BEHAVIOR OF FRICTION DAMPING ON SEMI-RIGID "KHORJINEE" STEEL FRAMING CONNECTION

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SUMMARY

The use of mechanical damper provides the means for consuming the kinetic energy of a vibrating building without sacrificing the integrity of primary structure elements, and also represents an effective method for reducing the possibility of resonant response. Recent analytical and experimental investigations suggest that it is possible to significantly increase damping in buildings through the use of mechanical damping devices. In this paper, among numerous different types of energy-absorbing devices, effect of pall-friction damping and added damping and stiffens (ADAS) device on an interesting type of semi-rigid steel framing connection which is commonly used in Iran (including in seismic zone) have been investigated. analytical results are first summarised to illustrate the earthquake performance of damped structures compared to the performance of conventional building systems. On the basis of extensive analytical and experimental investigations, some theoretical issues associated with application of a particular type of friction damped bracing and ADAS elements to two different groups of common building structures in Iran, 1) simple steel braced frames, 2) semi-rigid "khorjinee" steel braced frames, for seismic performance enhancement are considered.

INTRODUCTION

In order to achieve economical earthquake-resistant constructions building structures must be constructed to dissipate a large amount of seismic energy. In the last decade, many energy dissipating systems have been proposed to raise the seismic design of structures beyond the conventional ductility design approach. Among these new systems, friction damping has shown some great potential. In a friction damped system, friction damping devices are inserted in a structure and slip at a predetermined optimum load during sever seismic excitations, before and yielding of the structural members has occurred. Slipping of the devices allows the structure to dissipate the input seismic energy mechanically by friction rather than by inelastic deformation of the structural elements. Added damping and stiffness (ADAS) elements are designed to dissipate energy through the flextural yielding deformation of mild-steel plates.

It has long been recognised that it is not economical to design ordinary structures to remain free of damage during a major earthquake. In recent years, many researchers and engineers have directed their efforts to the development of innovative a seismic structural systems which are intended to limit the dynamic forces that are developed in the structural members. The particular type of friction damped bracing which is used in this study, basically consist of a special mechanism containing slotted friction brake lining pads introduced at the intersection of frame cross-braces. The device is designed not to slip under normal service loads and moderate earthquake. During sever seismic excitations, the device slips at a predetermined load, before any inelastic deformation of the main members has occurred. The optimum slip loads distribution for two different systems, have been evaluated by a series of non-linear time-step dynamic analyses using the computer program DRAIN-2D and also a series of non-linear time-history dynamic analysis were made to determine the displacement, velocity and acceleration response spectra, under the time earthquake records El Centro, Naghan and Tabas earthquakes, which were compared to the response of conventional building systems. In addition, the influence of slipping of a device and vertical distribution of friction dampers on natural frequency of the structure and its fundamental dynamic characteristics during a sever earthquake are investigated.

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In this paper, also recent research findings on the effectiveness of using steel plate welded as the added damping and stiffness (ADAS) device for earthquake-resistant structure on an interesting type of semi-rigid steel framing connection which is commonly used in Iran (including in seismic zone) are presented.

DESCRIPTION OF FRICTION DAMPING SYSTEM

The novel structural a seismic system discussed in the paper was originally proposed by two Canadian researchers [Pall and Marsh, 1982]. The system basically consists of a special mechanism containing slotted friction brake lining pads introduced at the intersection of frame cross-braces. Figure 1a shows the location of the friction devices in a typical frame. The device is designed not to slip under normal service loads and moderate earthquakes. During severe seismic excitations, the device slips at a predetermined load, before any inelastic deformation of the main members has occurred. Slipping of a device dissipates the seismic energy mechanically and also changes the natural frequency of the structure and allows it to alter its fundamental dynamic characteristics during a severe earthquake. The friction devices can be used in any configuration of the bracing system needed to meet architectural requirements.

