Technical Note

Seismic Performance of Tall Buildings with Impact Damper under Near and Far-Field Earthquakes

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ABSTRACT

Impact dampers are considered among passive control devices. Experimental and analytical research studies have shown that this group of nonlinear dampers has a better performance for reducing structural vibrations as compared to linear vibrating neutralizers. Tall building is a structure that is different from other buildings in design aspects, construction, and operation due to its height. Medium height and tall models are used in the present paper in order to compare the performance of impact dampers in tall buildings. In this study, seismic performance of tall buildings with impact dampers is evaluated by using SAP2000 software. The condition of tall buildings with impact dampers is subsequently introduced. In order to achieve more desirable results for tall buildings subjected to seismic vibration, the earthquake records applied to multi degree of freedom systems are selected from both near and far-field seismic events. This study aims to represent how the impact damper operates in tall buildings and to determine the best location for its installation in order to reduce the response of vibrating system. Using non-linear time history analysis, structural elements have been investigated based on AISC360-10 regulation in the design process. Among the results obtained in this research, reduction in the response of multi-degree-of-freedom systems in vibration condition using impact damper placed on the top floor can be mentioned. Moreover, it was observed that the more the frame height and its number of spans, the better the effect of placing impact damper in a story close to the roof as compared to placing it in the middle stories, which is due to the combination of vibration modes.

Keywords:
Nonlinear damper; Impact damper; Tall building; Near and far-field earthquakes; Numerical analysis

1. Introduction

The use of impact damper in order to prevent the state of resonance in structures has been formerly investigated, such as the research work by Chalmers and Semercigil [1], in which two impact dampers were used in a cantilever beam to control resonance. The first idea of attaching a discontinuous mass to a vibrating plate with the aim of reducing the plate vibration returns to the distant past about 70 years ago, when Leiber [2] performed his experimental and analytical studies in order to control airplane in discontinuous segments of the wing having free vibrations. The chained models of impact damper provided a simple and reliable method to reduce the vibration caused by wind blow in high-rise structures such as antennas and chimneys. In the proposed theory by Masri et al. [3] the important parameters of impact dampers in multi-degree-of-freedom systems have been investigated and the results have been compared to experimental studies and mechanical models from which proper results were deduced.

Zahrai and Rod [4] studied the seismic performance of a single-degree-of-freedom structure equipped with impact damper subjected to impact and harmonic loadings. They have concluded that by a few changes in the parameters of the impact damper, various changes in the structure response were observed. They have obtained the optimum values of the impact damper parameters under impact and harmonic loads. In his master dissertation, Afsharifard [5] has studied the distance between bumpers, mass ratio and the rate of return of bumpers that are the main three parameters affecting the performance of impact dampers. He presented the effects of these parameters on the efficiency of the vibrating system. He has also studied the efficiency of smart materials and the effects of their use in the bumpers of impact dampers and showed the positive performance of the materials on the efficiency of these systems.

Dehghan-Niri et al. [6] have investigated the effects of impact damper parameters on the optimum performance of the damper and studied the optimum performance of impact damper in both resonance and out of resonance modes. They have achieved in the research that the impact damper designed for higher amplitudes has a better performance than for lower amplitudes. Then, the vulnerability of optimum impact damper against the structure parameters was clearly defined, so that it was observed that the system with more efficiency is of less stability. Afsharfard and Farshidianfar [7] designed non-linear impact damper based on acoustic behavior and damped. The target of this research was to gain the optimal impact damper (mass ratio, gap size and return ratio). Jam and Afsharifard [8] tried to reduce vibration of robot with impact damper so that better performance was achieved with optimal mass ratio, gap size and other impact damper values.

Zahrai and Rod [9] investigated the seismic performance of a single-degree-of-freedom structure under shaking table tests. In this research, the single-degree-of-freedom structure was subjected to the Kobe earthquake and a harmonic load with amplitude of 0.4 g through shake table tests in two cases of with and without impact damper. Then, by changing the impact damper parameters, they have concluded that the effect of increasing mass coefficient on the reduction of the vibration amplitude would be higher. Goel et al. [10] gained an important achievement on experimental study of the impact damper under harmonic vibration. Their major outcome was to identify the relation between the earthquake frequency and impact damper parameters (mass ratio and return ratio).

Lampart and Zapomel [11] investigated the dynamic behavior of three-degree-of-freedom systems with impact damper under simulated earthquakes having a range of different frequencies. Afsharifard and Farshidianfar [12] discussed the use of impact damper to improve energy dissipation and reduce amplitude vibration of SDOF system. The main result of this research was to design based on input energy and induced vibrations. Phillip and Luca [13] experimentally studied the multiple-mass impact dampers. In their research, the SDOF system was subjected to different harmonic loads, and the main result was to reduce vibration amplitude using multiple-mass impact damper.

