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The effect of mainshock-aftershock on the residual displacement of buildings equipped with cylindrical frictional damper

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Abstract. Recently, Friction dampers become popular due to the desirable performance in the energy dissipation of lateral loads. A lot of research which has been conducted on these dampers results in developing friction dampers with low sensitivity to the number of cycles and temperature increases. Friction dampers impose high residual drifts to the buildings because of low post-yield stiffness of the damper which results from increasing lateral displacement and period of buildings. This issue can be more critical under strong aftershocks which results in increasing of structural damages. In this paper, in addition to the assessment of aftershock on steel buildings equipped with friction dampers, methods for controlling residual drifts and decreasing the costs of retrofitting are investigated. Utilizing rigid connections as a lateral dual system and activating lateral stiffness of gravity columns by adding elastic braces are as an example of effective methods investigated in this research. The results of nonlinear time history analyses on the low to medium rise steel frames equipped with friction dampers illustrate a rise in residual drifts as the result of aftershocks. In addition, the results show that different slip loads of friction damper can affect the residual drifts. Furthermore, elastic stories in comparison to rigid connections can reduce residual drifts of buildings in an effective fashion, when most slip loads of friction dampers are considered.

Keywords: steel buildings; residual displacement; cylindrical frictional dampers; mianshock-aftershock earthquake; nonlinear time history analysis

1. Introduction

Earthquake is one of the natural hazards on this planet which has destroyed many buildings in different regions of the world. The purpose of the current construction regulations is to avoid from total collapse of buildings during severe earthquakes, but partly allowed to limited structural failures. This inelastic response causes residual displacements in the buildings which is not desirable. Residual drifts greater than 5% after earthquake in building may represent a complete loss of the structure from an economic point of view (Erochko *et al*. 2011). Seismic response control techniques can be grouped into passive, active and semi-active control systems. Active control requires a power supply activating the dampers and hence may be undependable during seismic events when the power supply may be disrupted. On the other hand, passive energy dissipation systems have emerged as special devices that incorporated within the structure to absorb a portion of the input seismic energy (Marko 2006). Damping is a specific property of a material which may be disturbed due to some environmental effects. This issue is a significant drawback in viscoelastic and steel dampers. On the contrary, one of the main passive control devices is frictional damper independent of the applied loading frequencies, number of load cycles, and variation in temperature (Marko 2006). However, friction devices have a number of drawbacks and their behavior may be affected by various conditions, such as surface finish, sliding velocity, normal force, contact pressure, wear, temperature, sensitivity on dirtiness, corrosion, uncertainty of onset of sliding, and dissipated energy per cycle being proportional to displacement. Previous research by the authors (Samani *et al*. 2014) clearly demonstrate the issues mentioned above.

Many different types of passive frictional energy dissipation devices have been developed in recent years. The idea of using frictional dampers was first proposed by Pall (1979). Pall and Marsh (1982) proposed frictional dampers installed at the crossing joint of the X-brace. Tension in one of the braces forces the joint to slip thus activating four links, which in turn force the joint in the other brace to slip. This device is usually called the Pall frictional damper (PFD). Monir and Zeynali (2013) introduced and tested a modified friction damper (MFD) which was similar to Pall friction damper however it was applied in the diagonal bracing. Most of frictional dampers compromise a set of steel plates that are clamped by pre-tentioned bolts to produce friction between the involved elements. The possible relaxation or loosening of the link elements such as spring or bolts makes the behavior of frictional dampers unpredictable and may lead to decay of slippage load. Amiri *et al*. (2011) studied the evaluation of eccentric braced steel frames (EBF) equipped with friction damper (FD). The result indicates that FD reduces the response compared to EBF and is more efficient than EBF for taller story frames. Recently, Mirtaheri *et al*. (2011)

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proposed an innovative type of frictional damper called Cylindrical Frictional Damper (CFD). In contrast with other frictional dampers, the CFDs do not use high-strength bolts to induce friction between contact surfaces. This reduces construction costs, simplifies design computations, and increases reliability compared with other types of frictional dampers.

Friction dampers such as Cylindrical Frictional Damper (CFD) unlike the viscose dampers are independence from velocity. These dampers are designed by a specific slip load. Hence if the applied load become greater than the slip load, these dampers will start to dissipate the energy by friction between two surfaces. Friction dampers compare to others are less affected by loading frequency, number of loading cycles and temperature changes (Mirtaheri *et al*. 2011). Despite of desirable performance and significant energy dissipation of friction dampers, these systems increase period of buildings which results in undesirable residual drifts. These residual drifts are major concerns in their performance particularly under long-term earthquakes and strong aftershocks. Therefore, relative residual displacements must be investigated in the buildings equipped with friction dampers as the main weakness of the system. Aftershocks can amplify the problem dramatically, therefore in order to reduce relative residual displacements and structural damages, an acceptable solution should be considered. Christopoulos and Pampanin (2004) studied the possibility of considering residual drifts in performance-based seismic design. The research determined that post-yielding stiffness (amount of stiffness remaining in a building after members have yielded) influences residual deformations significantly. In addition, dynamic response of two adjacent single degree-of-freedom (SDOF) structures connected with friction damper under base excitation was investigated (Patel and Jangid 2011). It is observed that there exists an optimum value of the limiting frictional force of the damper for which the mean square displacement and the mean square absolute acceleration responses of the connected structures attains the minimum value. Residual displacements are significantly more sensitive to both higher modes and p-delta effects. Garcia (2010) summarized results of a comprehensive analytical study aimed at evaluating the influence of strong ground motion duration on residual displacement demands of single-degree-of-freedom (SDOF) and multi-degree-of-freedom (MDOF) systems. The result shows that the strong motion duration does not have a significant influence on the amplitude of peak residual drift demands in MDOF systems, but records having long strong-motion duration tend to increase residual drift demands in the upper stories of long-period generic frames. In general, rigid connections, Post-tensioned (PT) moment connections, self-centering energy dissipative (SCED) bracing system and dual systems (BRBF's Coupled with Gravity Columns) have been found to be an effective way to reduce residual drifts (Ricles *et al*. 2001, Fahnestock *et al*. 2007, Christopoulos *et al*. 2008, Chou and Chen 2012)

The main objective of this study is to gain further understanding on the effects of mainshock-aftershock seismic sequences in the behavior of steel buildings equipped with Cylindrical Frictional Damper (CFD). In addition, utilizing rigid connections and activating lateral stiffness of gravity columns by adding elastic braces (CFD frames Coupled with Gravity Columns) as a lateral dual system are investigated to reduce residual drifts as the result of seismic shocks (mainshock-aftershock). For this purpose, four 3D steel frames including 4, 6, 8, 10 stories are designed symmetrically in two directions based on AISC360_05 code. Then, different 2D steel frames in term of height are selected and modeled using OpenSees software. CFDs are added to the models subsequently. Non-linear time history analyses are performed. In these analyses, seven seismic records are selected from Site Peer and scaled based on UBC 2010. Relative residual displacements obtained at the end of the first analysis (mainshock) are compared with those obtained at the end of the second analysis (aftershock). In order to find the optimum slip-load leading to minimum relative residual displacement, four slip loads are examined. Subsequently, a parametric study is conducted. Afterwards, rigid connections and activating lateral stiffness of gravity columns by elastic braces as two effective methods are compared to reduce relative residual displacements.

