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RESEARCH ARTICLE

Analysis of X-shaped and Double X-shaped Metallic Dampers on Multistorey Frames.

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Abstract: Metallic yielding dampers are passive energy dissipating devices that are designed to disperse earthquake energy through hysteretic behavior. This research used ETABS software to analyze the performance of two metallic yielding dampers of the type Added damping and Stiffness (ADAS); X-shaped damper and Double X-Shaped damper. The story shear response of two frames, one a low-rise building of five stories, and another high-rise building of 20 stories was analyzed. Each damper had three types of material; A992 steel, A36 steel and aluminium. The site location for both structures were in the region of California in the United States of America. The structures were analyzed by subjecting them to two earthquakes Loma Prieta and San Fernando as they were two of the major earthquakes that struck California in the nineties. The results showed that both dampers performed satisfactorily. But their performance depended on the magnitude of the earthquake and the number of stories of the structure. Dampers that were made of steel performed better than the ones made of aluminium. Both X-shaped and Double X-shaped dampers were concluded as good energy dissipating devices according to the results obtained.

***Keywords**: Metallic Yielding Dampers, ADAS, Energy Dissipation, Time History Analysis, ETABS*

Introduction

The traditional way of designing structures was to design them so that they resist dynamic forces by strength then energy absorption and finally deformation. During a seismic event these conventionally designed structures deform beyond their elastic limit. Nowadays. structural protective systems are designed to prevent this from happening. These modern structural protective systems can be divided into three parts. They are:

1. Seismic Isolation
2. Passive Energy Dissipation
3. Semi Active and Active Systems

This study has considered passive energy dissipation technique of metallic yielding dampers. The other types of passive energy dissipation devices are Friction dampers, Viscoelastic dampers, tuned mass dampers, Tuned liquid dampers. These devices absorb the energy from seismic activities and therefore reduce the dissipation of energy throughout the structure. They do not require an external power source and also cannot add energy to the structural system.

These systems have been developed because earthquakes are one of the most unpredictable natural disasters in the world. The duration of an earthquake can vary from a few seconds to a few minutes according to its magnitude (USGS, 2014). In the USA the most affected region is California. These seismic activities are mainly due to two plates; the North American plate and Pacific plate; make contact and slide over each other. One of the worst earthquakes to hit California was the Loma Prieta earthquake in 1989 which had a magnitude of 6.9. The slip had occurred on 35 km of the San Andreas Fault at depths ranging from 7 to 20 km. It caused very severe ground shaking and liquefaction of floodplain deposits near the Pajaro and Salinas rivers and also along the San Francisco Bay (USGS, 2014).

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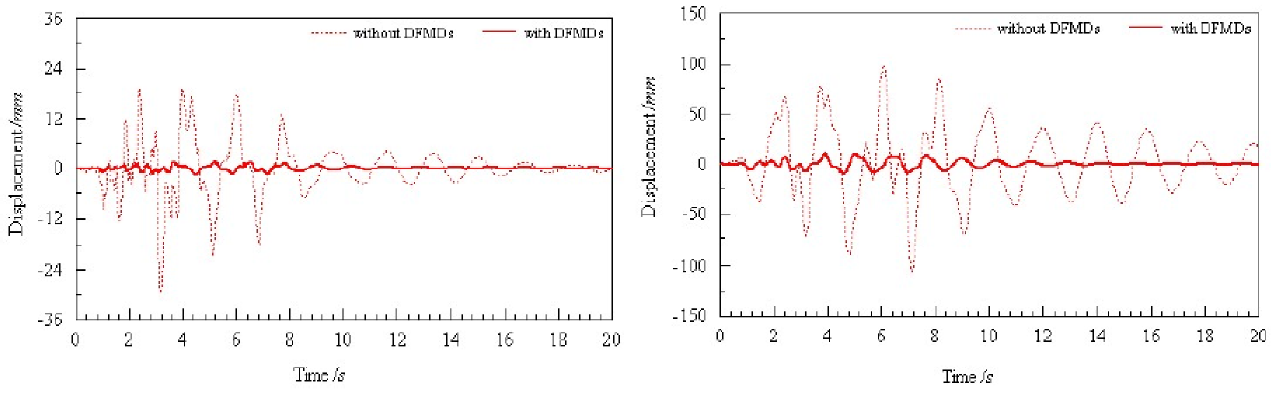
Structures that were constructed before 1960s were designed to tolerate only vertical loads. But when an earthquake hits, the structure is subjected to a horizontal load. Today, there are two methods used to prevent damage done by horizontal loads (Li & Li, 2007). They are:

1. **For houses and low-rise buildings**: increasing the strength and stiffness of the structure so that the structure is in the elastic range.

2. **For multi storey and high-rise buildings**: using external applications like dampers and base isolation techniques.



(a) (b)

Figure 1: Displacement Responses of a steel structure (a) Base Floor (b) Top Floor

Hysteretic damping mechanism

Hysteresis loops are a sequence of loops in the force-displacement or resistance-deformation relationship created due to successive loadings and unloading on structures. These are a result of cyclic characteristics of ground motion. When a structure is affected by a severe earthquake, the deformations experienced are beyond the elastic range. These inelastic deformations depend on the magnitude of the earthquake and also the load-deformation characteristics of the structure.

Hysteresis loops are used to measure the structure's capacity to dissipate energy. The structural stiffness and yield displacement determine the shape and orientation of the loop. Hysteretic behavior is affected by factors like structural system, structural material and type of connection (Maneetes, 2007).

