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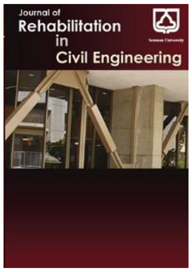

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Analytical Assessment of Reinforced Concrete Frames Equipped with TADAS Dampers

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ABSTRACT

In recent years, it is considerably attempted to develop the concept of energy dissipation as an applicable technology to overcome the energy released by earthquakes. The passive control systems such as metallic dampers have been widely considered. Energy dissipating dampers are used to modify the response of structures as well as to reduce the damages in structure members. This study is conducted to investigate the seismic response of three normal concrete moment resisting frames with 4, 7 and 10 stories equipped with Triangular Added Damping and Stiffness (TADAS) metallic dampers. OpenSees software is employed for nonlinear time-history analysis using seven earthquke records to determine the structure response. The results showed the considerable modifed seismic responses. It is observed that the story drifts are constant and the maximum values in retrofitted 4, 7 and 10 story frames have been decreased 54%, 56% and 55%, respectively. Also, the maximum floor acceleration, the maximum roof displacement and the maximum story shears are lower in the frames equipped with damper and the lateral behavior of the majority of the retrofitted frame members has been upgraded to Immediate Occupancy (IO) and Live Saftey (LS) performance level.

1. Introduction

Iran is located in one of the high seismic hazard regions and the earthquake is considered as an effective factor to cause severe damages and structural collapses. Structures shall not encounter severe damage and shall remain in elastic limit during low and moderate earthquakes but the structure is often allowed to enter the plastic limit while the strong earthquakes are considered in designing. Such inelastic deformations can develop plastic hinges at structure which can cause an increase in ductility and also energy

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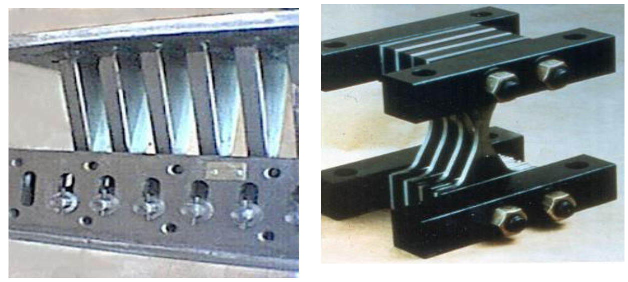
dissipation [1]. Consequently, a significant amount of energy released by earthquakes will be dissipated due to local deterioration in lateral resisting system of the structure. While the repair or replacement of the damaged elements is costly and sometimes impossible, the deterioration of structural elements is considered an improper phenomenon even structural collapse is not observed. Therefore, the subsequent damages to the main structural elements will be reduced and the operation after occurrence of earthquake will be provided if the energy absorption of earthquake can be concentrated in special devices such as dampers [2,3]. There are different passive control methods to retrofit concrete structures such as dampers [4].

Added Damping and Stiffness (ADAS) [5] metallic dampers are passive control systems which are integrated of some parallel steel plates which significantly increase the structural damping by inelastic deformation in steel plates [6]. Such dampers act as structural fuses and restrain the occurrence of nonlinear behavior and damages in other structural and nonstructural elements by concentrating nonlinear behavior. One of the advantages of such dampers can be the capability of being substituted and operated after earthquake and also the structure can return to the initial strength and behavior condition before the occurrence of earthquake [7].

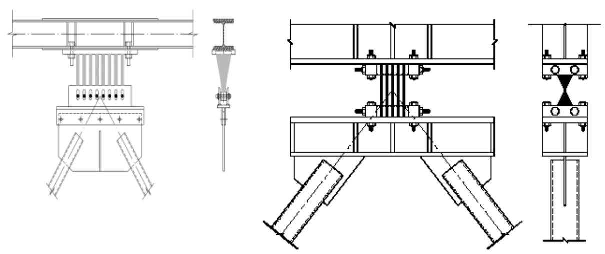
The configuration of this damper is illustrated in Fig 1.



TADAS damper [4] XADAS damper [3]

Fig. 1. Various types of ADAS damper

As it can be seen in figure 2, the dampers are generally attached to the frames by using chevron bracings.



Configuration of TADAS damper in frame [8] Configuration of XADAS damper in frame

Fig. 2. Damper configuration in frame

X-shape Added Damping and Stiffness (XADAS) and Triangular Added Damping and Stiffness plates (TADAS) in ADAS dampers have more appropriate performance in energy dissipation rather than rectangular plates. Because merely both ends of a rectangular steel plate are yielded but the X-shape and triangular plates are constantly yielded throughout the plate height and nearly all volume of the steel can contribute the energy dissipation [9].

Comparing to XADAS dampers, TADAS dampers have some advantages such as more stable hysteresis behavior due to nonexistence of buckling of steel plates.

