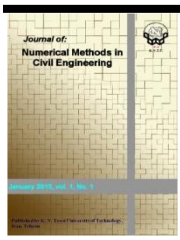

Numerical Methods in Civil Engineering

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Seismic response sensitivity of the structures equipped with cylindrical frictional dampers to the value of slippage load

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Abstract:

Cylindrical Frictional Damper (CFD) is a new revolutionary frictional based mechanical damper. Unlike the other types of frictional dampers, CFDs do not utilize bolts to produce friction between contact surfaces. These dampers consist of two main parts, the inner shaft and the external cylinder. These two parts are assembled such that one is shrink-fitted inside the other.

In this investigation, seismic response of steel structures equipped with CFDs is studied. Special attention is given to the sensitivity of the seismic response to the value of the slippage load. To do so, the optimum slippage load of the structure (the slippage loads which results in minimum displacement response) is obtained for various seismic excitations. The seismic response of the structure is obtained for various slippage loads in the range of plus and minus %20 of the optimum slippage load. Moreover; the seismic performance of steel structures equipped CFDs is investigated using non-linear time history analyses.

The results show that value of the optimum slippage load is completely dependent to seismic excitation. It is further shown that if the slippage load has a difference up to 20% from its optimum value, the maximum displacement response can increases up to 35%, however, it is still less than the maximum displacement response of the frame without CFDs. It was also shown that CFD can significantly improve the performance of steel structures subjected to earthquake loads.

1. Introduction

Seismic response control techniques can be grouped into passive, active and semi-active control systems. One of the main passive control devices are frictional dampers.

Such dampers are suitable candidates for control of dynamic systems since they have advantages over the other types of energy dissipating devices including less the degradation due to environmental effects, being less sensitive to the change of ambient temperature, low cost of manufacture and maintenance, and no material yielding and replacement problems after an earthquake event. Many different types of passive frictional based energy dissipating devices have been developed and tested for seismic applications in recent years, and more are still being investigated. Pall and Marsh [1] proposed frictional dampers to be installed at the crossing joint of the X-brace. This device is usually called the Pall frictional damper. Wu et al. [2] introduced improved Pall frictional damper (IPFD), which replicates the mechanical properties of the Pall frictional damper, but offers some advantages in terms of ease of manufacture and assembly. Sumitomo friction damper [3] utilizes a more complicated design. The pre-compressed internal spring exerts a force that is converted through the action of inner and outer wedges into a normal force on the friction pads. Fluor Daniel Inc. has developed

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and tested another type of frictional device which is called Energy Dissipating Restraint (EDR) [4]. The design of this friction damper is similar to Sumitomo friction damper since this device also includes an internal spring and wedges encased in a steel cylinder. The EDR utilizes steel and bronze friction wedges to convert the axial spring force into normal pressure on the cylinder. Constantine et al. [5] proposed frictional dampers composed of a sliding steel shaft and two frictional pads clamped by high strength bolts. Mualla and Belev [6] proposed a friction damping device and carried out tests for assessing the friction pad material. Monir and Zeynali [7] introduced and tested a modified friction damper (MFD) which is similar to Pall friction damper however it is applied in the diagonal bracing. Most of frictional dampers compromise a set of steel plates that are clamped by pretentioned 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. Recently, Mirtaheri et al. [8] 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 increase reliability in comparison with other types of frictional dampers. Seismic design procedure of structures equipped with frictional dampers has previously been addressed by many researchers. However, most of the works on this topic are focused on Single Degree of Freedom (SDF) or linear elastic structures. Min et al. [9] proposed a simple design procedure of a friction damper for reducing seismic responses of a single-story structure. Seong and Min [10] proposed a simple design process to determine desired control force of a friction damper to satisfy a given target performance of a SDF system subjected to an earthquake ground excitation. Lee et al. [11] proposed a design methodology of friction damper–brace systems, to determine the quantity and slip-load of the frictional damper and the brace stiffness systematically for an elastic multistory building structure based on the story shear forces. Fus and Cherry [12] studied the application of a quasi-static design procedure for a friction damped system. They normalized the seismic response of the friction-damped system with respect to the response of its corresponding linear system. The resulting closed-form solutions obtained for the normalized response were then used to define a force modification factor for friction-damped systems. This force modification factor, together with the condensation procedure for Multi Degree of Freedom (MDF) structures, enables them to establish a strength-based design procedure for friction-damped structures.