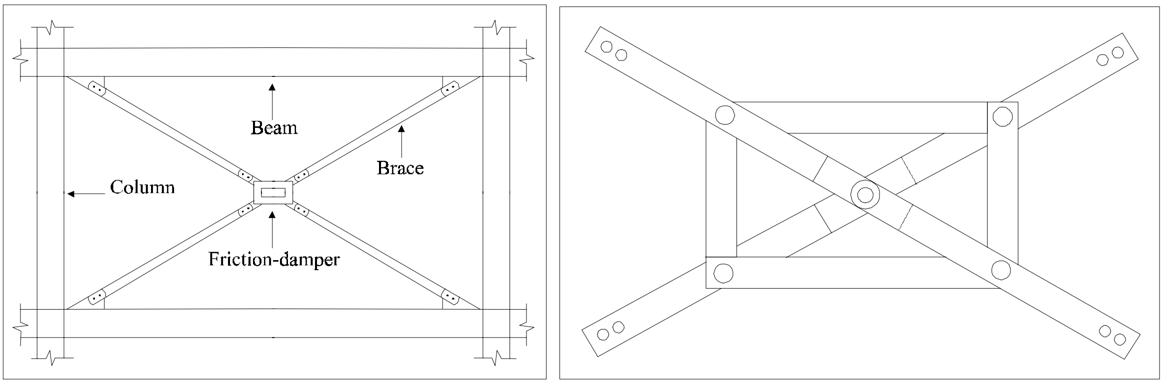


Figure 1: Typical braced bay and pall friction damper device

If the diagonal braces of an ordinary braced frame structure were designed not to buckle in compression, a simple slotted friction joint could be inserted in each diagonal member. In this case the slip joints would act independently of each other.

However, in many buildings, the braces are quite slender and are affective in tension only. In such cases, a simple friction joint would slip in tension but would not slip back during reversal of the tension load, or in the compression (buckled) regime. The energy absorption therefore would be relatively poor, since the brace would not slip again until it is stretched beyond the previous length , as illustrated in Figure 1b. The introduction of the friction damping mechanism described earlier significantly improves the energy absorption capability of the diagonal cross-braces.

BASIC MECHANICAL CHARACTERISTICS OF ADAS DEVICE

Up to now, the numerical modelling of the stiffness and non-linear behaviour of the ADAS device has been primarily based upon experimental data from test of prototype devices (scale 1:1), similar to those that will be used in the structure. Whittaker et al., have presented an analytical procedure to define the load-deformation curve of the ADAS device, assuming an equivalent X-triangular-shaped geometry. Although the method is simple, its results are limited if more rigorous analyses are to be done. The use of a detailed finite element mesh to model an ADAS device is reasonable to study the behaviour of the device alone; however, it is not practical for studying the non-linear dynamic behaviour of multi-storey structures with several ADAS devices. Recently, a microscopic mechanist approach has been proposed for metallic dampers the applicability of which could be tested for the ADAS device.

An idealisation of the geometry of an ADAS device is given in Figure 2a. Here, the layout of the ADAS is hour glass- shaped. These devices are made with tapered structural steel plates designed to work primarily in double curvature, which makes their layout more efficient as these elements yield almost entirely along their length.

Because of its particular tapered shape, the computation of the stiffness and the plastic capacities of the ADAS device are nontrivial. Whittaker et al., Proposed a simple procedure to define the load-deflection curve for the

ADAS devices, using an equivalent X-shaped idealisation of the plates Figure 2b, are inscribed inside the actual profile of the ADAS. Their method is based on the following assumptions; firstly, the X-plates are rigidly restrained at their ends; secondly, the X-plates deform in double curvature, anti symmetric about their mid height; and finally, the equivalent width of the X-plates at their ends is equal the equivalent width of the X-plates at their ends is equal to half its height (b1eq= l/2). The load-deformation curve in shear of the ADAS can be idealized as and elastic perfectly plastic curve (Figure 2c), or as a bilinear one (Figure 2d), as recommended in the literature. In the procedure by Whittaker el al., the yielding point is defined from the proposed equivalent geometry.

