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Performance-Based Design of RC Structures Subjected to Seismic Load Using a Hybrid Retrofitting Method with Friction Damper and Steel Bracing

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ABSTRACT

In this paper, five storey RC (Reinforced Concrete) building is retrofitted using friction damper and steel bracing methods to achieve a target seismic performance level in terms of inter-storey drift and plastic hinge rotations. Firstly, a static pushover analysis is performed to get the required damping value for the target performance limit. Then a friction damper is designed for this required damping value. To study the effectiveness of friction damper, a time history analysis of building is performed using scaled time history compatible with IS 1893 response spectrum (zone V, soil type 1) in SAP2000 v20. To bring inter-storey drift to the permissible limit, steel bracing along with friction dampers are used. Further response spectrum analysis is carried out to compare the results of storey displacement, drift with that of time history results. So, the combination of friction damper and steel bracing is found to be effective in retrofitting five storey RC buildings.

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1. Introduction

Today buildings are designed to satisfy the requirement of strength and deflection limits given in building design codes (IS 456 [1], IS 1893 [2], etc.). These requirements are given so that the ability of buildings meet specific performance objectives such as resistance to loads without failure and provide comfort to the user. Still, the building designed using such codes failed in the earthquake. Also, this design codes method does not give a reliable estimation of the danger to life, property, and economic damage that may occur due to future seismic events.

Performance-based design (PBD) is a method in which buildings are designed for target performance level to satisfy the limits of inter-storey drift, displacement, etc. recommended by the various codes such as ATC 40 [3], FEMA 356 [4], FEMA 440 [5], ASCE 41-13 [6]. The most popular structural performance levels are Operational (O), Immediate Occupancy (IO), Life Safety (LS), Collapse Prevention (CP), as shown in Fig. 1. Generally, nonlinear analysis is carried out to evaluate the structure's inelastic behaviour, such as post yielding behaviour, ductility of structural components, potential for progressive collapse and modes of failure, etc. Bento et al. [7] performed a non-linear static analysis of 4, 8-storey RC frames using the method recommended by different codes namely ATC 40 [3], FEMA 273 [8], Eurocode 8 [9], and results obtained are compared with that from Non-linear Dynamic Analysis (NLDA). Sharma et al. [10] experimentally carried out pushover analysis of scaled down 3-storey Reinforced Concrete building without infill wall and results obtained were verified with that of analytical solution. Zameeruddin and Sangle [11] has given review on recent developments in PBD of RC structures subjected to seismic load.

Nowadays, dampers are popular in seismic retrofitting of structures as they improve seismic performance limits as explain in Fig.1. There are different types of dampers that are used by various researchers in their research work, such as viscous damper (Kim et al. [12], Lee and Taylor [13], Domenico et al. [14]), viscoelastic damper (Shen et al. [15], Tsai and Lee [16], Ying and Tchamo [17]), metallic damper (Lin et al. [18], Chaudhary and Singh [19], Saghafi et al. [20]) which are capable of reducing seismic demand of structure by introducing additional damping through dampers. Fig. 2 shows the IS 1893 acceleration response spectrum, in which the acceleration response decreases as the damping in a structure increase. Sadek et al. [21] recommended that the damping ratio greater than approximately 40 % should not be used, as the reduction in displacement response is not significant and may affect (increase) the absolute acceleration of flexible structures. In such cases use of only dampers are not sufficient in reducing seismic demand. So, in those cases passive strengthening techniques like concrete, steel jacketing, steel bracing is recommended along with dampers to take care of the remaining seismic demand.

Kim et al. [12] developed a direct design procedure for viscous dampers using the Capacity Spectrum method. They applied this method to the SDOF system with various design parameters such as yield strength, natural period, stiffness after the first yield. This method was then applied to 10, 20 storey steel frames, and results obtained were compared with that from Nonlinear Time History (NLTH) analysis which was in good agreement. Chaudhary and Singh [19] proposed step-by-step design procedure for a structure with yielding and friction damper. This methodology was used to achieve the target performance level of IO in terms of plastic hinge rotation and inter-storey drift. Vezinz S. and Pall T. [22] carried out seismic retrofitting of 10 storey RC building with 88 friction dampers in diagonal and chevron configuration with slip load of 500-600 *kN*. Moon et al. [23] proposed designing friction damper to retrofit low to midrise RC buildings. They applied this method to retrofit six-storey RC buildings and observed that friction dampers could dissipate about 62 % of the total energy of retrofitted structures. Safarizki et al. [24] retrofitted G+2 storey existing reinforced concrete building with X-type steel bracing. They observed that the steel bracing is effective in reducing the displacement, drift of buildings. A study is carried out to retrofit RC structure considering combined advantages of friction damper and steel bracing in the present work.

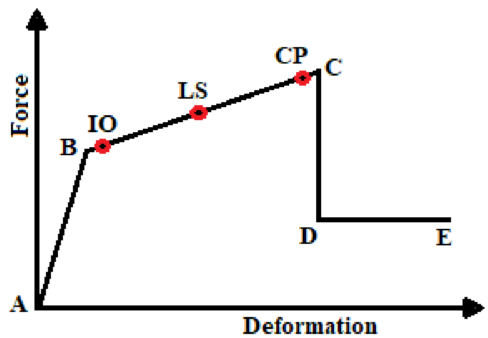


Fig. 1. Graphical representation of structural performance levels.

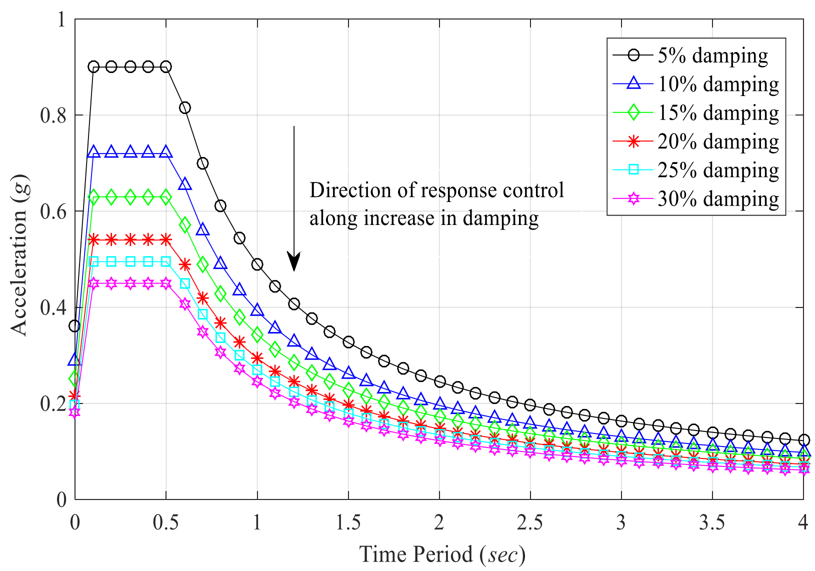


Fig. 2. Acceleration response spectra.

