Effective Peripheral Distribution of Base Isolators for Plan Asymmetric Buildings to Minimise Torsion

R. Rithuparna, V. N. Varada, and S. C. Mohan

Abstract The naturally occurring ground motion results in disasters such as the collapse of structure and fatality if the built structures are not adequately designed to take the seismic load. Buildings with irregularities in plan and elevation are more prone to seismic damage due to the torsional effect that comes into play because of the eccentricity created between their centre of mass and centre of stiffness. Base isolation is a very effective way to eliminate the ill-effects of seismic forces and is one of the most widely implemented techniques. The main challenge in using base isolation for asymmetric buildings is to address the associated torsional vibrations. This study focusses on the influence of base isolation techniques in mitigating the torsional effect on plan asymmetric buildings. L-shaped buildings with greater plan eccentricity in *X*-direction was chosen for the study. The response of fixed base and base isolated asymmetric structures was compared and analysed using SAP2000 software. The effectiveness of various distribution of isolators was also explored to obtain the most economical option of isolating a building. Among the distributions studied, peripheral distribution gave a similar performance as that of uniform distribution for almost all the cases. Hence, the provision of isolators under the peripheral columns alone can be an effective way of reducing the total cost incurred in isolating a building.

Keywords Asymmetric building · Base isolation · Peripheral distribution

1 Introduction

The study of past earthquakes has revealed that they have caused massive damage to properties and life loss. Various measures were developed for safeguarding these structures from the adverse effect of earthquakes. The conventional techniques adopted involve strengthening and stiffening the building by providing special structural components such as shear walls and bracings. However, alternate means to

R. Rithuparna (✉) · V. N. Varada · S. C. Mohan
Department of Civil Engineering, Birla Institute of Technology and Science Pilani, Hyderabad Campus, Hyderabad, India

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reduce the demand on the structure by providing dampers and base isolators have proved to be more effective. Many researchers have reported a reduction in the seismic response of base isolated buildings owing to the decoupling of the building from the ground. These isolators help shift the fundamental period of building vibration to a higher range outside the predominant period of ground motions. Therefore, isolating a building will eliminate the building's probability of resonating with the seismic force acting on it. Besides, the energy dissipating mechanism of base isolators reduces the seismic demand on the superstructure.

With more and more architectural styles reflecting complex and irregular building plans, torsion becomes inevitable when the structures are dynamically excited. The torsion in the building can be attributed to the eccentricity between the centre of mass (CM) through which the external force acts and the centre of rigidity (CR) through which the resistance is offered. The torsional effect causes differential displacement of the stiff and flexible edges at the same floor level of the building under lateral loads. Asymmetric buildings in seismically active regions are more vulnerable to damage and necessitate careful and well-planned design. One solution for bringing down torsion in the building is to isolate them from the ground motions seismically. Various researchers studied the torsional behaviour of base isolated plan asymmetric buildings, and the seismic response was reported to reduce substantially [1–3]. It was stated by the researchers that eccentricity in the isolation system has a more remarkable effect on the torsion in the building compared to the superstructure's eccentricity [4, 5].

On the contrary, Nagarajaiah et al. reported that the eccentricity of both superstructure and the isolation system plays a crucial role in the behaviour of isolated buildings [6]. Furthermore, a proper design of base isolators will ensure the building's first mode of vibration to be predominantly translational with minimal contribution from the torsional motion. The complete decoupling of the building will result in a uniform distribution of stresses in all the columns [1]. An eccentricity between the centre of the isolation system (CI) and CR of the superstructure was necessary to effectively counteract the torsion created in the superstructure [7]. The most preferred distribution of base isolators is the one in which CI coincides with CM of the superstructure. The displacement at the isolator level was reported to be minimum for this distribution. However, Kilar and Koren observed that this distribution resulted in more significant roof level displacement and caused greater damage to the flexible sides of the superstructure. Location of CI farther away from CM develops torsion due to inertial force (acts through CI), which neutralises the torsion due to external force (acts through CM). CI = –CM/2 was suggested to be the most favourable distribution to keep the top displacement and the base displacement well under the tolerance limit [8].

To investigate base isolators' influence on plan asymmetric buildings, L-shaped building models were created and analysed for seven ground motion data in SAP2000 software. Since employing a base isolator is an expensive option, research on bringing down the cost is gaining attention. A comparative study on the seismic responses of the buildings was carried out for various distributions of base isolators to arrive at an effective and economical option. Parametric study of buildings with different eccentricities located in seismic zone 5 was conducted. The responses in terms of storey drift and difference in roof displacement of flexible and stiff edges of the model are presented. The design procedure, as per UBC 97 recommendations for lead rubber bearings as seismic isolators, is discussed [9].

