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ORIGINAL RESEARCH ARTICLE

Earthquake response control of ground soft storey

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ABSTRACT

In the present study, friction damper, an energy dissipating passive device is explored to reduce the response of open ground storey building under lateral loading due to earthquake. This damper is installed in the selected bays of open ground storey so that the response is reduced. The masonry infill wall is macro-modeled in the form of compression only diagonal members. Three different types of bracing system were installed along with Pall friction damper – single diagonal tension – compression brace with friction damper, tension only cross brace with friction damper and chevron brace with friction damper were modeled using Wen's plastic link element in SAP2000. G+4 storey buildings were analyzed using nonlinear time history analysis. The storey displacement and inter-storey drift for all the cases were compared in the study.

Keywords: Ground Storey; Friction Dampers; Infill Masonry Wall; Floor Displacement Response

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1. Introduction

Buildings resting on ground experience motion at base due to earthquake. According to Newton's law of inertia, even though the base of the building moves with the ground, the roof has a tendency to retain its original position. But the flexible columns will drag the roof along with them. Due to this flexibility of columns, the motion of roof is different from that of the ground. As the ground moves, the building is thrown backwards and the roof experiences inertia force. Internal forces are developed in the columns as they are forced to bend due to the relative movement between their ends as shown in **Figure 1**.

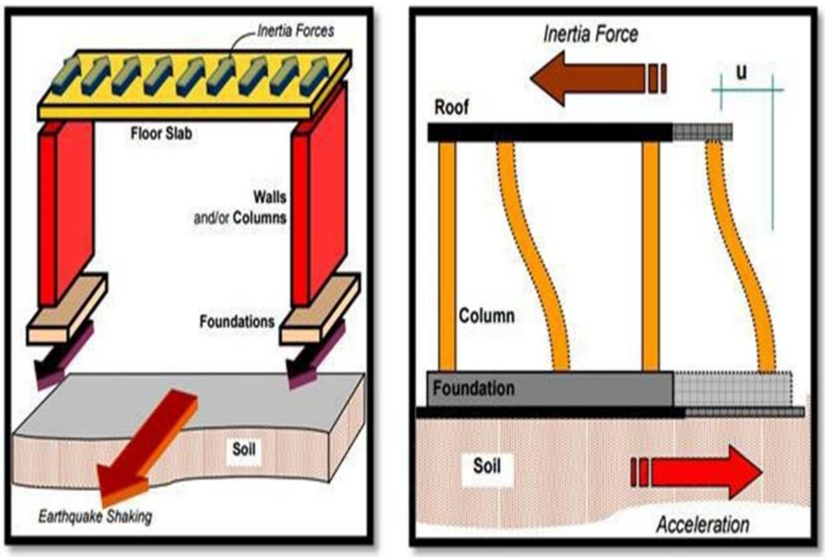


Figure 1. Effect of Inertia in a building when shaken at its base**.**

Earthquakes are thus a severe structural hazard for structures designed for gravity loads as they may not sustain the horizontal shaking. Structures like buildings, elevated surface reservoir, bridges, towers, etc. may experience extreme vibrations during earthquake.

Reinforced concrete (RC) is the most commonly used construction material used these days, primarily owning to its low cost, easy availability of materials, simpler execution without requirements of any special machineries or labour. Generally, the RC buildings are analyzed and designed such that, the moment resisting frame actions are developed in each member. The masonry infill walls are normally considered as non-structural elements used to create partitions or to protect the inside of the building and thus are ignored in analysis and design. Such construction practices are followed by many countries, including India. However, under the action of lateral forces like the once due to earthquake and wind, these infill wall panel's stiffness, strength and mass affect the behavior of RC frame building.

At times, due to uneven distribution of mass, strength and stiffness in either plan or in elevation, irregularities are introduced in RC frame buildings. If the masonry walls are not symmetrically placed, then in that case, the eccentricity between centre of mass and centre of rigidity may induce torsional effects causing additional stresses. In recent times, it has been a common practice to construct RC buildings with open ground storey, i.e., the columns in the ground storey do not have any infill walls between them. This provision generally kept for the purpose of parking, garages, and various recreational purposes introduce a vertical irregularity in the structure.

An open ground storey building, having only columns in the ground storey and both partition walls and columns in the upper storey have two distinct characteristics, namely:

1) It is relatively flexible in the ground storey, i.e., the relative horizontal displacement it undergoes in the ground storey is much larger than what each of the storey above it does.