2. Prototype building layout and design parameters

Fig. 1 shows a plan view of the basic building layout used in this study. The basic design has 3 bay widths of 5 m in each direction. The height of each story is 3.2 meter. The middle columns have rigid connections and side columns have pinned connections to the base. The braces are located at the middle bay locations on each side of the building. Basic building including 4, 6, 8, 10 stories are designed based on AISC seismic provision for seismic zone 2 and soil type ц. An importance factor of 1.0 is used. According to the Mirtaheri *et al*. (2011) research, the value for Impact Factor is derived to be 6 for Cylindrical Frictional Damper (CFD). In this study, the authors decide to use the same value which is consistent with the previous study. The effects of P-delta and vertical earthquake component are considered in the design of prototype models. Pinned connections are also considered to all models. A permanent load of 6 kN/m^2 and a live load of 2 kN/m^2 are adopted in

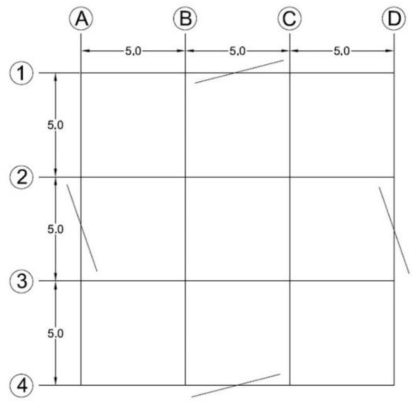


Fig. 1 Plan view of the basic building (dimensions in meter)

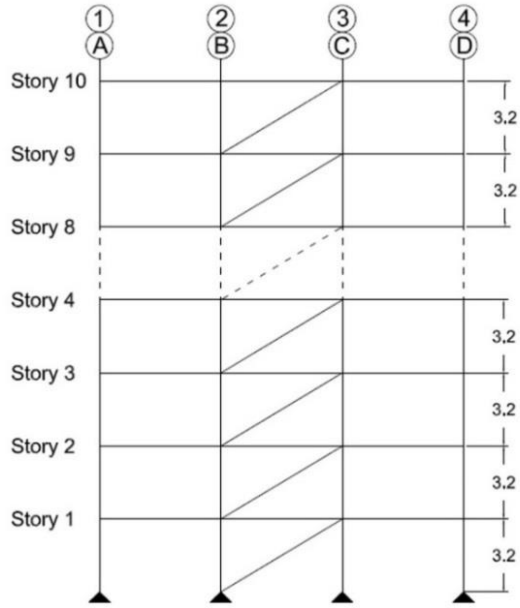


Fig. 2 The elevation of 2D frames modeled in OpenSees (dimensions in meter)

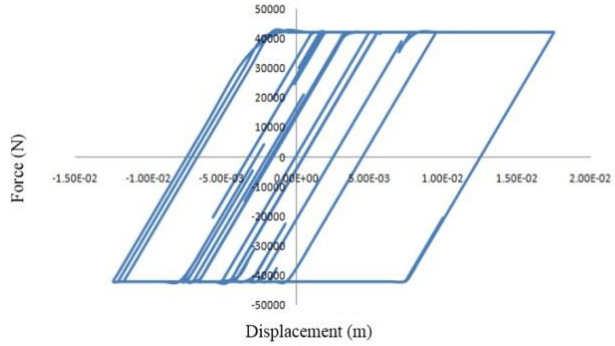


Fig. 3 The hysteretic behavior of CFDs in the first floor of 4-story frame

the design of the building. The only exception is the roof, which has a permanent load of 5 kN/m^2 and a live load of 1.5 kN/m^2. After the complete design, 2D steel frames (frame A) in terms of height are modeled and analyzed using the structural seismic behavior modeling software OpenSees. CFDs are added to the models subsequently. The elevation of 2D frames regarding 4, 6, 8, 10 stories are shown in Fig. 2. The beams are chosen to be W6×20 at the middle bay and W10×39 at the two side bay locations of all different frames in term of height. The frame designs for the 4-, 6-, 8-, and 10-story control buildings can be found in Appendix A (Table a).

3. Analytical model assumptions

2D steel Frames are modeled and analyzed using Software OpenSees (Mazzoni *et al*. 2006). OpenSees is an open-source program developed at the University of California-Berkeley that can be used to simulate the response of structural and geotechnical systems subjected to earthquakes. In order to utilize OpenSees, the brace frames have to be defined using TCL programming language and files. Yield stress and Young's module of 2.4×e7 and 2.1×e10 are used to model steel material, respectively. Strain hardening coefficient is assumed to be 0.01. In addition, following factors are used to define the transition from elastic to plastic branch: R_0=15, CR_1=0.925, CR_2=0.15. Yielding and hardening are simulated using the Steel material model in OpenSees which incorporates the Giuffre-Menegotto-Pinto Model without isotropic hardening (McKenna *et al*. 2000). Beams and columns are modeled using nonlinear beam-column elements. Beam-column connections are considered pinned. The value of 0.05 as Riley Damping for first and second modes are considered. The idealized elasto-plastic behavior is considered for CFDs with the assumption of low strain hardening ratio. Due to the almost constant behavior of CFDs after several loading cycles (Mirtaheri *et al*. 2011), the behavior of them is modeled without hardening isotropic assumption. Also, there are no restrictions for capacity length for the damper in both tension and pressure. It is assumed that the damper is able to tolerate limitless capacity length. According to the specific percentage of the weight of each story, slip loads (F_i) of each CFDs are calculated using Eqs. (1)-(3), where W_i is the mass of each story, W_j is the total mass of joints in each story. The applied percentages are chosen due to the laboratory research which is conducted by Mirtaheri *et al.* (2011) on the Cylindrical Frictional Damper (CFD). These percentages are 0.5%, 10%, 15.5% and 20%. Calculations of obtaining the slip load of CFDs and distribution in each story is presented in Appendix A (Table b)

$$F_i = X\% \times \frac{W_i h_i}{\sum_{i=1}^{n} W_i h_i} \times \sum_{i=1}^{n} W_i \tag{1}$$

$$W_i = \sum_{j=1}^{n} W_j \tag{2}$$

$$W_{total} = \sum_{i=1}^{n} W_i \tag{3}$$

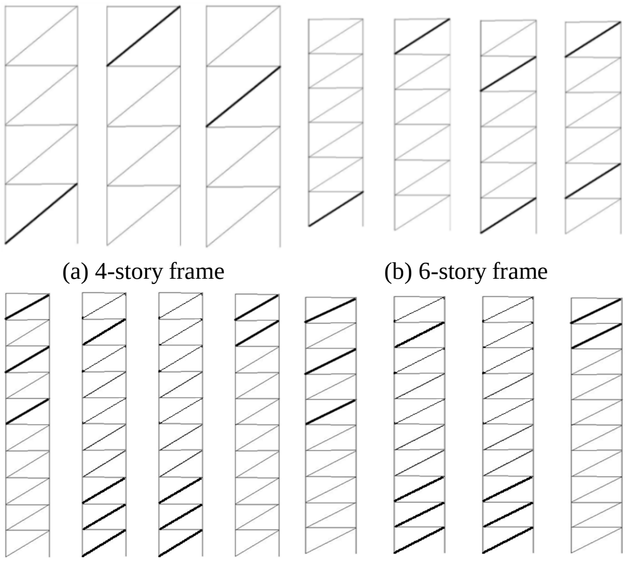
Command Element Zero Length is used to model the CFDs. With this command, an element with zero length, is defined by two nodes with the same coordinates in the middle of braces. The hysteretic behavior of CFDs in the first level of 4-story frame with 5% of the story weight which is defined as the slip load of damper is shown in Fig. 3.

