

Performance Evaluation of RC Framed Hill Buildings with and Without Shear Walls



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1 Introduction

Buildings built on hill slopes demonstrate distinct seismic behaviour than conventional buildings resting on a plain ground. Due to asymmetric elevation and plan, irregular buildings exhibit variation in mass and stiffness at different floor levels, leading to the development of additional shear forces and moments in the frame members apart from lateral loads [1–10]. Further, short column effect in hill buildings due to columns of varying lengths at same storey level makes the structure more vulnerable to earthquake. The shorter columns on the uphill side have higher stiffness and attract much more forces as compared to that of the columns on downhill side [11].

Previous research studies conducted on irregular structure buildings presented different techniques regarding mathematical modelling formulation and earthquake analysis of hill buildings. Cheung and Tso [1] investigated setback buildings under lateral loads. Shahrooz and Moehle described a mathematical model for the analysis of buildings with setbacks when subjected to seismic loads [2]. Paul [3] proposed a simple one-dimensional approach for dynamic analysis of asymmetric buildings. Kumar and Paul developed a method of analysis in which each storey of the building was modelled with multi-degree of freedom (D.O.F.) per floor; then, the obtained results were compared with the Codal provisions [4, 5]. Further, Kumar [6] and Kumar and Paul proposed a three-dimensional modelling approach for the dynamic analysis of irregular and asymmetrical hill structures [7, 8]. Birajdar and Nalawade [9] analysed various configurations of hill buildings and parametrically compared dynamic properties of the buildings and suggested the suitability aspect. Singh et al. [10] applied time history analysis and evaluated seismic properties in along and across slope of a setback buildings. The obtained parameters in the study were

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compared with the damage pattern in case study of damaged hill building in Sikkim earthquake (2011). Mohammad et al. [11–13] investigated the seismic performance of hill buildings and observed that stepback-setback configurations showed better resistance than the stepback building configuration under earthquake loads.

It has been observed that the shear walls impart restraint to the extensive damage in buildings in earthquakes. A well-designed system of shear walls in the building enhances its seismic performance. Past studies simplified the modelling and analysis of the structural system with shear walls and evaluated seismic response of the buildings. Medhekar and Jain [14] discussed seismic behaviour, modes of failure and factors influenced by shear walls on structural response. Wallace [15] presented an analytical approach to determine the requirement of transverse reinforcement in RC structural walls with various cross sections and found that the strain distribution in shear wall is significantly affected by its aspect ratio, configuration and reinforcement ratios. Patel et al. [16] studied and discussed the effect of varying columns and seismic response of RC frame building on sloping ground with shear walls at different positions in the structure.

The position and form of shear walls play significant role in structural performance of the building [17–19]. Generally, shear walls are provided in the symmetrical fashion, hence do not generate any torsional forces and moments due to any kind of asymmetry in the structure. Therefore, it is more important to analyse buildings with vertical irregularities like hill buildings. There is a need to explore the seismic response of hill buildings with shear walls present at different locations in the structure, to opt what or which position is best for structures constructed on hill slopes.

Thus, in present study, the effect of shear walls on the seismic performance of two hill building configurations was studied. Both stepback and stepback-setback hill buildings have been modelled with shear walls at three different locations, viz. at corners, at mid-edge and at the centre of building. The finite element models were analysed using both equivalent static as well as response spectrum methods, and the dynamic parameters have been presented and compared in terms of fundamental time period, storey drift, storey shear and shear forces induced in the columns at foundation level in buildings. Further, for better comparison and suitability of position of shear walls, the total concrete volume and number of shear walls were kept equivalent in the respective geometric variations as well as in different direction of hill slopes.

2 Materials and Methods

The present study investigates the effect of reinforced concrete shear walls on two hill building configurations, viz. stepback and stepback-setback. All the configurations are modelled in three dimensions without (bare frame) and with the inclusion of shear walls. Seismic analyses of the structures have been performed using equivalent static and response spectrum method with SRSS combination in a finite element software. Important dynamic parameters, viz. fundamental time period, top storey

displacement, story shear, story drift and base shear at ground level in along as well as across hill slope directions, are obtained and compared with the respective bare frame configurations.

