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Friction damper dynamic performance in seismically excited knee braced steel frames

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Abstract

High performance and reliability of refurbish able knee braced steel frames has been confirmed in previous researches trying to get an optimal design for its configuration. Buckling of diagonal member which affects the hysteretic behavior of KBF under cyclic loadings has not been foreseen in previous evaluations of this system. This deficiency can be improved by utilization of adjustable rotary friction damper device (FDD) as knee element. Diagonal element buckling can be prevented considering a suitable value for FDD sliding threshold moment Mf. Lower values of Mf Lower energy dissipation rate in FDD and this leads to an optimization problem.Nonlinear time history analyses have been performed in addition to lateral cyclic loading analyses to evaluate the response of single story KBF subjected to seismic excitation. Optimal Mf in FDD has been chosen according to these analyses results. Roof displacement and acceleration, base shear and diagonal element's buckling status have been compared in optimally designed KBF and FDD utilized KBF (FKBF) with different configurations. Nonlinear dynamic analyses have been performed for one, four, eight and twelve story frames under different seismic records with several PGAs. More than 60% displacement response reduction has been earned for the FKBF without considerable increase in base shear.

Keywords: *Knee braced steel frame, Buckling, Friction damper, Dynamic analysis.*

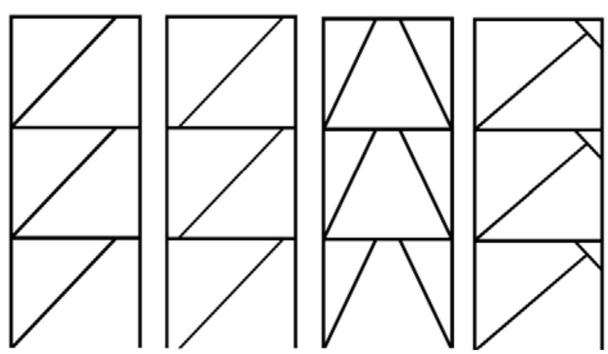
1. Introduction

The demands of building owners have changed in recent years: they now wish to be able to continue using buildings with small repair cost even after a severe earthquake. A building system with dampers is one structural type which meets these performance requirements, for which the dampers need good performance and applicability.

Moment-resisting frame (MRF) and concentrically braced frame (CBF) are ordinary types of earthquake resisting systems for steel structures. Excellent ductility of MRF which provides energy dissipation in a goodlevel and considerable stiffness of CBF which limits the drifts are major advantages of these traditional systems. These advantages have been gathered together in eccentrically braced frame (EBF) proposed by Roeder and Popov [1], see Figure 1(a). In this system brace elements provide frame's stiffness and ductility is provided by links with flexural or shear hinges.

These sacrificial components form on the end or mid of gravity loads bearing girders in the mostly known configurations of EBF systems leads to uneconomically large sections for beams. Furthermore, fuse element as a part of a main structure is needed to be changed after plastic formationwhich is not economically in the most cases.However, recently lots of researchers have been interested in seismic performance of EBF and preformed so many useful studies on this topic [2], [3].

Consequently, separation of the yielding component from the beam elements and its renewability are the main advantages of knee bracing frame (KBF) presented by Aristizabal -Ochoa [4], Figure 1(b).



(a) (b)

Fig. 1 (a) Conventional EBF Systems, (b) KBF System General Configuration

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Different features of this bracing system have been investigated by Balendra and Sam [5], [6], [7] also Mofid and Khosravi [8] studied it for its optimal configuration.
Buckling of diagonal members which is the main deficiency of CBF systems is probable for KBF systems too. Plastic moment capacity of knee member shall be limited not only for buckling prevention of diagonal member but also for yielding at determined ductility level. Considering the buckling effects in seismic performance and energy dissipation of KBF systems which has not been considered in aforesaid investigations is the main objective of this study.
Different approaches have been proposed for buckling prevention in brace members. Buckling restrained brace (BRB) was firstly designed by QiangXie [9]. It consists of an axial steel brace which freely slides inside an encasing mortar and shall be used as precast modules. Golafshani and Kabiri [10] proposed semi active ribbed bracing system (RBS) to prevent buckling in compressive member. Another useful method to restrain braces against buckling is to cover them with concrete [11].Diagonal member in knee bracing system can be also protected against buckling with stiffness adjustment of knee anchor. Using novel friction damper device innovated by Mualla [12] as knee element is another preferable choice for buckling prevention of diagonal.
In modeling, SI system of units was used. Steel mechanical parameters in order to model were; F_y = 2.35e8 N/m^2, E_s =2e11 and second stiffening ratio of 2%. For the steel used in friction pad; E = 1e16, Friction sliding threshold moment (M_f) of 7000~22000N.m and second stiffening ratio of 0% for perfectly plastic stress-strain behavior.The structural frequency of the system having FD elements and without it is presented in Table 1 for 1, 4, 8 and 12-story structures.

