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RESPONSE OF THE WIND EXCITED BENCHMARK BUILDING UPGRADED WITH SAEMFDs

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Dynamic behavior of the wind excited benchmark building using Semi-Active Electro-Magnetic Friction Dampers (SAEMFDs), with modulated homogeneous friction algorithm is presented. The performance of the benchmark building is studied under across wind loads by installing the SAEMFDs with smooth boundary layer semi-active friction (SBLSAF) algorithm. The governing equations of motion are solved by employing state space formulation. Initially, one damper in each of the upper 26 storeys of the building is installed and later on the optimization of the location and the number of dampers required is carried out till the comparable performance criteria are obtained. The criterion selected for optimality was controllability index, obtained with the help of root-mean-square (RMS) value of the inter-storey drift. The performance of SAEMFDs is compared with that of passive friction dampers. Further, a parametric study is carried out by varying the value of controller gain (β). For each value of β, a parametric study of SAEMFDs by varying the value of the parameter representing the measure of the thickness of the boundary layer (α) is carried out. From the numerical study, it is found that SBLSAF algorithm is quite effective in enhancing the quality of the performance of the benchmark building. Optimization of location of dampers gives an economical solution to the vibration control of the benchmark building.

Keywords: benchmark building, tall building, semi-active control, SAEMFDs, wind load

1. Introduction

Various structural control methods like passive, active, semi-active and hybrid controls have

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been studied on different buildings subjected to different dynamic loads. Significant progress has also been made in the area of structural control. Some of the control methods have been implemented on real structures. However, to streamline and focus the study of structural control on the same building with the same load, the concept of benchmark problems has come into picture. Therefore, based on realistic full scale buildings, two structural control benchmark problems have been proposed for earthquake and wind excitations (Yang *et al*., 2004). The wind excited benchmark building is a 76-storey, 306 m high concrete office tower proposed for the city of Melbourne, Australia. The building is tall and slender with a height to width ratio of 7.3. Hence, it is wind sensitive. Wind tunnel tests (Samali *et al.*, 2004a) for the 76-storey building model have already been conducted at the University of Sydney and the results of the across-wind data are also provided in order to have the analysis of the benchmark problem.

Performance of various dampers like tuned liquid column dampers (Min *et al*., 2005), liquid column vibration absorbers (Samali *et al*., 2004b), hybrid viscous-tuned liquid column damper (Kim and Adeli, 2005), variable stiffness tuned mass damper (Varadarajan and Nagarajaiah, 2004) on the benchmark building have been studied. Patil and Jangid (2009) studied the response of the benchmark building with the various arrangements of linear viscous dampers (LVDs) and semi-active variable friction dampers (SAVFDs) by connecting them to alternative floors of the building. Bhaskararao and Jangid (2006a) proposed two numerical models to evaluate the frictional force in the connected dampers for multi-degree of freedom (MDOF) structures and validated with the results obtained from the analytical model considering an example of single degree of freedom (SDOF) structures. Further, the effectiveness of dampers in terms of the reduction of structural responses, of connected adjacent structures is investigated. They also conducted a parametric study to investigate the optimum slip force of the damper. In addition, the authors studied the optimal placement of dampers. So far, the conventional dampers have been used to control the vibration of the structures. Bhaskararao and Jangid (2006b) studied the dynamic response of two adjacent single storey building structures connected with a friction damper under harmonic ground excitation. Here, an attempt is made to study the performance of SAEMFDs with modulated homogeneous friction algorithm. Further, to improve the performance of passive dampers, semi-active dampers are proposed in the literature. A semi-active friction damper is able to adjust its slip force by controlling its clamping force in real-time, depending upon the structure’s motion during an earthquake. This adaptive nature makes a semi-active friction damper more efficient. The control by semi-active friction dampers requires a feedback control algorithm and on-line measurement of structural response, in order to determine the appropriate level of adjustable clamping forces of the dampers. Akbay and Aktan (1995) proposed the control algorithm that determines the clamping force at the next time step. Other proposed control laws include the bang-bang control (Kannan *et al*., 1995), modulated homogenous control (Inaudi, 1997), linear quadratic regulator (Sadek and Mohraz, 1998), friction-force incremental control (Xu *et al*., 2001), modal control (Lu and Chung, 2001; Lu, 2004a), predictive control (Lu, 2004b), modal and optimal control (Lu *et al*., 2004). Kori and Jangid (2008) studied the performance of SAVFDs by placing them in various storeys of multi-storeyed buildings using predictive control law. Optimization of location and the number of dampers is also carried out by adopting a sequential search procedure (Shukla and Datta, 1999) with the help of a controllability index which is obtained with the help of RMS value of inter-storey drift. It is revealed by the above literature review that the performance of SAEMFDs on the wind excited benchmark building is not studied so far. Hence, it will be interesting to apply SAEMFDs dampers on the slim building. The performance of SAEMFDs on the wind-excited-benchmark-building subjected to the across wind loads is investigated in this paper. The specific objectives of the present study may be summarized as: (i) to study the improvement in the performance of wind excited benchmark building with the proposed SAEMFDs, as compared with that of the passive friction dampers, (ii) to optimize the location and number of SAEMFDs and (iii) to carry out the parametric study by varying the value of the parameter representing the measure of the thickness of the boundary layer (α).

2. Benchmark Building

The wind excited benchmark (Yang *et al.,* 2004) building is a 76-storey, 306 m high office tower proposed for the city of Melbourne, Australia. The building is a reinforced cement concrete building consisting of a concrete core and concrete frame. The mass density of the building is 300 kg per cubic meter. The building is slender with a height-to-width ratio of 306.1/42=7.3. Therefore, it is wind sensitive. The outer dimension for the central reinforced concrete core is 21m×21m. The 24 columns on the periphery of the building are distributed equally on each of the four sides of the building. These columns are connected to a 900 mm deep and 400 mm wide beam on each floor. The light weight floor construction is made up of steel beams with a metal deck and a 120 mm slab. The compressive strength of concrete is 60 MPa and the modulus of elasticity is 40 GPa. Column sizes, core wall thickness, and floor mass are varying along the height. The building has six plant rooms. It is modeled as a vertical cantilever beam (Bernoulli–Euler beam). The portion of the building between adjacent floors is considered as a classical beam and the finite element model is constructed. The 76 rotational degrees of freedom have been removed by the static condensation. This results in 76 degrees of freedom, representing the displacement of each floor in the lateral direction. The first five natural frequencies of the model are 0.16, 0.765, 1.992, 3.790 and 6.395 Hz.

2.1. Semi-active Electromagnetic Friction Dampers (SAEMFDs)

A semi-active electromagnetic friction damper consists of a friction pad sandwiched between two steel plates. These three layers are slot-bolted together so that sliding takes place between the steel plates and the friction pad. The friction force between steel plates and the friction pad depends on the coefficient of friction (μ) and the normal force $N(t)$. Two insulated solenoids are installed on the outer surfaces of steel plates and the electric current in these solenoids is regulated so that an electromagnetic attractive force exists between the two solenoids. Hence, the normal force $N(t)$ between the steel plates is directly proportional to the square of the current in solenoids and it can be operated easily using stand-by batteries.

