Suitable Energy Dissipation Device for Private Typical Buildings with Poor Seismic Performance

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ABSTRACT

Different kinds of passive and active control methods, their advantages and disadvantages, and their feasibility for buildings in Iran are investigated during this study. The main focus of this study is on passive control techniques used in private typical buildings with relatively low seismic performance, which are quite common in Iran. This study also includes a brief outline of different passive dampers and vibration absorbers. According to the technical and economical issues, it is shown that tuned liquid column-gas damper, TLCGD, is one of the best options for enhancing the seismic behavior of typical buildings in the country. A simple yet accurate procedure is proposed to estimate equivalent damping ratio corresponding to the TLCGD. Finally, through a numerical assessment, effect of TLCGD is investigated. Based on the obtained results, TLCGD can reduce rout mean square (RMS) response of buildings, but its capability in reducing the maximum response depends on the excitation itself. TLCGD was shown an efficient scheme for enhancement of seismic capacity of both new and under-operation existing buildings.

Keywords:
Passive control; TLCGD; Vibration absorber; Seismic retrofit; Seismic excitation; Equivalent damping ratio

1. Introduction

Alpine-Himalayan orogenic belt is one of the most highly seismic zones in the world. Iran is located within this belt, and consequently is considered as one of the most earthquake-prone countries in the world. According to Iranian code of practice for seismic resistant design of buildings [1], Tehran, the capital of Iran, has been located in one of the most seismically active zones in Iran. The city is surrounded by several active faults, such as Mosha, North Tehran, North-Ray, South-Ray, etc. According to the location of Tehran and earlier studies [2-4], earthquake event is inevitable for this highly populated city.

Unfortunately, old buildings with poor seismic capacity are quite common not only in Tehran, but also in the whole country, and this makes the country very vulnerable to the earthquake hazard. Recently, some limited financial supports have been provided by the government in order to retrofit old buildings for enhancing their seismic capacity, but they are not enough. It seems that the main drawback is the economy. Traditionally, seismic retrofit in Iran means stiffness increasing and this is why the procedure is costly so that most people cannot afford that. In addition to lateral stiffness increasing, there are many other techniques in order to mitigate the seismic hazard of private typical buildings. By and large, these techniques can be classified as three groups: base isolation [5-6], passive control [7-9], and active control [10]. Each of these methods has its merits and demerits.

Active methods can effectively suppress the seismic response of different structures. However, according to the current technology, active control methods are very expensive and their reliability is not still in an acceptable level. Consequently, at the present time, active control methods are not appropriate for typical buildings.

Base isolation can change the fundamental mode shape of the building into a rigid mode shape and in this way highly reduces story drifts and saves the buildings from damage during an earthquake. However, base isolation has two drawbacks. First, it is only effective for short-period buildings, and second, implementing a base isolation system is a costly procedure that private owners cannot usually afford it.

It is clear that base isolation and active control methods are not feasible for typical buildings in the country, mainly because of cost problems. In contrast with active methods and base isolation, passive control techniques are commonly cost-effective and can be proposed for typical private buildings in seismic prone zones. In this paper, different passive control methods are considered, and their advantages and disadvantages are investigated for typical buildings.

In this study, typical buildings are referred to three to five-story private buildings, most of which have relatively poor seismic performance, see Figure (1). The objective is to find a cost-effective and feasible method for enhancing the seismic performance of these buildings, frequently observed in the entire country.

2. Passive Control

Passive control principles can be illustrated in two languages, the language of Energy and the language of Force. Eq. (1) demonstrates the Force statement:

$$m\ddot{x} + c\dot{x} + kx + f_p = -m\ddot{x}_g \tag{1}$$

Eq. (1) is the equation of motion of an elastic system under passive control where m, c, and k indicate mass, inherent damping coefficient and lateral stiffness of the system, respectively, x represents the displacement of the system, and f_p is the control force which reduces the excitation force. According to the Energy statement:

$$\begin{gathered} \int m\ddot{x}dx + \int c\dot{x}dx + \int kxdx + \int f_p dx = \int -m\ddot{x}_g dx \\ Kinetic + Damped + Elastic + Dissipated = Input \end{gathered} \tag{2}$$

Eq. (2) shows that a portion of the input energy is dissipated by the passive controllers and presented by the term "Dissipated" at the left-hand side of the equation. According to Eqs. (1) and (2), it is obvious that passive controllers would reduce the seismic demand on the main structural elements and, in this way, save them from seismic induced failures.

In the following sections, some of the more common passive control devices are addressed and their advantages and disadvantages, in the case of typical private buildings in the country, are investigated.

2.1. Yielding Dampers

Yielding dampers have been first proposed by Bergman and Hanson in 1989 and then developed

Figure 1. Typical buildings with private owners with poor seismic considerations.

by Xia and Hanson [11]. Many studies have been focused on the yielding dampers as an energy dissipation device and their main parameters, namely yielding displacement and stiffness, have been optimized [11-13]. Yielding dampers through their inelastic deformations dissipate the input energy and reduce seismic demands on the structural elements. Figure (2) shows a typical configuration for the yielding damper.

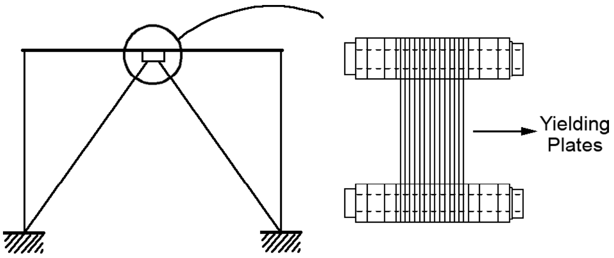


Figure 2. Typical configuration of yielding dampers.