2. General details of five storey RC building

In the present work, five storey RC building with five bays of 4 *m*, three bays of 5 *m* in *X*-direction, *Y*-direction respectively and floor to floor height of 3 *m* is modeled in SAP 2000 v 20 [25] as shown in Fig. 3 (a), (b). Columns and beams are modeled as line elements, slab as shell elements with rigid diaphragm assigned to all floor nodes. Grade of concrete and steel used are M 25, Fe 415. Beams of size 230 x 500 *mm*, columns of 300 x 300 *mm*, a slab of 120 *mm* thick are used. Building analysis and design are made as per IS 456. From the model analysis of the building, the fundamental period is 1.4 *sec*, 1.3 *sec* with modal mass participation are 85.29 %, 84.66 % in *X* and *Y* direction respectively. Columns consist 8 nos-16 *mm* diameter longitudinal steel with lateral link at 150 *mm* spacing. The beam consists of 2 nos-16 *mm* diameter top and bottom steel as shown in Fig. 3 (c), (d).

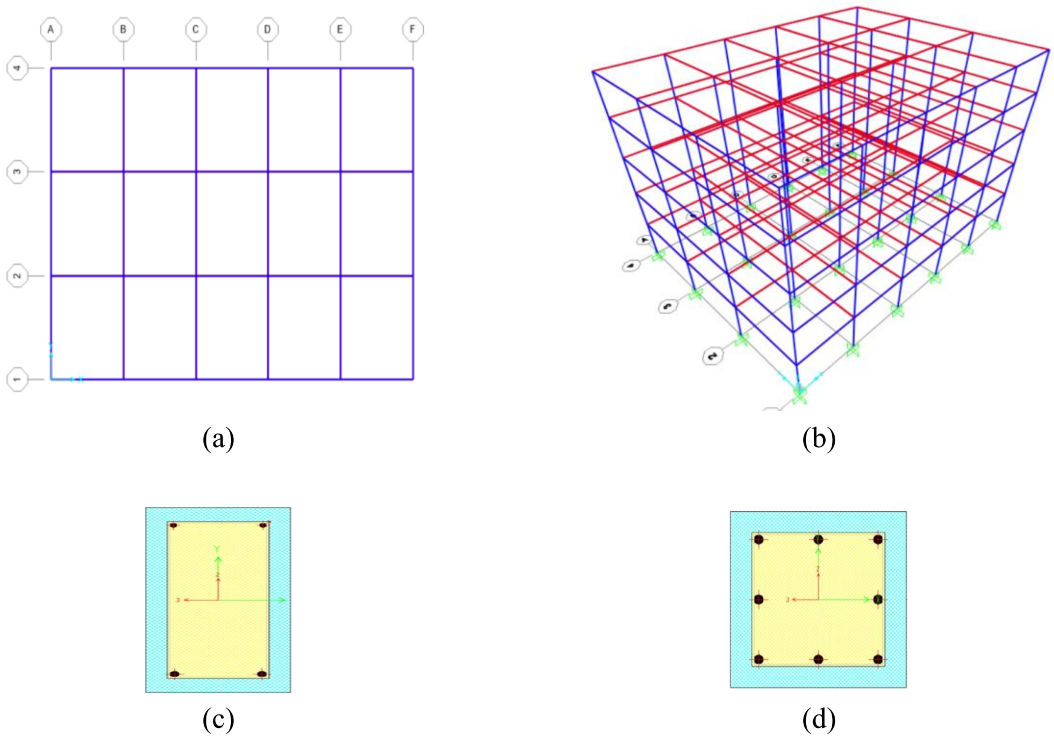
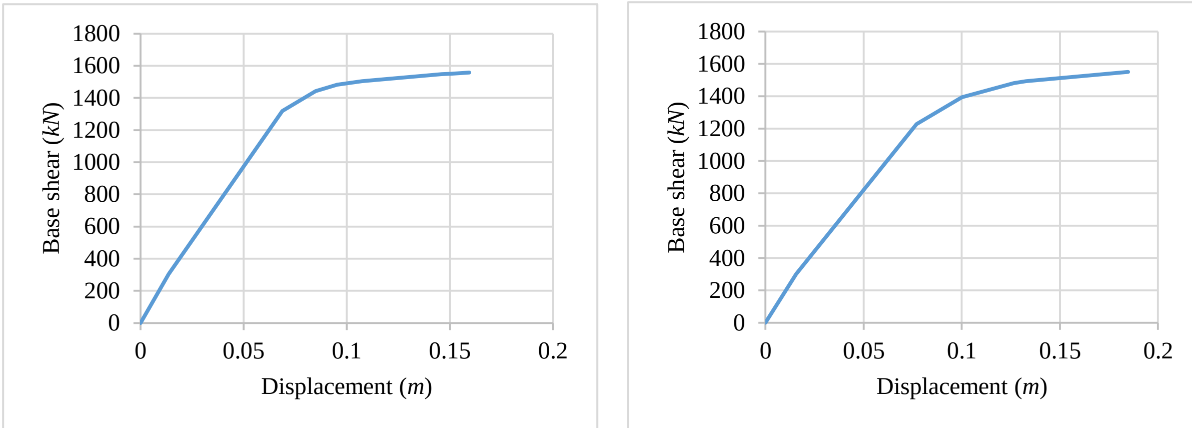


Fig. 3. (a) Plan, (b) 3D view of building, (c) Typical beam c/s, (d) Typical column c/s.

3. Capacity spectrum of five storey RC building

Beam and column sections are considered crack sections for seismic analysis as per ASCE 41-13 (Table 10-5). For a pushover analysis, gravity load case and push load case in *X* and *Y* direction are defined in SAP 2000 v20. The lateral load pattern is applied proportional to the first mode shape in the *X* and *Y* direction, respectively. Auto hinges M_3 for beam and PM_2M_3 for the column are assigned at a relative distance of 0.05 and 0.95. Fig. 4 shows the capacity curve obtained due to the push load case in *X* and *Y*-direction, respectively. Performance point is obtained by selecting the ATC 40 method in SAP 2000. In ATC 40 method, the intersection of the capacity spectrum of building with demand spectrum of zone V, soil type-1 of IS 1893 gives the performance point. At the performance point, it is observed that all the member's plastic hinges were within the target immediate occupancy performance level, and roof displacement are 0.127 *m*, 0.141 *m* in *X* and *Y*-direction, respectively.



(a) (b)

Fig. 4. Capacity curve due to (a) Push-x, (b) Push-y.

Fig. 5 shows the capacity demand spectrum obtained from the push load case in *X* and *Y*-direction, respectively. From the analysis, effective damping required to achieve the target performance point is equal to 20.10 %, 18.4 % in *X* and *Y*-direction, respectively. The building is retrofitted using friction dampers, to provide required damping values of 16.1 % and 13.4 % (subtracting 5 % inherent damping) in *X* and *Y*-direction. Design steps for friction dampers are given in the next section.