Sanap et al. [14] studied the seismic performance of structural systems equipped by impact damper under axial vibration and resulted that amplitude vibration reduction was particularly depending on mass ratio, vibration frequency and gap size. Gharib and Karkoub [15] studied the seismic performance of the impact damper called "Linear Particle Chain" used for MDOF systems. Experimental result clearly showed that the LPC damper is effective on vibration reduction. Nakamura and Watanabe [16] investigated the seismic performance of SDOF system with impact damper under vertical vibration. According to their article, the impact damper with 3% to 4% mass ratio was optimal in reducing vertical vibration of structural system.

Since there have been few research studies on using impact dampers to improve the seismic performance of buildings, particularly comparing their behavior under near and far-field earthquakes, in this paper, seismic performances of relatively tall buildings with impact dampers are investigated under far and near-field earthquakes.

2. Numerical Modeling and Verification

As it is obvious in the experimental study by Zahrai and Rod [9], main components of the damper include a metal ball having a mass relative to the total mass of the single-degree-of-freedom system and two stations for the impact of metal balls during vibration, and at a certain distance from the ball. In the mentioned study, the effect of the impact damper in a single degree of freedom system has been discussed and investigated by changing the stations location (free path length) and changing in the metal ball mass ratio. Finally, the appropriate impact damper characteristics have been obtained for the single-degree-of-freedom system.

In this section, a single-degree-of-freedom system is subjected to a triangular impulsive loading (Figure 1). Details of mass and stiffness of structure and damper are selected to improve main dynamic parameters of structure. Metric units are used and the amount of impact loading F_0 begins at t = 0 while linearly reduces to zero at td (Figure 2). Comparing the response of structure would be based on cases with and without the impact damper. Mass of m= 1 Kg, stiffness of k = 10 kN/m^2 and zero damping ratio under transitional loading, i.e. ζ = 0 are used. Since impulsive loading does not allow viscous damping to form, so zero damping ratio is justified.

At the same time, since closed form solution has been used for dynamic response of structure and such results is available for triangular loading just with ζ = 0, viscous damping of the structure has been ignored. Impact loading equation on this system is expressed by:

$$p(t) = F_0(1 - t / t\,d) \qquad (1)$$

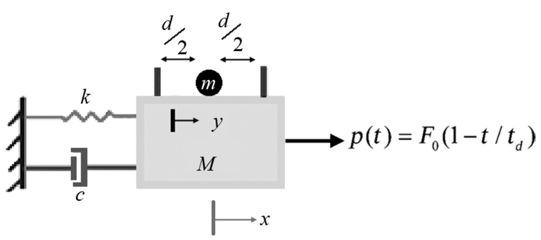

Figure 1. Impact damper position in middle of case.

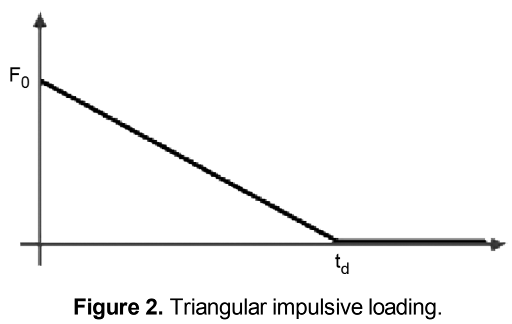

Figure 2. Triangular impulsive loading.

In Equation (1), F_0 and *td* are maximum impact force and excitation duration, respectively. The position of moving mass is initially assumed in the middle and not stuck at the ends (Figure 1). This situation is the best position inducing movement of the free mass due to an applied force from any direction creating the first impact. Otherwise, when mass is stuck at one end, damper influence would be dependent on the force direction and might not create any impact as long as it is stuck at that end.

In the analysis conducted in this part, response of the SDOF system under impact excitation is obtained at each step from closed form solution of Equation (2):

$$x(t) = \begin{cases} \dfrac{F_0}{k}(1-\cos\omega t) + \dfrac{F_0}{kt_d}\left(\dfrac{\sin\omega t}{\omega} - t\right) & t \le t_d \\ \dfrac{F_0}{k\omega t_d}\left[\sin\omega t - \sin\omega(t - t_d)\right] - \dfrac{F_0}{k}\cos\omega t & t > t_d \end{cases} \qquad (2)$$

Since no force exists between the moving mass and damper container before any impact due to the motion of the SDOF system, absolute position of moving mass is constant while its relative position compared to the damper is obtained from y= Y-x. Then, amount of y is controlled to be in [0,d] range, otherwise impact influence is appeared as linear momentum transfer to the SDOF system.