Therefore, TADAS dampers are aimed to be investigated at the present research. Applications of different kinds of dampers are evaluated in previous researches. Khazaei [10] has evaluated the effect of ADAS damper in steel frames with multiple stories under nonlinear time history analysis. This study showed by increasing number of floors, more uniform displacement pattern has been observed in the height of structures. Mahjoubi and Maleki [11] have investigated Infilled-Pipe Damper (IPD) as energy dissipation devices in three steel structures with 5, 10 and 20 stories under seven earthquake excitations. Their results show efficiency of proposed damper in reducing response of structures; also they suggested a new damper performance index for optimization of structures equipped with different type of damper. Benavent et al. [12] experimentally investigated the seismic performance of reinforced concrete Waffle-Flat Plate (WFP) structures with hysteretic dampers. Lateral strength and stiffness provided by dampers were between 3 and 7 times greater than bare WFP structures. They showed that structural performance of associated structures with damper could be in immediate occupancy range with maximum interstory drifts up to 1%. Milani et al. [13] have assessed a new anti seismic product as Multi –Directional Torsional Hysteretic Damper (MTHD). This system contains of symmetrical arrangement of identical cylindrical steel energy dissipaters that is configured to yield in torsion while the structure is under earthquake excitations. They present many stage of design conceptually and experimental phase for verification. The current investigation is done to study the effect of using TADAS dampers for seismic retrofit of concrete moment frames. For this purpose, OpenSees [14], a well-recognized program for nonlinear analysis of structures, is employed. Seven earthquake acceleration records are selected for the time-history analysis of the frames. TahamouliRoudsari et al [15] experimentally investigated the effect of using the Chevron brace with ADAS and TADAS yielding dampers in retrofitting RC moment resisting frames. The frames were subjected to cyclic loading. The results showed that the yielding dampers not only increase the strength of the RC frame, they also elevate its strength reduction factor and ductility. Saeedi et al [16] investigated the seismic behavior and global damage parameter (GDP) of the moment resisting frames equipped with triangular-plate added damping and stiffness (TADAS) devices. In their study Four frame types with 3, 6, 9 and 12-story and three bays are modeled and nonlinear analyses results are estimated and compared for two case of moment resisting frames (MRFs) and moment resisting frames equipped with TADAS devices (TMRFs). The results showed that the response modification factors for TMRFs are higher than the MRFs ones and decrease by 40 percent gradually with an increase in the height of the frames. They were also found by using TADAS devices, GDP decreases up to 55 percent averagely. Dareini et al [17] introduced the idea of modified TADAS device with a new viewpoint of passive energy dissipation devices. The goal of their research was first to make TADAS devices start energy dissipation in moderate earthquakes and short displacements moreover that they work as common TADAS device in severe earthquakes. Further desirable results of using the Modified – TADAS are reducing base shear force, Maximum story displacement and interstory displacement. Mahmoudi et al [18] evaluated overstrength, ductility and response modification factors in special moment resisting frames with TADAS devices. Their results showed that the response modification factors for T-SMRFs were higher than the SMRFs ones. They were also found that the number of stories of buildings has had greater effect on the response modification factors. Oinam et al [19] evaluated effectiveness of a strengthening technique using the combined metallic yielding devices (CMDs) as passive energy dissipation systems to enhance the lateral load resistance and the deformation capacity of the damaged reinforced concrete (RC) frames. An experimental investigation has been conducted on two geometrically-identical damaged RC frames under the lateral cyclic loading condition. Their study highlighted the importance of the positioning of CMDs, the selection of local strengthening strategy, and the proper installation of CMDs on the lateral load resistance and energy dissipation potential of the damaged RC frames. The strengthened frames exhibited the enhanced lateral strength, lateral stiffness, lateral deformation capacity, energy dissipation and damping potential up to a storey drift of 6%.

2. Modeling of Structural Elements and Materials in Software

At the present study, OpenSees, an open source software has been used as a reliable software for studying the seismic nonlinear behavior of structures.

The stress-strain relationship of the concrete has been simulated using *Concrete01* model and the stress-strain relationship of the steel has been simulated using *Steel02* model in OpenSees [14]. The concrete moment resisting members have been modeled by *nonlinearBeamColumn* with *Fiber Sections* [20]. TADAS dampers have been modelled by *Steel02* and *Zero-Length* in OpenSees. Low cycle fatigue which is one of the important parameters in durability of the steel dampers has been assigned to the model [21].

Tsai et. al. (1993) developed different TADAS dampers and conducted several experiments under cyclic tests in National Center for Research on Earthquake Engineering of Taiwan University. Also, a two story steel moment resisting frame in 2/3 scale, having height of 2.71m and 2.51m equipped with TADAS dampers was developed. Then North-South component of El Centro record was applied and the influence of TADAS damper on seismic performance of such structure was investigated [7]. According to Fig 3, tested frame is shown.

