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Complete decentralized displacement control algorithm

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Abstract. Control systems have been greatly studied in recent years and can be classified as: passive, active, semi-active or hybrid systems. Most forms of control systems have been applied in a centralized manner where all the information is sent to a central node where control the algorithm is then calculated. One of the possible problems of centralized control is the difficulty to scale its application. In this paper, a completely decentralized control algorithm is analytically implemented. The algorithm considers that each of the control systems makes the best decision based solely on the information collected at its location. Semi-active control is used in preference to active control because it has minimal energy consumption, little to no possibility of destabilization, a reduction in the possibility of data saturation, and a reduction in the response time in comparison to centralized control.

Keywords: control; passive; active; semi-active; decentralized

1. Introduction

Several important cities are constructed near seismic areas located on the Ring of Fire. The seismic activity that occurs in such places could incur the loss of human lives and detrimental economic losses due to structural damage. Vibrations produced by earthquakes or strong winds can be controlled through structural modification (such as changing the mass, stiffness, damping, or structural configuration), or including passive or active devices. A possible solution to reduce damage is to limit the displacement of the structure. This can be achieved using a more robust design or implementing control devices. The first option usually results in a more expensive structure due the increase in area sections and therefore material costs. The second option, using control devices, has been used mainly in countries like Japan, USA, and China. Structural control is defined as a mechanical system installed on a structure to reduce structural vibrations during external shocks, thus providing greater safety and building lifetime (Lynch 2002). These mechanical systems can be applied in different forms such as: active, passive, hybrid and semi-active. Housner et al (1997) presents an extensive description of such systems and types of devices. Semi-active control will be used in this paper. This control form requires a small amount of energy to operate when compared with active control. Also, since semi-active control does not add mechanical energy to the structural system, these devices cannot destabilize the structure.

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One of the problems with the implementation of control is the requirement that all of the sensors in the structure be connected to a central node. This centralized scheme allows for a complete solution of the control algorithm. However, the drawback of this methodology is the high cost of installation and therefore its scalability is impractical. Decentralized paradigms offer a scalable solution. The cost of the decentralization is paid in the performance of the control system.

In previous work regarding decentralized schemes, Lynch (2002) presents two decentralized control methodologies: market based control (MBC) and energy market-based control (EMBC). These control algorithms were inspired by the interaction of free-market buyers and sellers that lead to an optimal control solution. A 20-story structure was selected as an illustrative example to compare the performance of the MBC, EMBC, and a centralized linear quadratic regulation (LQR) approaches.

Loh and Chang (2008) present smart control strategies for active or semi-active devices under seismic excitations using the concept of a decentralized control algorithm. This algorithm control is based on the H2 control theory that uses accelerometer feedback control. The authors explore five different techniques: (a) partially decentralized control, (b) fully centralized control, (c) half centralized control, (d) fully decentralized control, (e) partially decentralized control (coupled and uncoupled). The results for a 20-story structure are presented.

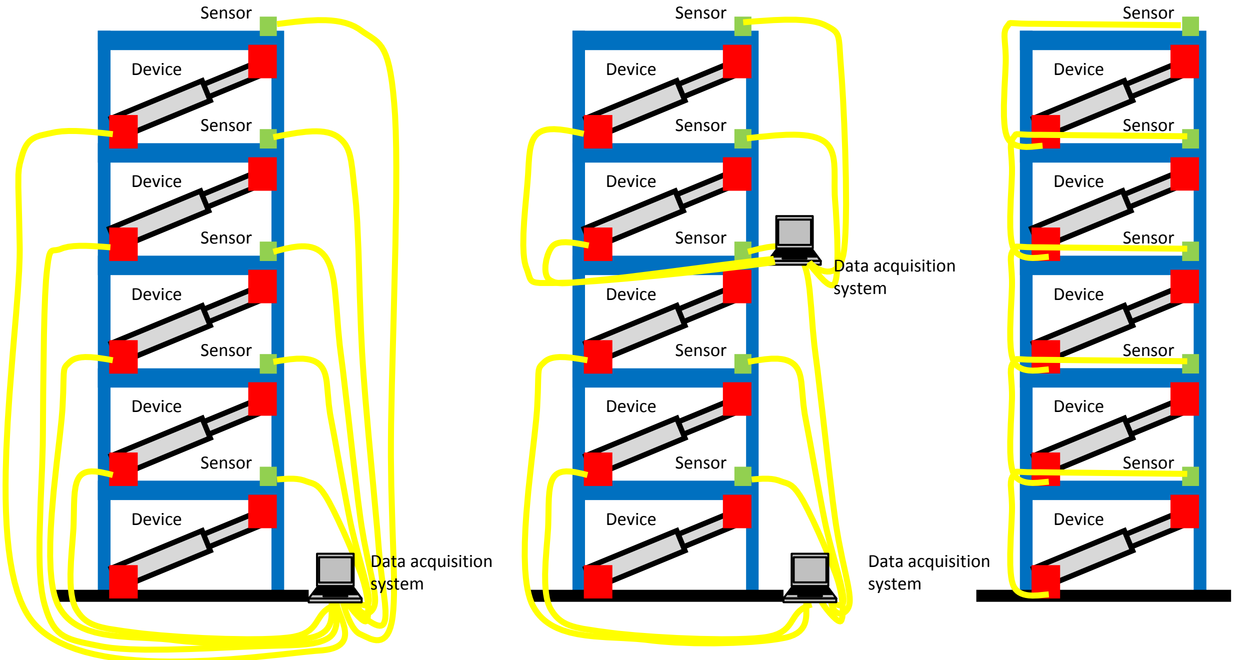
Ma *et al*. (2008) propose a robust decentralized control algorithm. The decentralization is done by decomposing the structure into several subsystems. Connections between each subsystem are treated as uncertain, but bounded, disturbances to the subsystems. The algorithm uses a linear feedback component, and a nonlinear feedback term. Results from this approach are compared with traditional LQR design. Examples demonstrate the effectiveness and robustness of the proposed controller.

Wang *et al*. (2009) present a decentralized $H\infty$ control for large-scale civil structures. Two approaches were used: full and partial decentralization. In the first strategy, the system is subdivided and the control algorithm takes into account the information from neighborhood sensors. The second approach was based solely on the information provided by the local sensor data. A 3-story structure was initially used to demonstrate the $H\infty$ control, and later used the 20-story benchmark building. The control algorithm has a better performance than passive control. Also, decentralized control strategies produced results that were equivalent to or better than their centralized counterparts.

The objective of this paper is to explore the performance of a completely decentralized control scheme using semi-active systems. In the first part of the paper, a LQR control algorithm with semi-active and active systems is applied in a centralized fashion to be used as a reference. The structures used are the five-story steel structure Kajima Shizuoka Building (Kurata *et al*. 1999) and the 20-story SAC1 building. Then, a decentralized scheme is explored in a partially and completely decentralized form. Finally, a modified control algorithm based on the switching control algorithm proposed by Kurino *et al*. (2006) is presented. Results show that a completely decentralized scheme using semi-active systems have a similar performance to active control systems.

