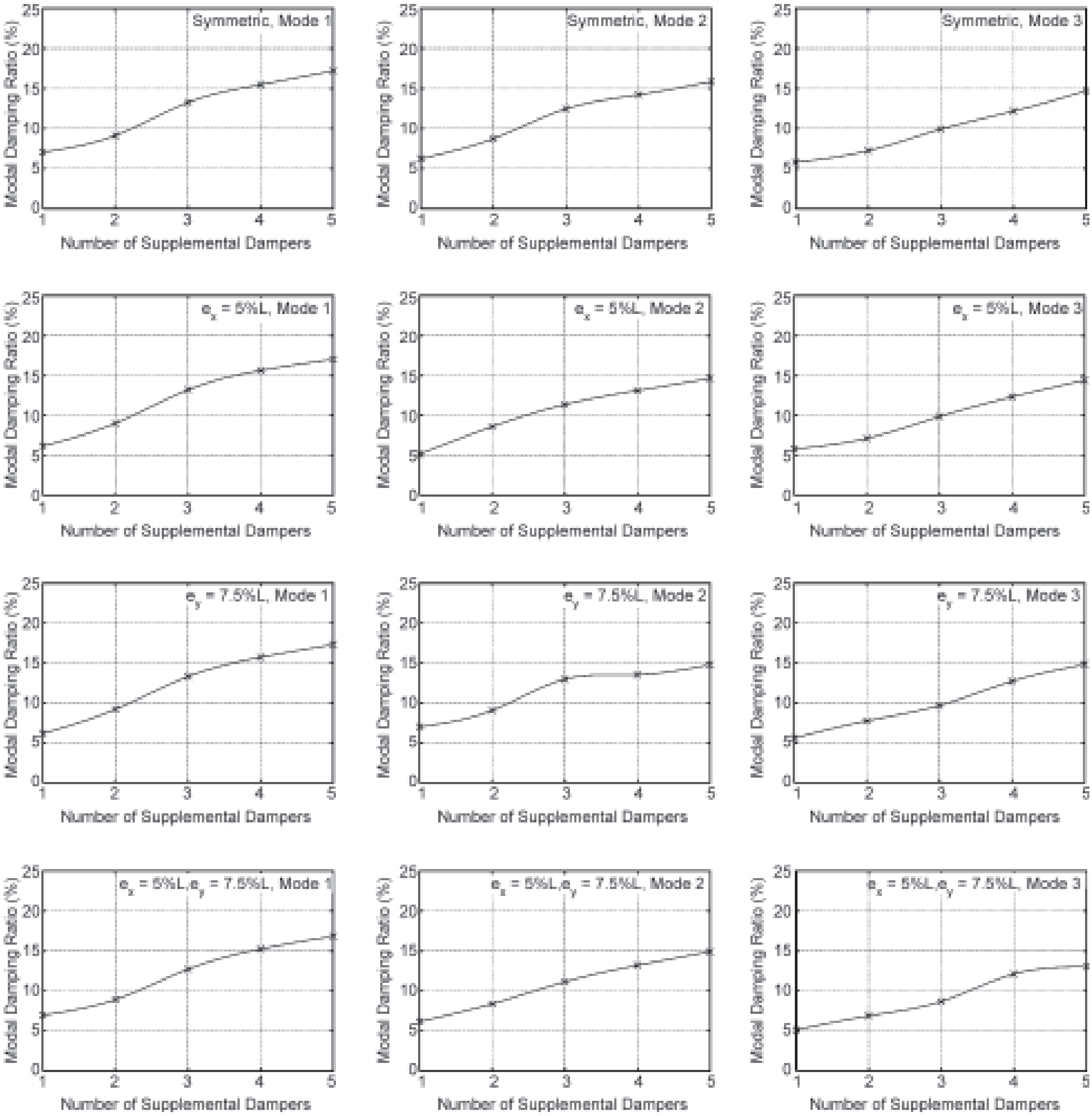

Figure 3. Variation of modal damping ratio in first three modes of example building on fixed base with different eccentricities.

example building with different plan eccentricities, are determined by the minimisation of the composite objective function comprising linear combination of normalised maximum base shear and normalised maximum drift. It might be prudent to mention here that the optimal damper locations depend on the nature of the objective function and a different criteria for minimisation may, in general, lead to different patterns. Thus, it is necessary to take care in proper specification of the objective function for the optimisation process. The patterns of best locations for 5 dampers of different plan configurations are given in Tables (5) to (8) for the fixed base case. It may be noted that the dampers are more effective in lower, and top storeys in the case of symmetric building. The best location for some dampers shifts to intermediate storeys as the eccentricity increases, see e.g. Table (8), due to the increased participation of higher modes of vibration in seismic response. The shift of best damper locations to intermediate storeys is more pronounced in the case of flexible base building, as shown in Table (9) for an asymmetric plan with eccentricity $e_x = 5\%L$. Here, the 0^{th} storey corresponds to the foundation level. Similar results are obtained for other plan configurations.