2.2. Governing Equations of Motion

The governing equation of motion for the controlled building structure model subjected to wind excitations can be written as:

$$\mathbf{M\ddot{x}} + \mathbf{C\dot{x}} + \mathbf{Kx} + \mathbf{\Lambda u} = \mathbf{F} \tag{1}$$

where the mass matrix M and stiffness matrix K, each of the order of (76×76) are constructed for the finite element model of the building and provided for the analysis. $\zeta = 1\%$ is assumed for the first five modes to construct the damping matrix C of the order of (76×76) using Rayleigh's approach (Yang *et al.,* 2004); x is displacement vector, $\mathbf{\dot{x}}$ and $\mathbf{\ddot{x}}$ the first and second time derivatives, u= $[f_{d1},\ f_{d2}, \ldots f_{dr}]^T$; F are control force vector and wind load vector respectively; and Λ is a matrix of zeros and ones, where one will indicate location of the damper force being applied.

The Equation (2) is expressed as a set of first order differential equations as:

$$\mathbf{\dot{z}} = \mathbf{Az} + \mathbf{Bu} + \mathbf{EF} \tag{2}$$

where z is the state vector of structure, and contains displacement and velocity of each floor; A denotes the system matrix composed of structural mass, damping and stiffness matrices; B represents the distributing matrices of the control forces; and E represents the distributing matrices for excitation.

The Equation (2) is discretized in the time domain and excitation force is assumed to be constant within any time interval and can be written into a discrete-time form (Lu, 2004b).

$$\mathbf{z}[k+1] = \mathbf{A}_d\mathbf{z}[k] + \mathbf{B}_d\mathbf{u}[k] + \mathbf{E}_d\mathbf{F}[k] \tag{3}$$

where $A_d = e^{A\Delta t}$ represents the discrete time system matrix with Δt as the time interval.

2.2.1. Boundary Layer Semi-Active Friction Algorithm

The performance of semi-active variable friction dampers depends mainly on the particular control algorithm used. Inaudi (1997) proposed a semi-active control algorithm for variable friction dampers in which the control force is proportional to the absolute value of the previous local peak of the damper deformation, i.e.

$$u_i(t) = \left\{ \mu \beta_i \left| \mathrm{P}\left[d_i\left(t\right) \right] \right| \mathrm{sgn}\left(d_i \right) \right. \tag{4}$$

However, the algorithm does not guarantee a continuous slipping at all time. Therefore, it will go both in stick and slip states. The transitions between stick and slip phases result in spikes in the acceleration response.

To overcome the above difficulty, DSAF controller is proposed (He *et al.,* 2003). The control force by DSAF algorithm is as follows:

$$u_i(t) = \begin{cases} \mu \beta_i \left| \mathrm{P}\left[d_i\left(t\right) \right] \right| \mathrm{sgn}\left(\dot{d}_i \right) & \text{if } \dot{d}_i \neq 0 \\ 0 & \text{if } \dot{d}_i = 0 \end{cases} \tag{5}$$

However, the DSAF algorithm induces high-frequency components due to the high-frequency (abrupt) switching and chattering around $\dot{d}_i \approx 0$, resulting in spikes in the acceleration response. This difficulty can be overcome by introducing a boundary layer δ_i around $\dot{d}_i \approx 0$. Two types of boundary layers can be introduced - linear boundary layer and smooth boundary layer. In linear boundary layer friction force varies linearly around $\dot{d}_i \approx 0$. Such a boundary layer eliminates spikes in the acceleration response by avoiding high-speed chattering around $\left|\dot{d}_i\right| \cong 0.$ It has been observed that the performance of the controller may be sensitive to the boundary layer parameter δ_i. This sensitivity can be reduced by introducing a smooth boundary layer in place of the linear boundary layer. With smooth boundary layer, the control force is determined as follows:

$$u_i(t) = \mu \beta_i \left| \mathrm{P}\left[d_i\left(t\right) \right] \right| \tanh(\alpha_i \dot{d}_i) \tag{6}$$

3. Numerical Study

The response of the wind-excited-benchmark-building using SAEMFDs is investigated. In the first part of the study, one damper in each of the upper 26 storeys is installed as shown in Figure 1; and various response quantities with the SBLSAF algorithm are compared with those of the uncontrolled benchmark building. In the second part of the study, the optimization of the location and the number of dampers required is carried out till the performance criteria are acceptably comparable to those with one damper in each of the upper 26 storeys of the building. A parametric study is carried out by varying the values of β and α. The values of the parameter β=3000000 and 6000000 are considered. For each value of β, α is varied from 400 to 2400. Then, for each value of α, the parametric study is carried out by placing 10 dampers at their optimized locations. The coefficient of friction for SAEMFDs is maintained as 0.15 throughout the study. The 12 performance criteria of the benchmark building are defined in the basic paper (Yang *et al.,* 2004). Wind tunnel tests (Samali *et al*., 2004a) for the benchmark building model have been already conducted at the University of Sydney and the results of the across-wind data for a duration of 3600s is also provided in order to have the analysis of the benchmark problem. However, in the present study, the performance of dampers is studied only upto duration of 900 s.

3.1. SAEMFDs Dampers in the Upper Storeys of the Building

In this part of the study, the response quantities obtained by the installation of one damper in each of the upper 26 storeys of the building are compared with those of the uncontrolled building. The values of β=3000000 and $\alpha = 1200$ are maintained for all the 26 dampers. The peak displacement quantities of various floors are presented in Table 1. Peak displacement quantity of the 76th floor is found to be reduced by 30.80 % with dampers. The peak displacement quantities of all the other floors show a similar trend. Similarly, the peak acceleration quantities are also presented in Table 1. The peak acceleration quantity of 76th floor is found to be reduced by 64.2 %. Peak acceleration quantities of all the other floors show a similar trend.

Therefore, peak displacement quantities are considerably reduced and the peak acceleration quantities are also reduced significantly in all floors.

The RMS displacement quantities of various floors are presented in Table 2. RMS displacement quantity of the 76th floor is found to be reduced by 46.7 % with the dampers. The RMS displacement quantities of all the other floors show a similar trend. Similarly, the RMS acceleration quantities are also presented in Table 2.

The RMS acceleration quantity of 76th floor is found to be reduced by 66.00 %. The RMS acceleration quantities of all the other floors show similar trend. Therefore, the RMS displacement quantities are considerably reduced and the RMS acceleration quantities are also reduced significantly in all floors.

Comparison of time variation of top floor displacement obtained by the installation of dampers with that of the uncontrolled building is made in Figure 2. Similar comparison of time variations of top floor acceleration quantities is made in Figure 3. The top floor displacement quantities are considerably reduced and the top floor acceleration quantities also have reduced significantly.

The performance criteria of the uncontrolled building and the building installed with (i) one SAEMFD (with β=3000000 and α=1200) in each of the 76 storeys and (ii) one SAEMFD in each of the upper 26 storeys, with the same parameters are presented in Table 3.

