ORIGINAL ARTICLE VW Applied Sciences

DOI: 10.36297/vw.applsci.v1i1.29 ISSN: 2582-5615

VW Applied Sciences, Volume: 1, Issue: 1, 37-47

Effect of Un-reinforced Masonry Infills on Seismic Performance of Hill Buildings

Zaid Mohammad[1]

[1]Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee, India
Author Email: zaidzhcet@gmail.com

Received:
Oct. 22, 2019
Accepted:
Nov. 21, 2019
Published online:
Nov. 24, 2019

Abstract: The present study investigates the influence of un-reinforced masonry infill panels on the seismic performance of stepback and stepback-setback hill building configurations. Masonry infills are often used for partition in RC frame construction and its significance as a structural element in the analysis and design is generally neglected. Thus, to observe structural effect on the seismic response of hill buildings, masonry infill panels are modelled as diagonal struts and analysed as truss elements. In all, sixteen models with and without masonry infills are modelled and analyzed by using response spectrum method and dynamic properties are presented and compared within considered configurations. It is observed that masonry infills not only reduce overall storey drift and base shear at different foundation levels but also increase the shear demand in the surrounding frame due to high lateral stiffness when subjected seismic loads. It is concluded that the masonry infill panels entirely change the seismic response of a building and thus, it is important to incorporate these elements in the analysis and design of the building structure, in order to understand the true structural response.

Keywords: Hill buildings; Stepback and Stepback-setback; Masonry infill panels; Equivalent diagonal strut model; Response Spectrum analysis.

1. Introduction

In the last five decades, with development of reinforced concrete and steel, a new era of building techniques has emerged and construction with these materials became popular due to their inherent advantages. Houses built on the steep slopes, pose special structural and construction problems and hence, their structural behavior is entirely different from a building on a plain ground. On steep slopes, buildings are generally constructed in stepback configuration, though a combination of stepback with setback is also common. However, due to the unsymmetrical nature of these buildings, there is development of torsional moments due to the eccentricity caused by the difference in the alignments of the center of mass and center of stiffness at each floor. Also, at the location of setbacks and stepbacks, an increase in the stress concentration has also been reported, when the building is subjected to seismic forces.

A significant amount of research work [1-11] has been carried out to ascertain the seismic behavior of hill buildings. Previous studies have reported various problems and suggested different modelling techniques for lateral load analysis of stepback and setback buildings. Analytical and experimental studies were presented stating static and dynamic design requirements for setback buildings [1 & 2]. Paul and Kumar [3-7] suggested a simplified approach for dynamic analysis of hill buildings. A method of analysis was developed in which each storey of the building was modelled with 3 D.O.F. per floor with rigid floor diaphragm rigid and, results obtained have been compared with the IS Code method 1893: 1984 and then, with the rigorous method having 6 D.O.F. per node considering flexibility of floor. Birajdar and Nalawade [8] studied various configuration of stepback and setback buildings and parametrically compared dynamic properties of the buildings and suggested the suitability aspect. Singh et al. [9] investigated a case study validating the damage pattern of a hill building (Sikkim earthquake, 2011), with Linear and Non-linear Time History analysis. Narayanan et al. explored the adequacy of fixidity of column foundations in stepback buildings subjected to earthquake loads and suggested the suitability of the plan aspect of the buildings on slopes [10]. Mohammad et al. [11] presented a parametric study involving the plan aspect ratio of stepback and stepback-setback configurations subjected to seismic load in along and across hill slope direction. Three dimensional models of buildings were analyzed using Response Spectrum analysis and the results were obtained, then compared within the configurations. It was observed that the upper most storey were subjected to larger shear forces than the rest storeys. Further, stepback-setback configuration showed 45 % reduction in the base shear, when compared with stepback configuration buildings and experienced lesser torsional moments and seismic forces.

Masonry infills are non-structural elements and are often used for partition in RC or steel frame construction, with the assumptions that these infills do not take part in resisting any kind of load either axial or lateral, hence its significance in the analysis and design is generally neglected. Also, non-availability of realistic and simple analytical models of infills becomes another complexity in the analysis. Fardis [12], Kappos et al. [13], Singh [14] and Demir and Sivri [15] reported that masonry infill panels affect the seismic performance of the frame structure by increasing the lateral stiffness, when subjected to seismic loads. Also, these infills dissipate more energy than the surrounding framed structure. In fact, an infill wall enhances considerable strength and rigidity of the structure. It was observed that frame with infill panels has more resistance to the lateral forces compared with the bare frames and their ignorance in the analysis and design causes unexpected failure of the multistoried buildings. The main reason of the failure is the stiffening effect of infilled frame which enhances the axial forces and bending moments in the surrounding frame of the masonry infill. Structural behavior of infill panel is itself very complex, when subjected to lateral loads. In last five decades, various failure modes were identified and proposed based on experimental and analytical investigations carried out by Thomas, Wood, Mainstone, Liauw & Kwan, Mehrabi & Shing, Ghosh & Made and El-Dakhakhni et al. [16-24]. The failure modes were categorized as; corner crushing (CC), diagonal compression (DC), sliding shear (SS), diagonal cracking (DK) and frame failure mode (FF). Out of these, the corner crushing mode and sliding shear mode were found to be prime failure modes [25]. To evaluate these failure modes and incorporate in the analytical and numerical analyses, various macro-models were proposed involving single (Polyakov, Holmes, Smith, Smith & Carter, Mainstone, FEMA-274, Bazan and Meli [26-34]) and multiple diagonal strut models (Thiruvengadam, FEMA-356, Chrysostomou, Saneinejad & Hobbs, Madan et al., El-Dakhakhni, Crisafulli, Crisafulli & Carr [24, 35-42]). Asteris et al. [43] presented a review study of the comprehensive models and pointed out various advantages and disadvantage of each macro models. Further, practical implementations in the numerical analysis for commercial purposes were recommended as, the finite element modelling of single strut model was simple and can be used easily in engineering design problems, however lacked the ability to capture the masonry infill and RC frame interaction. Whereas, multi-strut models provided better modelling of the RC frame-infill interaction, but due to their complex modelling approach cannot be used in day to day engineering practice.

From the previous studies, it can be concluded that masonry infill panels entirely change the seismic performance of RC framed structure building by increasing the lateral stiffness, when subjected to seismic loads. The seismic behavior of hill building, itself is observed to be very different and complex when compared with that of normal building [11]. Hence, this effect of infill panels on hill buildings will be more pronounced due to the unsymmetrical structure configuration along and across the hill slope. Thus, there is a need for further study to reflect the true behavior of hill building configurations with the inclusion of masonry panels during the analysis. To observe the influence of masonry infill panels on hill configuration buildings (stepback and stepback-setback), the present study analyses two types of models, first is bare frame model in which only distributed load of masonry wall is considered, wherein second type models, masonry infill panels are modelled as diagonal strut and incorporated as truss elements with 3 degree of freedom per node at each end of the element, in the analyses. In all, sixteen models are modelled and analyzed by using Response Spectrum method and dynamic properties are presented and compared within considered configurations.