2. Decentralized and centralized control

Structural control is effective in improving the dynamic behavior of civil structures. The origin of control was based on centralized control algorithms - algorithms that required that all the information be collected in a single node (Fig. 1(a)). This paradigm needs a large number of cables, some of which could be very long in tall buildings. To overcome this, the whole problem can be divided in sub-problems so there is more than one point where the algorithm control is calculated. This scheme is usually called partially decentralized (Fig. 1(b)). If each device uses only its information to calculate its control algorithm, it is referred to as a completely decentralized scheme (Fig. 1(c)).



(a) (b) (c)

Fig. 1 (a) Centralized, (b) partially centralized and (c) complete decentralized

In general, the performance of control algorithms that use only partial structural information is reduced in comparison to a centralized paradigm. However, the benefit of the decentralized algorithm is a reduction in the amount of investment required to set up the system.

3. Descriotion of the structures and earthquakes used

3.1. Kajima Shizuoka Building

The Kajima Shizuoka Building is a five-story regular structure located at Shizuoka City in Japan. The plan dimension is 24 x 11.8 meters with a height of 18.95 meters. It has eight collocated Semi-active Hydraulic Damper (SHD) systems in the short direction, on stories 1 through 4. The fifth floor does not have a SHD. The connection between the damper and the structure is made with steel braces. Also, elasto-plastic steel dampers are collocated in the short and long directions of the building (Fig. 2).

In order to simulate the real model of the Shizuoka Building the mass and stiffness properties reported by Kurata *et al.* (1999) were used. Using the geometric properties of the elements, the dynamic characteristics are determined. The first five natural frequencies obtained from the analytical model are shown in Table 1.

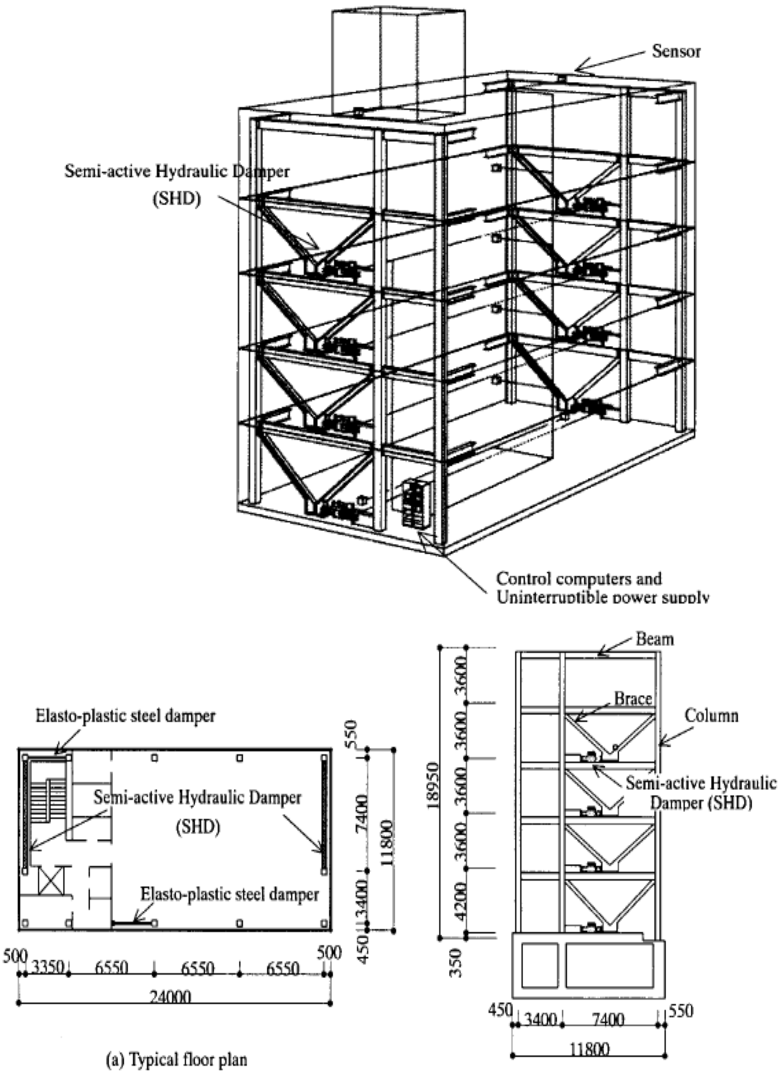


Fig. 2 Shizuoka Building (Kurata *et al.* 1999)

Table 1 Dynamic properties of the model

Analytical model	
Mode	Frequency Hz
1	1.009
2	2.826
3	4.495
4	5.801
5	6.777

3.2. SAC building

The other structure used in this research was designed by the SAC under the current code that governs the region of Southern California. The structure consists of 20 levels based on steel frames; its plan dimensions are 30.48 by 36.58 m, and it has a height of 80.77 m. There are 36 damping devices placed in the positions shown in Fig. 3, with variations according to height. This building demonstrates the effectiveness of structural control in tall buildings.

The analytical model developed for this work is based on the structural properties of the building. It is important to notice that at levels 1, 6, 11 and 16 there are no devices and therefore the change in stiffness is considerable. The dynamic characteristic of the structure is summarized in Table 2. The frequencies of the first five modes are consistent with those obtained by Lynch (2002).

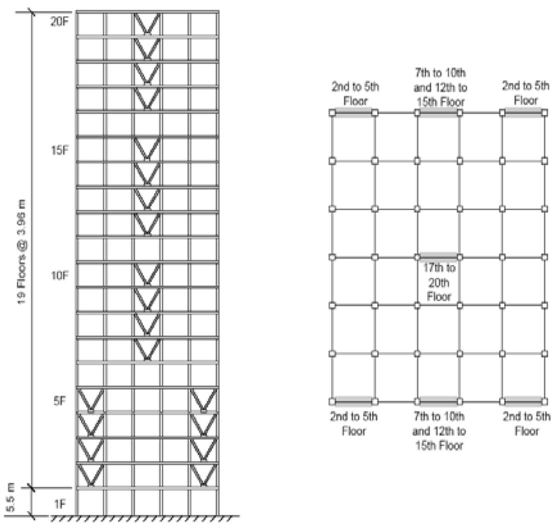


Fig. 3 Benchmark structure and the location of the devices (Lynch 2002)

Table 2 Dynamic properties of the SAC analytical model

SAC building		
Modes	Frequency Hz	Damping %
1	0.28214	
2	0.73293	
3	1.218	
4	1.6464	
5	2.0733	
6	2.5322	5
7	2.9164	
8	3.3851	
9	3.7361	
10	4.1214	

