Impact of lateral load on torsional behavior of building in hilly region using SAP2000

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Abstract*: Buildings on slopes are particularly vulnerable due to their lower lateral load capacity. These types of buildings are asymmetrical and have irregular configurations. The height of the columns varies, resulting in the eccentricity of the structure because the centre of mass and centre of stiffness do not coincide. This irregularity leads to torsional behavior and gives us the need to analyze these buildings in terms of their basic conditions and their behavior when the floor plan configuration is changed. In this paper, torsion is calculated, which is an effective parameter to determine the behavior of the building. In this study, an RCC building with G+3 floors and floor slopes of 15o, 26o, and 40o with a change in aspect ratio was considered for the analysis and tested for the vulnerability and suitability of the configurations against lateral loads. Further, bare frame building is modelled with the addition of bracing throughout the height of the building. The assumed angle section is equal angle ISA 150 x 150 x 12 mm. Modelling of bracing was done in three types; bracing in both plan directions, bracing only in one ridge direction (Y-Z axis) and bracing only in one valley direction (X-Z axis). These were analyzed on the slope of 26˚ with a change in aspect ratio and tested for the vulnerability and suitability of the configurations against lateral loads. SAP2000 was used to analyze buildings on slopes, changing the aspect ratio, slope of the site, and effect of adding bracing. Results shows that global bracings have minimum displacement and rotation compared to bracing in Y-Z axis, X-Z axis or without bracings for all aspect ratio considered in this study.

***Keywords*: Lateral load, aspect ratio, slope, Earthquake load, bracings.**

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I. INTRODUCTION (*HEADING 1*)

Buildings constructed on a hillside have a special structure with foundations at different levels. When subjected to ground movements, buildings on slopes constructed of masonry with mud mortar/cement mortar that did not comply with regulations have proven unsafe and resulted in the loss of life and property. [1] The lack of plain ground in hilly areas forces construction activities on sloping ground. Buildings on slopes constructed of masonry with mud mortar/cement mortar without complying with seismic ordinance requirements have proven unsafe when exposed to earthquake-induced shaking. [2] Fig. 1 shows 3 main configurations of buildings build on slopes; a Setback building, a Step-back building, and a Set-back Step-back building. [3,4] The study mainly concentrates on Step Back buildings as they are more vulnerable to seismic force than other configurations. Generally, the step-back structures are used on undulating and sloping areas for the successful performance of the structure. Thus, it is not achievable to execute successfully without the load resisting system. [5]

Earthquakes are one of the most dangerous natural hazards. An earthquake is caused by the sudden movement of the tectonic plates, thus releasing a large amount of energy in a few seconds. The effects are extremely damaging as it affects the large surrounding area. To deal with the problem, we need to determine the seismic performance and lateral stability of the building structure. [6] Framed structures constructed on slopes show different structural behavior than that on plain ground. Since these buildings are unsymmetrical, hence attract a large number of shear force and torsional moments; and show unequal distribution due to varying column lengths. [7] To get stability to the building, the number of bays can be increased in the ridge direction so that the gravity load distribution path doesn't change, and all the buildings should take their own self-weight.

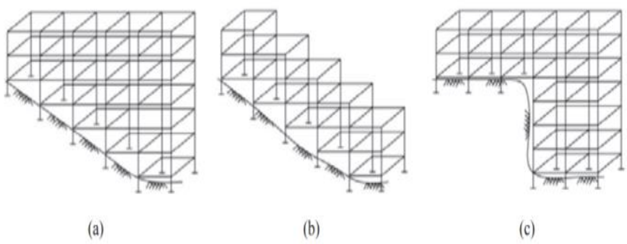


Fig.1 Configuration of buildings build on hill slopes: (a) Set-back building, (b) Step-back building, (c) Set-back Step-back building. [4]

There is a high axial force on the hilly buildings in the ground floor beams of frame perpendicular to the direction of applied load under the lateral load action applied along the ridge direction. [8] Mohd et. al. [9] analyzed the seismic behavior of hill buildings on slopes, which was compared with that of a normal building. It also compares the susceptibility and suitability of the configurations to seismic loading. It was found that for setback buildings with step-back setbacks, the value of base shear is reduced by about 26% and 33% compared to step-back and normal buildings on a level floor. Shanu et.al. [10] analyzed two types of conditions used for the study along the sloping floor, as set back and step back configurations. The results of this analysis are projectile drift, nodal displacement, and base shear. The different cases were analyzed using different parameters such as minimum and maximum values. The minimum values are considered as part of the conclusion that the structure was in the worst case. Arun et.al. [11] studied the construction of a building on sloping terrain. The Step back-Set back building configuration is suitable, in addition to a shear wall that provides stability in the corner of the building. The step back-set back building configuration has 19% lower base shear compared to the step back building on terrain with different slopes. According to the results, the base shear was found to decrease from lower angle to higher angle. Sawant et.al. [12] present analyses performed on 24 RC buildings with three different configurations: Step back building, Step back Set back building, and Set back building. A 3-D analysis including the torsional effect was performed. For step back buildings and Step back-Set back buildings, it is observed that the left column on the floor, which is short, is the most affected. Special attention should be paid to these columns during design and detailing.

In addition to all previous research, it is necessary to analyze a multi-story RC building on a sloped floor against lateral loading and to find an optimal relationship between aspect ratio, sloping ground, and floor height. Therefore, the objective of this study is to analyze the multi-story RC building on the sloping ground from different angles. In this study, a multi-story RC G+3 building with different slope angles (15˚, 26˚, and 40˚) was considered and tested for the vulnerability and suitability of the configurations against lateral loads. SAP2000 was used to analyze buildings on slopes, changing the aspect ratio, and slope of the site, and adding bracing.

II. Methodology

Geometric Properties and Material Properties are given below:

i. No of storey: G+3
ii. Floor height: 3 m
iii. Grade of Concrete: M25
iv. Grade of Steel Reinforcement: Fe 415
v. Spacing in X direction: 4 m
vi. Spacing in Y direction: 4 m
vii. Beam Sizes: 300 X 300 mm
viii. Column sizes: 350 X 350 mm
ix. Slab Thickness: 150 mm
x. Live load: 2.5 KN\m^2
xi. Floor finish: 1 KN\m^2

The equivalent static analysis defines a series of forces acting on a building to represent the effect of earthquake ground motion, typically defined by a seismic design response spectrum. In the equivalent static force method, the inertial forces are specified as static forces using empirical formulas. The empirical formulas do not explicitly account for the "dynamic characteristics" of the particular structure being designed or analyzed. The formulas were, however, developed to adequately represent the dynamic behavior of what are called "regular" structures, which have a reasonably uniform distribution of mass and stiffness. For such structures, the equivalent static force method is most often adequate. The concept employed in the equivalent static lateral method is to place static loads on a structure with magnitudes and directions that closely approximate the effects of dynamic loading caused by earthquakes. The lateral load applied to the structure is calculated as per the equivalent static method of plain building and the same load is applied to the other three structures. The load applied due to the equivalent static analysis is shown in table 4.1 and it is applied along the ridge direction.