As per IS 1893 (Part 1): 2002, the zone factor V was taken as for hilly regions. The importance factor (I) and response reduction factor (R) were taken as 1.5 (for important buildings) and 5 (for SMRF system), respectively. The gravity and imposed loads were taken as per IS 875 (Part 1 and 2): 1987, respectively, for a typical residential building. All the models have been analysed, designed and checked for any failure in the frame structure. The reinforcement in the columns was varied from 1% to 3.5%, whereas in beam and slab, nominal designed percentage of rebar was provided in both the directions (see Table 1).

The bare frame configurations without shear walls have been modelled for step-back (BSTEPALS) and stepback-setback (BSETALS) configurations. All buildings have similar geometrical and material properties (see Fig. 1 and Table 1). The modulus of elasticity of concrete is taken as $25,000 \text{ N/mm}^2$ and value of Poisson's ratio to be 0.2. The foundation is assumed as a fixed support system. Both building configurations have six bays in length along the hill slope; however, width of all the models was kept constant to four bays (Fig. 4) [11, 13]. The thickness of the slab at all floors in all the models was considered as 125 mm.

Shear walls resist large portion of horizontal forces originating from wind or earthquake. The position of shear walls in the structure, influence its overall response of the structure. The hill buildings are modelled with shear walls at three different types of positions. In the numerical study, shear wall is modelled as reinforced concrete bar-bell-shaped shear wall of M 25 grade of concrete using four node shell elements (Figs. 2 and 3). The shear wall is 150 mm thick with the minimum percentage of reinforcement as 0.25%. The shear walls are positioned in three ways, namely at corners, at middle of edges and at the centre of the building (Figs. 5 and 6). To achieve better comparison and keeping the economical view, the surface area and the concrete volume of shear wall in each category were kept equal.

3 Results and Discussion

The present study investigates the influence of shear walls on the seismic performance of two hill building configurations. In all, eight models were geometrically modelled in a finite element software and analysed for gravitational as well as seismic loads. Further, for better assessment of suitability of position of the shear walls, the concrete volume and number of shear walls were designed to be equal in the respective geometric variations as well as in different direction of hill slopes.

Table 1 Geometrical properties of different configurations of hill building

Building configuration	Designation of models			Column size (mm)	Beam size (mm)
	Bare frame	Frame with shear wall			
		In corners	In middle		
Stepback	BSTEPALS	WCRSTEPALS	WMDSTEPALS	450 × 450	Along slope: 300 × 500 Across slope: 300 × 450
Stepback-setback	BSETALS	WCRSETALS	WMDSETALS	400 × 400	