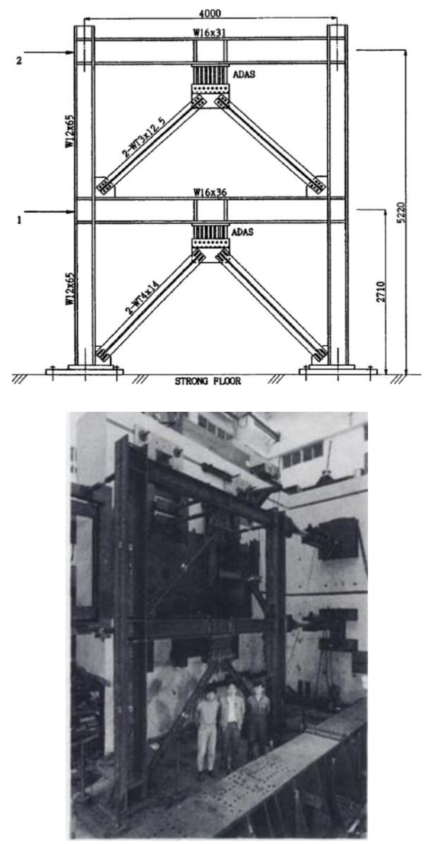
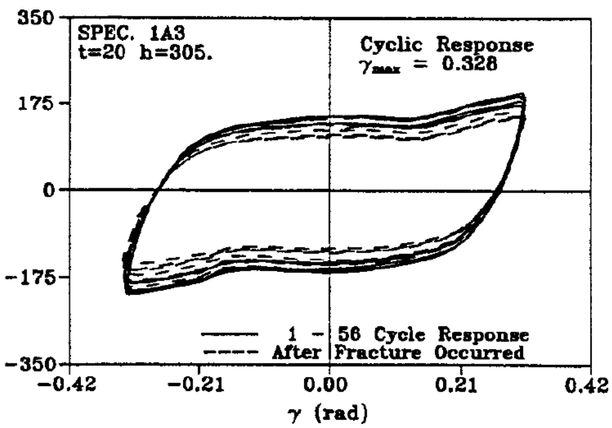
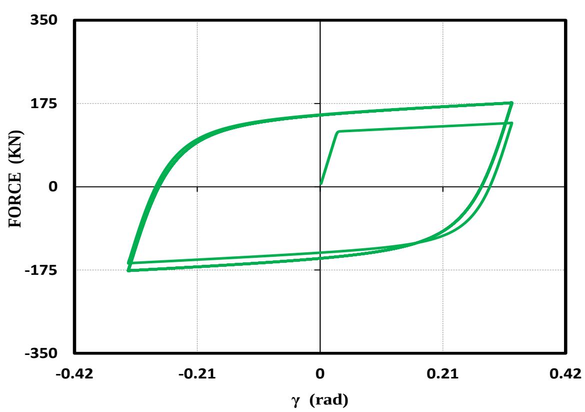


Fig 3. Structures tested by Tsai et. al. [7]

The structure and TADAS dampers are modelled in OpenSees to validate the modelling. According to Fig 4, the experimental and analytical results of 1A3 damper are shown under cyclic loading with constant $\gamma = 0.328$ rad. It can be seen that the hysteresis loops obtained from modeling results of OpenSees match with experimental studies.



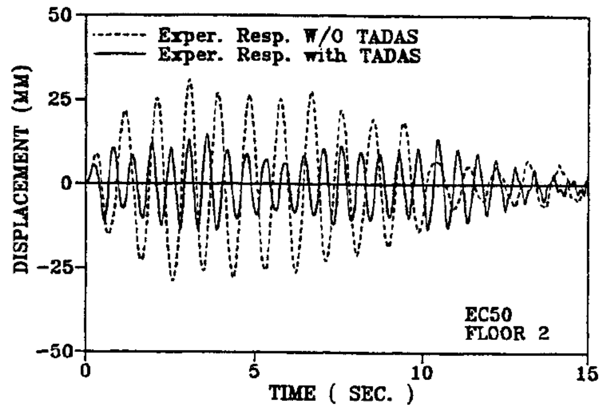
a) Experimental results [7]



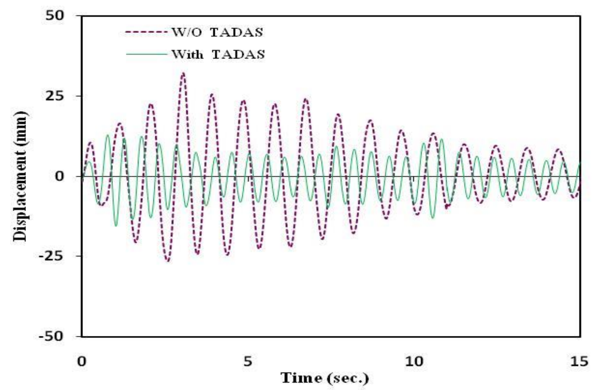
b) Analytical results in OpenSees

Fig 4. Hysteresis loops of 1A3 damper

According to Fig 5, the experimental and analytical results from displacement history of the structure with and without damper under El Centro earthquake with maximum acceleration of 50 cm/s^2 are shown. It can be seen that the maximum displacement resulted from experimental and analytical results are in good accordance.