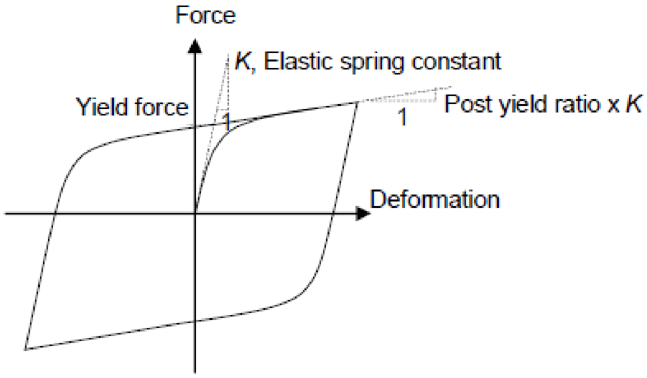


Figure 2: Bouc Wen's Plasticity Model

Metallic yielding dampers (MYD)

Metallic yielding dampers use hysteretic behavior to dissipate energy absorbed from a seismic activity. Energy is dissipated during the plastic deformation of the metallic components of the dampers. This was first proposed by Kelly in 1972 (Kelly, 2006). During a seismic activity larger amount of the energy will be absorbed by the metallic dampers than the structure itself. The dampers have to be placed at selected locations of the main structure. Since they are not embedded to the main structure, replacement of them after deformation is easier (Benavent-Climent, 2010). These damping devices must have the suitable characteristics like adequate elastic strength and stiffness so that the device does not reach inelastic region under service loads. The other characteristics include; having a good capability to dissipate energy and a resistance to low cycle fatigue. The results of numerical and analytical investigations have revealed that the key parameters involved in the design of these dampers are: the ratios of bracing stiffness to device stiffness, brace-device assemblage stiffness to device stiffness, and assemblage stiffness to that of the corresponding story

Added damping and stiffness (ADAS)

Added damping and stiffness devices were first studied by Whittaker. This device has a number of X-shaped plates. The two ADAS devices that are analyzed in this study are X-shaped metallic damper and Double X-shaped metallic damper. The X shaped structure makes sure that yielding occurs over the entire length of the device. ADAS devices improve the behavior of the main structure by increasing its stiffness, increasing its strength and its ability to dissipate energy (Whittaker, 1989).

ADAS have some advantages: they do not require sophisticated technology to get produced, they can easily be integrated into structures, and they show a stable behavior under the effect of the earthquake, as well as environmental factors (temperature, humidity) which do not affect their performance. These dampers are usually mounted in a frame of a bracing system. After the earthquake, they can easily be replaced for the reinforcement of the structure for future earthquakes (Rais, Qunis & Chebili, 2013).

The equations used to determine the required parameters are given below:

The initial elastic stiffness: $K_{ADAS} = n\left(\frac{2Ebt^3}{3h^3}\right)$ (1)

The yield force: $F_y = n\left(\frac{\sigma_y bt^2}{2h}\right)$ (2)

Where n is the number of plates which compose the ADAS system, b is the width of the plates, h the height of the plates and E the elasticity modulus of the material .

X-shaped Metallic DamperThis has properties like large initial stiffness and high bearing capability. But experimental results have shown that stress concentrates in the center and the corner of the damper and experiments have also shown that bending deformation is less than stress deformation (Li & Li, 2007).

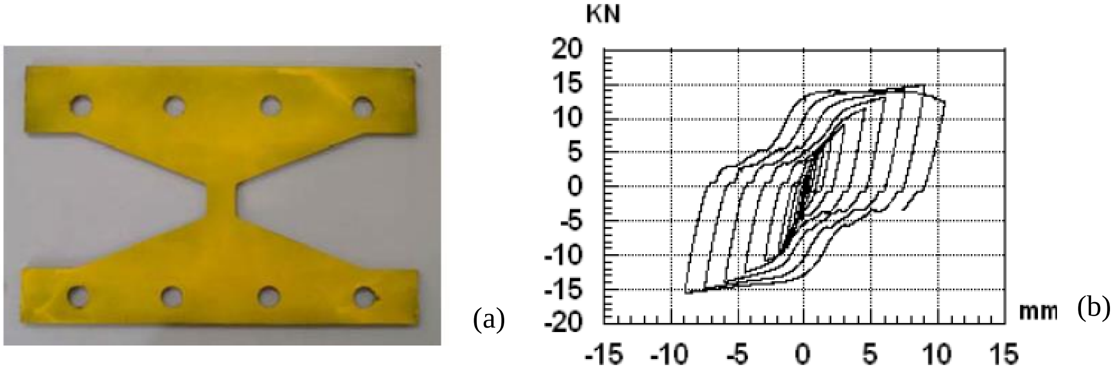


Figure 3: (a) X-shaped metallic damper (b) Hysteretic curves of X-shaped metallic damper

Double X-shaped Metallic Damper

This type of damper was first proposed by Li and Li in 2008. The photograph and the hysteresis curve for this damper is shown below. From the experiments they concluded that this damper has both large initial stiffness and energy dissipating capability. The double X shape makes it more resistant to buckling.