PROPOSED ANALYTICAL METHOD

The stiffness matrix of an elastic nonprismatic element, such as the plates that compose the ADAS device, can be defined using the flexibility method. The hourglass shape of each plate that composes the ADAS (Figure 2a) can be approximated using exponential function as

$$b(z) = b_1 e^{-az};\ 0 \le z \le l/2 \quad \text{and} \quad b(z) = b_2 e^{a(z-l/2)} \quad l/2 \le z \le l \tag{1}$$

Where $\alpha = 2/l\, 1n\,(b_1/b_2)$ A regression analysis of geometry of the ADAS devices tested at the University of California at Berkeley and reported by Whittaker et al., Was conducted to obtain the best fit for the proposed exponential function. The geometry of the ADAS device is closely represented by the exponential functions. The width of the device is slightly underestimated near the fixed ends and at midspan. This underestimation should not be critical because the curvatures on those regions are small, as computed and reported by Whittaker et al. . The dimensions b1 and b2 for the best fit of the proposed exponential function are defined by

$$b1 = 0.6l \quad ;\ b2 = 0.1l \tag{2}$$

The influence of various ADAS element parameters on seismic response of building structures has been extensively analysed [Xia and Hanson, 1992]. In order to gain further insight in to the effects of some important ADAS parameters on the seismic response of building frames, non-linear response spectra of SDOF system were studied [Tsai and Chen 1992, Tsai et al., 1993]. For the purpose of discussion, an ADAS element is defined as an ADAS device and two braces that support the device. The horizontal stiffness of the ADAS element, Kt, is a function of the lateral stiffness of the braces, Kb and the device stiffness Ka. If the ratio of the horizontal ADAS element stiffness, Kt , to the structural story stiffness, without the ADAS device and braces in place, Kf , is defined as SR [Xia and Hanson, 1992], then:

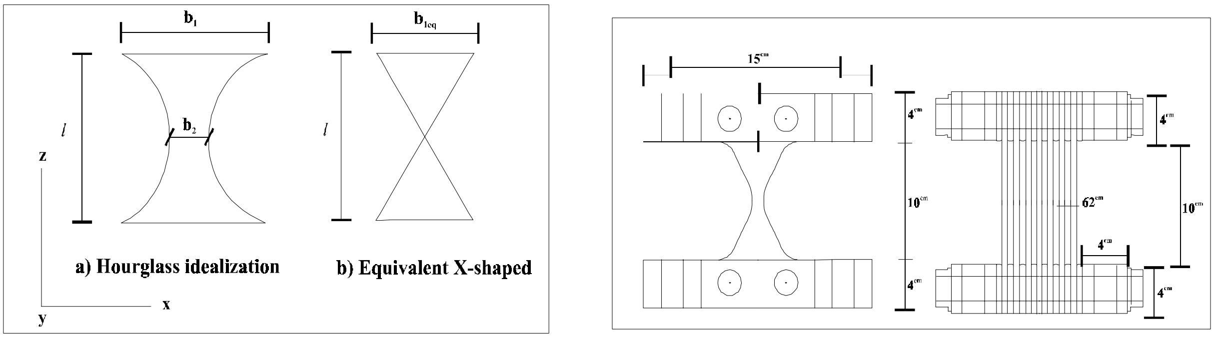
$$SR = \frac{K_t}{K_f} \quad ; \quad K_t = \frac{K_b K_a}{K_b + K_a}; \tag{3}$$

DESCRIPTION OF ADAS ELEMENTS

ADAS elements consist of multiple X-shaped mild steel plates configured in parallel between top and bottom boundary connections Figure 2c and 2d. The ADS elements used in this study were made from A-36 steel and consisted of either four, or five plates.