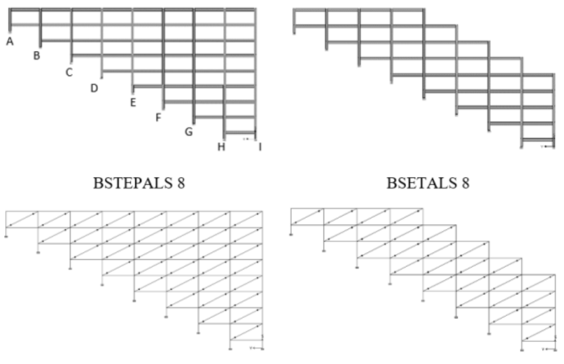
2. Method of analysis

In this study, the effect of masonry infills is investigated on two hill building configurations, viz. stepback and stepback-setback configuration. The two configurations are also varied parametrically to observe the variation in seismic parameters with increase in height and length of the buildings. All the configurations are modelled three dimensionally without and with the inclusion of unreinforced masonry infill panels as bare frame models and models with infill walls, respectively. Seismic analysis is carried out by using Equivalent Static approach and Response Spectrum method with SRSS combination as per IS 1893 (Part 1): 2000, by using finite element code ETABS v 9.0. Important seismic parameters such as fundamental time period, maximum top story displacement, storey shear, storey drift and column shear at ground level in each direction, i.e. along slope and across slope of hill, are obtained and compared with respective bare frame configurations.

The seismic parameters considered in dynamic analysis of all the models are assumed as per IS 1893 (Part 1): 2002. The hill buildings are assumed to be in Zone V with the peak ground acceleration value of 0.36g. The importance factor, I is taken as 1.5 (for important building). Also, the response reduction factor R taken as 5 for SMRF system of the buildings. The soil strata beneath the foundation is assumed as medium soil. The gravity and imposed loads are taken as per IS 875 (Part 1 and 2): 1987, self-weight of the structure is calculated and imposed load is assumed to be 3 kN/m2 for a typical residential building. The effect of lateral earth pressure is neglected in the analysis to observe only the effect of lateral forces due to seismic loads. In bare frame models, only gravity load of infill panels is considered as uniformly distributed on the respective beam members. All the models of both building configurations are analyzed, designed and checked for any failure of members and hence the size of the columns is varied accordingly as the height of the structure increases. The reinforcement in the columns is varied from 1% to 3.5%, whereas in beams and slabs, nominal designed percentage of rebar is provided in both the directions as per codal provisions.

2.1 Geometrical modelling

All configurations have been modelled with same geometrical and material properties, and rest on the same inclination of ground which is 26° (Fig. 1). The geometrical properties of the structural elements in the models with designation of different model types are given in Table 1. The material is assumed to be homogenous, isotropic and elastic in nature with modulus of elasticity of concrete is taken as 25000 N/mm^2 and value of Poisson's ratio is 0.2. The grade of reinforcement steel is taken as Fe 415. The floor system in the all the configurations is modelled as rigid frame diaphragm and all beam and column members are modelled as two node beam elements. The foundation in all the models is assumed to be fixed support system. The torsional effects and accidental eccentricity is considered in the analysis as per IS 1893 (Part 1): 2002. The hill building configurations are geometrically varied in height and length along the hill slope and width of the model is kept constant to four bays in all models. The inter-storey height is taken as 3 meters and foundation depth is 1.5 m in all the buildings. The thickness of the slab at all floors in all the models is considered as 125 mm. Further, variation in length of both configurations (stepback and stepback-setback) along the slope is carried out from four bays (6 m each) to eight bays with an increment of one bays at each step (Fig. 1).



BSTEPALS 8

BSETALS 8

MSTEPALS 8

MSETALS 8

Fig. 1. Typical models of stepback and stepback-setback configurations

2.2 Constitutive model for masonry infill panel

As inflicted from the previous investigations [44], single diagonal strut model is used in the analyses to impart the behavior of infill panels onto surrounding RC frame. The masonry infill walls of 230 mm thickness are taken only at the periphery of the building at each storey. These infill walls are incorporated as diagonal struts with the specification of a truss. The condition of a truss member is achieved by releasing all the moments at each end, hence each strut consists only three degrees of freedom (translational only) per node at each end of the member. The formulations for the length of contact between wall and frame (Fig. 2), αh and αL, as given by Smith [28-30] for equivalent diagonal strut model, are described in the equations 1 and 2. The values of different parameters taken for the calculation for the width of equivalent diagonal strut along and across the slope are mentioned in Table 2. The value of Young's modulus of elasticity of brick masonry is assumed as 4500 N/mm2 and Poisson's ratio is taken to be 0.17 (Rai et al. [45]).

$$\alpha_h = \frac{\pi}{2}\sqrt[4]{\frac{4\,E_f\,I_c\,h}{E_m t\ \sin 2\theta}} \tag{1}$$

$$\alpha_L = \pi\sqrt[4]{\frac{4\,E_f\,I_b L}{E_m t\ \sin 2\theta}} \tag{2}$$

where,

Em and Ef = Elastic modulus of the masonry wall and frame material, respectively

t, h, L = thickness, height and length of the infill wall, respectively.

Ic and Ib = Moment of inertia of the column and beam of the frame, respectively

$\theta = \tan^{-1}\left({}^{h}\!/_{L}\right)$

Hendry [46] recommended that the equivalent or effective strut width w, where the strut is assumed to be subjected to uniform compressive stress.

$$w = \frac{1}{2}\sqrt{\alpha_h^2 + \alpha_L^2} \tag{3}$$

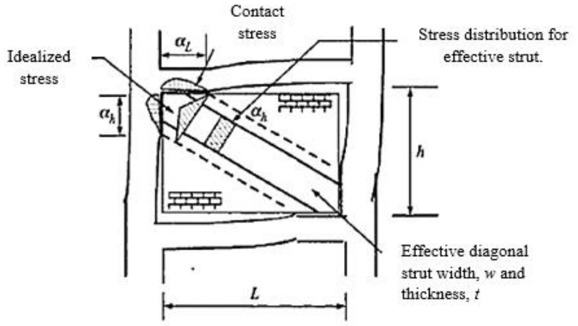


Fig. 2. Equivalent diagonal strut formulation of masonry infill panel.

3. Discussion of results

The present study investigates the effect of un-reinforced masonry infills on the seismic behavior of two hill building configurations. Two types of models are considered, first is bare frame model in which distributed load of masonry wall is considered, wherein second type, masonry infill panels are modelled as diagonal strut. In all, sixteen models are modelled and analyzed by using response spectrum method and dynamic properties are presented and compared within the considered configurations.