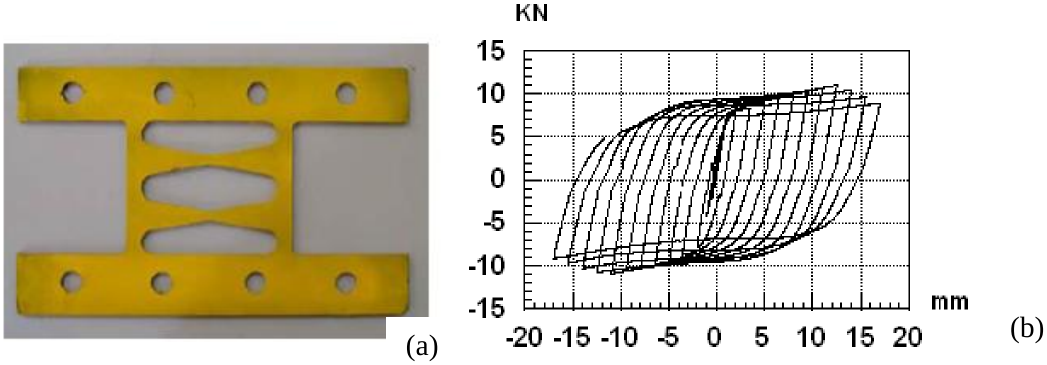


Figure 4: (a) Double X-shaped metallic damper; (b) Hysteretic curves of Double X-shaped metallic damper

Different materials used for metallic yielding dampers

Aluminium 6061-T6; 6061-T651

The shear yielding of aluminium had been found to be very ductile and very large inelastic deformations are possible without tearing or buckling (Summers et al., 2015). The low yield strength of aluminium in shear allows the use of thicker webs which further reduces the chances of web buckling. The yielding in shear mode maximizes the material participating in plastic deformation without excessive localized strains.

Table 1: Mechanical Properties of Aluminium 6061-T6; 6061-T651

Physical Properties	**Metric**
Ultimate Tensile Strength	310 MPa
Tensile Yield Strength	276 MPa
Elongation at Break	12 %

High Yield Steel: A992 steel

A992 is a high strength, low alloy steel. Its best applied where there is need for more strength per unit of weight. This structural steel alloy is typical used for wide flange and I beams. It has a high material ductility as it has a high yield to tensile strength ratio and is resistant to atmospheric corrosion (Segui, 2007).

Table 2: Mechanical Properties of A992 steel

Physical Properties	**Metric**
Ultimate Tensile Strength	450 MPa
Tensile Yield Strength	345-450 MPa
Elongation at Break	21 % and over

Mild Yield Steel: A36 steel

As the dampers are passive to seismic input they should fail before any other component of the main structure does. Therefore, using a low yield steel is the best option for damping devices. For a large earthquake the device is going to undergo great repeated deformations in the plastic region. This shows that the device needs to be made of a material that has excellent elongation and low cycle fatigue characteristics.

Table 3: Mechanical Properties of A36 Steel

Physical Properties	**Metric**
Ultimate Tensile Strength	400-550 MPa
Tensile Yield Strength	250 MPa
Elongation at Break	250

Base frame modeling

The site location for this study was chosen as Los Angeles, California. Throughout the study 5 storey and 20 storey ordinary base frames were analyzed. Chevron bracing (inverted V-braces with vertical slotted connections) was selected. Chevron bracing has slotted connections provide only horizontal load transfer from the braces to the beam therefore the vertical components of the brace loads become equal. Thus, the brace loads are governed by the buckling resistance of the compression brace and not the member tensile strength. Also, vertical load transfers to the beam are also avoided (Bubela, 2003).

The assignment of loads along with gravity loads were done according to ASCE 7-10. The ASCE 7-10 linear static load of 1.2D ± 0.5L ±1.0E was used where D= Dead Load, L= Live Load & E=Earthquake Load. Table 4 shows the characteristics of frames that were designed.

Table 4: Characteristics of the frame

Frame Name	Building Type	No. of Stories	No. of Bays	Bay Size	Story Height	Dead Load	Live Load	Material
CB05	Office	05	3	24ft	15ft (base) 12ft	Self-Weight + 60psf	50psf	Al, A36 A992
CB20	Office	20	3	24ft	15ft (base) 12ft	Self-Weight + 60psf	50psf	Al A36 A992

Table 5: Seismic design Parameters (ASCE 7-10)

No	Design Parameters	Symbol	Value
1	Response modification coefficient for steel ordinary concentrically braced frames (Table 12.2-1 from ASCE 7-10)	R	3.25
2	Over strength factor for steel ordinary concentrically braced frames (Table 12.2-1 from ASCE 7-10)	Ω	2
3	Deflection amplification factor Steel ordinary concentrically braced frames (Table 12.2-1 from ASCE 7-10)	C_d	3.25
4	Seismic importance factor for building with substantial risk to human life in event of failure (Table 1.5-2 from ASCE 7-10)	I	1.25
5	Mapped MCER, 5 percent damped, spectral response acceleration parameter at short period based on the site location (Section 11.4.1 of ASCE 7-10)	S_s	2.042g
6	Mapped MCER, 5 percent damped, spectral response acceleration parameter at a period based on the site location (Section 11.4.1 of ASCE 7-10)	S_1	0.843g
7	Long-Period transition period based on the site location (Section 11.4.5 of ASCE 7-10)	T_L	8
8	Soil type of the location site class C used for very dense soil or soft rock. (Section 11.4.2 of ASCE 7-10)	SC	C

ETABS 2013 software was used for the modelling and analysis of the above-mentioned frames. Figures 6 and 8 show the two base frames (5 storeys and 20 storeys) with section properties while Figure 7 shows load assignments, with Chevron bracing.

Application of time history to the modeling frame

Time history data was applied after finishing the base modeling process. The time history data was obtained from Pacific Earthquake Engineering Research (PEER) database. These data were then converted to response spectrum curves by Fast Fourier transformation. This conversion was done using PRISM computer software. Then time histories were scaled to meet the requirement of the design spectrum according to ASCE 7-10.