a) Experimental result [7]



b) Analytical results from OpenSees

Fig 5. Roof displacement history of structure with and without damper under El Centro earthquake

3. Definition of Numerical Model

In addition to the concrete frames considered for retrofitting investigation, three other 4, 7 and 10 story concrete frames with lower ductility having are examined according to an old edition of code [22]. Number of stories for frames is selected based on the normal concrete buildings built in Iran. The story heights are considered to be 3.5 meters in all frames. All frames has 3 spans with 5 meters length. The structures are considered to be residential buildings in Tehran on Type II soil condition according to Iranian code of practice for seismic resistant design of buildings (standard no 2008). The lateral load resisting system is moment frame and Joists and filler blocks are used in floors. Dead and live loads on the floors are respectively 6 and 2 kN/m^2. The sum of dead load and 20% of live load is considered for calculating seismic effective load [23]. The considered concrete compressive strength is 21 N/mm^2 and the yielding strength of steel reinforcements is 400 N/mm^2.

2D models are employed in the current study. The top view of the studied structures is shown in Fig 6.

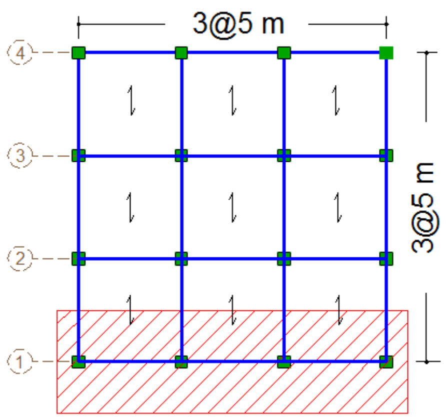


Fig 6. Plan of the selected structure and frame

4. Time History of Accelerations

Tabas, San Fernando, Landers, Kern county, Bam, Avaj and Northridge far-field records are selected for the study. Type II soil according to Iranian code of practice for seismic resistant design of buildings is assumed for acceleration records whose average shear wave velocity for the top 30 m of soil is within the range of 375–750 m/s. The properties of applied records are presented in Table 1. The records are scaled using the acceleration response spectrum according to the Iranian code of practice for seismic resistant design of buildings (standard no 2008- 3rd edition) [24].

Table 1. Properties of applied earthquakes

Earthquake	Magnitude (Ms)	Recording Station	Epicentral Distance (km)
Kern County	7.36	USGS 1095 Taft Lincoln School	43.49
San Fernando	6.61	USGS 262 Palmdale Fire Station	31.61
Tabas	7.35	70 Boshrooyeh	74.66
Landers	7.28	CDMG 12149 Desert Hot Springs	27.33
Northridge	6.69	USC 90020 LA - W 15th St	29.59
Avaj	6.5	NEIC 2769-2 Darsejin	48
Bam	6.7	NEIC 3162-1 Mohamad Abad	49

The scale factor should be applied first due to the period differences of the structures. Thus, for 4, 7 and 10 story frames, the maximum spectrum acceleration of the selected records is deemed respectively as 0.49g, 0.51g and 0.59g. According to Fig 7, the average acceleration response spectrum of selected records and the calculation procedure for scale factor of 4 story frame is presented. The period and scale factor of each frames are presented in Table 2.

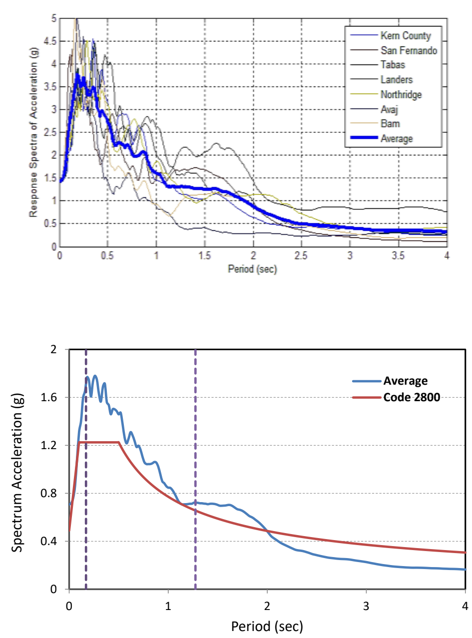


Fig 7. Calculation procedure of scale factor

Table 2. Period of frames and scale factor of selected acceleration records

Scale factor	1.5T	0.2T	Period	Story
0.49	1.27	0.17	0.85	4 story
0.51	1.99	0.27	1.33	7 story
0.59	2.61	0.35	1.74	10 story