4. Methods used to reduce residual relative displacement

As mentioned earlier, according to the Kiggins and Uang (2006), Boston and Richards (2012) researches, rigid connections and using lateral stiffness of gravity columns by adding elastic stories are two effective methods to reduce the residual relative displacement. Therefore, study and comparison of these two methods in this research lead

Table 1 Cross-sections for elastic braces

	4-Story	6-Story	8-Story	10-Story
Elastic brace (story 1)	HSS 10×8×0.37	HSS 14×10×0.25	HSS 16×12×0.37	HSS 14×14×0.50
Elastic brace (story 2)		HSS 14×10×0.25		HSS 14×14×0.50
Elastic brace (story 3)	HSS 10×8×0.25			HSS 14×14×0.50
Elastic brace (story 4)	HSS 8×4×0.50		HSS 16×8×0.37	
Elastic brace (story 5)		HSS 14×10×0.25	HSS 14×10×0.25	
Elastic brace (story 6)		HSS 10×6×0.312		HSS 12×10×0.50
Elastic brace (story 7)			HSS 10×6×0.25	
Elastic brace (story 8)			HSS10×6×0.25	HSS10×10×0.375
Elastic brace (story 9)				HSS10×10×0.25
Elastic brace (story 10)				HSS6×6×0.25



(a) 4-story frame (b) 6-story frame

(c) 8-story frame (d) 10-story frame

Fig. 4 Elastic story locations

to a suitable solution to reduce residual relative displacement of buildings equipped with CDFs. In order to increase the post-yield stiffness of the building which leads to decreasing the residual relative displacement, connections of two lateral bays of the frames are changed to fixed mode. These changes affect the re-centering performance of frames which is followed by a significant decrease in the residual relative displacement. As mentioned previously, in order to activate the stiffness of gravity columns and used them as the secondary resistant system to lateral loads, at least one of the stories of the frame must be changed to the elastic conditions. The elastic behavior of each story results from happening no yielding in braces of the same story. Although the utilization of elastic braces in some stories deactivates the role of CFD due to the elastic behavior of that specific story, the energy dissipation characteristics of CFD in other stories (without elastic braces) can affect the general behavior of the frame. In this way, both positive roles of elastic braces and CFD are considered simultaneously. Elastic stories (both in terms of the number and position in the frame) can affect the performance of gravity columns differently as the lateral resistant system. As a result, various cases for each frame are considered to achieve an efficient condition. Fig. 4 represents various positions of elastic braces of frames including 4, 6, 8 and 10 stories. For simplicity, only the middle bays equipped with braces are depicted. The first cross-section for brace which is designed in 3D model is selected. Then, finding the appropriate elastic cross-section for brace requires an iterative trial and error process. If the strain in the steel brace become less than yield strain of steel, the brace behaves like an elastic element. Otherwise, larger cross-section for brace is selected and the analysis requires to be repeated. Chosen cross-sections for elastic braces for different stories of 2D frames are shown in Table 1. By increasing the height of frames including 4, 6, 8 and 10 stories, more elastic stories are considered to reduce residual displacements more effectively.

5. Analysis

5.1 Ground motions

Nonlinear time history analyses are performed under 7 different earthquake records which are obtained from Northridge, San Fernando, Loma Prieta, Cape Mendocino and San Simeon earthquakes. Table. 2 represents ground motions characteristics used for analyses. These earthquake records are scaled based on UBC 2010. The ground motion acceleration records are each scaled up to match particular design spectra. The average spectrum of 7 records and the standard spectrum are presented in Fig. 5. In addition, scaling factors obtained due to the period of first mode of each frame are shown in Table. 3.

In this paper, aftershocks are generally assumed to be similar with mainshocks. First, the frames are analyzed under the mainshock, and their residual relative displacements are recorded. Then, aftershocks are imposed immediately to observe the most critical behavior of frames. According to the similarity between the PGA of aftershock and mainshock (the worst case scenario), and the weakness of structure at the end of the mainshock, the aftershock is able to impose the greater residual displacement to the building.

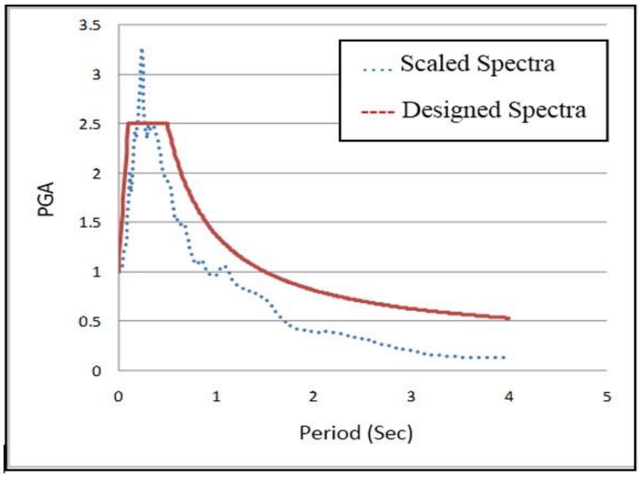


Fig. 5 Scaled spectra and Designed spectra

Table 2 Ground motions used for analysis

Earthquake	Station	M_W Moment magnitude	PGA Peak ground acceleration	Distance (km)
Northridge-01	LA - UCLA Grounds	6/69	0/474	22/49
Northridge-01	LA - Brentwood VA Hospital	6/69	0/185	22/5
San Fernando	Castaic - Old Ridge Route	6/61	0/32	22/63
San Fernando	Pasadena - CIT Athenaeum	6/61	0/109	25/47
Loma Prieta	Gilroy Array #6	6/93	0/171	18/33
Cape Mendocino	Butler Valley Station 2	7/01	0/154	45/43
San Simeon CA	San Luis Obispo	6/52	0/165	31/39

Table 3 Scale factors

Frame	Period of first mode	Scale Factor
4-Story	0.642	1.56
6-Story	0.868	1.56
8-Story	1.159	1.9
10-Story	1.589	2

6. Results

6.1 Procedure

The outputs from analyses are inter-story residual relative displacement values. Due to the conciseness of the paper, just three time-history results as the example are presented in Figs. 6 and 7. Fig. 6 represents the displacement time-history response of the roof for 6-story frame under San Simeon CA (San Luis Obispo) equipped with cylindrical frictional damper with slip load of 20% of the story weight. As shown in Fig. 6, the effect of seismic sequence (mainshock followed by aftershock) on the residual displacement responses for rigid connections and elastic braces at story 3 are presented. As a result, better restraint of the residual displacement is achieved by rigid connection as a dual system method at the mainshock and aftershock.

In addition, Fig. 7 represents displacement time-history responses of the roof for 4 and 8-story frames under Northridge-01 (LA - UCLA Grounds, aftershock) equipped with cylindrical frictional damper with slip load of 10% of the story weight. As shown in Fig. 7, only the response of the frames under the aftershock (immediately after the mainshock) are presented. With regard to the Fig. 7(a), it can be concluded that using elastic is a good method in reducing displacement of the roof during the after-shock. However, rigid connections are more effective than elastic brace in decreasing the residual displacement. Fig. 7(b) which is related to 8-story frame shows that this special distribution of elastic stories method has better performance in reducing displacement and residual displacement of the roof.

