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Reduction of seismic forces on existing buildings with newly constructed additional stories including friction layer and dampers

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Abstract

This paper presents a new approach to improve seismic readiness of story-increased buildings by utilizing passive structure control techniques. This approach uses passive structural control techniques such as sliding-friction layer and dampers. The sliding-friction layer is sandwiched between the bottom surface of the increased structure and the rooftop of the original building. The energy dissipation dampers are installed between the supporting outer frame for the increased-structure and each floor of the original buildings. To assist dynamic analysis and control design, a simplified structural model of the building system is derived. To increase computational accuracy and to reduce computation time, a novel Coulomb friction representation is incorporated into the non-linear dynamic analysis. The proposed method is applied to a story-increased building and numerical results demonstrate the effectiveness of the proposed method.

1. Introduction

China, a heavily populated developing country, has a large portion of its population live in cities. How to best utilize the limited space in these cities attracts increasing attentions from city planners and researchers, as these cities are experiencing unprecedented economic growth in

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recent years. Most of these cities have a large number of old buildings designed and built without seismic protection about a quarter century ago. Seismic protection was not included in the building codes during that time. Now city planners and land developers are facing a dilemma, whether to demolish these old buildings to build new ones or reuse these old buildings through approaches such as adding new stories. Due to economic constrains, the later choice is often preferred since this choice involves less investment. At present time, many old buildings with sound structures in China have additional new stories [1–3]. However, in many cases the first choice has to be taken since the foundations and supporting walls of the old buildings do not satisfy the current seismic requirements, let alone to support additional stories. It is worthwhile to point out that more than 80% of cities in China are located in regions susceptible to the hazards of seismic activities [4].

How to reuse these structurally weak buildings to add new stories and to satisfy seismic requirements poses a challenge to engineers and researchers. The traditional design approach to make the story-increased buildings resistant to earthquakes, for instance, has been based on improving a combination of their strength, rigidity and ductility. Normally, the implementation of this approach significantly increases cost. Sometimes the traditional approach results in a poorer performance and it may not meet a building owner's needs. Also the traditional approach is difficult to strengthen a building so it is structurally sound when subjected to a variety of earthquake intensities and characteristics. Till now, an earthquake and its characteristics cannot be accurately predicted.

Structural control is a new technology to increase structural seismic protection without modifying the existing structural strength, rigidity and ductility. Structural controls, including active control, semi-active control, passive control, and hybrid control, have been developed and used in civil engineering [5]. Passive structural control, with advantages of low cost, simple construction, easy installation, and less or even free maintenance, is the mostly used structure control technology. Passive control often employs various types of dampers [6–10], such as friction damper, metallic damper, viscoelastic damper, and viscous fluid dampers, to passively dissipate energy. Such passive devices can be found in many structures throughout the world. They are commonly employed via seismic elements such as braces in the beam-column frames. Other passive control techniques include rubber bearings for seismic isolation and sliding-friction layer for energy dissipation [11,12]. Experiments and analyses have shown that these passive control methods are quite effective to reduce the responses of structures under the action of earthquake.

The objective of this study is to develop a new approach to reclaim the structurally weak buildings so that new stories can be added and seismic standards can be met by utilizing passive structure control techniques. In this approach, additional stories are supported by an outer-frame to reduce load to the original building. This approach uses passive structural control techniques of sliding-friction layer and dampers. The sliding-friction layer is sandwiched between the bottom surface of the increased structure and the rooftop of the original building. The energy dissipation dampers are installed between the supporting outer frame for the increased-structure and each floor of the original buildings. With a proper design, these passive devices significantly reduce seismic response of the original building and the add-on structure. To assist dynamic analysis and control design, a simplified structural model of the building system is derived. To increase computational accuracy and to reduce computation time, a novel Coulomb friction representation is incorporated into the non-linear dynamic analysis. The proposed method is applied to a story-increased building and numerical results demonstrate the effectiveness of the proposed method.

2. Simplified model and formulation

2.1. Model descriptions and basic assumptions

A simplified diagram of the original building with increased stories is shown in Fig. 1. It is clear from Fig. 1 that the increased stories are supported by a new frame, which is constructed outside of the original building. In this paper, this new frame is called the outer frame. Through this design, no significant load is added to the original building. A sliding-friction layer is sandwiched between the bottom surface of the increased structure and the rooftop of the original building. The energy dissipation dampers are installed between the supporting outer frame for the increased-structure and each floor of the original buildings.