In this section, in modeling impact damper behavior, the effect of damping just due to impact forces is considered while ignoring effect of moving mass in the course between two ends although might be a bit different from experimental results. To neglect the effect of friction, energy loss due to the frictional and non-linear collision at the ends is simply considered by Equation (3):

$$\dot{y}^{+} = -\dot{e}\bar{y} \qquad 0 < e < 1 \qquad (3)$$

As shown later, structural vibration would be damped sooner using smaller amount of e. Momentum equilibrium between the SDOF system and damper is expressed by:

$$\begin{aligned} m\left(\dot{y}^{-} + \dot{x}^{-}\right) + M\left(\dot{x}^{-}\right) &= \\ m\left(\dot{y}^{+} + \dot{x}^{+}\right) + M\left(\dot{x}^{+}\right) \end{aligned} \qquad (4)$$

Substituting Equation (3) into Equation (4) would result in:

$$(m+M)\ddot{x}+m(1+e)\dot{y}^{-}=(M+m)\dot{x}^{+} \quad (5)$$

According to Equation (5), linear momentum transfer due to an impact would help to reduce structure vibration when $\dot{y}^{-}$ and $\dot{x}^{-}$ have opposite signs. Therefore, if *d* is taken too small, unfavorable impacts will increase. The best choice for *d* is an amount a little less than the amplitude of structure vibration under imposed loading, as in this way, total number of induced impacts would reduce while increasing the number of favorable impacts. In such conditions, using smaller e, we would get more damping because of two reasons: first, if *e* is selected close to zero and direction of impact with structure motion is unfavorable ($\dot{x}^{-}$ and $\dot{y}^{-}$ have the same sign) the amount of structure momentum increase or $m(1+e)\dot{y}^{-}$ will be decreased. Second, if direction of impact is favorable with structure motion, so reduction of damper velocity with its changed movement direction will create next impact favorably. In this condition, according to the above discussion, the best choice for e is almost 0.5.

Since there was not any special link in the SAP2000 software for such an impact damper, hence it was attempted to build it in the software. Among available links, the GAP link has this property of having the role of two stations in building the impact damper. Thus, by assigning the amount of movement path length in the properties of GAP link as the free path, and by assigning infinite stiffness, which means the metal balls impact place and its return, the stations have been modeled. It was used from Joint element to define the metal balls and was used between two GAP links.

In the new version of SAP, many options have been added such that it is now more useful for research studies. For example, it is quite possible to simulate impact damper behavior under harmonic vibration in SDOF system with SAP2000 and obtain appropriate results comparable to those of ANSYS software simulation and experimental work. According to Figure (3), the result of SAP is even closer to experimental result compared to that of Ansys software.

Models of 10 and 30-story frames with two and five spans were used in the present study, which are considered among tall buildings, according to

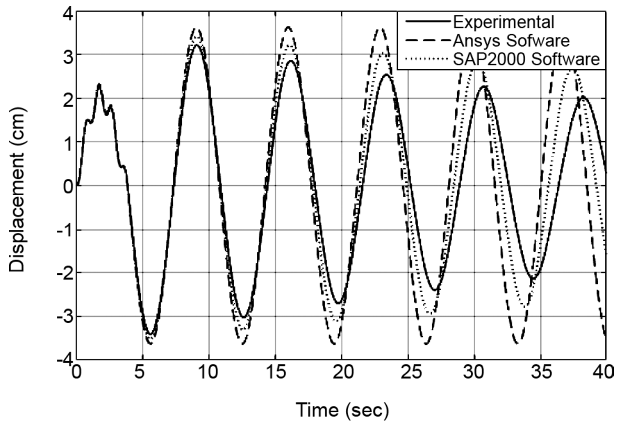

Figure 3. Comparing SAP2000 and Ansys software results with that of experimental study.

relation $3.14 < \frac{H}{D} < 4.7$.

Impact dampers are placed in three cases of lower, middle, and upper stories in each mentioned model. It must be noted that the optimal case of the parameters of the impact damper was selected among the cases studied in the previous research, from which the most optimal case is an impact damper with $\mu = 0.1$, 0.5 m , which are mass ratio and the movement path length of the impact damper, respectively.

The free-mass is obtained as the ratio of the main structure mass; for example, 0.3 or 0.5%. To simulate free-mass and rigid stopper in software: the rigid link from define menu bar of SAP is first modeled, then the free-mass is modeled as a point mass between two rigid links (Figure 4). Finally, to connect the impact dampers in real structures, they can be used in 1/3 length of beginning and end of main beams in all stories.