5. Designing of Dampers and Related Bracings

The most important factor to design the structures equipped with TADAS dampers is optimization of damper properties in stories to achieve the most effective damping and utilizing the capacity of energy dissipation of all used dampers in structure [24]. The best result can be obtained if the contribution of strength and stiffness of devices in stories can provide the occurrence of immediate mechanism due to lateral displacement based on the first mode of the structure. The initial properties of dampers have been chosen based on recommendations of reference [25]. The appropriate selection of initial values for parameters of dampers is considerably effective to shorten the try and error process. Optimization for appropriate selection of initial geometric properties of dampers such as number of metallic plates has been done by try and error process. Also damper is located in all stories such that uniform distributions of story drifts occur in the height of frames. For access to this goal, extensive time history analysis is done to development of initial damper design and better geometric optimization for dampers in the structures. Design and modeling of dampers is carried out in this study based on [26-27].For modeling of TADAS damper, a rigid link with combine of zero length element is used that its behavior is assigned using Steel02 material. Also for modeling of Low-Cycle Fatigue that is crucial parameters in durability of dampers, uniaxialMaterial Fatigue is selected from OpenSees material library. This model use modified cyclic algorithm for calculating of cumulative damage based on logarithmic relation and Miner’s rule. At the end of Fatigue life, failure of damper is occurred and force-displacement response of damper becomes zero. Also slit-hinge connection at the top of damper cause non-axial force in the damper and because of complicated deformations in damper, Vertical degree of freedom in location of damper and brace connection is free. Other structural elements such as bracings, beams and connections are designed based on forces contributing to ultimate capacity and they will be practically remained in linear limit during earthquakes. While the excess strength coefficient of TADAS dampers is 2.25, the maximum capacity of dampers are considered to calculate the design forces related to their connected elements (Fu=2.25Fy) [28]. The geometric properties of the dampers at different stories of the studied frames are presented in table 3.

6. Seismic Examination

In this part, maximum base shear, story acceleration, hysteresis loops, story drifts, and roof displacement of the dampers and the performance level of the members of the frames with and without dampers are mentioned. By employing seven earthquake records and retrofitting criteria, the average maximum responses are used to calculate the frame responses [28, 29].

6.1. Displacement History of Roofs

As it can be seen in Fig 8, displacement history at the roof of studied frames with/without dampers exposed to one of the records is shown. Since TADAS dampers increase stiffness and damping, it is expected that roof displacement decreases. As it can be seen, TADAS dampers have decreased the roof displacement by more than 30%. As can be evident from results, the effect of TADAS damper in mitigation of maximum roof displacement is decreased when the number of story is increased.

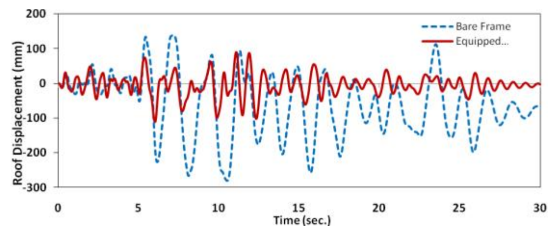
Table 3. Geometric properties of the dampers at the stories of 4, 7 and 10 story frames

4 story frame				
Story	N	h (mm)	b (mm)	t (mm)
1	6	300	150	30
2	6	300	150	28
3	5	300	150	28
4	4	300	150	20

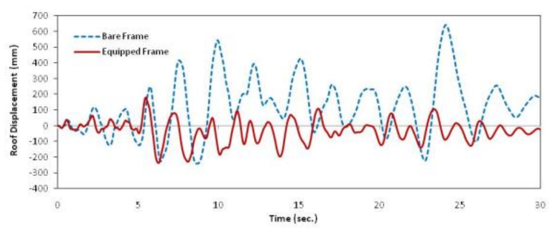
7 story frame				
Story	N	h (mm)	b (mm)	t (mm)
1	11	300	150	30
2	11	300	150	28
3	10	300	150	28
4	8	300	150	28
5	7	300	150	28
6	5	300	150	25
7	4	300	150	20

Story	10 story frame			
	N	h (mm)	b (mm)	t (mm)
1	13	300	150	30
2	12	300	150	30
3	12	300	150	30
4	11	300	150	30
5	9	300	150	30
6	8	300	150	30
7	7	300	150	30
8	5	300	150	30
9	5	300	150	25
10	4	300	150	20

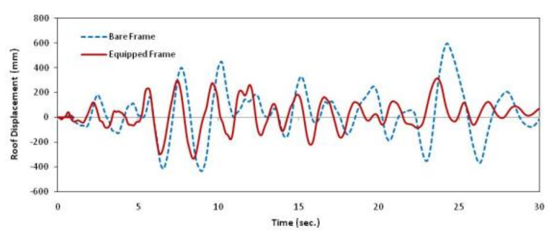
This can be relating to vibration period of structures and frequency content of earthquakes. Also, it's observed that equipped frames have less residual displacement at the end of earthquake than bare frames. This can be attributed to nonlinear behavior in TADAS damper and limitation of nonlinear behavior and damages in other structural elements such as columns. Comparison of structural behavior from nonlinear analysis for bare frames and corresponding equipped frames are mentioned through section 4.2 to 4.7.