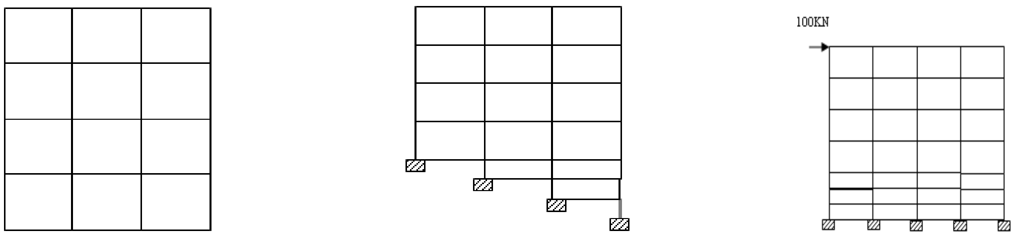
Table 2.1 Lateral load applied on floors

Applied load on floors (KN)				
Floor/ frame	**Frame A**	**Frame B**	**Frame C**	**Frame D**
4	411	411	411	411
3	318	318	318	318
2	209	209	209	209
1	122	122	122	122
ground	60	60	60	60

Applying equivalent static analysis, it is considered that the total base reaction of the individual frame along the ridge direction and the applied load that is taken by the individual frame and the ratio will give us the percentage of the load taken by that frame. The load applied on a building may not be done by equivalent static analysis it can also be a random value because for calculating the percentage the ratio of load taken by the applied load is used. The bare frame building is modelled to increase the number of bays. The number of Bays in the side direction is increased one by one. The initial bays being 3 are increased by 1, 2 and 3 to get 4, 5 and 6 bays. The analysis of such models is done by comparing the twist along with the floors and axial forces along the ground floor. Further, the analysis is Conclude by providing the best bay scenario. Simultaneously, the building model is analyzed by providing different slopes. The slopes of 15°, 26° and 40° are taken for analysis. The behavior of the building is analyzed to get the results resembling the stability element. The results can be then compared with twist behavior and load distribution along with the floors. The analysis is done on 9 cases of the building by applying a lateral load on the top floor of the building in the direction perpendicular to the valley.

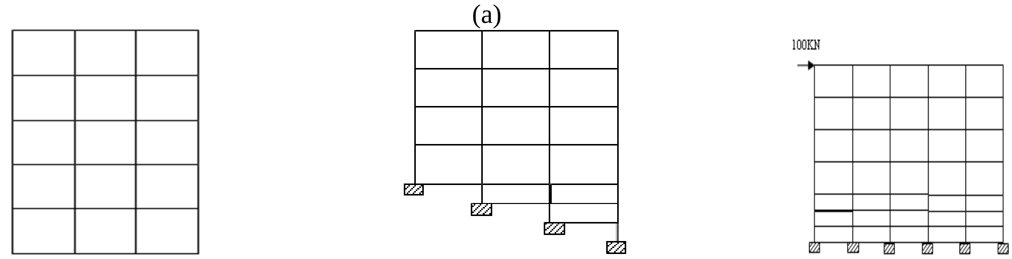
Table 2.2 Lateral load applied on floors

Aspect ratio	**Slopes**		
Bays (xXy)	15º	26º	40º
3X4	BV-11	BV-12	BV-13
3X5	BV-21	BV-22	BV-23
3X6	BV-31	BV-32	BV-33



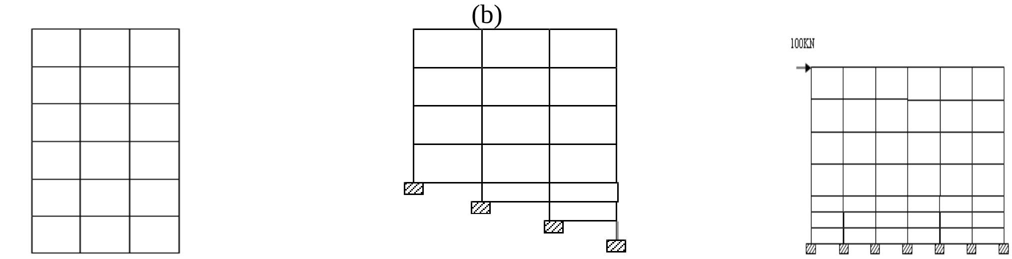
Plan (3x4) X-Z Axis (valley direction) Y-Z Axis (ridge direction)

(a)



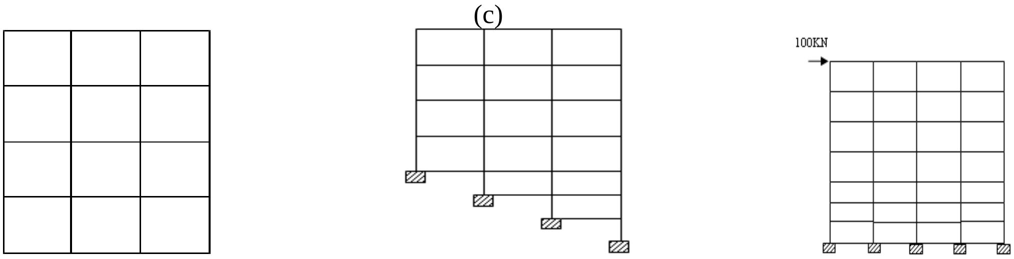
Plan (3x5) X-Z Axis (valley direction) Y-Z Axis (ridge direction)

(b)