3.3 Earthquakes used

This paper uses four earthquakes: El Centro (1940 NS), Taft (1952 NS) and Hachihone (1968 NS). These records were used to provide a reference with the models developed by other authors. The earthquakes have a record length of 53, 54 and 119 seconds respectively and a sample time of 0.02 seconds. Additionally, the records have been normalized to have a maximum velocity of 50 m/s (Kurata *et al*. 1999)

4. Description of the semi-active device

There are many types of semi-active dampers, among them are: present: variable-orifice, variable-friction, controllable tune liquid and controllable-fluid dampers (Housner *et al.* 1997). This research uses a hydraulic damper with a controllable valve. The hydraulic system is composed by a flow control valve, a check valve, and an accumulator. The control valve has two stages -main and pilot spool - resulting in a power requirement of about 70 W. In case of an energy failure, the valve is opened letting oil flow throughout the orifice allowing the damper to work as a passive device (Kurata *et al.* 1999). The properties of this damper are presented in Table 3.

Table 3 Specifications for SHD

Maximum damping force	1000 kN
Relief load	800-900 kN
Maximum pressure	30 Mpa
Maximum displacement	+-60 mm
Stiffness (with bracket)	>400 kN sec/mm
Maximum damping coefficient	>200 kN sec/mm
Minimum damping coefficient	< 1 kN sec/mm
Maximum velocity	250 mm/sec
Diameter	390 mm
Weight	1300

5. Centralized control algorithims

The objective of this paper is to present a decentralized control algorithm using semi-active control. Nevertheless, in order to justify the use of a semi-active control, the performance of the two buildings under no control, passive damping, semi-active control, and active control under a typical centralized scheme is presented.

5.1 Models without control

The structures can be represented by an open cycle using a state space representation as shown in Fig. 4. The input signal of the model is an earthquake with a gain to normalize it with respect to the other earthquakes used. In the next block, the structure is represented using a state space representation with the matrices A, B, C and D. Finally, the desired outputs are obtained from the system.

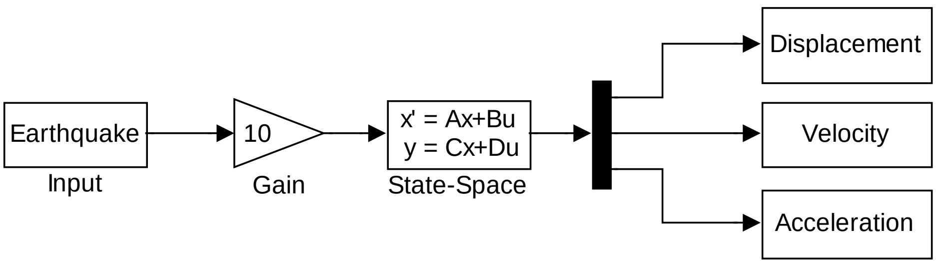


Fig. 4 Simulink model for the structure without control

5.2 Models with passive control

Passive control models were developed for the two structures. In order to achieve this, the SHD devices were collocated over the structure but with no energy input; therefore, they produced only a constant force.

Fig. 5 presents the maximum values of the five story structure without control when subject to the earthquakes of El Centro (C), Taft (T) and Hachihone (H) respectively. The three earthquakes yielded slightly different maximums even though the earthquakes had all been scaled to the same speed (50 m/s). It is noted that Hachihone and El Centro demand more from the structure than the Taft earthquake.

Fig. 6 presents the behavior of the 20-story structure when subject to the three selected records. The Taft earthquake produced the largest displacement which differs from the results of the five-story building.

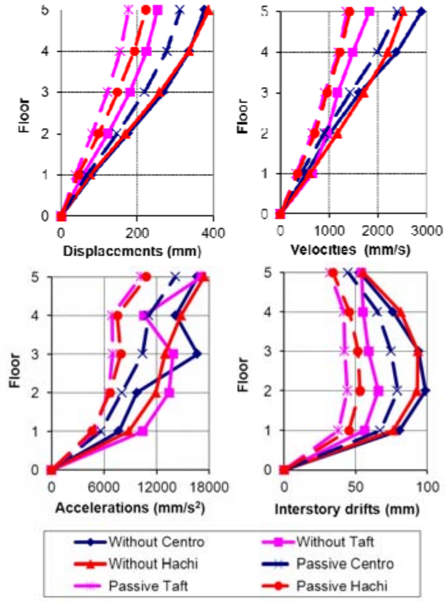


Fig. 5 Displacements, velocities, accelerations, and interstory drifts for the three selected earthquakes

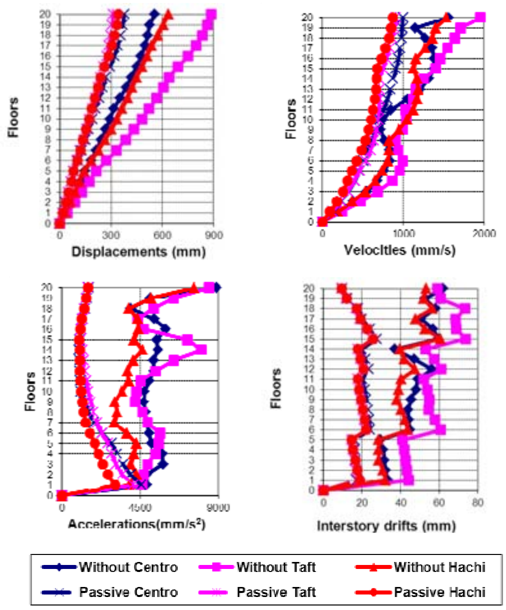


Fig. 6 Displacements, velocities, accelerations and interstory drifts for the three selected earthquakes

5.3 Models with active control

A Linear Quadratic Regulator (LQR) was used as the active control algorithm (Eq. (1)). LQR control seeks to minimize the amount of energy (forced applied) needed to achieve a desired performance (level of displacement).

$$J = \int_{o}^{tf} \left[x^T(t) * Q * x(t) + u^T(t) * R * u(t) \right] dt \tag{1}$$

Where J is the performance index and Q and R are the importance values for the controlled variables and the forced applied to the structure respectively. A SimuLink system was implemented as presented in Fig. 7.

