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Original Article

Seismic Response of Soft Storied Building and Secondary System Installed with Semi-Active Dampers

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Abstract *- Secondary systems are defined as the elements that are attached to, or installed on, the main structural system. The secondary systems do not support the main system; however, they are significant to ensure the normal operation and safety of the building. Structural vibration produced during an earthquake can be a threat to systems inside the structure, and it can damage the systems, partially or totally. To preserve systems installed in a building, semi-active variable dampers, which use a 2-step viscous damping force, are used to dissipate seismic forces and minimize vibrations of the building to reduce the risk of damaging the secondary systems. The reduction of seismic vibration in secondary systems mounted on a five-storied building with semi-active dampers is analysed in this study. The displacement and acceleration parameters are determined analytically by formulating and solving equations of motion using the state-space representation. Optimal configuration of semi-active dampers identified through numerical simulations. A comparative evaluation of the controlled seismic responses and their uncontrolled counterparts is executed to evaluate the efficiency of semi-active dampers within the structural framework. The study shows that using semi-active dampers, along with proper structural design, can greatly reduce earthquake-induced deformations in secondary systems as well as primary structures.*

Keywords *- Secondary system, Seismic response, Semi-active variable damper.*

1. Introduction

The principal load-bearing framework of a structure does not encompass the secondary system. Consequently, these components are frequently overlooked during the evaluation of structural design. A structure is deemed secure only if its contents, appendices, services, and utilities, along with its occupants, are capable of enduring seismic ground vibrations at its foundation without incurring any detriment. (Murty et al. (2012). The seismic events have demonstrated that building contents, building appendices, and services and utilities remain vulnerable to damage and failure. Significant social or economic consequences have ensued from such damages and failures, particularly in the context of essential buildings. Sofi, Hutchinson, and Duffield (2015) suggested that for certain categories of structures, neglecting the secondary system may lead to a substantial underestimation of lateral deflection in the event of seismic activity. Gabbianelli et al (2020) elucidated that secondary systems possess the capacity to substantially influence the operational efficiency of a building, even under conditions of moderate seismic intensity, particularly in relation to essential infrastructures such as hospital facilities, nuclear power plants, and similar entities. Chalarca et al. (2020) suggested that for secondary systems highly responsive to acceleration, it is highly advisable to utilize the absolute floor acceleration response as a primary parameter. By implementing this approach, the genuine seismic demands encountered by these secondary systems during an earthquake can be represented with greater accuracy.

Madhekar and Jangid (2009) investigate that variable damper, especially those based on Magnetorheological (MR) technology with friction-type or 2-step viscous damping force schemes, offer a highly effective solution for earthquake protection of highway bridges. This makes them a viable option for enhancing the seismic resilience of lifeline structures like highway bridges. Filiatrault and Sullivan (2014) emphasize that, despite progress in earthquake field, non-structural components continue to pose a considerable vulnerability, resulting in large losses and operational disruptions. It advocates a widespread method based on seismic activity for non-structural components, through advanced analysis, testing, and evaluation methods to enhance overall building performance. Mohsenian et al. (2023) point out that non-structural components play a vital role in evaluating a structure's overall seismic stability. It goes beyond traditional approaches that often overlook the combined effects and cumulative nature of damage by introducing the block diagram method and performance area concept as more comprehensive tools for seismic reliability analysis. The direct displacement method was recommended by G. Collantes (2022) for analyzing the non-structural elements. Involves allocating a maximum allowable displacement for the non-structural element and using Hooke's law to compute the allowable force. The non-structural components were designed using the direct displacement method for multiple variations of a reinforced concrete building, and the outcomes were compared with force-based design.

Two specific anchoring systems were used to model the seismic movements of 5 different-height reinforced concrete buildings. To sum up, the direct displacement design method is effective than traditional force-based design. Martino Zito et al. (2022) proposed experimental methodologies that are used for seismic qualification. The study discusses and assesses the primary international testing methods for the seismic performance of non-structural elements. Additionally, different methods for non-structural elements are sensitive to acceleration and displacement, and both factors are covered in this paper. For Non-structural elements responsive to acceleration, single-floor dynamic testing is advised, quasi-static tests for those that are displacement sensitive, and multi-floor dynamic tests for both. The author previously found that semi-active variable dampers are useful for lowering seismic responses in torsionally coupled systems after examining the seismic behaviour of single-story asymmetric buildings fitted with them.

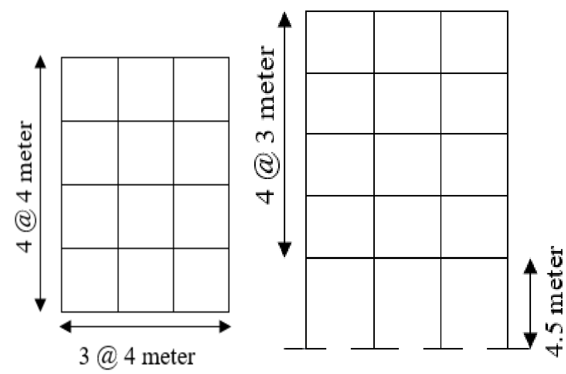
Kazantzi A et al. (2020) show that acceleration demands for non-structural elements whose time periods are matched to primary structure are greatly underestimated by component amplification factors currently used in codes. The data employed in this study were derived from recorded floor motions in US instrumented buildings. Current US/European design codes do not provide an adequate estimation of seismic acceleration demands imposed on non-structural elements. The objective of the article was to examine the sustainability of the most recent non-structural system design provision and propose a robust approach to calculating seismic acceleration demand.