Table 6: Earthquake Data (PEER, 2015)

Earthquake Name	Year	Magnitude	PGA	Frequency (Hz)	Label
Loma Prieta	1989	6.93	0.2435g	0.4-1.0	LP
San Fernando	1971	6.60	1.25g	11.23	SF

To calculate the period of the structure the following equation was used;

$$\boldsymbol{T = C_t h_n^x} \qquad \textbf{(3)}$$

Values for coefficient Ct=0.02 and x=0.75 values and h_n is the structural height. These values were obtained according from ASCE 7-10 for moment resist frame systems. The following table was obtained from the above equation.

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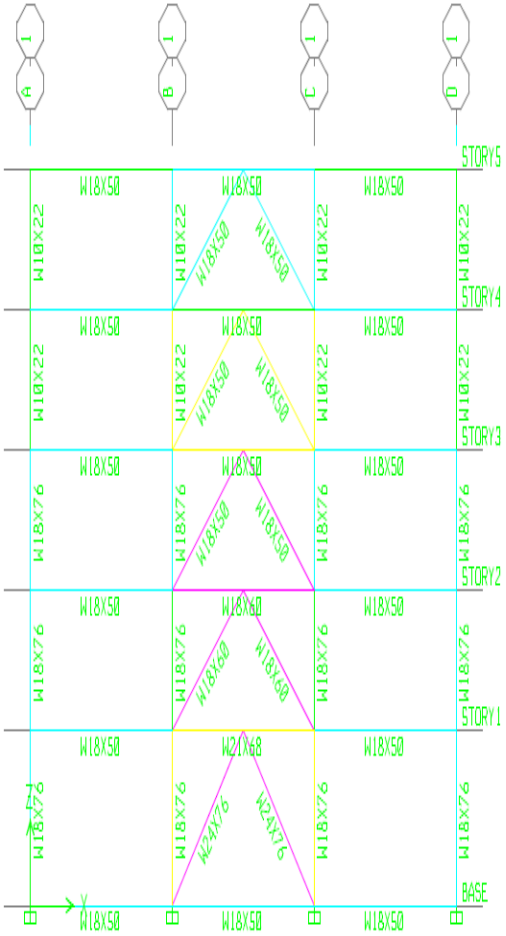
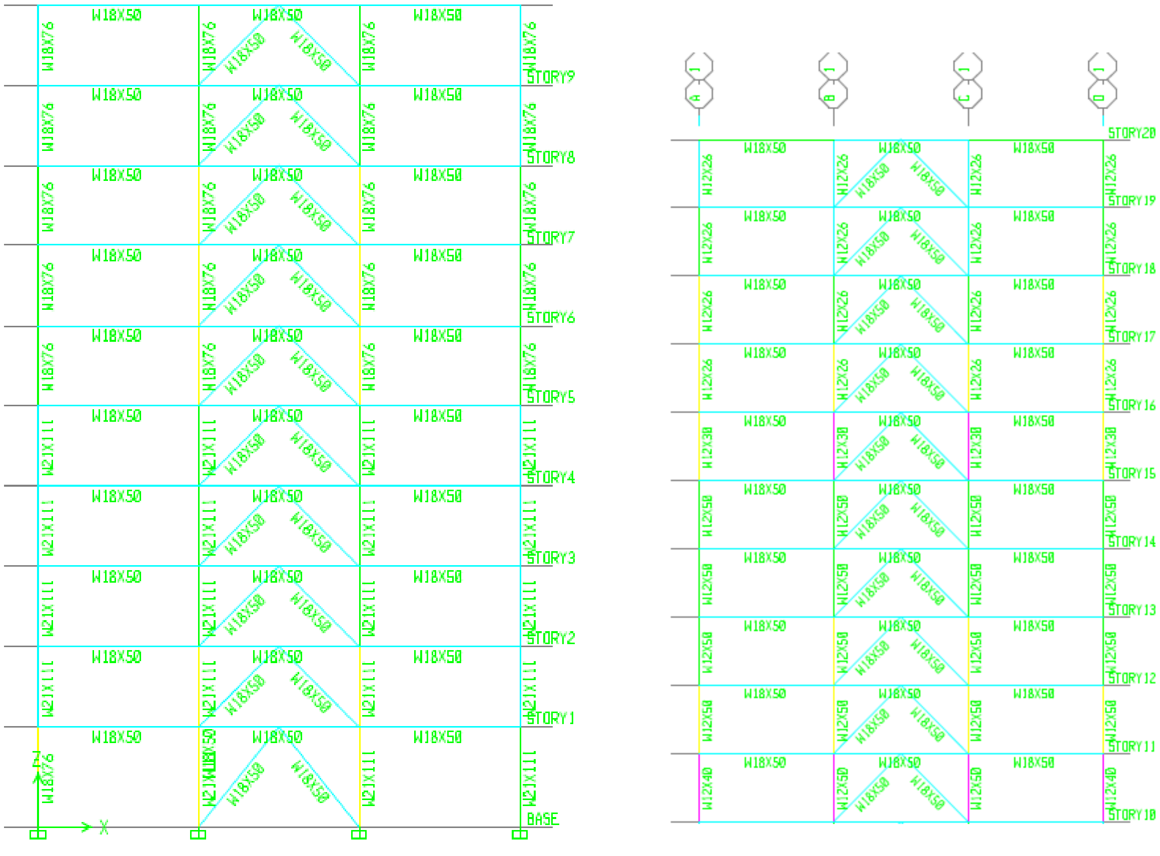