Yielding dampers are easy to manufacture and also virtually they need no maintenance. Moreover, they have stable hysteretic behavior, which can dissipate a large portion of input energy. Yielding dampers are quite compatible with the concept of performance base design. In other words, they remain elastic during weak and moderate earthquakes and reduce response of the building through their stiffness increasing capability. However, in the case of strong earthquakes, they dissipate input energy through their inelastic deformations. Nevertheless, yielding dampers have to be implemented in conjunction with chevron or diagonal braces. These braces should be designed to remain elastic during the design earthquake. The main drawback of the yielding damper is due to imposing architecturally some limitations.

2.2. Friction Dampers

Friction dampers are similar to yielding dampers, but in the case of friction dampers, energy dissipation occurs through solid friction between two sliding solid bodies. In contrast with yielding dampers, friction dampers cannot be easily manufactured and need a relatively high technology. However, as reported by Foti et al. [12], compared with yielding dampers, they can dissipate more energy with respect to their rectangular hysteretic loops. As reported by Soong and Dargush [7], there are many kinds of friction dampers. Figure (3) shows one of them, innovated by Mualla and Belev [14].

Friction dampers have stable hysteretic loops with rectangular shapes which increase energy dissipation capacity. Just like yielding dampers, friction dampers are also compatible with the concept of performance-based design. However, in addition to disadvantages that were mentioned for yielding dampers, friction dampers are relatively expensive and cannot be manufactured in the site.

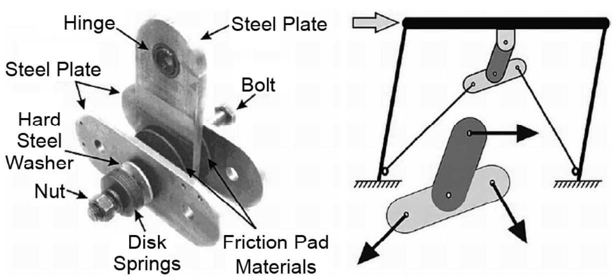


Figure 3. A typical friction damper developed by Mualla and Belev [14].

2.3. Viscous Dampers

There are many forms of viscous dampers, but a viscous damper commonly includes a piston with small orifices on its head through which a fluid with high viscosity can pass from one side of the piston head to another side. Therefore, the energy dissipation occurs by the movement of viscous fluid through orifices. In contrast with yielding and friction dampers, viscous dampers can dissipate the response of the building only by energy dissipation mechanism. In other words, viscous dampers do not impose any change in the stiffness of the building.

Viscous dampers suppress response of the building through damping increase. This means that, in contrast with yielding and friction dampers, viscous damper would dissipate energy for all earthquakes, whether a weak motion or a strong one occurs. Moreover, viscous dampers are velocity dependent, and they do not need large displacements in order to activate. In spite of these advantages, however, viscous dampers are expensive and need continuous maintenance. Besides, they should be implemented into the building through some excessive elements such as diagonal braces.

2.4. Viscoelastic Dampers

Viscoelastic dampers reduce dynamic response of a building through two mechanisms, damping increasing and stiffness increasing. The force of a viscoelastic damper consists of two parts, a velocity dependent and a displacement dependent part. The displacement dependent force acts like a spring and cannot dissipate energy because it is in the same phase with the damper displacement. In contrast, the velocity dependent part is out of phase with the damper displacement, and it is responsible for the energy dissipation capacity of the damper [7, 9, 15].

The main advantage of viscoelastic dampers is the fact that they act both by stiffness and damping increasing. This feature makes them more effective compared with other dampers. For example, Patil and Jangid [16] have considered the effect of friction dampers, viscous dampers, and viscoelastic dampers on the response of offshore jacket platforms. According to their study, the viscoelastic dampers perform better in comparison to the other dampers. This is because the viscoelastic dampers contribute to the increased viscous damping as well as lateral stiffness. However, viscoelastic dampers need continuous maintenance so that by a small change in the temperature, their performance varies significantly. In other words, their damping and stiffness characteristics are temperature and frequency dependent. Moreover, in the case of viscoelastic dampers implementation, again some additional elements, such as diagonal braces, are needed.

2.5. Vibration Absorbers

Vibration absorbers, VA, can be classified as three major groups, tuned mass dampers, TMD, tuned liquid dampers, TLD, and tuned liquid column dampers, TLCD. All VAs act based on vibration of a secondary mass. The input energy transmitted to the structure, and through structure, a portion of the input energy transmitted to the secondary mass of the VA. This amount of energy would be dissipated through damping mechanism of the VA. The energy cycle in the case of a building-VA system is illustrated in Figure (4).

It should be noted that in the case of TMD, the secondary mass is a concrete or steel block, and the damping of the VA would be provided using some additional dampers, such as viscous dampers. In the case of TLD and TLCD, the secondary mass is liquid, commonly water, inside a container and the damping mechanism is hydraulic resistant, such as elbows and orifices.