2. Modelling of Structure and Damper

The seismic performance of a five-storied building is investigated through numerical simulations utilizing the MATLAB program. The parameters related to the structure are described in Table 1. The architectural layout and elevation of the structure are illustrated in Figure 1.

Table 1. Structure parameters

Parameter	Value
Plan Dimension	12m x 16m
Typical storey height	3m
Storey height (First floor)	4.5m
Column Section	400 mm x 400 mm
Beam Section	300 mm x 400 mm
Slab thickness	150 mm
Live load	3 kN/m^2
Concrete Grade	M25
Steel Grade	Fe500



(a) (b)

Fig. 1 Five storied structure (a) Plan, and (b) Elevation.

2.1. Modeling of Semi-Active Variable Damper

Structure is equipped with semi-active variable dampers that utilize a 2-step viscous damping force approach. It was formulated employing a Magnetorheological (MR) damper and is engineered to allow for the modulation of the damping coefficient C_d in accordance with the displacement and velocity parameters. Control law articulated as (Ruangrassamee et al. 2001) (Madhekar S. and Jangid R. 2009)

$$C_d \begin{cases} = C_{d1} & \text{When } x_d \dot{x}_d > 0 \\ = C_{d2} & \text{When } x_d \dot{x}_d \leq 0 \end{cases} \quad (1)$$

Here, x_d represents relative displacement and $\dot{x}_d$ denotes relative velocity measured between the two ends of the damper

Structural system displaced from equilibrium condition, damping coefficient is adjusted to a higher magnitude, denoted as C_{d1}, in order to mitigate the dynamic response; conversely, when the system is back towards equilibrium condition, the damping coefficient is decreased to a lesser amount, designated as C_{d2}. Figure 2 shows the mathematical working principle of the 2-step viscous damping force method considered in the damper.

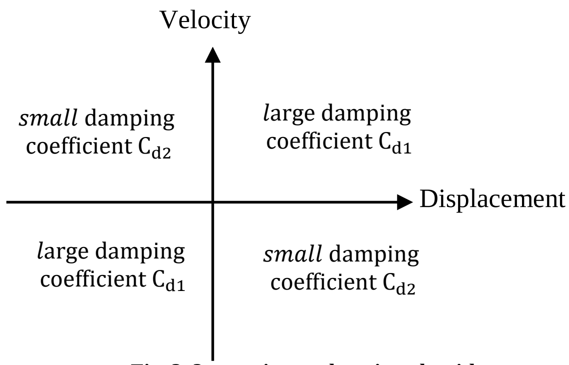


Fig. 2 2-step viscous damping algorithm

Damping force is derived as

$$F_d = C_d \dot{x}_d \tag{2}$$

Here C_d is C_{d1} or C_{d2} as per Equation (1)

2.2. Equation of Motion and Its Solution

Understanding the dynamic behaviour of a structure is crucial for ensuring the safety and stability of the structure. The basic matrix form in the field of structural dynamics is necessary to monitor the performance of the building under motion. This mathematical representation includes the balance of all the forces acting on the structure, which includes inertial forces, damping forces, stiffness forces, ground acceleration, and forces due to control devices.

$$M\ddot{x} + C\dot{x} + Kx = -M\Gamma\ddot{x}_g + \Lambda F_d \tag{3}$$

Where $M\ddot{x}$ represented the inertial force, here M is the mass matrix, $\ddot{x}$ acceleration vector, $C\dot{x}$ represented the damping force, here C damping matrix with velocity vector $\dot{x}$, stiffness forces are given through Kx, here K is the stiffness matrix along with displacement vector x, forces due to seismic acceleration are represented through $M\Gamma\ddot{x}_g$ where the influence coefficient vector is given as Γ with seismic acceleration vector $\ddot{x}_g$, the forces due to control devices are given through ΛF_d where the matrix defining the location of control devices is given through Λ with a vector of control forces F_d.

$$M_{5\,x5} = \begin{bmatrix} m_1 & 0 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 & 0 \\ 0 & 0 & m_3 & 0 & 0 \\ 0 & 0 & 0 & m_4 & 0 \\ 0 & 0 & 0 & 0 & m_5 \end{bmatrix} \tag{4}$$

Similarly, the stiffness matrix as

$$K_{5\,x\,5} = \begin{bmatrix} k_1 + k_2 & -k_2 & 0 & 0 & 0 \\ -k_2 & k_2 + k_3 & -k_3 & 0 & 0 \\ 0 & -k_3 & k_3 + k_4 & -k_4 & 0 \\ 0 & 0 & -k_4 & k_4 + k_5 & -k_5 \\ 0 & 0 & 0 & -k_5 & k_5 \end{bmatrix} \tag{5}$$

Damping matrix C is formulated based on Rayleigh damping, taking into account proportionality with respect to both mass and stiffness, as (Hart & Wong, 2000)

$$C = \alpha M + \beta K \tag{6}$$

In this context, α and β represent the coefficients that are contingent upon the damping ratio associated with 2 distinct modes. For purposes of the current investigation, a damping ratio of 5% is considered for both vibration modes of the system. State space methodology is used to address the governing equations of motion. Formulation involves representing equations in a state space format, where the state vector $z = \{x, \dot{x}\}^T$ are the displacement and velocity vectors. The governing equations of motion are (Lu,LY, 2004)

$$\dot{z} = Az + BF + E\ddot{x}_g \tag{7}$$

$$\text{System matrix A} = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \tag{8}$$

$$\text{Distribution matrix of control forces B} = \begin{bmatrix} 0 \\ -M^{-1}\Lambda \end{bmatrix} \tag{9}$$

$$\text{Distribution matrix of excitation E} = -\begin{bmatrix} 0 \\ \Gamma \end{bmatrix} \tag{10}$$

$$\text{State vector } z = \begin{bmatrix} x \\ \dot{x} \end{bmatrix} \tag{11}$$

Where I expresses the identity matrix, the state-space model is transformed into its discrete-time form by assuming that both the external excitation and the control input remain constant over each time interval. The discrete-time solution is expressed in an incremental form in Equation (12) by using Equations (13) and (14).