Figure 5: Structural model for 5 storey building



(a)

(b)

Figure 6: Structural model for 20 storey building

Table 7: Time periods for 5 and 20 storey frames

5 story			**20 story**		
T	0.2T	1.5T	T	0.2T	1.5T
0.447	0.089	0.671	1.231	0.246	1.846

The table below shows the scale factors used for each earthquake; Loma Prieta and San Fernando

Table 8: Scale factors for 5 and 20 storey frame

Earthquakes	**PGA**	**Stories**	**Scale Factors**
Loma Prieta	0.2435g	5	2.2
		20	2.9
San Fernando	1.25g	5	1.8
		20	1.8

Application of dampers to the base frame

Each damper; X-shaped and Double X-shaped, was applied to each of the designed brace frames. To do this ETABS was provided with stiffness and yielding parameters of each damper type. Firstly, link elements (nonlinear dynamic properties) were defined. Then to assign dampers, panel zones were used. The time history functions were applied to each case and analyzed by ETABS.

Damper properties like effective stiffness and yield force for each material; A992 steel, A36 steel and aluminium were calculated and input in ETABS when the link elements were defined. Each property was calculated for different number of plates. This information is given in the following tables.

Calculated non-linear damper properties

Effective stiffness and yield force for each damper type for three types of material was calculated according to the equations mentioned. The number of plates for each damper was varied in order to observe its effect to the performance of the damper.

Table 9: Calculated Effective and Yield force Values (X-Shaped damper)

Non-Linear Property	**A992**			**A36**			**Aluminium**		
	5 plates	8 plates	10 plates	5 plates	8 plates	10 plates	5 plates	8 plates	10 plates
Damper Name	X-5-A992	X-8-A992	X-10-A992	X-5-A36	X-8-A36	X-10-A36	X-5-AL	X-8-AL	X-10-AL
Effective Stiffness (N/mm)	8533.3	13653.6	17066	8533.3	13653.6	17066	2939.75	4703.6	5879
Yield Force (N)	27600	44160	55200	20000	32000	40000	22080	35328	44160

Table 10: Calculated Effective and Yield force Values (DX-Shaped damper)

Non-Linear Property	A992			A36			Aluminium		
	5 plates	8 plates	10 plates	5 plates	8 plates	10 plates	5 plates	8 plates	10 plates
Damper Name	DX-5-A992	DX-8-A992	DX-10-A992	DX-5-A36	DX-8-A36	DX-10-A36	DX-5-AL	DX-8-AL	DX-10-AL
Effective Stiffness (N/mm)	8533.3	13653.6	17066	8533.3	13653.6	17066	2939.75	4703.6	5879
Yield Force (N)	27600	44160	55200	20000	32000	40000	22080	35328	44160

Results

Five Storey Analysis

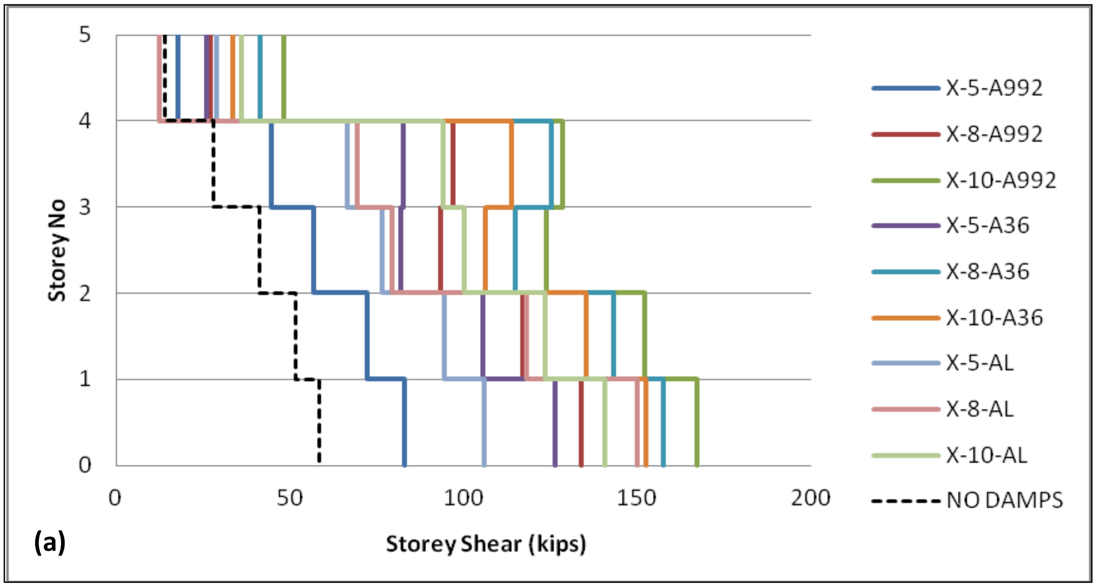
The story shear graphs obtained for the 5 storey frame for Loma Prieta and San Fernando earthquakes respectively for X-shaped damperand DX-shaped damper are shown below. The 5 storey frame without any dampers was also analyzed under the time histories to understand how the dampers work. This is shown from the dotted line in the graph.