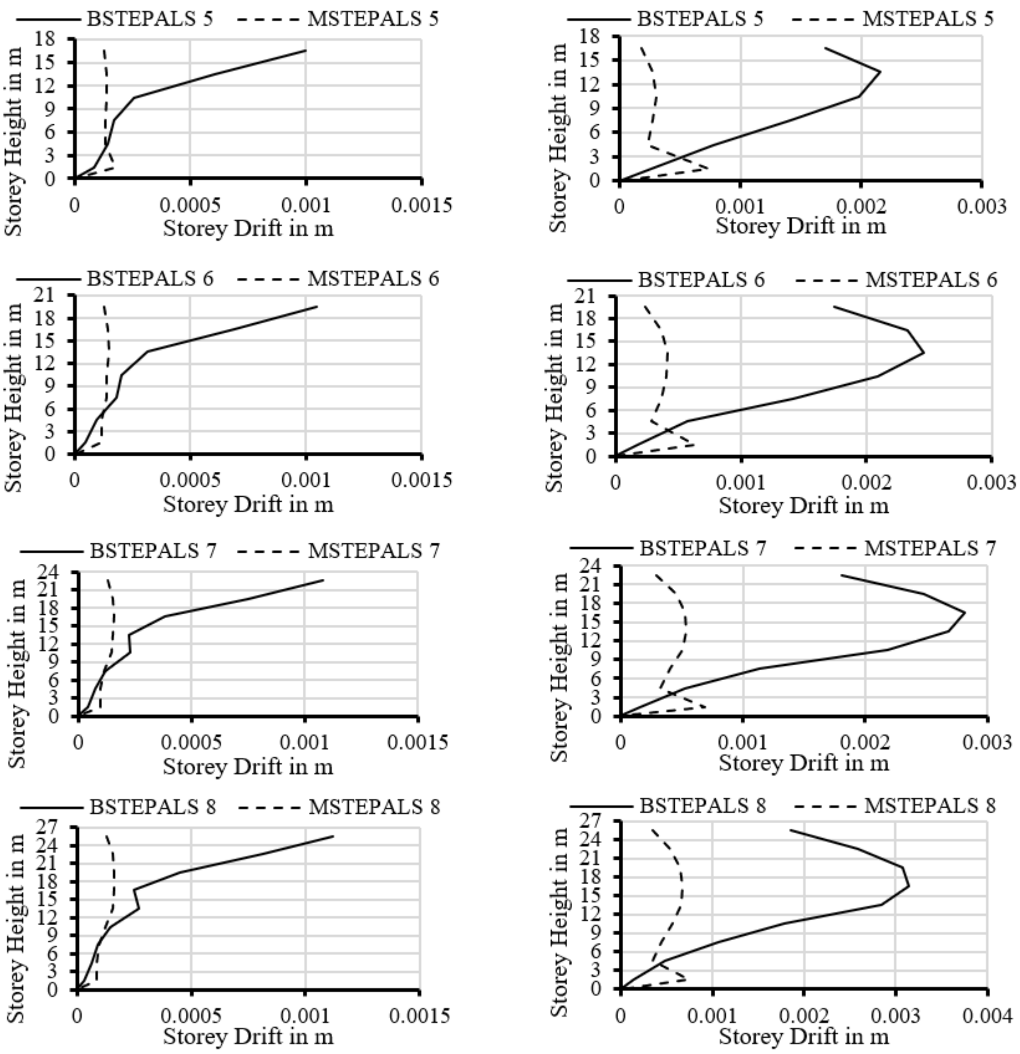


Fig. 3. Comparison of storey drift variation in stepback buildings in; (a) along slope, (b) across slope direction.

3.1 Seismic performance of stepback configuration

Both the models viz., bare frame and frame with equivalent diagonal strut are varied in length (as well as the height of the structure is simultaneously increased) from 4 bays to 8 bays, one bay at a time, in along slope direction. The length of the model is kept fixed in across slope direction to four bays. These buildings are designated as BSTEPALS for bare frame buildings and MSTEPALS for buildings with diagonal struts. The dynamic response is tabulated in Table 3 and Table 4. In case of bare frame models, a marginal increase is observed in the value of fundamental time period obtained from modal analysis as compared to values calculated by empirical formulations. Also, there is increase in the top storey displacement is observed, as the height of the structure is increased. Whereas, after the inclusion of equivalent diagonal strut, a significant decrease in the values of time period and top storey displacement is observed. In model MSTEPALS 8, the time period is reduced by 27.3% and top storey displacement is reduced by 59.11% as compared to that of bare frame model (BSTEPALS 8).

The values of fundamental time period and top storey displacement are found to be increased when the considered models are subjected to seismic force in across slope direction as compared to values obtained in the along slope direction. In the analysis of bare frame models, the maximum values of time period and storey displacement are found to be 0.736 sec and 48.37 mm (BSTEPALS 8). Whereas, models with diagonal struts show significant reduction in time period and top storey displacement. In MSTEPALS 8, this reduction is found to be 44.56% in time period and 71.67% in displacement of the top storey.

A substantial decrease in storey drift variation of the models with diagonal struts is observed, when subjected to earthquake load in both the direction (Fig. 3). However, this decrease, in storey drift is due to the stiffness imparted by masonry infills in all storey levels. At maximum, the storey drift is reduced by 88.3% of that in case of bare frame model in along slope direction and in across slope direction, the value reduced by 78.4% of that in the case of MSTEPALS 8.

The storey shear distribution shows the similar pattern of increase in shear demand due to truss action induced in the infill panels also, these infills attract larger forces due to their higher stiffness. Further, the storey shear in across slope direction is found to be more as compared to that in along slope direction. The largest increase in the value of storey shear in along slope direction is obtained at third storey from the top, is 995.4 kN. Whereas, in across slope direction this value is found to be 1678.75 kN at second storey level. This increase is due to the less stiffness in across slope direction (Fig. 4). In Fig. 5(a), the bar graphs show the comparison of shear force at foundation level of stepback configuration varied in length along hill slope.