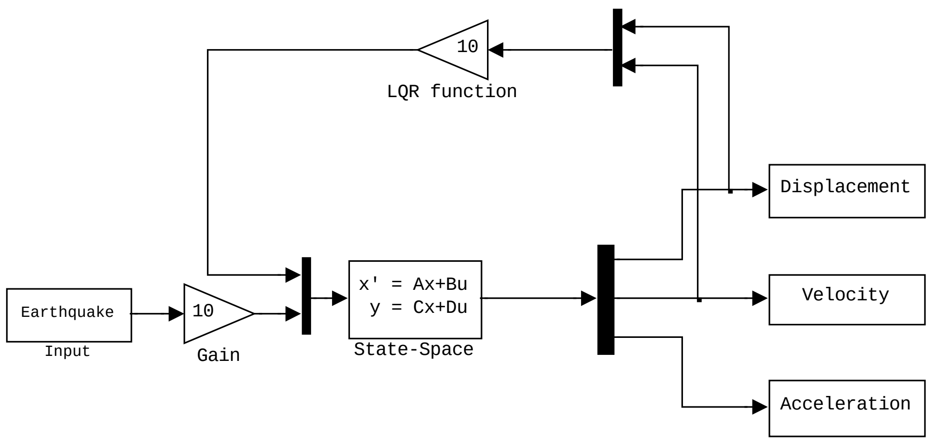


Fig. 7 Basic scheme for an active centralized control algorithm

Based on research conducted by Kurata et al. (1999), the active control was implemented with different values of *R*, but with constant values of *Q*. A comparison of the effectiveness of the active control versus passive and without any control was made. In order to achieve a better performance, large forces are needed, that is, lower values of *R*. However, very small values of *R* do not produce any optimal solutions and sometimes destabilize the system. Additionally, providing the large forces would prove difficult. Fig. 8 shows the behavior of the five-story structure subject to the El Centro earthquake with three different weights of *R* (0.01 0.03 0.1).

Fig. 8 illustrates that the best displacement performance is due to the active control with R equal to 0.01. However larger forces are needed and the acceleration levels increase. Fig. 9 presents the behavior of the 20-story building with R values of 0.1, 0.03, 0.01 and 0.005 for the Taft earthquake. The additional R term in this study was because the Taft earthquake produced such large displacements in the structure without control.

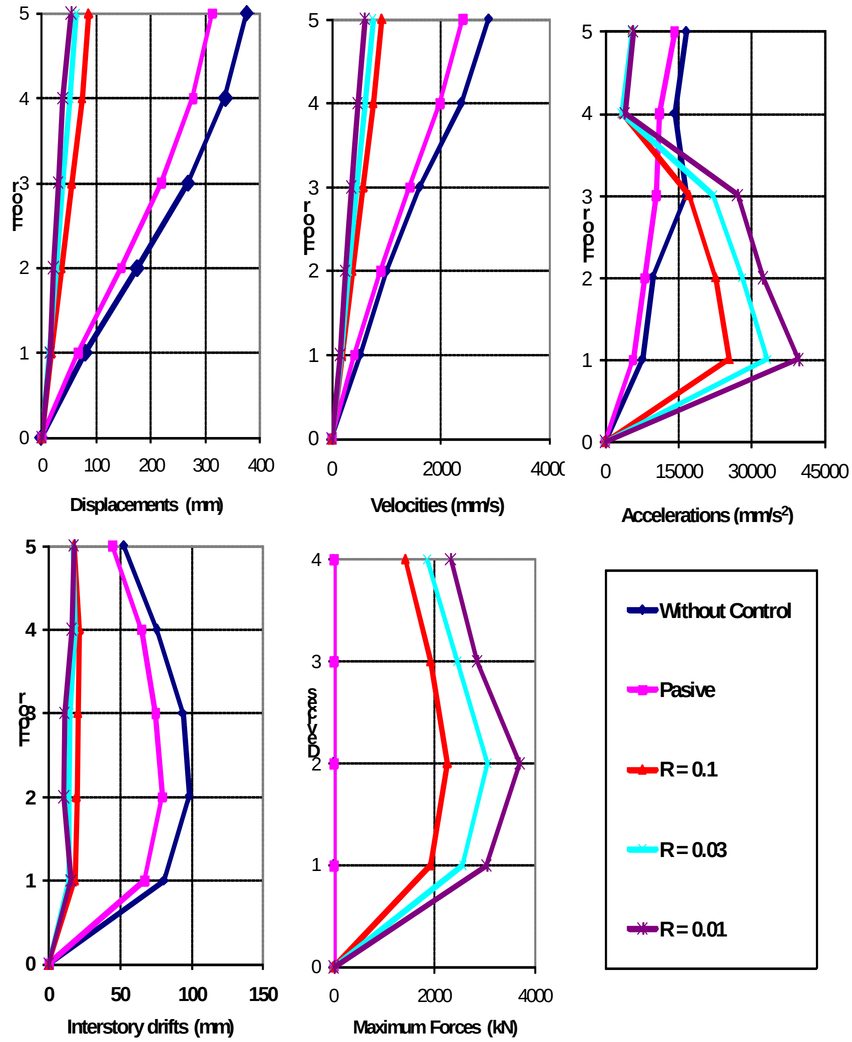


Fig. 8 Displacements, velocities, accelerations, inter-story drifts, and maximum forces due to El Centro earthquake with *R* values of 0.1, 0.03 and 0.01

As with the Shizuoka building, the lowest displacements in the building result from the smallest *R* value (0.005). However, as before, larger forces are needed and there is an increase in the accelerations.

5.4 SEMI-active control algorithm

Jansen and Dyke studied several control algorithms applied to semi-active dampers. Results showed that, among others, the Clipped-Optimal Control (COC) algorithm is suitable for semi-active dampers. The rules for the damping force f_{si} in this semi-active algorithm are expressed in Eq. (2) to (5)

$$f_{si}\begin{cases} f_{\max} sign(v_i) \xrightarrow{if} (fd_i * v_i) > 0, |fd_i| > f_{\max} \\ c_{\max} * v_i \xrightarrow{if} (fd_i * v_i) > 0, |fd_i / v_i| > c_{\max}, |fd_i| \le f_{\max} \\ c_i(t) * v_i \xrightarrow{if} (fd_i * v_i) > 0, |fd_i / v_i| \le c_{\max}, |fd_i| \le f_{\max} \\ 0 \xrightarrow{if} fd_i * v_i \le 0 \end{cases} \qquad \text{Eq. (2) to (5)}$$