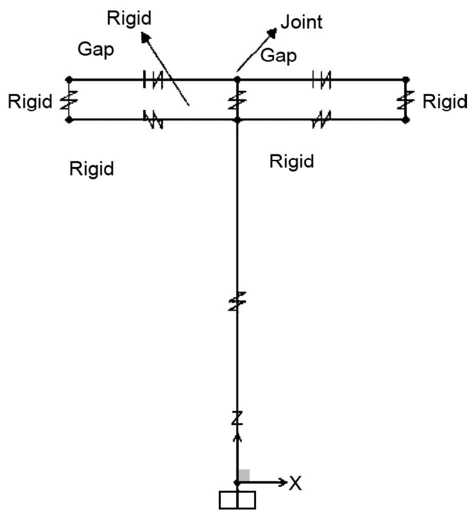

Figure 4. Details of impact damper.

Dead and live loads are 3250 kg/m and 1250 kg/m, respectively. LRFD method is used to design frames based on AISC 360-10. Details of beams and columns used in the numerical models as shown in Figure (5) are listed in Tables (1) and (2).

3. Numerical Results

In the conducted research, results have been derived from each model with and without damper in different earthquakes (near or far-field earthquakes). For convenience and to avoid presenting long detailed results, only the results from 10-story frame with 2-span model are presented in the following:

The imposed earthquake records are near and far fields scaled to Iranian code earthquake design spectrum. Seven near-field and seven far-field earthquakes are selected and their details are presented in Tables (3) and (4). Non-linear time history analysis is used to investigate the seismic performance of the frames.

Figure (6) shows the story shear forces for the 10-story 2-span model with and without impact damper. According to the figure, impact damper induced to reduce story shear forces up to 71%.

Table 1. Details of sections used in the 10 story model.

Stories	Beam Section	Column Section
1 to 5	IPE300	C 60 X 3
6 to 10	IPE300	C 50 X 2.5

Table 2. Details of sections used in the 30 story modell.

Stories	Beam Section	Column Section
1 to 5	IPE400	C 80 X 3.5
6 to 10	IPE400	C 70 X 3.0
11 to 15	IPE400	C 65 X 2.5
12 to 20	IPE400	C 65 X 2.0
21 to 25	IPE400	C 60 X 2.0
25 to 30	IPE400	C 60 X 2.0

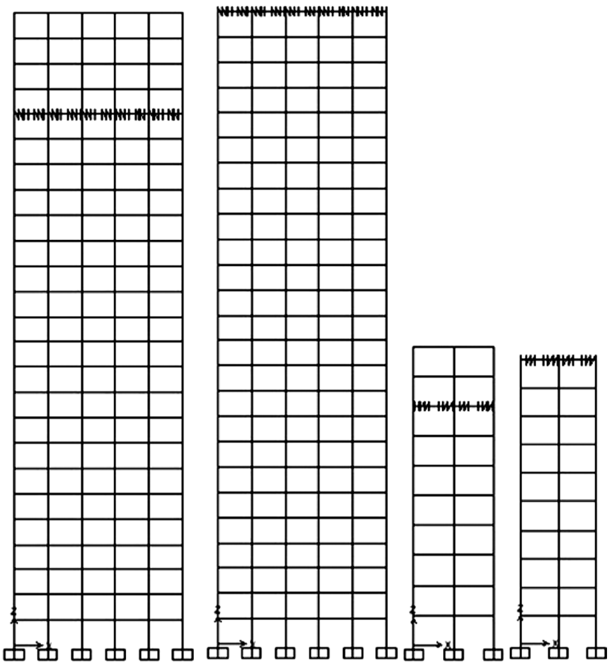

Figure 5. Models of 30 and 10-story frames in the software with location of impact damper.

Table 3. Properties of near-field earthquake records.

No.	Name of Record	Station	M	d-Closest to Fault Rupture (km)	PGA
1	Norhtridge	90056 Newhall	6.7	7.1	0.455
2	Chi Chi	WNT	7.6	1.18	0.626
3	Imperial Valley	5054 Bonds Corner	6.5	2.5	0.588
4	Parkfield	Cholame #5	6.1	5.3	0.442
5	Kobe	KJMA	6.9	0.6	0.821
6	Northridge	24087 Arleta	6.7	9.2	0.344
7	Tabas	Tabas	7.35	2.05	0.862

Table 4. Properties of far-field earthquake records.