After performing several nonlinear time history analyses under various earthquake records, the values of residual relative displacement for mainshocks followed by aftershocks are obtained (mainshock and aftershock are selected from the same earthquake records which are similar). Based on each mianshock and aftershock, residual relative displacement values for each story of frames in different slip loads are recorded. Therefore, for frames including 4, 6, 8 and 10 stories, seven residual relative displacement values are obtained for each story. Then, these seven residual relative displacement values for each story are averaged together for mainshock-aftershock to determine one residual relative displacement value per story. To compare the effects of aftershock on the residual relative displacement values in each frame, the sum of residual relative displacements obtained in stories are divided by the number of stories. As a result, in each specific slip load, one certain residual relative displacement value for each frame are obtained. This process can be repeated for elastic stories, rigid connections methods. Then appropriate comparisons can be made. This process helps to highlight the overall reduction of residual displacements that results from rigid connections and adding elastic stories to increase the lateral stiffness of gravity columns in buildings equipped by CFDs.

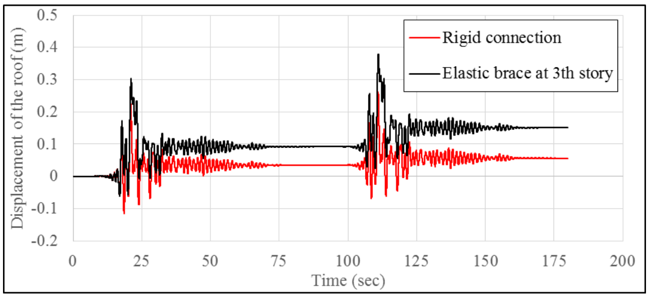
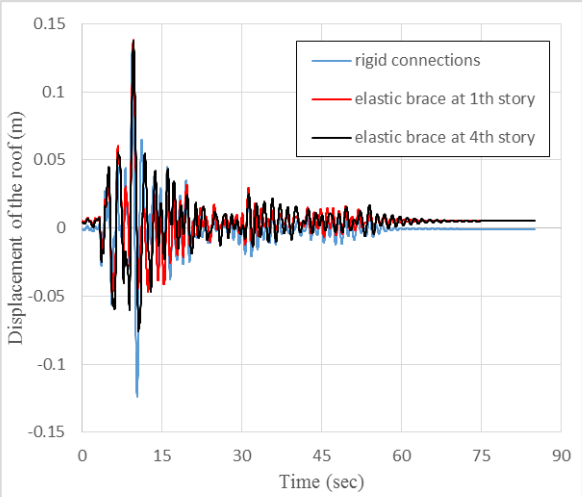
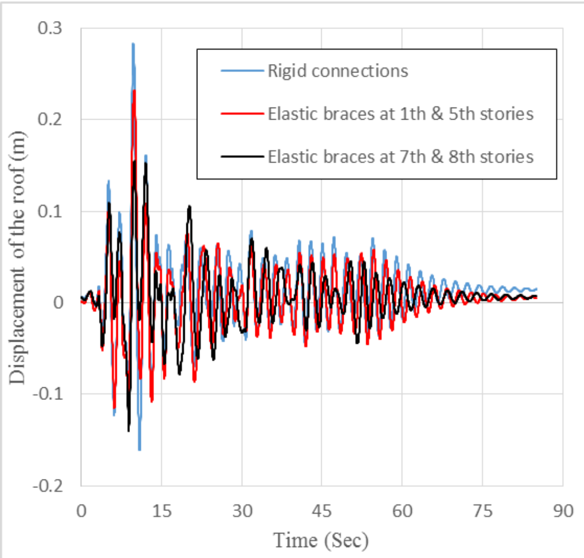


Fig. 6 Displacement time-history response of the roof for 6-story frame under San Simeon CA equipped with CFD (slip load of 20% of the story weight)

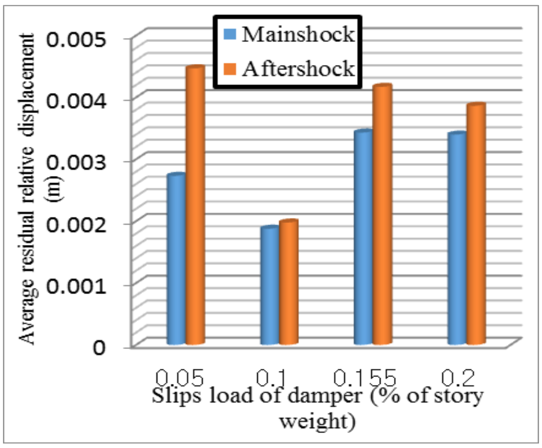


(a) 4-story frame



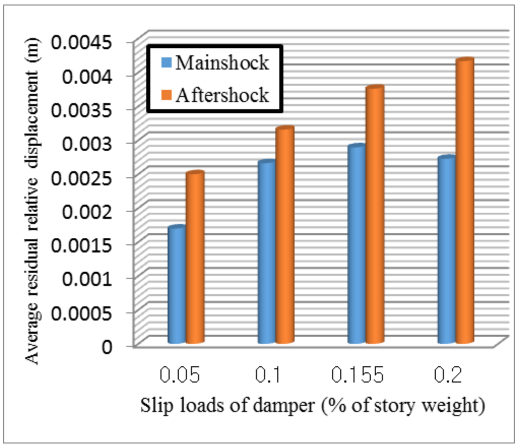
(b) 8-story frame

Fig. 7 Displacement time-history responses of the roof under Northridge-01 (LA - UCLA Grounds- aftershock) equipped with cylindrical frictional damper (slip load of 10% of the story weight)

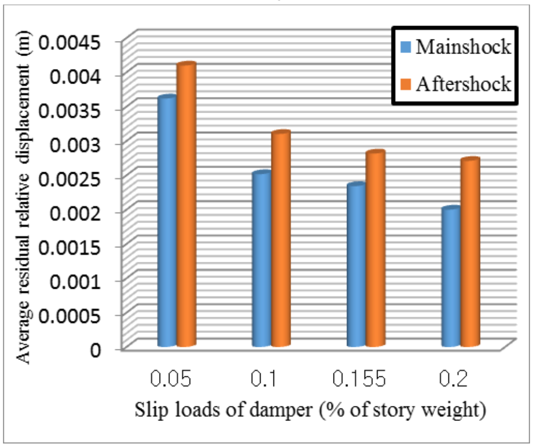


(a) 4-story frame

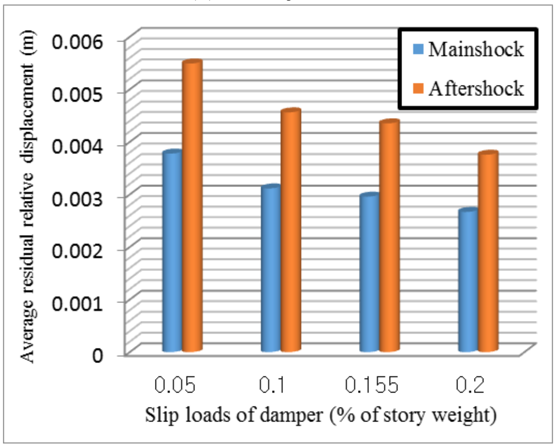
Fig. 8 The effect of mianshock-aftershock on the residual displacement of frames