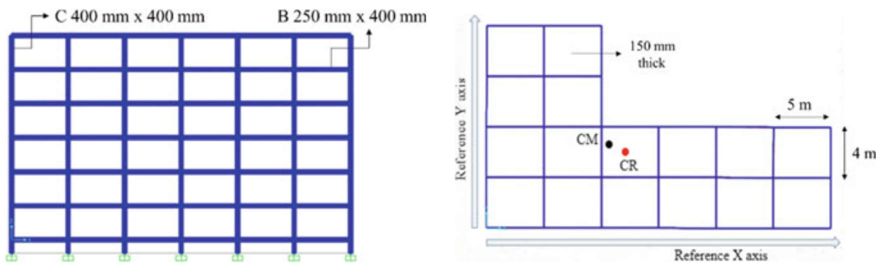
2 Building Models Description

The numerical modelling technique used is a standard procedure followed for modelling and analysing buildings in SAP 2000 software, which is verified to be in line with the existing study. For details of the model used for validation, refer to the paper published by Mounashree et al. [10].

2.1 Fixed Base Buildings

An asymmetrical six-storey L-shaped building (model 1) of 3 m storey height was modelled in SAP2000. An exterior wall load of 13.11 kN/m and an interior wall load of 8.55 kN/m was applied on the beams. A load of 10 kN/m^2 was provided on the left side bay slabs alone, apart from the 3 kN/m^2 of live load. These loads were uniformly distributed on all the slabs except the roof. The additional UDL of 10 kN/m^2 brought about an eccentricity of 5.8% in *X*-direction and 1% in *Y*-direction. Hence, an earthquake in *Y*-direction is more critical while studying the torsional effect of this building. Figure 1a, b shows the elevation view and plan view of the building, respectively with its CM at (11.05, 6.38) and CR at (12.78, 6.22).

To study the effect of higher eccentricity, a second model with columns of size 300 mm x 500 mm was provided at two frames in the right end of the L-shaped building (L-shaped model 2). This created an eccentricity of 10.4% in *X*-direction and 2.3% in *Y*-direction. The actual behaviour of these buildings was studied by performing linear dynamic time history analysis, according to IS1893: 2016 [11].



(a) Elevation (b) Plan view

Fig. 1 Model of L-shaped building

They were subjected to seven real-time ground motions, namely El Centro, Loma Prieta, Kobe, Northridge, Chamba, Uttarkashi and Trinidad earthquake data as per NEHRP recommendations [12]. These data were scaled up or down to match the target response spectrum corresponding to the building's location. Buildings of importance factor equal to 1 and a response reduction factor of 3 were chosen. They are located in a site of medium soil type in Rann of Kutch, Gujarat. Since the location is prone to frequent earthquakes of high magnitude, it falls under seismic zone 5 as per IS 1893:2016 classification [11].

2.2 Base Isolated Buildings

The buildings were isolated using lead rubber bearings (LRB), and the design procedure for LRB as per UBC 97 is explained below [9, 13]. The isolated period (T_D) is assumed to be thrice the time period of fixed base building.

Design displacement: It is the minimum lateral displacement of the isolation system in the direction of the seismic force under consideration.

$$D_D = \frac{\left(g/4\pi^2\right) C_{VD} T_D}{B_D} \tag{1}$$

C_{VD} is a seismic coefficient that depends on the seismic zone factor and the soil profile type. The coefficient is chosen from Table 16R of UBC 97. The type of soil profile is assigned based on the average shear wave velocity in the soil. If sufficient details of the soil property are unavailable, then the soil type is taken as S_D.

B_D is the damping coefficient related to the effective damping of isolators at the design displacement. Referring to Table A-16-C of UBC 97, the damping coefficient is obtained corresponding to the required effective damping of the system.

Bearing horizontal stiffness:

$$k_{\text{eff}} = \frac{W}{g}\left(2\pi/T_D\right)^2 \tag{2}$$

W is the maximum load to be sustained by a single isolator which is obtained from the analysis of the fixed base building.

