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Improving lateral load bearing capacity of RC buildings using non-linear dampers

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Abstract

Seismic vulnerability of building structures is a burning issue in the South Asian countries such as Bangladesh. Structural damper enhances the seismic capacity of existing building without necessitating excessive reconstruction and repair. This research paper investigates the behavior of existing mid-rise RC building structures against potential earthquake before and after the application of dampers using ETABS-2015. Estimation of the effectiveness of different type dampers against several well-known earthquake motions forms the core of this paper. A series of finite element models investigates the influence of bilinear, friction spring and exponential damper. The study further extends into time history analysis to observe actual spectral responses. The building analysis reveals that with the application of dampers the time period of the structure increases whereas lateral drift, shear force and bending moment. Furthermore, the application of damper increases base shear and maximum joint displacement capacity for different earthquake motions as evident from the linear and nonlinear time-history analyses of the typical RC frame structures of Bangladesh.

Keywords: Earthquake; non-linear damper; finite element analysis; time history.

1. Introduction

Since the beginning of time, natural hazard like Earthquakes has been one of the source of unavoidable damages. With the advent of modern era the height and complexity of the man-made structures have been increased, which also worsened the potential damage scenario associated with earthquakes. However, research on seismically damaged structures suggests that enforcing earthquake resistant design regulations, which results in their proper implementation in building constructions, is a critical safeguard of these structures against earthquake-induced damages, saving significant amount of lives and properties (Chang and Soong 1980; Kaynia, Biggs *et al.* 1981; Jangid 1995; Jangid and Datta 1997; Jangid 1999; Wong and Johnson 2009). Furthermore, it is necessary to evaluate and strengthen the existing structures before an earthquake strikes based on identified evaluation criterion. Earthquake damage depends on many parameters, such as duration, frequency, intensity, geological condition, ground motion and quality of construction (Jansen and Dyke 2000; Varadarajan and Nagarajaiah 2004; Yang, Agrawal *et al.* 2004). One of the prime reasons causing collapse or significant damage of a building structure during an earthquake is the failure to adopt seismic engineering practices and unavailability of seismic resistant features in the design and construction phase. Installation of energy absorbing devices both active and passive, can improves the seismic performance of a buildings. Damper in building structure is a well-known seismic strengthening arrangement that deadens, restrains, or depresses violent shocks from earthquake by absorbing significant amount of the forces from vibrations. There are many types of dampers, such as, tuned mass damper, viscous damper, friction damper etc (Hrovat, Barak *et al.* 1983; Sarker, Ansary *et al.* 2009; Tavakoli, Naghavi *et al.* 2013). Time history analysis employing macro-finite element software, ETABS v 15 (a popular finite element based structural analysis and design software) observes the actual behavior of building structures against previously recorded earthquake motions. In view of time history response of the structure, this study utilizes the nonlinear time history analysis to investigate the performance of dampers in enhancing the seismic capacity of typical mid-rise RC building in Bangladesh. It is important to note that ETABS v15 is completely new package and the features of dampers properties are also added in this latest version only. The main objective of this research paper is to investigate the performance of dampers under different previous earthquake for typical RC building at Dhaka City of Bangladesh. Current study investigates the influence of mass dampers against lateral loadings, such as, wind & earthquake load using finite element analysis software ETABS 2015. A series of time history analysis assists in observing the actual behavior of an eleven-story frame structure building in terms of base shear, and joint displacement for the structure with and without damper for different earthquake motions.

2. Structural modeling

This study develops the model of a building structure (Figure 2) using structural design and analysis software, ETABS version 2015 considering the actual scenario of the building. The model of this building is based on an existing RC structure situated Dhaka, Bangladesh. This investigation places the dampers at the top three floors of the 11 storey building. These dampers perform in linear and non-linear static analysis as well as linear and non-linear dynamic analysis. This study considers the following geometry, material property and loading types.