4. Design of friction damper for target damping value

The friction damper is used to achieve the target damping values calculated in section 3. Following are the steps for the design of friction damper for target damping value

Step 1: Estimate effective damping (β_{eff}) required for target performance level using capacity spectrum method. It is also expressed as the sum of inherent damping ($\beta_{elastic}$ = 5 %) of structure plus hysteresis damping (β_0) due to damper and is given by equation (1)

$$\beta_{eff} = \beta_{elastic} + \beta_0 \tag{1}$$

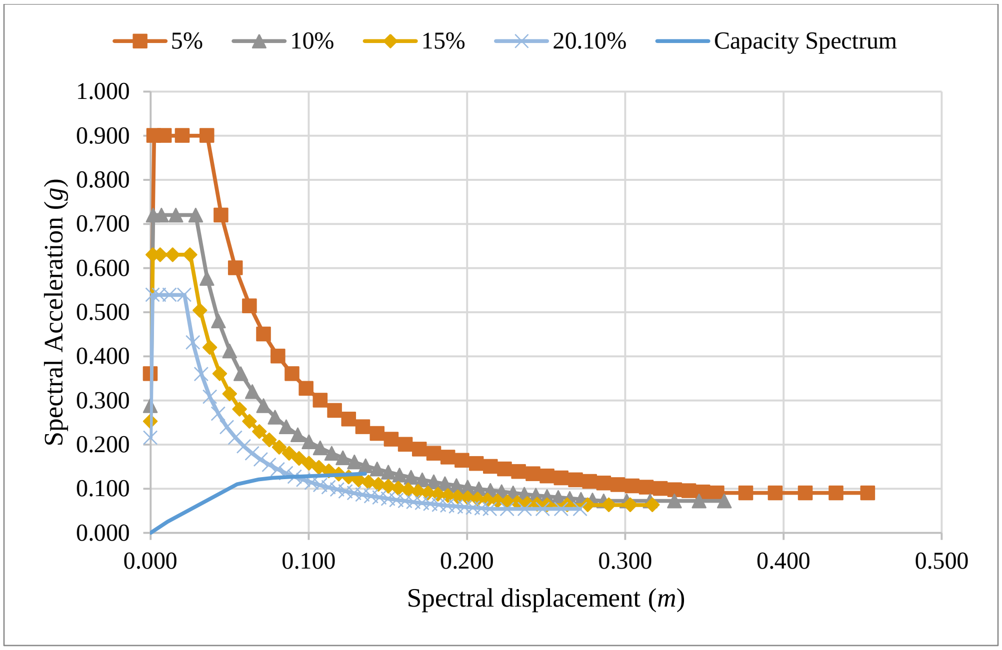
Step 2: Hysteresis damping or required damping can be expressed as the ratio of energy dissipated (E_D) by a damper in one cycle to total strain energy (E_{S0}) of the structure and is given by equation (2)

$$\beta_0 = \frac{E_D}{4\pi E_{S0}} \tag{2}$$

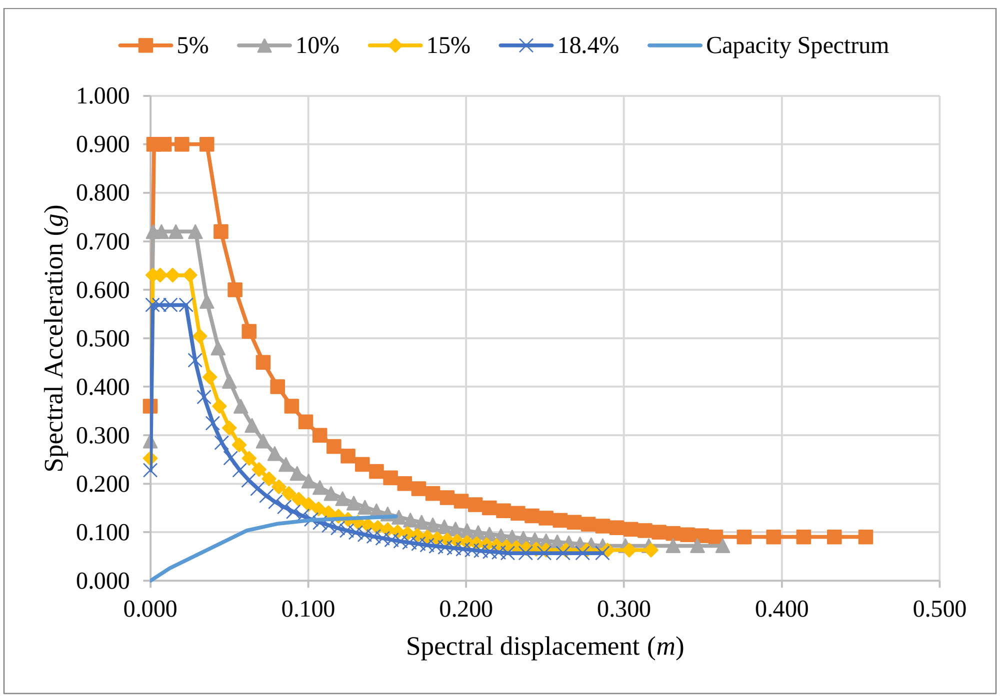
Strain energy (E_{S0}) of structure can be estimated using equation (3)

$$E_{S0} = \frac{1}{2}\sum_{i=1}^{n} F_i \Delta_i \tag{3}$$

Where, F_i is storey shear and Δ_i is the storey displacement of the i^{th} floor.



(a)



(b)

Fig. 5. Capacity demand spectrum due to (a) Push-x, (b) Push-y.

Step 3: Now calculate energy dissipated by the damper from required damping and strain energy. Energy dissipates by the friction damper per cycle can be determined using equation (4)

$$E_D = \sum_{j=1}^{n} 4F_{Sj}\delta_j \tag{4}$$

Where, F_{Sj} is Slip force in a j^{th} damper, δ_j is the relative axial displacement of j^{th} damper between the two ends.

Calculate slip force in a damper from the above equation (4)

Step 4: Next steps, select appropriate steel section for bracing member and design it as tension and compression member as per IS 800 [26].

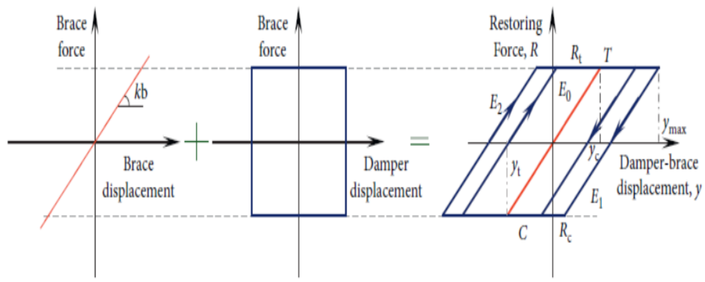
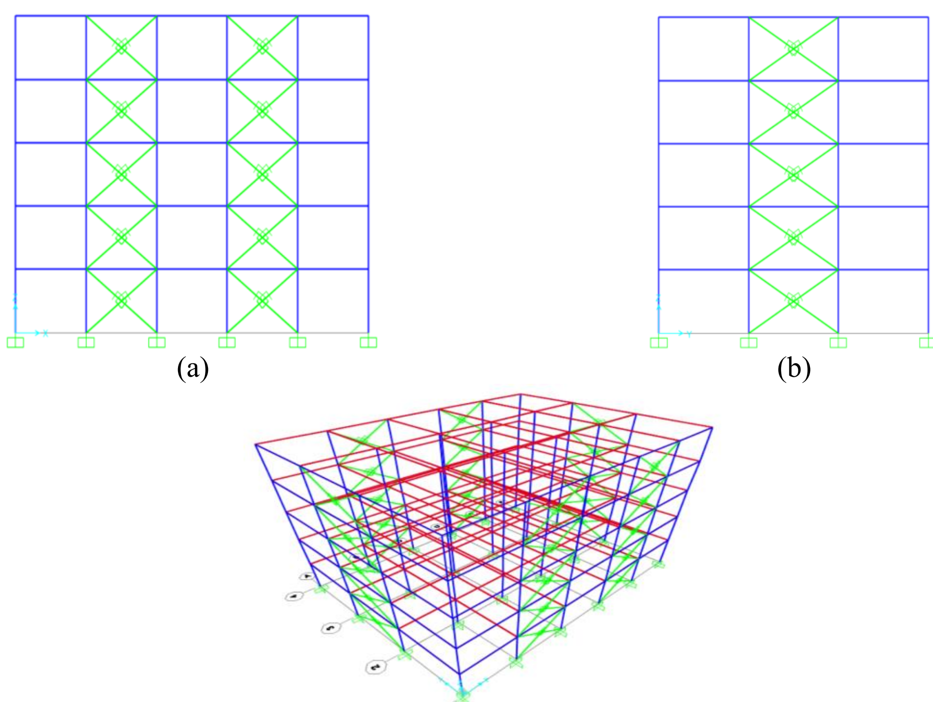


Fig. 6. Force-displacement behavior of the friction damper in brace (Malhotra et al. [27]).