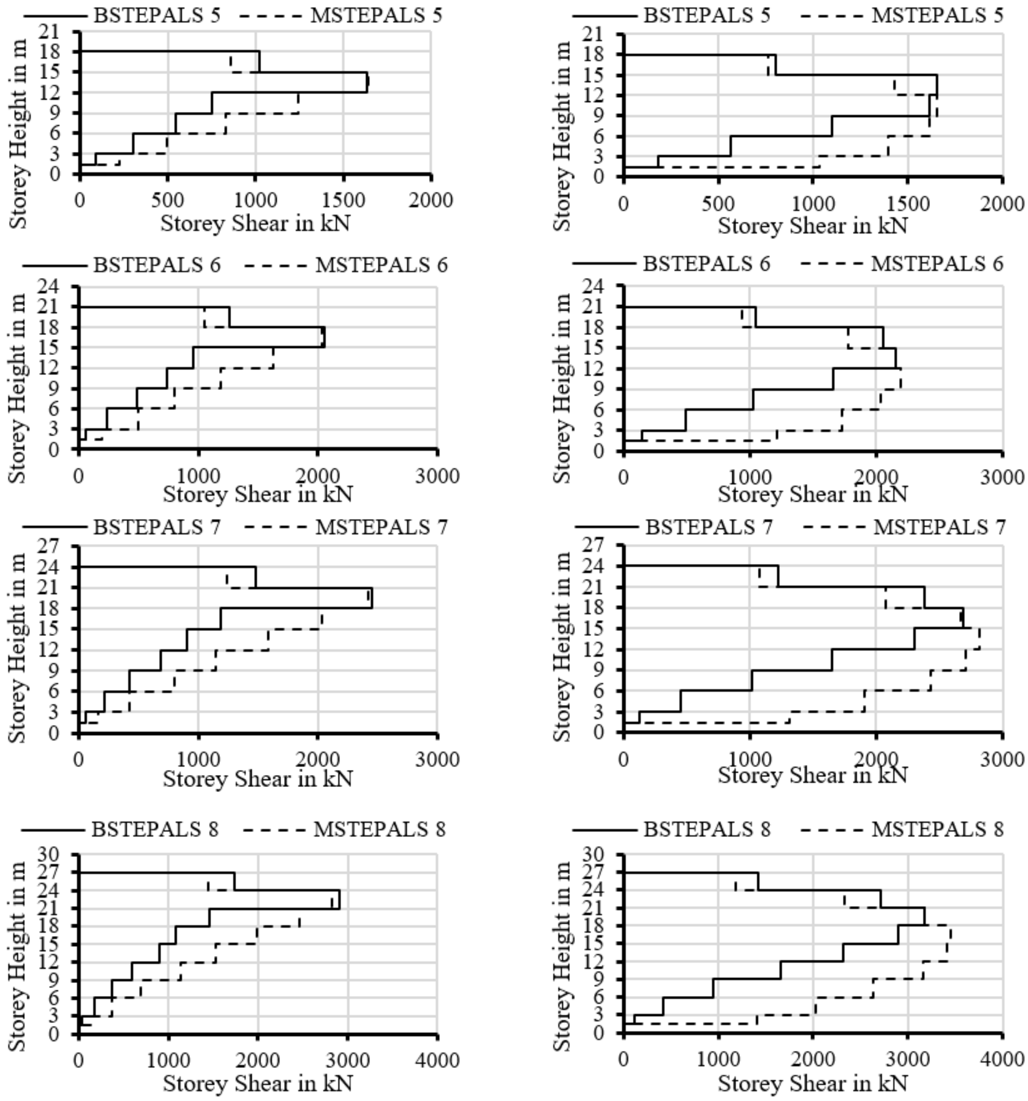


Fig. 4. Comparison of storey shear distribution in stepback buildings in; (a) along slope, (b) across slope direction

A substantial decrease in the value of shear force at upper foundation level at frame 'A' is observed when the infills are used as diagonal struts and the maximum reduction in the value is found to be 34.8% in case of MSTEPALS 8. Whereas, in other frames such as 'B', 'C', 'D', etc. a marginal difference is observed between the values obtained from BSTEPALS and MSTEPALS. On the other hand, when these models are subjected to seismic forces in across slope direction, the seismic response show drastic change in the values obtained from the analysis of MSTEPALS. The graphs (Fig. 5b) show that the shear forces developed due to the torsional effects in shorter frames, get distributed to other frames when the diagonal struts are incorporated in the bare frame models. The maximum reduction in shear force is found at frame 'A' in MSTEPALS 8 is 41.32%. Whereas, at the frame 'I' of the same model, the shear force is increased by 154.5 kN as compared to that in bare frame model.

3.2 Seismic performance of stepback-setback configuration

In this section both bare frame models and models with infill panels of stepback-setback configuration are varied geometrically in length along hill slope direction from 4 to 8 bays. As in the previous geometric variation, the length of the analytical models is kept fixed to 4 bays (5 m each) in across slope direction. The bare frame models in which the masonry infills are incorporated as uniformly distributed load are designated as BSETALS and models with diagonal strut are designated as MSETALS.

The seismic parameters obtained from the analysis of BSETALS and MSETALS in along slope direction are given in Table 5 and Table 6, respectively. In the case of bare frame models, a marginal difference is observed in fundamental time period, obtained from empirical relation given in IS 1893, as the length of models is increased. However, the values of time period given by modal analysis are found to be approximately same, as the length of the model is increased. This surprising behavior may be due to the same length of columns present in the structure of stepback-setback configuration buildings. Whereas, models with diagonal struts show different behavior than the bare frame. As the length of the models is increased, there is an increase in the values of time period is observed.