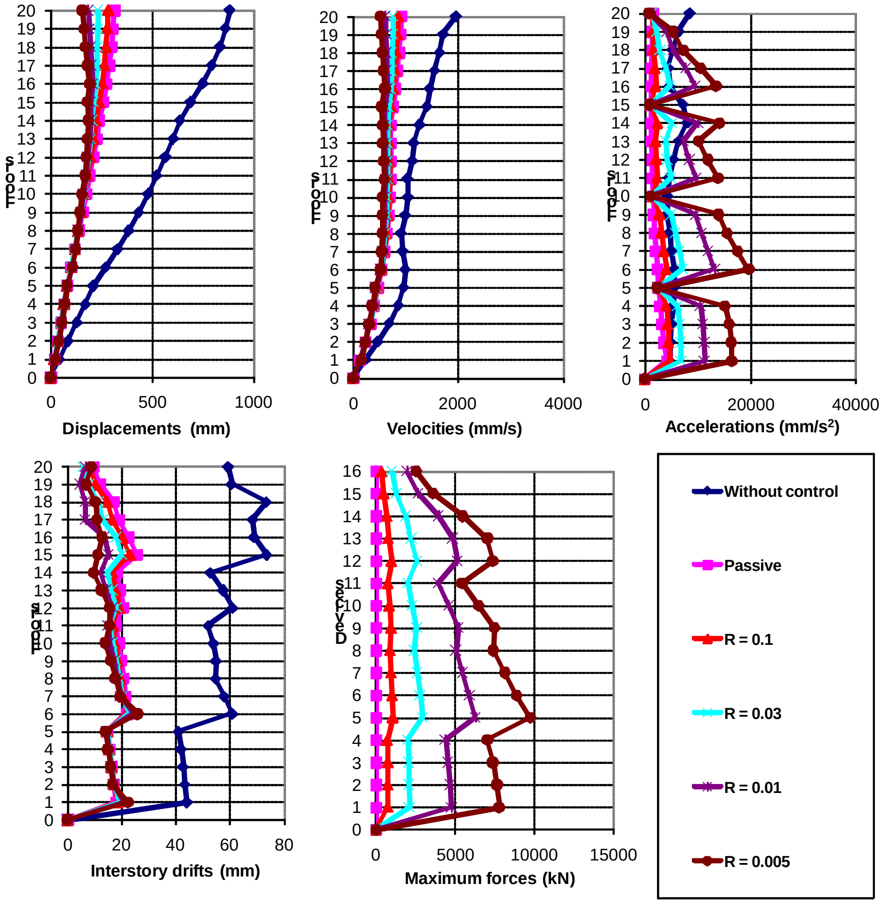


Fig. 9 Displacements, velocities, accelerations, inter-story drifts, and maximum forces due to the Taft earthquake with *R* values of: 0.1, 0.03, 0.01 and 0.005.

Where f_{di}, is the damping force command, v_i is the velocity of the SHD, c_{max} is the maximum damping coefficient, and f_{max} is the maximum damping force. In Eq. (2) through 4, a force can only be applied if the velocity is moving in the same direction, otherwise the force is zero (as per Eq. (5)) In addition to Eq. (2) through (5), Eqs. (6), (7) and (8) are used to define the final force to be applied.

$$f_i \begin{cases} f_{si} \xrightarrow{if} (f_{si}) > 0,\ f_{si} \le f_{lqr} \\ f_{lqr} \xrightarrow{if} (f_{si}) > 0,\ f_{si} > f_{lqr} \\ 0 \xrightarrow{if} f_i = 0 \end{cases} \qquad \text{Eq. (6) to (8)}$$

Where f_i, is the final damping force command and f_{lqr} is the optimal force command according to the LQR law. The description of control flow is presented in Fig. 10.

Semi-active control was implemented with a 0.03 value for *R*, but with constant values of *Q*. A comparison of the effectiveness of the active control versus passive, semi-active and without any control was made. In order to achieve a better performance, large forces are needed, that is, lower values of *R*. However, very small values of *R* do not produce any optimal solutions. Additionally, providing the large forces would prove difficult. Fig. 11 shows the behavior of the five-story structure subject to the El Centro earthquake.

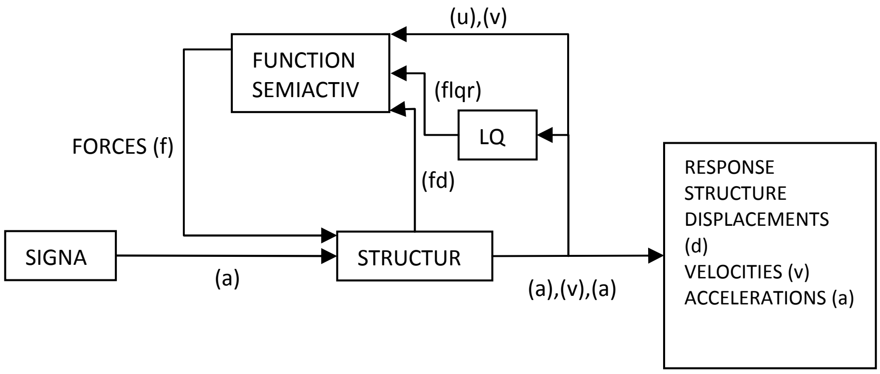


Fig. 10 Semi-Active control scheme

A comparison of the effectiveness of the active control versus passive, semi-active and without any control was made. Fig. 12 presents the behavior of the 20-story building with $R = 0.01$ for the Taft earthquake. The difference with respect of R the 5-story building is because in this study was because the Taft earthquake produced such large displacements in the structure without control.

In both structures, 5 and 20 stories, active control achieves the greatest displacement reduction. Nevertheless, an acceleration increment, as well as a larger amount of damping forces is needed.

6. Decentralized control algorithims

Three types of organizational schemes were described in this paper: centralized, partially decentralized and completely decentralized. Centralized schemes have been presented using both structures with active and passive systems. Completely decentralized schemes will only be implemented using semi-active control. Active control algorithms in both completely and partially decentralized schemes were also investigated; however, there was no decrease in the displacement and therefore the results are not presented here.

The decentralized control algorithm uses a relative displacement and velocity feedback based on the Linear Quadratic Regulator (LQR). Both feedbacks (displacement and velocity) were equally weighted. The control gain was fixed at 0.03 following the results of Kurata *et al*.