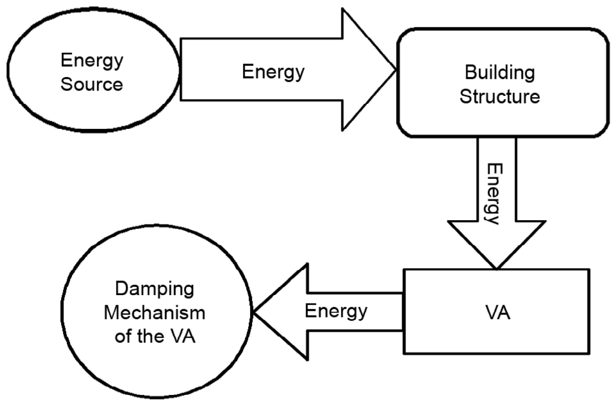


Figure 4. Energy cycle in a building-VA system.

Among different VAs, TLCD and TLD are very cost-effective, easy to manufacture, and virtually they need no maintenance. Besides, in contrast with other dampers, they need no additional elements for implementing. It should be elaborated that among different VAs, TMD has a relatively complex structure and needs expensive springs and dampers. TLD is easy to construct, but its equation is highly nonlinear and its frequency strictly depends upon wave amplitude of its liquid. In the case of VA, the control force has two parts; one part has a destructive effect and the other part is responsible for the response mitigation. This feature makes their energy dissipation capability less than other dampers.

3. Appropriate Damper for Private Typical Buildings

According to different kinds of passive dampers, and their advantages and disadvantages, it seems that TLCD is the best option for typical buildings with private owners. TLCGD is easy to build, cost-effective, and it needs no additional elements such as chevron braces or other elements. Moreover, its behavior is relatively simple because there are no fluid waves inside the TLCGD in contrast with TLD. The only thing that is needed is a U-shaped container with a pressure regulator. Classical tuned liquid column damper, TLCD, was first proposed by Sakai et al. [17] and developed into liquid column vibration absorber, LCVA, by Watkins and Hitchcock [18]. Recently, a new version of LCVA, called tuned liquid column-gas damper, TLCGD, has been proposed and developed by Hochrainer and Ziegler [19] and Ziegler [20]. The main difference between TLCD, LCVA, and TLCGD is due to their flexibility in frequency tuning. Frequency of a TLCD can be adjusted only by tuning its columns length, but in the case of a LCVA, in addition to columns lengths, the frequency can be tuned by tuning columns cross-sectional areas. Finally, in the case of a TLCGD, besides column length and cross section, one can adjust its frequency by tuning the gas pressure in the vertical columns. This feature of TLCGD makes it appropriate for typical buildings with a limited space on their roof.

3.1. Mathematical Model

Consider a U-tube TLCGD as shown in Figure (5), where y denotes the elevation change of the TLCGD liquid in the vertical columns, x the base horizontal displacement of the TLCGD, ρ the density of the liquid, b and h, respectively, length of the horizontal and vertical columns of the TLCGD that filled with liquid, A_b and A_h, the cross-sectional area of the horizontal and vertical columns respectively, P_0 the initial gas pressure in the vertical columns and h_a, length of the vertical columns of the TLCGD occupied by gas. According to [19], the equation of motion of the fluid inside the TLCGD can be written as:

$$\ddot{y}+\delta_L|\dot{y}|\dot{y}+\omega_A^{\,2}y=-k_1\ddot{x} \tag{3}$$

where

$$\omega_A^{\,2}=\frac{2g\left(1+{nP_0}/{\rho g h_a}\right)}{2h+b\lambda} \quad , \quad k_1=\frac{b}{2h+b\lambda} \tag{4}$$

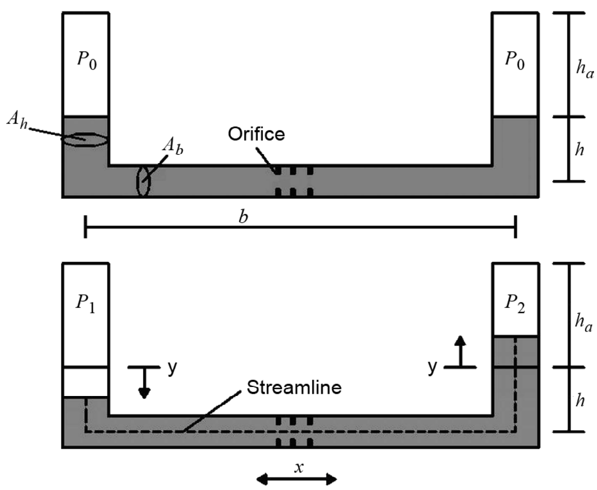


Figure 5. TLCGD subjected to a base displacement x.

It should be elaborated that second derivative of x in Eq. (3) is the absolute acceleration at the base of the TLCGD.

In Eq. (4) it was assumed that $\frac{|y|}{h_a}\le 0.3$. The TLCGD force can be evaluated as [19]:

$$f_{TLCGD}(t)=m_f\,(\ddot{u}\,(x_{TLCGD},t)+\ddot{u}_g(t)+\bar{k}\,\ddot{y})$$

$$\bar{k}=\frac{b}{2h+{b}/{\lambda}} \tag{5}$$

In above equations, λ called area ratio which is defined to be the ratio of the vertical column cross section to the horizontal one.