Energy dissipated per cycle: Lead rubber bearings are modelled as bilinear elements with the area under the hysteresis giving the energy dissipated per cycle.

$$W_D = 2\pi k_{\text{eff}} D_D^2 \beta \tag{3}$$

β is the effective damping ratio of the isolator.

Characteristic strength of lead: It is the value at which the hysteresis loop of the lead intercepts the axis representing force applied.

$$Q_D = \frac{W_D}{4D_D} \tag{4}$$

Post-yield stiffness of rubber: Since LRBs are modelled as bilinear elements, they have a pre-yield (k_1) and a post-yield stiffness (k_2).

$$k_2 = k_{\text{eff}} - \frac{Q_D}{D_D} \tag{5}$$

Owing to the difficulties in measuring k_1, it is assumed to be ten times k_2.

Yield displacement (Distance from end-J):

$$D_y = \frac{Q_D}{k_1 - k_2} \tag{6}$$

Recalculating characteristic strength:

$$Q_R = \frac{W_D}{4\left(D_D - D_y\right)} \tag{7}$$

Area of lead plug:

$$A_{\text{LRB}} = \frac{Q_R}{\text{yield strength of lead}} \tag{8}$$

Assume yield strength of lead = 10 MPa.

Recalculation of rubber stiffness:

$$k_2 = k_{\text{eff}} - \frac{Q_R}{D_D} \tag{9}$$

Total thickness of the rubber:

$$t_r = \frac{D_D}{\gamma} \tag{10}$$

Assume maximum shear strain of rubber, $\gamma = 100\%$

Area of bearing:

$$A_{\text{LRB}} = \frac{k_{\text{eff}} t_r}{G} \tag{11}$$

Single layer rubber thickness:

$$t = \frac{D_{\text{LRB}}}{4S} \tag{12}$$

Shape factor:

$$S = \frac{f_v}{2.4 f_H} \tag{13}$$

f_v and f_H are the vertical and horizontal frequency, respectively.

No. of rubber layers:

$$N = \frac{t_r}{t} \tag{14}$$

Assume the thickness of steel shim plates and endplates. Calculate the total height of bearing.

Yield strength:

$$F_y = Q_R + k_2 D_y \tag{15}$$

Vertical stiffness:

$$k_v = \frac{E_c A}{t_r} \tag{16}$$

E_c—instantaneous compression modulus under vertical load

$$E_c = 6\mathrm{GS}^2\left(1 - \frac{6\mathrm{GS}^2}{K}\right) \tag{17}$$

K—bulk modulus of rubber.

Post-yield stiffness ratio:

$$n = \frac{k_2}{k_1} \tag{18}$$

Base isolators of the same lateral stiffness and damping were modelled as two joint link elements (rubber isolator) in SAP2000 v21. Details of linear and nonlinear properties which were assigned to the link element are shown in Table 1. Plinth beams (300 mm × 450 mm) were provided at the ground level of the building to ensure proper transfer of load from the superstructure to the base isolator.

Firstly, base isolators were distributed uniformly with a bearing under each column. The second distribution was associated with a peripheral arrangement of bearings wherein they were placed only under the exterior columns with roller support under the interior columns.

Table 1 Link element properties

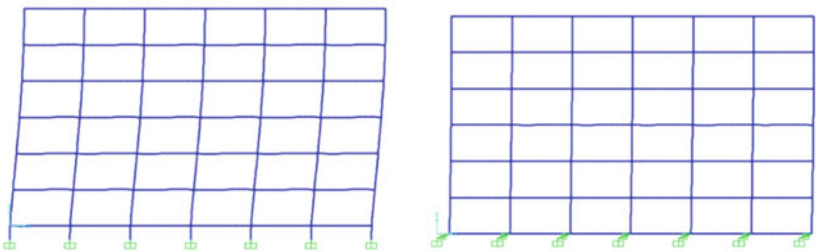
Axial direction	
Effective stiffness, k_v	285,442 kN/m
Effective damping	0
Lateral direction	
Linear	
Effective stiffness	765.32 kN/m
Effective damping	0.25 kN-sec/m
Distance from end J, D_y	0.0108 m
Non-linear	
Stiffness	578.602 kN/m
Yield strength, F_y	65.21 kN
Post-yield stiffness ratio	0.1

3 Results and Discussions

3.1 Modal Analysis

Eigenvalue analysis was performed for all the building models. Figure 2a, b depicts the deformed shape for mode 1 of fixed base and base isolated buildings. The mode shape for the isolated building seems very different from the fixed base building. The isolated building showed rigid body motion, and hence, it causes minimal discomfort to the people residing in the building.