Table 1 The structural frequency of the system having FD elements and without it

Story number	KBF frequency (Hz)	FKBF frequency (Hz)
1	9.17	14.43
4	1.679	1.97
8	1.146	1.176
12	0.619	0.716

2. Analytical Model

2.1. Brace buckling

Phenomenological analytical model, physical theory approaches or three dimensional finite element models can be used for consideration of the post buckling behavior of brace elements in structural analysis. Interaction between the second order bending moment and the axial force in the nonlinear beam column elements should be considered to provide a powerful utility for post buckling analysis of members with axial forces by nonlinear analysis software. Accuracy of this method has been verified in accordance with experimental results by Uriz and Filippou [13]. They utilized OpenSees computational framework for parametric study of brace buckling. The analytical model of the brace consists of several inelastic beam-column elements.

For inducing buckling in an axially loaded brace, it is necessary to include an imperfection to the geometry of the system in the form of initial camber as shown on Figure 2, or to the properties of the member over the cross section. According to Uriz and Filippou,peak initial camber, δ , at the center of the element is assumed to be 3% of total length of the brace [13], [14].

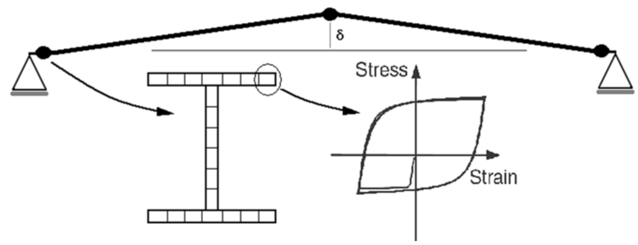


Fig. 2 Illustration of multi-element beam-column member with initial camber (exaggerated) and uniaxial stress-strain relationship for fibre elements [12]

2.2. Frames

The finite element model which used for the analysis of proposed system is verified by comparing the results with Huang Zhen study [15], Figure 3. The research of Mofid and Khosravi [8] showed that the structure could have maximum earthquake resistance if the knee anchor and inclined brace were parallel to the diagonal of the frame and the diagonal brace passes through beam-column intersection. The position and stiffness of knee element and its yielding moment compared to other elements were studied by Zhen et al [15].

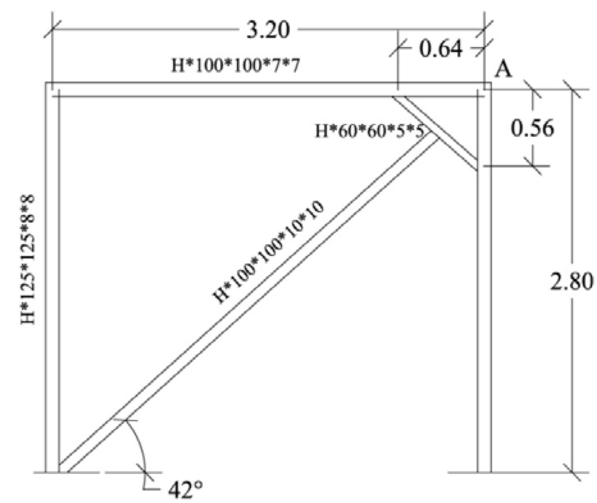
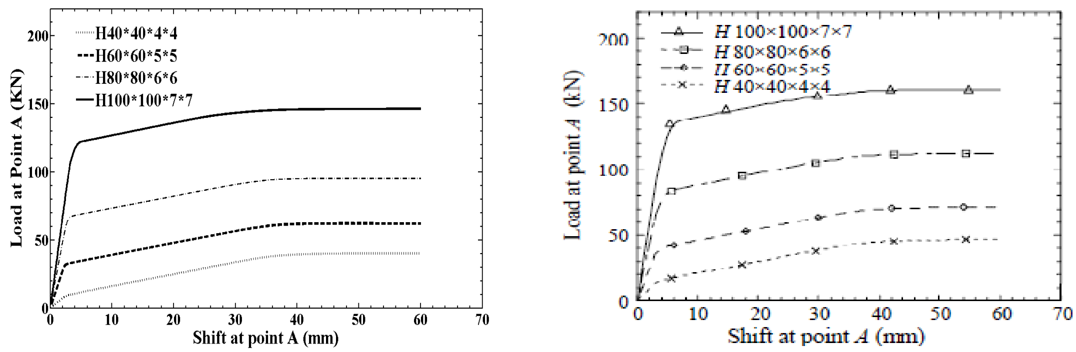


Fig. 3 Structural configuration of KBF studied for modelling validation [13]

Results of pushover analyses performed for four different knee element sections in this study are in good agreement with Zhen [15] reports according to Figure 4(a), (b). This is just to validate static analyses reliability.