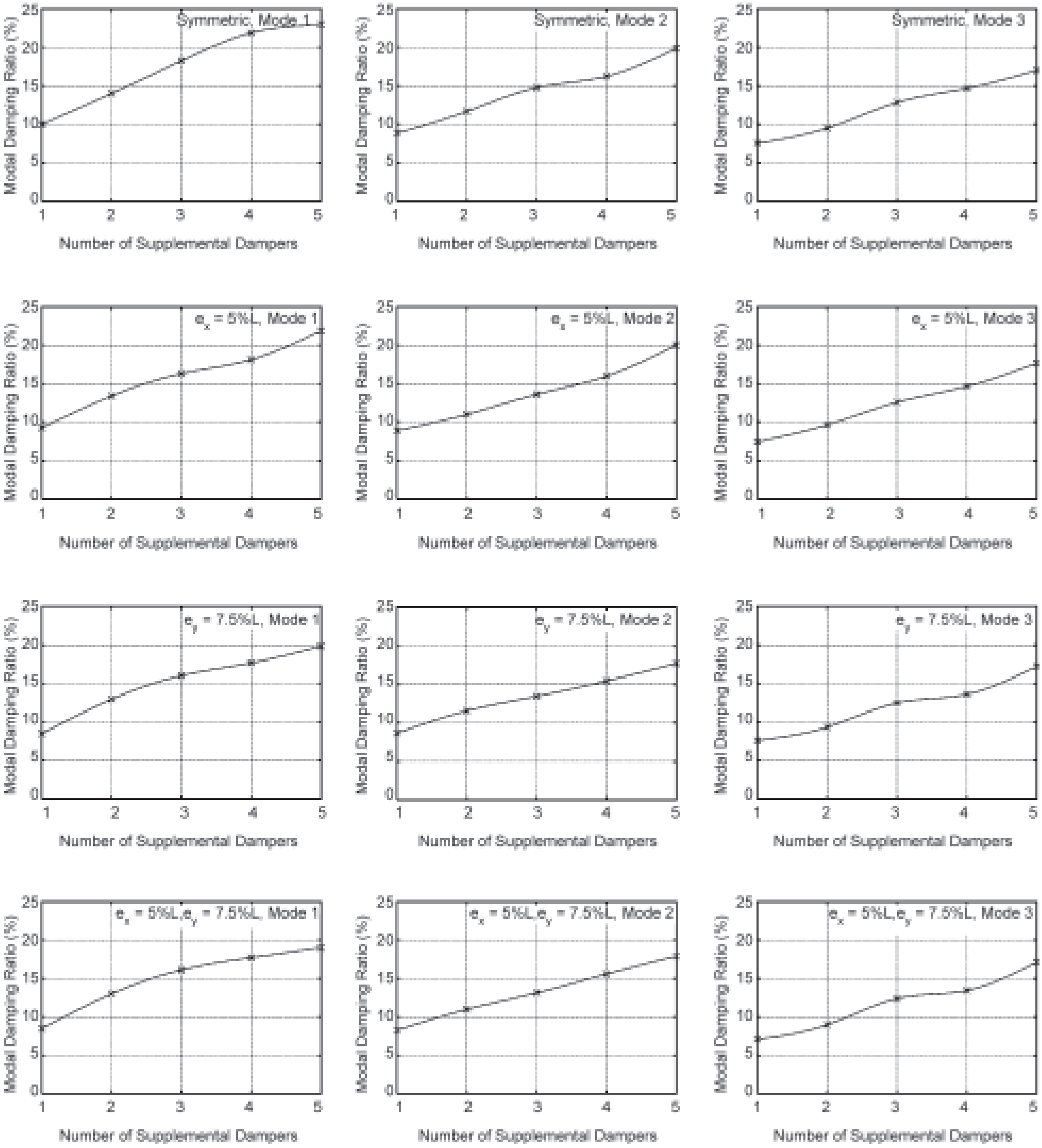

Figure 4. Variation of modal damping ratio in first three modes of example building on flexible base (v_s = 300m/s) with different eccentricities.

Table 5. Optimal damper location matrix for the fixed base, symmetric building, number of dampers: 5.

Face	Storey Level									
	1	2	3	4	5	6	7	8	9	10
North	0	0	1	0	0	0	0	0	0	1
South	0	1	0	0	0	0	0	0	0	0
East	0	0	0	0	0	0	0	0	1	0
West	0	1	0	0	0	0	0	0	0	0

Table 6. Optimal damper location matrix for the fixed base, asymmetric building (e_x = 5%L), number of dampers: 5.

Face	Storey Level									
	1	2	3	4	5	6	7	8	9	10
North	0	1	0	0	0	0	0	0	0	1
South	0	0	0	0	0	0	0	0	0	0
East	0	1	1	0	0	0	0	0	0	0
West	0	0	0	0	0	0	0	0	0	1

Table 7. Optimal damper location matrix for the fixed base, asymmetric building (e_y = 7.5%L), number of dampers: 5.