(a)



(b)



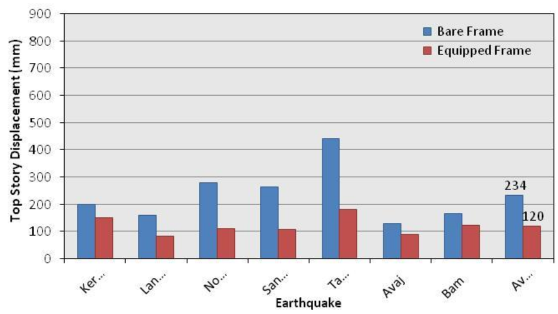
(c)

Fig 8. Roof displacement history of the frames

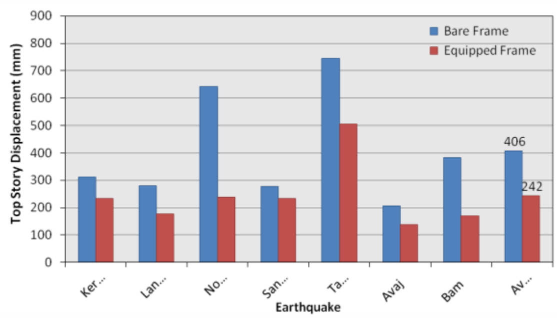
4 story frame b) 7 story frame c) 7 story frame

6.2. Maximum Displacement of Roofs

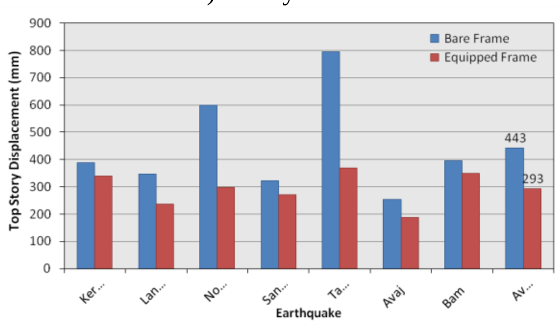
As it can be seen in Fig 9, the maximum displacement of roof in the frames with/without dampers induced by the acceleration records is presented. It is observed that in 4, 7 and 10 story frames equipped with dampers, the mean maximum displacements of roof induced by the seven acceleration records are respectively decreased by 48%, 40% and 34%, compared to that of the frames without damper.



a) 4 story frame



b) 7 story frame

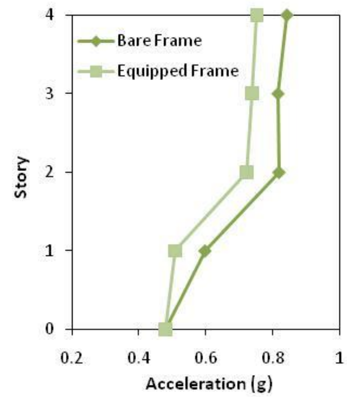


c) 10 story frame

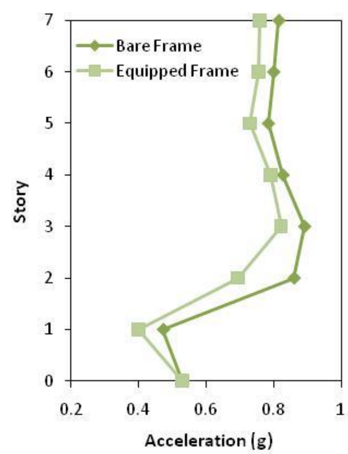
Fig 9. Maximum roof displacement of frames

6.3. Maximum Acceleration of Stories

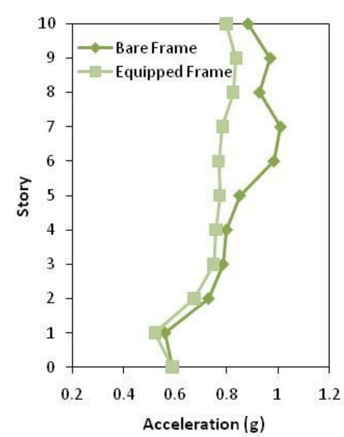
The maximum accelerations of stories of the frames with/without dampers are shown in figure 10. It is observed that the maximum accelerations in the frames with 4, 7 and 10 stories is respectively reduced by 12%, 19% and 22%. Therefore, the nonstructural element damages during earthquake as well as the input energy is reduced.