1) Material:
    Compressive strength of concrete-28 MPa
    Yield strength of steel – 60 grade
2) Geometry:
    Rectangular, 11 storey building
    Beam-Column Frame Structure
3) The typical story height:
    i) GF and 1st floor height 4.3 m
    ii) Typical floor height 3 m
4) Loading:
    i) Dead Loads: 0.5 Mpa (includes Partition Wall & Floor Finish)
    ii) Live Loads: 0.4 Mpa
    iii) Wind Load: Wind Speed 235 Km/h (as per BNBC 2014)
5) Types of dampers:
    i) Exponential Damper
    ii) Bilinear Damper
    iii) Friction Spring Damper

Generally, the top floors of a building experience maximum force and lateral displacement in the event of an earthquake or severe wind. In this study, the dampers are place at the top three floors to reduce the overall drift as well as the vibration in the structure. A comparison of structure in EQ of different mass percentages and various time history analyses with and without mass dampers demonstrate the effectiveness of such devices.

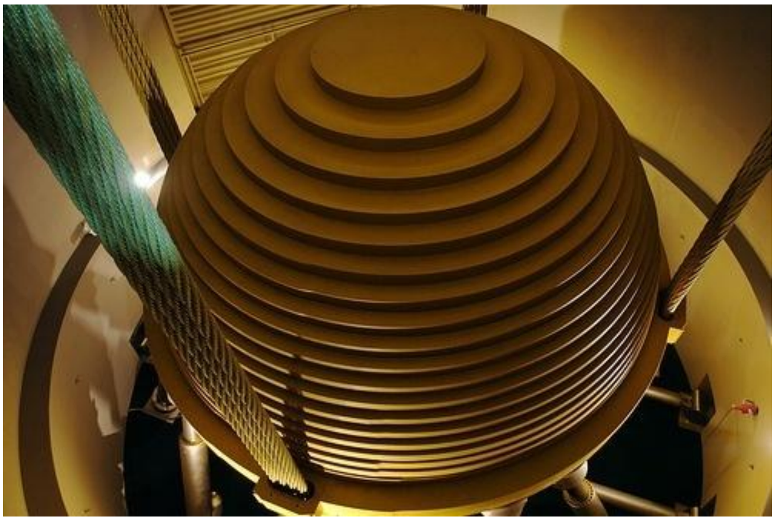

Fig. 1. Typical mass damper (courtesy Taipei 101).

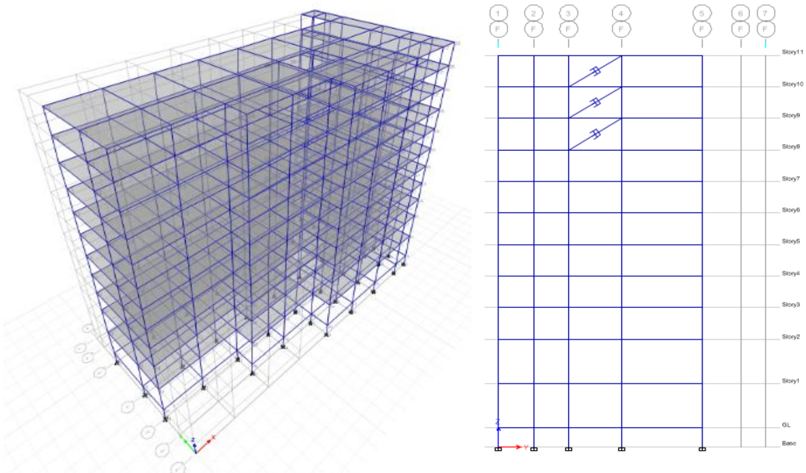

Fig. 2. 3D view & Elevation of building model.

Figure 2 shows the 3D and elevation views of the building model. Dampers, placed in three different configurations in top three floors, demonstrate their effectiveness with respect to varying orientations. Current investigation applies them as column, beam and diagonal member. The figure also shows the dampers as diagonal member connected to different floor level. Table 1 compares the properties of different type of dampers as provided input in ETABS 2015.

3. Results and discussions

This study carries out a number of analysis with different mass percentages of dampers with respect to the mass of the actual factory building. Time history analyses consider different earthquakes motions as well as wind loads in some cases. In this study, the results are presented in terms of modal time period, moment and shear values of frames, base shear, residual drift, joint acceleration and maximum joint displacement. Comparison against the original building (without damper) is also highlighted. Since the aspect ratio of the building is high in Y direction, the structure is expected to be weak in this direction and hence analysis results are presented mainly in Y direction.