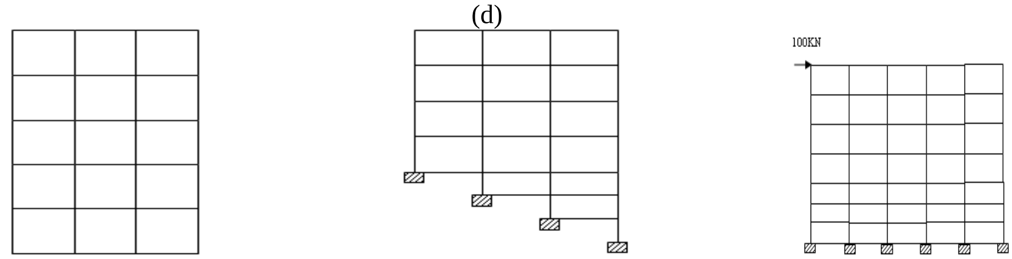
Plan (3x6) X-Z Axis (valley direction) Y-Z Axis (ridge direction)

(c)



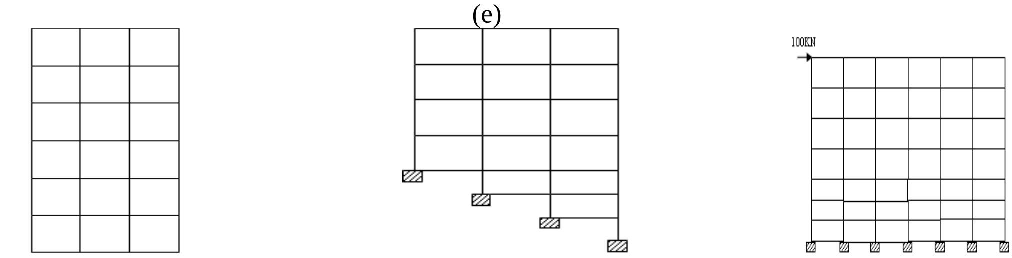
Plan (3x4) X-Z Axis (valley direction) Y-Z Axis (ridge direction)

(d)



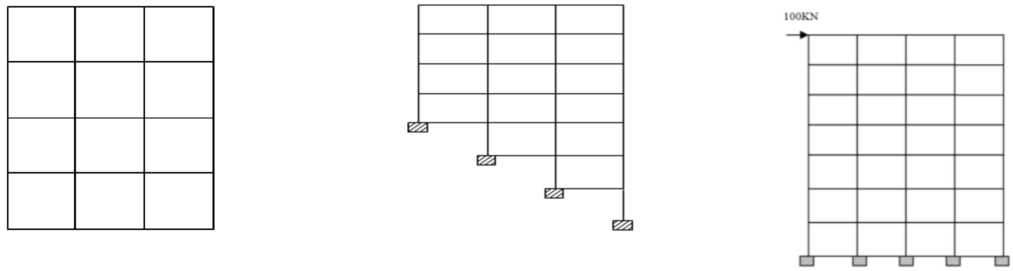
Plan (3x5) X-Z Axis (valley direction) Y-Z Axis (ridge direction)

(e)



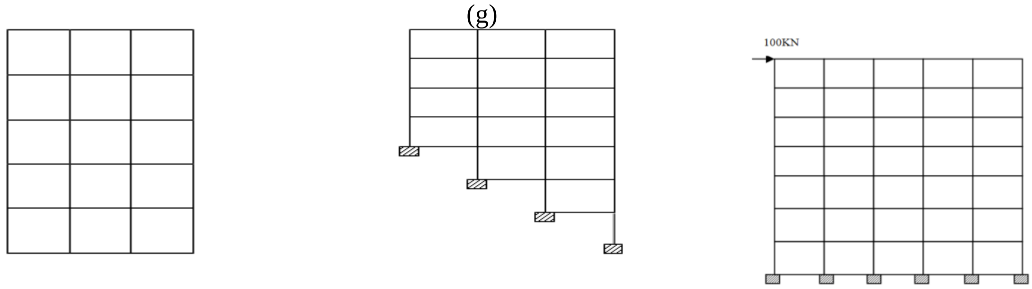
Plan (3x6) X-Z Axis (valley direction) Y-Z Axis (ridge direction)

(f)



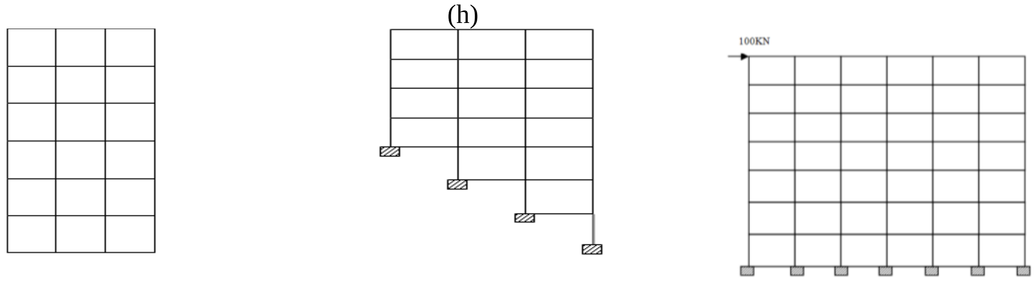
Plan (3x4) X-Z Axis (valley direction) Y-Z Axis (ridge direction)

(g)



Plan (3x5) X-Z Axis (valley direction) Y-Z Axis (ridge direction)

(h)



Plan (3x6) X-Z Axis (valley direction) Y-Z Axis (ridge direction)

(i)

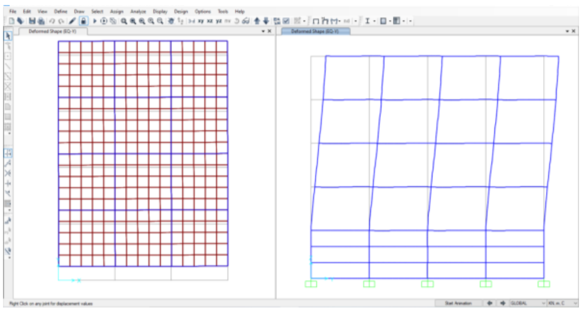
Fig. 2 Plan and elevation of Building Variation; (a) Plan and elevation of BV11, (b) Plan and elevation of BV21 (c) Plan and elevation of BV31, (d) Plan and elevation of BV12, (e) Plan and elevation of BV22, (f) Plan and elevation of BV32, (g) Plan and elevation of BV13, (h) Plan and elevation of BV23, (i) Plan and elevation of BV33.