The model analysis and numerical simulations in this paper are based on the following assumptions:

1. The stiffness of each floor in the horizontal plane is infinite.
2. Masonry and reinforced concrete frame structures are used and the deformations between adjacent stories and the deformation of the whole structure are shear patterns.
3. The mass of each story is concentrated at the corresponding floor elevation.
4. The sliding-friction force between original building and the increased-structure obeys the Coulomb friction law.

2.2. Analysis model and equation of motion

The story-increased structural system shown in Fig. 1 consists of two structures: the original structure as structure I and the outer-frame structure as structure II. The connections between

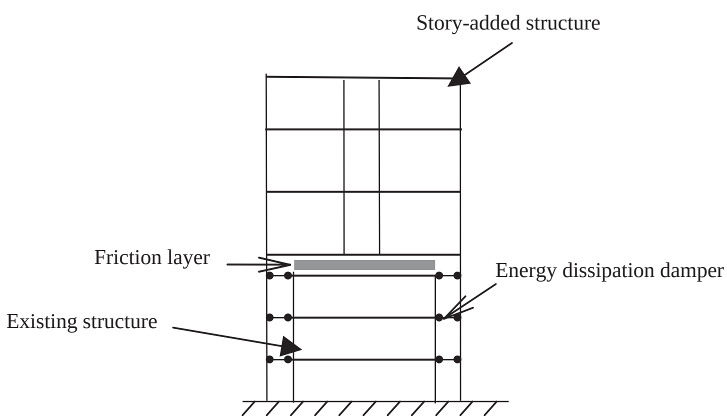

Fig. 1. Structure system model.

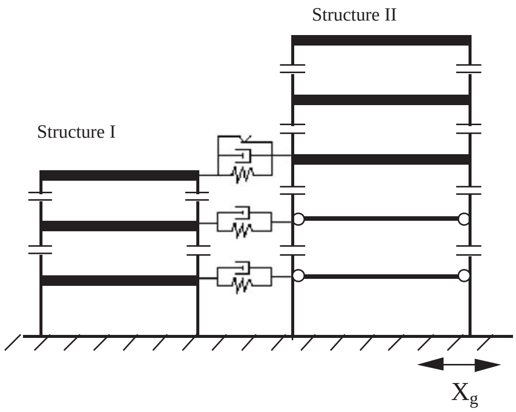

Fig. 2. Simplified computational model for structural system.

both structures are made through passive devices: a sliding-friction layer and passive dampers. The simplified computational model of system is illustrated in Fig. 2.

Assume the numbers of degree-of-freedom of structures I and II are n and m, respectively. Also assume N is the number of the degree-of-freedom of the whole structure, therefore, $N = n + m$. The equations of motion for structures I and II under the action of earthquake can be derived as follows:

$$\begin{aligned}[M]_{\mathrm{I}}\{\ddot{x}\}_{\mathrm{I}}+[C]_{\mathrm{I}}\{\dot{x}\}_{\mathrm{I}}+[K]_{\mathrm{I}}\{x\}_{\mathrm{I}}+\{F\}_{\mathrm{I}}&= -[M]_{\mathrm{I}}\{I\}\ddot{x}_g,\\ [M]_{\mathrm{II}}\{\ddot{x}\}_{\mathrm{II}}+[C]_{\mathrm{II}}\{\dot{x}\}_{\mathrm{II}}+[K]_{\mathrm{II}}\{x\}_{\mathrm{II}}+\{F\}_{\mathrm{II}}&= -[M]_{\mathrm{II}}\{I\}\ddot{x}_g.\end{aligned} \tag{1}$$

Eq. (1) can be combined and rewritten as the following matrix form:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} + \{F\} = -[M]\{I\}\ddot{x}_g, \tag{2}$$

where $[M]$, $[C]$ and $[K]$ are respectively the mass, damping (Rayleigh damping), and stiffness matrices of the system. $\ddot{x}_g$ denotes the seismic ground acceleration. $\{x\}$, $\{\dot{x}\}$and $\{\ddot{x}\}$ represent the displacement , velocity and acceleration vectors of the system expressed as