Table 1
Damper properties

Properties	Exponential	Bilinear	Friction Spring
Mass (KN-s^2/m)	236	236	236
Weight (KN)	2315	2315	2315
Effective stiffness (KN/m)	11667	11667	11667
Effective Damping (KN-s/m)	17850	17850	17850
Stiffness (KN/m)	17500	17500	17500
Damping coefficient (KN-s/m)	22225	-	-
Damping Exponent	1	-	-
Initial Damping coefficient (KN-s/m)	-	99400	-
Yielded Damping coefficient (KN-s/m)	-	0	-
Linear Force Limit (KN)	-	0.00445	-
Slipping Stiffness (loading) (kip/in)	-	-	21000
Slipping stiffness (unloading) (KN/m)	-	-	17500
Stop displacement (m)	-	-	0

3.1 Time period for different modes

In order to investigate the influence of dampers on the natural time period of the structure, a number of analysis has been conducted in models with dampers and without dampers. Table 2 lists the influence on time period of the building in different modes due to the presence of dampers. From the table it is clear that with the application of dampers in the building, the time period of the building increases significantly (4 to 21%). The result also agrees with the fundamental concept presented in Equation 1. The increment in time period is higher in first 2 modes compare to the higher modes. The basic equation to estimate the time period of the building structure is as follows,

$$T = 2\pi \sqrt{\frac{m}{k}} \qquad (1)$$

Here, m = mass of damper & k = stiffness of damper

As per Equation 1, with the increase of the mass of the building, the time period also increases. Therefore, from the result it may be concluded that the dampers are active in the model and influence building time period.

3.2 Variation in moment and shear

Analyses have also been conducted to identify the influence of dampers on other design factors, such as, shear and moment of frame against later load, particularly wind and earthquake load. Results are presented for a particular frame 34FF as shown in Table 3. In addition, Figure 3 to Figure 6 show the changes of moment and shear of frame 34 of all storey level are presented for Bilinear and Friction Spring dampers as well as for the building without (WO) any damper. The analysis result shows that both moment and shear force reduce significantly due to the application of dampers.

It can be concluded from the figure that, the application of dampers, significantly reduces both shear and moment due to earthquake and wind in all storey level except at the Ground level. The maximum variation occurs in Storey 1 and gradually reduces to till the second to top floor. Among the dampers, friction damper facilitates more reduction in both shear and moment of the floor. Table 3 also identifies that both bilinear damper and friction damper are capable to reduce the design factor, such as, shear and moment significantly. Current investigation finds that, application of dampers reduces a maximum 74 percent of the total moment and shear values at the floor level.

Table 2
Increment of building time period

Mode Number/ Shape	Time Period (sec) Without Damper	Time Period (sec) With Exponential Damper	Percent Increased (%)
1	1.389	1.635	18
2	1.285	1.552	21
3	0.219	1.288	5
4	0.428	0.461	8
5	0.396	0.434	10
6	0.376	0.392	4

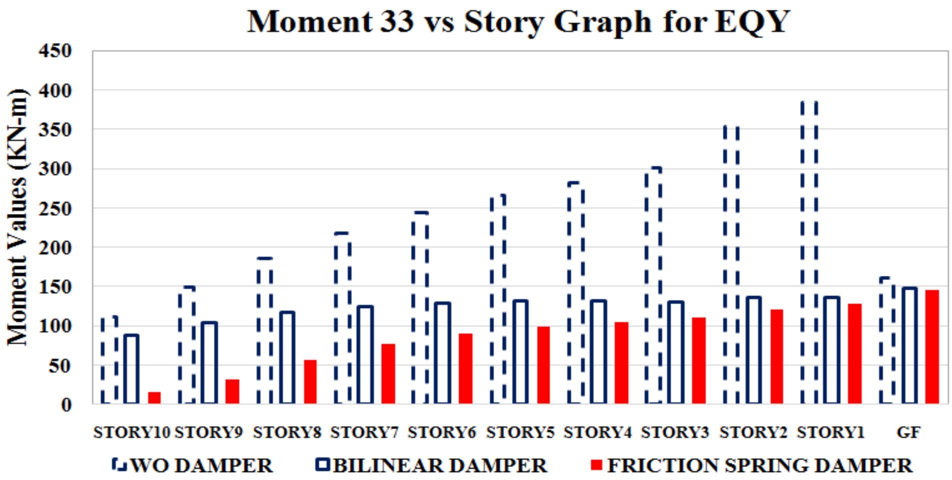

Fig. 3. Comparison of moment caused by EQY.