In this investigation, seismic response of the structures equipped with CFDs is studied. Special attention is given to the sensitivity of the seismic response to the value of the slippage load. To do so, the optimum slippage load of the structure (the slippage loads which results in minimum displacement response) is obtained for various seismic excitations. Subsequently, the seismic response of the structure is obtained for various slippage loads in the range of plus and minus %20 of the optimum slippage load.

2. Cylindrical Frictional Dampers

CFD was proposed by Mirtaheri et al. [8] as an innovating type frictional damper which does not use bolts or any other pretention element to induce friction between contact surfaces. CFDs consist of two main parts, the internal solid shaft (Fig.1a) and the external hollow cylinder (Fig.1b). A longitudinal section of the CFD is shown in Fig.2a. The inner diameter of cylindrical element is slightly smaller than the diameter of the shaft at the contact length namely *L0*. Heating the cylindrical part its diameter will increase due to thermal expansion and the unheated shaft can be easily placed into the cylinder.

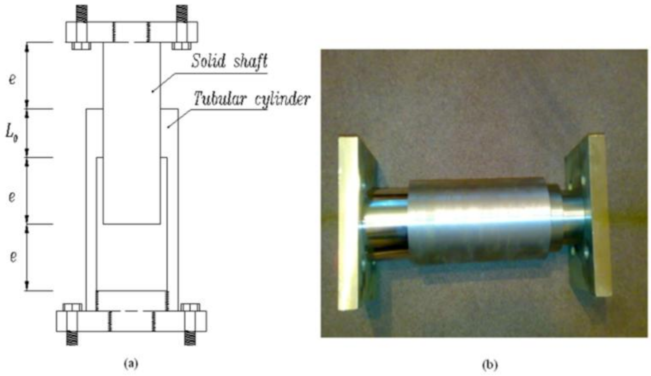


Fig. 1: a) Longitudinal section of CFD; b) Manufactured CFD [8]

The desired slippage load can be set by changing L_0 as follows [8]

$$L_0 = \frac{F_s}{P.\pi.D.\delta} \tag{1}$$

in which F_s is the slippage threshold, D is the diameter of the shaft and L_0 is the contact length (as shown in Fig.1). P is the pressure between contact surfaces and is calculated as follows:

$$P = \frac{E\delta(r_0^2 - r_i^2)}{4r_i r_o^{\,2}} \tag{2}$$

where E is the modulus of elasticity, r_i and r_o are the inside and outside radii of the cylinder respectively, and δ is the difference in the diameters of the solid shaft and the cylinder along L_0. These formulas are derived based on the theory of thick-walled cylinders. However, these analytical formulas are based on some simplifying assumptions and can be used for initial design only. Numerical models can be developed in order to assess more accurate results. A three-dimensional finite element model of CFD can be developed as shown in Fig.2. Modeling 1/4 of the total device is sufficient due to the fact that the damper is symmetrical. The outer cylinder can also be solely modeled at contact length. Solid elements should be used to model the solid shaft and the outer cylinder may be modeled using shell elements with constant thickness. Surface to surface contact may be utilized to simulate the friction.

Axial force-displacement curve of the CFD is determined by experimental tests as well as numerical analysis in previous research [8] as shown in Fig.3.

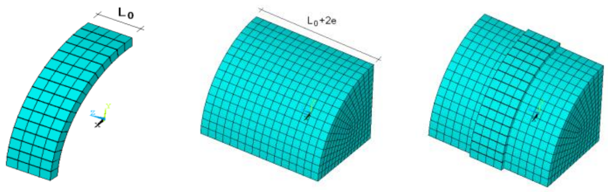


Fig. 2: Finite element model of CFD a)Cylinder; b) Solid shaft; c)Assembled CFD

Fig. 4 shows the experimental hysteretic behavior of a CFD specimen with slippage load of 130kN. As can be seen, the CFD exhibits rectangular stable hysteresis loops. Furthermore, the CFD has almost the same performance in tension and compression.