$$\{\ddot{x}\} = \begin{Bmatrix} \{\ddot{x}\}_{\mathrm{I}} \\ \{\ddot{x}\}_{\mathrm{II}} \end{Bmatrix}, \quad \{\dot{x}\} = \begin{Bmatrix} \{\dot{x}\}_{\mathrm{I}} \\ \{\dot{x}\}_{\mathrm{II}} \end{Bmatrix}, \quad \{x\} = \begin{Bmatrix} \{x\}_{\mathrm{I}} \\ \{x\}_{\mathrm{II}} \end{Bmatrix}$$

and

$$\{I\} = \underbrace{\{1\cdots1\cdots1\}^{\mathrm{T}}}_{n+m}, \quad \{F\} = \begin{Bmatrix} \{F\}_{\mathrm{I}} \\ \{F\}_{\mathrm{II}} \end{Bmatrix},$$

where $\{I\}$ is the unit vector. $\{F\}_{\mathrm{I}}$ and $\{F\}_{\mathrm{II}}$ are, respectively, the vectors of control forces between the structures I and II. They can be written separately as

$$\begin{aligned}\{F\}_{\mathrm{I}}&= \{f\}_{\mathrm{I}} + \{R\},\\ \{F\}_{\mathrm{II}}&= \{f\}_{\mathrm{II}}+\{R'\},\end{aligned} \tag{3}$$

$$\{f\}_{\mathrm{I}}= \left\{f_{1,1}\cdots f_{1,i}\cdots f_{1,n}\right\}^{\mathrm{T}}, \tag{4a}$$

$$\{f\}_{\mathrm{II}}=\left\{f_{2,1}\cdots f_{2,i}\cdots f_{2,n}0\cdots 0\right\}^{\mathrm{T}}, \tag{4b}$$

$$\{R\} = \mu\, m_0 g\, \mathrm{sgn}(\dot{x}_{1,n} - \dot{x}_{2,n}), \tag{5a}$$

$$\{R'\} = \mu\, m_0 g\, \mathrm{sgn}(\dot{x}_{2,n} - \dot{x}_{1,n}), \tag{5b}$$

where $\{f\}_{\mathrm{I}}$ and $\{f\}_{\mathrm{II}}$ imply the vectors of control forces provided by the energy dissipation dampers. $\{R\}$ and $\{R'\}$ are the vectors of the sliding-friction forces between the bottom surface of the increased structure and the rooftop of the original building. μ is the friction coefficient. g is the acceleration due to gravity and m_0 is the floor mass set on the friction layer in order to provide control force. $\dot{x}_{1,n}$and $\dot{x}_{2,n}$ represent the relative velocities of the nth degree in the structures I and II. And sgn(s) is the sign function that is equal to $+1$ when s is positive, and –1 when s is negative. The value of sgn(0) is zero. And the ith representations of the vectors of $\{f\}_{\mathrm{I}}$ and $\{f\}_{\mathrm{II}}$ are shown as follows:

$$\begin{aligned} f_{1,i} &= k_{0i}(x_{1,i} - x_{2,i}) + c_{0i}(\dot{x}_{1,i} - \dot{x}_{2,i}), \\ f_{2,i} &= k_{0i}(x_{2,i} - x_{1,i}) + c_{0i}(\dot{x}_{2,i} - \dot{x}_{1,i}), \end{aligned} \tag{6}$$

where k_{0i} and c_{0i} represent the stiffness and damping of the ith energy dissipation damper, $x_{1,i}$ and $x_{2,i}$ are the ith relative displacement vectors of the structures I and II, respectively.

2.3. Stick–sliding criteria and introduction of friction representation

For the story-increased structural system discussed in this paper, the sliding-friction is a major source of energy dissipation. Prior to establishing the stick–sliding transition criteria, the following relationships are defined:

$$\begin{aligned} I1 &= \left|\sum_{i=1}^{n} m_{1,i}(\ddot{x}_{1,i} + \ddot{x}_g) + k_{1,1}x_{1,1} + c_{1,1}\dot{x}_{1,1} + \sum_{i=1}^{n} k_{0,i}(x_{1,i} - x_{2,i}) + \sum_{i=1}^{n} c_{0,i}(\dot{x}_{1,i} - \dot{x}_{2,i})\right|, \\ I2 &= \left|\sum_{i=1}^{n+m} m_{2,i}(\ddot{x}_{2,i} + \ddot{x}_g) + k_{2,1}x_{2,1} + c_{2,1}\dot{x}_{2,1} + \sum_{i=1}^{n} k_{0,i}(x_{2,i} - x_{1,i}) + \sum_{i=1}^{n} c_{0,i}(\dot{x}_{2,i} - \dot{x}_{1,i})\right|, \end{aligned} \tag{7}$$

where $I1$ and $I2$ are, respectively, the summations of all forces on structures I and II. These forces include total horizontal inertial forces, elastic restoring forces, damping force due to sliding-friction layer, as well as the passive control forces produced by energy dissipation dampers.