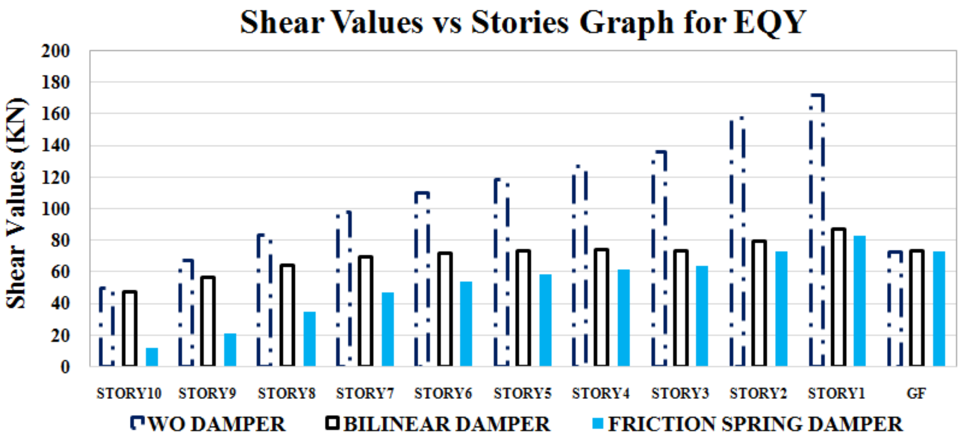

Fig. 4. Comparison of shear force caused by EQY.

This part of the study suggests that installation of mass dampers in RC frame structures, can reduces the moment and shear values to a required level. As a result, the amount of reinforcement in the structural elements can be reduced and the frames become safer with improved performance against lateral loading.

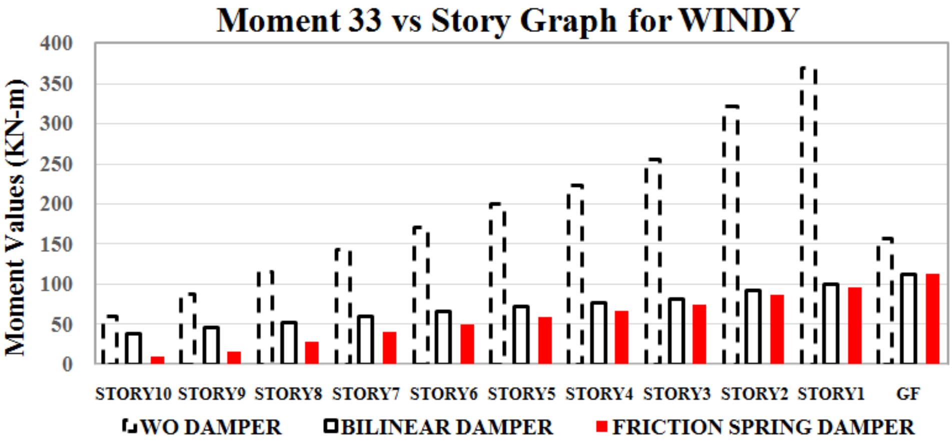

Fig. 5. Comparison of moment caused by WINDY.

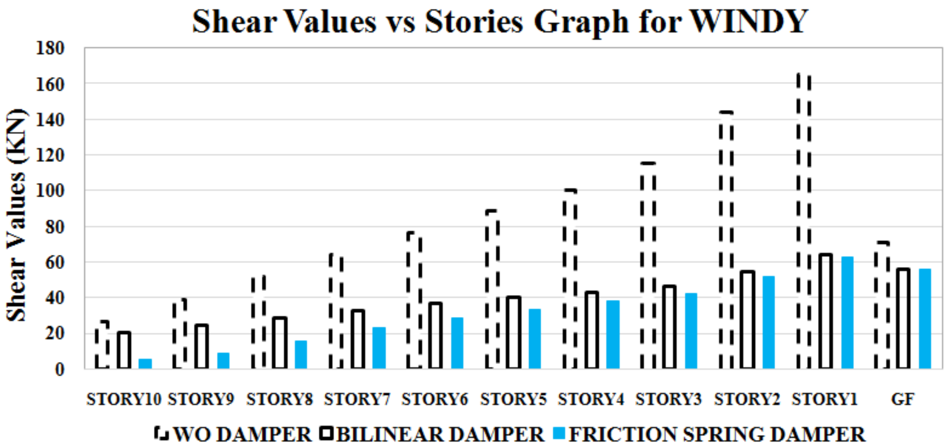

Fig. 6. Comparison of Shear caused by WINDY.