III. RESULTS AND DISCUSSION

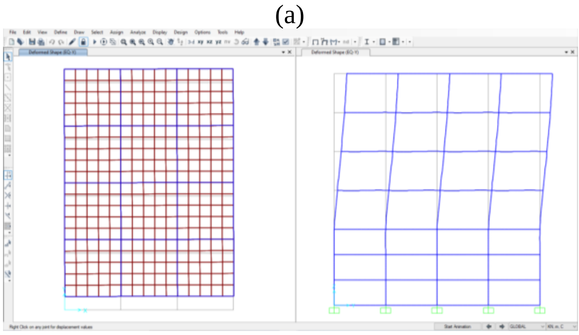
After the Analysis of all 9 cases of building model with variation in aspect ratio and slope, table 5. shows rotation and displacement of buildings with variations. Rotation or twist is in radian and displacement is in mm.
Furthermore, figure 4.3.1 shows graph of rotation and BV (Building Variation) and figure 4.3.2 shows graph of displacement and BV (Building Variation).

Table 3.1 Rotation and Deflection after analysis

Building variation	**Rotation (radian)**	**Displacement (mm)**
BV11	0.00183	50.599
BV21	0.0011	28.58
BV31	0.00157	45.197
BV12	0.00174	48.861
BV22	0.00159	45.76
BV32	0.00148	43.65
BV13	0.00166	46.85
BV23	0.0015	43.66
BV33	0.0014	41.49



(a)



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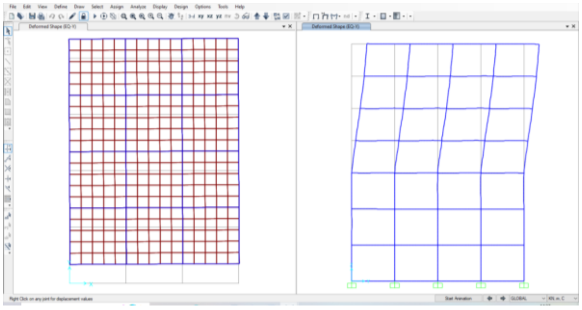

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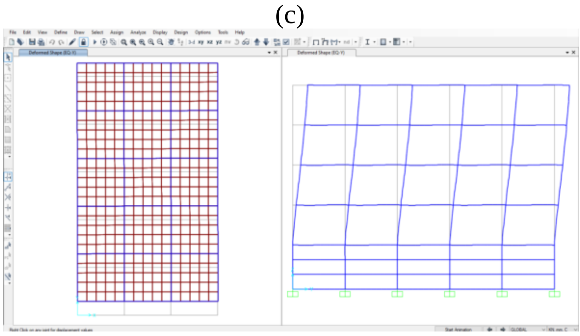

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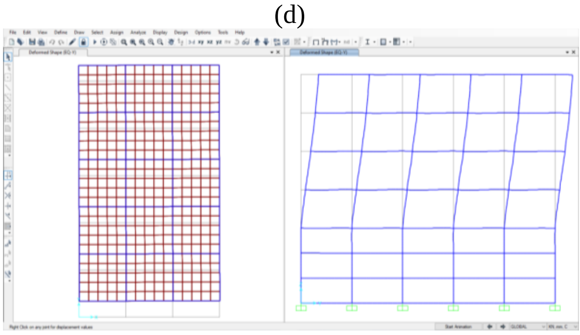

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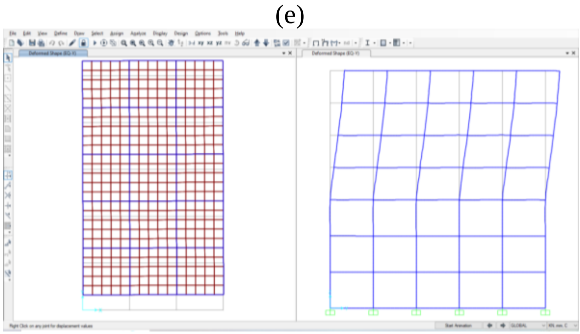

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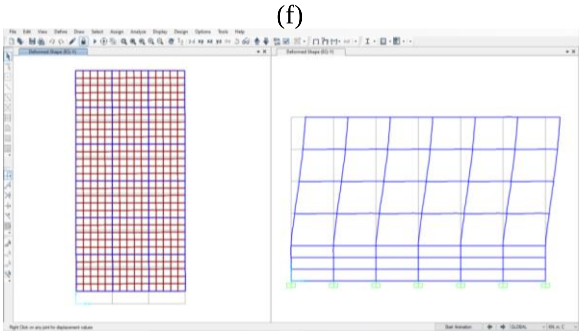

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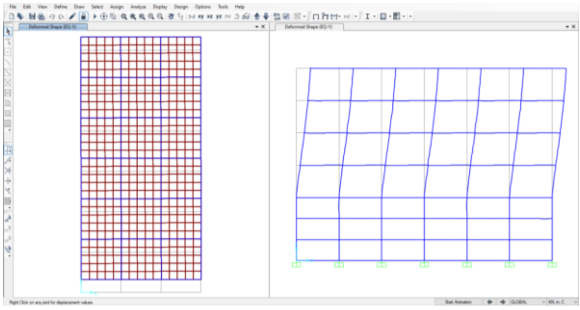

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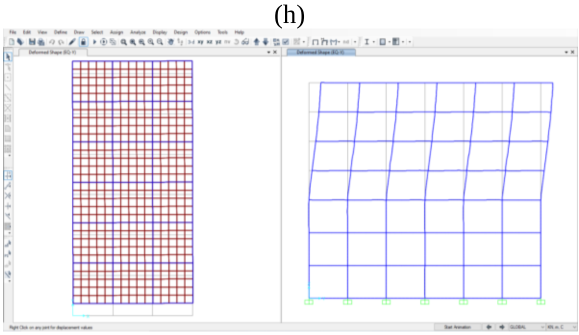
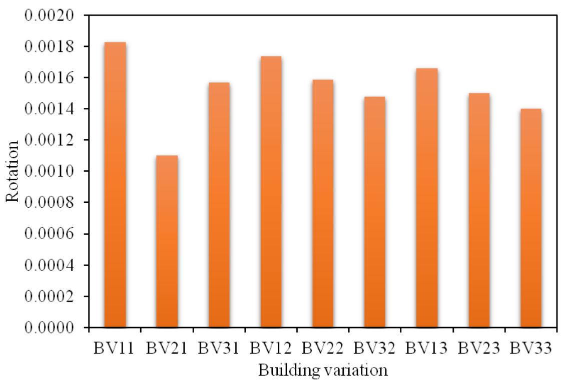
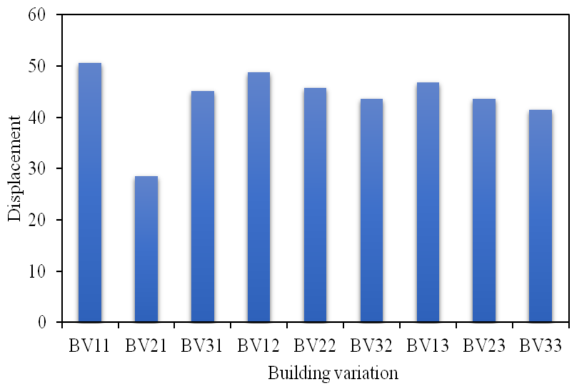