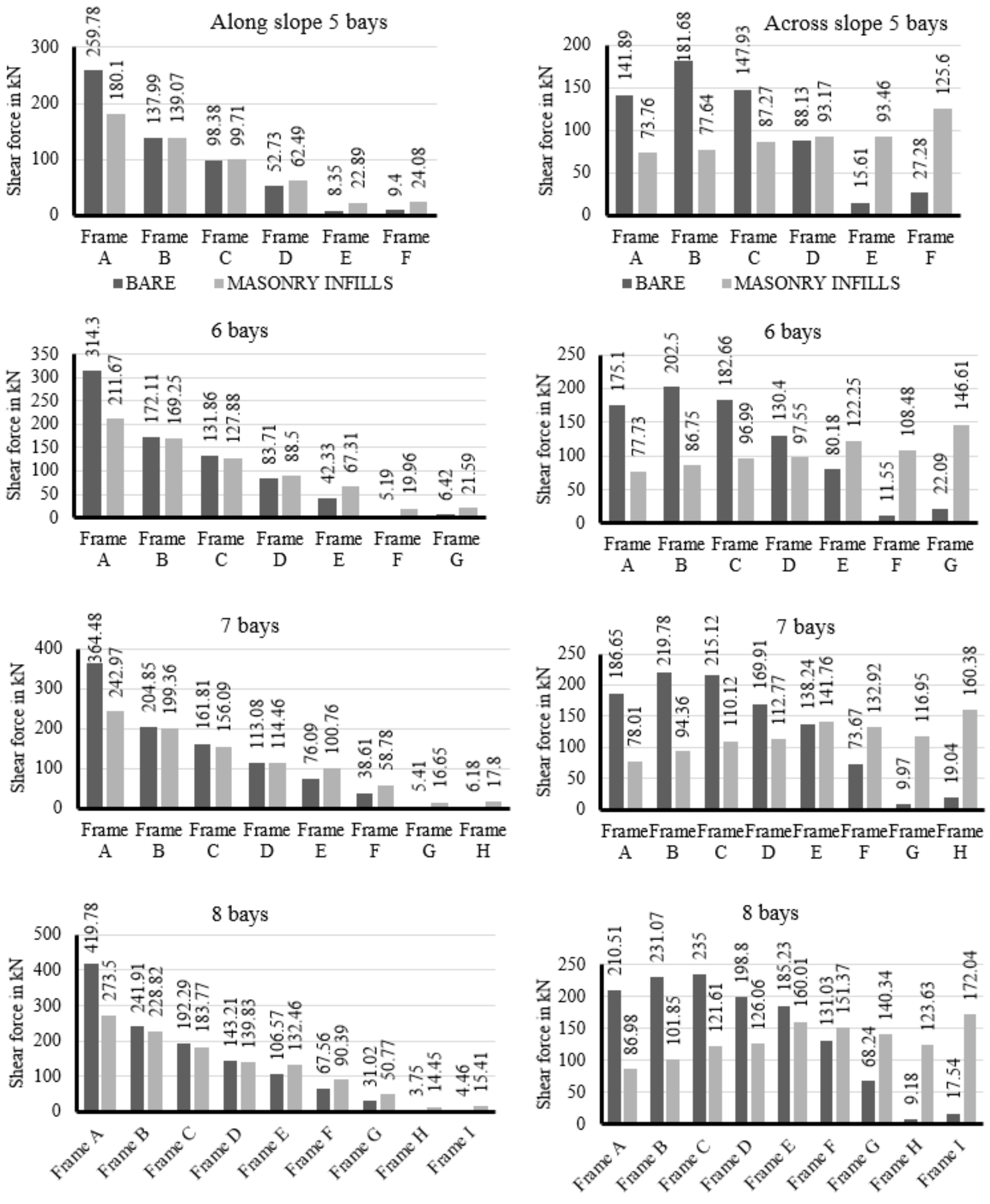


Fig. 5. Base shear distribution at foundation level in stepback buildings in; (a) along, (b) across hill slope direction

Also, the values of time period and top storey displacement obtained in analysis of **MSETALS**, are found to be reduced as compared to that in case of bare frame models, due to extra stiffness imparted by diagonal struts.

Bare frame models and models with infill panels, also behave different across the hill slope direction. The time period of bare frame models obtained from the modal analysis, is found to be ranging from 0.418 to 0.467 seconds. Also, the maximum storey displacement at the top floor show increased value ranging from 16.53 mm to 18.92 mm, as compared to the bare frame models (Table 5). Whereas, when the infill panels are incorporated as diagonal struts, a significant reduction in the time period and storey displacement is observed. The reduced values of time period obtained from modal analysis and top storey displacement vary from 0.211 sec to 0.277 sec and from 2.79 mm to 4.02 mm, respectively (Table 6).

The storey drift values obtained from the analysis of BSETALS and MSETALS, show entirely different variation from the previous models (Fig. 6). In along slope direction, as the length of the models are increased, there is almost no deviation is observed in the store drift values. However, in across slope direction, the maximum values of storey drift obtained in the analysis of bare frame models, are found to be decreasing as the length of the model is increased. Whereas, models with diagonal struts show similar patterns of storey drift variation as in previous geometric variations. However, due to reduced seismic weight, the storey drift is observed to be less as compared to stepback configuration models.

Fig. 7 (a) and (b) show the storey shear distribution of bare frame model and models with diagonals struts in along and across slope direction. There is no change observed in the values of storey shear obtained from BSETALS at second last storey, as the length of the stepback-setback models is increased. However, a sudden decrease in the storey shear is observed at third and fourth storey from the top in BSETALS 8.

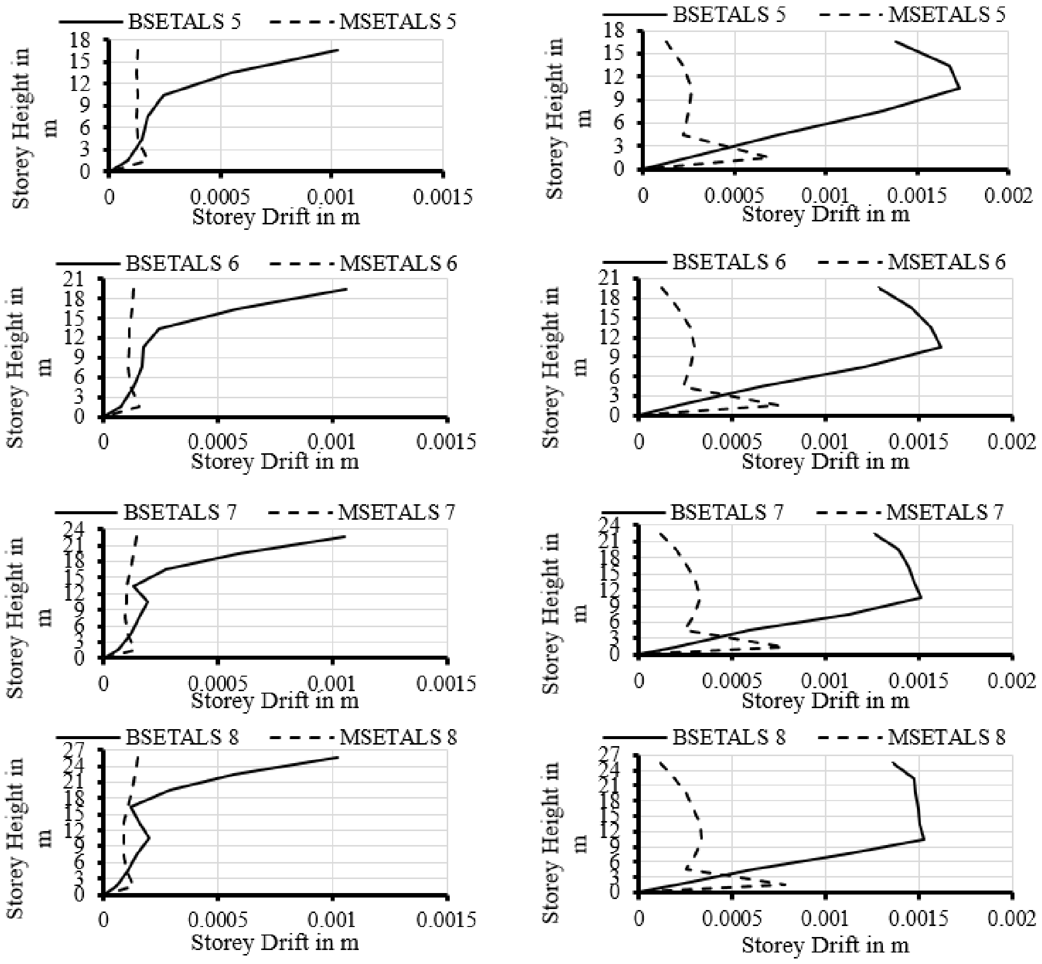


Fig. 6. Comparison of storey drift variation in stepback-setback buildings in; (a) along, (b) across slope direction.