3.2. Optimum Parameters

Optimum parameters of the TLCGD, namely frequency, head loss coefficient, and geometric parameters, have been investigated in earlier studies [21-24]. According to Sadek et al. [21], the optimum frequency and optimum head loss coefficient can be evaluated as:

$$f_{opt}=\frac{\sqrt{1-\frac{\mu}{2}}}{1+\mu} \quad , \quad \delta_{L,opt}=\left(\frac{1}{2(2h+b\lambda)}\right)\frac{3.58\mu}{{a}/{g}} \tag{6}$$

where, f is the frequency ratio, i.e. the ratio of the TLCGD frequency to the fundamental frequency of the building, and δ_L is the head loss coefficient of the TLCGD, which can be evaluated according to Eq. (7) [24], μ is the mass ratio, i.e. the ratio of mass of the TLCGD liquid to the effective mass of the fundamental mode of the building, and finally, a is the peak ground acceleration of the considered ground motion. It should be clarified that in Eq. (6), the optimum head loss coefficient is modified according to its definition in this study, which is different from what suggested by [21].

$$\delta_L=\frac{1}{2(2h+b\lambda)}\times\left\{K_{el}(1+\lambda^2)+N_bK_{or}\lambda^2+N_hK_{or}+K_C+K_E+\frac{2\,fh}{D_h}+\frac{fb}{D_b}\lambda^2\right\}$$

$$if\,\lambda>1\Rightarrow K_C=0.5\lambda^2\ ,\ K_E=(\lambda-1)^2 \tag{7}$$

$$if\,\lambda<1\Rightarrow K_C=0.5\ ,\ K_E=(1-\lambda)^2$$

$$if\,\lambda=1\Rightarrow K_C=K_E=0$$

where K_{el} and K_{or} are the resistance coefficients for elbow and orifice, respectively, N_h and N_b, are number of orifices in the vertical columns and horizontal column, respectively, f is the Darcy's coefficient of friction, D_h and D_b are diameters of the vertical and horizontal columns, respectively. K_c and K_E are the contraction and expansion coefficients, respectively.

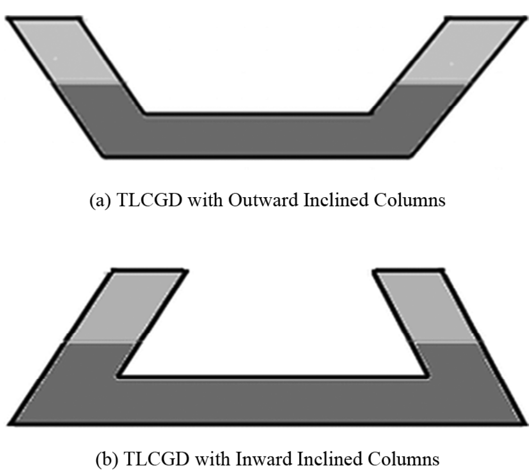
3.3. Optimum Geometry of TLCGD

Important parameters of the TLCGD are column lengths, cross-sectional area of columns and the configuration of the TLCGD itself.

As stated earlier by Sadek et al [21], if the length ratio of TLCGD columns is defined as the ratio of horizontal column to vertical column, by increasing the length ratio, efficiency of the TLCGD would increase. This is because that the inertial force of the liquid in the horizontal column is responsible for the damper force which counteracts external forces. Therefore, the more the length ratio, the more the counteracting force of the damper.

According to [24], a value greater than one is appropriate for the area ratio, λ. Vertical columns of TLCGD can be replaced with inward or outward inclined columns, as shown in Figure (6).

As reported in [25], inward columns reduce the TLCGD efficiency because the inertial force of the fluid in inclined columns counteracts the inertial force of the fluid in the horizontal column since the fluid acceleration in horizontal column differs with those in inward inclined ones. In contrast, in the case of outward inclined column, these accelerations have the same direction. Accordingly, TLCGD with outward inclined columns imposes more counteracting force to the structure compared with TLCGD with vertical columns. However, in the case of TLCGD with outward inclined columns, fluid displacements and velocities increase, and it may not satisfy the assumption $\frac{|y|}{h_a} \le 0.3$ as stated for Eq. (4). Moreover, as suggested by Linder-Silvester and Schneider [26], in order to prevent gas entrance into fluid, maximum velocity of the fluid should be restricted to $|\dot{y}| \le 10\frac{m}{s}$ which may not be satisfied in TLCGD with outward inclined columns. Therefore, it seems that TLCGD with vertical columns are the best configuration because it has good efficiency and reliability to avoid entrance of gas into the fluid.



(a) TLCGD with Outward Inclined Columns

(b) TLCGD with Inward Inclined Columns

Figure 6. Maximum floor Velocities, five R_i Settings, meter/seconds.

3.4. Equivalent Damping Ratio

As TLCGD has a nonlinear equation of motion and its implementing in conventional computational software is impractical, it is useful to define an equivalent damping ratio corresponding to the TLCGD with different mass ratios. A simple yet accurate procedure is adopted in this study to obtain the equivalent damping ratio. In the proposed procedure, it is assumed that, the building is subjected to harmonic base acceleration with resonance frequency. This assumption imposes the worst condition on the building. In such case, response of the building is highly dominated by its first mode of vibration. Accordingly the building can be considered as a single degree of freedom, SDOF, system.

Ten SDOF systems having natural periods of 0.1 s to 1 s with 0.1 s increments are considered and their inherent damping ratios are assumed to be 5%. Because displacement responses are the main interest, value of 1 kg is assumed for the mass of all ten SDOF systems. Equation of motion for each system is as Eq. (8):

$$\ddot{u} + 2\omega_j\zeta\,\dot{u} + \omega^2 u = -\sin(\omega_j t) \tag{8}$$

The maximum displacement of above equation can be evaluated by a close formed relation.

As stated earlier, the mass ratio of the TLCGD is the variable, and its frequency is tuned to its optimum value according to Eq. (6). It is worth noting that using optimum value for the head loss coefficient is not always practical because its optimum value is too small to be achieved in real construction. This claim is addressed in more details in Section 4. Therefore, a value of 0.5 is used as the head loss coefficient in all cases.