The particular advantage of an X-plate is that, when deformed in double curvature, the plate deformation is uniform over its height, and when deformed in to its plastic regime, the yielding will be distributed. A rectangular plate, when deformed plastically in double curvature, will yield only at its ends. This concentration is particularly undesirable both in terms of the amount of energy that can be absorbed by such a deformation pattern and by its inherent lack of stability and repeatability in the plastic range.

The X-plate is a development from triangular plate devices, which were developed in New Zealand (Tyler 1978, Boardman, 1983) and was first developed as a piping support element (Steimer, 1980 and 1981). X-plates have been used as the energy dissipating component of a base isolation system in shake table tests.



(a) (b) (c) (d)

Figure 2: Added damping and stiffness (ADAS) element

CHARACTERISTIC OF ANALYTICAL MODELS

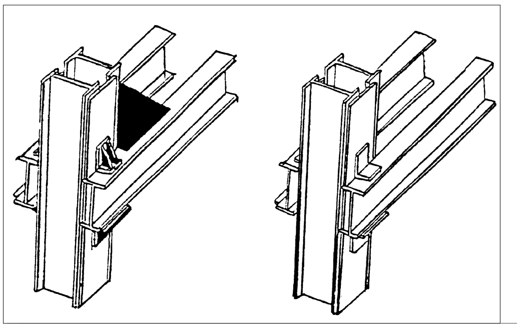
Khorjinee Connection Characteristic

Semi-rigid connections in steel structures has taken considerable attention in recent years due to simple details and possibility of tuning the connection’s stiffness which can optimise the distribution of moment between connected elements An special type of semi-rigid beam-to-column connections named as “Khorjinee connection” has been developed in past fifty years by practising engineers in Iran because of its simplicity and economic advantages, Figure 3a. In these connections a pair of continuos beams cross several columns and connect to the sides of columns by means of angle sections. This type of construction save not only on erection time and labour cost, but also the limitations on the availability and the cost of deep rolled sections in the country, makes the use of two parallel beams instead of one deeper beam the only alternative in most cases. Out-of-plane partial beam-to-column transfer of bending moments and early onset of failure in the angles are most likely the cause of failure under lateral forces in these connections. The flooring systems, simply connected steel joists are used to bridge the main beams. The space between these joists are filled with bricks and mortar as a bonding agent in a shape of an arch with approximately 2-5cm from the head of the arch to its larger stresses in the main beams compared to two-way floor systems, where all beams in a bay between four columns share the same floor weight. This is another reason why two parallel beams are needed for taking up the floor loads. Also most of the existing steel structures were not designed to resist lateral loads. Several theoretical and experimental researches have been performed to study the static behaviour of this connection as well as its workability, stiffness and strength using different models [Tehranizadeh and Alavi, 1997] and [Ghafory-Ashtiany, et al., 1995). It was found that the behaviour of this widely used connection can not be modelled by classical semi-rigid connection and that special model has to designed to satisfy its dynamic behaviour as well [Tehranizadeh and Alavi, 1997].

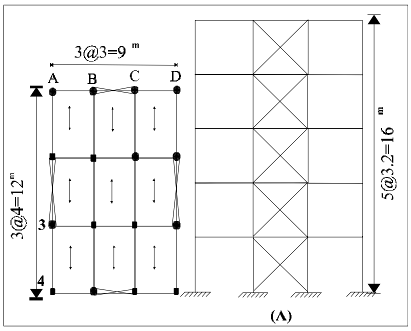
Semi-rigid connection can be divided in two groups of continuous and discrete connections. In order to model the continuos semi-rigid, Khorjinee, connection a spring element at the connection of beam and column have been used [Chen and Matsuoka, 1987]. This element in the ETABS program is in the form of frame element that works between beam and column and has very large flexural stiffness in two directions and the torsional stiffness equal to K=G.J/L.