Under the assumption of the Coulomb friction principle, the non-slip stage remains as long as

$$I \leqslant F_s = \mu_s m_0 g \quad \text{and} \quad \dot{x}_{1,n} - \dot{x}_{2,n} = 0, \tag{8}$$

where I denotes the larger value in $I1$ and $I2$. F_s is the maximum of static friction force and μ_s is the static friction coefficient. During a stick period, the friction force equals to the inertial force from the outer frame structure.

The sliding stage starts as soon as the following condition is met:

$$I > F_S = \mu_S m_0 g \tag{9}$$

and the friction force is now equal to the so-called slip friction, given as

$$F_d = \mu_d m_0 g \,\mathrm{sgn}(\dot{x}_{1,n} - \dot{x}_{2,n}), \tag{10}$$

where μ_d is the slip friction coefficient.

Due to the strong non-linear property of friction layer, the time interval of numerical integrations has to be very small in order to achieve certain accuracy. Otherwise, simulation errors can be accumulated to a large value. However, no matter how tiny the time steps are, it is impossible to identify the exact time when the sliding velocity passes the zero value. Hence, a continuous function is introduced here to replace the discontinuous relationship between the friction force and sliding velocity. This may avoid tracing difficulty during each stick–slip phase and its transiting boundary [13]. Through a reasonable selection, the following function, which closely approximates the exact discontinuity, is employed:

$$f_1(\alpha_1, v) = \mathrm{Erf}(\alpha_1 v), \tag{11}$$

$$\mathrm{sgn}(v) = f_1(\alpha_1, v) \cdot F = \mu m_0 g f_1, (\alpha_1, v), \tag{12}$$

where v is the sliding velocity, α is a non-unit parameter and $\mathrm{Erf}(\cdot)$ represents the error function. In order to visually illustrate the relationship between the $f_1(\alpha, v)$ and v, the continuous function f_1 with the changing parameters of α and v is depicted in Fig. 3. It is obvious from this figure that the larger the α is, the closer the $f_1(\alpha, v)$ continuously comes to the sign function $\mathrm{sgn}(v)$. If $\alpha = 3600$, the function $f_1(\alpha, v)$ changes from -1 to $+1$ as the velocity changes from -10^{-3} to $+10^{-3}$, and its errors fall to 10^{-6}. Thus, such a simplification makes the maximum error of analytical results stay below the 1% relative to the accurate values when α is assigned as a value of 100.

Based on the fourth order Runge–Kutta method, a MATLAB program is developed to solve the equations of motion for the system subjected the excitations of earthquake ground acceleration and numerical simulations are used for parametric study.

3. Parametric study

Parameters of interests include the ratio of natural vibration periods of the outer frame to the original structure, the friction coefficient of the sliding-friction layer, the stiffness and damping of

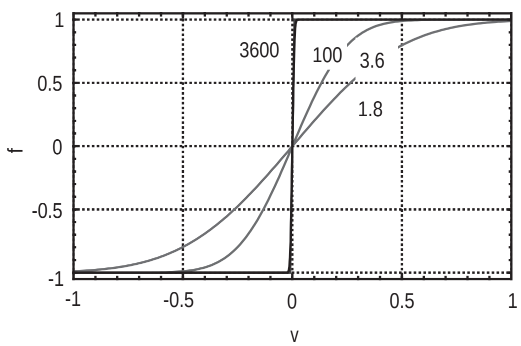

Fig. 3. $f(\alpha = 1.8, 3.6, 100, 3600)$.

the energy dissipation dampers. The effects of these parameters on the seismic response behaviors and vibration reduction rates of the system will be investigated. Also, the influence the earthquake intensity will be studied.

To simplify the numerical simulations, both the original and the outer frame structures are assumed to be single story. Here, it is assumed that the weights of the original structure and the outer frame structure are 316 and 111.7 tons, respectively. A 5% damping ratio is used in simulations.