Fig. 3: Test setup[8].

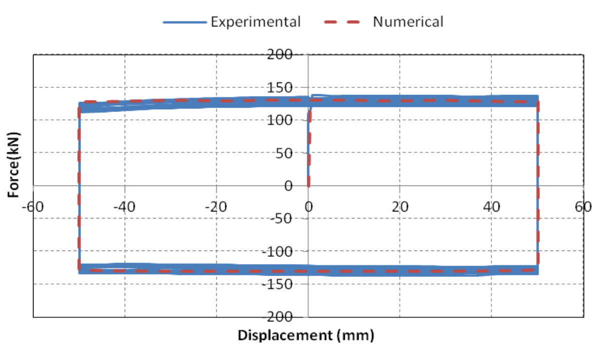


Fig. 4: The experimental hysteretic behavior of a CFD specimen with design slippage load of 130kN.

3. Numerical Modeling of Structures Equipped With Cfds

In this section the effect of CFDs on seismic response of a real steel building is assessed. Numerical models of a 6-story frame (Fig.5) and the counterpart without CFD are developed and studied comparatively to emphasize the effectiveness of CFD in altering seismic responses. The framing members are designed according to AISC seismic provisions for seismic zone 2 with a response factor of 6. Numerical models are developed using OpenSees software. Beams and columns are modeled using force-based nonlinear fiber beam–column elements with five integration points along their length. The element cross-section is discretized into uni-axial fibers. Column bases have been fully fixed. Gravity loads consists 550 kN/m2 dead load and 2 kN/m^2 live load. CFDs are incorporated to the model utilizing nonlinear zero-length elements, with elastic–perfectly plastic behavior at the middle of bracing members. Rayleigh damping theory with damping ratio of 5% is used to account for the inherent damping of the structure.

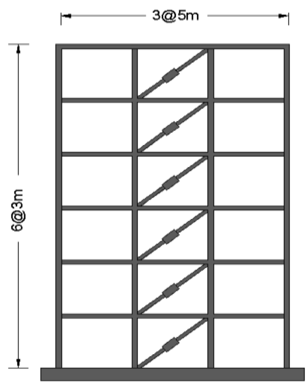


Fig.5: Elevation of the 6-storey frame

4. Optimized Value for the Slippage Load

If the slippage load of the CFD is set too high (greater than buckling load of the bracing member in which the CFD is engaged) the dissipated energy is equal to zero since no slippage occurs. In this case the frame behaves like a braced frame. On the other hand, if the slip load is too low, excessive slippage occurs but due to small amount of slippage load the dissipated energy is negligible. In this case the frame behaves like a moment resisting frame. Between these to limit states, one could find a slippage load which result in the optimum energy dissipation or optimize other structural responses such as displacement. This slippage load is called optimum slippage load.

In this study, in order to find the optimum slippage load, various slippage loads is examined. As the first trial load, 80% of the buckling load of the brace member is selected as the CFDs slippage load. Subsequently, a parametric study is conducted and the slippage load is bracketed until the minimum displacement of the top of the frame is reached. The result of this parametric study for Elcentro earthquake is shown in Fig. 6

The value of the optimum slippage load is completely dependent to the external seismic load and change to some degree from record to record. Optimum slippage loads of ten different records are presented in Table 1. Records belong to distances of 50 to 150 km, bearing no mark of directivity. The earthquakes are scaled to produce a peak ground acceleration of 1 g. As can be seen optimum slippage load is completely dependent to external seismic load. The question is how much the response of the frame is sensitive to the value of the slippage load and its difference with the optimum slippage load.

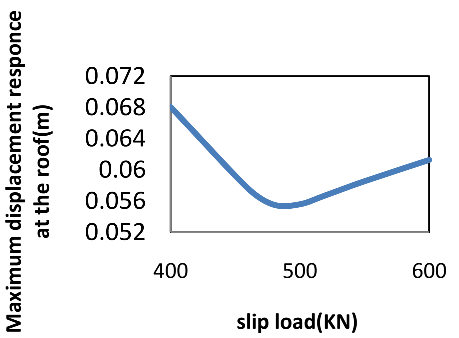


Fig. 6: Maximum displacement at the top of the frame versus slippage load

Table.1: Optimum slip load of earthquake records.