Whereas, in MSETALS, there is a linear increase in the storey shear is observed as the models are geometrically varied in length. On the other hand, in across slope direction, a marginal increase in the storey shear in

BSETALS is observed, which increased gradually with the length of the models. Also, in case of MSETALS, the storey shear is found to be increased as compared to bare frame models, due to increase in the shear demand in lower foundation columns of the models. At the maximum, the value of storey shear is found to be increased by 1082.23 kN in MSETALS 8 model.

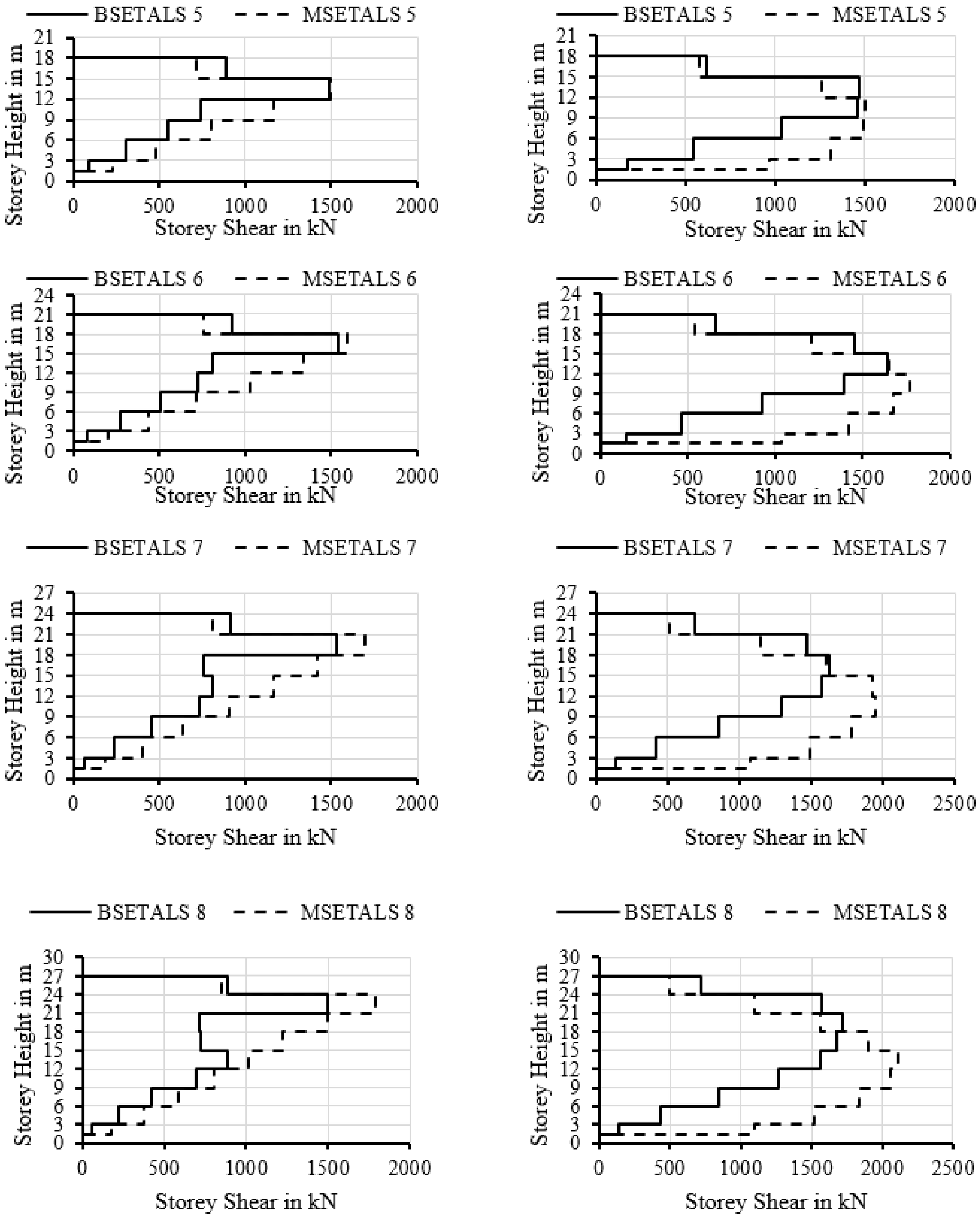


Fig. 7. Comparison of storey shear distribution in stepback-setback buildings in; (a) along, (b) across slope direction

Fig. 8 (a) show the base shear distribution in columns at foundation level, in along hill slope direction. Following the similar pattern as in the previous geometric variations, the shear force is reduced at frame 'A' and marginal difference is observed in other frames in MSETALS 5. However, as the length is increased in along slope direction, a small decrease is also obtained in the middle frames in MSETALS 8. On the other hand, base shear in across slope direction show significant reduction in frames 'A', 'B' and 'C' as well as an increase is observed in other remaining frames of MSETALS 5 (Fig. 8b). Also, as the length of the models is increased, in frames 'A, B, C, D and E' of MSETALS 8, the reduction in the values is increased. However, in other frames from 'F' to 'I', a substantial increase in the base shear force is detected. This increase is due to the distribution of shear forces caused by the truss action developed in masonry infill panels.

4. Conclusions

The present study explores the effect of un-reinforced masonry infills on stepback and stepback-setback configurations of hill buildings. Two types of models are modelled viz., bare frame model in which distributed load of masonry wall is considered, wherein second type, masonry infill panels are modelled as diagonal strut.