The vibration reduction rate, δ, of system due to the seismic excitations is defined as

$$\delta = \frac{D - D_1}{D} \times 100\%, \tag{13}$$

where D and D_1 are the displacement response peaks without control and with control, respectively.

3.1. Ratio of periods

Considering the common range of the predominant periods ($T1$) of candidate buildings for floor increase in China, five different periods are selected here as: $T1 = 0.1$, 0.25, 0.3, 0.4, 0.5, 1.0 s. The outer frame structure is relatively more flexible than the original structure, its period ($T2$) is therefore longer. Keeping this in mind, nine period ratios are chosen as $T2/T1 = 0.2$, 0.5, 1, 2, 3, 4, 5, 10, 15 in this parametric study. The vibration reduction rates of the system with different period ratios are investigated.

Figs. 4 and 5 illustrate the typical curves of displacement reduction rate of seismic responses as a function of $T2/T1$. Other parameters are set to their typical values: $\mu = 0.25$, $k_0 = 0$ and $c_0 = 0$. The seismic acceleration of May 18, 1940 in El Centro is used as the input. It can be seen from the two figures that, when $T2/T1$ less than 1, δ of the original structures decreases with the increase of period ratio; meanwhile, however there is no clear trend for δ of the outer frame structure. When the ratio is equal to 1, the vibration reduction rate is zero. This means that both original and the outer frame structures vibrate at a same pace as if they are bonded together and the sliding-friction layer does not dissipate any energy. When the ratio of periods is greater than 1, especially when it ranges from 2 to 5, the reduction rate δ of seismic responses of the system generally reaches a satisfactory value. After the ratio of periods continues to increase, the reduction rate

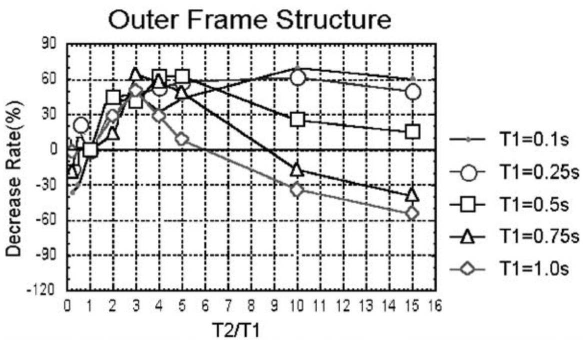

Fig. 4. Seismic displacement reduction rate of outer frame structure versus ratio of period.

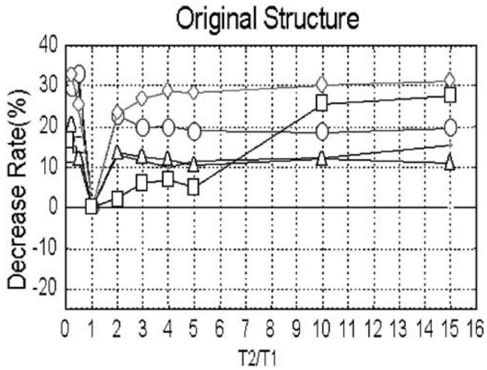

Fig. 5. Seismic displacement reduction rate of original structure versus ratio of period.

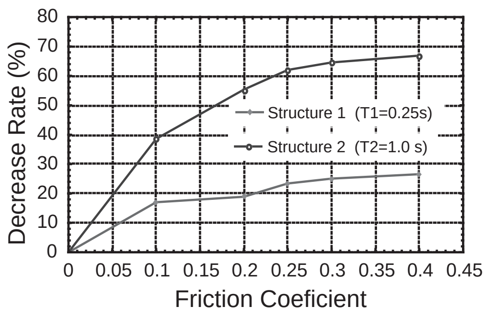

Fig. 6. Displacement reduction rate versus friction coefficient.

begins to decrease in some cases of outer frame structure. This is not observed in the original structure. It is noted that the seismic responses of outer frame structure may be amplified when the periods of it are relatively very large, for instance, when $T1$ is equal to 1.0 or 0.75 s. This may probably be due to the reason that the differences between the stiffnesses of outer and original structures are so large that their vibration direction may sometimes be same, and then action of original structure helps the response of outer frame while the outer frame resists the motion of original structure. Therefore, by adjusting the ratio of periods of the original structure and the outer frame structure, an optimal result can be obtained for the seismic reduction of story-increased structural system.