Earthquake	Optimum slip load (kN)	Deviation from average (%)
Coalinga	750	47
Elcentro	620	22
Imperial valley	500	-2
Loma perita	420	-17
N.palm spring	240	-53
Northridge	550	8
Victoria,mexico	480	-6
Whitter narrows	400	-21
Kobe	430	-16
Tabas	700	38
Average	509	

5. Seismic Response Sensitivity of the Structures Equipped with Cylindrical Frictional Dampers to Slippage Load

In order to assess the sensitivity of the response of the frame to the selected slippage load the following parameters are defined:

$$\alpha = 1 - \frac{F_s}{F_{so}} \tag{3}$$

$$\beta = \frac{R_{df}}{R_{dfo}} - 1 \tag{4}$$

$$\eta = 1 - \frac{R_{df}}{R_d} \tag{5}$$

where, F_{so} is the optimum slippage load, R_d is the displacement response of the frame without CFD, R_{df} is the displacement response of the frame with CFD and finally R_{dfo} is the displacement response of the frame utilizing CFDs with optimum slippage load. Fig. 7 shows β versus α for Victoria earthquake. As can be seen, when $\alpha = -20\%$, that is the slippage load is 20% less than optimum slippage load, β is equal to 22% that is the maximum displacement response of the frame is increased 20% with respect to the maximum displacement response of the frame with optimum slippage load. Fig. 8 shows η versus α for the same earthquake. As can be seen when $\alpha = -20\%$, η is equal to 38%. In other words when the slippage load is 20% less than optimum slippage load, the maximum displacement response of the frame is decreased 38% respect to the maximum displacement response of the frame without damper. The values of β and η for other ground motion records are presented in Table 2.