$$z_{k+1} = A_d z_k + B_d F_k + E_d \ddot{x}_{gk} \tag{12}$$

$$B_d = A^{-1}(A_d - I)\,B \tag{13}$$

$$E_d = A^{-1}(A_d - I)\,E \tag{14}$$

Step time given as 'k', discrete-time step matrix $A_d = e^{A\delta t}$, δt *is* time interval, discrete-time counterparts B_d, E_d of matrices B, E.

3. Seismic Response of Structure

The seismic behaviour of a five-story building, installed with semi-active viscous dampers utilizing a 2-step viscous damping force mechanism positioned at the centroid of mass for each level, is comprehensively examined through numerical simulations conducted via MATLAB. The natural time period of the building is 0.54 seconds. Various earthquakes, as listed in Table 2, are incorporated into the numerical simulations. An analogous investigation is performed for a secondary system situated at Level 5.

The response parameters of primary interest encompass reductions in both displacement and acceleration for the primary structure as well as the Secondary System (SS).

Structural parameters are specified in accordance with Table 1. Figure 3 illustrates the ground acceleration in conjunction with the responses of the floors.

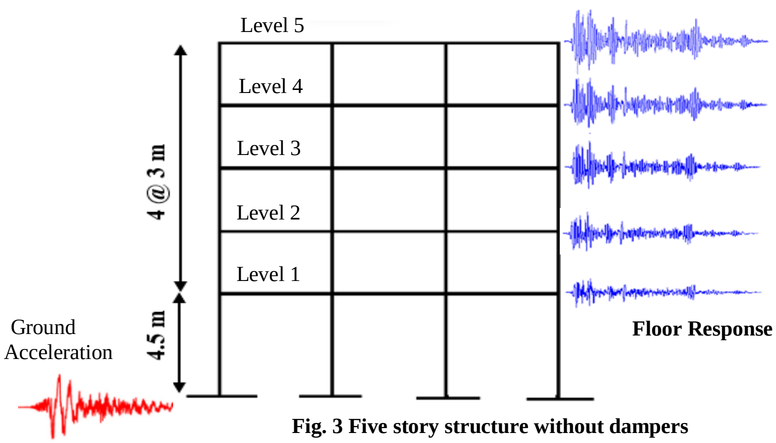


Fig. 3 Five story structure without dampers

The floor response pertains to the manner in which each individual level of the structure responds to the ground acceleration. In the subsequent numerical investigation, semi-active Dampers were integrated into the structure, as illustrated in Figure 4.

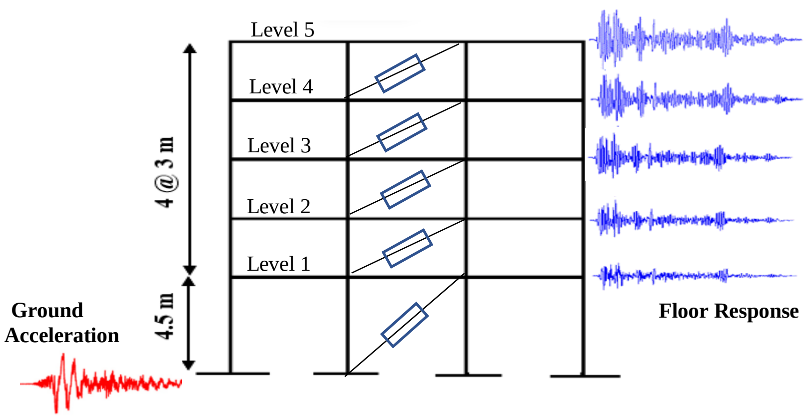


Fig. 4 Five story structure with semi-active variable dampers

Table 2. Earthquake details

Earthquake	Station	Component	Duration (sec)	PGA (*g*)
Imperial Valley, 15th October, 1979	El Centro (Array # 5)	E05230	39.375	0.38
Imperial Valley, 15th October, 1979	El Centro (Array # 7)	E07230	36.865	0.47
Northridge, 17th January, 1994	Newhall	WPI046	24.980	0.42
Landers, 28th June, 1992	Lucerne Valley	LCN260	48.120	0.73
Northridge, 17th January, 1994	Rinaldi	RRS228	19.900	0.87
Northridge, 17th January, 1994	Sylmar	SCE011	54.685	0.85
Loma Prieta, 18th October, 1989	Gilroy – Gavilan Coll	GIL067	39.990	0.36
Kobe, 16th January, 1995	Nishi-Akashi	NIS000	40.950	0.48
Chi-Chi, 20th September, 1999	TCU071	N	89.995	0.65
Duzce, 12th November, 1999	Lamont 531	N	41.490	0.16

3.1. Parametric Study on Semi-Active Variable Dampers Employing a 2 Step Viscous Damping Force Mechanism

In primary structure, a total of five semi-active variable dampers are installed at the centre mass location of each level. 2-step viscous damping mechanism of the damper, higher damping coefficient C_{d1} and lower damping coefficient C_{d2} are considered. The ratio between higher and lower damping coefficients, *R*, is taken as 2. The maximum acceleration and displacement responses are derived under the considered seismic time histories. Utilizing the data from all seismic time histories, the mean values of acceleration and displacement are calculated for all levels and illustrated in Figures 5 and 6. In light of these findings, the optimal value of the large damping coefficient C_{d1} is considered to be 60 x 10^5 N.s/m.