3.2. Friction coefficient

The friction coefficient of the sliding-friction layer, μ, is a key parameter to determine the frictional force produced by the friction layer. It is well known that the larger the friction coefficient is, the greater the frictional resisting force is during a sliding process. To study the change of δ with μ, the ratio of periods is chosen as 4, which represents large vibration displacement reduction rates for both the original and the outer frame structures from Figs. 4 and 5. According to the characteristics of the commonly used engineering materials, the friction coefficients in the range from 0 to 0.4 have been taken into consideration during the parametric study. The results are shown in Fig. 6. It is clear from this figure that the seismic response reduction rate of the system increases with the increase of friction coefficient, μ, especially for the outer frame structure with an increase rate greater than that of the original structure.

3.3. Damping and stiffness of energy dissipating damper

The energy dissipating dampers at the connections between the original structure and the outer frame structure also play an important role. Other parameters are the same as those used in Sections 3.1 and 3.2. Figs. 7 and 8 present the seismic displacement response reduction rates versus the stiffness k_0 and damping factor c_0 of dampers. It can be seen from these figures that, as k_0 is fixed, the reduction rate declines with the increase of c_0, while the reduction rate changes slightly with the variances of k_0 for a constant c_0. Hence, the damping coefficient is here the main factor in the seismic response system.

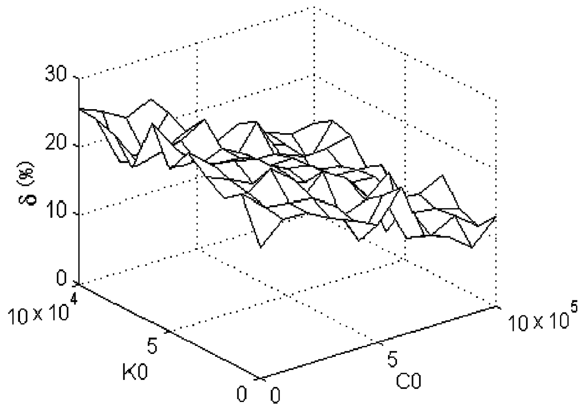

Fig. 7. Reduction rate of original structure.

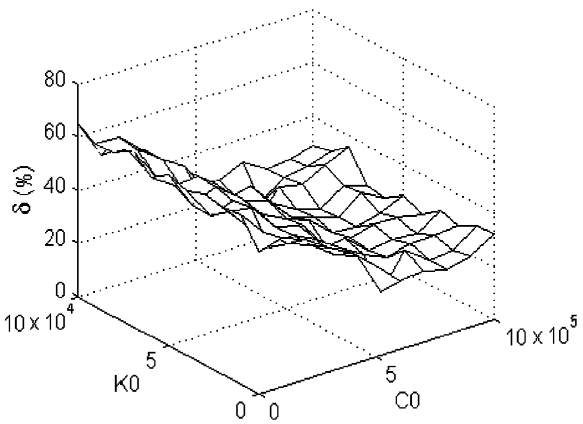

Fig. 8. Reduction rate of outer frame structure.

Table 1
Seismic displacement reduction rates of system

Earthquake site intensity	Qian An Record, $\Delta t = 0.01$ s, dominant period 0.1 s		El Centro Record, $\Delta t = 0.02$ s, dominant period 0.5 s		Ning He Record, $\Delta t = 0.01$ s, dominant period 0.9 s	
	Original structure (%)	Outer frame structure (%)	Original structure (%)	Outer frame structure (%)	Original structure (%)	Outer frame structure (%)
VII	17.23	42.43	30.33	88.56	19.79	84.58
VIII	15.91	35.23	28.59	76.56	15.34	53.82
IX	9.56	22.67	20.52	60.93	5.90	27.98

3.4. Earthquake intensity

Earthquake intensities may influence the effectiveness of the structural control on the story-increased structure. In this section, three earthquake acceleration records, Qian An Bridge, 1976 in China, El Centro, 1940 in USA, Tian Jin Hospital, 1976 in China, are used to calculate the seismic displacement reduction effectiveness of this passive control system presented. To match the seismic acceleration peak values for different earthquake intensities in China Code (GBJ89-11) [5], the three record peaks are correspondingly adjusted to $100\,\text{cm/s}^2$ (VII degree), $200\,\text{cm/s}^2$ (VIII degree) and $400\,\text{cm/s}^2$ (IX degree). All the structural characteristic parameters are the same as those of Section 3.1. Typical seismic reduction rates are shown in Table 1. A period ratio $T2/T1 = 4$ is used in this study.