5. Retrofitting of building with friction damper and scaled time history record

Friction dampers are modeled as plastic (Wen) link elements with elastic perfectly plastic force deformation relationship as shown in Fig. 6. Friction dampers are placed as shown in Fig 7. Slip load of friction dampers is 77 *kN*, 127 *kN* (calculated using steps described in section 4) in *X* and *Y*-direction, respectively. Modeling parameters for friction dampers in *X* and *Y*-direction are shown in Table 1.



(a) (b)

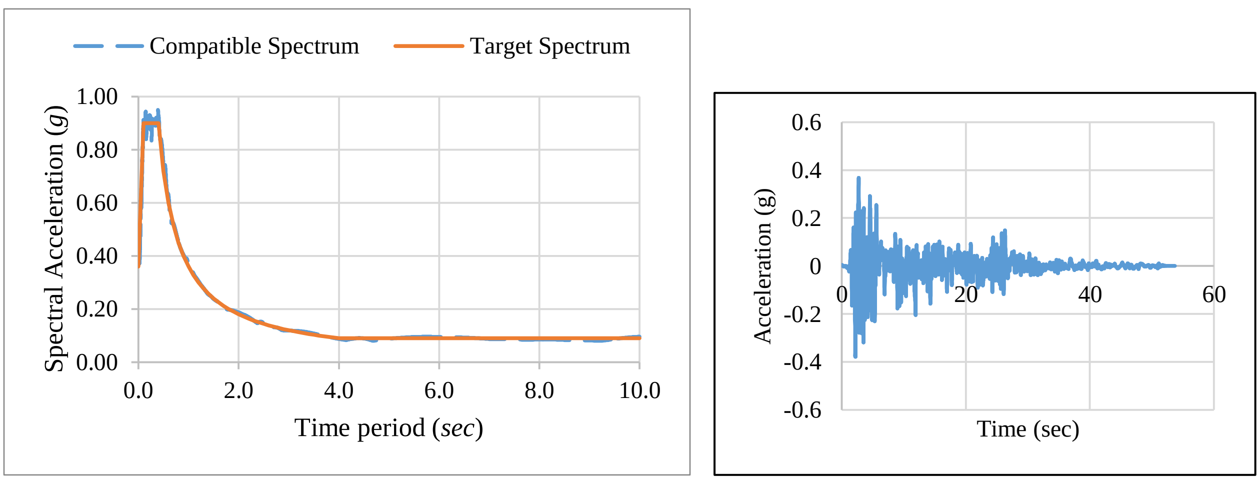
(c)

Fig. 7. Friction dampers (a) along *X*-direction, (b) along *Y*-direction (c) in 3D view

Table 1
Parameters for friction dampers in *X* and *Y* direction.

Parameters	*X*-direction	*Y*-direction	Units
Mass	**95.50**	**111.37**	***kg***
Effective stiffness	**97520**	**83622.71**	***kN/m***
Yield strength	**77**	**127**	***kN***
Post yield stiffness ratio	**0.0001**	**0.0001**	
Yielding Exponent	**10**	**10**	

To study the effectiveness of damper, NLTH analysis is performed. In this, initially, the imperial valley earthquake record is considered from PEERC earthquake data-based, then this is modified to match with target IS 1893 response spectra with peak ground acceleration of 0.36 *g*, zone V, soil type I using ETABS v16 [28]. Following Fig. 8 (a), shows compatible spectrum and target spectrum whereas Fig. 8 (b) shows scaled time history (SCTH) record, which is applied to building in *X* and *Y*-direction as TH-x and TH-y, respectively. Response of building obtained by using this SCTH is given in the next section.

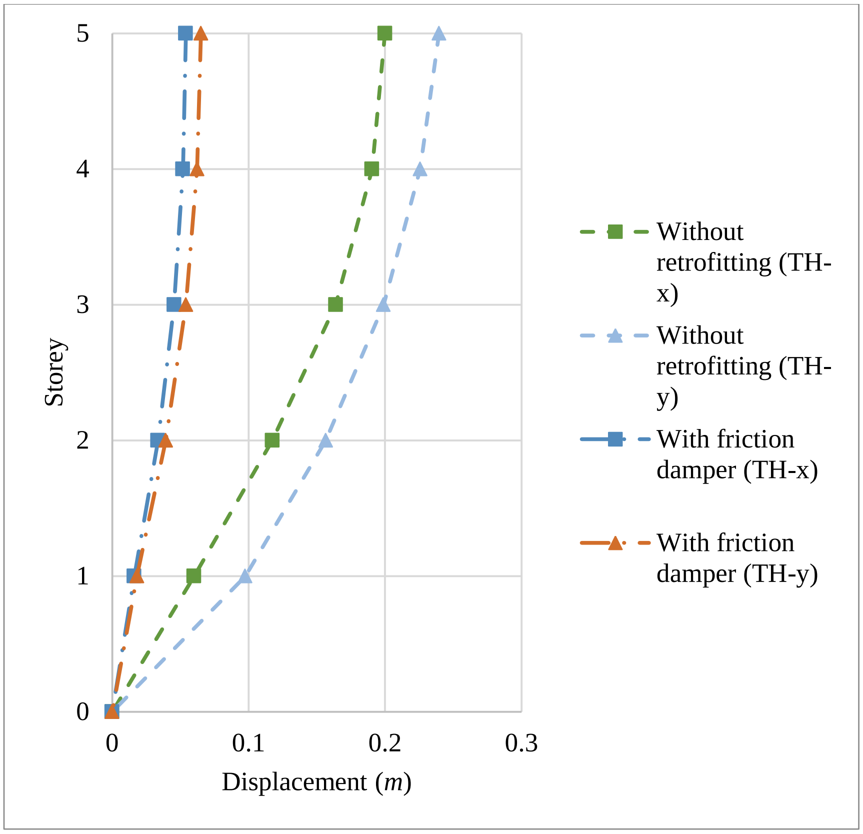


(a) (b)