In order to obtain the controlling force, Eq.(5), the values of λ, *b*, and *h* should be predefined. A value of 2 is adopted for λ, and it is assumed that $h = 0.2\ b$. Accordingly, the values of λK and K_1 would be 1.11 and 0.42, respectively. It should be noted that the adopted values for area ratio and columns length of the TLCGD are reasonable and near optimum.

The mass ratios are considered to vary from 0.5% to 15% with 0.5% increments. Obtained results are summarized in Table (1) and Figure (7).

From Figure (7), it is obvious that TLCGD is useful to increase the damping ratio up to 10%. For more levels of damping, TLCGD is not recommended because a large mass ratio is required, which can make some problem for the gravity load bearing system of the building.

Above results is obtained from a Matlab/Simulink [27] model as shown in Figure (8).

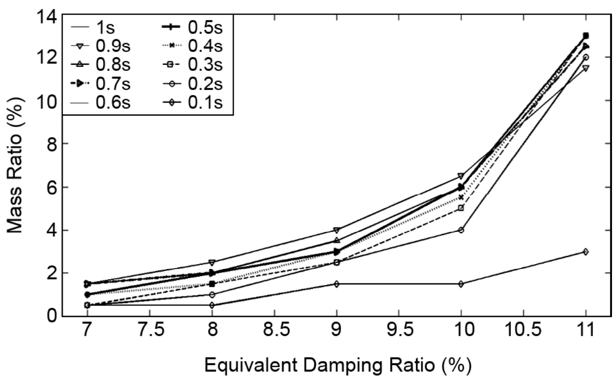


Figure 7. Required Control Forces, five Ri Settings, kN.

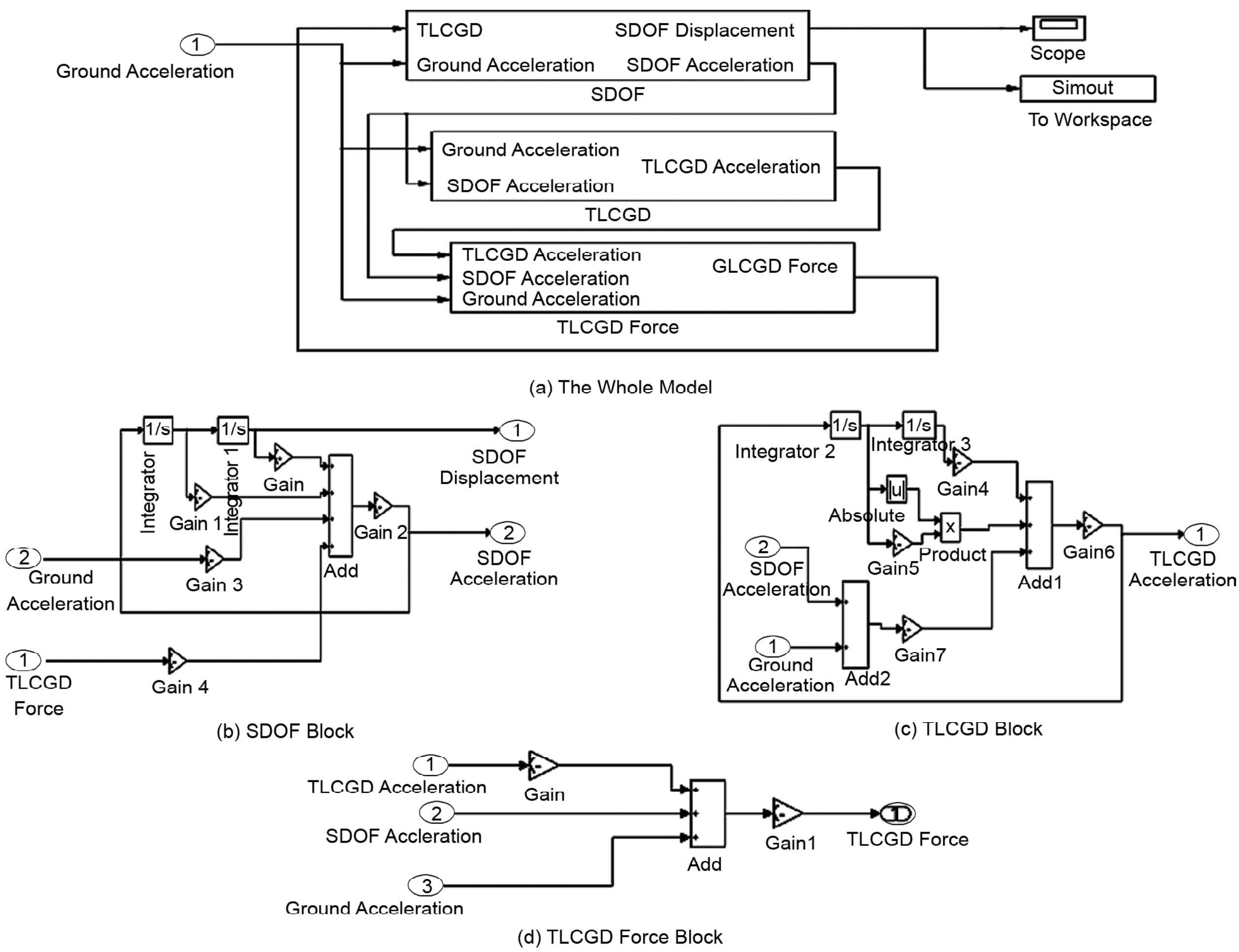


Figure 8. Maximum floor Displacements, five nr Settings, meters.