No.	Name of Record	Station	M	d-Closest to Fault Rupture (km)	PGA
1	Duzce	Lamont 1061	7.1	15.6	0.107
2	Northridge	Hollwood Stor	6.7	25.5	0.358
3	Kobe	Nishi-Akashi	6.69	11.1	0.509
4	Imperial Valley	Delta	6.5	43.6	0.351
5	San Fernando	Lake Hughes#12	6.6	20.3	0.366
6	Northridge	Manhatan Beach	6.7	42	0.201
7	Cape Mendocino	Fortuna	7.1	23.6	0.116

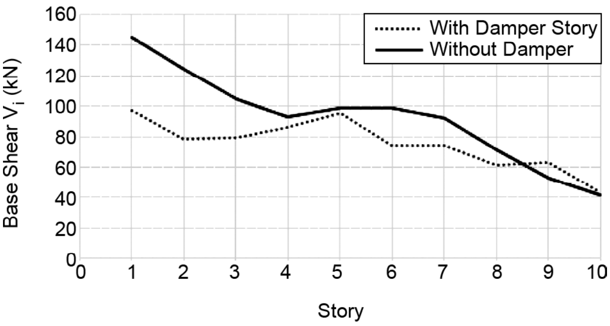

Figure 6. Story shear forces for the 10-story 2-span model with and without impact damper.

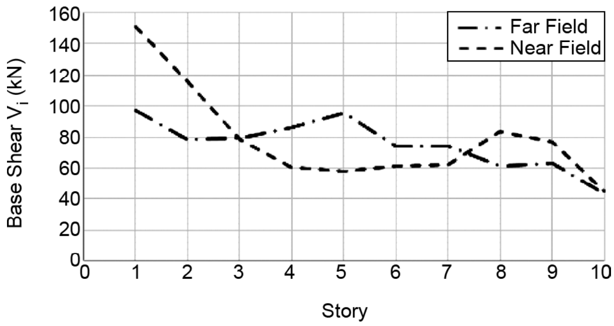

Figure 7. Story shear forces for the 10-story 2-span model with impact damper in far and near-field earthquakes.

When placed in middle stories for such 2-span frames, the impact damper has proper performance to reduce story shear forces and thus lateral displacements due to the effects of vibrational modal combination, increase in period of structure and increase in number of effective collisions.

Figure (7) compares base shear stories in the same MDOF system with impact damper in far and near-field earthquakes. According to the figure, performance of impact damper to reduce the story shear forces in far-field earthquake is 60% better than the case under near-field earthquake. Considering the above two figures, there is a jump in the 5th story shear force. With regard to placing impact damper in that floor, it seems that a sort of resonance occurred to increase its shear force.

The mode of placing damper in the tenth story has come up as the optimal mode in maximum reduction of the roof displacement. According to Figure (8), similar to previous curve, all three cases have the expected effect on the reduction of the vibration amplitude of the 10-story frame example. The case of placing damper in the tenth story is 33% better than the other two cases in terms of reducing roof maximum displacement. According to Figure (8), the effect of placing damper in the tenth story becomes tangible from sixth second onwards, which can be related to the high and peak ground acceleration in that time period. Because, as it was mentioned, the performance of impact damper is related to the input acceleration; i.e. the larger the input acceleration, the more number of impacts and consequently, the more effect of the damper in neutralizing structure vibration is achieved.

Results of analyses including the maximum base shear, drift and maximum roof displacement were obtained for the 30-story 5-span model with and without impact damper as shown in Figure (9).

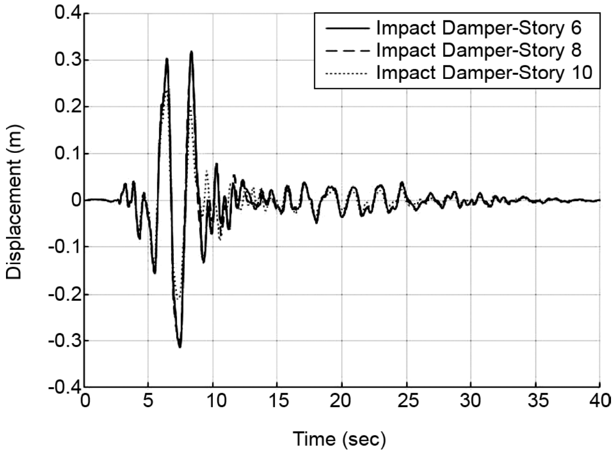

Figure 8. Average maximum roof displacement for the 10-story 2-span model under near-field earthquake.