From Table 1, notice that the displacement reduction rates in both structures decrease with the increase of the earthquake intensity for all three cases. To the El Centro excitation, the reduction rates reach above 60%, which is especially advantageous for the outer frame structure as it usually has a flexible first floor. Therefore, satisfactory seismic reduction rates are obtained for the outer frame structure and the original structure.

4. Engineering project

A practical building photograph of this story-increased structure after construction is shown in Fig. 9. The original four-story office building with its planar sketch shown in Fig. 10 is chosen as an object for further numerical studies. This building was constructed in the 1950s along Beiling Street in Shenyang, a major city in northeastern China. No seismic design was involved in the original building since there was no seismic code at that time in China. The original building is composed of brick masonry structure; its design is not in compliance with the current Seismic Code [14] in China. The seismic protection intensity on this building site is VII degree, and the site soil belongs to the type II in China Code. Using the passive structural controls presented in Section 2.1, a four-story structure with an outer frame will be added to the original building to improve seismic performance of both structures.

According to the parametric studies in Section 3, the range 2–5 for the ratio of periods of the original structure and outer frame structure represents an effective seismic reduction for the

Fig. 9. Practical building photograph of the story-increased structure after construction.

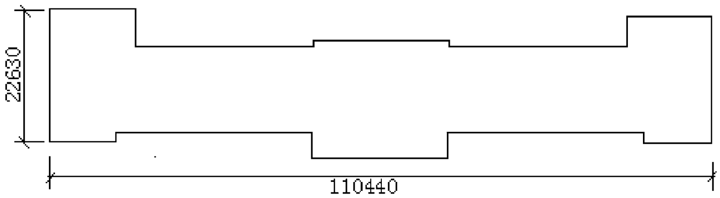

Fig. 10. Building layout.

Table 2
Parameters of structural system

Floor no.	Outer frame structure		Original structure	
	Floor mass (t)	Story stiffness (10^3 K N/m)	Floor mass (t)	Story stiffness (10^3 K N/m)
1	336.6	1420	1282.54	3620
2	321.8	1420	1170.93	3620
3	321.8	1420	1170.93	3580
4	427.0	1856	987.68	3580
5	1071.2	2252	—	—
6	1106.2	2252	—	—
7	1106.2	2252	—	—
8	1158.0	2252	—	—
Period	$T_1 = 0.8502, T_2 = 0.2027, T_3 = 0.1331, T_4 = 0.0989$		$T_1 = 0.3153, T_2 = 0.1119$	

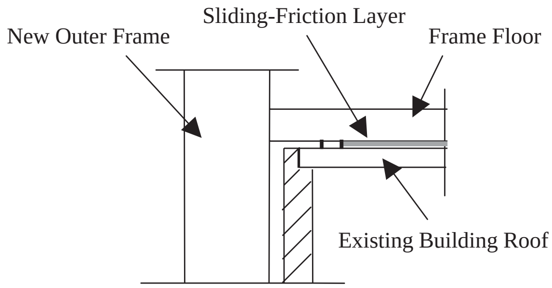

Fig. 11. Construction of friction layer.

Table 3
Friction layer parameter

Material	μ	Above weight
Sand	0.25	300 t

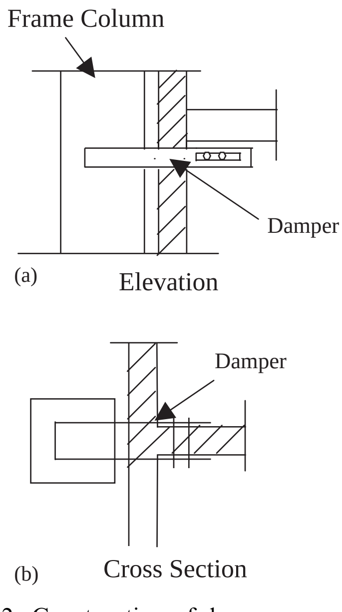

Fig. 12. Construction of damper connection.

story-increased structural system. Hence, the period ratio is chosen as 2.7 in this study. The parameters of the outer frame and original structure are listed in Table 2. The outer frame is composed of four stories over the original building. The friction layer is set between the lower floor of upper structure and top floor of the original structure with sands as the friction material. Its construction scheme is depicted in Fig. 11. To produce the internal frictional force, the first floor's self-weight of the addition structure is directly laid on the friction layer on the top of

Table 4
Damper parameters

Floor No.	Stiffness (KN/m)	Damping (K N s/m)
1	1.0×10^7	1.0×10^5
2	1.0×10^7	1.0×10^5
3	0.0	0.0
4	0.0	0.0

original structure and then this floor is not connected to the columns of outer frame structure by using the approach of post-pouring concrete. The sliding-friction layer parameters are shown in Table 3. The energy dissipation dampers, for example, simple friction dampers, are placed at the joints connecting two structures at the first two floors, as shown in Fig. 12. The parameters of the dampers are given in Table 4.