Table 1. Equivalent damping ratio (%) corresponding to each mass ratio (%).

Equivalent Damping Ratio (%)	Natural Periods of the SDOF Systems (s)									
	1	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
7	1.5	1.5	1.5	1.5	1	1	1	0.5	0.5	0.5
8	2.5	2.5	2	2	2	2	1.5	1.5	1	0.5
9	4	4	3.5	3	3	3	3	2.5	2.5	1.5
10	6.5	6.5	6	6	6	6	5.5	5	4	1.5
11	11.5	11.5	12.5	12.5	12.5	13	13	13	12	3

4. Numerical Assessment

4.1. Five-Story Residential Building

In order to investigate the contribution of the TLCGD in reducing seismic induced vibrations, a typical five-story building is considered. The building is located in East of Tehran and has a relatively small plan, as depicted in Figure (9). Its lateral resistant system is moment frame in the *y* direction and concentric brace in the *x* direction. During this numerical example, the main concern is the *y* direction; therefore, two TLCGDs are located in this direction. The building is modeled by a five-DOF system and its characteristics are presented in Table (2). Besides, inherent damping ratios of all modes are assumed to be 5%.

It should be noted that the fundamental period of the building in the y direction is 1.08 s, and the effective mass in the first mode is 310 ton. According to the roof plan of the building, it is possible to have two TLCGDs in two sides of the roof. With respect to the dimensions of the roof plan, it is possible to have a 4% mass ratio for the vibration absorber of the building. Therefore, the liquid mass for each TLCGD should be about 6.2 ton. The following dimensions are selected,

According to Eq. (6), the optimum frequency ratio would be 0.95 and consequently, the optimum frequency of both TLCGDs is 5.54 rad/s. According to Eq. (4) and Table (3), the initial gas pressure for the TLCGDs 1 and 2 should be 50 KPa and 74 KPa, respectively. Final configurations of both TLCGDs are illustrated in Figure (10).

Table 3. Dimensions of the considered TLCGDs.

	b (m)	h (m)	A_b (m^2)	A_h (m^2)	Width (m)	m_f (ton)
TLCGD1	2.5	1	1.4	1.4	1.4	6.3
TLCGD2	4.3	1	1	1	1	6.3

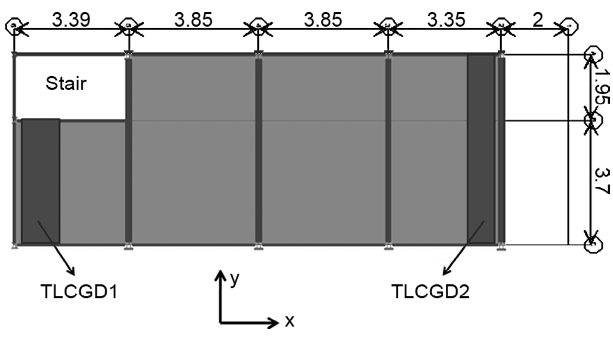


Figure 9. Maximum story Drifts, five nr Settings, meters.

Table 2. Mass and Stiffness of different stories in the y direction.

Story	Mass (Ton)	Stiffness (MN/m)
1	100.2	69.4
2	84.4	31.1
3	84.4	24
4	84.4	19.6
5	65.8	14.4

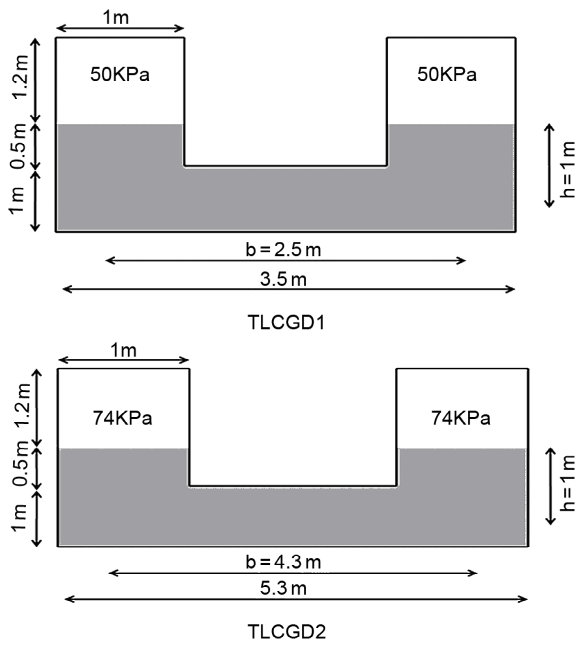


Figure 10. Maximum floor accelerations, five nr Settings (absolute).

According to Eq. (6), considering PGA = 0.35 g for Tehran [1], the optimum head loss coefficient for TLCGD1 and TLCGD2, respectively, are 0.023 and 0.016, but according to Eq. (7) the minimum values for the head loss coefficient, which can be practically achieved, are 0.244 and 0.175, respectively. It should be noted that, however, using such small values for the head loss coefficient would increase the liquid displacement in the vertical columns which is not a good point. As a result, a semi opening orifices with a resistant coefficient of about five is added to both TLCGDs, in this way, the head loss coefficient would be 0.8 and 0.57 for TLCGD1 and TLCGD2, respectively. The building-TLCGD system is modeled in Matlab/SimuLink. It should be elaborated that Eqs. (3) and (5) are used in the SimuLink model for the TLCGD and its force, respectively. It should be noted that commonly linearization are adopted for modeling TLCDs [28], but in this study, nonlinear characteristics of the TLCGD are considered. In other words, in this study, damping of the TLCGD remains nonlinear.