(a) From Opensees Analyses (b) As per Zhen[13] reports

Fig. 4 Lateral deflection of frames with different knee elements

Two different 2D models have been analysed statically and dynamically with OpenSees software; conventional KBF, and KBF equipped with friction damper (FKBF) utilizad as knee element, Figure 5. Each one has been considered with and without buckling effects in diagonal member.

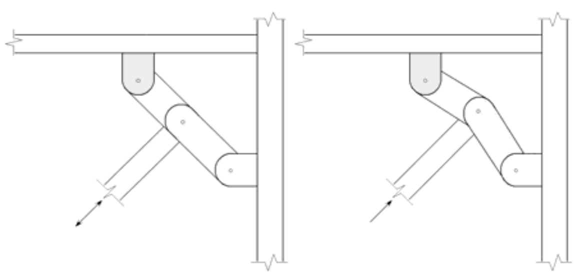


Fig. 5 Friction damper used as knee element [16

Mualla [12], [14] presented an analytical description of friction damper behaviour which follows an idealized hysteretic loop as shown on Figure 6. The novel friction damper consists of 3 steel plates rotating against each other and in between these plates, there are two circular friction pad discs, In order to have dry friction lubrication in the unit, ensuring stable friction force and reducing noise of the movement.In this paper its behaviour is modeled via OpenSees Zero Length element. So three Zero Length Elements are used in the frame to model a friction damper device. Reliability of this model has been validated in comparison with analytical and experimental results reported by Mualla [17].

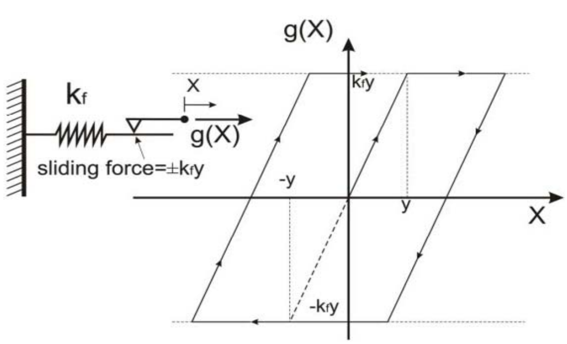


Fig. 6 Friction device idealized behaviour [15]

3. Static Analyses

First, frame's behavior affected by buckling of diagonal element is studied by performing nonlinear pushover analysis. Lateral force is in the direction that causes diagonal element act in compression. Three Different values have been taken as FD sliding moment (M_f = 7000, 1400 &21000) to evaluate FKBF's sensitivity to M_f variations. Using friction damper prevents buckling of the diagonal element, but M_f shall be limited to guarantee the diagonal element never buckles and yields assumed ductility level, Figure 7. Consequently frame B for its better response is chosen to be compared with KBF under cyclic loading to compare the energy dissipation capacity of models, displacement control analyses have been performed considering ATC-24 cyclic loading protocol for steel structures [19] , Figure 8.

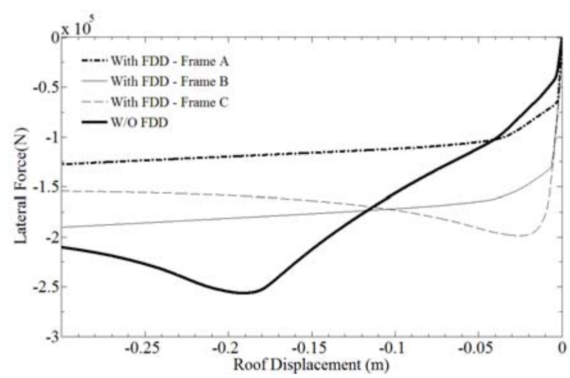


Fig. 7 Diagonal element buckling effect on pushover analysis of FKBF

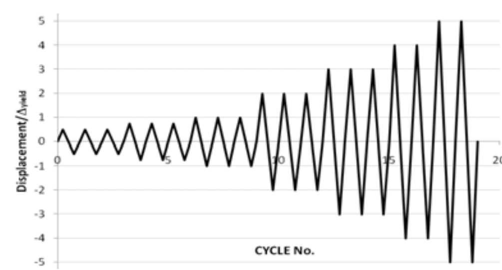


Fig. 8 ATC-24 cyclic loading protocol for displacement control analysis of steel structures [17]

This cyclic loading has been modulated regarding to bilinear diagram of pushover analysis.