(b) 6-story frame



(c) 8-story frame



(d) 10-story frame

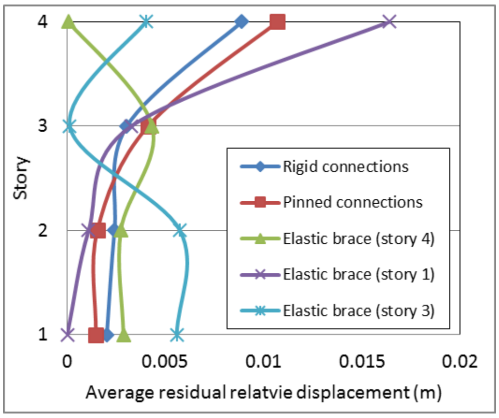
Fig. 8 Continued

6.2 The effect of mianshock-aftershock on the residual relative displacement

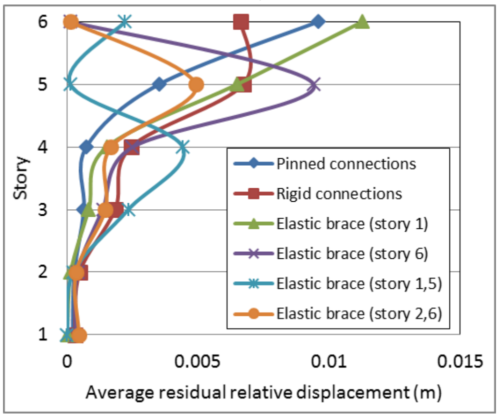
Fig. 8 represents the effects of mianshock-aftershock on the average residual relative displacement of frames including 4, 6, 8 and 10 stories. Due to the fact that the aftershock is assumed to be similar to the mainshock, and the weakness of the structure at the end of the first analysis (mainshock), the second analyses (aftershock) can impose greater residual displacement to the building (Fig. 6). As shown in Fig. 8(a), in the 4-story frame, the highest residual relative displacement value is 0.0044 under the mainshock effect which is corresponding with the slip load of 0.5% of story weight. This residual relative displacement value under the mainshock can be reduced about 55.74% by increasing the slip load to the 10% of story weight. It can also be seen that, the effect of aftershock on the average residual relative displacement is significantly dependent to the slip load values. In the case of 10% of story weight as the slip load in 4-story frame, the effect of aftershock on the residual relative displacement can be significantly reduced. As shown in Fig. 8(b), the 6-story frame with 5% of story weight as the slip load under the mainshock has the lowest average residual relative displacement (0.0017). By increasing the slip load of damper to the 15% of story weight, average relative residual displacement value is in a growing trend and then decreased. The effects of aftershock almost follow the same upside and downside trend. It can be generally seen that in the 6-story frame with pinned connections, low slip loads can control the average residual relative displacement more effectively. Fig. 8(c) represents the positive effect of increasing the slip load of damper on the reduction of average residual displacement values due to the mianshock-aftershock in the 8-story frame. The highest relative residual displacement in the 8-story frame is related to the slip load of 20% of story weight. As shown in Fig. 8(d), increasing the slip load of damper in the 10-story frame leads to the decreasing the average residual relative displacement due to the mianshock-aftershock. The effects of aftershock in the 10-story frame are more significant in comparison to the other frames.

6.3 The result of methods used to reduce the relative residual displacement

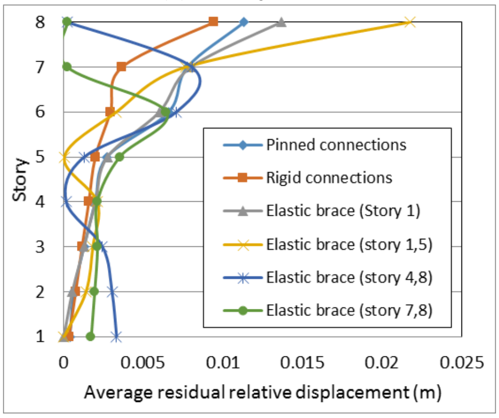
According to the descriptions that are given in the previous sections, two solutions have been investigated in this research to reduce the residual displacement in buildings equipped with cylindrical friction dampers (CFD). The first method is the use of rigid connections in the two side bay locations of the frame, the second one is the activating of lateral stiffness of gravity column by using the elastic braces in stories. Fig. 9 represents the effect of these two solutions on the average residual relative displacement values of the frames with slip load of 5% of story weight. As shown in Fig. 9(a), pinned connections are defined as the basic case. In this case, the average residual relative displacement increases by the building height (4-story frame). The comparison between the graphs of pinned and rigid connections results in the positive effect on the decreased residual relative displacement in two top stories, and negative effect of rigid connections on the residual relative displacement of two bottom stories. According to the graph related to the use of elastic story at the first level in the 4-story frame, it can be concluded that although in this method the story 4 experiences the residual relative displacement nearly 0.016 which it is not suitable, generally can provide an average of 23.6% reduction in the residual relative displacement. In addition, the use of elastic story at the level 3 and 4 cannot provide suitable performance in



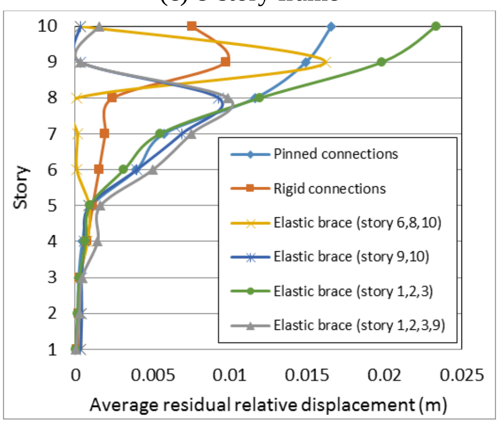
(a) 4-story frame



(b) 6-story frame



(c) 8-story frame



(d) 10-story frame

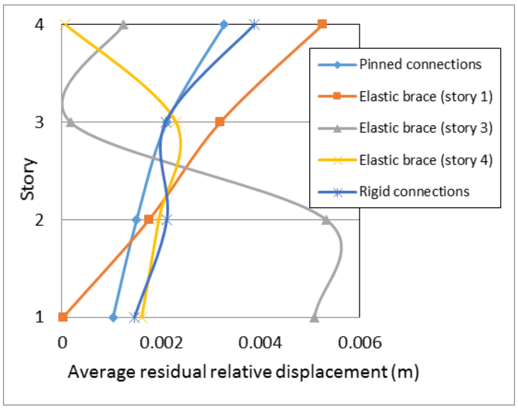
Fig. 9 Methods used to reduce residual displacement (slip load of 5% of story weight)

this slip load of damper. Fig. 9(b) represents the effect of mentioned methods on the residual displacement value in 6-story frame. As shown in Fig. 9(b), none of the methods are totally effective, but in comparison to other solutions adding elastic story at level 1, 2 and 2, 6 are more effective for damper slip load of 5% of story weight. As shown in Fig. 9(c), adding elastic story at level 4, 8 and 7, 8 have positive effect on the residual relative displacement value of topper stories in 8-story frame, but the residual displacement of bottom stories is greatly increased. Fig. 9(d) shows the results of adding elastic braces at level 6, 8, and 10 reduce effectively the residual relative displacement of top half stories in 10-story frame with slip load of 5% of story weight. However, due to the increase of residual displacement in bottom stories, on average this method is just able to provide 12% decrease in the residual relative displacement of 10-story frame. Other solutions cannot have positive effect on the decreasing of residual relative displacement. The summary of results related to the frames with damper slip load of 5% of story weight are shown in Table 4.