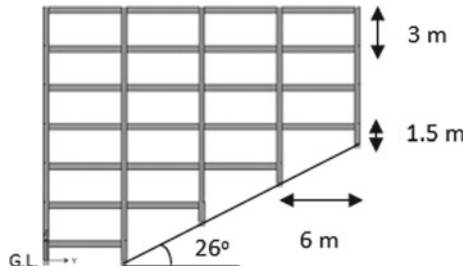


Fig. 1 Terrain properties of hill slope

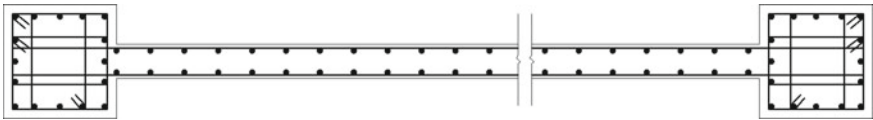


Fig. 2 Typical section of a bar-bell-shaped shear wall

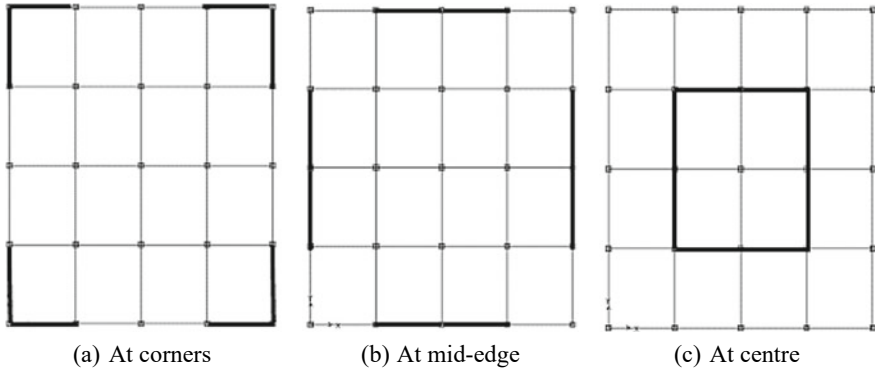


Fig. 3 Different positions of shear walls

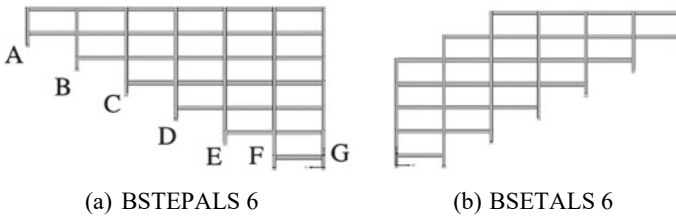


Fig. 4 Bare frame models; a stepback configuration and b stepback-setback configuration

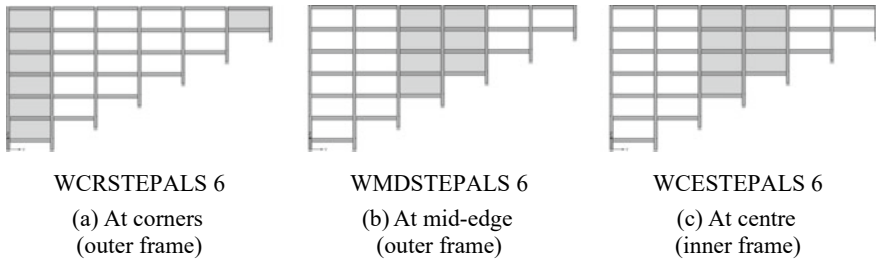


Fig. 5 Stepback buildings with shear walls

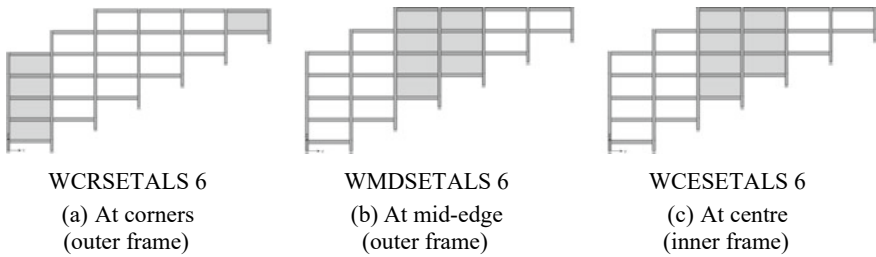


Fig. 6 Stepback-setback buildings with shear walls

3.1 Seismic Response of Stepback Configuration

The dynamic properties of bare frame models and models with shear walls at three considered locations, subjected to seismic forces along and across hill slope direction, have been mentioned in Tables 2 and 3. It was observed that shear walls significantly reduced the time period as well as top storey displacement of the building as compared to the values obtained in bare frame. In case of buildings subjected to seismic load in across slope direction, both fundamental time period and top storey displacement values were found to be increased.

Table 2 Seismic response of stepback building along hill slope

Designation	FTP* by RSA (sec)	FTP as per IS 1893 (sec)	Max. Top storey displacement (mm)	Base Shear ratio (λ)
BSTEPALS 6	0.313	0.293	6.37	1.345
WCRSTEPALS 6	0.225	0.293	2.60	1.154
WMDSTEPALS 6	0.22	0.293	2.25	1.111
WCESTEPALS 6	0.222	0.293	2.10	1.080