Stable and symmetric hysteresis curve with maximum inside area for strucure or element whitout any pinching is the design ideal goal [20]. It is obvious from Figure 9 that buckling of diagonal member reduces the energy dissipation capacity of the knee bracing systemand unstable hysteresic response causes main deficiency in KBF. As a prelaminary result, diagonal member buckling should be taken into account in the optimal design of knee element. FKBF hystertic response implies friction damper effect on improving lateral response by increasing energy dissipation capacity approximately 80% and controling diagonal element not to buckle.

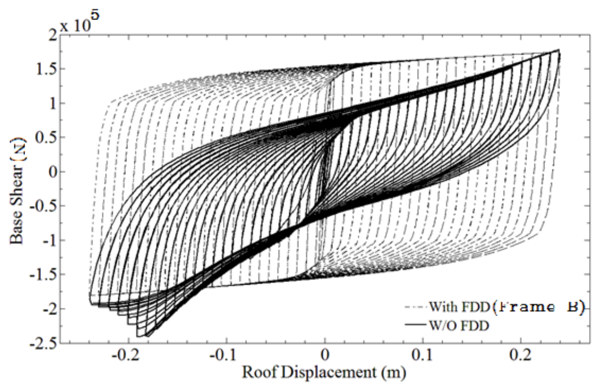


Fig. 9 Hysteretic curves of FKBF in comparison with KBF considering brace buckling (M_f = 14KN.m)

4. Dynamic Analysis

4.1. Single story frame

Based on Iranian code for seismic design (ISIRI 2800), in time history analysis it have to be chosen three earthquake records at least and all of them to be scaled to maximum PGA of 1.0g. The same scaling method has been considered in this study. To evaluate dynamic performance of proposed frame, nonlinear time history analysis under five far-field horizontal records (Elcentro, Tabas, Kobe, Naghanand Northridge) was performed in single story frame. In order to evaluate FKBF's sensibility on earthquake severity, each record is analyzed for five level of PGA (0.1g, 0.3g, 0.5g, 0.7g, 0.9g). Naghan and Tabas records are two important Iran region earthquakes. El Centro, because of its special frequency contain is usually used in most of the researches. Kobe and Northridge records have been taken as a strong and special earthquakes.

The roof displacement and base shear time history response for El Centro 0.3g case is plotted in Figure 10. Utilization of FD instead of plastic knee anchor has caused considerable reduction in lateral displacement without significant increase in base shear according to Figure 11.

It is obvious from Figure 12; there is smooth increase in maximum roof displacement reduction rate for bigger PGAs. However, friction damper effect on the maximum base shear reduction rate decreases when PGA grows up. Figure 13 refers to base shear that shows base shear changes increasingly with earthquake sensitivity increase.

