Optimizing the Placement of Semi-Active Hydraulic Dampers in Buildings Using FEA

S. Abdel Salam, Osman Shallan , Yasser Ibrahim and Ebtsam Fathy

1 Department of Structural Engineering, Zagazig University, Sharkia, Egypt
s.salam@link.net. **Osmacon2@yahoo.com**. **yibrahim@vt.edu** **efsadik@gmail.com**

Abstract: A new idea for the number and placement of semi-active hydraulic dampers (SHDs) achieving high performance is developed in this paper. This proposed method depends on using a few number of semi-active control devices distributed along the building's height instead of the uniform distribution of these devices in all stories (traditional placement). Also, a design methodology for this proposed method is demonstrated. Two different strategies for structural designers are introduced; to obtain overall reduction in structural responses (strategy (A)) or to have more reduction in floor displacements with smaller reduction in total base shear (strategy (B)). The efficiency of proposed method, is compared firstly with the traditional placement of SHDs on low, medium, and high rise buildings. Secondly, it is investigated under different earthquake intensities using material nonlinearity. Several semi-actively controlled structures were considered in this paper starting gradually from three to sixty-story buildings. These buildings are modeled and analyzed using the finite element program ANSYS. Semi-active control forces are derived according to the Linear Quadratic Regulator (LQR) algorithm. However, to get control force for *Proposed New Placement of SHDs* some adoptions are done on inputs of LQR algorithm to be appropriated for this method. The results demonstrated that, compared to the traditional placement of SHDs, the new proposed arrangement of SHDs provides better structural performance in addition to being less costly

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1. Introduction

Semi-active control has received increasing attention, because it has high reliability and the adaptability of active control without requiring the associated large power source. Several numerical and experimental studies were done to examine the efficiency of semi-active control on seismic performance of structures. These studies showed the capability of semi-active control in achieving performance levels nearly the same as comparable active control with few of the detractions (Kurata *et al.,* 1999, Aldemir and Bakioglu, 2000, Fukukita *et al,* 2004, Seth *et al.,* 2004, Reynolds and Christenson, 2006, Wang *et al.,* 2007, and Chen and Xu; 2008). Most of the previous researches investigated the efficiency of semi-active control devices on low-rise structures from one to ten-story structures with uniform distribution of control devices over the stories of the structure. It was observed from the results of these studies that the efficiency of the semi-active control devices decreased slightly as the number of stories increased (Zhang and Iwan, 2002 and Lynch and Law, 2004). In order to investigate this observation, the effect of traditional placement of semi-active hydraulic dampers (SHDs) in all floors on the performance of one, three, seven, fifteen, thirty, and sixty-story structures was examined by (Abdel Salam *et al.,* 2010). They indicated that the traditional placement of SHDs gives superior efficiency in low rise structures while this efficiency decreases in higher structures. (Abdel Salam *et al.,* 2010) attributed this loss in the efficiency to that the control forces decrease in most cases (according to mode shape) with increasing the number of successive semi-active control devices. This is occurs due to at each floor in traditional placement of SHDs there are two forces from semi-active control system. The first is direct force from SHD at this floor. The second is the force resulting from chevron brace which is equal to the next control force but works in the opposite direction. Therefore, the direct control force from SHD at any floor must be greater than the next control force to work in its actual direction. In this way, they found that the maximum control forces occur in most cases in the first stories. On the other hand the control forces decrease in higher floors while, at these stories the responses needed to reduce is larger.

Thus, this paper concerns to confirm the latter conclusion and seek for more enhancing in performance of high-rise structures. The first part of this paper investigates the effect of using just few numbers of SHDs, distributed on the whole structure on several multi-story structures under three earthquake records. From the obtained results, a new proposed placement strategy of SHDs, along the structures with its design procedures is developed. The efficiency of proposed method, is compared firstly with the traditional placement of SHDs on low, medium, and high rise buildings. Secondly, it is investigated under different earthquake intensities using material nonlinearity. The semi-actively controlled structures are modeled and analyzed in this paper using the finite element program ANSYS version 10.0 (2005). The Linear Quadratic Regulator (LQR) Optimal Control Algorithm is undertaken with a wireless sensor network to implement a real-time closed-loop control. The MATLAB control toolbox (2002) is used to get the state feedback gain matrix that is used by ANSYS program for modeling SHDs using the control elements (Combin37).