In this example, two digitized ground acceleration records are used, the Cape Mendocino 1992 (Magnitude = 7.1, closest distance to surface projection = 13.7 km, PGA = 0.12 g), and the Northridge 1994 (Magnitude = 6.7, closest distance to surface projection = 12.2 km, PGA = 0.41g) earthquakes. These two seismic events are adopted because of their Fourier spectrum, as depicted in Figure (11). It is clear that in both cases, resonance would occur. It should be noted that both records are scaled to 0.35 g PGA.

The results are presented in Figure (12) and Table (4). It is clear from Table (4) that TLCGD can effectively reduce seismic responses, especially RMS (Root Mean Square) response of the building. However, efficiency of the TLCGD in reducing maximum responses depends on the excitation itself. From Figure (12), it is obvious that the TLCGDs are not activated within first seconds of the quakes.

Maximum displacement of the water in the vertical columns of the TLCGDs and also maximum force of the TLCGDs are illustrated in Table (5). All connections of the TLCGDs to the beams and columns of the building should be designed according to the maximum force of the TLCGD with an appropriate factor of safety. From Table (5), it is clear that the lengths of vertical columns of the TLCGDs are appropriate because water remains in the vertical columns and also the essential assumption of Eq. (4), i.e. $\frac{|y|}{h_a} \le 0.3$, is approximately satisfied.

According to Sec. 3.4, it is possible to estimate the obtained equivalent damping ratio. First mode period of the building is 1.08 s. According to Table

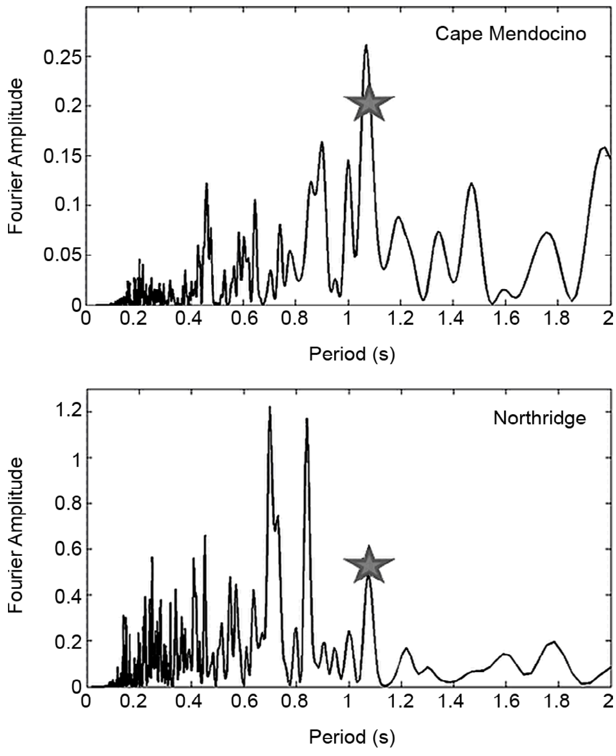


Figure 11. Maximum floor Velocities, five nr Settings, meter/seconds.

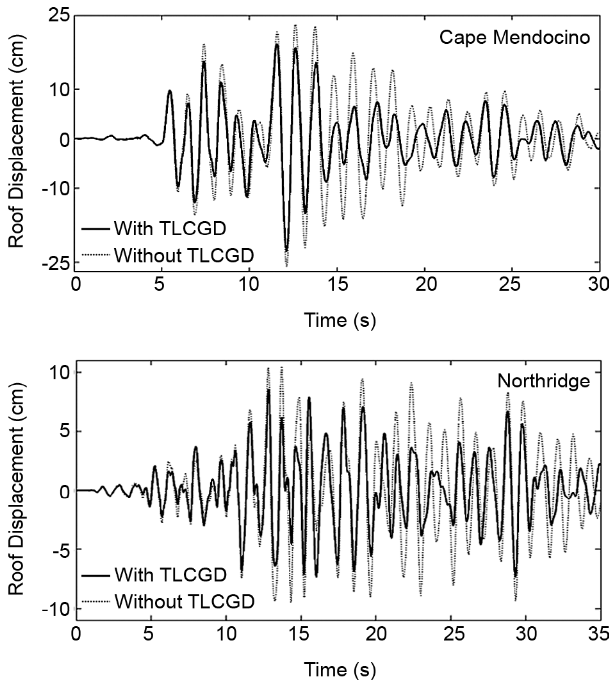


Figure 12. Required Control Forces, five nr Settings, kN.

Table 4. Maximum and RMS response of the five-story building with and without TLCGD.

	Maximum Response					
	Without TLCGD		With TLCGD		Reduction	
	Roof Displacement (cm)	5th Story Drift	Roof Displacement (cm)	5th Story Drift	Roof Displacement (%)	5th Story Drift (%)
Cape Mendocino	25.9	0.0153	22.8	0.0139	12	9
Northridge	10.4	0.0144	8.6	0.0139	17	3
	RMS Response					
	Without TLCGD		With TLCGD		Reduction	
	Roof Displacement (cm)	5th Story Drift	Roof Displacement (cm)	5th Story Drift	Roof Displacement (%)	5th Story Drift (%)
Cape Mendocino	8.0	0.0040	5.7	0.0030	29	25
Northridge	3.9	0.0027	2.8	0.0024	28	11

Table 5. Maximum liquid displacements and forces of the TLCGDs for the five-story building.