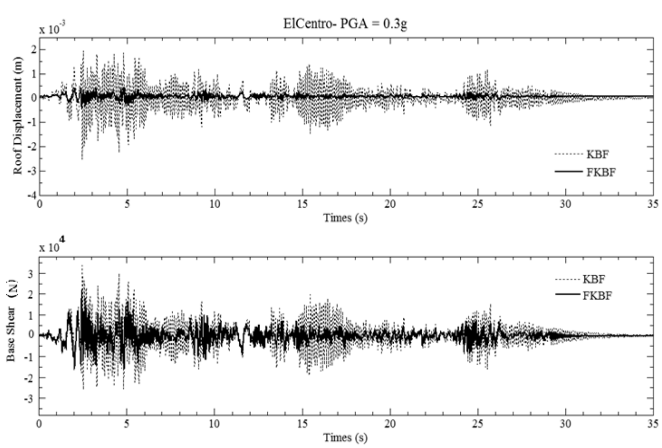


Fig. 10 Time history analysis results, El Centro earthquake with 0.3g PGA

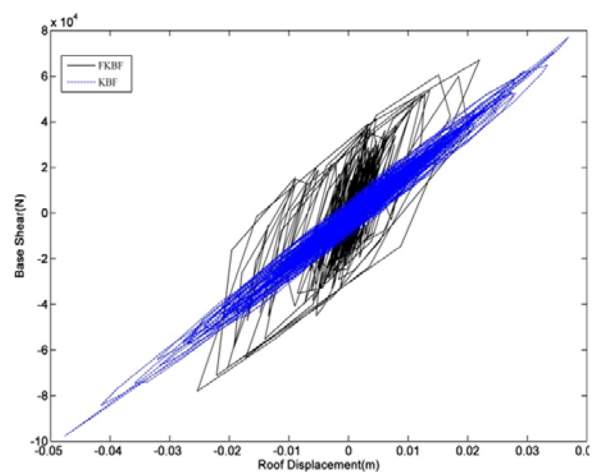
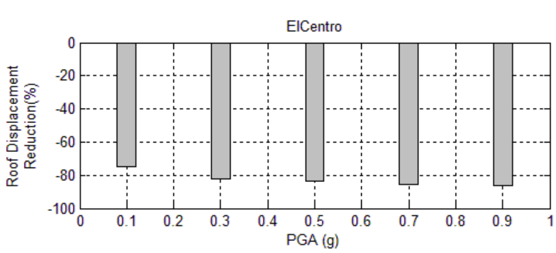
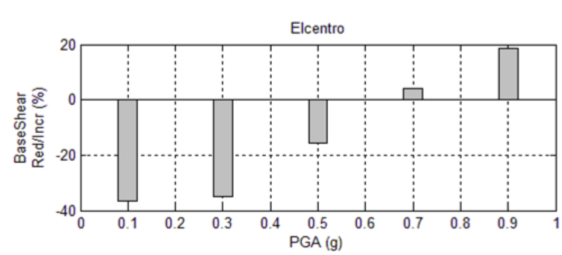


Fig. 11 Hysteretic behaviour of 8 storeyKBF and FKBF, for El-Centro earthquake with PGA of 0.9g





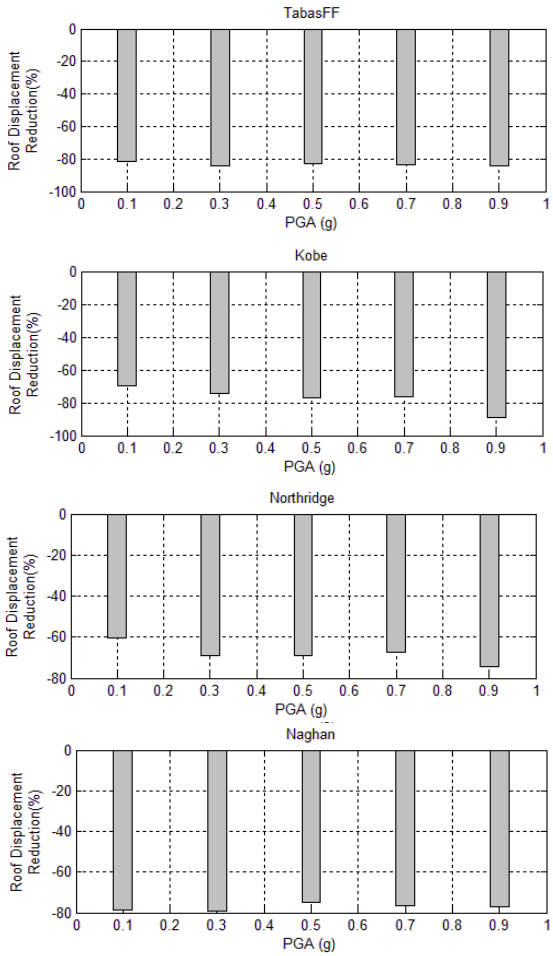


Fig. 12 Maximum Roof displacement

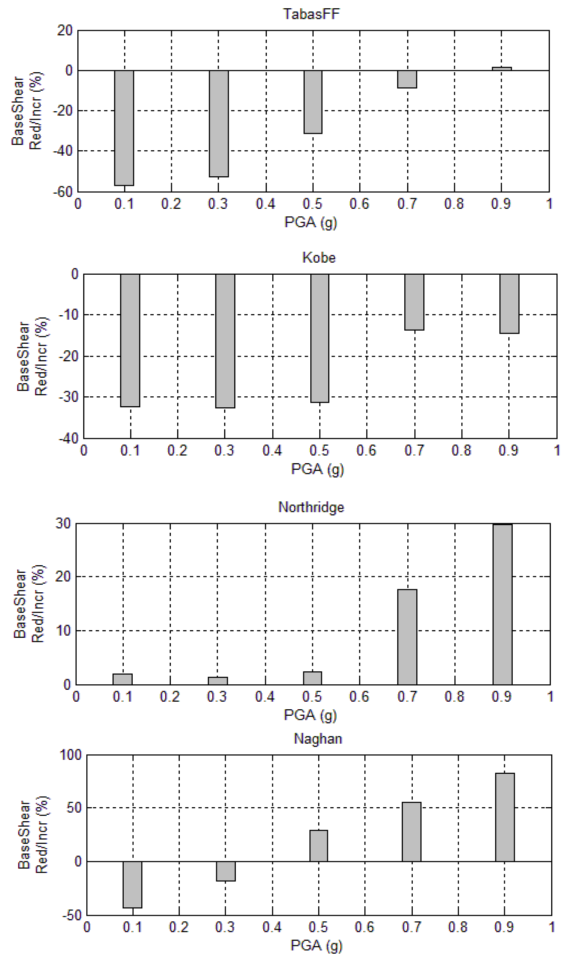


Fig. 13 Maximum Base Shear

4.2. Multi story frame

Multi-story knee braced frames are first modeled as Figure 14. Middle span is chosen for all of the frames as braced span. There are three frictional hinges in each story level utilized as knee elements. Four, eight and twelve story frames are chosen as short, moderate and long period structures, sequentially.