Table 3
Influence on Bending Moment and Shear Force

Kind of Response	Without Damper	Bilinear Damper	Percent Reduction %	Friction Dampers	Percent Reduction %
Moment (KN-m) EQY	387	137	65	129	69
Moment (KN-m) WINDY	372	100	73	97	74
Shear (KN) EQY	171	87	49	85	52
Shear (KN) WINDY	165	65	61	62	74

3.3 Variation due to different orientation of dampers

Maximum allowable top displacement is one of the major serviceability criteria for the building structures. Thus, one of the main objectives in installing dampers in the building is to reduce the lateral displacement particularly for tall and slender structures. Such lateral load, as wind load may become very crucial for slender buildings. In order to reduce the displacement caused by wind, this investigation analyses three different combinations of dampers and compares the results against the original building without any damper. Figure 7 displays that the dampers reduced the lateral displacement of the building. Current research identifies the dampers installed in the floors is more effective option compared to their placement as beams or columns.

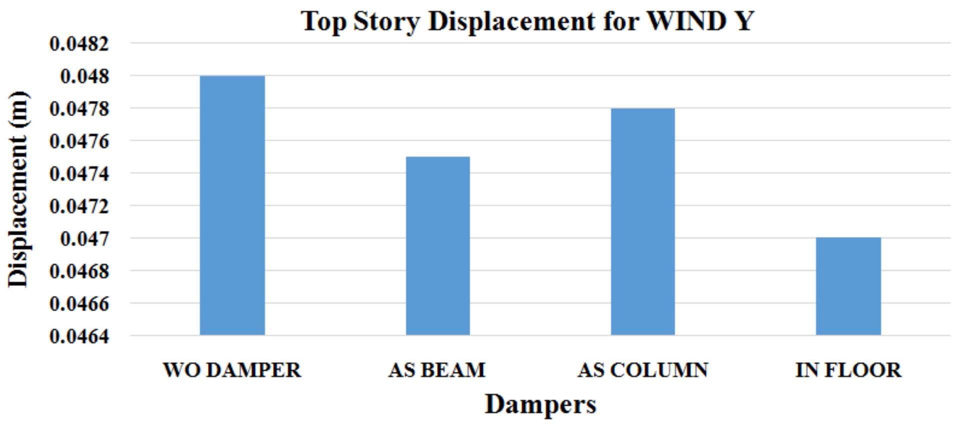

Fig. 7. Lateral displacement due to WIND-Y.

3.4 *Time history analysis*

This section compares the time history analysis of the building with varying damper properties, such as exponential, bilinear and friction dampers. In the time history, three major time earthquake motion namely, S_Monica, Altadena and Corralit are considered in the model.

3.4.1 *Residual drift*

Residual drift is very threatening for a building as it is the permanent deformations that remain after an earthquake. This part of the study investigates the influence of dampers on the residual drift against EQ ground motion denoted as S_Monica. Table 4 presents the analysis results. All three types of dampers significantly reduce the residual drift of the building. Among the dampers, friction spring damper is the most effective as it reduces the maximum 39.5% of the residual drift with respect to the building without any dampers. Therefore, this study concludes that the application of dampers controls the residual drift successfully and may achieve the desired level serviceability.

Table 4
Residual drift for S_Monica

Dampers	Residual Drift ($\times 10^{-4}$)	Percent Reduction (%)
Without Damper	2.92	-
Exponential Damper	1.84	37
Bilinear Damper	1.99	32
Friction Spring Damper	1.77	39.5

3.4.2 *Maximum base shear*

Figure 8 compares the resultant base shear of the 11 storey building with damper for different EQ time history. This Figure shows the effect of the dampers on the resultant base shear, it also increases for different earthquake compared to the case with no damper. Figure 9 shows the variation of base shear with the change of different dampers for same time history S_Monica. Mass dampers results in higher base shear than that of the bare structure. This reasoning is that, with the application of mass dampers, the total weight of the building increases and hence base shear which is function of total weight of the structure also increases. However, base shear significantly reduces for the time history of EQ Altadena, when the analyzed damper is Bilinear.