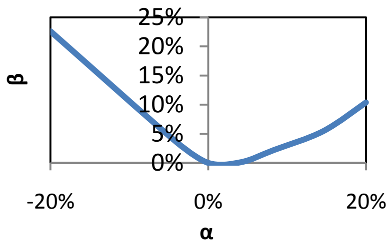


Fig.7: β versus α

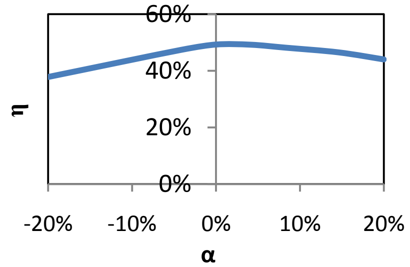


Fig.8: η versus α

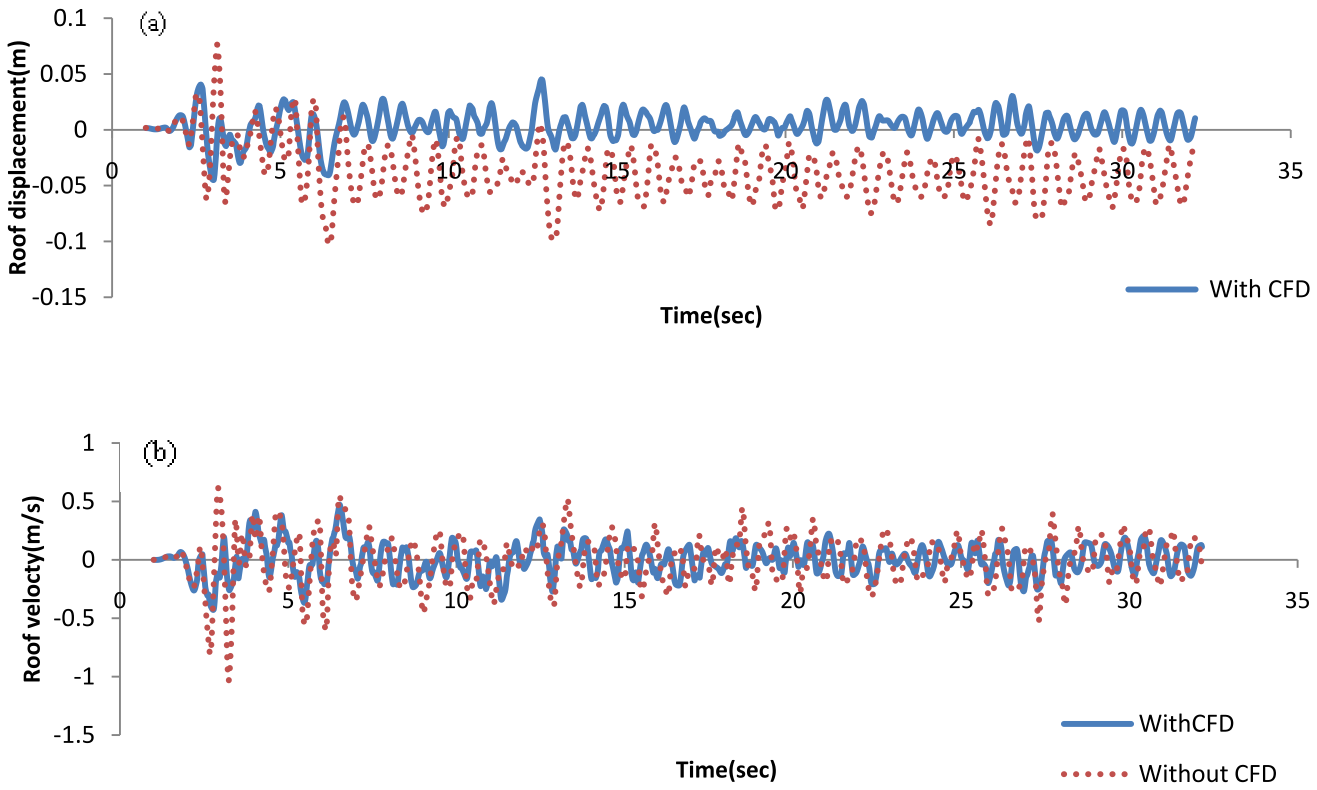
Table.2: Values of β and η at $\alpha = -20\%$ and $\alpha = -20\%$

Earthquake	$\alpha = -20\%$		$\alpha = 20\%$	
	β	η	β	η
Coalinga	16.54	7.87	15.61	8.62
Elcentro	35.96	16.98	11.22	32.09
Imperial valley	8.63	67.55	8.40	67.62
Loma prieta	24.02	-6.42	6.11	5.62
N.palm spring	1.73	50.42	4.36	49.13
Northridge	5.14	3.55	3.55	5.01
Victoria,mexico	22.58	37.82	10.36	44.01
Whitter narrows	20.38	9.39	10.54	16.08
Kobe	17.35	22.01	14.26	27.46
Tabas	12.35	27.43	8.42	33.58
Average	16.47	23.66	9.28	28.92

As can be seen, the maximum value of β is 35% which is related to Elcentro earthquake. The average value for β is about 16% and 10% at $\alpha = -20\%$ and $\alpha = 20\%$ respectively. As it can be noticed, the value of η is positive for all earthquake records except Loma prieta which means that the maximum displacement of the frame is still less than the maximum displacement response of the frame without CFD.

6. Effect of Cfds on Seismic Response of Steel Structures

The responses of the frame with and without dampers are compared using three of selected earthquake as shown in Table 3. The comparative plots of displacement, velocity and acceleration responses at the top of the frame and the base shear are shown in Fig.9 for Elcentro earthquake event. As can be seen, utilizing CFDs with slippage load of 600 kN, maximum displacement of the roof is reduced by 56% and maximum base shear is reduced by 72%. The peak responses of the frame for all three selected earthquake records are shown in Table 3.