a) 4 story frame



b) 7 story frame



c) 10 story frame

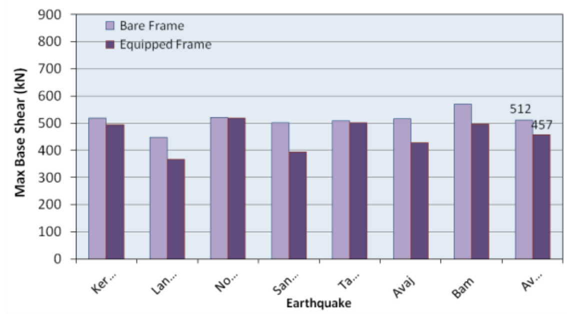
Fig 10. Maximum story acceleration

6.4. Maximum Base Shear Force

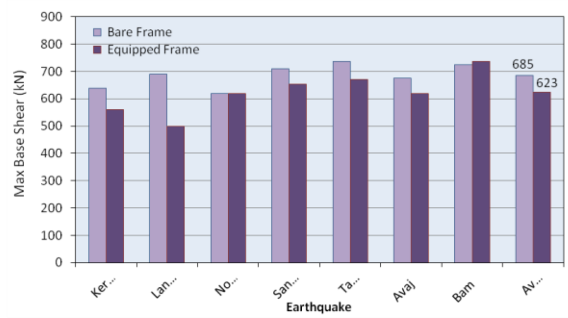
In Fig 11, the peak base shear force of the frames with/without damper induced by the earthquake records is presented. It can be seen that average maximum base shear force in 4, 7 and 10 story frames with dampers is respectively reduced 10%, 9% and 7%. It can be seen that the average maximum story shear and base shear force of retrofitted frames have not been considerably decreased and even in some cases, an increase can be seen in base shear. Noted that an increase in structural damping can reduce the base shear and an increase in structural stiffness can increase the base shear force. While the TADAS dampers increases the structural damping and stiffness, the base shear can be increased or decreased based on the increasing value in structural stiffness and damping.

6.5. Story Drift

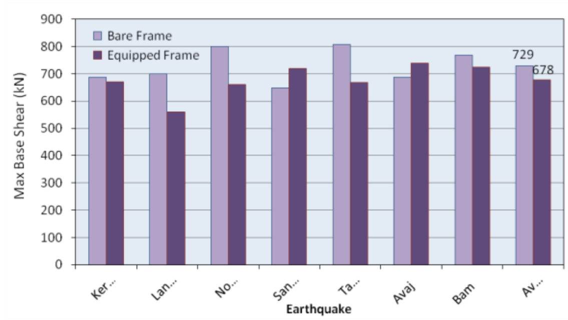
The average story drift in the retrofitted frames as well as the base frames induced by the selected records are compared in figure 12. The maximum story drift in 4, 7 and 10 story retrofitted frames are respectively reduced by 54%, 56% and 55%. Furthermore, the distribution of drift at different structure stories in the frames equipped with damper remained constant, implying that the damages at different stories are reduced and the distribution of damage also remained unchanged. The performance level of Live Safety (LS) in Iranian code of practice for seismic resistant design of buildings [23] from a gloobal view is based on story drift control. For frames which maximum story drifts are less than 2%, (LS) performance level is satisfactory and for frames that remain in elastic range during earthquake, Immediate Occupancy (IO) performance level is satisfactory. The performance level of individual elements could be evaluated based on plastic rotation in FEMA 356 [29]. It is seen from the Fig 12 that for all equipped frames with damper, story drift in all story level is less than 2%, while in bare frames story drift in top stories violate from 2% limit for (LS) level.



a) 4 story frame

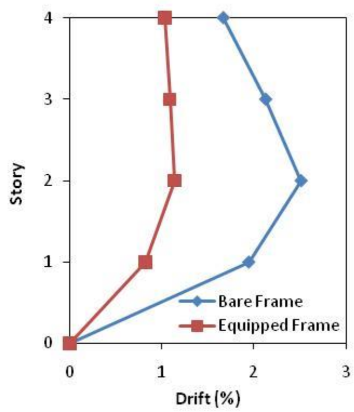


b) 7 story frame

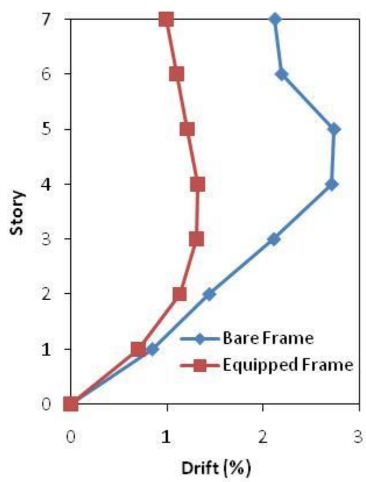


c) 10 story frame

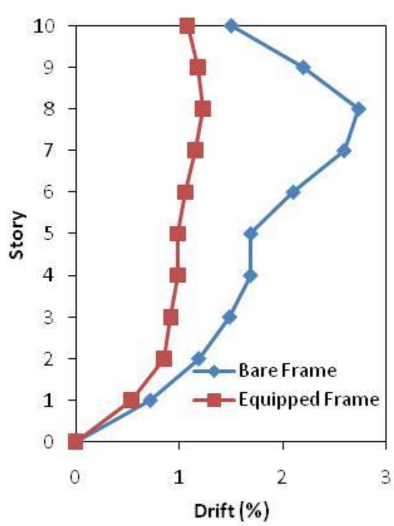
Fig 11. Maximum base shear of the frames with and without damper