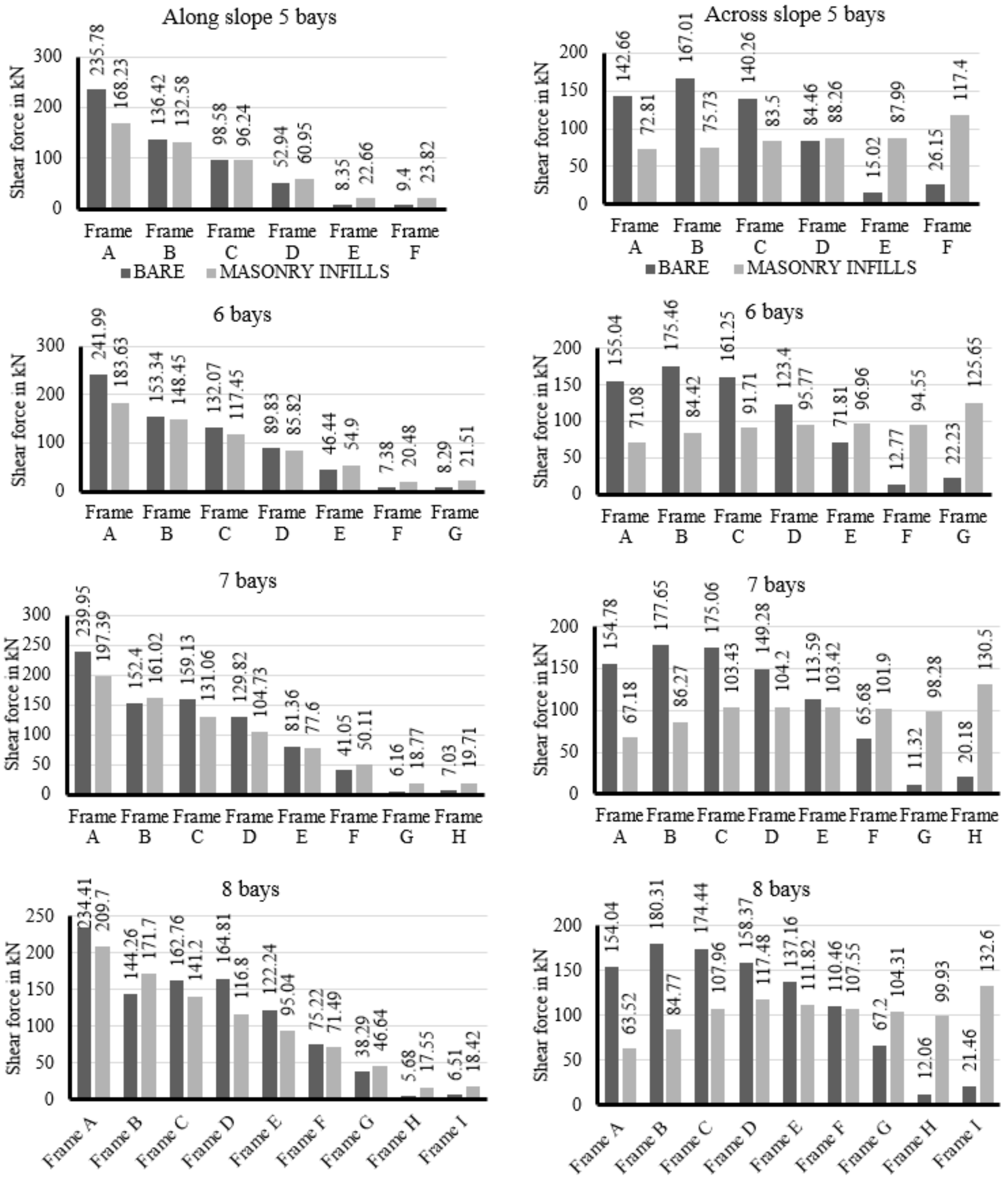


Fig. 8. Base shear distribution at foundation level in stepback-setback buildings in; (a) along, (b) across hill slope direction

In all, sixteen models are analyzed by using response spectrum method and dynamic properties are presented and compared within the considered configurations.

As the masonry infills are incorporated in structural analysis of hill buildings, the values of time period and top storey displacement in stepback configuration, are drastically reduced in both along and across slope direction, respectively. However, a marginal change is observed in case of stepback-setback buildings. Also, both the hill building configurations show substantial decrease in the storey drift in along and across hill slope. Moreover, stepback-setback buildings produce less storey drift as compared to stepback configurations, due to less seismic weight in the structure.

The masonry infills attracts larger portion of forces due to their high in-plane stiffness, enhancing the stresses in the surrounding frame elements and total storey shear at lower foundation levels in both configurations.In stepback models, a substantial reduction in base shear at the upper foundation level (frame 'A'), is observed in along and across slope direction after the consideration of masonry infills in the analysis and found to be about 35% and 60%, respectively. On the other hand, in stepback-setback models, the base shear is reduced by 11% and 58% in along and across slope direction. Whereas, in other frames, an increase in the value is observed due to high axial forces and shear demand induced by masonry infill panels.

It is concluded that the masonry infill panels entirely change the seismic response of a building and thus, it is important to incorporate these elements in the analysis and design of the building structure, in order to understand the true behavior of structure. Also, infills not only provide bracing effect in the structure, but also attract large shear forces due to their high in-plane lateral stiffness and increase storey shear by increasing shear demand in the surrounding frame elements of the structure. Thus, suitable design measures should be taken during the construction of the frame members to encounter the severe increase in the shear demand due to masonry infill panels.

References

[1] Cheung VWT, Tso WK. Lateral load analysis for buildings with setbacks. J. ASCE Structural Division, 1987, 113 (2), 209-227. https://doi.org/10.1061/(ASCE)0733-9445(1987)113:2(209)

[2] Shahrooz BM, Miele JP. Seismic response and design of setback buildings. J. of Structural Engg. ASCE, 1990, 116 (5), 1423-1439. https://doi.org/10.1061/(ASCE)0733-9445(1990)116:5(1423)

[3] Paul DK. Simplified seismic analysis of buildings on hill slopes. Bull. Indian Society of Earthquake Technology, 1993, 30 (4), 113-124.

[4] Kumar S, Paul DK. 3-D analysis of irregular buildings with rigid floor diaphragm. Bull. Indian Society of Earthquake Technology, 1994a, 31 (3), 141-154.

[5] Kumar S, Paul DK. Dynamic analysis of stepback and setback buildings. Proc. Tenth Symposium on Earthquake Engineering, 1994b, 1, 341-350.

[6] Kumar S, Paul DK. A simplified method for elastic seismic analysis of hill buildings. Journal of Earthquake Engineering, 1998, 2 (2), 241-266. http://dx.doi.org/10.1080/13632469809350321

[7] Kumar S, Paul DK. Hill buildings configuration from seismic consideration. Journal of Structural Engineering, 1999, 26 (3), 179-185.

[8] Birajdar BG, Nalawade S. Seismic analysis of buildings resting on sloping ground. Proc., In Thirteenth World Conference on Earthquake Engineering (13WCEE), Vancouver, Canada, 2004.

[9] Singh Y, Gade P, Lang DH, Erduran E. Seismic behavior of buildings located on slopes: An analytical study and some observations from Sikkim earthquake of September 18, 2011. Proc., In Fifteenth World Conference on Earthquake Engineering, 15 WCEE, Lisbon, Portugal, 2012.

[10] Narayanan ARV, Goswami R, Murty CVR. Performance of RC buildings along hill slopes of Himalayas during 2011 Sikkim earthquake. Proc., In Fifteenth World Conference on Earthquake Engineering, 15 WCEE, Lisbon, Portugal, 2012.

[11] Mohammad Z, Baqi A, Arif M. Seismic response of RC framed buildings resting on hill slopes. In the Proceedings of 11th International Symposium on Plasticity and Impact Mechanics, Implast, Dec. 11 to 14, 2016. Procedia Engineering, 2017, 173: 1792-99. https://doi.org/10.1016/j.proeng.2016.12.221

[12] Fardis MN. Experimental and numerical investigation on the seismic response of R.C. infilled frames and recommendations for code provisions. European Consortium of Earthquake Shaking Tables and Performative Research in Support of Eurocode 8(6), 1996.