2) It is relatively weak in ground storey, i.e., the total horizontal earthquake force it can carry in the ground storey is significantly smaller than what each of the storey above it can carry. Thus, there is a requirement of seismic strengthening of such open ground storey RC frame buildings. Various types of energy dissipating devices based on wide range of concepts have been explored in the recent past.

1.1 Requirement of retrofitting of open ground storey structures

In many densely populated urban cities of the world, including many cities in India, it has been a common practice since last two-three decades to provide an open ground storey in the multistorey reinforced concrete buildings for parking, garages, or various recreational purposes.

To avoid this huge forecasted hazard, it is very essential to strengthen the open-ground storey buildings, which are having a very poor performance history during earthquake. **Figure 2** shows the collapse of an open ground storey building of 5 storeys in Kathmandu, Nepal.

Figure 2. Open ground storey failure of 5 storeys building in Kathmandu during the 2015 Nepal Earthquake**.**

The five-general passive energy dissipation approaches can be mentioned as:

1) Controlled by structural design;

2) Controlled by conventional localized additions – by using shear walls, braced frames;

3) Controlled by additional damping – by using dampers;

4) Controlled by base isolation – using base isolators;

5) Combinations of the above mentioned.

Arlekar *et al.*[1] analyzed the seismic response of four storeys RC frame building with open ground storeys, using equivalent static analysis and response spectrum analysis to find the resultant forces and displacements. Negro and Verzeletti[2] studied the effects of the infills on the global behavior of the structure by performing series of pseudo-dynamic tests on the full-scaled four-storey reinforced concrete frame. In an attempt to determine the seismic vulnerability of masonry-infilled non-ductile reinforced concrete frames, Al-Chaar[3] carried out an experiment to evaluate the behavior of five half scale, single-storey laboratory models with different number of bays. Davis *et al.*[4] illustrated the influence of masonry infill on the response of multi-storeyed building under seismic loading by considering two existing buildings in which one building has soft storey while the other is symmetric.

While Pall[5] was describing the merits of Pall Friction Dampers, its various practical applications and its design criteria, mentioned that, the slippage of friction damper in an elastic brace consists of non-linearity. For the MUCTC Building used friction dampers in steel bracing, as upgrade with conventional methods of seismic rehabilitation, would have required expensive and time consuming foundation work besides interfering with the heritage character of the structure[6]. Lee *et al.*[7] dealt with the numerical model of a bracing-friction damper system and its operation used the optimal slip load distribution for the seismic retrofitting of a building. Singh and Moreschi[8] focused on the optimal design of friction dampers for multi-story buildings exposed to seismic motions. The procedure defined the optimal locations, slip loads for the dampers and the stiffness of the bracings that must be used. Kitajima *et al.*[9] outlined the response control retrofit method, using external damping braces equipped with friction dampers. They highlighted the advantage of the retrofit method without interrupting the use of building.

2. Modeling of friction dampers

The slippage of friction damper in an elastic brace consists of non-linearity. The amount of energy dissipation or equivalent structural damping is proportional to the displacement. Therefore, the design of friction-damped buildings requires the use of nonlinear time-history dynamic analysis to accurately understand the response of the structure during and after an earthquake. The "NEHRP Guidelines for the Seismic Rehabilitation of Buildings, FEMA 356, issued in 2000"[10] can be used for the analysis and design of friction dampers. Since different earthquake records, even of the same intensity, give widely varying structural responses, results obtained using a single record may not be conclusive. Therefore, at least three time-history records which are suitable for the region should be used, one of which should be preferably site specific. The average response for design should be used. NEHRP guidelines require that friction dampers are designed for 130% MCE displacements and all bracing and connections are designed for 130% of damper slip load[11].

2.1 Modeling of chevron pall friction dampers

The Chevron Friction Damper as shown in **Figure 3** can be modeled, using the following link properties:

Type = Plastic (Wen)

W = Weight of damper = 2.22 (units: kN-m)

Rotational inertia 1 = Rotational inertia 2 = Rotational inertia 3 = 0

Direction = U1

Ke = Effective Stiffness = 1000 x damper slip load (units: kN-m)