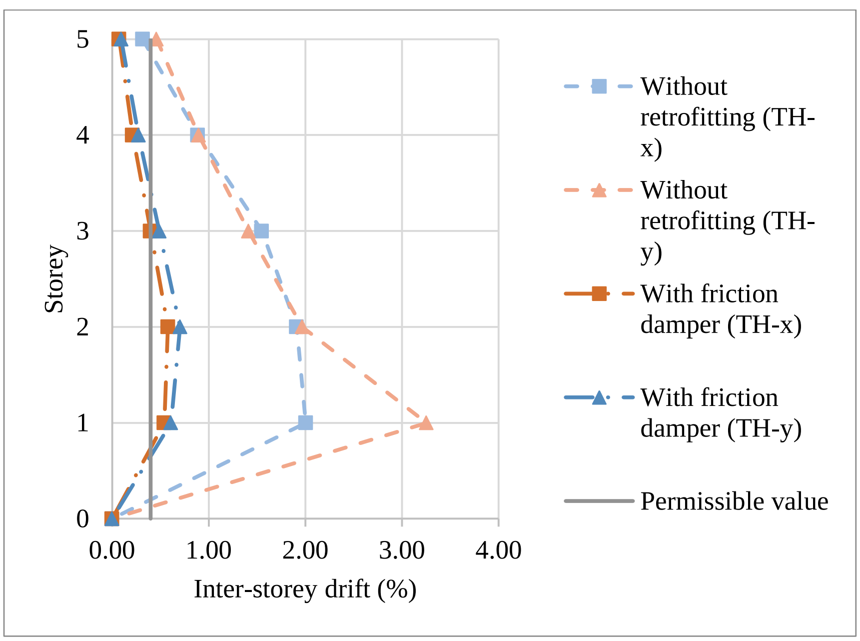
Fig. 8. (a) Compatible spectrum to IS1893 (zone V, soil type 1), (b) Scaled time history record**.**

6. Response of building with and without retrofitting

NLTH is carried out with and without dampers using scaled time history record as shown in Fig. 8 (b) in SAP2000 v20. Fig. 9 (a) shows storey displacement of building with and without damper. From Fig. 9 (b), the maximum inter-storey drift of building without dampers are 2 %, 3.25 % and for with dampers are 0.58 %, 0.70 % in *X* and *Y*-direction, respectively. So, by using a friction damper, the maximum inter-storey drift was reduced to about 71.17 %, 78.36 % in *X* and *Y*-direction, respectively. But as per IS 1893 permissible limit of inter-storey drift ratio is 0.4 %, only damper is not sufficient to limit the inter-storey drift. So, further retrofitting is carried out using steel bracing.



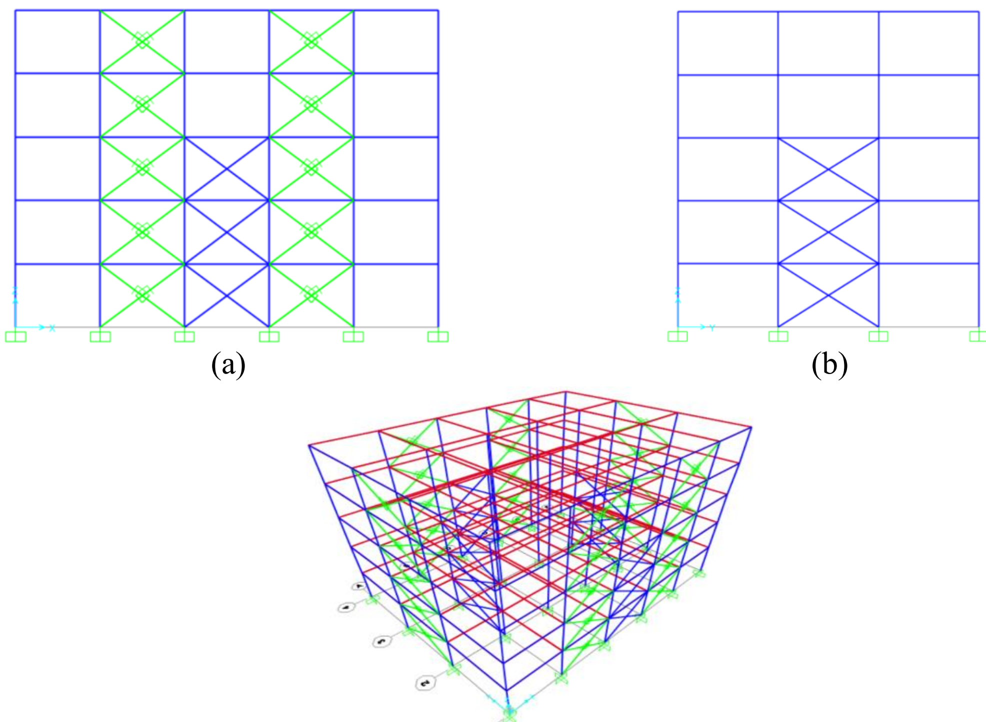
(a)



(b)

Fig. 9. Response of building due to TH (a) Storey displacement, (b) Inter-storey drift.

Steel bracings of ISMC 150 are used as shown in Fig 10 in *X* and *Y*-direction, respectively to bring the inter-storey drift in permissible limit. Fig 11 (a) shows storey displacement of building without, with damper and damper plus bracing. Using friction damper plus steel bracing, the maximum inter-storey drift of building is reduced from 2 %, 3.25 % to 0.33 %, 0.37 % in *X*, *Y*-direction respectively as shown in Fig. 11 (b). So, by using friction damper plus bracing, the maximum inter-storey drift reduced to about 83.59 %, 88.48 % in *X* and *Y*-direction, respectively.

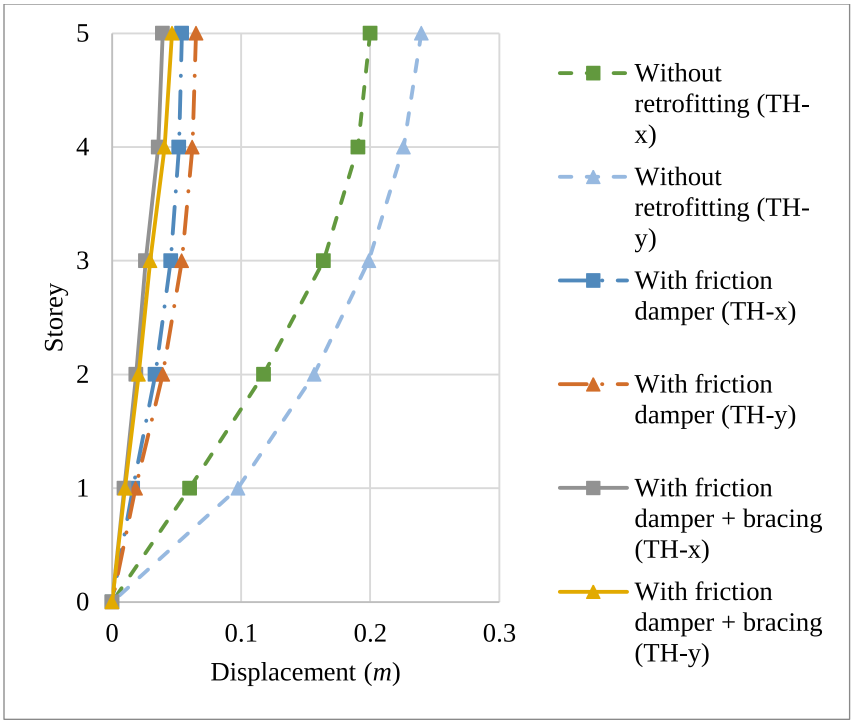


(c)