Face	Storey Level									
	1	2	3	4	5	6	7	8	9	10
North	0	0	0	0	0	0	0	0	0	1
South	0	0	0	1	0	0	0	0	0	0
East	0	1	0	0	0	0	0	0	0	0
West	0	0	1	0	0	0	0	0	0	1

Table 8. Optimal damper location matrix for the fixed base, asymmetric building (e_x = 5%L and e_y = 7.5%L), number of dampers: 5.

Face	Storey Level									
	1	2	3	4	5	6	7	8	9	10
North	0	1	0	0	0	0	0	0	0	1
South	0	0	1	0	0	0	0	0	0	0
East	0	0	0	0	0	0	0	1	0	0
West	0	0	0	1	0	0	0	0	0	1

Table 9. Optimal damper location matrix for the flexible base (v_s = 300 m/s), asymmetric building (e_x = 5%L), number of dampers: 5.

Face	Storey Level										
	0	1	2	3	4	5	6	7	8	9	10
North	0	0	1	0	0	0	0	0	0	0	0
South	0	0	0	0	0	0	0	0	0	0	1
East	0	1	0	0	1	0	1	0	0	0	0
West	0	0	0	0	0	0	0	0	0	0	0

8. Effectiveness of Supplemental Dampers

The effect of supplemental dampers in controlling structural response, as measured by the reduction in objective function, is studied for all four plan configurations of the building for different soil conditions. The representative results for 5 optimally placed dampers are presented in Table (10) for a symmetric building and in Table (11) for the asymmetric building with e_x = 5%L. The results for maximum reduction in objective function up to saturation limit --- number of supplemental dampers beyond which no further reduction is observed--- are also shown in these tables. Results for other plan configurations exhibit similar trend.

The maximum response reduction of 40% is achieved in the case of symmetric, fixed base buildings and the percentage reduction in seismic response with supplemental dampers decreases in the case of asymmetric buildings. It may be noted that the effectiveness of supplemental dampers in reducing seismic response decreases with increasing soil compliance --- only 16% response reduction for soil with v_s = 300*m/s* as against 40% for fixed base symmetric buildings for 5 optimally placed dampers. For buildings with asymmetric plans, similar differences in effectiveness of supplemental dampers in different soil conditions exist. This reduced effectiveness of supplemental dampers in case of compliant soils is due to softening effect of soil-structure interaction. The fundamental mode natural period shifts from ~1.0*s* to ~2.7*s*. At long periods, the effect of damping in reducing seismic response is not very prominent. Since a major contribution to the seismic response of shear buildings comes from the fundamental mode, not much variability in the seismic response is expected in this period range as suggested by the shape of the response spectrum in Figure (2). Further, the maximum number of dampers, designated as saturation limit, required to reach saturation (beyond which there is no significant reduction in the objective

Table 10. Summary of optimisation results for a symmetric building.

Shear Wave Velocity (m/s)	% Reduction in Objective Function for 5 Optimally Placed Dampers	Maximum % Reduction in Objective Function Till Saturation	Saturation Limit (Number of Dampers)
300	16.72	29.14	11
600	20.05	35.10	11
900	22.29	38.01	10
1500	27.69	42.69	10
2000	34.98	44.01	9
∞	40.24	48.59	8

Table 11. Summary of optimisation results for an asymmetric building (e_x =5%L).

Shear Wave Velocity (m/s)	% Reduction in Objective Function for 5 Optimally Placed Dampers	Maximum % Reduction in Objective Function Till Saturation	Saturation Limit (Number of Dampers)
300	14.89	18.42	11
600	18.72	24.79	10
900	21.58	27.02	10
1500	25.68	34.89	9
2000	31.89	36.02	9
∞	36.72	45.02	8

function), is also found to increase with the increase in soil compliance. It must be mentioned that these trends are largely qualitative in nature and the quantitative results would be influenced by the choice of analytical models for soil-structure system, objective function for optimisation process, etc.

9. Conclusions

A general approach for finding optimal placement of supplemental dampers in structural systems with arbitrary degree of complexity in configuration has been proposed. Although the example study dealt with a shear building model with, or without plan asymmetry, the proposed method can be readily extended to any other structural system with appropriate changes in the data structure for designating the feasible damper locations as a pattern of '0' and '1'. Since the optimisation is carried out entirely within a discrete set of patterns, the pattern search methods will always converge to the correct optimal configuration without breaking down --- a possibility in the case of gradient based optimisation methods.

Based on a study of an example 10 storey shear building, it is found that the supplemental damping is more effective in reducing the seismic response of a symmetric building and its effectiveness reduces as plan irregularity increases. The supplemental dampers are most effective in the lower storeys and upper storeys for a symmetric building. However, the best locations for some dampers shift to intermediate storeys as the plan asymmetry increases. This shift of best damper locations to intermediate storeys is more pronounced in the case of flexible base buildings. The reduction in the seismic response with the addition of dampers is not as significant in case of compliant soils as in the fixed base case and the damper effectiveness increases as soil stiffness increases. Increase in number of dampers beyond certain limit does not lead to any further reduction in the response of a building. However, this limiting number of dampers depends upon the structural configuration and soil flexibility.

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