Control Strategy

The linear quadratic regulator (LQR) algorithm is used in this study. It is based on the minimization of a quadratic function whose objective is to maintain the desired system state while minimizing the control effort. This quadratic function is known as performance index, J, which is defined as:

$$J = \int_0^\infty [z(t)^T Q z(t) + u(t)^T R\, u(t)]dt \quad [1]$$

where z(t) is the state vector, Q is a real symmetric positive semi-definite matrix containing the weighting factors for structural performance measures. R is a real symmetric positive definite matrix containing weighting factors relating to the cost of control effort. The results of minimization of the previous quadratic function is the state feedback gain matrix, G, that when multiplied by the state of the system yields the optimal control force vector, u(t) as the follow:

$$u(t) = -[G]\, z(t) \quad [2]$$

The control forces are calculated in this research depending on the equal weighting of both relative displacements and velocities in the buildings, where the matrices Q and R are assumed as the follow for the traditional placement of SHDs in all stories:

$$[R] = RI_{r\times r}\ , \quad [Q] = I_{2n\times 2n} \quad [3]$$

where, *I* is a unit diagonal matrix, *R* is a parameter which keeps the damping forces within the dampers' practical capacity, n number of degree-of-freedom of structure, and r number of SHDs.

Modeling And Analysis

Several semi-actively controlled structures were considered in this paper starting gradually from three-story to sixty-story buildings. The structures are idealized as two dimensional reinforced concrete frames, as shown in Fig. (1-a). The Rayleigh damping assumption is adopted to construct the structural damping matrix. The damping ratios in the first two modes of vibration of the buildings are assumed to be 5% of the critical. The semi-active control system designed by Seth *et al.* (2004) is employed in this research. It combines semi-active hydraulic dampers (Kurata *et al.,* 1999) installed between the chevron brace and rigid floor diaphragm and wireless sensor network to implement a real-time closed-loop control. This network contains wireless active sensing units designated to serve as a controller for each SHD and additional wireless sensors to measure the displacement and velocity response as shown in Fig. (1-b). The maximum actuation force that can be generated by the SHD actuator equals 1,000 kN. Control element (COMBIN37) in ANSYS is used to simulate the chosen semi-active control system as described in detailed in (Abdel Salam *et al.,* 2010).