a) 4 story frame



b) 7 story frame



c) 10 story frame

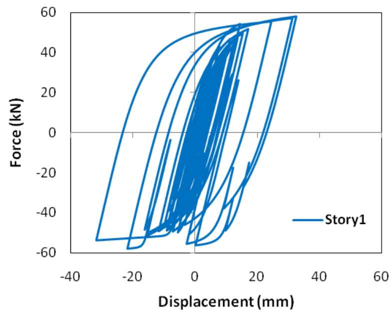
Fig 12. Average maximum story drift of the frames with and without damper

6.6. Performance Level of Structural Members

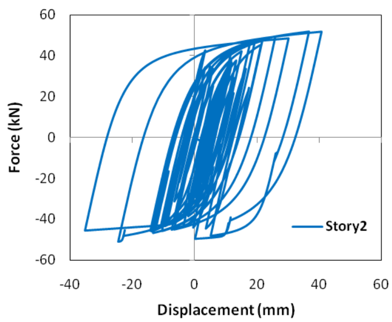
According to results from time-history analysis for 4 story frame without damper, 87% of columns and 75% of beams have been damaged, for 7 story frame without damper, 64% of columns and 71% of beams have been damaged and for 10 story frame without damper, 55% of columns and 70% of beams have been damaged but the vulnerability to damages in beams and columns have been eliminated in structure equipped with damper due to concentration of damages under earthquakes in dampers. The first story of braced spans is merely remained vulnerable due to an increase in axial forces resulted from dampers and chevron bracings which the capacity of such columns is required to be enhanced by local retrofitting techniques such as FRP wrapping methods.

6.7. Hysteresis Curves of Dampers

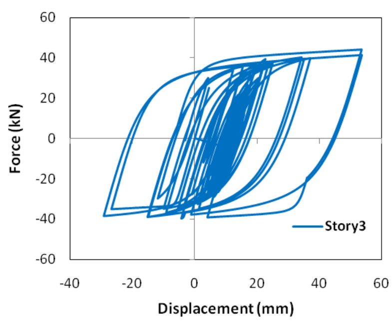
According to Fig 13, typical hysteresis curves of dampers in different stories of 4 story frame under San Fernando earthquake are presented. The shape of these curves properly shows the dissipation of most input energy to the structure by dampers which cause damage reduction to other structural elements.



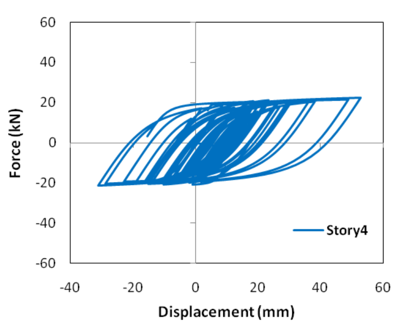
a)



b)



c)



d)

Fig 13. Hysteresis loops of dampers in different stories of 4 story frame under Kern county earthquake

7. Conclusion

At the present paper, the influence of TADAS dampers on seismic response of concrete moment frames is investigated. The results are summarized as follows.

- The employment of TADAS dampers in the frames reduced the maximum roof displacement and residual displacement whereas the average maximum roof displacement in 4, 7 and 10 story frames equipped with damper induced by the selected earthquake acceleration records are respectively reduced by 48%, 40% and 39%.

- Dampers decrease and keep the different story drifts constant while the maximum story drift in the retrofitted 4, 7 and 10 story frames is respectively reduced by 54%, 56% and 55%.
- The maximum acceleration of the roofs and story acceleration are reduced when such dampers are used while the existing maximum acceleration in 4, 7 and 10 story frames equipped with is respectively reduced by 12%, 19% and 22%.
- The average maximum story shear as well as base shear of retrofitted frame have not been significantly reduced even in some cases the base shear has been increased. The reason can be in such fact that an increase in structural damping can reduce the base shear and an increase in structural stiffness can increase the base shear. While the TADAS dampers can enhance the structural stiffness and damping, the base shear can be increased or

decreased based on the structural stiffness and damping increase value.

- The performance level of members in retrofitted frames and consequently the performance level of frames have been notably improved and the IO and LS performance level have been provided for most of the members.

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