Yield Strength = Slip load of friction damper

Post Yield Stiffness Ratio = 0.0001

Yielding exponent = 10

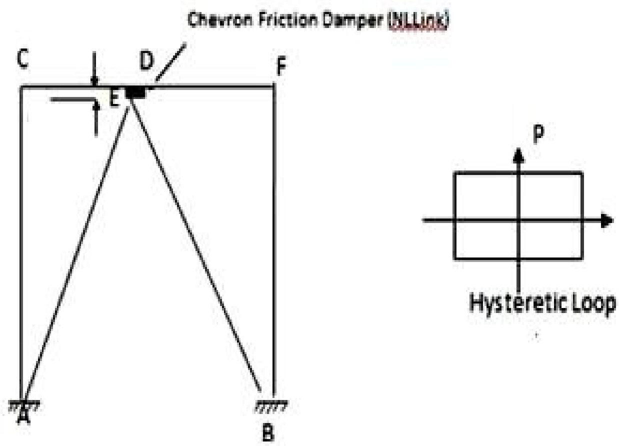


Figure 3. Chevron brace with pall friction damper.

The brace is modelled as frame element. Braces are from joints A and E and joints B and E.

The beams at top are from joints C and D and joints D and F. The friction damper is modeled as a nonlinear axial link element between joints D and E. Joint E is lower and away from joint D as in **Figure 3**.

3. Description of building

Typical five-bay five-storey, eight-storey and twelve-storey RC building with open-ground storey as shown in **Figure 4** and **Figure 5** are considered as the prototype structures in this study. Overall size of the building in plan is 30.0 m × 24.0 m with bay width of 6.0 m in each orthogonal direction.

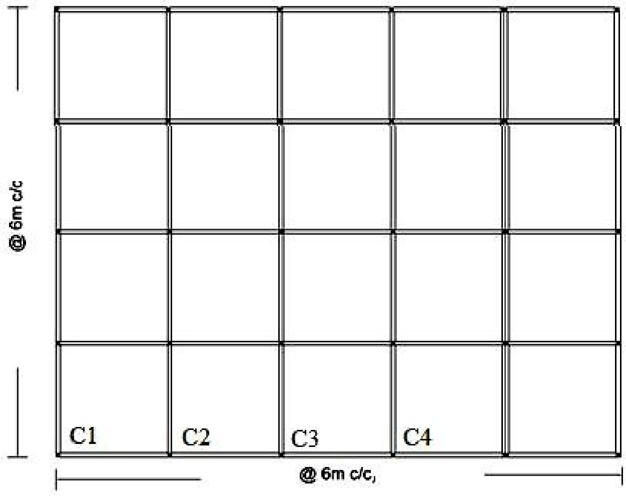


Figure 4. Plan of the prototype building.

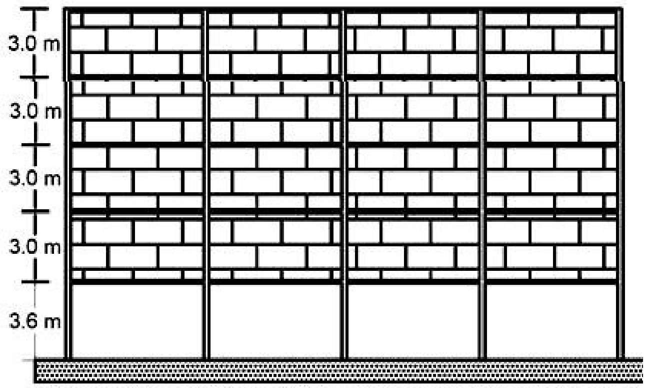


Figure 5. Elevation of the prototype building. G+4 storey.

The height of ground storey is considered as 3.6 m, whereas the storey height of upper storeys is assumed as 3.0 m. The upper storeys of building are fully in filled with unreinforced brick masonry of 250 mm thickness. The thickness of roof and floor slab is taken as 180 mm. The building is founded on a rock site in seismic zone-V, the region of highest seismicity as per IS: 1893 (Part 1): 2002. Since the buildings are symmetric in both orthogonal directions in plan, torsional response under pure lateral forces is avoided, and hence, the present study is focused only on the weak and soft storey problem due to open-ground-storey. Unit weights of concrete and masonry infill are considered as 25 kN/m^3 and 20 kN/m^3, respectively. Dead load on the beams consisted of self-weight of beam, slab and masonry infill, including floor finish of 1.0 kPa. Live loads on the floors and roof are assumed as 3.0 kN/m^2 and 1.5 kN/m^2, respectively.

3.1 Modeling of infill masonry wall

The properties of the masonry infill wall considered for analysis are as summarized in **Table 1**. The masonry is assumed to satisfy the requirements of good condition masonry as specified by FEMA 356 (2000). These properties can be used to macro-model. The infill panels in the form of two compression only strut joining the diagonally opposite corners of the infill panel.