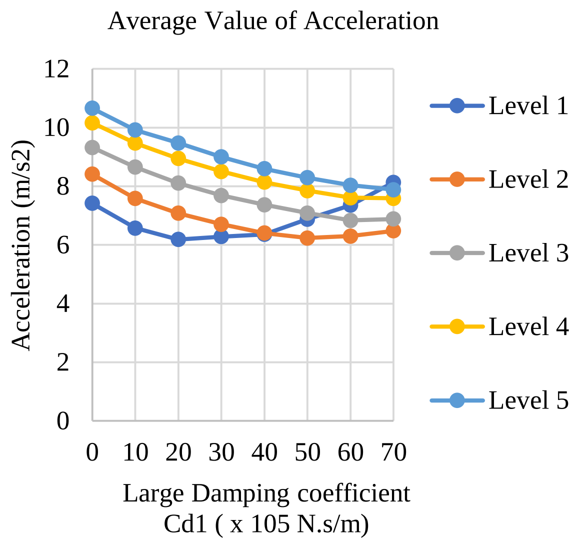


Fig. 5 Effect of Damping coefficient on Acceleration Responses when Semi-active variable dampers are provided in all storeys

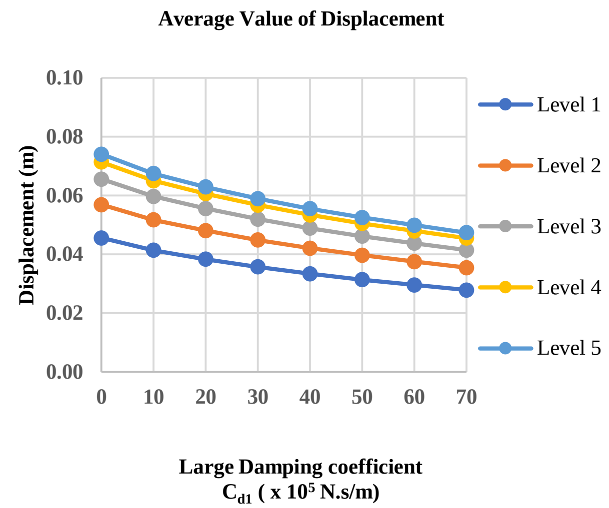


Fig. 6 Effect of Damping coefficient on Displacement Responses when Semi-active variable dampers are provided in all storeys

4. Results and Discussion

Controlled and uncontrolled responses pertaining to acceleration and displacement at level 5 during the Imperial Valley earthquake of 1979 are illustrated in Figure 7, specifically when Semi-Active variable Dampers (SAD) are integrated within the structural framework. Furthermore, the hysteresis loops representing the relationship between Damper force - Velocity, as well as Damper force - Displacement, are depicted in Figure 8, which concurrently elucidates the inherent characteristics of the damper and its capacity for energy dissipation. Comparable responses have been observed for other seismic events considered in this analysis. Table 3 illustrates the displacement and acceleration responses recorded at Level 5 under the considered earthquakes with and without the provision of Semi-Active variable Dampers (SAD).

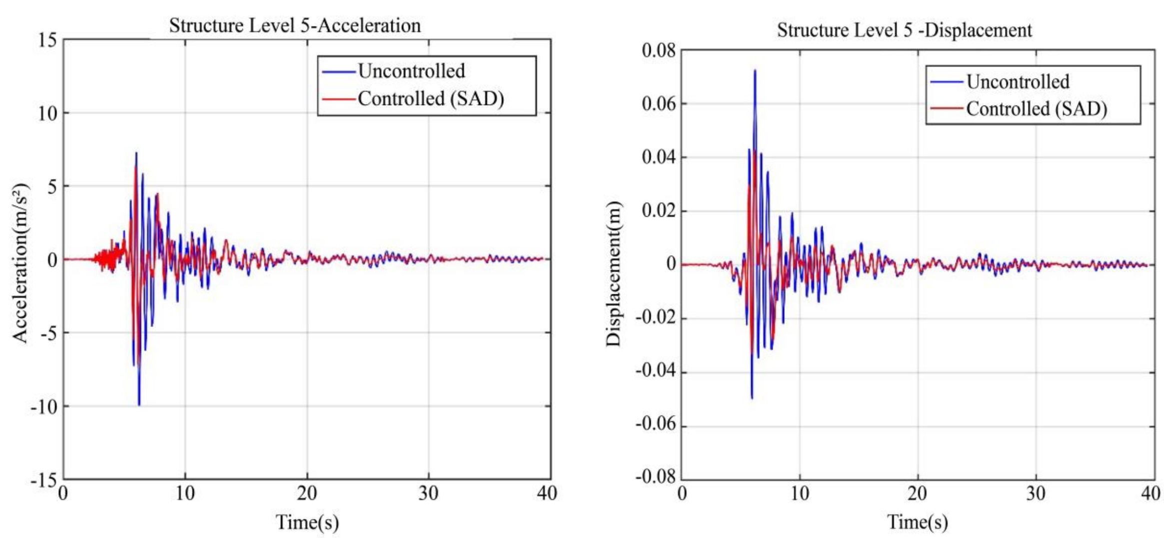


Fig. 7 Time history for controlled and uncontrolled acceleration & displacement responses at Level 5 under Imperial Valley, 1979 earthquake (SAD installed at all storeys)