Legend for the graphs

- Eg:

Type of damper	*No.of plates*	*Material type of damper*
X	*5*	*A992*

X-5-A992



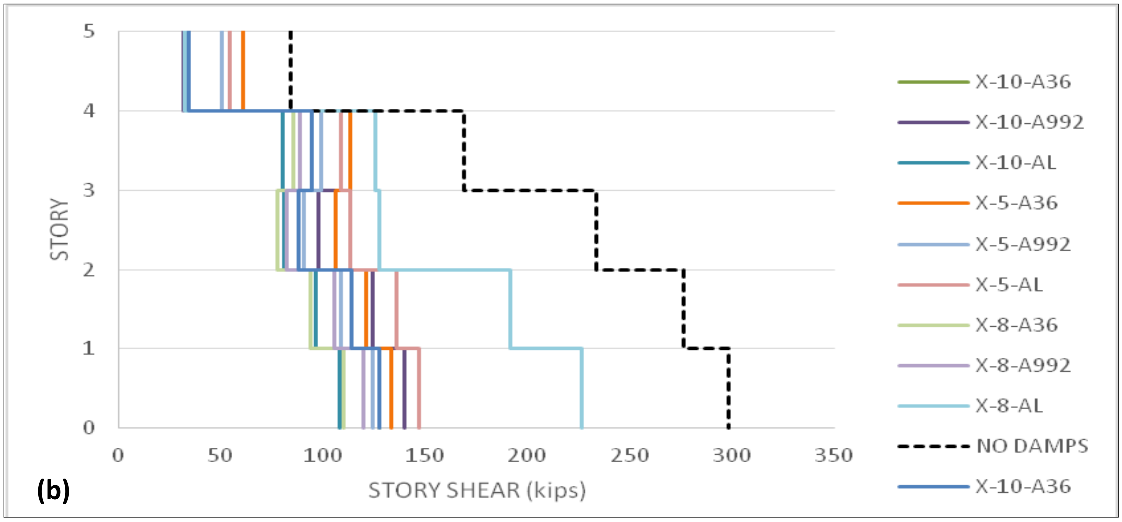


Figure 7: Shear displacement graphs for X-shaped damper under (a) Loma Prieta (b) San Fernando excitation

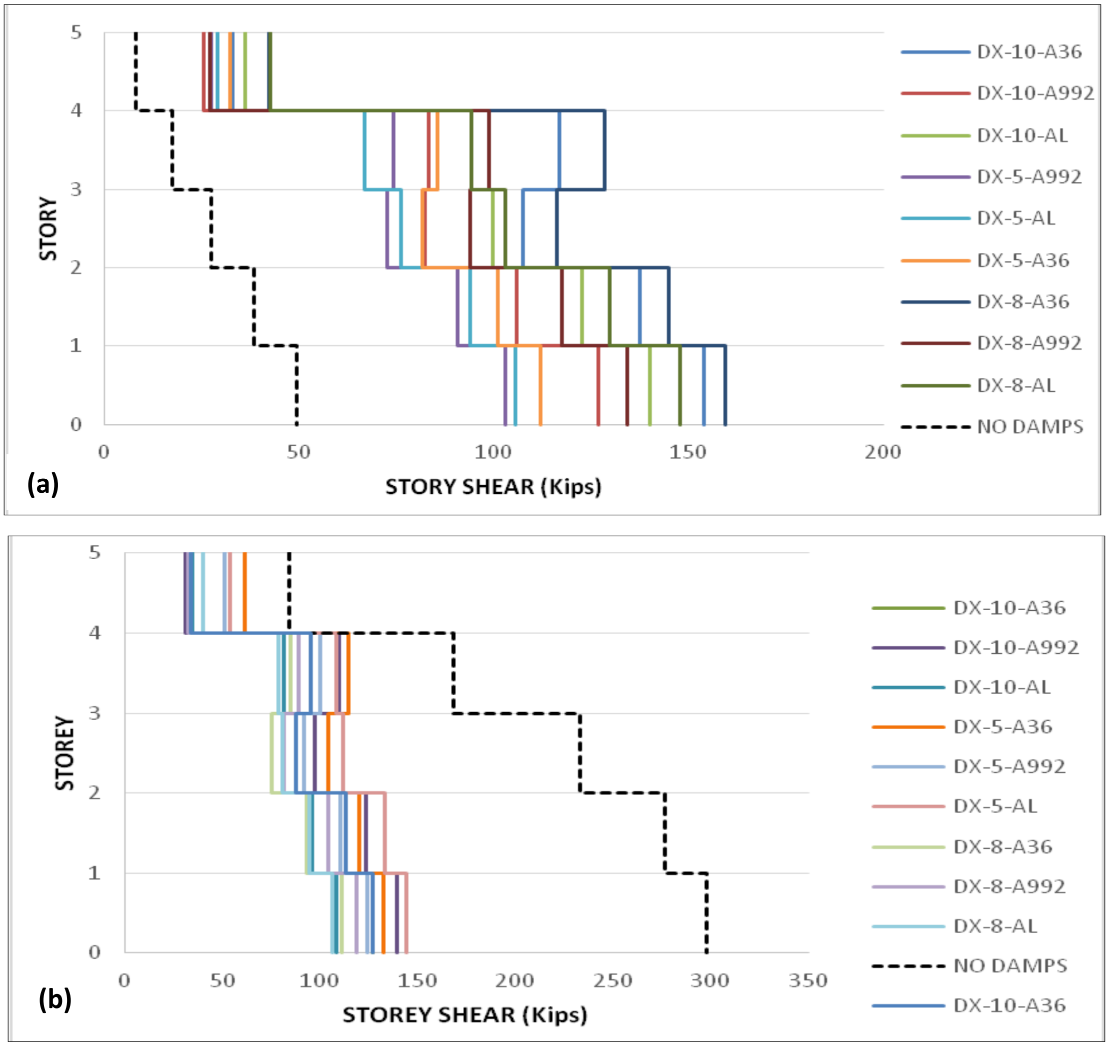
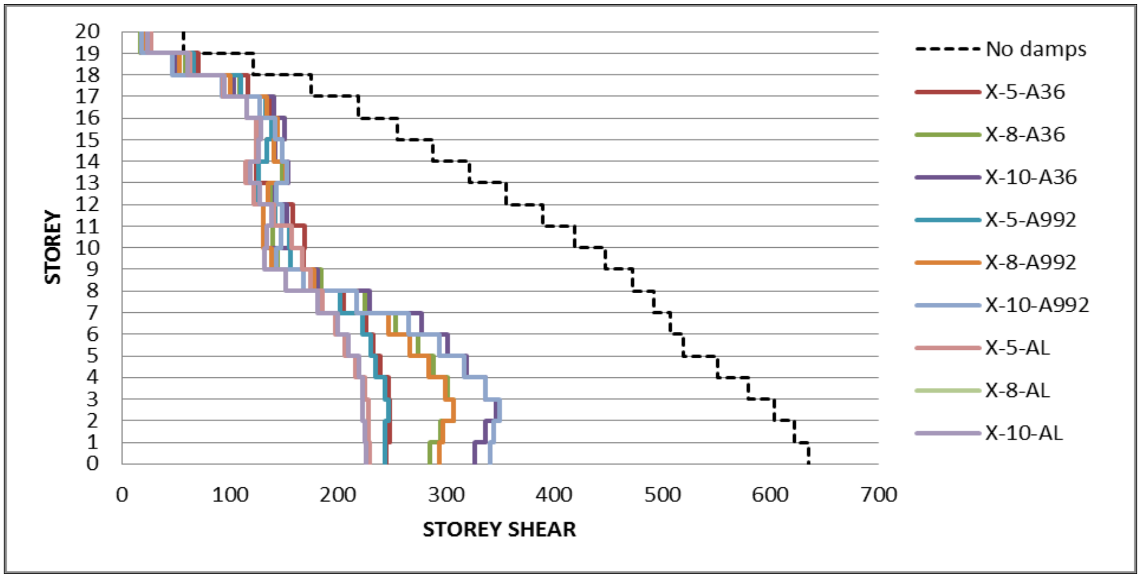