[13] Kappos AJ, Styliandis KC, Michailidis CN. Analytical model for brick masonry infilled R/C frames under lateral loading. Journal of Earthquake Engineering; 1997, 2(1): 59-87. http://dx.doi.org/10.1080/13632469809350314

[14] Singh H. Inelastic dynamic response of reinforced concrete infilled frames. Computers and Structures, 1998, 69(6): 685-693. https://doi.org/10.1016/S0045-7949(98)00124-2

[15] Demir F, Sivri M. Earthquake response of masonry infilled frames. ECAS2002, International Symposium on Structural and Earthquake Engineering, Middle East Technical University, Ankara, Turkey, 2002, 151-158.

[16] Thomas FG. The strength of brickwork. Struct. Eng., 1953, 31(2): 44-46.

[17] Wood RH. The stability of tall buildings. ICE Proc., 1958, 11: 69–102.

[18] Mainstone RJ. Discussion on steel frames with brickwork and concrete infilling. ICE Proc., 1962, 23: 94-99.

[19] Liauw TC and Kwan KH. Plastic theory of infilled frames with finite interface shear strength. ICE Proc., 1983a, 75(4): 707-723.

[20] Liauw TC and Kwan KH. Plastic theory of non-integral infilled frames. ICE Proc., 1983b, 75(3): 379-396.

[21] Liauw TC and Kwan KH. Nonlinear behaviour of nonintegral infilled frames. Comput. Struct., 1984, 18: 551-560.

[22] Mehrabi AB, and Shing PB. Finite element modeling of masonry-infilled RC frames. J. Struct. Eng., 1997, 123(5): 604-613. https://doi.org/10.1061/(ASCE)0733-9445(1997)123:5(604)

[23] Ghosh AK, and Amde AM. Finite element analysis of infilled frames. J. Struct. Eng., 2002, 128(7): 881-889. https://doi.org/10.1061/(ASCE)0733-9445(2002)128:7(881)

[24] El-Dakhakhni WW. Experimental and analytical seismic evaluation of concrete masonry-infilled steel frames retrofitted using GFRP laminates. Ph.D. thesis, Drexel Univ., Philadelphia, 2002.

[25] El-Dakhakhni WW. Elgaaly M, Hamid, AA. Three-strut model for concrete masonry-infilled frames. J. Struct. Eng., 2003, 129(2): 177-185.

Table 1. Geometrical properties of different configurations of hill building

Building configuration	Parametric variation	Designation of models		Column size (mm)	Beam size (mm)
		Bare frame	Frame with infills		
Stepback	4 to 8 bays	BSTEPALS	MSTEPALS	up to 5: 400×400 from 6 to 8: 450×450	along slope: 300×500 across slope: 300×450
Stepback-setback	4 to 8 bays	BSETALS	MSETALS	all: 400×400	

Table 2. Calculations for the width of Equivalent Diagonal Strut

Direction	H (m)	L (m)	E_f (GPa)	E_m (GPa)	Column Size (mm)	t (m)	α_h	α_L	w (m)
Across slope	2.55	4.6	25	4.5	400×400	0.23	1.392	3.283	1.783
Along slope	2.50	5.6	25	4.5		0.23	1.432	3.856	2.056
Across slope	2.55	4.6	25	4.5	450×450	0.23	1.522	3.179	1.762
Along slope	2.50	5.6	25	4.5		0.23	1.565	3.763	2.025
Across slope	2.55	4.6	25	4.5	500×500	0.23	1.688	3.166	1.794
Along slope	2.50	5.6	25	4.5		0.23	1.735	3.722	2.053

Table 3. Dynamic response of stepback building along and across hill slope (BSTEPALS)

Designation	No. of Bays	Height (m)	FTP by RSA (sec)		FTP as per IS 1893 (sec)		Max. Top storey displacement (mm)		Base Shear ratio (λ)	
			Along	Across	Along	Across	Along	Across	Along	Across
BSTEPALS 4	4	13.5	0.285	0.418	0.248	0.272	5.15	16.53	1.351	1.681
BSTEPALS 5	5	16.5	0.299	0.495	0.271	0.332	5.69	23.56	1.326	1.646
BSTEPALS 6	6	19.5	0.313	0.574	0.293	0.392	6.37	31.61	1.345	1.654
BSTEPALS 7	7	22.5	0.325	0.655	0.312	0.453	6.97	39.89	1.342	1.782
BSTEPALS 8	8	25.5	0.337	0.736	0.331	0.513	7.63	48.37	1.355	1.929

Table 4. Dynamic response of stepback building along and across hill slope (MSTEPALS)

Designation	No. of Bays	Height (m)	FTP by RSA (sec)		FTP as per IS 1893 (sec)		Max. Top storey displacement (mm)		Base Shear ratio (λ)	
			Along	Across	Along	Across	Along	Across	Along	Across
MSTEPALS 4	4	13.5	0.195	0.211	0.248	0.272	1.88	2.79	1.136	1.241
MSTEPALS 5	5	16.5	0.211	0.264	0.271	0.332	2.19	4.83	1.136	1.293
MSTEPALS 6	6	19.5	0.223	0.304	0.293	0.392	2.50	6.97	1.155	1.340
MSTEPALS 7	7	22.5	0.235	0.354	0.312	0.453	2.82	9.93	1.167	1.368
MSTEPALS 8	8	25.5	0.245	0.408	0.331	0.513	3.12	13.7	1.174	1.376

Table 5. Dynamic response of stepback-setback building along and across hill slope (BSETALS)

Designation	No. of Bays	Height (m)	FTP by RSA (sec)		FTP as per IS 1893 (sec)		Max. Top storey displacement (mm)		Base Shear ratio (λ)	
			Along	Across	Along	Across	Along	Across	Along	Across
BSETALS 4	4	13.5	0.285	0.418	0.248	0.272	5.15	16.53	1.351	1.681
BSETALS 5	5	16.5	0.285	0.443	0.271	0.332	5.52	17.07	1.344	1.618
BSETALS 6	6	19.5	0.285	0.455	0.293	0.392	5.69	17.40	1.328	1.573
BSETALS 7	7	22.5	0.285	0.462	0.312	0.453	5.67	17.67	1.297	1.538
BSETALS 8	8	25.5	0.285	0.467	0.331	0.513	5.56	18.92	1.259	1.615

Table 6. Dynamic response of stepback-setback building along and across hill slope (MSETALS)

Designation	No. of Bays	Height (m)	FTP by RSA (sec)		FTP as per IS 1893 (sec)		Max. Top storey displacement (mm)		Base Shear ratio (λ)	
			Along	Across	Along	Across	Along	Across	Along	Across
MSETALS 4	4	13.5	0.195	0.211	0.248	0.272	1.88	2.79	1.136	1.241
MSETALS 5	5	16.5	0.203	0.242	0.271	0.332	2.07	3.51	1.134	1.272
MSETALS 6	6	19.5	0.206	0.258	0.293	0.392	2.25	3.77	1.142	1.276
MSETALS 7	7	22.5	0.208	0.269	0.312	0.453	2.41	3.90	1.154	1.280
MSETALS 8	8	25.5	0.209	0.277	0.331	0.513	2.54	4.02	1.165	1.279