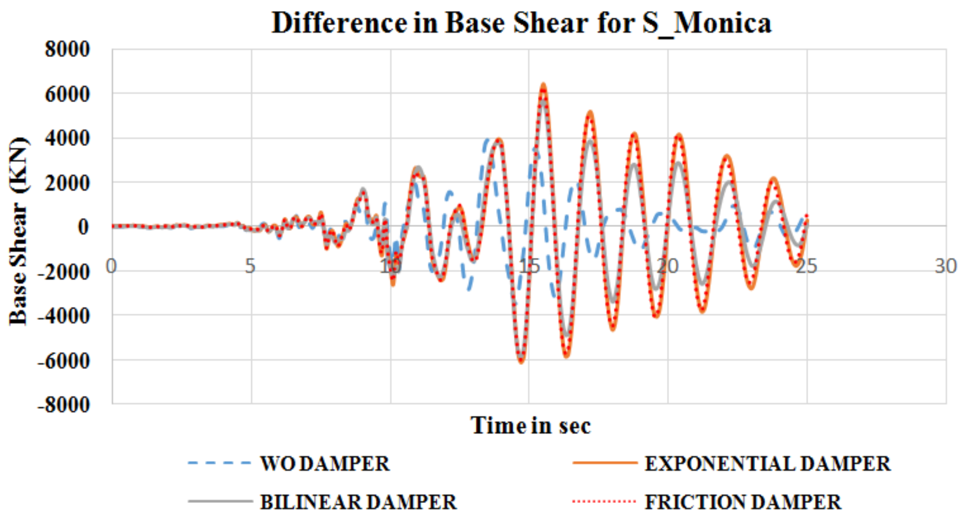

Fig. 8. Base shears for different dampers with time.

The base shears re maximum and almost same for Exponential Damper and Friction Spring Damper and significantly less for Bilinear Damper when compared to the other two time history with dampers.

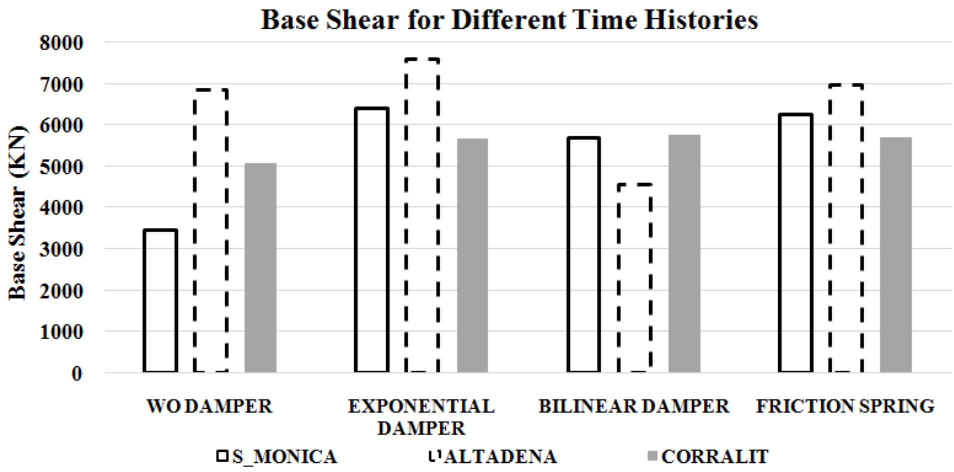

Fig. 9. Bar chart for base shear for different dampers and time histories.

Figure 8 also articulates that by installation of mass dampers the base shear upsurges for exponential damper and friction spring damper but drops down for bilinear damper in the case of EQ Altadena only.

3.4.3 Maximum joint displacement

Figure 10 and Figure11 present the influence of the dampers on joint displacement for different dampers under different earthquake motions. Table 5 shows that maximum joint displacement (compared to without dampers) increases for all three types of damper. Among the dampers, Exponential dampers results in maximum joint displacement for all three time history that has been highlighted in Figure10 and Figure 11. Therefore, dampers increase the time period as well as the displacement of the building and subsequently reduce the joint acceleration.