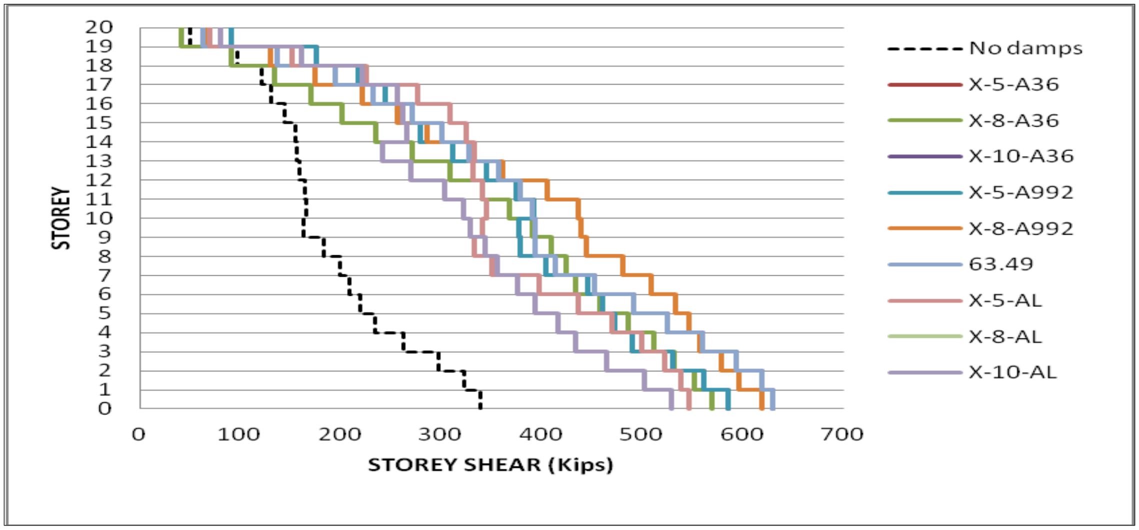
Figure 8: Shear displacement graphs for DX-shaped damper under (a) Loma Prieta (b) San Fernando excitation

Twenty Storey Analysis

Same as the 5 storey analysis the same time histories were applied to a 20 storey frame. Story shear graphs were obtained for X-shaped damper and DX-shaped damper. Here too, a 20 storey frame without any dampers was analyzed under the time histories to understand how the dampers work.