(i)

Fig. 3 Twist and Deflection of Building Variation; (a) Twist and Deflection of BV11, (b) Twist and Deflection of BV12, (c) Twist and Deflection of BV13, (d) Twist and Deflection of BV21, (e) Twist and Deflection of BV22, (f) Twist and Deflection of BV23, (g) Twist and Deflection of BV31, (h) Twist and Deflection of BV31, (i) Twist and Deflection of BV33



(a)



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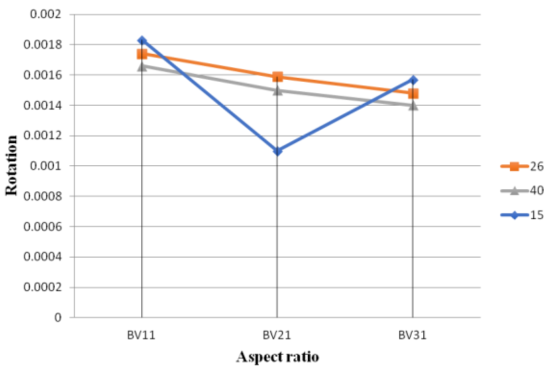

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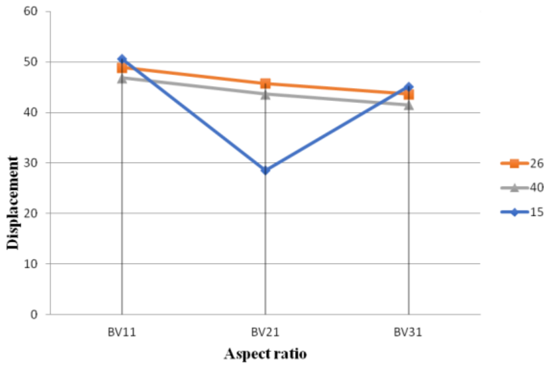


(d)

Fig. 4 Plot of rotation and displacement with respect to aspect ratio for different building structures. (a) Rotation with respect to building variation (b) Displacement with respect to building variation (c) Rotation with respect to aspect ratio (b) Displacement with respect to aspect ratio.

Fig. 3 and Fig. 4 show rotation/twist and displacement of buildings, where model BV21 is the most stable building as it has less rotation and displacement after lateral loads. BV21 has an aspect ratio and bay 3X5 with a slope of 15o with values of 0.0011radian and 28.58mm. From the graph, Model BV11 has maximum rotation and displacements of all, which means BV11 is the most unstable of all analyzed buildings which have an aspect ratio and bay 3X4 with a slope of 15o with values of 0.00183radian and 50.99mm.

Fig. 5 and Fig. 6 show that all 3 buildings BV-11, BV-12, and BV-13 with aspect ratio and bay 3X4 have more rotation and displacement. As bays increases in the ridge direction stability increases. However, BV-33 is exceptional in the above result as it is with a plan aspect ratio of 3X6 but due to 40o of a slope, it shows more value of twist and displacement.

A. *Variation of building with change in aspect ratio and bracings application*

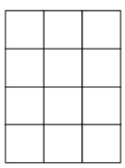
The bare frame building is modelled with addition of bracing throughout the height of the building. Assumed Angle Section is Equal Angle ISA 150 X 150 X12mm. Modelling of bracing will be done in three types as it is trial and error method for locating the bracings on building-

1. Bracing provided in both plan directions
2. Bracing provided only in one ridge direction (Y-Z axis)
3. Bracing provided only in one valley direction (X-Z axis)

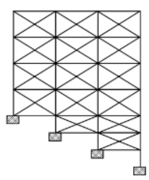
The building is modelled to increase the number of bays. The number of Bays in the side direction is increased one by one. The initial bays being 3 are increased by 1, 2 and 3 to get 4, 5 and 6 bays. The analysis of such models is done by comparing the twist along with the floors and axial forces along the ground floor. The building model is analyzed on the slope of 26°. Further, the analysis concludes by providing the best scenario for the location of bracings on the building. The behavior of the building is analyzed to get the results resembling the stability element.

Table 4.1 Building variation with aspect ratios and bracing system

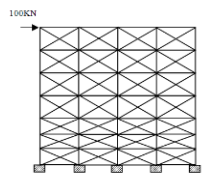
Aspect ratio	**Bracing System (BS)**		
Bays (xXy)	**All around the plan**	**(Y-Z axis)**	**(X-Z axis)**
3X4	BS-11	BS-12	BS-13
3X5	BS-21	BS-22	BS-23
3X6	BS-31	BS-32	BS-33



Plan 3X4

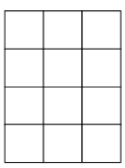


X-Z Axis (valley direction)

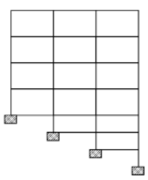


Y-Z Axis (ridge direction)

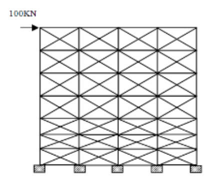
(a)



Plan 3X4

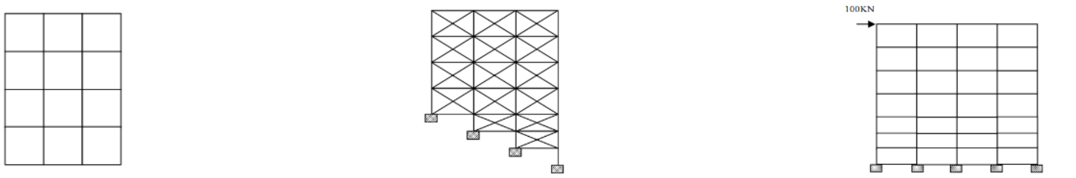


X-Z Axis (valley direction)