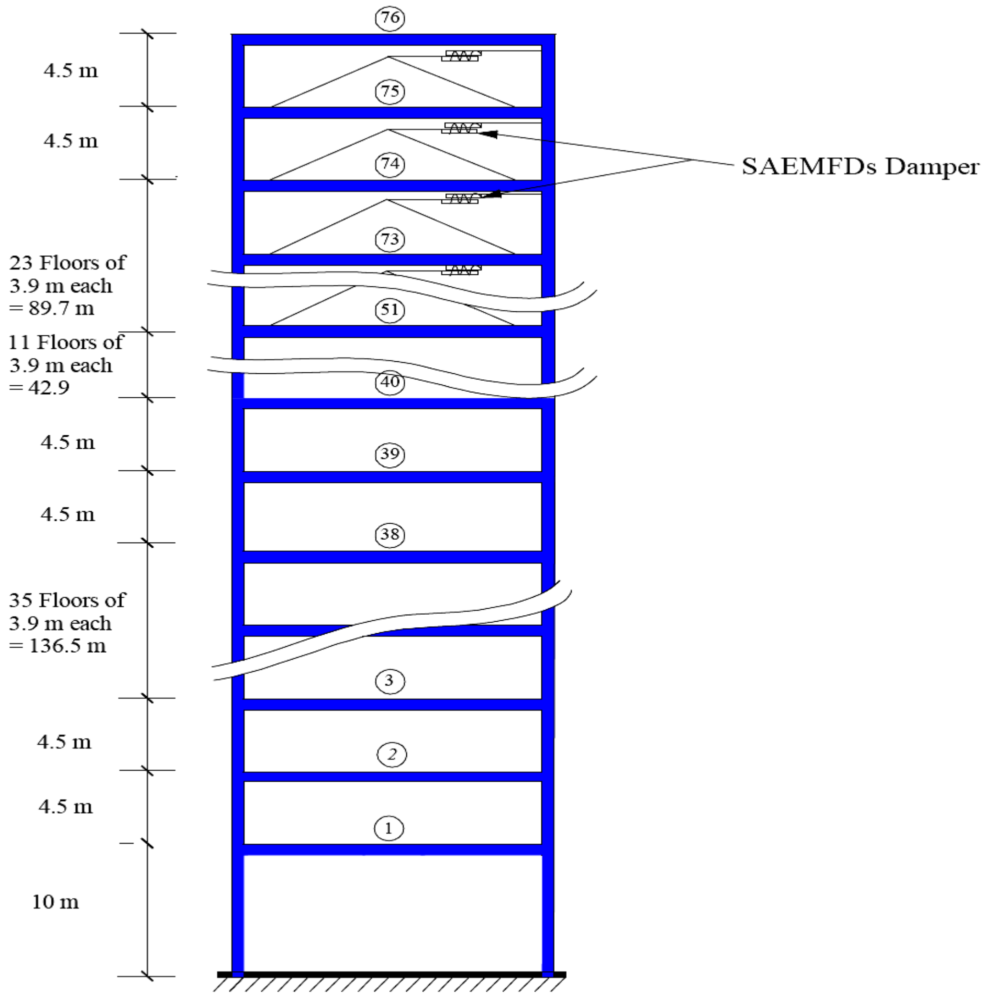

Figure 1. SAEMFDs installed in the upper storeys of the benchmark building

Table 1. Peak response quantities of the benchmark building

Algorithm	β	α	1	30	50	55	60	65	70	75	76	Location of Dampers
Peak displacement (x_p) in cm	---------	-------	0.053	6.836	16.579	19.407	22.331	25.344	28.404	31.577	32.287	Nil
		1200	0.039	4.973	11.806	13.739	15.719	17.736	19.772	21.877	22.349	U-26
	3000000	400	0.043	5.474	13.038	15.184	17.386	19.632	21.900	24.246	24.771	
		800	0.041	5.247	12.476	14.524	16.622	18.763	20.921	23.154	23.654	
		1200	0.041	5.159	12.258	14.266	16.324	18.422	20.538	22.727	23.217	
		1600	0.040	5.117	12.151	14.140	16.178	18.255	20.350	22.517	23.002	
		2000	0.040	5.091	12.087	14.066	16.093	18.158	20.242	22.397	22.879	
		2400	0.040	5.0734	12.048	14.020	16.040	18.099	20.176	22.324	22.805	76-10#
	6000000	400	0.041	5.144	12.221	14.224	16.275	18.367	20.478	22.660	23.150	
		800	0.039	4.958	11.778	13.708	15.684	17.699	19.732	21.833	22.304	
		1200	0.039	4.900	11.633	13.538	15.488	17.475	19.481	21.552	22.017	
		1600	0.039	4.885	11.595	13.492	15.435	17.414	19.411	21.475	21.938	
		2000	0.038	4.866	11.542	13.427	15.357	17.322	19.304	21.352	21.811	
		2400	0.039	4.887	11.600	13.496	15.439	17.418	19.414	21.477	21.939	
Peak acceleration ($\ddot{x}_p$) in cm/s^2	----------	-------	0.221	7.194	14.885	17.427	19.913	22.304	25.979	30.238	31.199	Nil
		1200	0.064	3.313	6.348	7.127	7.867	8.812	9.759	10.883	11.167	U-26
	3000000	400	0.072	3.671	7.894	9.006	10.131	11.597	13.217	14.832	15.333	
		800	0.089	3.4685	7.360	8.190	9.205	10.399	11.660	13.171	13.559	
		1200	0.108	3.628	7.362	8.000	8.806	10.065	11.536	13.303	13.715	
		1600	0.111	3.8483	7.455	7.987	8.842	9.915	11.574	13.521	13.961	
		2000	0.130	4.056	7.551	8.019	8.903	9.835	11.626	13.674	14.152	
		2400	0.144	4.266	7.625	8.054	8.939	9.840	11.651	13.776	14.833	76-10#
	6000000	400	0.078	3.282	6.739	7.689	8.646	9.553	10.463	11.811	12.669	
		800	0.145	3.073	6.289	7.082	8.010	8.951	9.735	11.975	13.059	
		1200	0.139	3.037	6.204	6.895	7.815	8.682	9.478	12.327	14.056	
		1600	0.131	3.392	6.164	6.879	7.795	8.597	9.471	12.802	15.026	
		2000	0.143	3.595	6.186	6.854	7.601	8.470	9.703	12.727	15.906	
		2400	0.149	3.836	6.251	6.947	7.776	8.664	10.028	14.358	17.758	