* FTP: Fundamental Time Period

Table 3 Seismic response of stepback building across hill slope

Designation	FTP by RSA (sec)	FTP as per IS 1893 (sec)	Max. Top storey displacement (mm)	Base Shear ratio (λ)
BSTEPALS 6	0.574	0.392	31.61	1.654
WCRSTEPALS 6	0.329	0.392	8.78	1.368
WMDSTEPALS 6	0.311	0.392	7.65	1.351
WCESTEPALS 6	0.326	0.392	6.41	1.148

Figure 7 shows the storey drift variation of stepback models in along hill slope direction. In case of hill buildings with shear walls at corners, the maximum reduction in the value of storey drift was found to be 77.7% and 67.81% in along and across slope direction, respectively, when compared with bare frame model. Whereas, in models with shear wall at mid-edge, this reduction was found to be 79.16 and 73.21% in along and across slope direction, respectively. Following the same pattern in this geometric variation, the maximum reduction in the values of storey drift was observed as 86.76% in along slope direction and 87.94% in across slope direction, when the shear walls were located in the centre. The peaks in the storey drift variation show the presence of soft storey at that level, which was due to the absence of shear walls at foundation level.

The maximum storey shear was obtained at the highest foundation level at the second last storey, in along slope direction, whereas in across slope direction, the maximum increase in the storey shear was observed at mid-storeys of the structure. The maximum increase in the storey shear was seen in hill buildings with shear walls at centre, at mid-storeys in both the directions. While at lower foundation levels, the maximum storey shear was observed in case of models with shear walls at corners, along hill slope direction, whereas in across slope direction, the maximum value of storey shear was observed in hill building with shear walls at mid-edge (see Fig. 8).

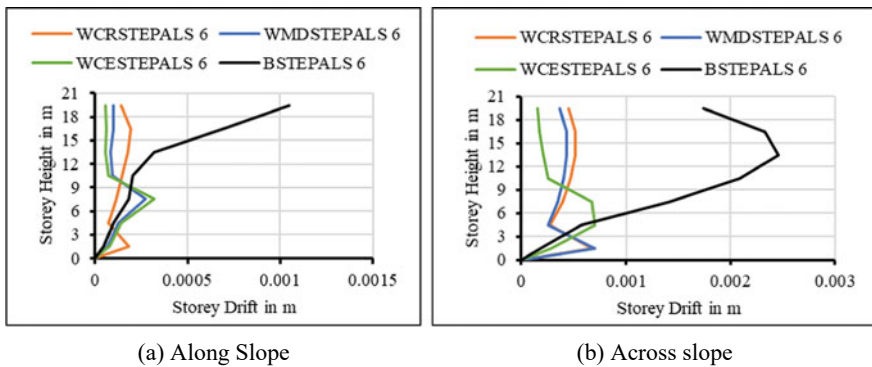


Fig. 7 Comparison of storey drift variation in stepback configuration

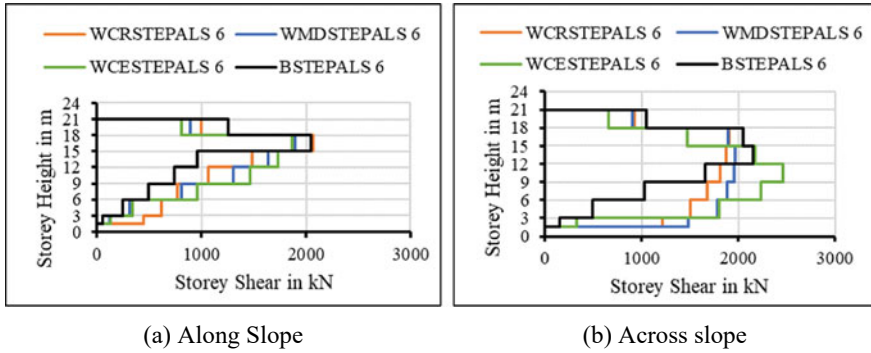


Fig. 8 Comparison of storey shear distribution in stepback configuration

In Fig. 9, the bar graphs show the comparison of shear force at foundation level in stepback configuration models with and without shear walls, in along slope direction. Following the similar pattern as in previous geometric variations. The maximum reduction in column shear force was observed at frame ‘A’, at which the highest reduction was shown by models with shear wall at mid-edge (WMDSTEPALS), but in other frames at the middle of building, an increase in the values of shear force was observed in the models with shear walls at mid-edge and centre.