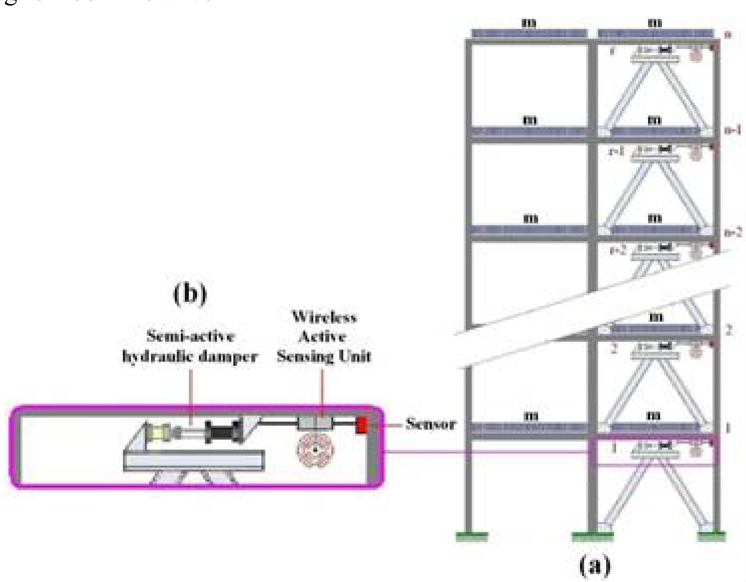

Fig. (1) (a) Traditional placement of SHDs and, (b) semi-active control system

Proposed New Placement Of SHDs

As explained before, (Abdel Salam *et al.,* 2010) found that, the efficiency of traditional placement of SHDs decreases with increasing the control devices along the buildings. Thus, the idea of the suggested placement of semi-active control in this paper depends on using few numbers of SHDs and distributing them along the building's height through chevron braces as shown in Figure (2). This figure shows some of the suggested placements for SHDs examined in this paper. In first suggestion, the building is controlled using only 2 SHDs distributed along the whole building. The chevron brace is not placed as in traditional case of control with SHDs, shown in Figure (1), it spans horizontally all bays which they are two bays in the investigated planner frames to reduce the application angle of control forces on this brace. Vertically, bracing is placed between N-stories, where N is the number of stories suggested to put SHD at their end floor. To construct this bracing system, it is suggested to be a truss system to overcome in plane buckling. For out of plane buckling, it is suggested to support these trusses horizontally by series of link members at different floor levels. In the next suggestion cases 1SHD is increased to be 3 SHDs, then 4SHDs etc. On that way, several suggestions are proposed.

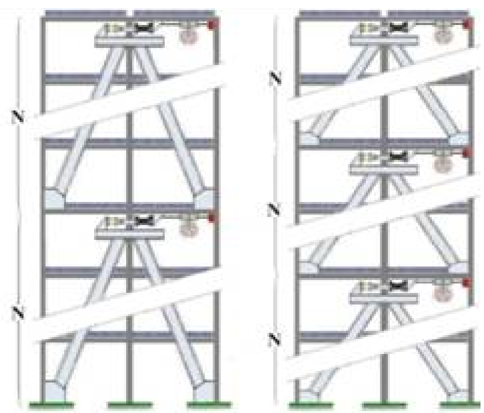

Fig. (2) Examples of different suggested placements

Adapted Inputs Appropriated For This Idea to LQR Algorithm

To apply this suggested idea some adaption are done on the inputs of LQR algorithm to get control forces at suggested floor only depending on the relative responses between these floors not between all floors as traditional case. For achieving the above requirements, the degrees of freedom of the buildings are assumed to be at the suggested floors only. In this case the adapted number of degrees of freedom (n_a) is being equal the number suggested number of SHDs (r) used to control the building's responses equation [4].

$$n_a = r \quad [4]$$

This assumption is made only to get state feedback gain matrix formed control forces at the suggested floors using MATLAB control toolbox. However, the building is modeled and analyzed in ANSYS program with its actual DOFs, number of stories. Consequently the weighting matrices Q and R are assumed as the follow:

$$[R] = RI_{r\times r}\ , \quad [Q] = I_{2n_a\times 2n_a} \quad [5]$$

Effect Of Different Suggested Placement On Several Multi-Story Structures

This section describes and investigates several suggestions for the numbers and placement of SHDs on five reinforced concrete plane frames have three, seven, fifteen, thirty, and sixty stories with fundamental time periods 0.54, 0.57, 0.88, 2.27, 6.2 sec, respectively Each story has the same mass, which equals 210 kN. sec^2/m and the same story height of 3.0 m. Table (1) shows the suggested cases examined for each building. Three different earthquakes are used to confirm the obtained results described in Table (2). The original time histories of these three seismic records are normalized to have the same peak ground acceleration of .15g. The assumptions used in this investigation are: 1-The beams are rigid to simulate the buildings as shear building; 2-the mass is lumped in each floor; 3- the material has linear elastic behavior; and 4- Perfect communications between controllers.

Table (1) Different suggested placements in considered buildings.

	No. of SHDs suggested to perform structural control				
Applied to	**First suggestion**	**Second suggestion**	**Third suggestion**	**Fourth suggestion**	**Fifth suggestion**
3-story building	1	2	3	—	—
7-story building	1	2	3	7	—
15-story building	1	2	3	15	—
30-story building	1	2	3	4	30
60-story building	2	3	4	5	60

Table (2) Properties of considered earthquakes

Earthquake	**Peak acceleration**	**Duration time (sec.)**	**Normalized peak acceleration**
El Centro earthquake	0.348 g	53.72	0.15 g
Kern County earthquake	0.155 g	53.58	0.15 g
Loma Prieta earthquake	0.158 g	38.98	0.15 g

It is found that, the results from the three different earthquakes are very close and give approximately the same trend for every corresponding placement in each building. Thus, in this section the main results for the seven, fifteen, thirty, and sixty-story building under El Centro earthquake only are illustrated. Figure (3) shows the effect of different suggested placements of SHDs on reducing top displacement.