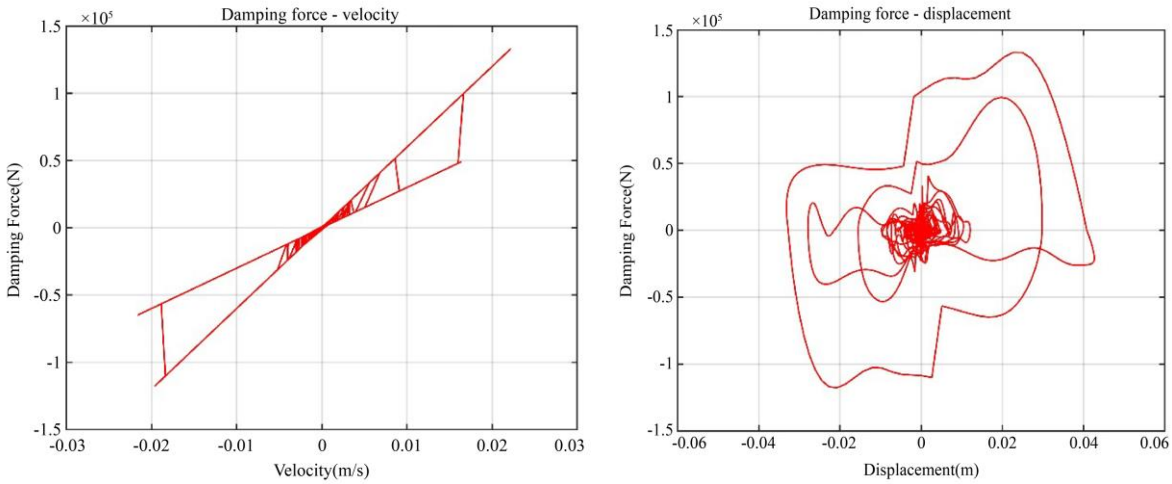


Fig. 8 Hysteresis loops for damping force – velocity & damping force – displacement at level 5 under imperial valley, 1979 earthquake (SAD are installed at all storeys)

Table 3. Maximum Response quantities of Structure at Level 5

Sr. No	Earthquake Name	Station	Uncontrolled Response		With SAD $R = C_{d1}/C_{d2} = 2$	
			Displacement (m)	Acceleration (m/s^2)	Displacement (m)	Acceleration (m/s^2)
1	Imperial Valley, 15th October,1979	El Centro (Array # 5)	0.0726	10.0084	0.0427 (41.19%)	7.1895 (28.17%)
2	Imperial Valley, 15th October,1979	El Centro (Array # 7)	0.0673	8.7003	0.0526 (21.92%)	7.3212 (15.85%)
3	Northridge, 17th January, 1994	Newhall	0.0626	7.8352	0.0448 (28.38%)	6.0085 (23.31%)
4	Landers, 28th June, 1992	Lucerne Valley	0.0395	7.9376	0.0334 (15.47%)	6.2812 (20.87%)
5	Northridge, 17th January, 1994	Rinaldi	0.1402	18.8053	0.1089 (22.29%)	16.0070 (14.88%)
6	Northridge, 17th January, 1994	Sylmar	0.1010	14.7782	0.0722 (28.59%)	12.0271 (18.62%)
7	Loma Prieta, 18th October, 1989	Gilroy – Gavilan Coll	0.0431	6.6198	0.0270 (37.42%)	5.6308 (14.94%)
8	Kobe, 16th January, 1995	Nishi-Akashi	0.1251	18.2020	0.0699 (44.09%)	11.6438 (36.03%)
9	Chi-Chi, 20th September, 1999	TCU071	0.0672	10.3309	0.0360 (46.47%)	5.9603 (42.31%)
10	Duzce, 12th November, 1999	Lamont 531	0.0222	3.3826	0.0117 (47.35)	2.2772 (32.68%)
		Average Reduction (%)			**33.32 %**	**24.77 %**

Note: The Value written in brackets indicates the percentage reduction with respect to the uncontrolled response

Table 3 presents a comparative analysis of the maximum acceleration and displacement of the structure, both with and without the integration of a semi-active variable damper. Additionally, it shows the mean percentage reduction in both acceleration and displacement attributable to the presence of the semi-active variable damper. Specifically, at Level 5, the semi-active variable damper achieves a reduction in average displacement of 33.32% alongside a decrease in acceleration by 24.77%. In conclusion, a semi-active damper significantly reduces displacement and acceleration responses. The effect of the semi-active damper is relatively stable at different level of assessment.

5. Seismic Response of Secondary System (SS) Installed in a Structure

Seismic responses of a Secondary System (SS) installed on Level 5 of a five-story structure, as shown in Figure 9, encompass four distinct time periods of the secondary system (0.5 sec, 1 sec, 1.5 sec, and 2 sec). The secondary system mass is considered to be 100 kg, and its stiffness is adjusted to get the required time period. Structure is subjected to seismic ground motions, seismic response is different at each floor level, and the acceleration measured at that particular floor is used as an input excitation for the secondary system placed at that floor. Time history analysis was conducted to study the response of the secondary system for various time periods. Maximum acceleration and displacement response of SS have been calculated under the given earthquake time histories. Considering the acceleration and displacement response of all the considered earthquakes, average values of acceleration and displacement of the secondary system have been calculated. Semi-active variable dampers have also been considered in the structure and secondary system, and their effectiveness in response reduction can be compared. Within the secondary system, the large damping coefficient C_{d1} has been optimized to 0.08 x 10^5 N.Sec/m, while the ratio between the large and small damping coefficients, R, is established at 2.