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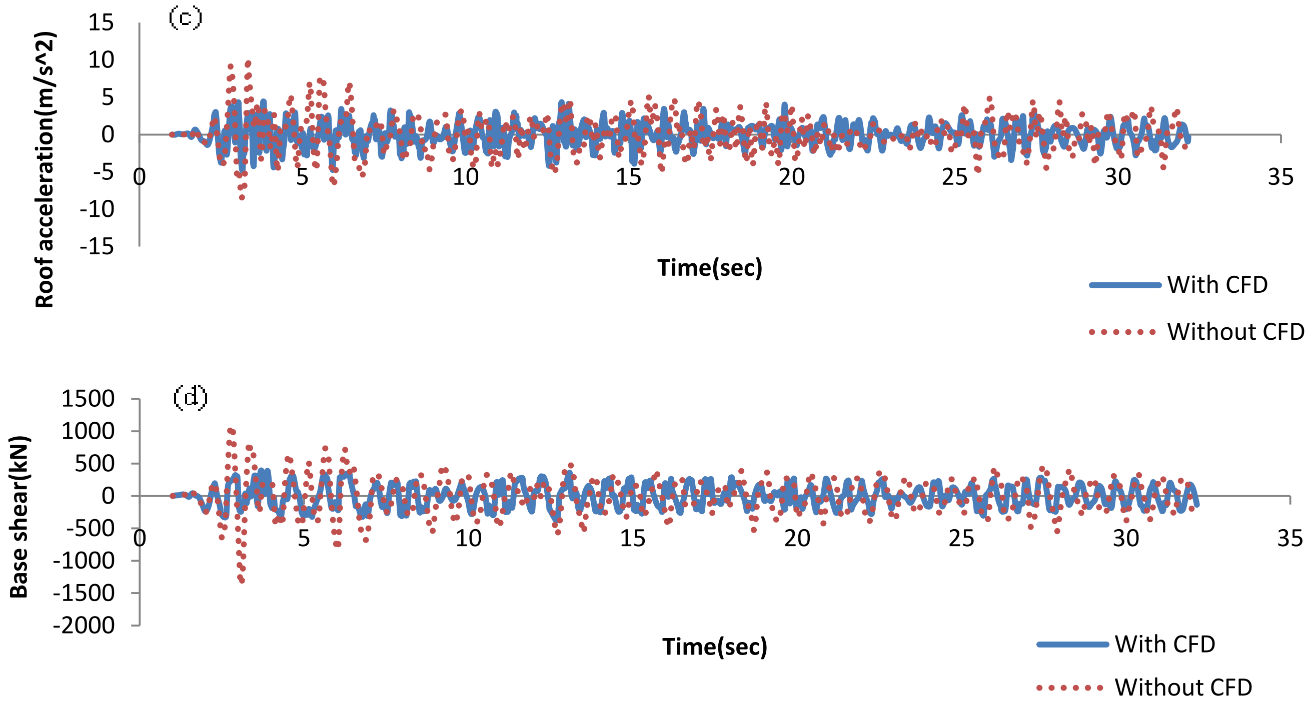

Fig.9: Response of the frame with and without damper: a) displacement of the roof, b) velocity of the roof, c) acceleration of the roof, d) Base shear.

7. Conclusion

Seismic response sensitivity of steel structures equipped with Cylindrical Frictional Dampers to the value of the slippage load was investigated. First of all, the optimum slippage load of the structures was found for ten earthquake excitation records. The results show that optimum slippage load is completely dependent to seismic excitation. Subsequently, the seismic response of the structure is obtained for various slippage loads in the range of plus and minus %20 of the optimum slippage load. It was shown that if the slippage load has a difference up to 20% from its optimum value, the maximum displacement response can increases up to 35%, however, it is still less than the maximum displacement response of the frame without CFD. It was also shown that CFD can significantly improve the performance of steel structures subjected to earthquake loads if appropriate value for slippage load of CFDs is selected.

Table.3: Peak responses of the frame.

Earthquake	PGA	Duration (sec)	Maximum displacement at the top of the frame (m)			Maximum base shear (kN)		
			Without CFD	With CFD	Reduction (%)	Without CFD	With CFD	Reduction (%)
Elcentro	31.16	0.318	0.1026	0.0451	56	1367.13	377.64	72
Kobe	47.98	0.599	0.4654	0.1769	62	1621.20	809.05	50
Tabas	32.82	0.836	0.1342	0.1204	10	1390.64	998.46	28

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