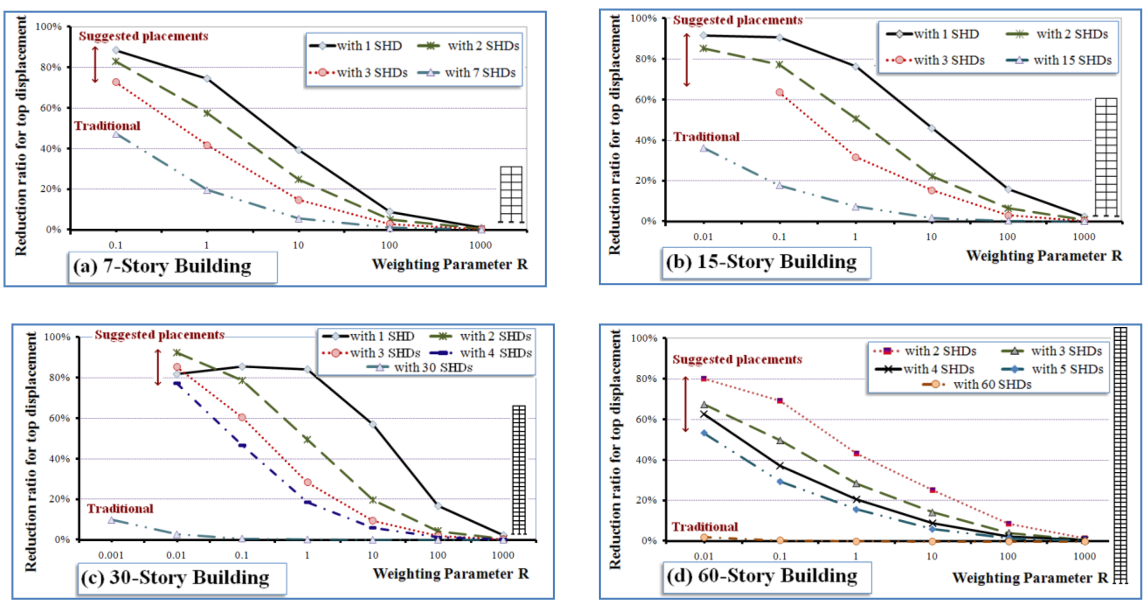

Fig.(3) Effect of different placements of SHDs on reducing top displacement under El Centro earthquake.

This figure indicates that the efficiency of semi-active control system in reducing lateral displacement increases as the number of SHDs decreases. This result confirms the conclusion obtained by (Abdel Salam *et al.,* 2010). As a result, the suggested cases using just few numbers of SHDs give high redaction ratios for lateral top displacement, while traditional placement gives the lowest case in reducing lateral displacement. Table (3) shows the suggested cases, which achieve the best and the lowest reduction in lateral top displacement. This table indicates that, using just 1 SHD in low and medium-rise buildings and 2 SHDs in high-rise buildings leads to large reduction in lateral displacement reaches moreover 80% of uncontrolled case. On the contrary, using 60 SHDs in 60-story building leads to insignificant reduction reaches 2% of uncontrolled case. It is found also, that using just 1 SHD in high-rise building doesn't achieve the best reduction in lateral top displacement. This occurs due to that at very small weighting parameter R the top displacement decreases largely more than the other cases but at the same time, the peak displacement is becoming at the middle of the building not at top. This problem disappears if 2 SHDs used at least to control the buildings.