Dynamic nonlinear time history analyses are performed for the evaluation of the seismic behavior of the structure. As what are done for single story building, these frames are analyzed with and without the friction dampers. The comparisons of achieved drifts for the structures with and without the friction damper are shown in Figure 15, 16, 17.

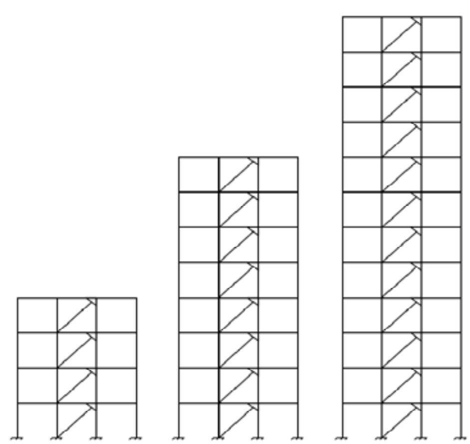


Fig. 14 Multi story knee braced frame 2D view

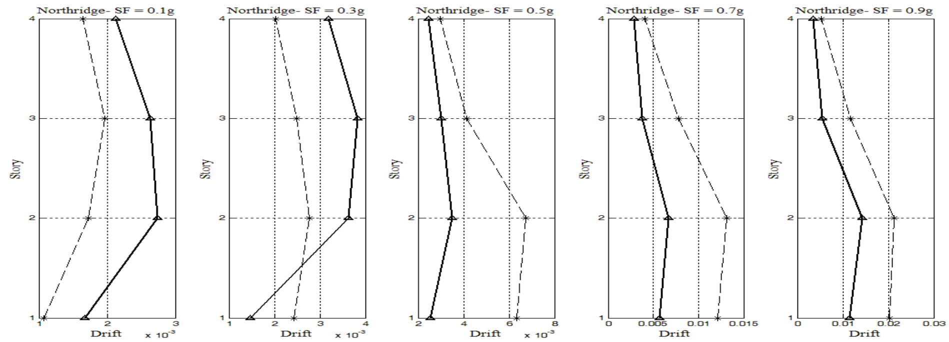


Fig. 15 4 story drift response under Northridge record

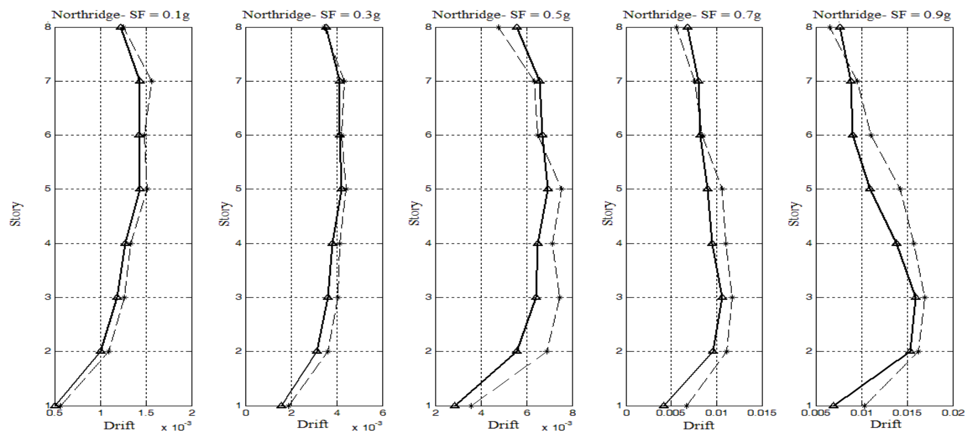


Fig. 16 8 story drift response under Northridgerecord

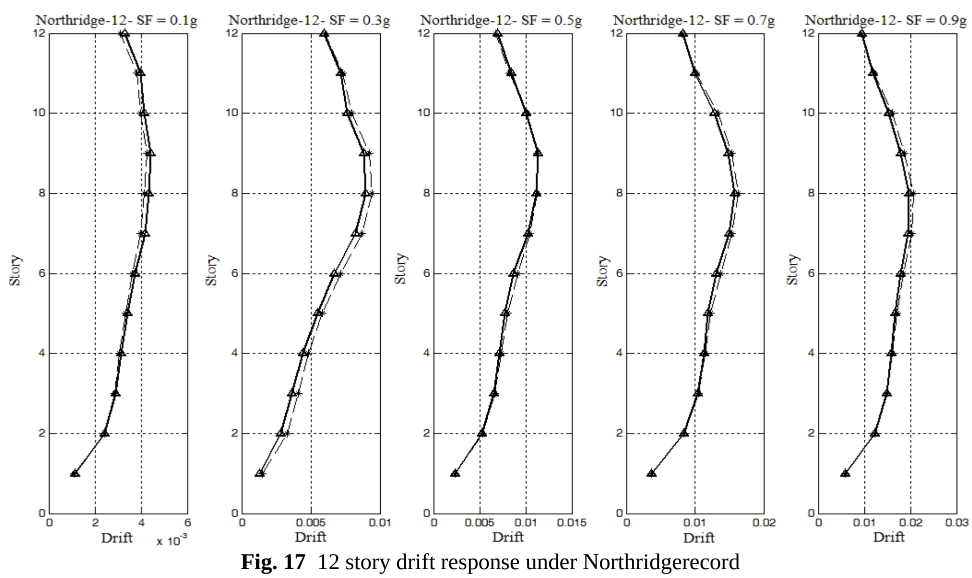


Fig. 17 12 story drift response under Northridgerecord

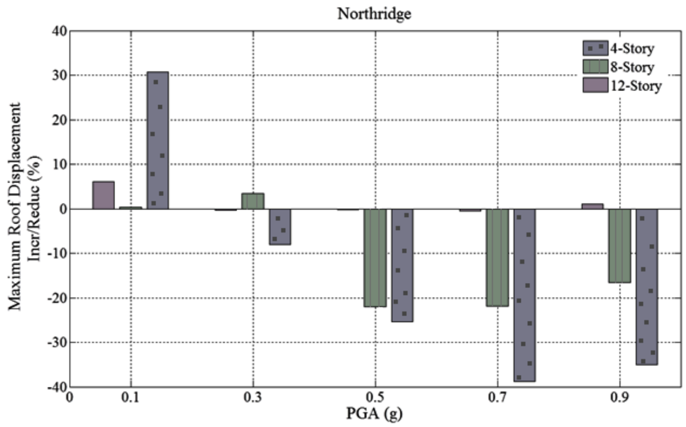


Fig. 18 Comparison of maximum Drift in multi story FKBF and KBF under Northridge earthquake with different PGA's

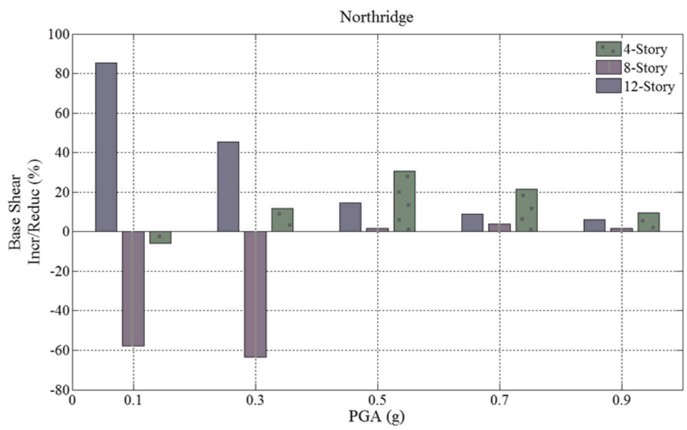


Fig. 19 Comparison of maximum Base Shear in multi story FKBF and KBF under Northridge earthquake with different PGA's

Results show thatin 4-story model, for the PGA range between 0.1 to 0.3g friction damper does not reduce the drift response but for the PGA between 0.5 to 0.9g it is effective for drift response reduction. It could be concluded from Fig. **15** that the friction damper is getting more effective by increasing the PGA of earthquake. In 8-story building drift reduction rate reduces by increasing the PGA from 0.1 to 0.9g. FDD improves the drift response of 12-story building but it is not considerable. Also the achieved results for maximum base shear and roof displacement imply that FD is effective for response improvement for these two cases.

To have a betterconclusion, different earthquakes' analysis results and reduction in maximum drift ratios have beencompared in Table 2. Table 2 had been provided comparing the maximum drift in FKBF and related value of KBF for the same story aiming to decrease the maximum drift of FKBF in comparison with the maximum drift of KBF however they happens in different stories.