However, in across the slope direction (Fig. 9), the shear force in columns at middle frames experienced a substantial decrease, as shear walls were incorporated in the buildings. Also, an abrupt increase was observed in the case of WCESTEPALS at frame ‘F’, which could be due to increased axial forces in the shear wall and hence, lead to high shear demand in column at that frame. Also, in larger frames ‘G’, ‘H’ and ‘I’, a significant increase in the values of shear force was observed in case of models with shear wall at corners and at mid-edge.

3.2 Seismic Response of Stepback-Setback Configuration

The seismic parameters obtained in analysis of stepback-setback models were found to be reduced in comparison with stepback configuration with same geometric variation. The dynamic properties for stepback-setback configuration with and without shear walls subjected to seismic forces in along as well as across slope direction have been mentioned in Tables 4 and 5. In case of model with shear walls at corners, a small reduction was observed in time period and top storey displacement, as compared with the values of bare frame model. On the other hand, model with shear walls at mid-edge showed highest reduction and found to be 25.96% in time period and 57.19% in storey displacement, when compared with respective bare frame model. However, in case of hill building with shear walls at centre, this reduction was observed to be 24.91% in time period and 61.51% in top storey displacement. Following the similar

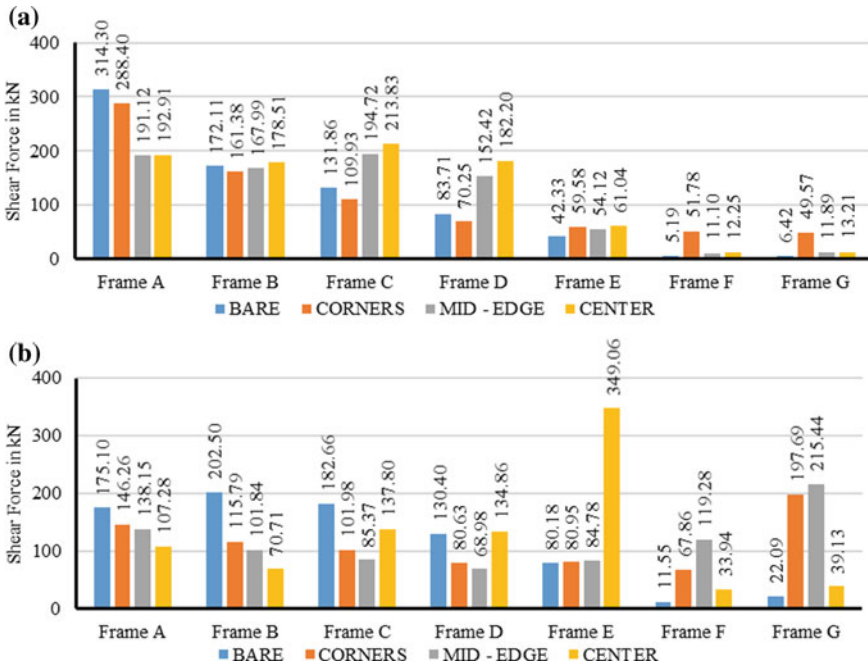


Fig. 9 Base shear distribution at foundation in stepback configuration in **a** along and **b** across hill slope

pattern as in the case of stepback models, the values of seismic parameters obtained in the analysis of stepback-setback models in across hill slope direction were found to be substantially increased as compared with the seismic response in along slope direction.