Table (3) Comparison between the best and lowest placements of SHDs in reducing top displacement for the considered buildings

For Top displ. reduction%	*The best case*		*The lowest case*	
	No. of SHDs	**Reduction ratio**	**No. of SHDs**	**Reduction ratio**
7-story building	1 SHD	88%	7 SHDs	47%
15-story building	1 SHD	92%	15 SHDs	36%
30-story building	2 SHDs	85%	30 SHDs	10%
60-story building	2 SHDs	80%	60 SHDs	2%

Moreover, it is found that the best efficiency for suggestion cases with just few numbers of SHDs occurs in most cases in the range of weighting parameter R between 10 to 0.1(i.e. at moderated R not at very small R as traditional case). This occurs due to at very small R large control force occurs that reduces lateral displacement largely but decreases the enhancements in shear force and base shear. The problem now is how to chose the required few number of SHDs for each building, where it is found that the cases achieve the best reduction in lateral displacement are not the best cases for other responses especially base shear and vice versa. Thus, to choose the best one in achieving overall reduction in structural responses, the average reduction ratios for all responses are determined. The best average reduction ratio for all responses occurs at the suggested placements with 2 SHDs, 2 SHDs, 3 SHDs, and 4 SHDs for seven, fifteen, thirty, and sixty-story buildings, respectively. It is found successive increase in the few numbers of SHDs, needed for each building, compatible with the increasing in the height of the building and the number of stories. This succession can be used to make a relation between the number of needed SHDs and number of stories of the buildings by making a correlation for the obtained results with a straight line as shown in Figure (4).The relation obtained from the correlation of the results can be introduced in the following equation:

$$r \approx \frac{No.of\ floors}{30} + 1.7 \qquad [6]$$

where, r is the number of semi-active hydraulic dampers achieves the best average reduction ratio for all responses

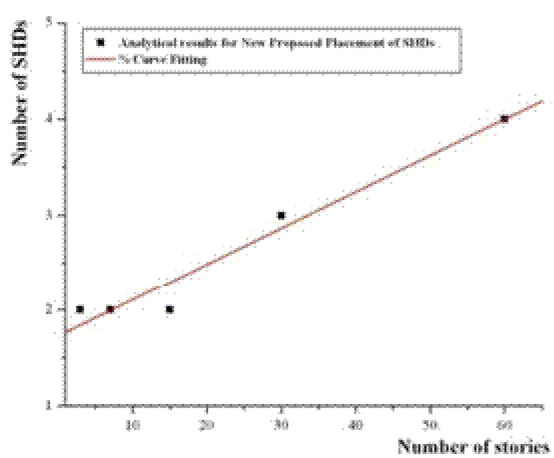

Fig. (4) Relation Between numbers of SHDs needed to achieve best average reduction in all responses for new proposed method and number of stories

Another observation obtained from this investigation that the case with less 1SHD than the case which achieves the best average reduction in all responses gives always better displacement reduction with less base shear reduction. Whereas, the case with more 1SHD gives always less displacement reduction but with more base shear reduction. This can be described by the following equation:

$$r \approx \frac{No.of\ floors}{30} + 0.7 \geq 2 \qquad [7]$$

Design Method for Proposed New Placement Of SHDs

Based on the good results obtained from previous investigation, new method for placement of a few number of SHDs along the building's height and its design methodology is proposed in this research namely *Proposed New Placement of SHDs*. The design aims to select the least number of SHDs that provides large reduction in building's responses and the associated weighting parameters achieve this aim. To meet various requirements for structural performance, this design method offers two different strategies for structural designers; to obtain overall reduction in structural response (strategy (A)) or to have more reduction in floor displacement with smaller reduction in total base shear (strategy (B)). These strategies are illustrated in Table (4).

Comparison between the Performance of Buildings Designed According Strategy (A), and the Traditional Case

The impact of *Proposed New Placement of SHDs,* according to type (A) of design methodology, on buildings responses is investigated in this section. Figure (5) shows maximum absolute interstory drift along the 7, 15, 30, and 60-story buildings for cases without control, with traditional placement of semi-active dampers and with the *Proposed New Placement of SHDs* under El Centro earthquake. It is found that, The *Proposed New Placement of SHDs* gives the best performance in all buildings with large differences than both uniform damper distributions in all stories (traditional case) and the initial design without SHDs. Moreover this high efficiency of *Proposed New Placement of SHDs* seems stable for all building's height. While efficiency of traditional placement of SHDs decreases with increasing height of the buildings to be insignificant in high rise buildings.