Table 2 reveals that the isolated building's time period was lengthened by almost three times that of the fixed base building. The fundamental time period was 10.5% higher for the peripheral distribution than for the uniform distribution of isolators. The increase in the time period can be attributed to the reduction in horizontal stiffness on providing roller support under the interior columns.



(a) Fixed base (b) Base isolated

Fig. 2 Deformed shape of building models

Table 2 Fundamental time period in sec

Category	L-shaped model 1	L-shaped model 2
Fixed base	1.43	1.43
Uniform	4.18	4.15
Peripheral	4.62	4.44

3.2 *Time History Analysis*

The results of the analysis performed on the models are presented in the following sections.

The Difference in Displacement at Roof Level. When asymmetric buildings are subjected to lateral loads, the displacement at one edge will be higher than that at the other edge due to the non-coincidence of CR and CM. The difference in displacement at the two edges can be considered as a measure of torsion in the building. Figure 3 depicts a significant reduction in the torsion for the uniformly distributed model compared to that of the fixed base model. Comparable results were obtained for the peripherally distributed model as well.

Inter-storey Drift. Inter-storey drift is a measure of how much a storey has displaced compared to the storey below it, thereby gives the relative displacement or drift between two successive storeys.

L-Shaped Model 1

Figures 4, 5 and 6 represent a comparison of drift for building model 1. A noticeable reduction in drift for isolated buildings subjected to both *X*- and *Y*-direction earthquakes is visible.

L-Shaped model 2

For the second variant of building with greater eccentricity, similar observations were made. Figures 7, 8 and 9 shows the comparison of drift for the building.

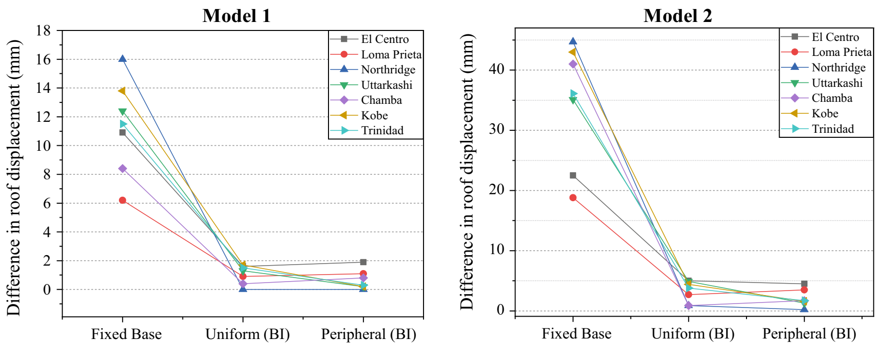


Fig. 3 Difference in roof displacement of flexible and stiff edge of building models