The storey drift variation in stepback-setback configuration was found to be entirely different from the previous geometric variations of stepback configurations (Fig. 10). This extreme change may be due to the asymmetric geometry of stepback-setback hill buildings. However, the values of storey drift were found to be minimum

Table 4 Seismic response of stepback-setback building along hill slope

Designation	FTP* by RSA (sec)	FTP*as per IS 1893 (sec)	Max. Top storey displacement (mm)	Base Shear ratio (λ)
BSETALS 6	0.285	0.293	5.69	1.328
WCRSETALS 6	0.214	0.293	2.71	1.238
WMDSETALS 6	0.203	0.293	1.88	1.084
WCESSETALS 6	0.207	0.293	1.79	1.066

* FTP: Fundamental Time Period

Table 5 Seismic response of stepback-setback building across hill slope

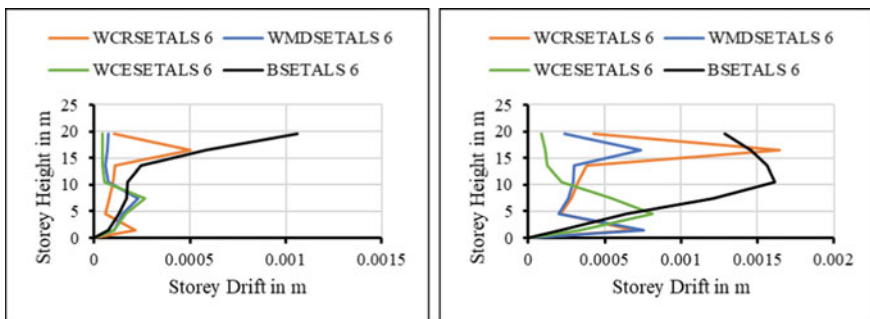
Designation	FTP* by RSA (sec)	FTP* as per IS 1893 (sec)	Max. Top storey displacement (mm)	Base Shear ratio (λ)
BSETALS 6	0.455	0.392	17.40	1.573
WCRSETALS 6	0.311	0.392	8.30	1.458
WMDSETALS 6	0.28	0.392	5.52	1.306
WCESETALS 6	0.297	0.392	3.65	1.170

* FTP: Fundamental Time Period

in all previously considered geometric variations. In model with shear walls at mid-edge (WMDSETALS 6), the reduction in the values was observed to be 90.92% and 57.69% in along and across slope direction, respectively. On the hand, model with shear walls at centre showed significant reduction in storey drift and the values get reduced to 8.0% along hill slope direction and 15.6% across hill slope direction, respectively.

The storey shear distribution in stepback-setback configuration showed entirely different behaviour than previously considered configurations (Fig. 11). The maximum storey shear obtained at upper and lowest foundation levels, in along slope direction, was observed in models with shear wall at corners. However, in mid-storeys, the maximum storey shear is observed in hill building with shear walls at centre. On the other hand, in across slope direction, the maximum storey shear at mid-storeys was observed in WCESETALS. Whereas, at lower foundation levels, this increase was seen in the models with shear wall at mid-edge.

Figure 12 shows the base shear distribution of stepback-setback models. In along hill slope direction, the shear force distribution shows the similar pattern of variation as seen in previous cases. However, in frame ‘A’, an increase in the shear demand was observed in case of models with shear wall at corners. Whereas, at middle frames,



(a) Along Slope

(b) Across slope

Fig. 10 Comparison of storey drift variation in stepback-setback configuration

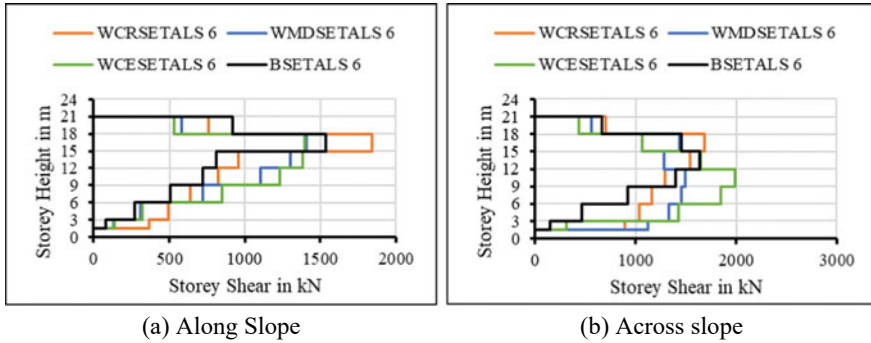


Fig. 11 Comparison of storey shear distribution in stepback-setback configuration

an increase in the shear force was observed in case of models with shear walls at mid-edge and at centre.