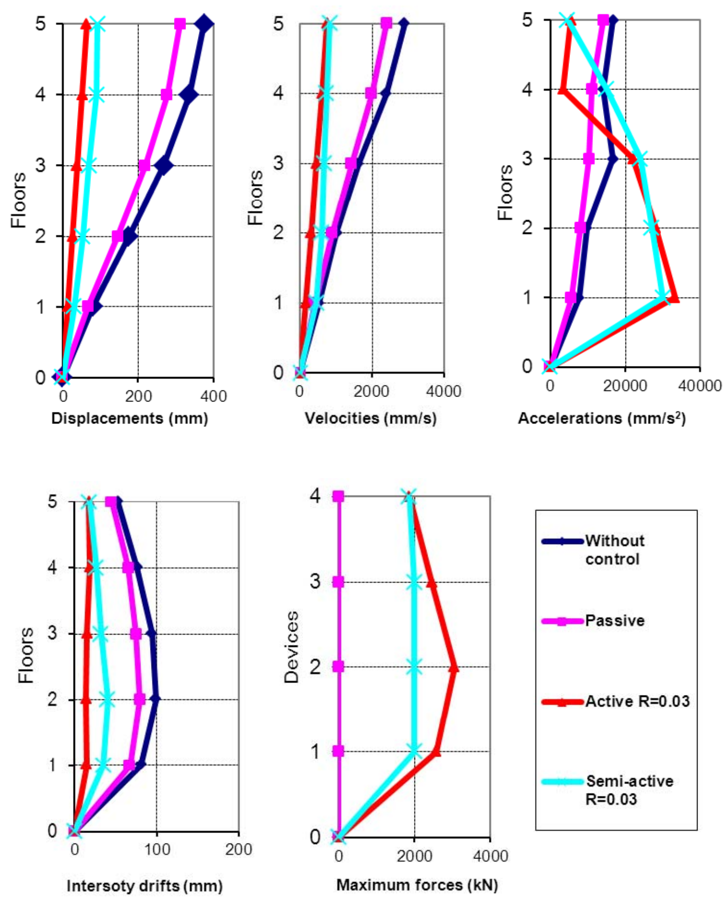


Fig. 11 Displacements, velocities, accelerations, inter-story drifts, and maximum forces due to El Centro earthquake with R value of 0.03

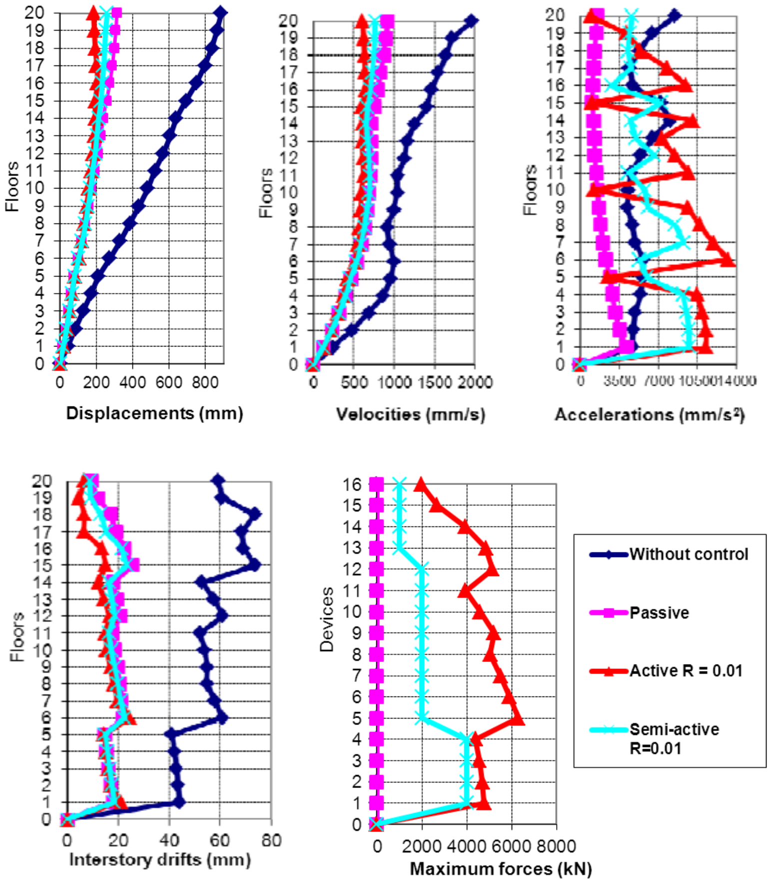


Fig. 12 Displacements, velocities, accelerations, inter-story drifts, and maximum forces due to Taft earthquake with *R* value of 0.01

6.1 Decentralized control algorithm

Kurino *et al*. (2006) developed an oil device that allows control of the damping coefficient. This damper called the "HiDAX" based its operation on the opening and closing of valves. The system allows the dissipation of a great quantity of energy (up to twice as much energy as a passive system). The algorithm works only in two modes - on and off.

The authors' application of the "HiDAX" consisted of a numerical simulation and its installation in a building in 2003. A model called a "bang bang" allows two levels of damping force: C_{min} and C_{max}.

Eq. (9) and (10) present the control algorithm.

$$F \times \dot{x} \geq 0 or |F| \leq F_0 \Rightarrow C(t) = C_{\max}$$
$$F \times \dot{x} < 0 and |F| > F_0 \Rightarrow C(t) = C_{\min}$$
Eq. (9) and (10)

Where *Fo* represents the minimum force applied by the device, *C(t)* is the damping coefficient, *F* represents the damper force, and $F \times \dot{x}$ expresses the Maxwell energy control of the damper.

Fig. 13 presents the energy´s absorption process as defined by Eqs. 9 and 10.

- If the damping force goes in the same direction, then the control is positive and an accumulation of potential energy takes place.
- When the damping force changes direction, the control is negative and it minimizes the damping coefficient.
- Finally, when the damping force is removed and is less than minimum force *Fo*, then the damping force is applied in the other direction.

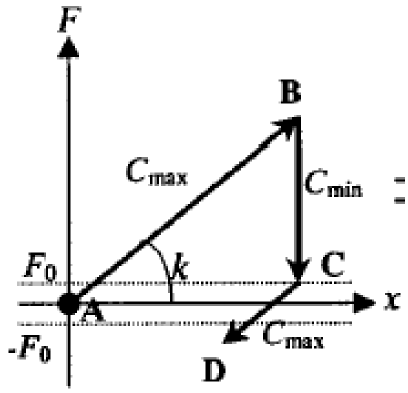


Fig. 13 Kurino *et al.* model

Kurino's control algorithm has been implemented in a building used as a hotel and office. Seventy-two “HiDAX” were installed, and the complete decentralized control algorithm described was used.

7. Proposed algorithm

The proposed algorithm is based on the idea that the control forces are independent and solely based on the information collected at the sensor; therefore, the algorithm is a completely decentralized scheme. As in Kurino’s method, the proposed algorithm uses a fixed damping value; however, how the maximum damping value is reached (slope) becomes a variable.

Incrementing the damping force gradually, instead of applying it suddenly, could prevent damage to the contents of the building. Basically, an ideal behavior would be to increment the forces with a certain slope until reaching the maximum value proposed by the device.

As with semi-active systems, the forces are applied only if the velocity is in the same direction. When a change in direction occurs, the forces are gradually diminished until reaching a minimum value and then the forces increment in the other direction. The algorithm details are presented in Eq. (11) through (16).

$$Fr\begin{cases} N*contp \rightarrow vi>0 \vert vi=0 \vert N*contp<1000 \\ -N*contn \rightarrow vi<0 \vert -N*contp<-1000 \\ 1000 \rightarrow N*contp>1000 \\ -1000 \rightarrow -N*contn<-1000 \end{cases} \qquad \text{Eq.(11) to (14)}$$

$$F-\begin{cases} Fr \rightarrow Fr \le \lvert vi*C_{\max}\rvert \\ vi*C_{\max} \rightarrow \lvert Fr\rvert > \lvert vi*C_{\max}\rvert \end{cases} \qquad \text{Eq. (15) to (16)}$$

Where *vi* is the velocity at each level where the device is located, *Fr* is the proposed force for the system, *F* is the final force applied to the system that is limited according to the device characteristics, C_{max} is the maximum damping coefficient according to the damper specifications, *N* is the slope, and *contp* and *contn* are counters (*contp* and *contn* are reinitialized to 1 when the system changes sign). A schematic of the rules described above are presented in Fig. 14. Based on the proposed algorithm, a set of different slopes, as described in Table 4, are used.