5.1. Results of Secondary System

This study examines two cases and compares the results to analyse the seismic behaviour of a secondary system (SS) located on Level 5 under ten distinct earthquake time histories.

Case 1 (a): Building without dampers and secondary system without dampers

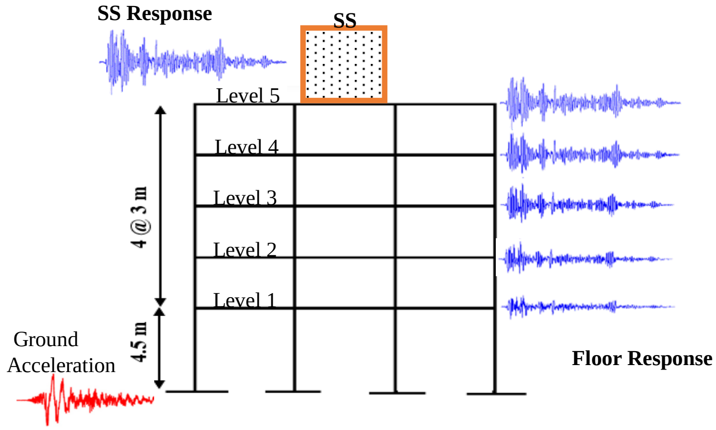


Fig. 9(a) Secondary system installed at level 5 (Case 1(a))

Case:1(b): Building without dampers and a secondary system with a semi-active variable damper

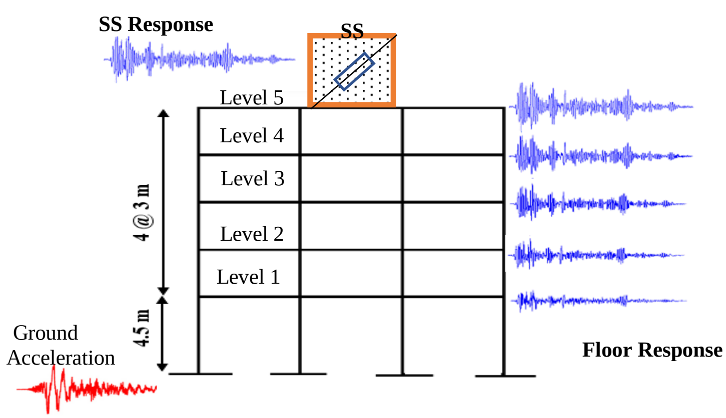


Fig. 9(b) Secondary system with semi-active variable damper, installed at level 5 (Case 1(b))

Case 2 (a): Building with semi-active variable dampers and a secondary system without dampers

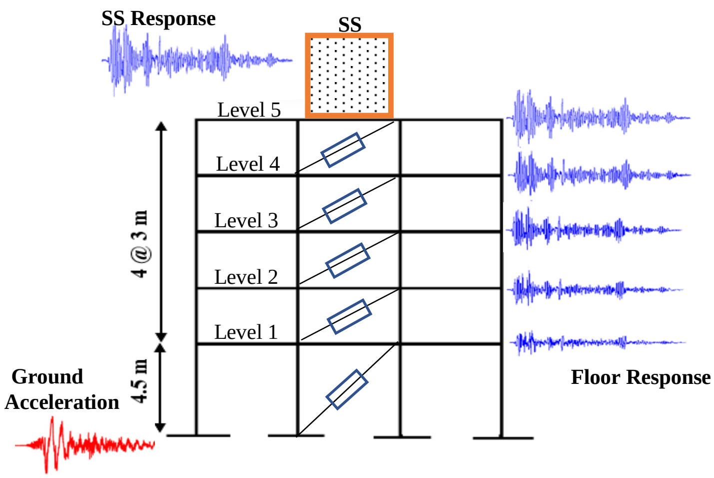


Fig. 10(a) Secondary system installed at level 5 (Case 2(a))

Case 2 (b): Building with semi-active variable dampers and a secondary system with semi-active variable dampers

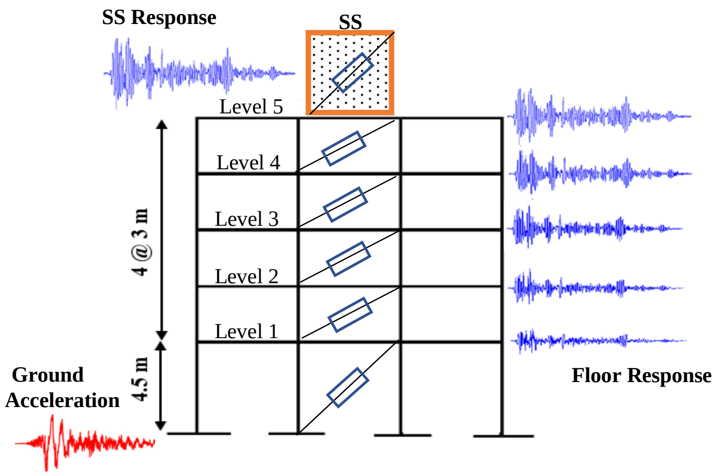


Fig. 10(b) Secondary system with semi-active variable damper installed at level 5 (Case 2(b))