Table (4) Design table for the Proposed New Placement of SHDs

<table>
<tr><th>*Strategies of design for*
Proposed New Placement of SHDs</th><th>Applicable for</th><th>No. of SHDs (r)</th><th colspan="2">Designed weighting matrices for SHDs (R, Q)</th></tr>
<tr><td rowspan="3">*Strategy (A)*
For overall reduction in structural responses</td><td>Low-rise buildings</td><td rowspan="3">$r \approx \frac{\text{No. of floors}}{30} + 1.7$</td><td colspan="2" rowspan="3">$Q = I_{2na*2na}$
$R = RI_{r*r}$
$R = 10^{-m}$
The designed range for m</td></tr>
<tr><td>Medium-rise buildings</td></tr>
<tr><td>High-rise buildings</td></tr>
<tr><td rowspan="2">*Strategy (B)*
For more displacement reduction</td><td></td><td rowspan="2">$r \approx \frac{\text{No. of floors}}{30} + 0.7 \geq 2$</td><td>(*ton, m, sec.*) units</td><td>(*kN, mm, sec.*) units</td></tr>
<tr><td>High-rise buildings</td><td>$3 \leq m \leq 5$</td><td>$0 \leq m \leq 2$</td></tr>
</table>

where,

n_a is the no. of adapted DOFs for inputs of LQR algorithm which $n_a = r$.

I is the 2n*2n unit diagonal matrix.

m is the parameters which achieves the best response reductions and keeps the damping forces within the dampers' practical capacity

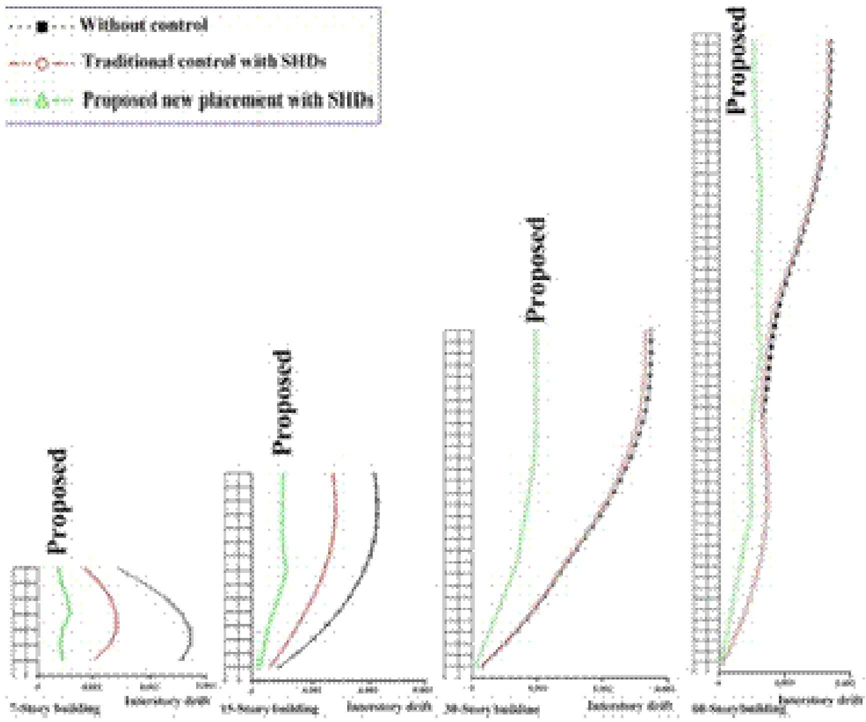

Fig. (5) Maximum interstory drift for different multi-story buildings subjected to El Centro earthquake.

Effect Of Earthquake Intensity On Proposed New Placement Of SHDs Method Including Material Nonlinearity

This section examines the efficiency of the *Proposed New Placement of SHDs* method on fifteen-story building under different intensities of ground motions to assess the validity of this proposed method under severe earthquakes. Moreover, the model of building used in this investigation has more imitation to the actual buildings. Whereas, the beams are simulated using its actual design dimensions and the mass is distributed along the length of the beams while elasto-plastic nonlinear material model is used to represent building damage. Two methods are used to make semi-active control for this building, the first by using traditional method where the semi-active dampers are distributed uniformly in all stories i.e 15 SHDs are used. The second method is *Proposed New Placement of SHDs*, where strategy (A) of this method is used because this building is considered medium-rise building. According to strategy (A) of design method, two SHDs, active sensing units, and wireless sensors are used along the whole building. The weighting matrices R and Q used for traditional case are $0.07*I_{15*15}$ and I_{30*30}, respectively, which, achieve the best performance in that case. For the *Proposed New Placement of SHDs* method the weighting matrices R and Q are I_{2*2} and I_{4*4}, respectively.