Three earthquake acceleration signals used in Section 3.4 are implemented to compute the seismic response reduction rates and reliability of system. The results are summarized in Table 5.

It is noted from Table 5 that the seismic reduction rate of each floor in the original structure increases from the lowest floor to the top floor under seismic actions. This means that the seismic responses of the original building are mainly reduced by the friction layer. As the horizontal stiffness of the outer frame structure is not uniformly distributed for each story, the law of seismic reduction rates is different from the original structure. Generally, the closer to the friction layers it is, the greater the response reduction is, for instance, at the 4th, 5th and 6th floor. On the other hand, it can also be seen that the seismic reduction rate is related to the basic periods of the input earthquake records. That is, the smaller the basic period of the record is, the larger the reduction rate of the structural system is, and vice versa.

5. Concluding remarks

The new energy dissipating system for story-increased buildings with the outer frame structure is presented in this paper by use of the sliding-friction layer and energy dissipation dampers. This system is typically suitable for the retrofits of seismic damaged and old city buildings. The effectiveness of the proposed approach is investigated by means of dynamic analysis of the structure subjected to earthquake excitations. The seismic performance of the system depends considerably on the ratio of periods of the outer frame to the original structure, the friction coefficient of the sliding friction layer, the damping and stiffness of dampers and the earthquake intensity. An appropriate selection of these parameters reduces the seismic response of the system to a desirable level. Some conclusions of practical significance can be drawn from the numerical analyses.

1. The period ratio of the outer frame structure to the original structure is the main factor, which can greatly affect the effectiveness of seismic reduction.

Table 5
Seismic reduction rate under different earthquake actions

Seismic records	Floor no.	Qian An			EL Centro			Ning He		
		Uncontrolled	Controlled	Reduction rate	Uncontrolled	Controlled	Reduction rate	Uncontrolled	Controlled	Reduction rate
Original structure	1	−3.03	−1.81	40.38	3.41	3.63	−6.31	−3.70	−3.60	2.65
	2	−5.57	−3.18	42.96	6.14	6.41	−4.34	−6.85	−6.50	5.14
	3	10.24	−4.21	58.85	10.24	8.64	15.60	−10.36	9.18	11.41
	4	12.76	−4.57	64.15	12.76	9.63	24.52	−12.17	10.75	11.62
Outer frame structure	1	−2.93	−1.79	38.78	3.37	3.59	−6.43	−3.66	−3.57	2.33
	2	−4.57	−3.16	30.87	5.82	6.28	−7.940	−6.47	−6.40	1.12
	3	6.60	−3.89	41.13	6.60	7.82	−18.41	7.27	−8.07	−11.03
	4	13.53	5.15	61.98	13.53	8.80	34.99	10.97	−9.23	15.92
	5	17.37	5.16	70.27	17.37	8.40	51.64	12.33	9.46	23.29
	6	14.51	−3.86	73.42	14.51	5.95	59.01	−10.14	7.83	22.82
	7	7.01	2.44	65.24	7.01	−3.02	56.97	−5.12	4.79	6.50
	8	11.26	3.67	67.38	11.26	−4.70	58.22	−8.21	7.51	8.49

2. The larger the friction coefficient of the sliding-friction layer, the better the seismic reduction rate for both structures.
3. The damping ratio of each energy dissipation damper plays a more important role than that played by the stiffness of the damper.
4. Under different earthquake intensities, the story-increased system with proposed passive damping devices perform wells and produces a good seismic reduction if the suitable parameters are selected.

Based on the parametric and case study presented in this paper, it may be concluded that in general the implementation of the proposed method can significantly improve seismic readiness of story-increase buildings. The modelling, analytical methodology and parameter studies conducted here open a new way in passive structural systems. The shaking-table experiment and design process for such a system are on-going and will be presented in the future.

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