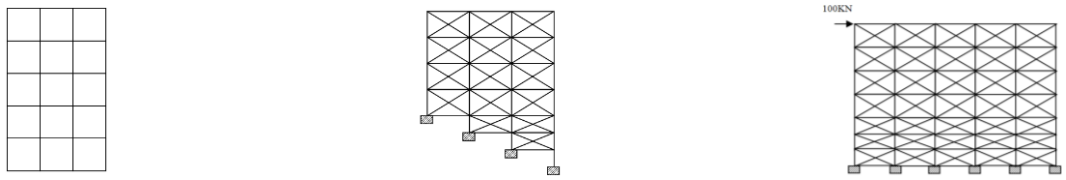
Y-Z Axis (ridge direction)

(b)



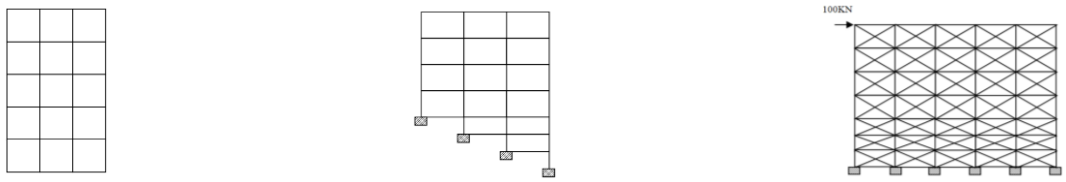
Plan 3X4 | **X-Z Axis (valley direction)** | **Y-Z Axis (ridge direction)**

(c)



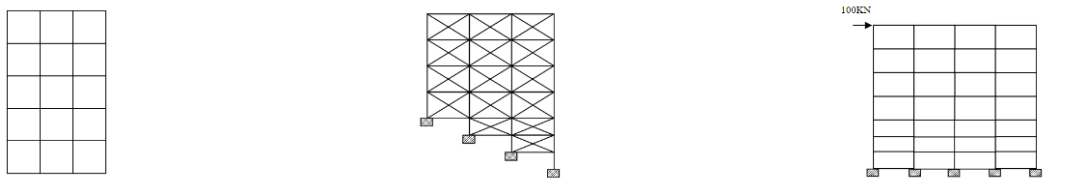
Plan 3X5 | **X-Z Axis (valley direction)** | **Y-Z Axis (ridge direction)**

(d)



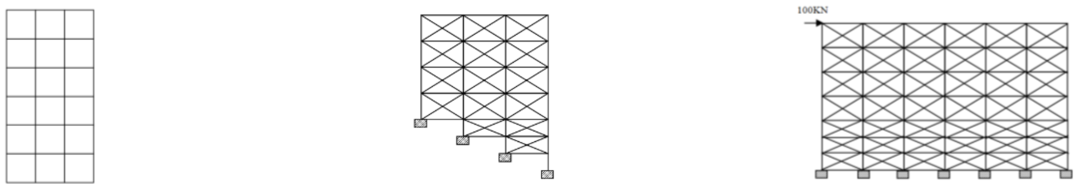
Plan 3X5 | **X-Z Axis (valley direction)** | **Y-Z Axis (ridge direction)**

(e)



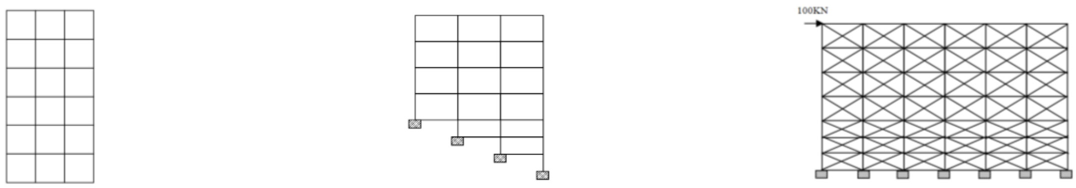
Plan 3X5 | **X-Z Axis (valley direction)** | **Y-Z Axis (ridge direction)**

(f)



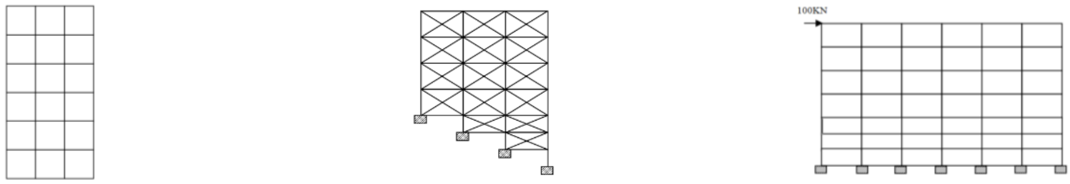
Plan 3X6 | **X-Z Axis (valley direction)** | **Y-Z Axis (ridge direction)**

(g)



Plan 3X6 | **X-Z Axis (valley direction)** | **Y-Z Axis (ridge direction)**

(h)



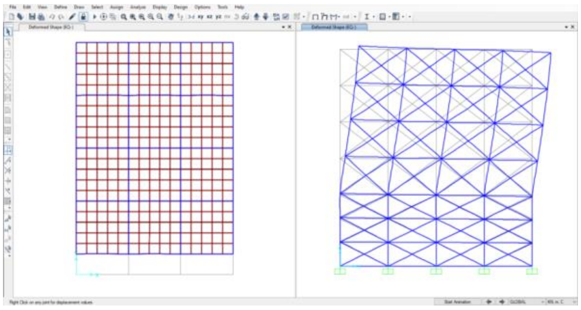
Plan 3X6 **X-Z Axis (valley direction)** **Y-Z Axis (ridge direction)**

(i)

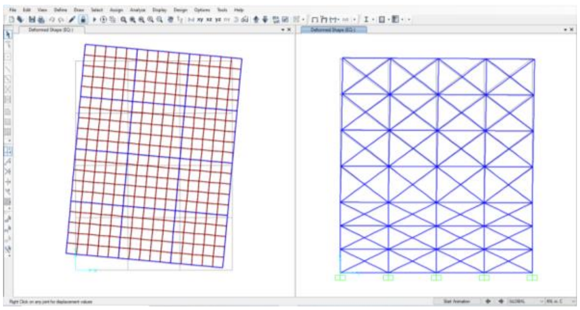
Fig. 4.1 Plan and elevation of Bracing system; (a) Plan and elevation of BS11, (b) Plan and elevation of BS21 (c) Plan and elevation of BS31, (d) Plan and elevation of BS12, (e) Plan and elevation of BS22, (f) Plan and elevation of BS32, (g) Plan and elevation of BS13, (h) Plan and elevation of BS23, (i) Plan and elevation of BS33.