Table 1. Properties of infill masonry wall

Properties	**Values**
Weight density (kN/m^3)	20
Poisson's ratio	0.2
Thickness of infill (mm)	250
Prism compressive strength	4.5
Elastic modulus in compression Eme (MPa)	3412
Flexural tensile strength, ftm (MPa)	0.1
Shear strength fvm (MPa)	0.14

The width "a" of equivalent diagonal compression strut can be calculated as below:

$$a = 0.175(\lambda_l h_{col})^{-0.4} r_{inf}$$

Where,

$$\lambda_1 = \left[\frac{E_{me} t_{inf} \sin 2\theta}{4 E_{fe} I_{col} h_{inf}}\right]^{\frac{1}{4}}$$

A reduction factor for existing infill panel damage can takes values from 0.7 to 0.4, and from moderate to severe damage. Thus, the infill masonry wall can be macro-modeled as an equivalent compression strut of depth 250 mm and thickness "a" mm.

3.2 Selection of ground motions

Four different ground motions recorded in different parts of the world were selected as direct integration time-history analysis in present study. The ground motions are so selected that, their recorded peak ground acceleration (PGA) value is nearly about 0.36g which represents the highest seismic zone-V in India as per IS: 1893 (Part 1): 2002. The recorded ground motions represent common site conditions with hypo-central distance from the source lie within 20 km to the site depicting near source-site effect. **Table 2** summarizes the earthquake data and site characteristics of selected ground motions.

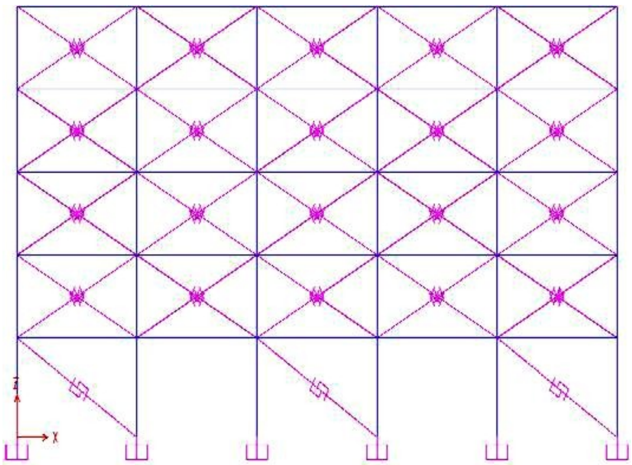
Table 2. Selected ground motions

Sr. No	Name of Earthquake	Richter Magnitude	PGA (g)
1	El Centro (1940)	6.9	0.35
2	Chi – Chi (1999)	7.6	0.31
3	Whittier (1987)	6.6	0.43
4	Superstition Hills (1987)	6.6	0.38

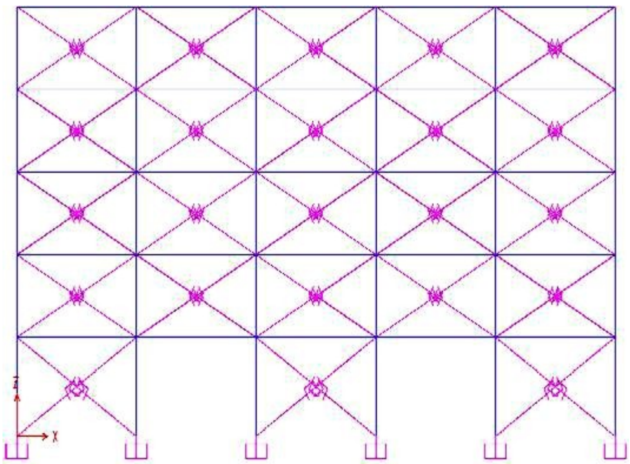
4. Evaluation of strengthened RC frame building

The seismic evaluation of typical non-ductile designed five-storey RC building with open ground storey by time history analysis uses a computer package SAP2000. A strengthening scheme involving friction damper is adopted to enhance the performance of the non-ductile prototype buildings considered. All columns of the study frame were chosen to be rectangular sections of size 450mm × 550mm, whereas the size of beam sections was considered as 300mm × 450 mm. As stated earlier, the unreinforced masonry infill in the upper storey of study frame was not designed for any forces to which it may be subjected to as followed in normal practice.