Dynamic Analysis Of Friction Damped System

In this study two types of simple and “Khorjinee” steel braced frames, for seismic performance enhancement with damper and without damper have been considered. Both of these structural models have the same configuration in plan for three cases of 3, 5 and 7 story buildings. These models have been analysed and the results are carried out and presented by tables and graphs. The model structures overall dimensions are 9m×12m in plan and 9.6, 16.0 and 22.4m in height for 3, 5and 7story buildings respectively as shown in Figure 3b.The damping ratio of structural frames without damper is assumed 1%.The lumped mass-system stimulating the dynamic properties of the analytical models is used. The lumped mass at each floor is 15.24 Tons for the first to 6th floors and 8.4 Tons for the top floor. The optimum slip load distribution has been evaluated for three different 3, 5 and 7 story buildings and listed in Table 1.



(a)



(b)

Figure 3 Plan and elevation of the braced frame model and typical shape of a khorjinee connection

The dynamic characteristic of friction damped structures can be predicted by a series of non-linear time step dynamic analyses using the computer program DRAIN-2D and also series of non-linear time-history dynamic analysis may be made to determined the seismic response at all levels of earthquake ground motions.

The displacement, velocity and acceleration response spectra for both cases of simple braced steel frames and friction damped frames, under 3 sever following time scaled earthquake records:
1- Naghan earthquake 1977, PGA = 0.72g
2- Tabas earthquake 1978, PGA = 0.43g
3- El Centro earthquake 1940, PGA = 1g (Scaled)
Have been carried out. The structural members design of analytical models have been accomplished based on the specification of Iranian Building Code (Iran 2800).

Five model structures with assumed connection's rigidity between zero and 100% (A, B, C, D and E frames) have been analysed with and without friction dampers. Tables 2 and 3 show behaviour of these frames. Maximum interstory drifts of Khorjinee frames with friction damper are less than the allowable limit of code, (Iran 2800).The experience of recent earthquakes in Iran especially Manjil earthquake of 20 June 1990, show the poor behaviour of Khorjinee connection and that most of the common steel structure fail due to their joint failure.

The main reason for failure of the Khorjinee steel framing connection is because of low-cyle fatigue. Therefore by controlling lateral displacements of this kind of steel frame, the behaviour of this connection will improved. Khorjinee frames with friction dampers show reduction in their deflections and base shear forces as may be observed in Figure 4. This means increasing safety of Khorjinee connection under earthquake loading and dissipation of input energy means reduction of forces.

Table 1: Optimum Slip Load For 3,5 And 7 Story Building

Frame	Optimum slip load (KN)
3 story	144.0
5 story	118.8
7 story	126.0

Effectiveness of an ADAS upgraded structure

In the case of analytical study of a model structure, the 4 story steel structure model, for seismic performance enhancement both with the ADAS upgrade and then again in its bare configuration (no any ADAS elements) have been considered. The model has been analysed and the results are carried out and presented by tables and graphs. It can deduced by comparing the geometric specification of the analytical model and the size of the ADAS elements that the columns, beams and braces have much more strength than the ADAS devices; thus, the non-linear action should be concentrated in the energy dissipation devices

Table 2: Maximum story drift of different "Khorjinee" steel braced frames for 3,5 And 7 story building under Naghan earthquakes