Table 4 Slopes used in the decentralized control algorithm with semi-active devices

Time step (s)	N (kN)	Slope (kN/s)
0.001	1	1000
0.001	0.1	100
0.001	0.01	10
0.001	0.001	1

8. Results

8.1. Five-story structure

Fig. 15 shows the structural response of the five-story building when different values of *N* are used. Active control (with *R* equal to 0.03) and without control are shown as references. Only the results from the El Centro earthquake are presented.

N has an effect on the performance of the structure. Lower values of *N* (shallow slopes), produce higher displacements – similar to the behavior of the building without control. Meanwhile, larger values of *N* (steep slopes) reduce the displacement of the structure – similar to the behavior of active control.

Fig. 16 presents the cumulative forces for the different slopes. When a small slope is used, a reduced amount of force is achieved but there is no improvement in the structure's behavior. In these cases, active control provided a better response. Using a larger slope increases the damping force that can be applied to the system and the structure has a slightly better response than the active control. However, the cumulative force required is almost double.

In general, the algorithm's response for the five-story structure presents improvements. An increase in the slope reduces displacements, velocities and the inter-story drifts to a level approaching that of active control.

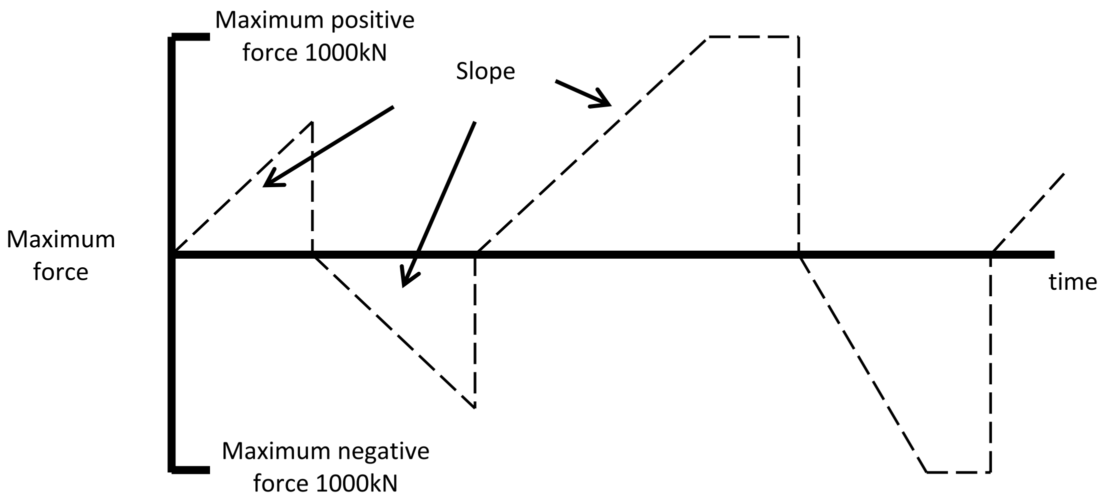


Fig. 14 Proposed control scheme

8.2. 20-Story building

For this structure, the applied slopes are shown in Table 5. The time step was reduced to get a numerical solution.

Fig. 16 shows the comparison between the structural responses of the 20-story structure for the five different slopes proposed. Active control with *R* equal to 0.03 is shown as a reference. For this structure, only the response to the Taft earthquake is presented.

In general, the maximum responses observed for displacement, velocity, acceleration and inter story drifts lay between the passive and active control. The main difference is the amount of force required for control.

Fig. 18 shows the cumulative forces applied to the structure under the different proposed slopes. Small slopes introduce low force levels to the structure and as a result no significant improvement in performance is achieved. Steep slopes demand great force levels without reaching ideal control levels.

In summary, the proposed algorithm has an acceptable performance in small height structures where the first mode is dominant. In tall buildings the algorithm has some limitations; nevertheless, the all slopes in the algorithm are able to regulate the dissipation of energy in the system.

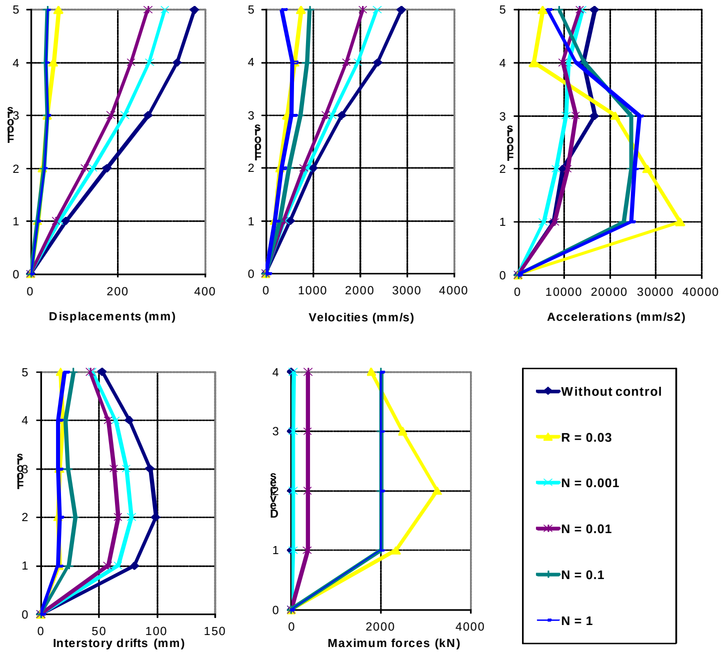


Fig. 15 Maximum displacements, velocities, accelerations, inter-story drifts, and forces for the five-story building for the El Centro earthquake