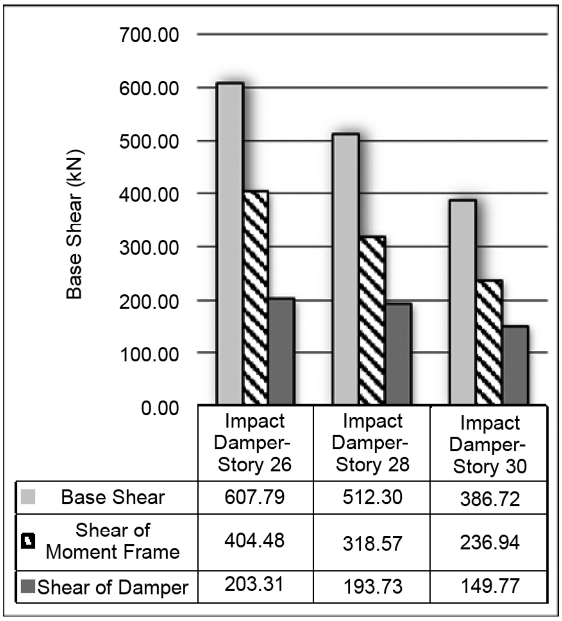

Figure 9. Average maximum base shear for the 30-story 5-span model under near-field earthquakes.

In Figure (9), due to the placement of the impact damper on the top floor and a concurrent decrease in drifts (which is observed in the subsequent curves) the base shear force acting on the structure decreases 36% and 33% respectively under the near and far-fault scenarios. Hence, this is the most suitable state for reducing the maximum base shear as compared to the other cases. In the far-field earthquake, the maximum base shear is larger on the 28th floor due to the presence of concurrent vibration modes on upper stories as compared to the case for the 26th floor, because vibration modes on upper floors and their combination on upper floors significantly affect the system response. It is also observed that placement of the damper on upper floors increases its effect on the decrease of the base shear. This is caused by escalation of vibration along the structure height and the eventual increase in efficiency of the impact damper.

According to Figure (10), under the far-field earthquakes, placement of the impact damper on the 26th floor was more effective than the 28th floor and the results were similar to the results obtained by placing the damper on the top floor. In other words, in tall buildings, with an increase in the number of spans, presence of combined vibration modes especially in the middle stories (26th story) is more evident. Seemingly, in the case of models under far-fault earthquakes, due to the longer earthquake duration and the subsequent higher earthquake acceleration, the impact damper acts under acceleration and performs better in this state than the case under near-field earthquakes.

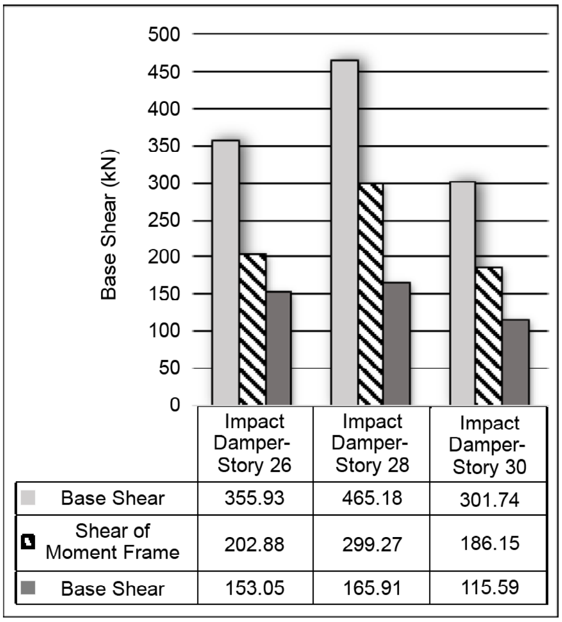

Figure 10. Average maximum base shear for the 30-story 5-span model under far-field earthquakes.

According to Figure (11), placement of the damper on the top floor more effectively reduced drift as compared to other states. In other words, the drift decreased to 37% and 12% under the near and far-field earthquakes, respectively. This can be attributed to the high vibration on higher stories. Placement of the damper on the 26th floor reduced drift more than placement on the 28th floor, which can be attributed to the combination of vibration modes on lower stories and dominance of these