SAEMFDs at optimized locations U-26 One SAEMFD in each of the upper 26 storeys

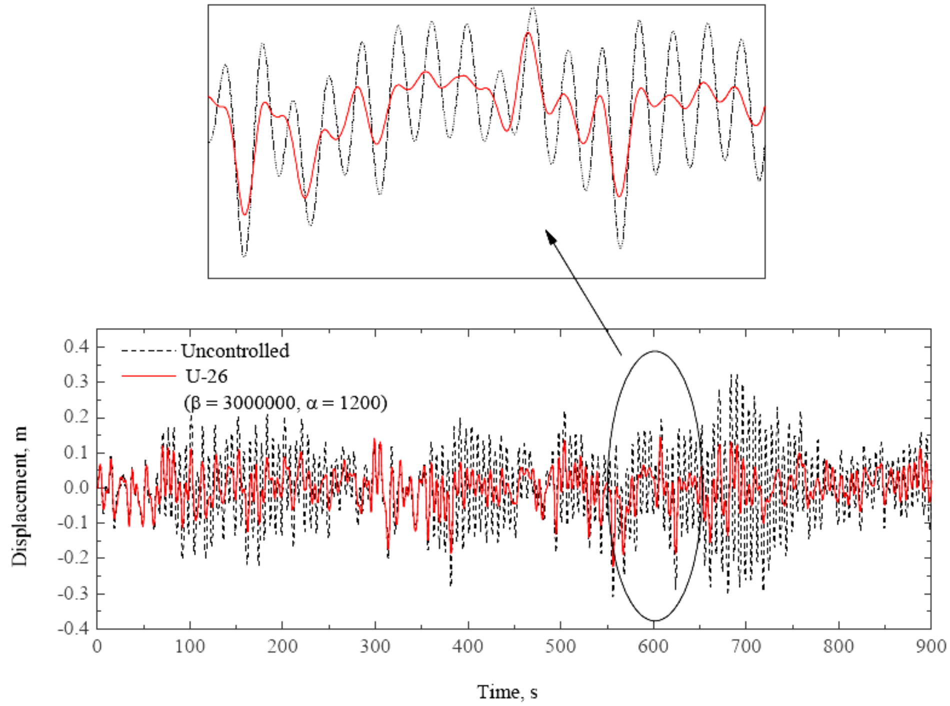

Figure 2. The comparison of time variation of the top floor displacement installed with SAEMFDs in the upper storeys with that of the uncontrolled benchmark building

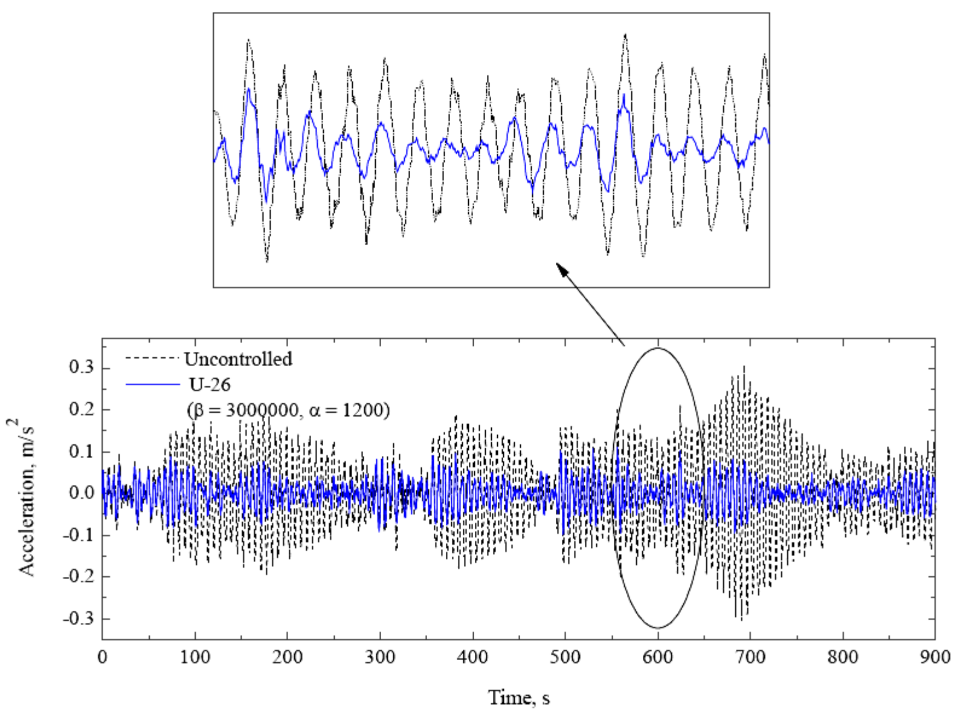

Figure 3. The comparison of time histories of the top floor acceleration installed with SAEMFDs in the upper storeys with that of the uncontrolled benchmark building

Table 2. RMS response quantities of the benchmark building

	β	α	1	30	50	55	60	65	70	75	76	Location of Dampers
RMS Displacement (σx) in cm	---------	-------	0.017	2.152	5.215	6.102	7.018	7.960	8.917	9.908	10.130	Nil
		1200	0.009	1.161	2.798	3.269	3.755	4.253	4.758	5.282	5.400	U-26
	3000000	400	0.011	1.388	3.349	3.914	4.497	5.096	5.704	6.334	6.475	76-10#
		800	0.010	1.298	3.131	3.659	4.203	4.761	5.328	5.917	6.049	
		1200	0.010	1.268	3.057	3.571	4.102	4.647	5.200	5.774	5.903	
		1600	0.010	1.256	3.026	3.536	4.061	4.600	5.148	5.716	5.843	
		2000	0.010	1.250	3.012	3.519	4.041	4.578	5.123	5.688	5.815	
		2400	0.010	1.247	3.005	3.510	4.032	4.567	5.110	5.674	5.801	
	6000000	400	0.010	1.247	3.006	3.512	4.033	4.569	5.113	5.678	5.805	
		800	0.009	1.173	2.823	3.298	3.787	4.289	4.799	5.329	5.448	
		1200	0.009	1.148	2.763	3.226	3.704	4.196	4.695	5.213	5.330	
		1600	0.009	1.137	2.735	3.193	3.666	4.152	4.646	5.159	5.275	
		2000	0.009	1.130	2.717	3.173	3.642	4.125	4.615	5.125	5.239	
		2400	0.009	1.127	2.709	3.163	3.631	4.112	4.601	5.109	5.223	
RMS Acceleration $(\sigma \ddot{x})$ in cm/s^2	----------	-------	0.019	2.018	4.773	5.578	6.413	7.282	8.177	9.119	9.331	Nil
		1200	0.008	0.715	1.634	1.901	2.180	2.471	2.775	3.099	3.173	U-26
	3000000	400	0.010	1.053	2.490	2.909	3.343	3.794	4.258	4.739	4.867	76-10#
		800	0.009	0.933	2.179	2.542	2.920	3.313	3.719	4.140	4.255	
		1200	0.010	0.904	2.073	2.414	2.771	3.145	3.533	3.939	4.047	
		1600	0.010	0.906	2.033	2.363	2.710	3.076	3.460	3.866	3.970	
		2000	0.011	0.919	2.018	2.340	2.682	3.046	3.430	3.840	3.945	
		2400	0.012	0.934	2.013	2.331	2.670	3.032	3.418	3.835	3.940	
	6000000	400	0.009	0.847	1.987	2.318	2.662	3.019	3.387	3.765	3.872	
		800	0.008	0.734	1.699	1.978	2.268	2.569	2.879	3.200	3.290	
		1200	0.009	0.706	1.603	1.862	2.133	2.414	2.705	3.009	3.090	
		1600	0.009	0.705	1.564	1.812	2.072	2.344	2.629	2.929	3.007	
		2000	0.010	0.715	1.544	1.785	2.039	2.307	2.589	2.891	2.967	
		2400	0.009	1.127	2.709	3.163	3.631	4.112	4.601	5.109	5.223	