Table 5
Comparison of Joint displacement with different dampers

EQ	WO Damper	Joint Displacement With Damper (m)		
		Exponential Damper	Bilinear Damper	Friction Spring Damper
S_Monica2	0.02	0.043	0.041	0.041
Altadena	0.03	0.047	0.048	0.046
Corralit	0.026	0.036	0.034	0.036

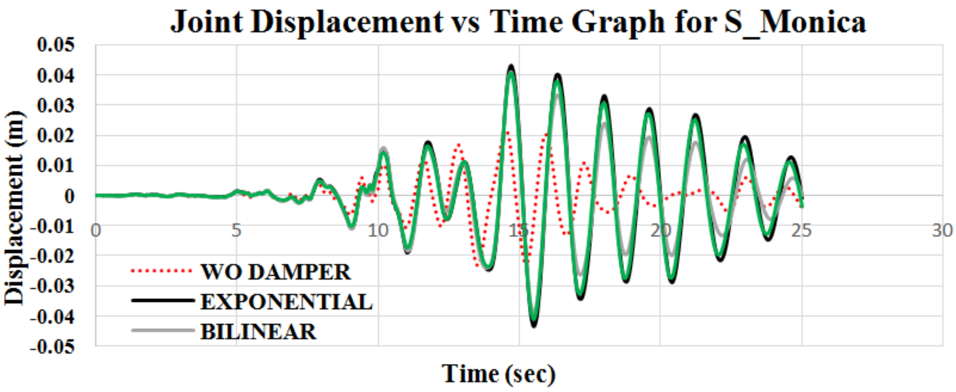

Fig. 10. Joint displacement for different damper.

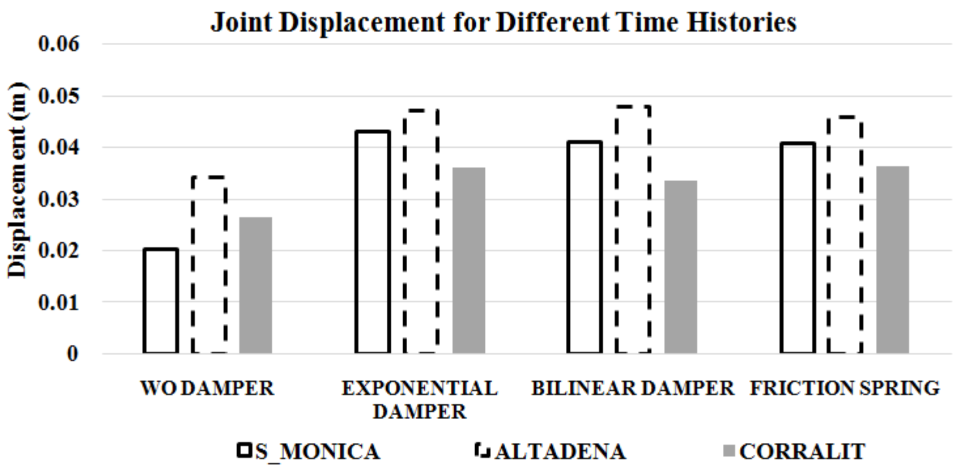

Fig. 11. Bar chart for joint displacement for different dampers and time histories.

5. Conclusion

This study investigates the application and performance of dampers in countering lateral loading specifically caused by several recorded earthquake motions. In the model, dampers occupy different configurations as well as different properties such as bilinear, exponential and friction spring damper. Based on the series of analysis, the key findings from this study are as follows. The application of dampers increases the time period of the structure in different modes. The second mode experiences a maximum of 21% time period increment. Analysis result also depict that with the application of dampers, the shear force and bending moment of typical floor reduces significantly due to lateral loading such as wind load and earthquake load. In addition, lateral displacement & drift of the structure also reduces with the introduction of the dampers. Another key parameter, residual drifts, which represent the post-earthquake permanent deformation, reduces about 40 % compared to the structure without damper. Generally, with the application of dampers, base shear of the structure increases since addition of mass ultimately results larger self weight and hence comparatively high base shear. However, the result shows that with the deployment of dampers in the structure the base acceleration decreases for some EQ motion thus reducing the inertia forces.

The recent frequent earthquake in South Asia particularly in Nepal and Imphal (India) force the structural engineer community to think alternative ways to reduce earthquake's impact on the structure. Optimum application of dampers, assisted by a detailed parametric study, will result in structures with enhanced reliability and improved safety and hence limits seismic hazards.

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