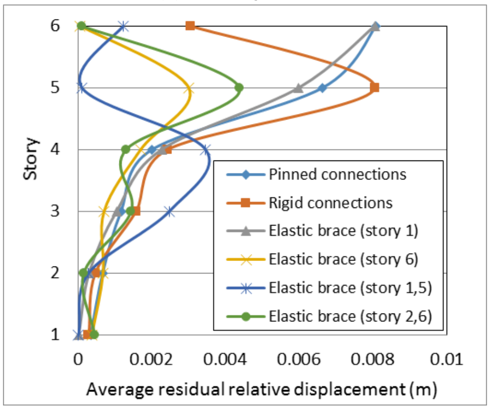
Fig. 8 represents the effects of mianshock-aftershock on the average residual relative displacement of frames including 4, 6, 8 and 10 stories. Due to the fact that the aftershock is assumed to be similar to the mainshock, and the weakness of the structure at the end of the first analysis (mainshock), the second analyses (aftershock).

Fig. 10 represents the effect of different methods on the residual displacement of the frames with slip load of 10% of story weight equipped with CFDs. As shown in Fig. 10(a), the proposed methods to decrease the residual relative displacement value are not effective in damper slip load of 10% of story weight. In addition, adding the elastic story at topper level (story 4) results in a significant decrease in the residual relative displacement of the same story. Generally, the optimal chose for proposed methods for the 4-story frame in the slip load of 10% of story weight cannot be concluded. Fig. 10(b) represents the residual relative displacement of 6-story frame equipped with CFDs which is reduced by proposed methods. It can be seen that all methods have the positive effect on the decreasing of residual relative displacement in this slip load of damper. The use of elastic story at the level 6 can decrease the average residual relative displacement nearly 33%. Fig. 10(c) shows the suitable performance of methods in the 6-story frame with slip load of 10% of story weight. On average, adding of elastic story at level 1, 5 results in nearly 50% decrease in the relative residual displacement value. Perhaps the only weakness of this method is the relatively large residual relative displacement of story 6 which is not decreased by this method. As shown in Fig. 10(d), the weaknesses of proposed methods to reduce residual relative displacement of lower stories in the 10-story frame are presented. For example, adding elastic braces at level 6, 8, and 10 shows a 77% decrease in the average residual relative displacement of upper 5 stories, but there is no improvement (decrease) in bottom stories.

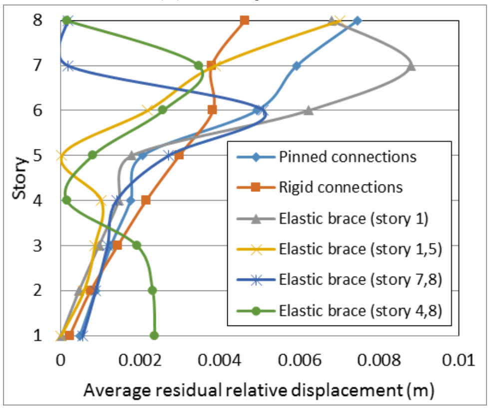
Fig. 11 shows the effect of different methods on the relative residual displacement of the frames with slip load of 15.5% of story weight equipped with CFDs. As shown in



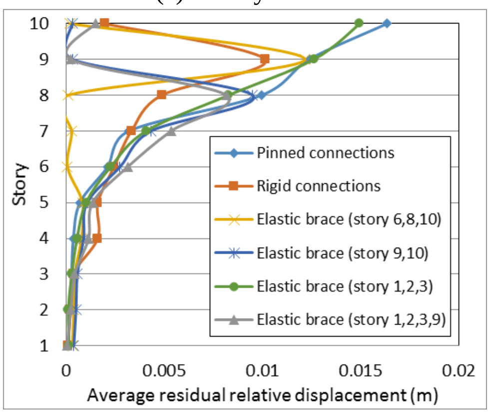
(a) 4-story frame



(b) 6-story frame

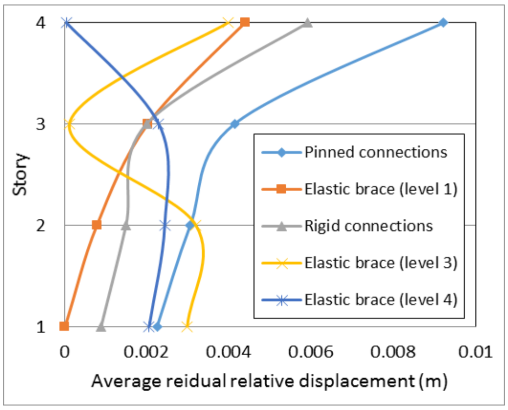


(c) 8-story frame

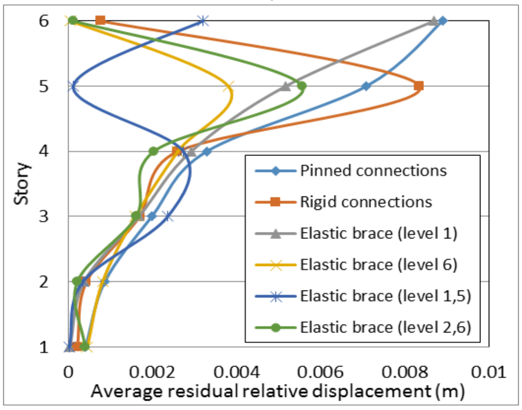


(d) 10-story frame

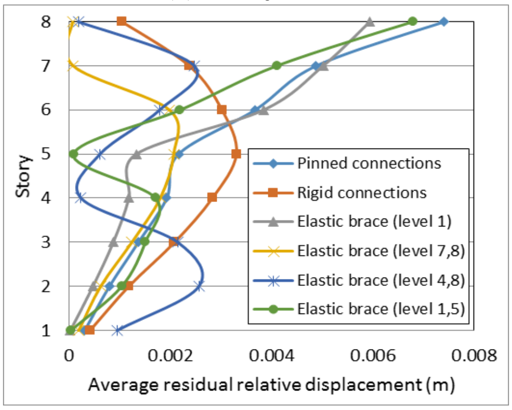
Fig. 10 Methods used to reduce residual displacement (slip load of 10% of story weight)