SAEMFDs at optimized locations U-26 One SAEMFD in each of the upper 26 storeys

Table 3. Performance criteria of the benchmark building

β	α	J_1	J_2	J_3	J_4	J_7	J_8	J_9	J_{10}	Location of Dampers
---------	---------	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	Nil
	1200	0.278	0.279	0.506	0.508	0.343	0.369	0.677	0.686	A.S.
3000000	1200	0.340	0.340	0.533	0.534	0.360	0.394	0.692	0.701	U-26
	1200	0.359	0.360	0.541	0.542	0.372	0.389	0.685	0.693	76-15, 75-1#
	400	0.519	0.521	0.639	0.640	0.491	0.513	0.767	0.775	76-10#
	800	0.454	0.455	0.597	0.598	0.436	0.463	0.732	0.741	
	1200	0.432	0.433	0.583	0.584	0.440	0.455	0.719	0.728	
	1600	0.424	0.424	0.577	0.578	0.447	0.457	0.712	0.721	
	2000	0.421	0.420	0.574	0.575	0.452	0.459	0.708	0.717	
	2400	0.420	0.419	0.572	0.574	0.456	0.462	0.706	0.715	
6000000	400	0.413	0.415	0.573	0.574	0.391	0.425	0.717	0.725	76-10#
	800	0.351	0.353	0.538	0.539	0.396	0.401	0.691	0.699	
	1200	0.330	0.332	0.526	0.527	0.408	0.395	0.682	0.690	
	1600	0.321	0.323	0.521	0.522	0.423	0.396	0.679	0.688	
	2000	0.317	0.319	0.517	0.518	0.421	0.394	0.675	0.684	
	2400	0.316	0.317	0.515	0.517	0.475	0.410	0.679	0.688	

SAEMFDs at optimized locations U-26 One SAEMFD in each of the upper 26 storeys A.S. One SAEMFD in each of the 76 storeys

From the Table, it is seen that there is no much appreciable reduction in the values of all the performance criteria obtained with one SAEMFD in each of the 76 storeys as compared to those with one SAEMFD in each of the upper 26 storeys.Hence, the performance of the optimized number of SAEMFDs at their optimized locations is made with that obtained with one damper in each of the upper 26 storeys. From the Table, it is also seen that the performance criteria $(J_3, J_4, J_9 \text{ and } J_{10})$ which depend on peak displacement and RMS displacement quantities are considerably reduced and those $(J_1, J_2, J_7 \text{ and } J_8)$ which depend on peak acceleration and RMS acceleration are also significantly reduced in each of the controlled cases.

Thus, SAEMFDs are quite effective in controlling both acceleration and displacement quantities. Further, when the SAEMFDs are in the upper 26 storeys of the building, acceleration quantities of all floors are better controlled than displacement quantities.

3.2. Optimization of Location of Dampers

After studying the performance of the proposed dampers in all the floors, optimization of location and the number of dampers is carried out. Shukla and Datta (1999) studied the optimal use of visco-elastic dampers (VEDs) in the control of seismic response of multi-storey building frames using optimally placed VEDs. There can be various controllability indices depending upon the response quantities to be controlled. Here the controllability index is considered to be:

$$\chi(L) = \max \frac{\sigma_x(L)}{h(L)} \tag{7}$$

where $\chi(L)$ and $\sigma_x(L)$ are location index and RMS value of inter-storey drift at the L^{th} storey, respectively; and $h(L)$ is the L^{th} storey height. Thus, the L^{th} storey is the optimal location of a VED if $\chi(L)$ is maximum.

Each damper is successively installed in that storey where the inter-storey drift is maximum. This is done with a view that a damper is optimally located if it is placed in the storey in which the displacement (or relative displacement) of the uncontrolled (or modified) structure is the largest. This procedure is repeated until all the performance criteria obtained are comparable to those obtained with one damper in each of the upper 26 storeys.

From Table 3, it is seen that at optimized locations, only 16 dampers are sufficient to achieve the performance criteria comparable to those obtained with one damper in each of the upper 26 storeys. In Figure 4, comparison of time variation of top floor displacement with dampers at their optimized locations and one damper in each of the upper 26 storeys is made. Only 16 dampers are sufficient to achieve the comparable time history. In Figure 5, the comparison of time variation of top floor acceleration with dampers at their optimized locations and one damper in each of the upper 26 storeys is made. By optimization, only 16 dampers are sufficient to achieve the comparable time history.

Thus, the optimization procedure adopted here gives an economical solution to the vibration control of the benchmark building.

3.3. Parametric Study

Two values of β (3000000 and 6000000) are considered for the study of SAEMFDs with SBLSAF algorithm installed in the benchmark building. For each value of β, a parametric study is carried out by varying the value of α from 400 to 2400. For each value of α, 10 dampers are placed sequentially by the optimization procedure.

Peak displacement quantities obtained from the study are presented in Table 1. From the Table, it is seen that for both the values of β, peak displacement quantities of all floors have reduced. These reductions are slightly more in case of β=6000000 as against to those with β=3000000. Peak acceleration quantities obtained from the study are also presented in Table 1. From the Table, it is seen that for both the values of β, peak acceleration quantities of all floors are also reduced. These reductions are slightly more in case of β=6000000 as against to those with β=3000000.

Similarly, the RMS displacement quantities obtained from the study are presented in Table 2. From the Table, it is observed that for both the values of β, the RMS displacement quantities of all floors are reduced. These reductions are slightly more in case of β=6000000 as against to those with β=3000000. The RMS acceleration quantities obtained from the study are also presented in Table 2.

From the Table, it is observed that for both the values of β, the RMS acceleration quantities of all floors have also reduced. These reductions are slightly more in case of β=6000000 as against those with β=3000000.

Performance criteria obtained from the parametric study are presented in Table 3. All the performance criteria have reduced for both values of β. However, the reductions are slightly more in case of β=6000000.