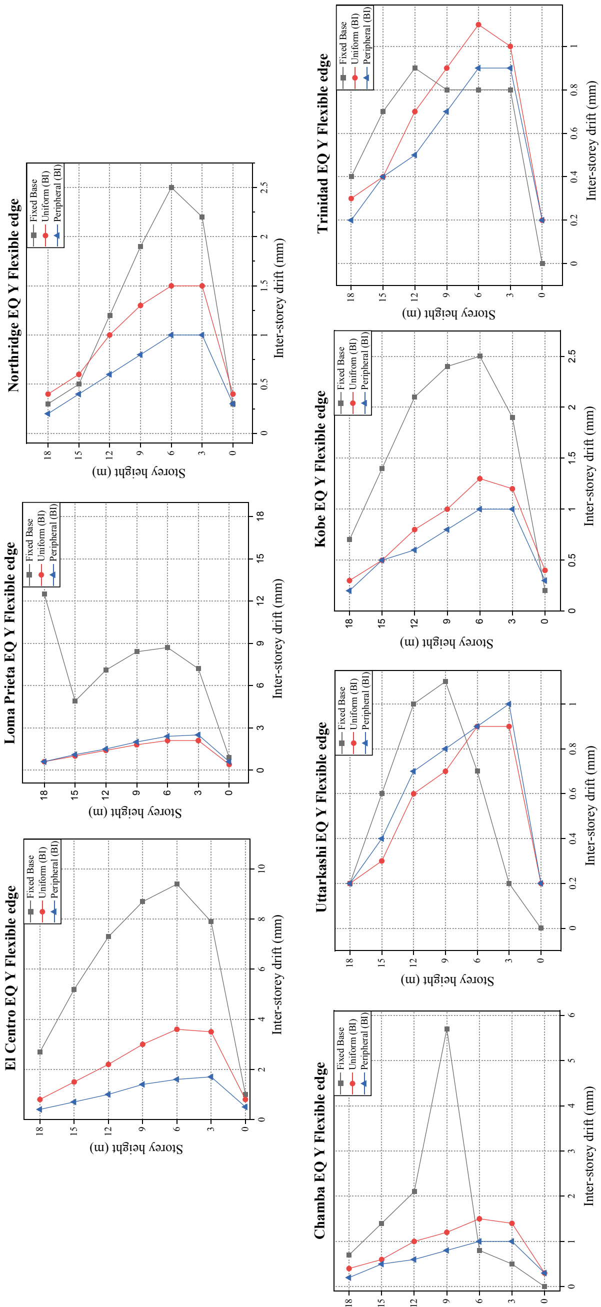


Fig. 4 Comparison of inter-storey drift for the flexible edge of model 1 subjected to EQY

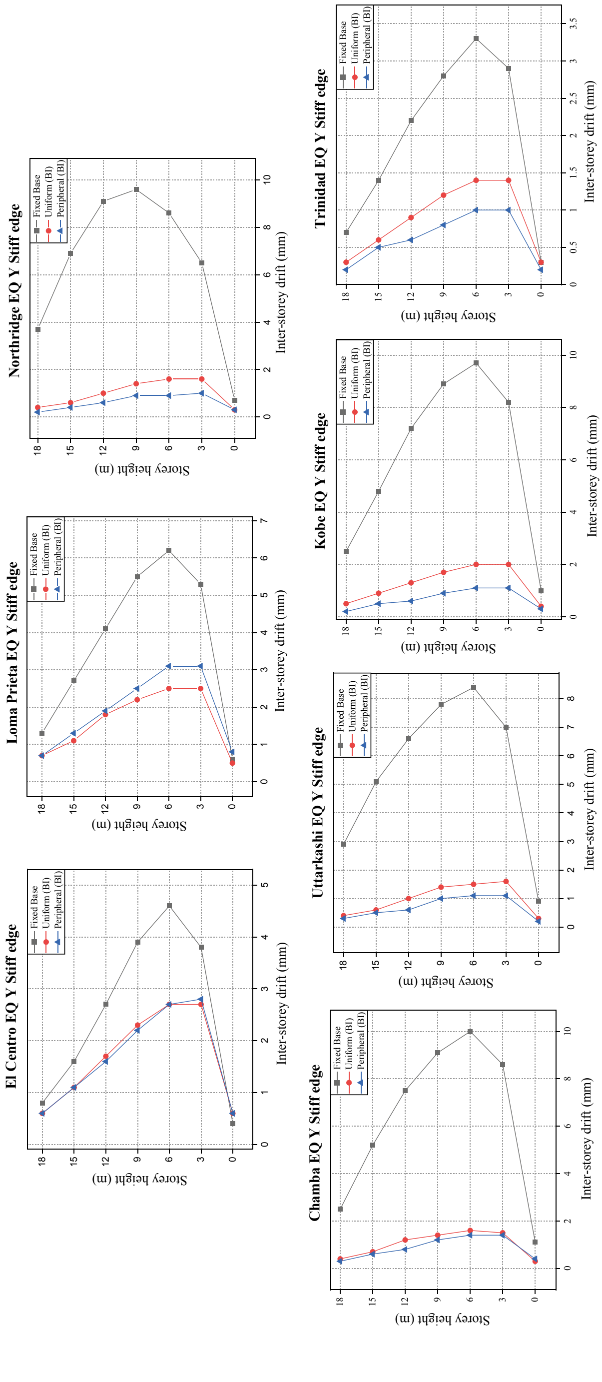


Fig. 5 Comparison of inter-storey drift for the stiff edge of model 1 subjected to EQY