Table 2 Maximum drift ratio variation in different records of earthquakes for five level of PGA

4 Story	Northridge		Kobe		Elcentro		Tabas		Naghan	
PGA	Max Drift story level	Drift Ratio variation (%)	Max Drift story level	Drift Ratio variation (%)	Max Drift story level	Drift Ratio variation (%)	Max Drift story level	Drift Ratio variation (%)	Max Drift story level	Drift Ratio variation (%)
0.1g	2	-36.75	2	+26.2	2	-28.94	3	-30.07	2	-38.87
0.3g	2	-45.8	2	-10.97	2	-28.2	2	-10.32	2	-26.32
0.5g	2	-12.5	2	-15.3	2	-13.68	2	-26.55	2	+38.06
0.7g	2	-27.4	2	-42.5	2	-5.67	2	+24.34	1	+0.56
0.9g	2	-19.8	3	-5.72	3	+11.1	2	+19.78	1	-24.88
8 Story	Northridge		Kobe		Elcentro		Tabas		Naghan	

PGA	Max Drift story level	Drift Ratio variation (%)	Max Drift story level	Drift Ratio variation (%)	Max Drift story level	Drift Ratio variation (%)	Max Drift story level	Drift Ratio variation (%)	Max Drift story level	Drift Ratio variation (%)
0.1g	7	-8.50	5	-9.53	4	-12.46	5	-8.6	5	-2.37
0.3g	5	-5.06	5	-8.36	5	-5.6	5	-12.23	5	-3.63
0.5g	5	-8.05	5	-5.35	5	-24.08	5	-4.26	5	-2.57
0.7g	3	-9.46	7	-21.63	5	-17.75	5	-4.5	5	-7.54
0.9g	3	-5.89	7	-34.71	5	-1.07	7	-7.08	5	-4.56

12 Story	Northridge		Kobe		Elcentro		Tabas		Naghan	
PGA	Max Drift story level	Drift Ratio variation (%)	Max Drift story level	Drift Ratio variation (%)	Max Drift story level	Drift Ratio variation (%)	Max Drift story level	Drift Ratio variation (%)	Max Drift story level	Drift Ratio variation (%)
0.1g	9	+4.42	9	-0.83	9	+4.13	11	+10.26	9	-7.51
0.3g	8	-5.28	9	-1.26	9	-5.41	11	+13.83	9	-8.27
0.5g	8	+0.27	10	-4.57	8	+3.74	9	-3.91	9	-9.55
0.7g	8	-3.26	10	-8.86	8	-3.24	9	-2.85	9	-5.99
0.9g	8	-4.64	10	-6.58	9	-6.57	10	+2.04	9	-3.42

5. Conclusion

A new buckling restriction method for KBF is described and evaluated. Cyclic hysteretic behavior of steel frames with and without utilization of friction damper device was analyzed applying ATC-24 cyclic loading protocol for steel structures. Seismic behavior was also studied under three far-field earthquake records with five PGA for each one by nonlinear time history analysis. For nonlinear analysis Opensees software was employed. For modeling a friction damper Zero length elementshave been used in three hinges.

To evaluated friction sliding threshold moment effect on frame's behavior three different values has been assumed and the results has been compared in static analysis.

Numerical static analysis of single-story KBF models indicated the following results:

(1) There is no buckling in diagonal member under cyclic loading in FKBF;

(2) Energy dissipation rate comparing with conventional KBF is considerably increased;

(3) FKBF compared with KBF has more ductility and stiffness which improve frame's performance.

Nonlinear time history analysis was also performed under far-field earthquake records (Elcentro, Tabas and Kobe). For M_f = 14e3 (N.m), 83% reduction for maximum roof displacement was calculated in El-Centro (PGA = 0.3g) and 36% reduction for maximum base shear.

The numerical studies results clearly demonstrate that the friction damper is an appropriate alternative to the conventional ductility-based earthquake-resistant design both for new construction and for seismic rehabilitation of existing structures in the single story frames. Using this device is economically beneficial and also installation is easy and can protect the building in moderate and severe earthquakes.

Nonlinear time history analysis for three multi story frames (4, 8, 12 stories) is performed under Northridge far-field record. The results show a smooth change in the frames responses by the use of FDDs. FD utilized knee braced frames have presented the best performance for moderate earthquakes**.**In multi-story structures, as the building height increases, the modes effects on structural behavior improve. According to this, friction damper's performance is affected and as it is obvious from the results dampers effects reduce.

Considering the achieved results, optimization methods for placement of FDDs can be used for reaching the satisfactory result. These optimizations should be done considering several parameters including the number of braced openings in the frames, number of stories and earthquake intensity.

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