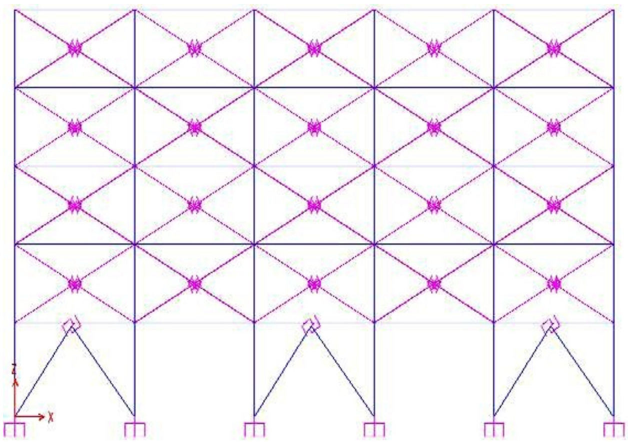
Seismic performance of the building was evaluated by linear modal analysis and nonlinear time history analysis using SAP2000. The properties of frame members, infill masonry, and friction dampers were used as discussed earlier. **Figure 6** shows the elevation of G + 4 open ground storey RC frame building with different types of friction dampers modeled in SAP2000 and installed in the selected bays of ground storey.



(a) Single diagonal tension/compression friction damped bracing



(b) Tension only cross braced friction dampers



(c) Chevron braced friction damper

Figure 6. Elevation of G + G open ground storey buildings strengthened with different types of friction dampers as modeled in SAP2000**.**

4.1 Floor displacement response

Figure 7 shows the variation of peak values of floor displacements for both non-ductile and strengthened RC frames in various ground motions.

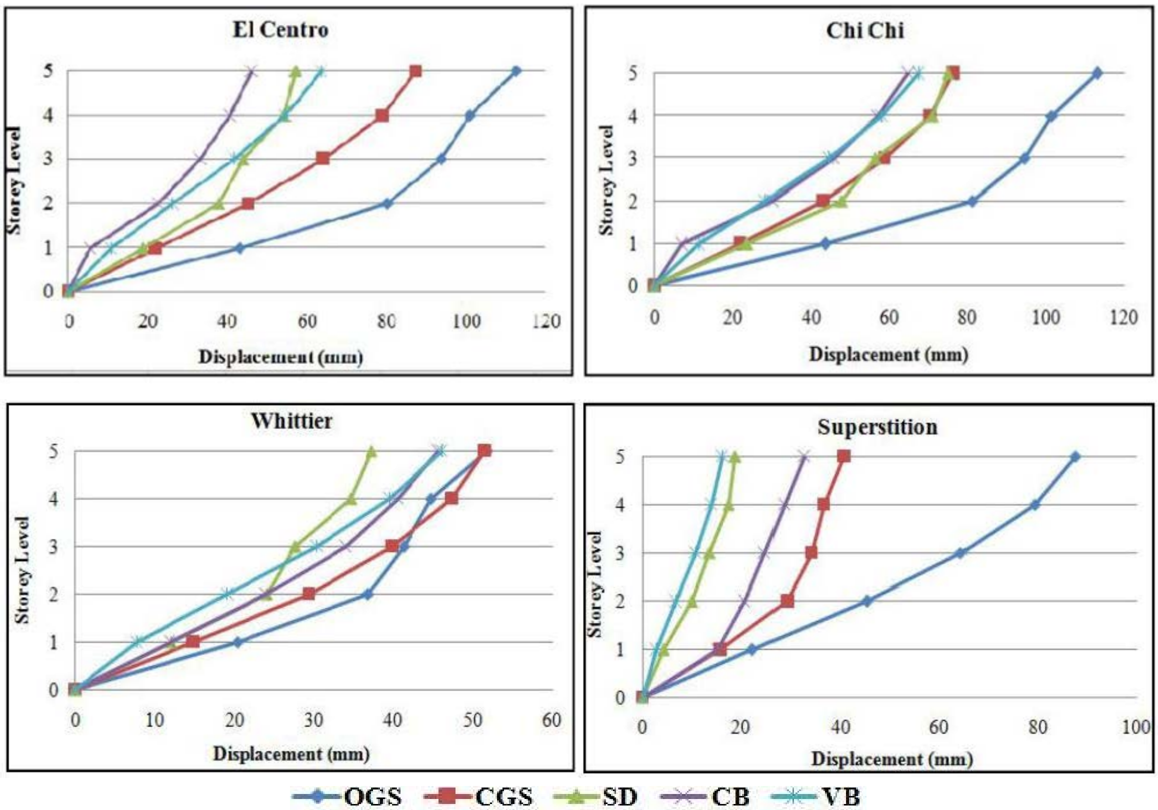


Figure 7. Store Displacement of building with and without dampers for the considered ground Motions.