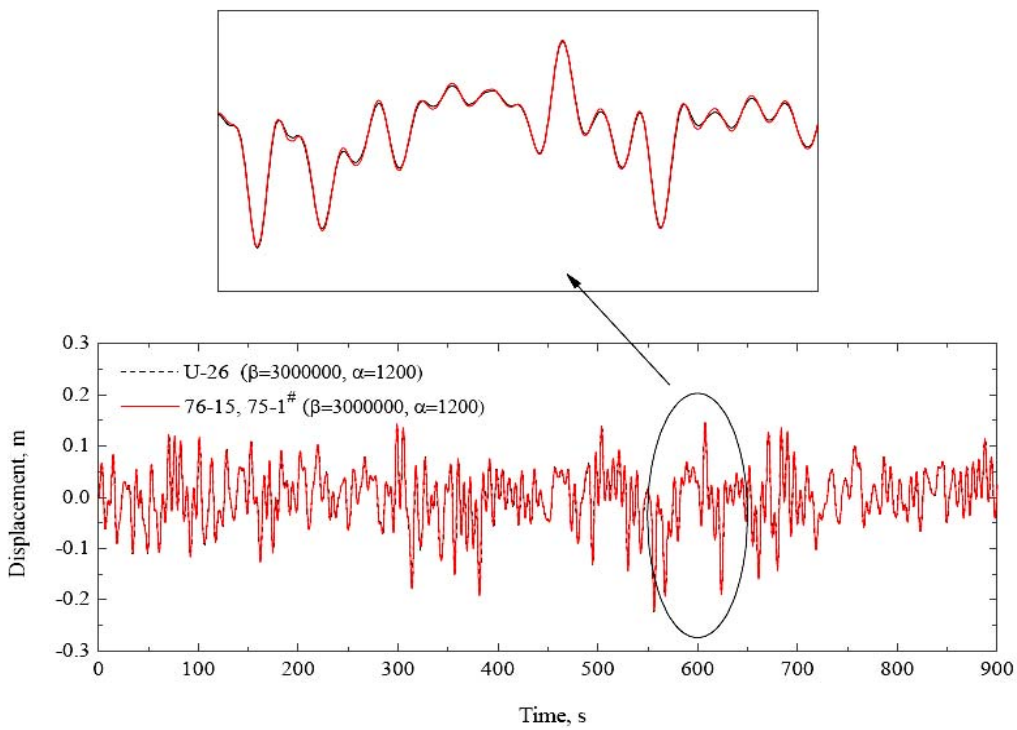

Figure 4. The comparison of time variation of top floor displacement of the benchmark building with one SAEMFD, each at the upper 26 storeys with that with the SAEMFDs at their optimized locations

The variation of the performance criteria with α values for β=3000000 is shown in Figure 6. All the performance criteria get reduced with the increase in the values of α except J_7 *and* J_8. However, these reductions are insignificant for $\alpha \geq 1200$. The values of J_7 *and* J_8 are minimum for α=1200. Therefore, the optimum value of α is 1200.

The comparison of time variation of top floor displacement quantities obtained by 10 optimally placed passive friction dampers and the same number of SAEMFDs (β=3000000 and α=1200) is made in Figure 7. Maximum damper force (of 2200 kN) is maintained the same in both the types of dampers. Top floor displacement quantities are more with SAEMFDs.

Comparison of time variation of top floor acceleration quantities obtained by 10 optimally placed passive friction dampers and the same number of SAEMFDs (β=3000000 and α=1200) is made in Figure 8. Maximum damper force (of 2200 kN) is maintained same in both the types of dampers. Top floor acceleration quantities are more with SAEMFDs. From the Figure, it is observed that at the peaks of the time variation of the acceleration quantities obtained by passive friction dampers, there are many abrupt variations (jerks). These abrupt variations are reduced in case of SAEMFDs and the acceleration time history has become smooth at the peaks.

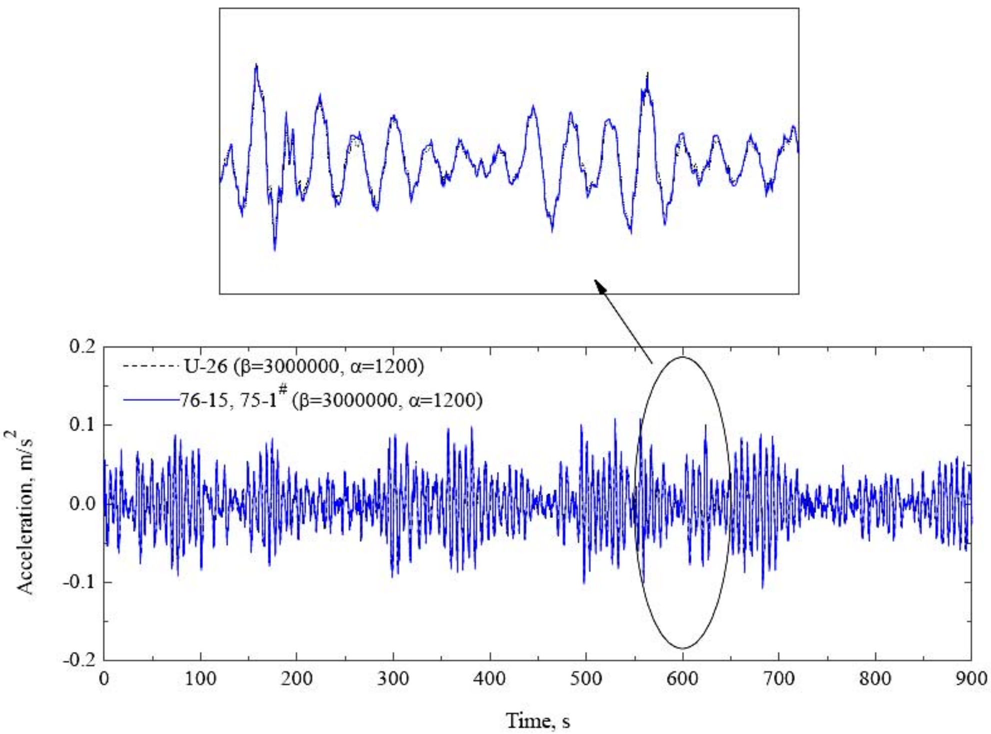

Figure 5. The comparison of time variation of top floor acceleration of the benchmark building with one SAEMFD, each at the upper 26 storeys with that with the SAEMFDs at their optimized locations

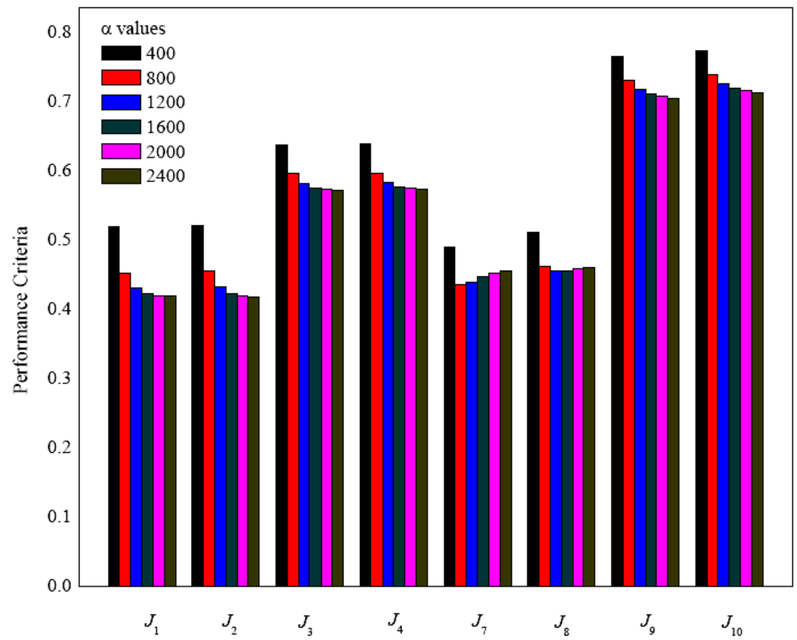

Figure 6. Variation of Performance criteria of the benchmark building with the values of α (β=3000000)