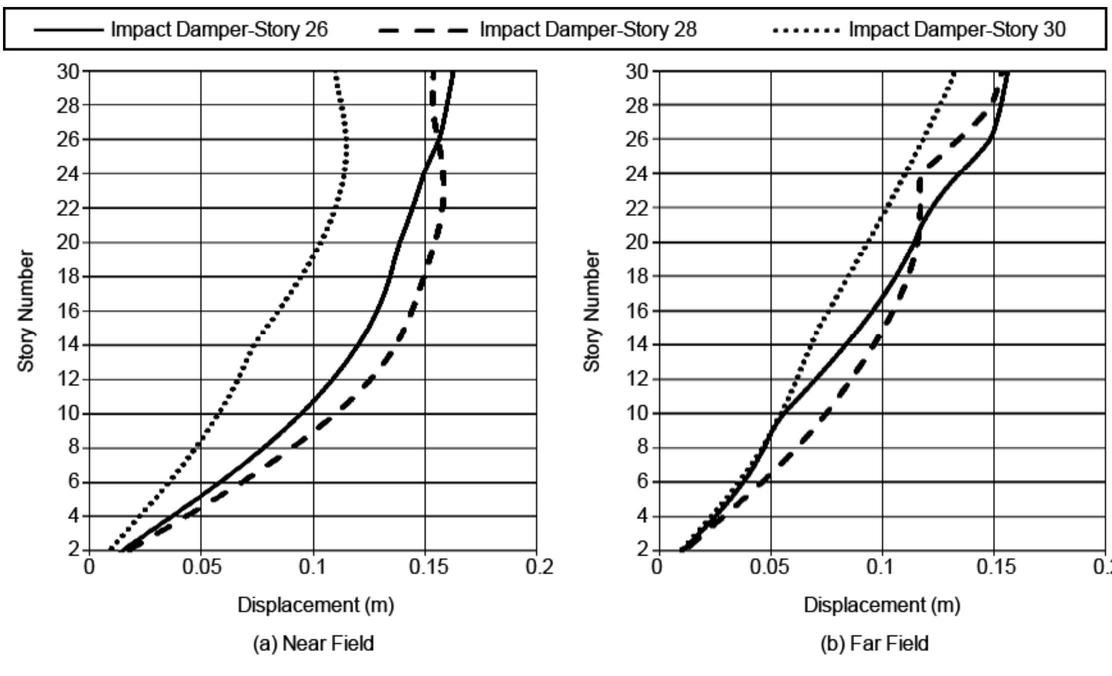

Figure 11. Average maximum drift for the 30-story 5-span model under near and far-field earthquakes.

vibration modes on large vibrations on higher stories. As stated in the case of previous models, with an increase in the number of spans, the combination of vibration modes occurs on lower stories.

Considering the results in Figure (12), all of those three impact damper placement states effectively reduced permanent drift. Under both far and near-field earthquakes, placement of the impact damper on the middle floors (26^{th} and 28^{th} floors) yielded the highest decrease in permanent drift. The combination of vibration modes directly influenced the permanent drift curve. Therefore, presence of the damper on the middle stories yielded better results than its presence on the roof floor. Placement of the damper on the 26^{th} floor (middle floor) showed a descending trend as compared to the other states, and the decreases in permanent drift in the near and far-field earthquakes were 25% and 50%, respectively.

Placement of the impact damper on the roof yielded the best results in terms of the decrease in maximum roof displacement. In Figure (13), all of three states led to expected results on the decrease in the vibration of the multi-degree of freedom system. In the point to point comparison, when the damper was on the top floor, 33% and 20% decreases in roof displacement were observed under the near and far-field earthquakes as compared to the other states, respectively.