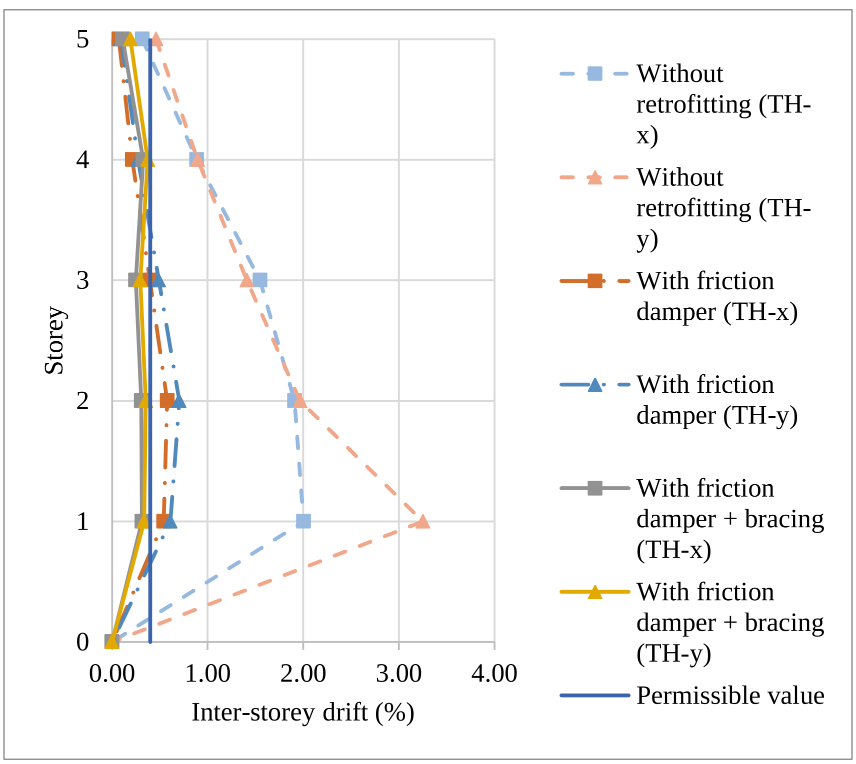
Fig. 10. Friction dampers and steel bracing (a) along *X*-direction (Outer frame), (b) along *Y*-direction (Inner frame) (c) in 3D view.

From Fig. 12 (a) and (b), the peak roof displacements obtained for a building without dampers are 0.20 *m* and 0.240 *m*, and for with friction dampers are 0.060 *m* and 0.075 *m* in *X* and *Y*-direction, i.e., the reduction of about 70 %, 68.73 % in *X* and *Y* direction respectively. With dampers plus bracing, the peak roof displacements reduced to 0.039 *m*, 0.046 *m* in *X* and *Y*-direction, i.e., the reduction of about 80.47 %, 80.65 % in *X* and *Y* direction respectively.

From NLTH analyses, forces (axial, shear force and moment) response history for a ground storey corner column (ID 101) are obtained for SCTH in *X*, *Y*-direction, and its peak values are shown in Table 2. Column's peak axial force has been reduced by 25.81 %, 16.53 % with friction damper and 26.87 %, 16.83 % with damper plus steel bracing in *X* and *Y*-direction, respectively. Shear force reduced to about 30.67 %, 35.0 % with friction damper, and 56.86 %, 48.43 % with damper plus steel bracing in *X* and *Y* direction, respectively. Moment reduced to about 18.26 %, 36.46 % with friction damper and 46.57 %, 47.18 % with damper plus steel bracing in *X* and *Y*-direction, respectively. All the plastic hinges in members are found to be within IO performance limit. Overall seismic performance of the building is improved.

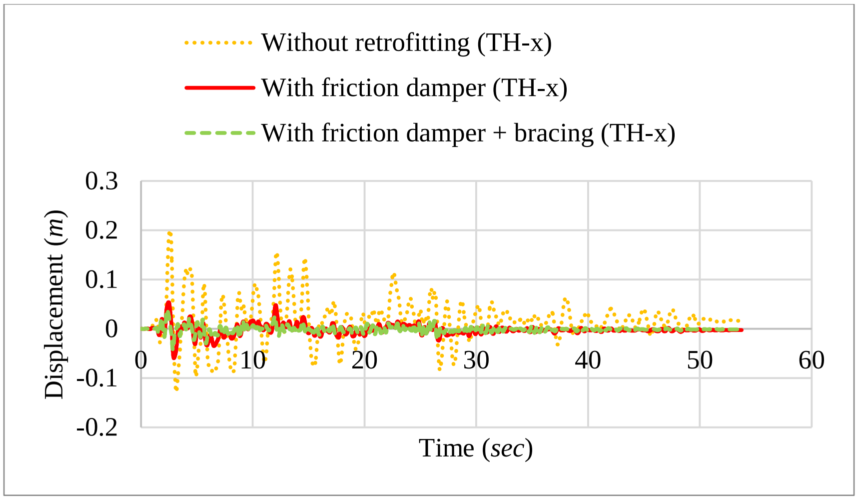


(a)

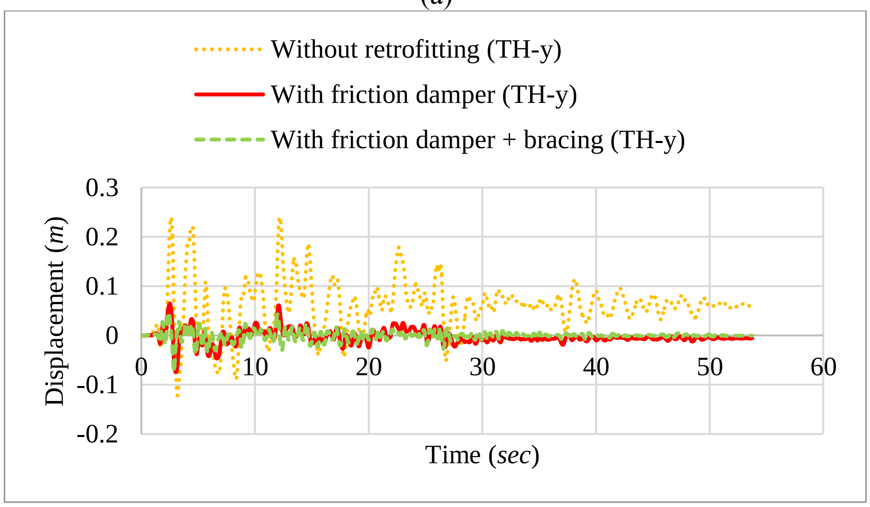


(b)

Fig. 11. Response of building due to TH (a) Storey displacement, (b) Inter-storey drift.