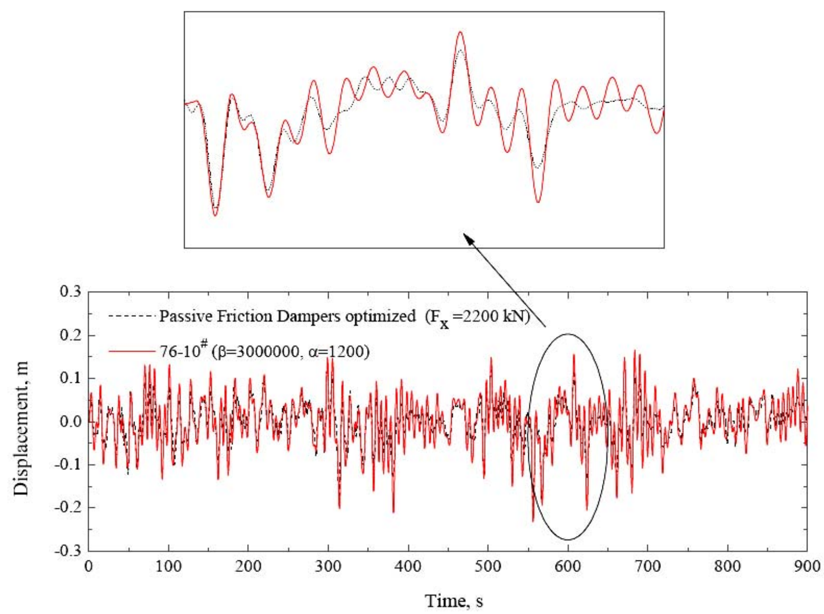

Figure 7. The comparison of time variation of top floor displacement of the benchmark building installed with 10 SAEMFDs at optimized location with that with the same number of passive friction dampers at their optimized locations

The variation of the performance criteria with α values for β=6000000 is shown in Figure 9. Similar observations as made from Figure 6 are made from the figure. For β=6000000 also the optimum value of α is 1200.

The comparison of time variation of top floor displacement with 10 optimally placed passive friction dampers and the same number of SAEMFDs (β=6000000 and α=1200) is made in Figure 10. Maximum damper force (of 4155 kN) is maintained same in both the types of dampers. Top floor displacement quantities are more with SAEMFDs.

The comparison of time variation of top floor acceleration with 10 optimally placed passive friction dampers and the same number of SAEMFDs (β=6000000 and α=1200) is made in Figure 11. Maximum damper force (of 4155 kN) is maintained the same in both the types of dampers. Top floor acceleration quantities are more with SAEMFDs. From the Figure, it is observed that at the peaks of the time variation of the acceleration quantities obtained by passive friction dampers, there are many abrupt variations (jerks). These abrupt variations are reduced in case of SAEMFDs and the acceleration time history has become smooth at the peaks.

Thus, there exists an optimum value of α for all the performance criteria. And even if the displacement and acceleration quantities obtained by the installation of SAEMFDs are more as compared to those with their conventional counterparts, the abrupt variations of acceleration quantities at the peaks of the time history are smoothened and hence the quality of the acceleration time history has improved. This is attributed to the continuously slipping state of the semi-active dampers.

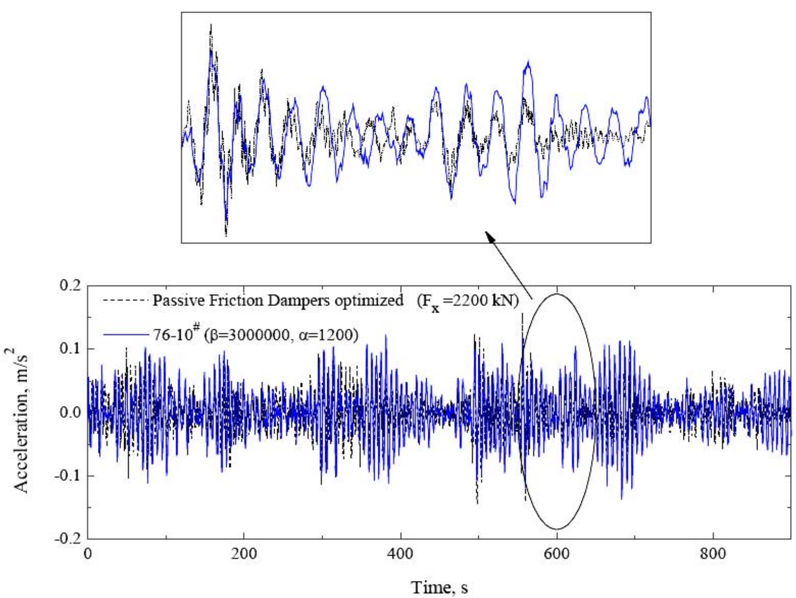

Figure 8. The comparison time variation of top floor acceleration of the benchmark building installed with 10 SAEMFDs at optimized location with that with the same number of passive friction dampers at their optimized locations

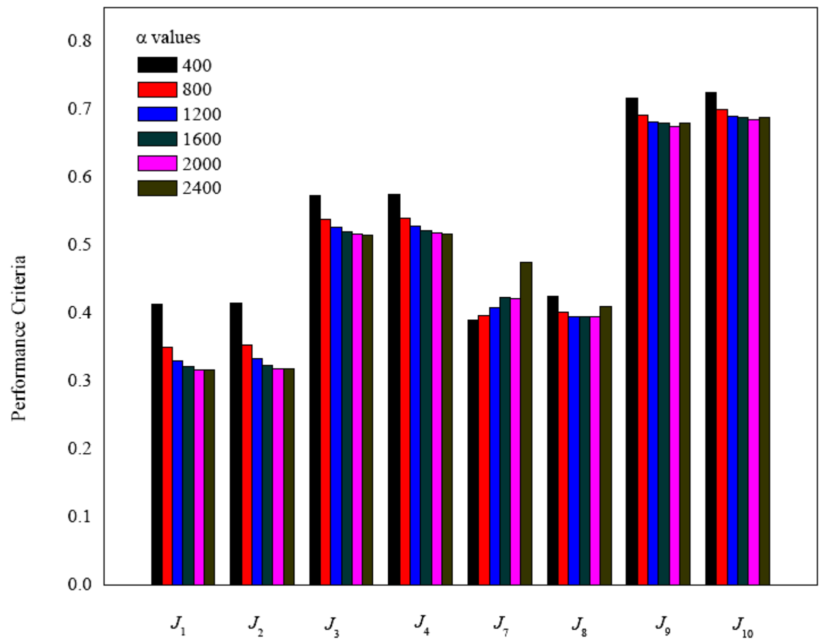

Figure 9. Variation of the Performance criteria of the benchmark building with the values of α (β=6000000)