It is worth stating that the comparison between

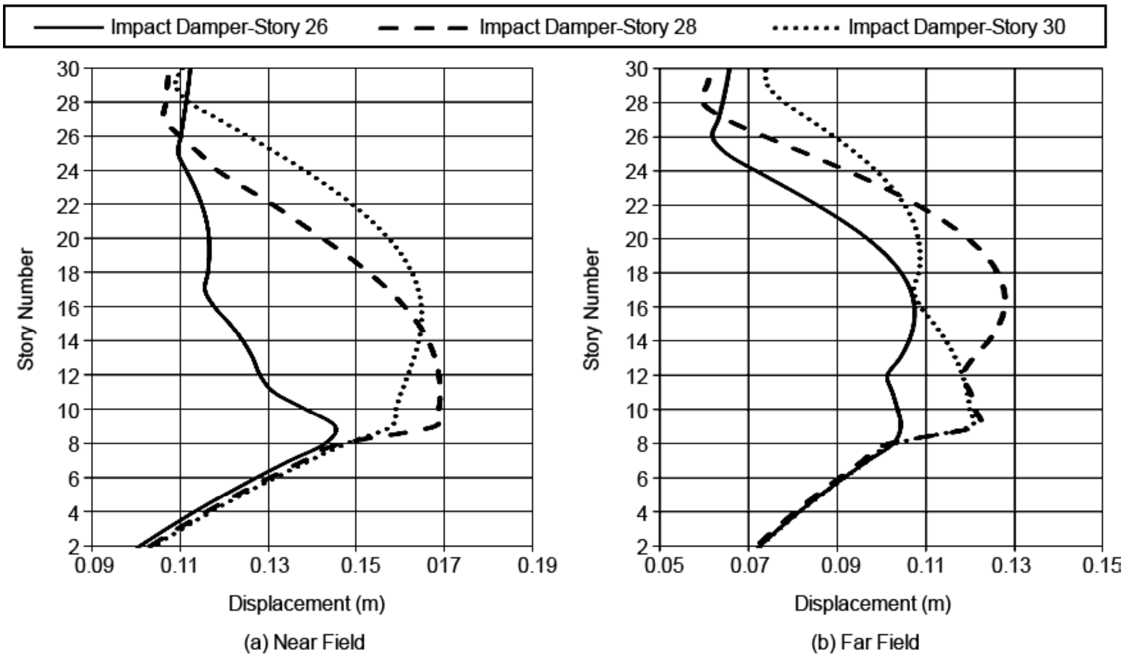

Figure 12. Average maximum permanent drift in the 30-story 5-span model under near and far-field earthquakes.

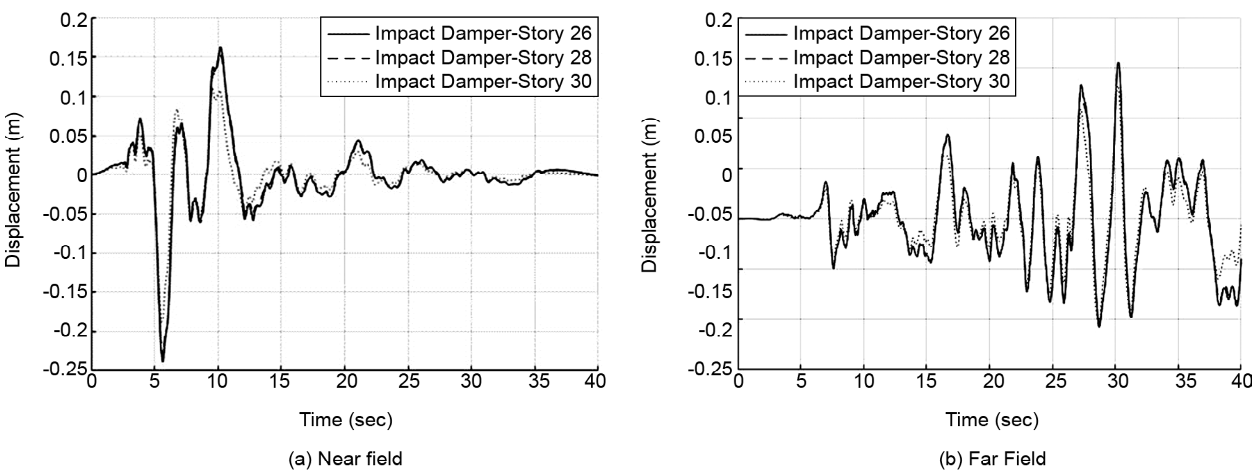

Figure 13. Average maximum roof displacement in the 30-story 5-span model under near and far-field earthquakes.

results of the aforementioned model and results of placing the system under a near-field earthquake revealed that the placement and the effect of the damper on the decrease in roof displacement are slightly delayed, which could be explained due to the longer duration of transfer of kinetic energy to the structure under far-field earthquakes as compared to near-field earthquakes. Moreover, due to the occurrence of the maximum earthquake acceleration in the last seconds, the impact damper displays its best performance in those moments.

4. Conclusion

In this paper, seismic performance of tall buildings with impact dampers was evaluated through nonlinear dynamic analysis under a series of near and far-field earthquakes using SAP2000. Models of 10 and 30-story frames with 2 and 5 spans were used.

Generally, in the studied multi-degree-of-freedom system, the case of placing impact damper in the roof story has a better performance comparing to other cases, averagely with 27% difference. Therefore, it is observed that similar to mass dampers, the best place for impact dampers is in the stories near the roof. This phenomenon could be interpreted because of the combination of vibration modes and consequently resonance in the input acceleration. Because, impact damper is actuated by acceleration, and the larger input acceleration leads to achieve damper efficiency in the reduction of vibration amplitude by increase in the number of mass ball impacts.

In the case of near and far-field earthquakes, the performance of impact damper in the reduction of system response amplitude for 10-story frame model is about 20% better under both far and near-field earthquakes. Moreover, the response amplitude of tall buildings (30-story-5 span) equipped by impact dampers under near-fault earthquake has 25% better performance as compared to a vibrating system subjected to far-field earthquake. Since impact damper requires acceleration to be actuated and the near-field earthquakes mostly have maximum acceleration in a short time period, an embedded impact damper in a few stories before the roof in addition to combination of vibrating modes, increases the excitation of impact damper and, consequently, leads to the reduction of response amplitude of a multi-degree-of-freedom system.

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