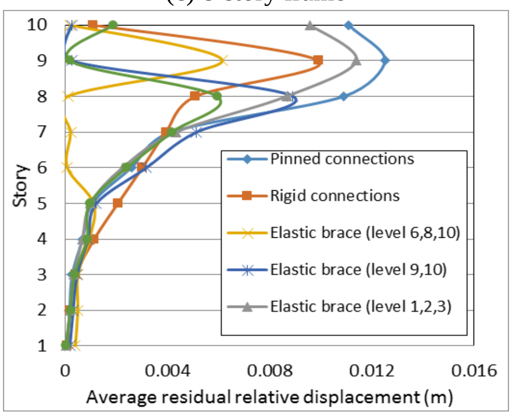
(a) 4-story frame



(b) 6-story frame

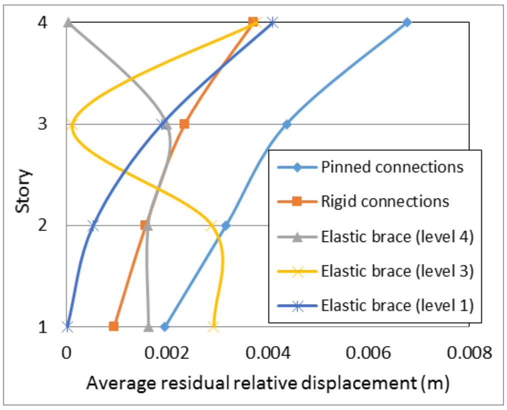


(c) 8-story frame

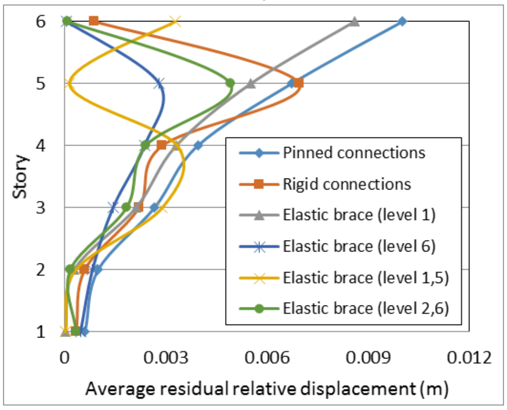


(d) 10-story frame

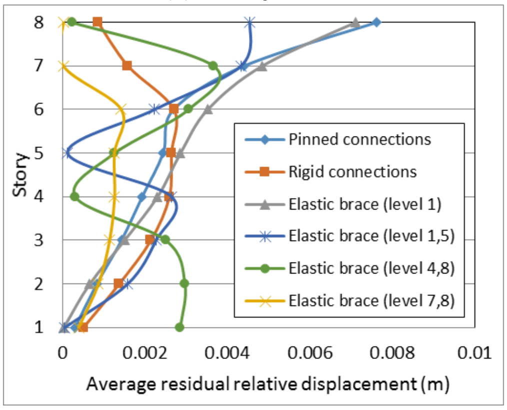
Fig. 11 Methods used to reduce residual displacement (slip load of 15.5% of story weight)



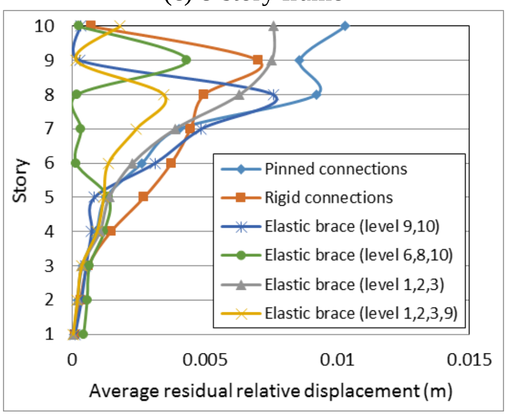
(a) 4-story frame



(b) 6-story frame



(c) 8-story frame



(d) 10-story frame

Fig. 12 Methods used to reduce residual displacement (slip load of 20% of story weight)

Table 4 Summary of results for methods used to reduce average residual relative displacement

4-story frame with slip load 5% story weight		**6-story frame with slip load 5% story weight**	
Used methods	% decrease in avg. residual displacement	Used methods	% decrease in avg. residual displacement
Rigid connections	-12.8	Rigid connections	-95.9
Elastic brace (level 1)	23.6	Elastic brace (level 1)	-16
Elastic brace (level 3)	2.6	Elastic brace (level 6)	-85.2
Elastic brace (level 4)	-19.5	Elastic brace (level 1,5)	-78.5
		Elastic brace (level 2,6)	-53.7
8-story frame with slip load 5% story weight		**10-story frame with slip load 5% story weight**	
Rigid connections	21.8	Rigid connections	21.4
Elastic brace (level 1)	11.4	Elastic brace (level 1,2,3)	0.7
Elastic brace (level 1,5)	-2.5	Elastic brace (level 6,8,10)	12.1
Elastic brace (level 4,8)	-119	Elastic brace (level 9,10)	-14
Elastic brace (level 7,8)	-54.7	Elastic brace (level 1,2,3,9)	-18
4-story frame with slip load 10% story weight		**6-story frame with slip load 10% story weight**	
Rigid connections	-25	Rigid connections	4.8
Elastic brace (level 1)	-8	Elastic brace (level 1)	25.6
Elastic brace (level 3)	-123	Elastic brace (level 6)	32.7
Elastic brace (level 4)	-1.2	Elastic brace (level 1,5)	24.9
		Elastic brace (level 2,6)	31.5
8-story frame with slip load 10% story weight		**10-story frame with slip load 10% story weight**	
Rigid connections	10.3	Rigid connections	-37
Elastic brace (level 1)	16.2	Elastic brace (level 1,2,3)	-11
Elastic brace (level 1,5)	49.4	Elastic brace (level 6,8,10)	-12
Elastic brace (level 4,8)	-38.6	Elastic brace (level 9,10)	-61
Elastic brace (level 7,8)	21.6	Elastic brace (level 1,2,3,9)	-23
4-story frame with slip load 15.5% story weight		**6-story frame with slip load 15.5% story weight**	
Rigid connections	49.8	Rigid connections	34.5
Elastic brace (level 1)	69.2	Elastic brace (level 1)	34
Elastic brace (level 3)	29	Elastic brace (level 6)	30.2
Elastic brace (level 4)	43.3	Elastic brace (level 1,5)	52.4
		Elastic brace (level 2,6)	42.5
8-story frame with slip load 15.5% story weight		**10-story frame with slip load 15.5% story weight**	
Rigid connections	-9.7	Rigid connections	-5.3
Elastic brace (level 1)	32.2	Elastic brace (level 1,2,3)	10
Elastic brace (level 1,5)	27.3	Elastic brace (level 6,8,10)	-23.6
Elastic brace (level 4,8)	-15.8	Elastic brace (level 9,10)	-14.6
Elastic brace (level 7,8)	40.5	Elastic brace (level 1,2,3,9)	22.4
4-story frame with slip load 20 % story weight		**6-story frame with slip load 20% story weight**	
Rigid connections	48.3	Rigid connections	35.8
Elastic brace (level 1)	69.5	Elastic brace (level 1)	39.1
Elastic brace (level 3)	25.3	Elastic brace (level 6)	47.1
Elastic brace (level 4)	54.8	Elastic brace (level 1,5)	55.4
		Elastic brace (level 2,6)	53.6
8-story frame with slip load 20% story weight		**10-story frame with slip load 20% story weight**	
Rigid connections	-8.9	Rigid connections	-20.7
Elastic brace (level 1)	4.3	Elastic brace (level 1,2,3)	13
Elastic brace (level 1,5)	6.2	Elastic brace (level 6,8,10)	9
Elastic brace (level 4,8)	-117	Elastic brace (level 9,10)	-30
Elastic brace (level 7,8)	39.4	Elastic brace (level 1,2,3,9)	40

Fig. 11(a), all methods utilized to decrease the average residual relative displacement values have positive effect on the 4-story frame. Among these methods, adding elastic story at level 1 is able to decrease the residual relative displacement more effectively over the entire frame. As shown in Fig. 11(b), rigid connections and elastic brace at level 1, 5 and 2, 6 have positive effect on the performance of the 6-story frame equipped with CFDs with slip load of 15.5% of story weight. Fig. 11(c) represents the performance of the 8-story frame with damper slip load 15.5% story weight. It can be concluded that adding the elastic story at level 8 results in a 32.2% decrease in the average residual relative displacement. As shown in Fig. 11(d), adding elastic story at bottom levels cannot decrease the residual relative displacement of bottom stories effectively. However, is able to avoid increasing the residual relative displacement of 0.005 m.