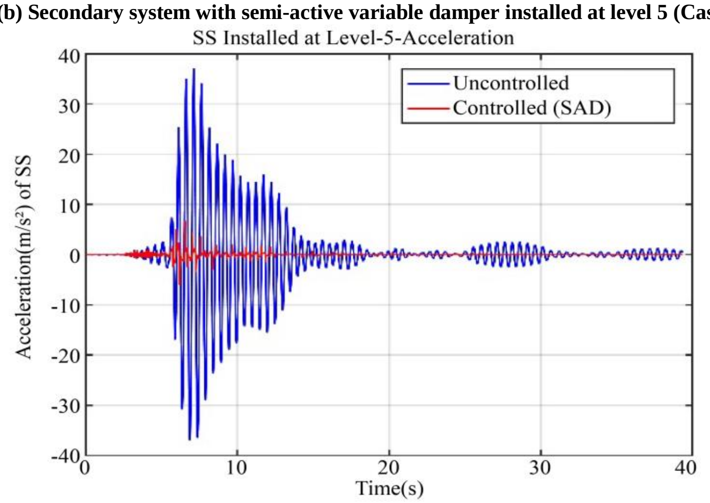


Fig. 11(a) Acceleration responses of the Secondary system have a time period of 0.5 seconds, which is installed at Level 5 under Imperial Valley, 1979 earthquake (semi-active variable damper installed at Secondary system)

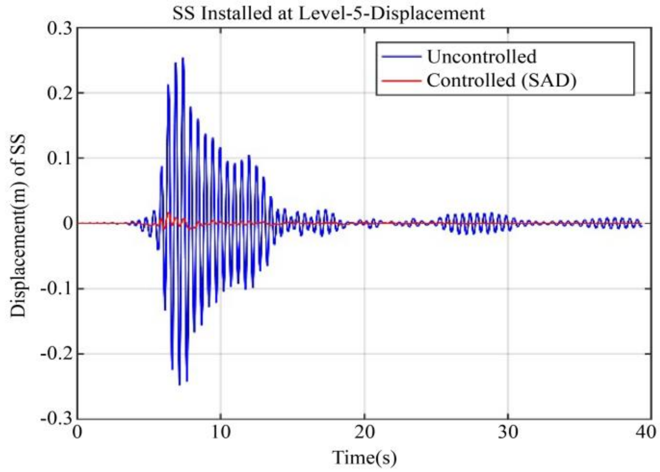


Fig. 11(b) Displacement responses of the secondary system have a time period of 0.5 seconds, which is installed at Level 5 under Imperial Valley, 1979 earthquake (semi-active variable damper installed at secondary system)

The controlled and uncontrolled responses of acceleration and displacement of the Secondary System (SS), which has a time period of 0.5 seconds and is situated at level 5, are illustrated in Figure 11(a) and (b), corresponding to the Imperial Valley earthquake of 1979, when a semi-active variable damper was incorporated within the Secondary System (SS).

5.2. Comparison of Seismic Responses of Case 1 (a) & (b)

Table 4. Average acceleration value (m/s^2) (Case 1)

Time period of SS	Case 1 (a)	Case 1 (b)	% Reduction w.r.t. Case 1(a)
0.5 sec	45.685	8.505	81.38%
1 sec	18.332	8.546	53.38%
1.5 sec	14.417	8.561	40.62%
2 sec	12.007	8.560	28.70%

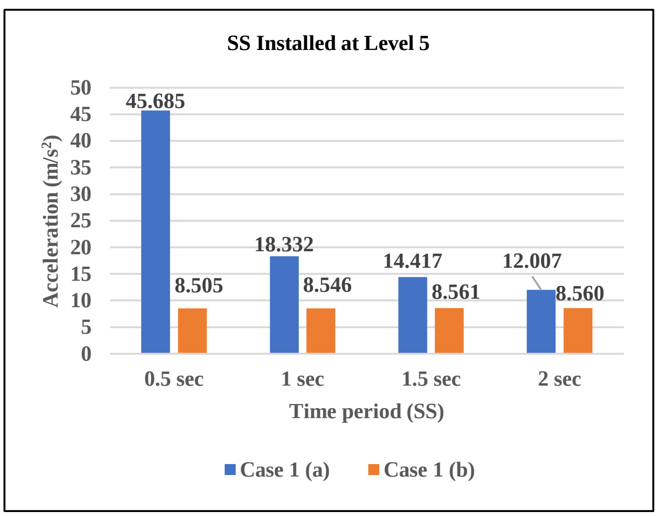


Fig. 12 Acceleration of secondary system (Case 1 (a) & (b))

Table 5. Average displacement Value (m)

Time period of SS	Case 1 (a)	Case 1 (b)	% Reduction w.r.t. Case 1(a)
0.5 sec	0.306	0.016	94.71%
1 sec	0.277	0.018	93.62%
1.5 sec	0.332	0.018	94.58%
2 sec	0.371	0.018	95.13%

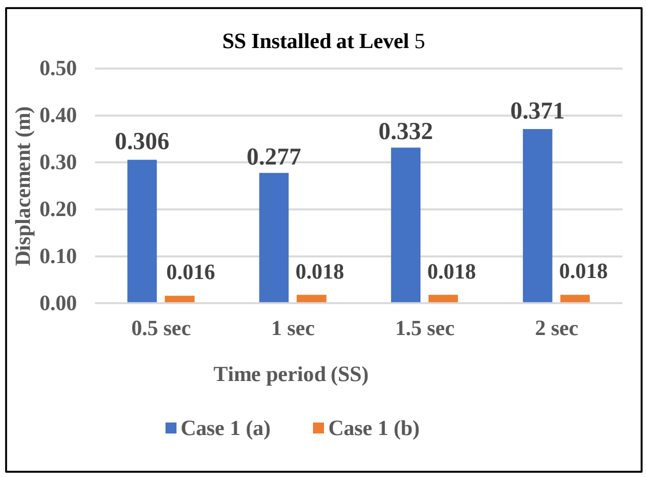


Fig. 13 Displacement of secondary system (Case 1 (a) & (b))