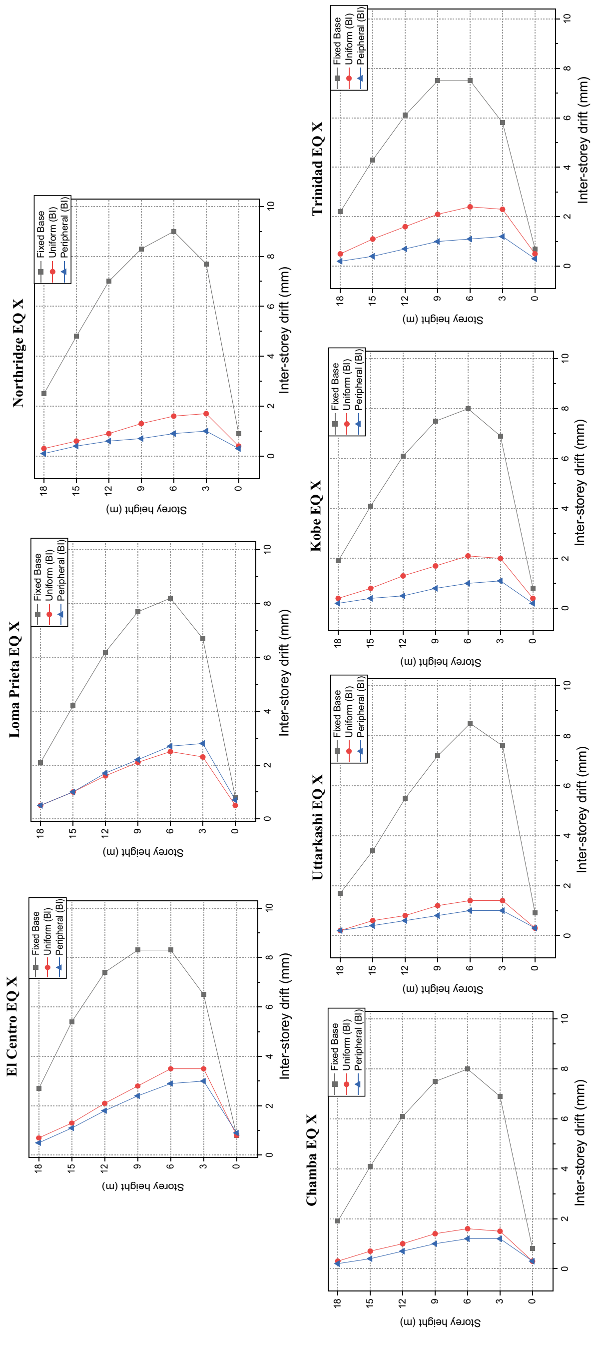


Fig. 6 Comparison of the inter-storey drift of model 1 subjected to EQX

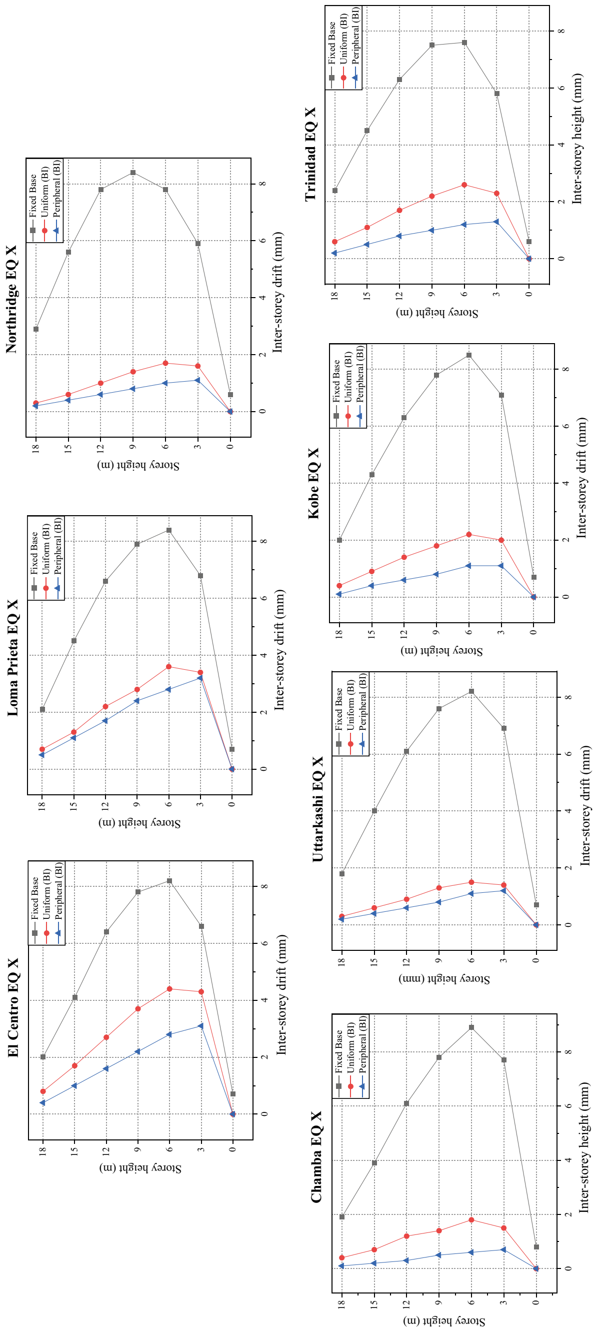