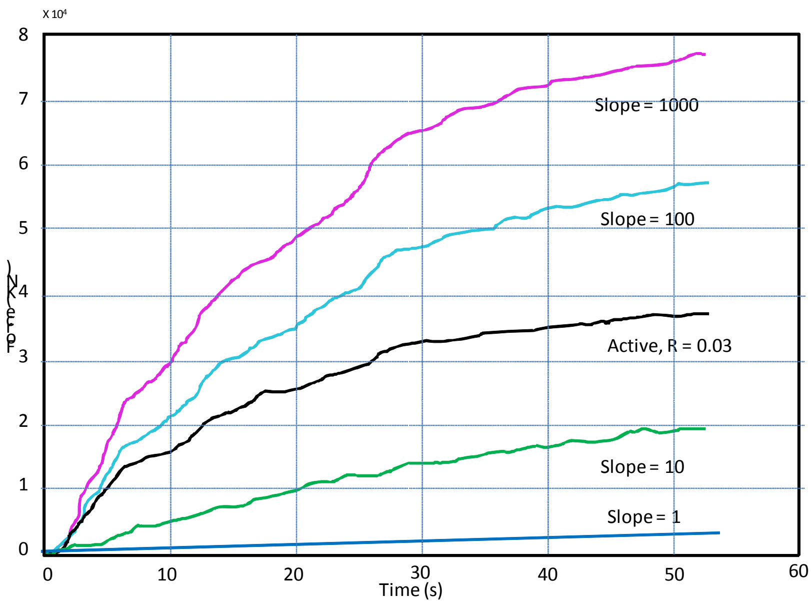


Fig. 16 Cumulative forces for the five-story structure

Table 5 Slopes used with the decentralized control algorithm with semi-active devices.

Time step (s)	N (kN)	Slope (kN/s)
0.0001	1	10000
0.0001	0.1	1000
0.0001	0.01	100
0.0001	0.001	10
0.0001	0.0001	1

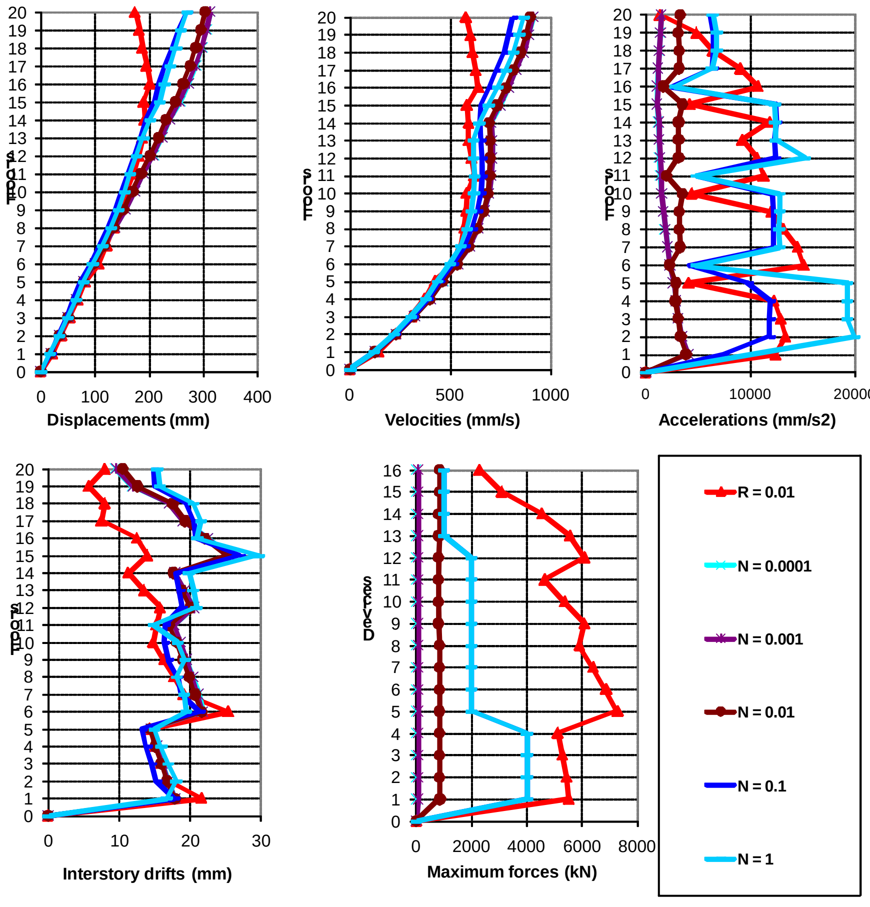


Fig. 17 Maximum displacements, velocities, accelerations and inter-story drifts, and forces for the five-story building for the Taft earthquake

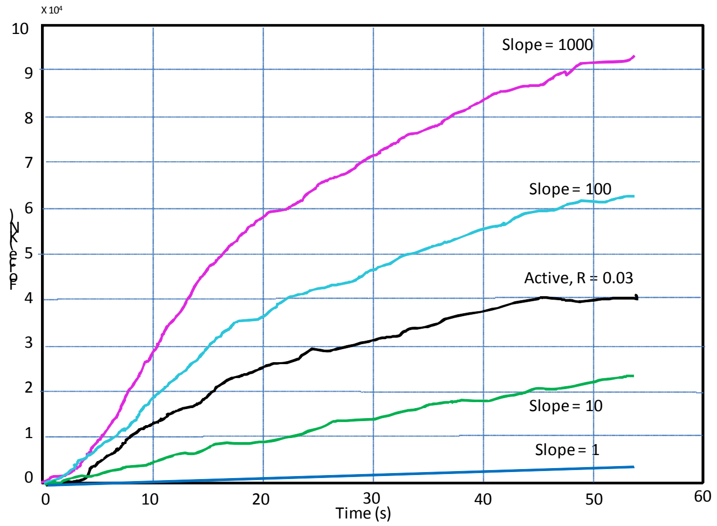


Fig. 18 Cumulative forces for the 20-story structure for the Taft earthquake

9. Conclusions

Earthquakes can significantly damage civil structures. Therefore, the structural engineers have proposed various techniques to improve structural behavior during such natural disasters. This research developed a decentralized algorithm for semi-active control.

The decentralized semi-active control algorithm was implemented in an analytical study for this paper. Two structures were selected for this study: a short building (five stories) and a tall building (twenty stories). These buildings have been studied by other authors and their behavior is well known. Three earthquakes were selected: El Centro, Hachi and Taft. These records have different frequency contents. The El Centro earthquake produces larger displacements for short structures, while the Taft earthquake produces larger displacements in tall buildings. A study of the response of the structures under, passive, active and semi-active control in a centralized manner was presented. The best behavior is achieved using active control; however, the level of force required to achieve this improvement constitutes a significant energy input.

The use of a completely decentralized control algorithm that uses only the information at the device level to calculate the force required to attain the desire displacement was then explored. Decentralized control presents an economical solution since a multichannel data acquisition system is not required. Also the installation cost is greatly reduced because no cables are required. The proposed algorithm focused on the use of semi-active systems due to the lower levels of energy needed compared to active systems. Other completely decentralized control algorithms are based on on-off systems. In this research the possibility of having the force applied gradually was explored. Different slope levels were studied. For short buildings, the proposed algorithm achieves displacement control similar to that of active control without using the same level of energy. For tall buildings, the improvement in the behavior of the system is not clear.

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