With the installation of dampers, there can be seen a significant reduction in the storey displacement predominantly at the ground level as well as at the upper storey levels. **Figure 8** shows inter-storey displacement response. Inter-storey displacements at various storey levels of RC frames were computed from the difference between their peak values of absolute displacements and adjacent storey. As expected, significant interstorey displacement was observed only at the ground storey and a very negligible difference was noted in the upper floors of each frame as shown in **Figure 8**. The frame without dampers exhibited maximum inter-storey displacement at the ground storey in all ground motions. In contrast, significant reduction in inter-storey displacement was observed in the strengthened frame.

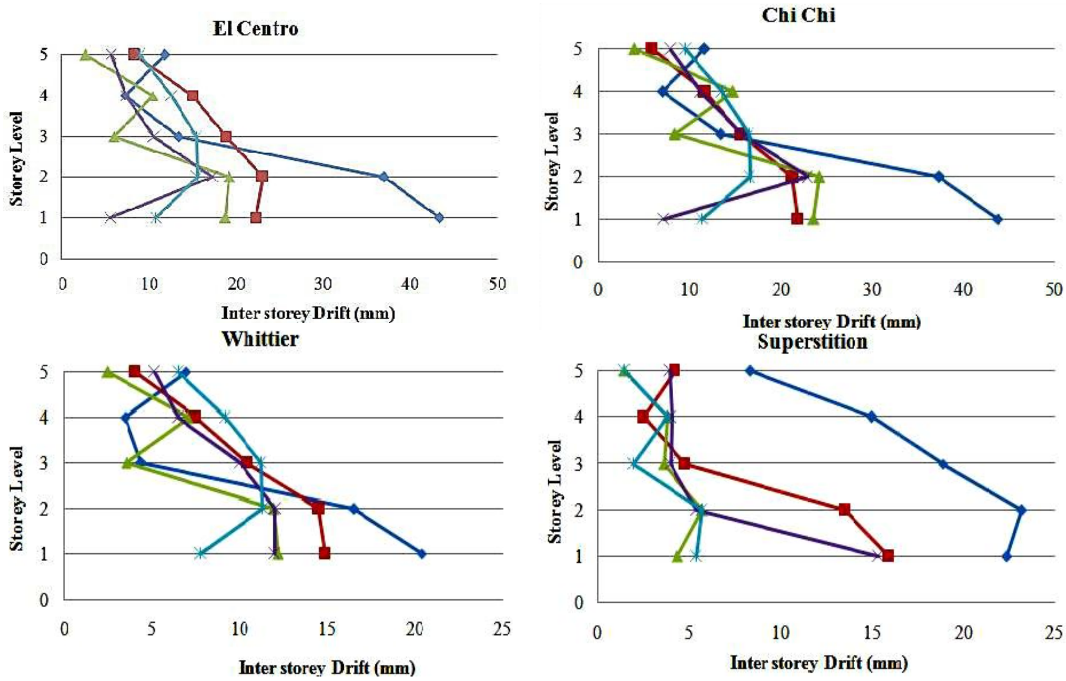


Figure 8. Inter storey drift of building with and without dampers for the considered ground motions.

Thus, strengthening of non-ductile RC frames with friction damper significantly reduces inter-storey displacement between floors.

5. Conclusion

The results obtained from the analytical study using software package SAP2000 are mentioned in this chapter. The various observations incorporated from the results are described in this chapter. With the installation of friction dampers, a considerable reduction was observed in the displacement of ground storey and inter-storey drift of the building. With the installation of dampers, the lateral-load transfer mechanism of the structure changes from predominant frame action to predominant truss action.

Following conclusions can be drawn based on the work performed in this project.

1) Use of friction dampers is an effective tool in seismically strengthening the buildings with open ground storey.

2) Use of passive energy dissipating devices is more predominant than others, owing to their reliable performance during earthquake.

3) The time period of the structure decreases with the installation of friction dampers, indicating the increase in the stiffness of the structure owing to strengthened ground storey.

4) The ground storey displacement and inter-storey drift are found to reduce with installation of dampers at the ground storey.

There is response reduction not just on the ground storey but also for the upper storey.

Conflict of interest

No conflict of interest was reported by the author.

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