Table 4.2 Rotation and Deflection after analysis

Building variation	Rotation (radian)	Displacement (mm)
BS11	0.000363	7.776
BS21	0.000199	2.34
BS31	0.000285	6.77
BS12	0.00155	6.238
BS22	0.00028	3.53
BS32	0.000517	1.045
BS13	0.00173	48.28
BS23	0.00106	27.79
BS33	0.00148	43.26



(a)



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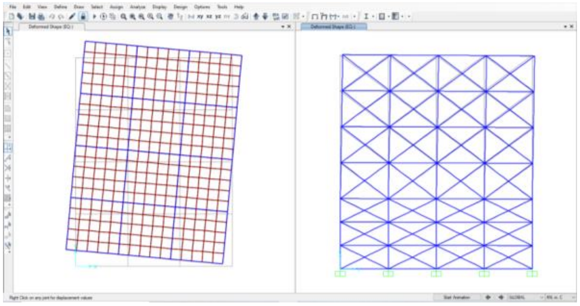

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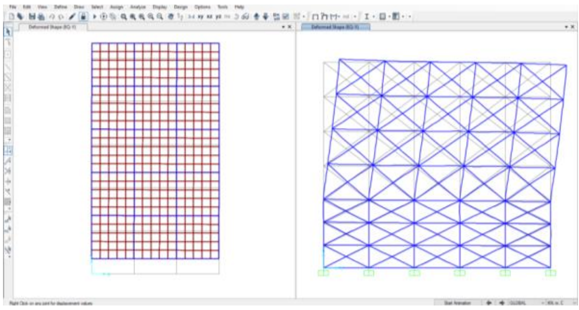

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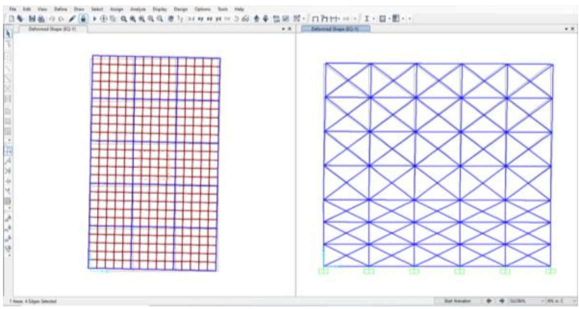

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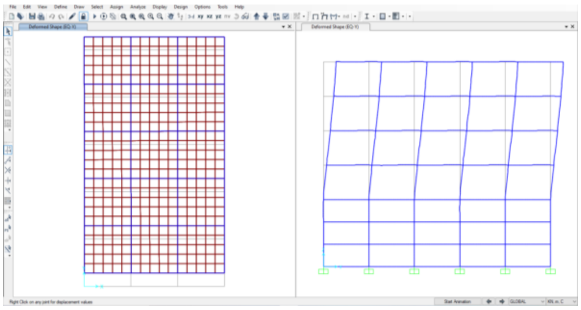

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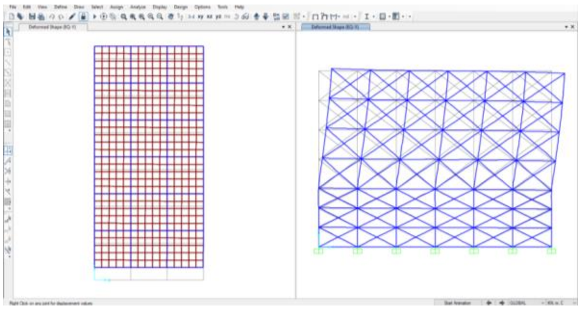
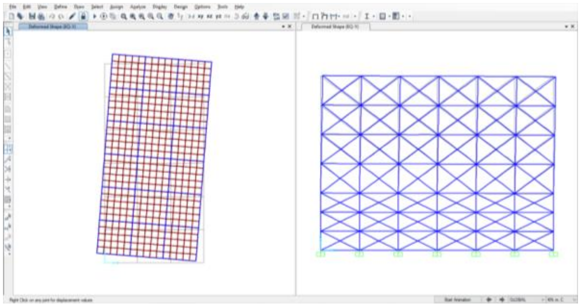


(g)



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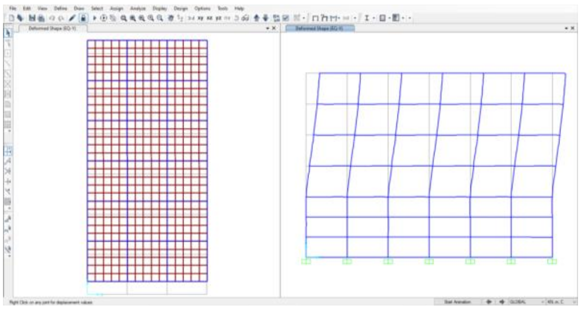
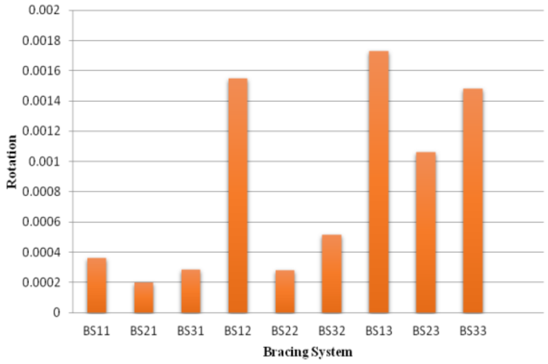
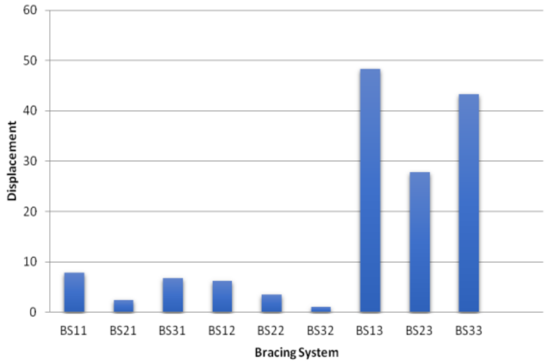


(i)

Fig. 5.3 Twist and Deflection of Bracing System; (a) Twist and Deflection of BS11, (b) Twist and Deflection of BS12, (c) Twist and Deflection of BS13, (d) Twist and Deflection of BS21, (e) Twist and Deflection of BS22, (f) Twist and Deflection of BS23, (g) Twist and Deflection of BS31, (h) Twist and Deflection of BS31, (i) Twist and Deflection of BS33.