Frame	Floor	Without damping					with friction damping				
		Fram	fram	fram	fram	Fram	fram	fram	fram	fram	Fram
3 story	3	3.0	2.9	2.6	2.6	2.3	1.4	4.5	1.5	1.5	1.6
	2	2.6	2.5	2.4	2.3	1.9	1.3	1.3	1.4	1.4	1.4
	1	1.1	1.0	1.0	1.1	1.2	0.5	0.5	0.6	0.6	0.6
5 story	5	11.9	11.6	10.4	9.9	8.8	5.9	6.2	7.5	7.7	8.1
	4	10.9	10.6	9.7	9.0	8.0	5.7	6.0	7.3	7.4	7.6
	3	8.6	8.4	7.9	7.8	7.1	5.3	5.7	6.9	7.0	6.8
	2	5.5	5.3	5.3	5.4	4.9	5.1	5.5	6.4	6.3	6.1
	1	3.5	3.3	3.3	3.4	3.5	3.7	3.9	4.4	4.3	4.4
7 story	7	19.5	19.7	19.4	19.1	18.0	7.5	7.6	7.9	8.0	8.0
	6	17.5	17.7	17.7	17.4	16.3	7.2	7.3	7.6	7.7	7.7
	5	15.4	15.3	15.2	15.0	14	6.9	7.0	7.3	7.4	7.0
	4	12.4	12.4	12.5	12.2	11.2	6.5	6.6	6.9	6.8	6.6
	3	9.0	9.0	8.8	8.4	7.4	5.9	6.0	6.3	6.1	5.7
	2	5.5	5.7	5.4	5.2	4.6	4.7	4.8	5.0	4.7	4.4
	1	2.4	2.6	2.5	2.4	2.3	2.7	2.8	2.9	2.8	2.6

Table 3. Maximum story shear and overturning moment of 5 story building for different "Khorjinee" steel braced frames under Naghan earthquake

Frame	Floor	Without damping					With friction damping				
		Fram	fram	fram	fram	Fram	Fram	fram	fram	fram	Fram
Maximum Story shear (KN)	5	86	207	128	195	124	17	16	16	17	32
	4	293	306	301	312	289	91	103	104	110	180
	3	377	378	383	397	400	120	126	127	132	193
	2	454	456	473	469	479	120	125	125	135	215
	1	483	486	496	500	509	140	164	164	173	254
Maximum Overturning Moment (KN.m)	5	275	664	410	624	397	45	52	52	53	102
	4	275	1031	1097	1121	1121	327	375	375	397	640
	3	1978	1992	2049	2107	2119	649	711	711	764	1220
	2	3357	3406	3513	3562	3653	1016	1080	1080	1130	1771
	1	4808	4853	4964	5020	5125	1285	1383	1353	1402	2289

In order to evaluate the effectiveness of an ADAS-upgraded structure, the response envelopes for the structure subjected to three sever following time scaled earthquake record:

1- Naghan earthquake 1977,   PGA=0.35g
2- Tabas earthquake 1978,   PGA=0.35g
3- El Centro earthquake 1940, PGA=0.35g

have been carried out. The structure members' design of analytical models has been accomplished based on the specifications of Iranian building code (Iran 2800).

Analytical results show that the ADAS devices are very effective in reducing seismic structural response at all levels of earthquake ground motion, since in all cases the maximum interstorey drifts of ADAS frame models are below the allowable maximum drift, (the maximum interstorey drift index is 0.03/R in Iran 2800 code). The response envelope for the structures under 3 different earthquakes are presented in tables 4. This table shows that the maximum interstorey drifts of ADAS frame is under allowable drift (0.6 cm). The numerical results show that, the application of ADAS devices in chevron braced frames causes 68%, 63% and 42% reduction in maximum lateral displacement under El Centro, Tabas and Naghan earthquakes respectively. Maximum storey shear and overturning moment for both with and without ADAS devices models are also given in Tables 4.

Table 4. Response envelope for the Khorjinee and ADAS structures under El-centro, Tabas and Naghan earthquake respectively

		El-Centro earthquake		Tabas earthquake		Naghan earthquake	
Response	Floor	Khorjin	ADAS	Khorjin	ADAS	Khorjin	ADAS
	4	310.0	112.0	320.0	105.0	301.0	104.0
Maximum	3	392.0	135.0	412.0	124.0	383.0	127.0
Story shear	2	480.0	162.0	545.0	154.0	473.0	125.0
(KN)	1	541.0	198.0	493.0	197.0	496.0	164.0
Maximum	4	1303.0	424.0	1126.0	330.0	997.0	312.0
Overturning	3	2395.0	808.0	2003.0	705.0	2012.0	673.0
Moment	2	3810.0	1157.0	3412.0	1025.0	3204.0	946.0
(KN-m)	1	5009.0	1609.0	5020.0	1602.0	4625.0	1212.0
	4	11.0	3.5	5.2	1.9	3.3	1.9
Maximum	3	8.6	3.2	4.2	1.5	2.8	1.6
Drift (cm)	2	3.7	2.9	3.1	1.3	2.4	1.4
	1	2.0	2.3	2.1	1.1	1.0	0.6