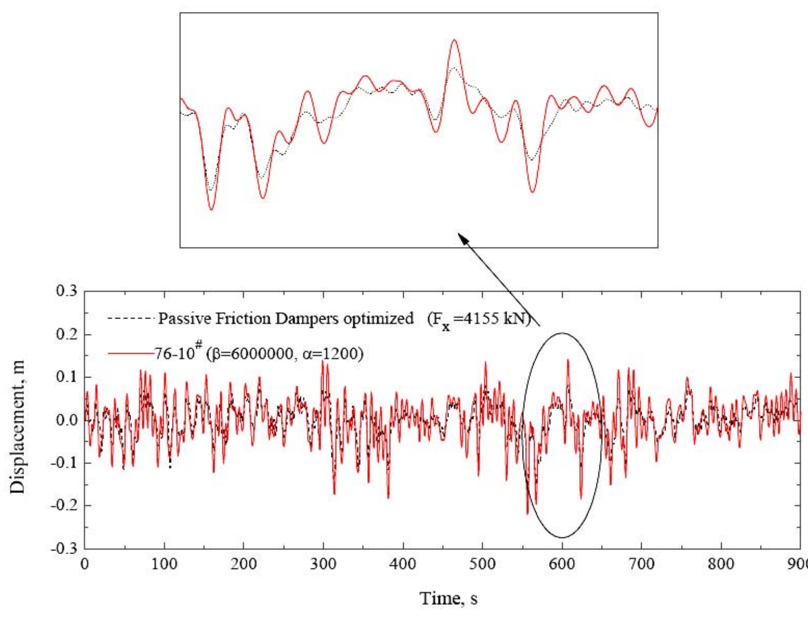

Figure 10. The comparison of time variation of top floor displacement of the benchmark building installed with 10 SAEMFDs at their optimized locations with that with the same number of passive friction dampers at their optimized locations

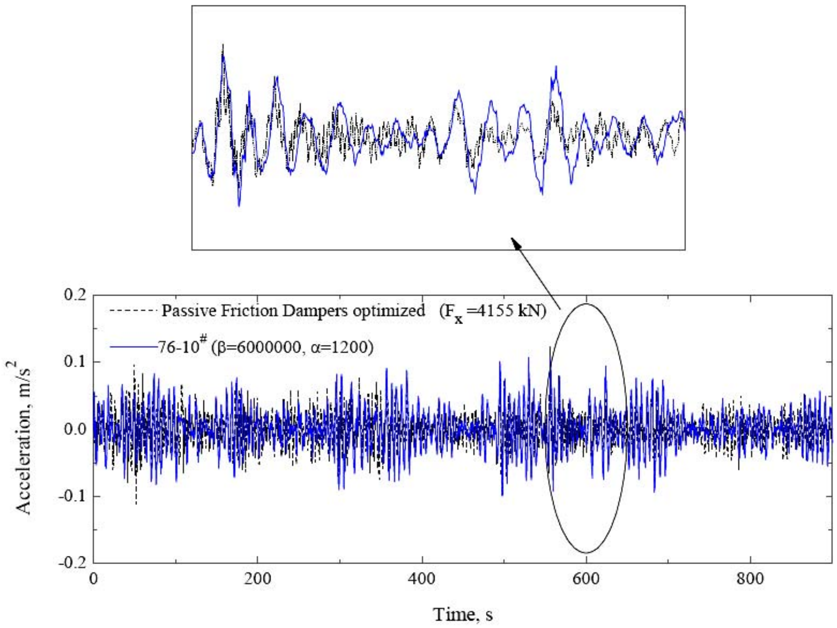

Figure 11. The comparison time variation of top floor acceleration of the benchmark building installed with 10 SAEMFDs at their optimized locations with that with the same number of passive friction dampers at their optimized locations

4. Conclusions

Numerical study of the wind-excited-benchmark-building installed with SAEMFDs is carried out under the deterministic across wind excitation. To verify the effect of the semi-active dampers, the comparison of the response quantities/performance criteria is made with those obtained with their conventional counterparts. The optimization of location of SAEMFDs is also carried out; and the results are compared. In addition, a parametric study is carried out to critically examine the performance of the building installed with SAEMFDs at their optimized locations. From the trends of the numerical results of the present study, the following conclusions can be arrived at:

1. SAEMFDs are quite effective in controlling the response quantities of the benchmark building. The performance against acceleration is better than that against displacement.
2. The quality of the performance of SAEMFDs (with SBLSAF algorithm) is better against acceleration than that of passive friction dampers.
3. The optimization of location of dampers gives economical solution to the vibration control of the benchmark building.
4. The optimized locations of SAEMFDs are at 76th and 75th storeys.

5. There exists an optimum value of the parameter (α) representing the measure of the thickness of the boundary layer in reducing all the performance criteria for SBLSAF algorithm.

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Notation

Λ	Matrix of zeros and ones of order ($n \times r$)
A	System matrix
A_d	Discrete-time system matrix
B	System matrix
B_d	Coefficient matrices
C	Damping matrix
D	System matrix
$\dot{d}_i$	Velocity of damper

E	Distributing matrices for excitation
E_d	Coefficient matrices
f_{di}	Damper force of i^{th} damper
$F[k]$	Vector of wind load at k^{th} time step
F_x	Slip force of passive friction damper
$h(L)$	L^{th} storey height
I	Identity matrix
J_1-J_{12}	Performance criteria
K	Stiffness matrix
M	Mass matrix
n	Degree of freedom
r	Number of dampers
x	Floor displacement vector
u[k]	Friction force vector at k^{th} time step
u_i	Control force of i^{th} damper
z	State space vector
$\chi(L)$	Controllability index
$\sigma_x(L)$	RMS value of inter-storey drift of L^{th} storey
x_p	Peak displacement
$\ddot{x}_p$	Peak acceleration
σ_x	RMS Displacement
$\sigma_{\ddot{x}}$	RMS Acceleration
Δt	Time interval
ζ	Damping ratio
β	Gain controller

α= Parameter representing the measure of the thickness of the boundary layer

δ_i= Boundary layer Parameter i^{th} SAEMFD

μ	Coefficient of friction
$N_i[k]$	Normal force of i^{th} damper at k^{th} time step

$|P(d_i(t))|$ = Absolute value of the local maximum prior to the current time

Abbreviations

FEM	Finite element method
LVD	Linear viscous damper
RMS	Root-mean-square
SAVFD	Semi-active variable friction damper
VED	Visco-elastic damper

MDOF	Multi-degree of freedom
SDOF	Single degree of freedom
SAEMFDs	Semi-active electromagnetic friction amperes
SBLSAF	Smooth boundary layer semi-active friction
U-26	One SAEMFD in each of the upper 26 storeys of the building
76-15, 75-1	15 AEMFDs in 76^{th} storey and 1 SAEMFD in 75^{th} storey

End Note

An over bar in the equations indicates an augmented vector or matrix Over-dot denotes derivative with respect to time.