	TLCGD1		**TLCGD2**	
	Maximum Force (kN)	Maximum Displacement (m)	Maximum Force (kN)	Maximum Displacement (m)
Cape Mendocino	52	0.36	66	0.46
Northridge	42	0.2	40	0.25

(1), for a TLCGD with mass ratio of 4% and fundamental period of 1s, the equivalent damping ratio is about 9%. If damping ratio of the first mode considered to be 9%, and 5% for other modes are adopted, the maximum roof displacement corresponding to Cape Mendocino and Northridge would be 20.6 cm and 8.6 cm, respectively. By comparing these values with those presented in Table (4), it is clear that a damping ratio of the first mode is increased to 9%. The authors would like to elaborate that this claim is only valid in first mode resonance condition.

4.2. Eight-Story Building

This example devoted to evaluate accuracy of the proposed technique to estimate equivalent damping ratio. A virtual eight-story building is adopted with the characteristics presented in Table (6).

Table 6. Mass and stiffness of each floor of the eight-story building.

Story	Mass (ton)	Stiffness (MN/m)
1	200	400
2	150	400
3	150	370
4	150	370
5	150	340
6	150	340
7	150	310
8	150	310

The first mode period of the building is 0.68 s, and its first mode mass participation is 82%. Inherent damping of all modes is assumed to be 5%.

In this numerical assessment, 10 ground acceleration records are used as shown in Table (7).

The intention is to increase the first mode damping ratio of the building to 10%. Therefore, according to Table (1), the mass ratio of the TLCGD(s) should be 6%. The following values are selected for the parameters of TLCGD(s):

Frequency ratio=0.93

Frequency=$0.93\times 2\pi/0.68=8.59$ rad/s

Head loss coefficient=0.5

Area ratio=2

$b=5$ m

$h=1$ m

$\overline{K}=1.111$

$K_1=0.417$

It should be pointed out that the number of required TLCGDs should be such that it can satisfy the required mass ratio. Besides, it is more convenient that frequency of the TLCGD be tuned by its gas pressure, rather than its geometric parameters. Obtained results are reported in Tables (8) and (9).

According to Table (8), TLCGD can successfully increase damping of the building to 10%, except for earthquake number 2 in which TLCGD has a destructive effect. Such destructive effect can be found in all vibration absorbers, such as TLCD, TMD and

Table 7. Adopted ground motions for the numerical example.

No.	Earthquake	Station Name	Magnitude	PGA(g)	Source
1	BORREGO MOUNTAIN 04/09/68	EL CENTRO ARRAY #9	6.8	0.13	USGS
2	BORREGO MOUNTAIN 04/09/68	EL CENTRO ARRAY #9	6.8	0.057	USGS
3	TABAS 09/16/78	BAJESTAN	7.4	0.094	-
4	TABAS 09/16/78	BAJESTAN	7.4	0.067	-
5	TABAS 09/16/78	TABAS	7.4	0.836	-
6	TABAS 09/16/78	TABAS	7.4	0.852	-
7	MANJIL,IRAN	STATION CODE: 18	7.37	0.184	-
8	SAN FERNANDO 02/09/71	LA HOLLYWOOD STOR LOT	6.6	0.174	USGS
9	SAN FERNANDO 02/09/71	LAKE HUGHES #4	6.6	0.192	USGS
10	SAN FERNANDO 02/09/71	LAKE HUGHES #4	6.6	0.153	USGS

Table 8. Maximum displacement at roof (mm) of the eight-story building.

Record No.	5% Damping	10% Damping	TLCGD
1	31	25	23
2	13	11	20
3	11	9	10
4	7	5	6
5	194	167	171
6	209	165	169
7	32	23	26
8	31	24	23
9	20	17	18
10	21	17	20

TMD. However, this undesirable effect is very rare such that in this study, only one earthquake out of 12 leads to such destructive effect. The main reason of this effect is still unknown; however, it seems that it depends upon pulse arrangement of the ground acceleration and period of the structure. More details about the pulse arrangement idea can be found in [25].

5. Conclusions

During this study, different passive techniques for structural vibration control are described. With emphasis on typical private buildings in Iran, their advantages and disadvantages are reviewed. Different passive dampers can effectively reduce dynamic responses of buildings, but commonly, they are expensive and need maintenance. Besides, most of them need additional braces, which impose limitation for the architectural features. According to the different limitations, especially economical issues, tuned liquid column-gas damper, TLCGD, seems to be a good option for typical private buildings. TLCGD is relatively low cost, easy to manufacture, and virtually it needs no maintenance. Moreover, TLCGD can be easily implemented both in new buildings and under operation existing buildings.

According to obtained results, the equivalent damping ratio of the TLCGD depends upon period of the building and its mass ratio. Using the proposed procedure, one can easily design the TLCGD to achieve a desirable level of damping ratio for the first mode.

According to the numerical example, TLCGD can reduce different responses of the building, especially RMS responses. The results show about 30% reduction in RMS roof displacement and about 15% reduction in maximum roof displacement. Besides, its design and construction are simple and do not need any special equipment or additional braces. However, the authors would like to elaborate that effect of the TLCGD weights should be considered on the columns of the building and roof beams. Moreover, temperature change and gas/liquid leakage would affect initial gas pressure and consequently TLCGD frequency. The authors, therefore, propose to isolate the TLCGD container to avoid both leakage and temperature variation.

However, TLCGD capability in the maximum response reduction is limited. Nevertheless, according to its costs and simplicity, it is probably one of the best options for retrofit of typical buildings in Iran and other similar countries.

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