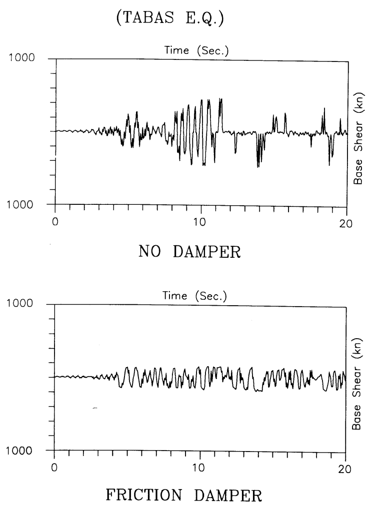


Figure 4: Base shear force time history of khorjinee braced frame with and without friction damper under Tabas earthquake.

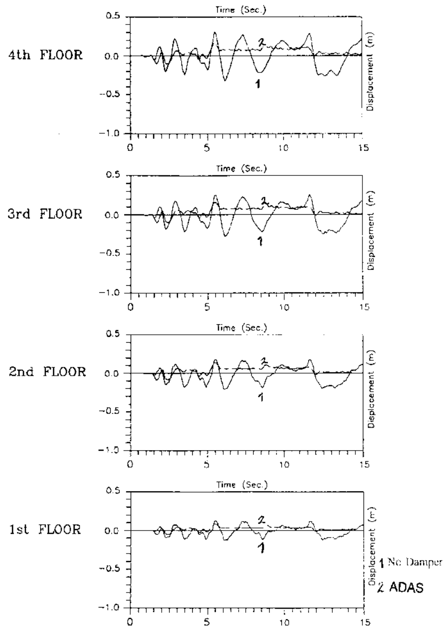


Figure 5: Comparison of displacement responses for the Khorjinee and ADAS structures under El-Centro earthquake.

It can be seen that, the displacement, velocity and acceleration response of ADAS frames in all cases are less than frames without ADAS devices for all different time duration of earthquake. Response to the El-centro earthquake are compared in Figure 5.

These results show that installation of ADAS devices in simple braced frames causes 40% to 60% improvement in response. The structure will remain in elastic region due to this amount of reduction in displacement and internal forces of structural members.

CONCLUSION

This paper studies an analytical investigation on the application of friction dampers and (ADAS) devices as energy dissipation devices in two types of simple and Khorjinee braced frames under seismic load. It can be concluded that friction dampers and (ADAS) devices are effective in reducing excessive vibration of structures under earthquake ground motion.

The response of steel structures, (simple and Khorjinee braced frames), in general, and those that already suffered previous damage can benefit from their strengthening using friction dampers and (ADAS) devices. The analytical studies of steel structures under various earthquake motion indicates that the amount of energy transmitted to a structure during an earthquake depends mainly on the ratio of the fundamental period of the structure to predominant period of the ground motion.

Installing the friction damper as an energy dissipation device in a new and existing Khorjinee braced frame to reduce its seismic response is a way to control low-cycle fatigue in these types of structures which is a main factor for their failure.

The research program demonstrated that ADAS elements possess characteristics that make them suitable for use as energy dissipation devices in new and existing buildings. One practical configuration for installing ADAS devices in a new and existing Khorjinee frame is in conjunction with a chevron brace assemblage in to reduce its seismic response and control low-cycle fatigue. Results of analysis of a structure indicate the benefit of the addition of ADAS elements and bracing to the lateral system in improving its seismic resistance.

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