Fig. 7 Comparison of the inter-storey drift of model 2 subjected to EQX

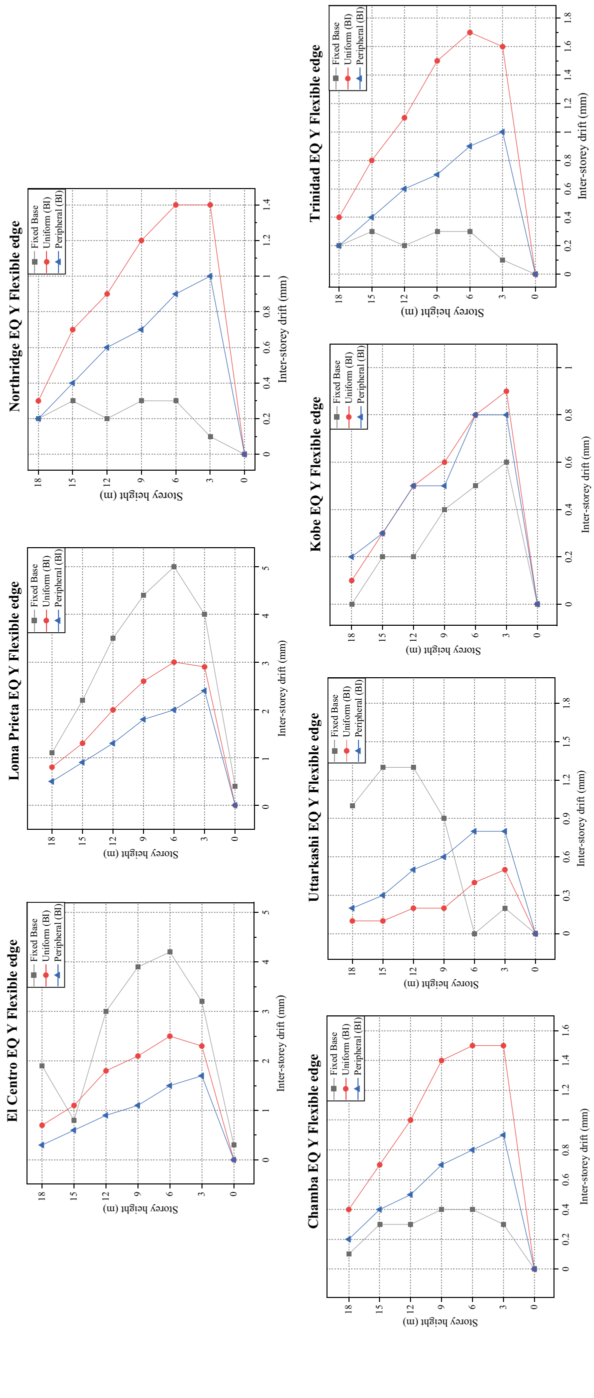


Fig. 8 Comparison of inter-storey drift for the flexible edge of model 2 subjected to EQY