(a)



(b)

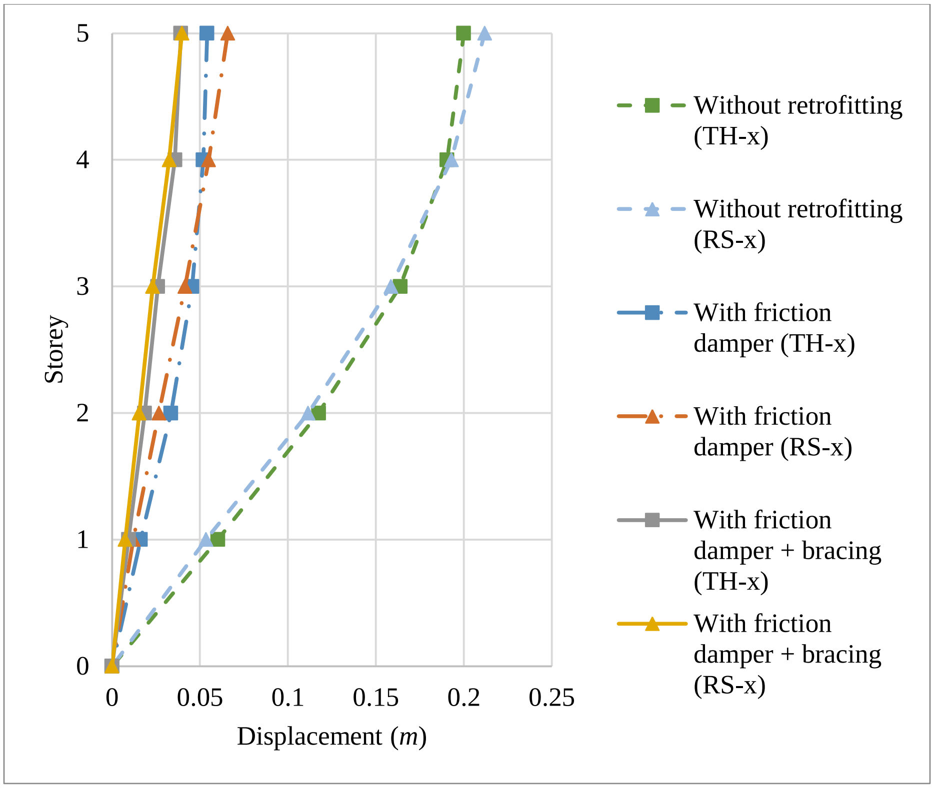
Fig. 12. Roof displacement due (a) TH-x, (b) TH-y.

To compare results obtained from NLTH, the Response Spectrum Analysis (RSA) of building with and without damper, bracing is carried out. Following Fig. 13 shows storey displacement of building obtained from response spectrum analysis. From Fig. 14, the maximum inter-storey drift of building without a damper is reduced from 1.94 %, 2.24 % to 0.49 %, 0.65 % with damper and 0.31 %, 0.37 % with damper plus bracing in *X* and *Y*-direction, respectively. So, by using friction damper, the maximum inter-storey drift reduced to about 74.59 %, 70.89 %, and with damper plus bracing reduced to 86.56 %, 84.29 % in *X* and *Y*-direction, respectively.

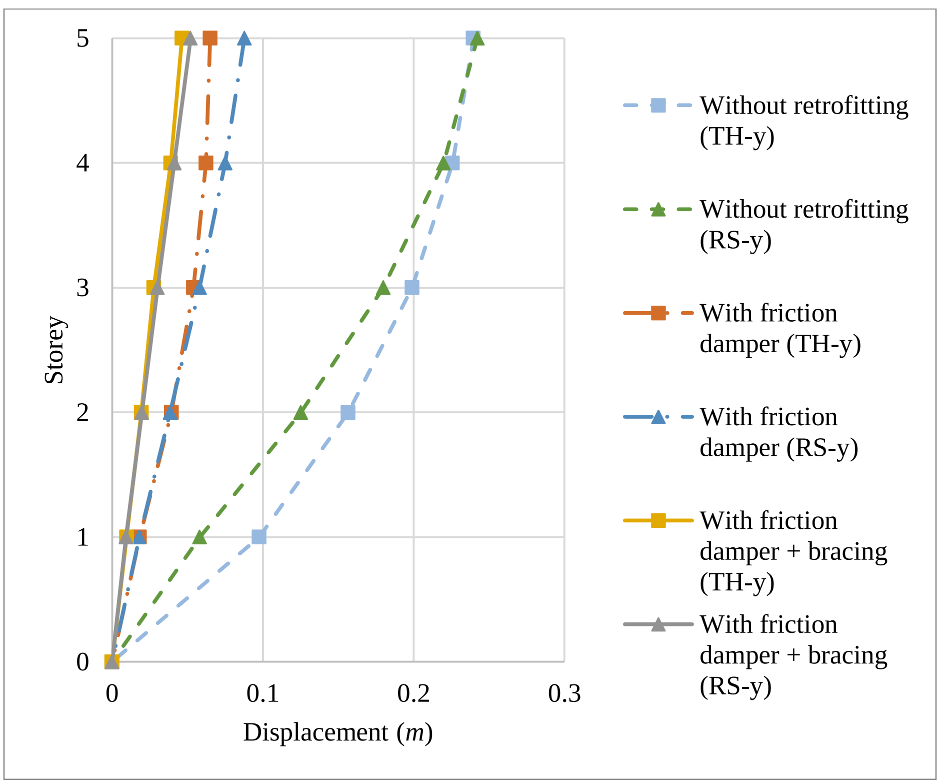
Table 2

Peak value of column (Id 101) forces from NLTH in *X* and *Y*-direction.

Sr. No.	Column forces	Without retrofitting		With friction damper		With friction damper + steel bracing	
		X-dir	*Y*-dir	*X*-dir	*Y*-dir	*X*-dir	*Y*-dir
1	Axial force (*kN*)	-707.6	-634.1	-524.96	-529.27	-517.47	-527.32
2	Shear force (*kN*)	88.03	89.31	61.03	58.05	37.98	46.06
3	Moment (*kNm*)	143.4	158.3	103.62	100.06	67.74	83.62

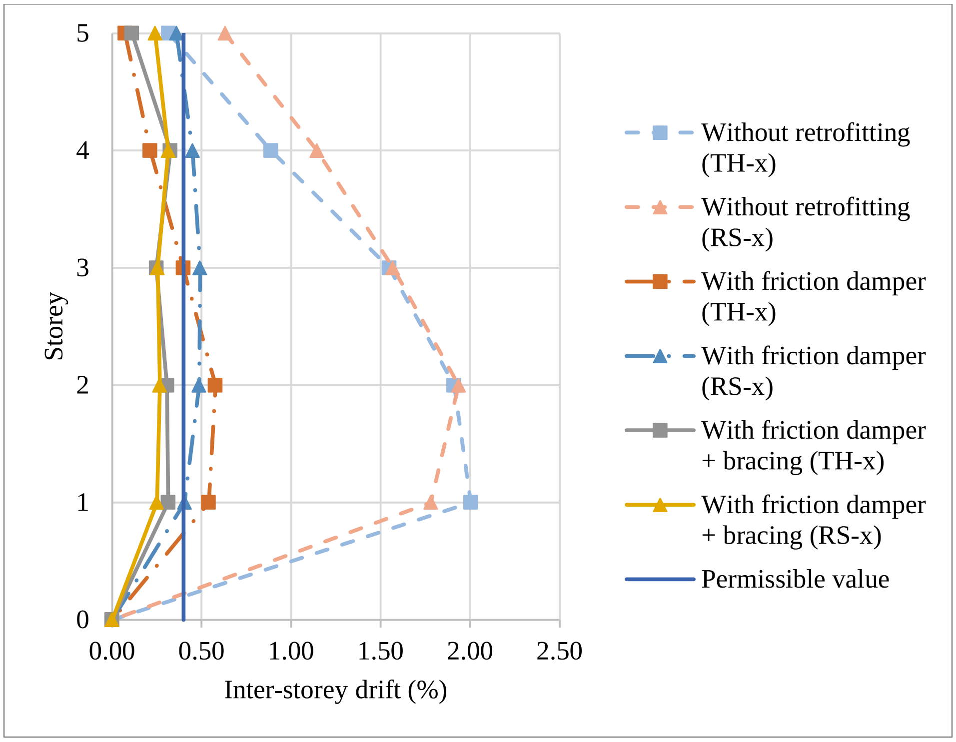


(a)