However, when models were subjected to seismic forces in across slope direction, the base shear distribution show different variation than in along slope direction. At frame ‘A’, an abrupt increase was observed in case of WMDSETALS, whereas, at

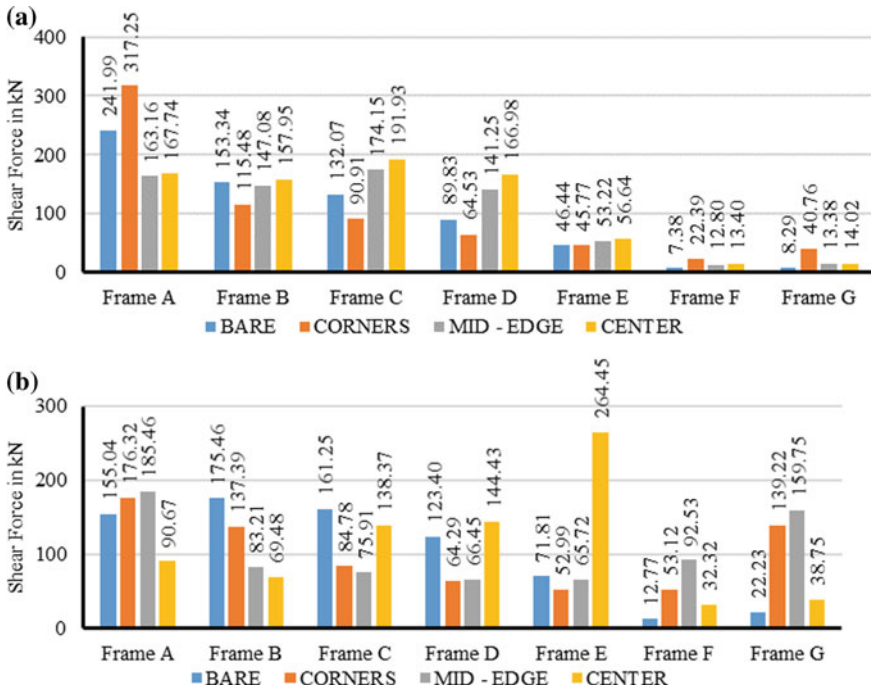


Fig. 12 Base shear distribution at foundation in stepback-setback configuration in a along and b across hill slope

middle frames, a significant reduction was observed in case of models with shear walls. Also, following the same pattern in previous geometric variation, the maximum shear force was developed at frame 'F' in WCESETALS. It was also found that stepback-setback buildings experience less base shear forces than that in stepback configuration of hill buildings.

4 Conclusion

This study investigates the influence of shear walls on the seismic performance of two hill building configurations. The buildings were modelled with shear walls at three different locations, viz. at corners, at mid-edge and at centre of building. Further, for better comparison of suitability of position, the total concrete volume and number of shear walls were designed to be equal in the respective geometric variations as well as in different direction of hill slopes.

In all the considered configurations, models with shear walls at centre showed maximum reduction in time period and top storey displacement in both hill slope directions. Following the same pattern, maximum reduction in storey drift was observed in buildings with shear wall present at centre and was found to be reduced by 85% as compared with bare frame models. The maximum base shear was observed in stepback models, at upper most foundation level in along slope direction, whereas in transverse direction, the maximum value was found in middle storeys, when the shear walls were kept at mid-edge position. The base shear at foundation level in all the cases was found to be reduced at frame 'A' (shortest frame) in along the slope direction, whereas a marginal increase is observed in other frames. In across the slope direction, a mixed response of increase and decrease in the shear force values was observed.

Thus, the models with shear walls present at centre are proven to be more effective than other configurations. However, a drastic increase observed in the base shear, in across slope direction, should be considered in the structural design, whereas buildings with shear walls at corners and mid-edge show reduced values of base shear at the foundation level and also provide extra stiffness to the structure therefore, reducing the torsional moments. Thus, a combination of shear walls at different positions should be provided for achieving better dynamic response of the hill buildings and to counter their asymmetric nature.

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