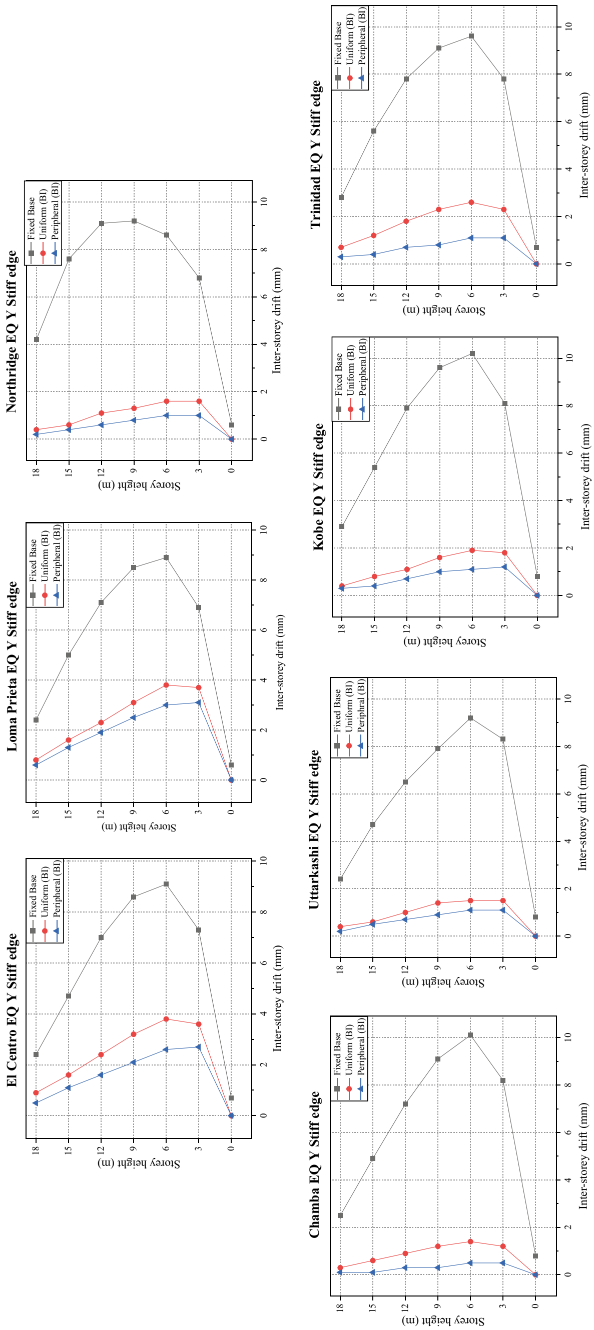


Fig. 9 Comparison of inter-storey drift for the stiff edge of model 2 subjected to EQY

Table 3 Percentage reduction in parameters for building with peripheral distribution

Seismic parameter	Building model	Direction of EQ	% Reduction
Difference in roof displacement for flexible and stiff edge	Model 1	Y	86.4–99.4
	Model 2	Y	78–98
Inter-storey drift	Model 1	X	68.7–88.2
		Y	65.2–82
	Model 2	X	65–93
		Y	71–97

It is evident that isolating the buildings has led to a considerable reduction in the drift. The only exception was the flexible edge of model 2 subjected to the *Y*-direction earthquake. The fixed base model seems to have performed slightly better than the base isolated models in this case. However, the difference is not of much significance since it falls below 0.9 mm. It is further observed that the reduction in drift for buildings with peripheral distribution has outperformed that of uniform distribution for all the cases.

The key findings from the study are discussed below.

- Provision of base isolators lengthened the time period of the building significantly. Moreover, the time period was higher for the peripheral distribution of isolators compared to the uniform distribution.
- Inter-storey drift was reduced by a large margin for base isolated buildings. Additionally, the percentage reduction in the drift was 60 to 90% higher for building with peripheral distribution than fixed base building, as shown in Table 3.
- For a building with 10% eccentricity, the inter-storey drift was found to increase for the flexible edge of base isolated buildings; nevertheless, the difference is not significant. On the contrary, base isolators were fully effective in reducing the drift at all the storey levels for the stiff edge of the building.
- Difference in the displacement of flexible and stiff edges gives a measure of torsion in the building. It was found to reduce considerably with the application of base isolators. The value was comparable and, in some cases, better for peripheral distribution of isolators.

4 Conclusion and Future Scope

The effect of providing base isolators in reducing torsion of plan asymmetric L-shaped buildings with different eccentricities was studied. The seismic response of building models was noted. It can be concluded that base isolators effectively reduced torsion in the buildings considered in this study. Cost effectiveness is one of the major aspects considered while choosing a seismic protection system. Although isolators perform well compared to other systems, their application is limited owing to their high cost. Peripheral distribution acts as an economical option since they produced similar or better results than the uniform distribution of isolators. Thus, enabling the use of fewer expensive isolators to achieve satisfactory performance of isolated buildings.

This study can be extended to other plan asymmetric buildings. Further research needs to be carried out for buildings with greater eccentricity since the isolators were found to be less effective in reducing the drift at the flexible edge of such buildings. Additionally, behaviour under more varieties of distribution of base isolators could be studied in future. A more economical option of base isolation using other techniques such as friction bearings, fibre reinforced elastomeric bearings can be explored.

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