(a)



(b)

Figure 9: Shear displacement graphs for X-shaped damper under (a) Loma Prieta (b) San Fernando excitation

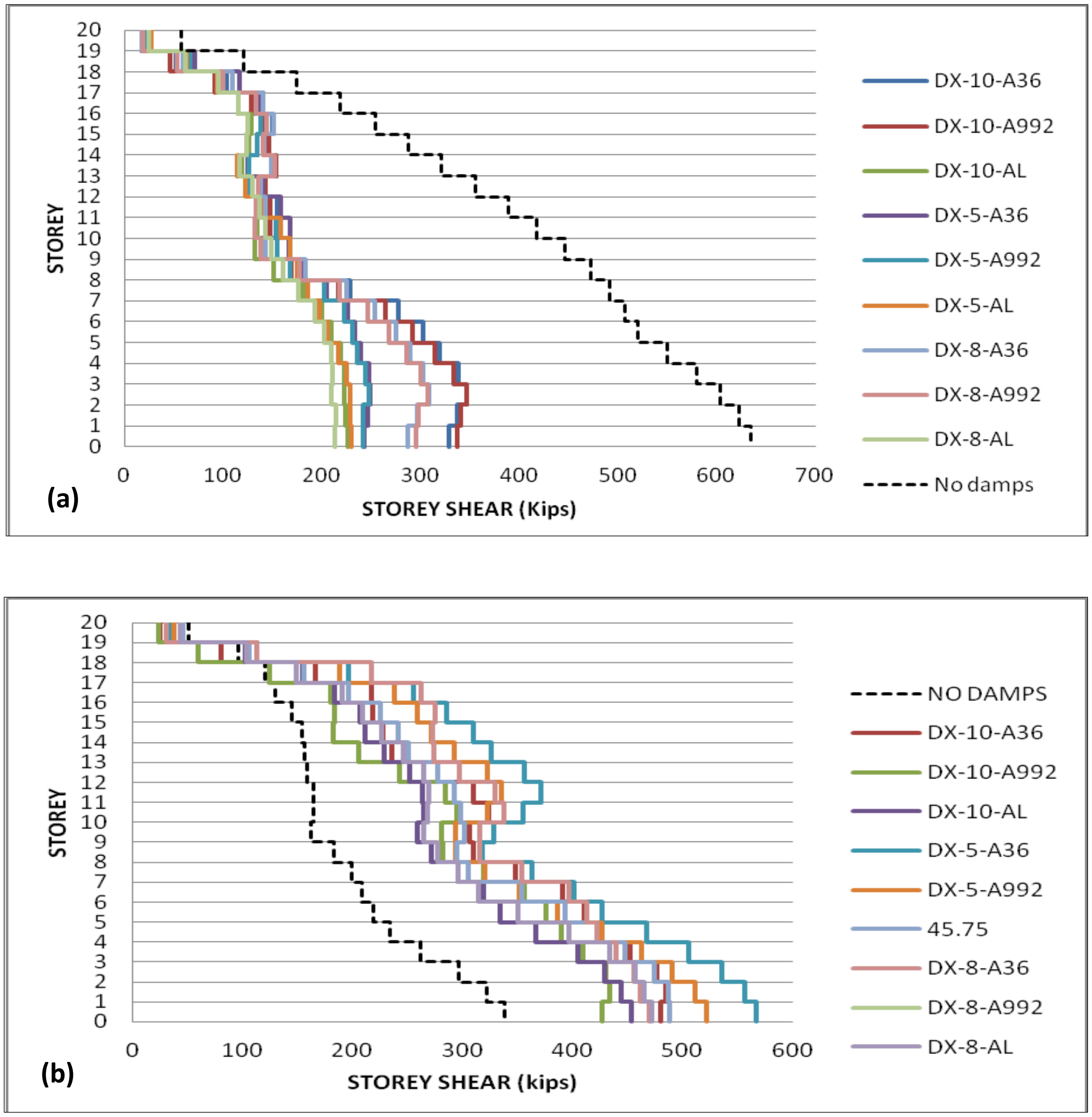


Figure 10: Shear displacement graphs for DX damper under (a) Loma Prieta (b) San Fernando excitation

Discussion

From the story shear values obtained from the graphs shown in the section above, the results of the analysis are discussed as follows.

The results from the five storey analysis showed that both the dampers performed poorly when subjected to a low frequency earthquake, like the Loma Prieta earthquake. According to the phenomenon known as resonance, previous studies have shown that low rise buildings are not greatly affected by low frequency earthquakes. Therefore, the reason for both dampers to show reduced performance, when subjected to the Loma Prieta excitation, is due to the insignificant motion of the building failing to activate the dampers. The displacement graphs above clearly show the dampers responding very well to San Fernando excitation in contrast to Loma Preita. The storey shear values of the frames with the dampers have a lesser value compared to the storey shear values of the frame without any dampers. When discussing the results from the three types of materials; both type dampers made from aluminium show better performance than dampers made from A992 and A36 steel. ADAS dampers with higher number of plates have a better performance.

The results for twenty storey analysis compliment the results obtained from the five storey analysis. Here, it can be seen that the dampers do not perform well under San Fernando excitation. This is because high frequency earthquakes do not affect high rise buildings severely. High rise buildings are most affected by low frequency earthquakes since the frame's motion is sufficient to activate the dampers. Both damper types show better performance under Loma Prieta excitation, which has a low frequency. The storey shear values shown in the above graphs confirm this statement. Same as in the five storey analysis ADAS dampers with 10 and 8 plates shows better performance than the dampers with 5 plates. The performance of ADAS dampers made of steel; A992 and A36, showed better performance than dampers made of aluminium.

Conclusion

The analysis done for 5 storey and 20 storey frames show that both dampers perform well when subjected to both high frequency and low frequency earthquakes. ADAS dampers made from steel performed better than the other ADAS dampers. The performance level was high for higher number of plates in both X-shaped and Double X-shaped dampers.

From this research it was established that both dampers work efficiently under seismic activity. As from the previous researches done for ADAS, this research too proves its efficiency. Coupled with its manufacturing easiness, ADAS dampers can be further researched to achieve higher performance levels.

Overall conclusion is that both dampers are efficient and shows great promise in making structures safer from seismic activity in the future.

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