(a)



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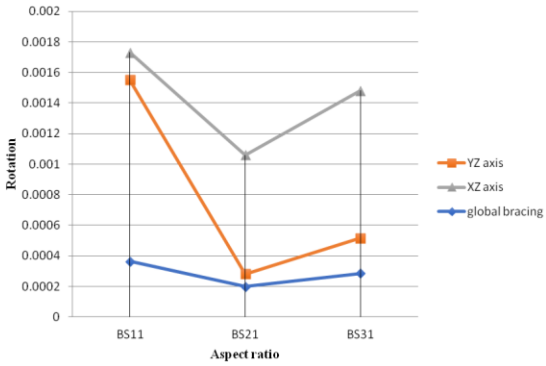

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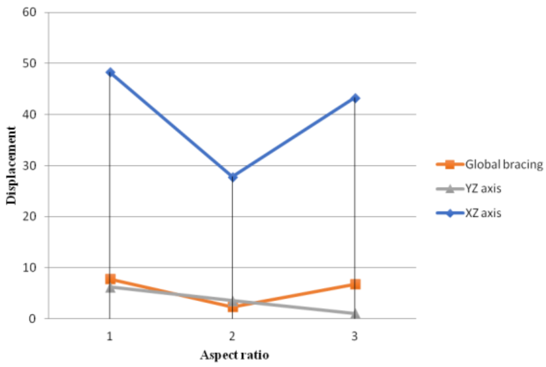


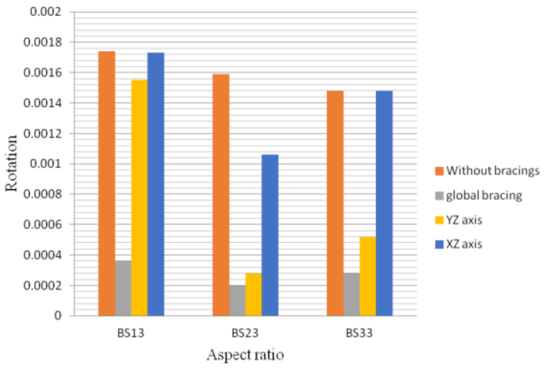
(d)

Fig. 4 Plot of rotation and displacement with respect to aspect ratio for different bracing system. (a) Rotation with respect to bracing system (b)

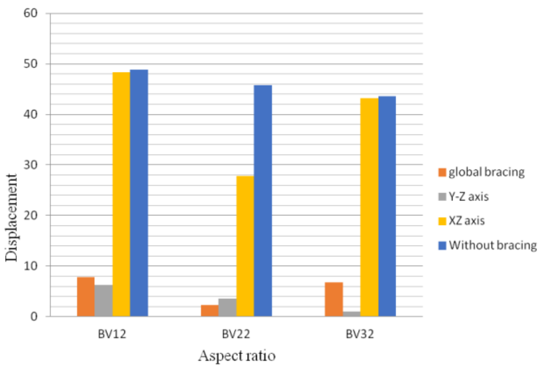
Displacement with respect to bracing system (c) Rotation with respect to aspect ratio (b) Displacement with respect to aspect ratio.

From graph 5.1, the Rotation/twist for building BS111, BS21, and BS31 is minimum as it is bracing all around the plan i.e. on both X-Z and Y-Z axis. From graph 5.2 displacements on the top floor are also minimum for BS11, BS21, and BS31. From graph 5.1 and 5.2 displacements and rotation for BS12, BS22, and BS32 is also minimum except for BS12. As BS22 and BS32 are more stable compared to BS12 it is because the number of the bay is more in the ridge direction. Graph 5.3 and 5.4 shows that bracing on the X-Z axis has more value of rotation and displacement compared to the other two conditions, it is unstable overall. Bracing in the Y-Z axis gives less displacement but not rotation, compared to global bracing.

Comparison of buildings with different variation but same slope of 26º. From table 4.4 results of rotation and displacement of buildings without bracing. BV12, BV22 and BV32 values are taken for comparison with table 5.2. Graph 5.5 gives complete results of twist of structure with respect to aspect ratio, where slope of 26º is constant. Graph 5.6 gives complete results of displacement of top floor with respect to aspect ratio, also slope of 26º kept constant. We can conclude from graph 5.5 and 5.6 that, bracing all over the outer wall i.e. global bracing gives stable results. Without bracing structure is unstable in all comparison. After the global bracings, bracing on Y-Z axis is stable.



(a)



(b)

Fig. 5 The rotation and displacement plot with respect to aspect ratio for structure with or without bracings in different directions (a) Rotation with respect to aspect ratio (b) Displacement with respect to aspect ratio.

IV. Conclusion

This analysis of the structures on hill slopes, suggests that the plan aspect ratio for the slope region should be proposed with a constant number of 3 bays along the valley direction and 4, 5, and 6 bays in the ridge direction. The analysis is carried out to obtain a suitable configuration of the building with slope, plan aspect ratio and bracings. After the analysis of bare frame RCC structure results we get, which shows that as an increase in bays in the ridge direction stability increases. Though its stability changes concerning slope variation. The main observation and conclusion are that buildings on slopes with higher slopes are unstable and the risk of lateral forces can be minimized by increasing the number of bays in the ridge direction.

The presence of cross-bracing(x) reduces the storey displacement, storey drifts and twists of buildings. Storey drift and twisting are reduced when Step back building is provided with X bracing. Step back building is more susceptible to earthquakes due to irregularities and hence when X bracing is provided in such cases it will perform better compared to without bracing building. The application of bracings can minimize the risk of lateral loads and makes the structure stable in any condition. As bays increases in ridge direction, the building structure becomes more stable.

After the application of bracings, we can conclude that Bracings applied in all directions i.e. in the X-Z axis and Y-Z axis is the most stable condition for structure on slope compared to another bracing system. Whereas bracings in the X-Z direction are unstable compared to another bracing system. Overall after comparing the structures, for bracings global bracing with cross bracing is the best configuration with an aspect ratio of 3X5 with 26o of the slope.

Best case for RCC structure on slope is that addition of bays in ridge direction. So that structure gets more stable. However, addition of bracing is best option. Bracing application to all outer walls gives most stability to structure. Twist and storey drift are minimized with bracings.

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