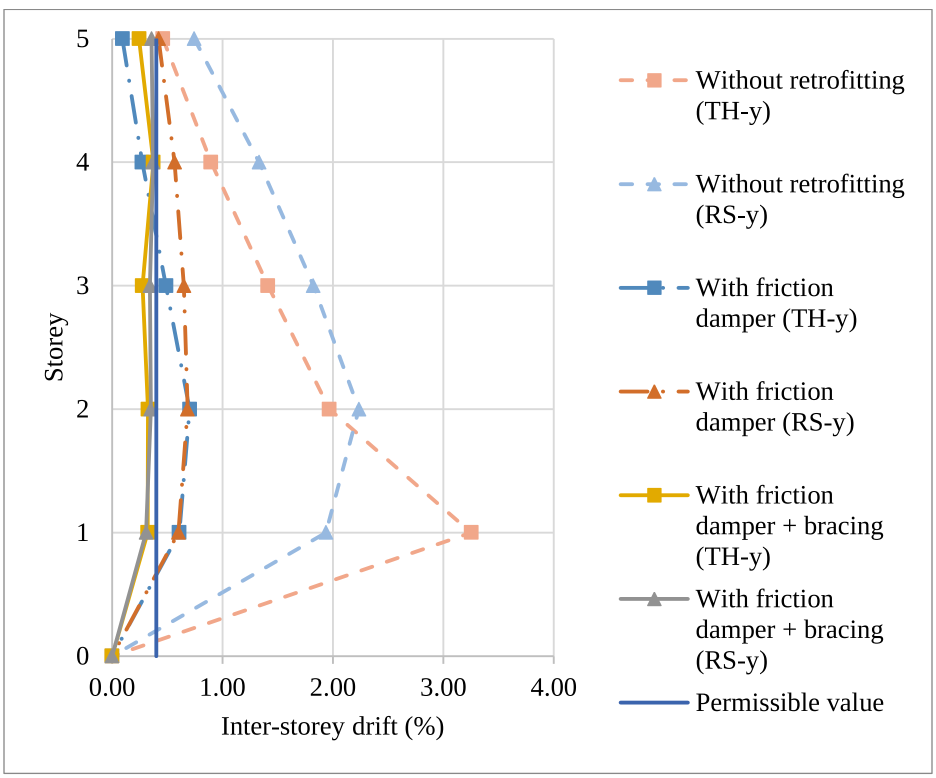


(b)

Fig. 13. Storey displacement due to RSM and TH in (a) X-direction, (b) Y-direction



(a)



(b)

Fig. 14. Inter-storey drift due to RSM and TH in (a) X-direction, (b) Y-direction

7. Summary and Conclusions

In the present work, pushover analyses of G+4 storey RC building are carried out in SAP2000 v20. From analyses, it is observed that the effective damping required for the building to achieve immediate occupancy performance levels are 20.1 %, 18.4 % in *X* and *Y*-direction respectively. So, to provide this supplementary damping, friction dampers are used. Friction dampers are designed and applied to the structure in SAP 2000 v20. From NLTH analysis of building without retrofitting, with friction damper plus following bracing conclusions can be made

- Peak roof displacement of building with damper reduced by 70 %, 68.73 % and with damper plus bracing reduces by 80.42 %, 80.58 % in *X* and *Y* direction respectively.
- Maximum inter-storey drift ratio with damper reduced by 71.7 %, 78.36 % and with damper plus bracing reduces by 83.74 %, 88.52 % in *X* and *Y* direction respectively.
- For Column (ID 101) with friction dampers, axial force reduced by 28.14 %, 17.6 %, shear force reduced by 35.93 %, 35.53 %, and the moment is reduced by 25.66 %, 42.76 % for TH in *X* and *Y*-direction respectively.
- For Column (ID 101) with dampers plus bracing, axial force reduced by 29.21 %, 17.39 %, the shear force is reduced by 57.16 %, 45.46 %, and the moment is reduced by 47.88 %, 49.41 % for TH in *X* and *Y*-direction respectively.
- All the plastic hinges in members are with IO performance levels.

So, due to the installation of friction damper plus steel bracing the roof displacement is reduced and column forces such as axial force, shear force, moment are also reduced. The overall seismic performance of the building is improved.

The response spectrum analysis observed that the inter-storey drift of buildings without damper reduced to 74.59 %, 70.89 % and with damper plus steel bracing reduced to 86.21 %, 83.81 % in *X* and *Y*-direction, respectively. So, the results obtained from RSA are in good agreement with that of obtained from nonlinear time history analysis.

The procedure mention in this paper for retrofitting of structure to the required performance level of IO is validate to linear system. The required damping is evaluated based on consideration of structure in linear domain.

In the present work, definite values of material and geometric properties etc are taken. As a future work, the variation in this parameter may be considered and reliability analysis needs to be carried out as explained by Ghasemi and Nowak A. S. [29], Ghasemi and Lee [30,31]. This may provide better estimation of the performance levels with definite confidence.

8. Validation of modeling and analysis of buildings

Chaudhari and Dhoot [32] perform pushover analyses of G+4 storey RC building located in seismic zone IV in SAP2000 v20. Considering the data given in their paper regarding model and loading, analysis is performed with theories explained in previous section and results are compared which are shown in Fig. 15. The present work result for capacity curve obtained from pushover analysis are in good agreement with Chaudhari and Dhoot [32] as shown in Fig. 15.

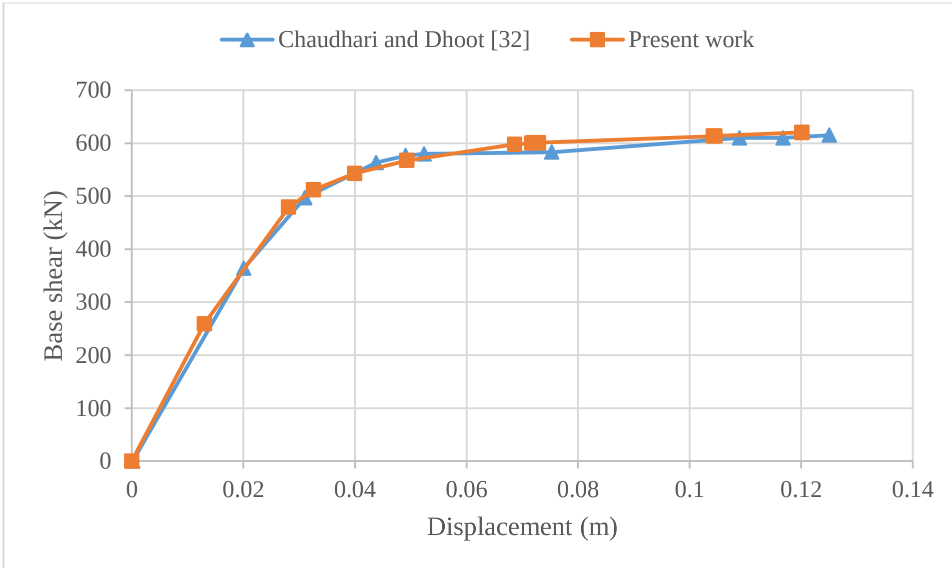


Fig. 15. Comparison of capacity curve.

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