Figures 12 and 13, as well as Tables 4 and 5, represent the seismic responses of a secondary system having various time periods. The percentage reduction in acceleration is significant: 81.38% for 0.5 seconds, 53.38% for 1 second, 40.62% for 1.5 seconds, and 28.70% for 2 seconds, and the percentage reduction in displacement is also significant: 94.71% for 0.5 seconds, 93.62% for 1 second, 94.58% for 1.5 seconds, and 95.13% for 2 seconds. This result shows that the semi-active variable damper is highly effective in mitigating seismic responses of the secondary system.

5.3. Comparison of Seismic Responses of Case 2 (a) and (b)

Table 6. Average acceleration value (m/s^2) (Case 2)

Time period of SS	Case 2 (a)	Case 2 (b)	% Reduction w.r.t. Case 2(a)
0.5 sec	23.138	6.185	73.27%
1 sec	13.941	6.574	52.85%
1.5 sec	10.836	6.687	38.29%
2 sec	9.158	6.657	27.31%

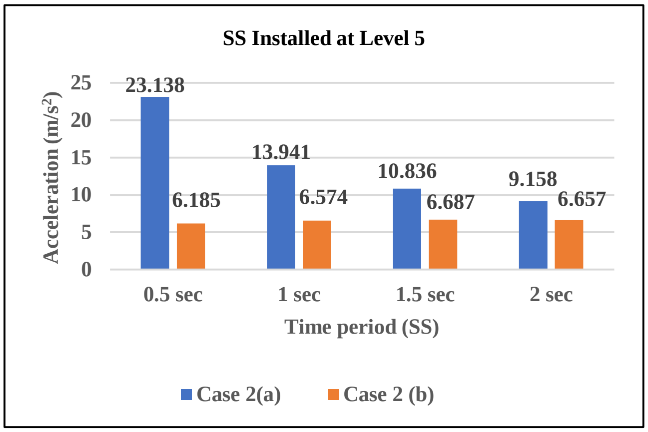


Fig. 14 Acceleration of secondary system (case 2(a) and (b))

Table 7. Average displacement value (m)

Time period of SS	Case 2 (a)	Case 2 (b)	% Reduction w.r.t. Case 2(a)
0.5 sec	0.148	0.012	91.86%
1 sec	0.245	0.014	94.34%
1.5 sec	0.300	0.015	95.12%
2 sec	0.353	0.015	95.76%

Figures 14 and 15, as well as Tables 6 and 7, represent the seismic responses of a secondary system having various time periods. The percentage reduction in acceleration is significant: 73.27% for 0.5 seconds, 52.85% for 1 second, 38.29% for 1.5 seconds, and 27.31% for 2 seconds, and the percentage reduction in displacement is also significant: 91.86% for 0.5 seconds, 94.34% for 1 second, 95.12% for 1.5 seconds, and 95.76% for 2 seconds. This result shows that the semi-active variable damper proves that it is competent in mitigating the seismic forces of the secondary system.

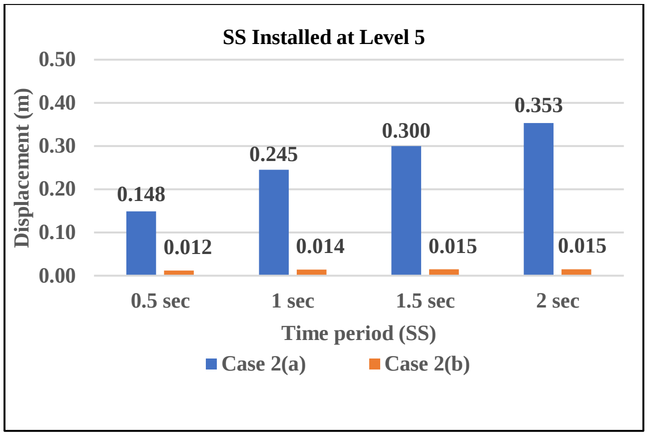


Fig. 15 Displacement of secondary system (case 2(a) and (b))

6. Conclusion

Seismic responses of a secondary system, which is integrated within a five-story structure equipped with a semi-active variable damper employing a 2-step viscous damping force mechanism, were meticulously examined under the influence of ten distinct earthquake excitations.

The responses are evaluated through the deliberate positioning of semi-active variable dampers within the structure and secondary system to investigate their efficiency in mitigating the responses of both the primary structure and secondary system. Based on observed trends in the current study, the subsequent conclusions can be drawn:

1. Semi-active variable dampers utilizing a dual-phase viscous damping force mechanism considerably reduced the seismic responses of both the primary and secondary systems.
2. The effectiveness of semi-active variable dampers is affected by both characteristics of the secondary system and the nature of the seismic excitation.
3. It is found that the displacement and acceleration of the secondary system reduce significantly for all values of the time period of the secondary system.
4. For the cases of secondary systems with a damper, with the increase in time period of the secondary system, the percentage reduction in acceleration decreases, as it remains unaffected for the displacement response of the secondary system.

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