Responses of Building under Different Intensities of El Centro Earthquake

For each case of nonlinear fifteen-story building, whether uncontrolled case, controlled with traditional case of SHDs or controlled case with *Proposed New Placement of SHDs* method, the building is analyzed under different intensities of El Centro earthquake. These intensities equal 0.1 g, 0.15 g, 0.2 g, 0.25 g, 0.3 g, and 0.35 g. Figure (6) shows the profiles of maximum absolute interstory drift along fifteen-story building for uncontrolled case, traditional case of control with SHDs, and controlled case with *Proposed New Placement of SHDs* method. The effectiveness of semi-active control using *Proposed New Placement of SHDs* method is clearly demonstrated in this figure. Whereas, the proposed placement with only 2 SHDs not only gives the best reduction in interstory drift with large differences more than the reduction given by traditional case of control but also, prevents collapses of the building which occurs in uncontrolled and traditional case of control under severe earthquakes.

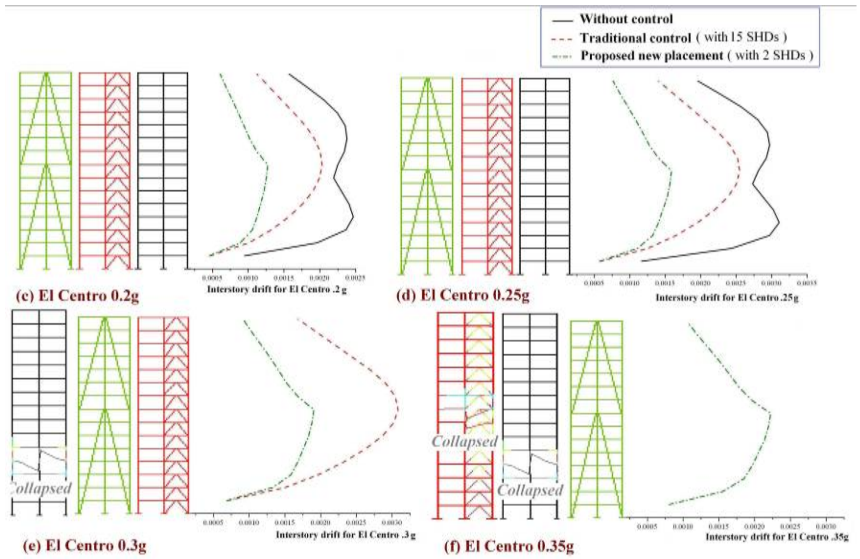

Fig. (6) Maximum interstory drift along 15-story building under different intensities of El Centro earthquake

Conclusions

Many conclusions are derived from this research, which can be summarized as follows:

1- Using few numbers of SHDs in structures distributed along the height as proposed in this research yields to better enhancements in structural response more than the traditional placement.

2- A design methodology for this proposed placement is demonstrated using simple equations which relate the number of SHDs needed in this proposed method and the number of stories. Two different strategies for structural designers are introduced; *strategy A* to obtain overall reduction in structural responses and *strategy B* to have more reduction in floor displacements with smaller reduction in total base shear.

3- The *Proposed New Placement of SHDs* method under El Centro earthquake with higher intensities not only gave the best reduction in responses but also prevented structural collapse, which occurred in uncontrolled and traditional case of control with SHDs.

4- In addition to its high efficiency, the *Proposed New Placement of SHDs* method is considered cost-effective method and more convenient in dampers installation, communication, and maintenance than traditional placement of SHDs.

5- Before applying this method in real applications, more analyses under several earthquakes with different intensities are needed. Also, an experimental work is recommended to investigate the behavior of braces in their new configuration and to check their in-plane and out-of-plane buckling.

Corresponding author
Yasser Ibrahim
Department of Structural Engineering, Zagazig University, Sharkia, Egypt
yibrahim@vt.edu

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