Fig. 12 shows the effect of different methods on the relative residual displacement of the frames with slip load of 20% of story weight equipped with CFDs. As shown in Fig. 12(a), increasing the slip load of damper from 15.5% to 20% of story weight results in same conclusions in terms of reductions in the residual relative displacement of the 4-story frame. Adding elastic braces at level 1 and upper story shows a 69.5% and 48.3% decrease in the residual relative displacement, respectively. Fig. 12(b) represents the residual relative displacement of the 6-story frame equipped with CFDs with slip load of 20% of story weight which is reduced by proposed methods. Adding the elastic story at upper level decrease residual relative displacement over the entire 6-story frame. Rigid connections similar to the previous method can be useful to decrease the residual relative displacement. As shown in Fig. 11(c) and Fig. 12(c), increasing the slip load of damper from 15.5% to 20% of story weight in the 8-story frame undermine the performance of methods to reduce residual relative displacement. As shown in Fig. 12(d), it can be concluded that adding elastic stories at top levels is an effective method for the 10-story frame in high slip loads of damper. However, rigid connections are not suitable method to reduce the residual relative displacement in high slip loads. In addition, adding elastic stories at level 1, 2, 3, and 9 decrease the overall residual relative displacement by 40%. The summary of results related to the frames with different slip loads of damper are shown in Table 4.

6. Conclusions

According to the results of 4 different frames in term of height equipped with cylindrical friction damper (CFD) which is analyzed under mianshock-aftershock, significant effects of aftershock on the residual relative displacement are investigated. Therefore, the effects of aftershock to control residual relative displacement of buildings must be considered to avoid heavy costs of demolish or retrofit. In addition, the value of slip load for friction dampers affect the residual relative displacement of frames significantly under mianshock-aftershock. Due to the fact that decreasing the residual relative displacement of building equipped with CFDs is not always possible by changes in the value of slip load of dampers, two methods are investigated to reduce the residual displacement. The results are presented in the following.

- Due to the low period of short buildings and high imposed acceleration (4 and 6-story frames), increasing the rigidity of the structure can significantly decrease the residual relative displacement. This performance can be achieved by using rigid connections or CFDs with high slip loads. However, in 8 and 10-story frames with higher period in comparison to short buildings, CFDs are required to be activated sooner to dissipate the energy in order to decrease residual relative displacements specially in top stories. As a result, rigid connections are more effective in 4 and 6-story frames in comparison to others.

- In 4-story frame with elastic brace at level 1, and 6-story frame with elastic braces at level 1 and 6, we can achieve to an optimum state on these frames in order to decrease residual relative displacement, specially in high slip loads. As a result, adding elastic braces in these states are more effective in comparison to rigid connections to decrease the residual relative displacement. This method decreases the residual relative displacement values of 4-story frame nearly 70%. In addition, in order to decrease the residual relative displacement of top stories in 6-story frame, adding the elastic stories at topper levels seems to be effective too.

- In 8-story and 10-story frames, only the use of elastic braces method at stories is not a suitable solution to decrease residual displacements. Because of the far distance between upper stories and elastic stories, upper stories tend to be displaced a lot. Therefore, utilization of elastic braces at upper stories or combination of both upper and lower stories can result in a significant decrease in residual displacements. In 10-story frame, adding elastic stories at level 6, 8, 10 in low slip loads of damper, and at level 1, 2, 3, and 9 in high slip loads result in an acceptable decrease of 36% and 40% in the residual relative displacement, respectively. Further research is also recommended to develop the relevant results for tall buildings which are behaved in different ways.

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Appendix A

Table a The cross-section designs for the 4-, 6-, 8-, and 10-story frames

Column Shape		Brace Shape	Story	Column Shape		Brace Shape
A-1, A-4	A-2, A-3			A-1, A-4	A-2, A-3	
4-Story Frame				**6-Story Frame**		
W8× 24	W14× 61	HSS10×8×0.375	1	W8× 28	W24× 117	HSS14×10×0.250
W8× 24	W14× 53	HSS10×8× 0.250	2	W8× 28	W24× 117	HSS14×10×0.250
W5× 16	W8× 24	HSS10×8× 0.250	3	W8× 28	W12× 65	HSS14×10×0.250
W5× 16	W5× 16	HSS8×40× 0.500	4	W6× 20	W12× 65	HSS14×10×0.250
10-Story Frame			5	W6× 20	W12× 65	HSS14×10×0.250
W14× 43	W33× 241	HSS12×10×0.500	6	W6× 15	W6× 15	HSS10×6×0.312
W14× 43	W33× 241	HSS12×10×0.375		**8-Story Frame**		
W14× 43	W33× 241	HSS12×10×0.375	1	W8× 35	W12× 170	HSS16×8×0.375
W14× 43	W14× 145	HSS12×10×0.375	2	W8× 35	W12× 170	HSS16×8×0.375
W8× 28	W14× 145	HSS12×12×0.500	3	W8× 35	W12× 120	HSS16×8×0.375
W8× 28	W14× 90	HSS12×10×0.375	4	W8× 35	W12× 120	HSS14×10×0.250
W8× 28	W14× 90	HSS10×10×0.250	5	W6× 20	W12× 120	HSS14×10×0.250
W6× 15	W14× 43	HSS10×10×0.250	6	W6× 20	W10× 49	HSS14×10×0.250
W6× 15	W8× 28	HSS10×10×0.250	7	W6× 20	W8× 35	HSS10×6×0.250
W6× 15	W6× 15	HSS6×6×0.250	8	W6× 9	W6× 20	HSS10×6×0.250

Table b The slip loads of damper and distribution in each story

	5% story weight	10% story weight	15.5% story weight	20% story weight
4-story frame				
F1 (KN)	42.05	84.10	130.36	168.21
F2 (KN)	42.01	84.03	130.24	168.06
F3 (KN)	41.91	83.82	129.93	167.65
F4 (KN)	34.96	69.92	108.38	139.84
6-story frame				
F1 (KN)	42.32	84.64	105.8	169.28
F2 (KN)	42.32	84.64	105.8	169.28
F3 (KN)	42.07	84.14	105.18	168.29
F4 (KN)	42.01	84.03	105.03	168.06
F5 (KN)	41.81	83.63	104.54	167.26
F6 (KN)	34.95	69.9	87.38	139.80
8-story frame				
F1 (KN)	42.64	85.29	132.20	170.58
F2 (KN)	42.43	84.87	131.55	169.74
F3 (KN)	42.43	84.87	131.55	169.74
F4 (KN)	42.38	84.76	131.381	169.52
F5 (KN)	42.11	84.23	130.55	168.46
F6 (KN)	41.95	83.9	130.04	167.8
F7 (KN)	41.87	83.75	129.81	167.5
F8 (KN)	34.93	69.87	108.30	139.74
10-story frame				
F1 (KN)	43.05	86.1	133.45	172.2
F2 (KN)	43.05	86.1	133.45	172.2
F3 (KN)	42.82	85.65	132.75	171.3
F4 (KN)	42.6	85.2	132.07	170.41
F5 (KN)	42.53	85.07	131.86	170.14
F6 (KN)	42.28	84.57	131.08	169.14
F7 (KN)	42.24	84.48	130.95	168.97
F8 (KN)	41.95	83.9	130.05	167.8
F9 (KN)	41.87	83.74	129.79	167.48
F10 (KN)	34.98	69.96	108.43	139.92