Seismic analysis of vertically irregular buildings

Shaikh Abdul Aijaj Abdul Rahman[1,*] and Ansari Ubaidurrahman Salik[2]

[1]Department of Civil Engineering, Mavin Switchgears and Control Pvt Ltd, Aurangabad 431 001, India
[2]Department of Civil Engineering, SND College of Engineering and Research Centre, Yeola 423 401, India

The greatest challenge for any structural engineer in today's scenario is to design seismic-resistant structures. A regular building, i.e. having mass and stiffness uniformly distributed through its height behaves normally. The presence of vertical irregular frame subject to devastating earthquakes is a matter of concern. Points of sudden change in stiffness, mass and strength in buildings are known as weak points. For the design of safe irregular buildings it is necessary to study the effect of irregularity on the response of buildings to lateral loads. Here we study the proportional distribution of lateral forces evolved through seismic action in each storey level due to changes in mass and stiffness of frame on vertically irregular structures. The effect of mass and stiffness irregularity of G + 10-storeyed vertical geometric irregular building is studied using finite element method-based software. Two methods of analysis, namely linear static and linear dynamic analysis are used to evaluate response of the structure in the form of storey shear, storey displacement and storey drift. Responses are plotted and compared, and conclusions have been made from the results.

Keywords: Finite element method, irregular buildings, seismic analysis, lateral load.

THE behaviour of a building during earthquakes depends on its overall shape, size and geometry, in addition to how the earthquake forces are carried to the ground. The earthquake forces developed at different floor levels in a building need to be brought down along the height to the ground by the shortest path; any deviation or discontinuity in this load transfer path results in poor performance of the building. Buildings with vertical setbacks cause a sudden jump in earthquake forces at the level of discontinuity. Most of the time earthquake damage to buildings is initiated at a storey which has less column or greater height or heavy mass compared to an adjacent storey. Many buildings with an open ground storey intended for parking collapsed or were severely damaged in Gujarat during the 2001 earthquake.

There have been several studies on such irregularities[1,2]. Estimation of storey shear of a building with mass and stiffness variation due to seismic excitation and evaluation of mass, strength and stiffness limits for regular buildings specified by UBC[3] and determination of structural irregularity limits – mass irregularity example[4]. In the present article, response of a G + 10-storeyed vertically irregular frame to lateral loads is studied for stiffness and mass irregularity at different floors with four models. Stiffness irregularity is introduced by increasing the column height at ground floor and fourth floor. Mass irregularity is introduced at fourth and eighth floors by increasing the mass.

Structural irregularities

There are various types of irregularities, IS Code 1893 (Part-1):2002 classifies irregularity in two sections: plan irregularities and vertical irregularities. In this study, vertical irregularities are considered and described as follows.

Stiffness irregularity

Soft storey: A soft storey is one in which the lateral stiffness is less than 70% of that in the storey above or less than 80% of the average lateral stiffness of three storeys above.

Extreme soft storey: An extreme soft storey is one in which the lateral stiffness is less than 60% of that in the storey above or less than 70% of the average stiffness of three storeys above. For example, buildings on stilts fall under this category.

Mass irregularity

These are considered to exist where the effective mass of any storey is more than 150% of effective mass of an adjacent storey. The effective mass is the real mass consisting of dead weight of the floor plus the actual weight of partition and equipment.

Vertical geometric irregularity

Geometric irregularity exists when the horizontal dimension of the lateral force resisting system in any storey is

*For correspondence. (e-mail: aijaj2@gmail.com)

more than 150% of that in an adjacent storey. The setback can also be visualized as a vertical re-entrant corner.

Discontinuity in capacity–weak storey

A weak storey is one in which the lateral strength is less than 80% of that in the storey above; the storey lateral strength is the total strength of all seismic force resisting elements sharing the storey shear in the considered direction.

Problem formulation

For the present study the vertical geometric irregular building model is taken from IS 1893 (Part-1):2002 and the same model is modeled with three different irregularities. This building model is G + 10-storeyed (35.5 m high) and is made of reinforced concrete (RC) special moment resisting frame (SMRF). Table 1 provides a detailed description. The four frames have been analysed using equivalent static method of IS 1893-part 1: 2002. Analysis has been carried out using ETABS software.

Modelling

In all the four models beams and columns are modelled as a two nodded frame element having six degrees of freedom at each node, three translations U1, U2, and U3 and three rotations R1, R2, and R3 along mutually perpendicular axis. Floor is modelled as a four-noded shell element having six degrees of freedom at each node, three translations and three rotations. All the beams and columns are connected with rigid joint. Imposed loads have been applied as uniformly distributed loads on the floor. No infill walls have been modelled, load of infill wall is directly applied on beams. Floor is considered here as a rigid diaphragm and masses are lumped at floor level.

Mesh sensitivity analysis

Mesh sensitivity analysis is carried out for base model and model-2, and *Y*-displacement (U_y) of model-2 for node number 92 of storey 7 for dead load case has been plotted here (Figure 1). Number 1 on the *x*-axis in Figure 1 *b* represents no meshing (one part) no. 2 indicates that beams, columns and slabs are divided into two parts. Similarly no. 3 indicates three parts, and so on. Convergence of displacement is obtained after 4 × 4 meshing. So all the models are meshed with 4 × 4 parts and results have been evaluated.

Table 1. Model description

Model no.	Description
1	Base model
2	Base model with mass irregularity at third and seventh floor
3	Base model with stiffness irregularity at fourth floor
4	Base model with stiffness irregularity at ground floor

Model-1: Base model

The basic model consists of (G+10) vertically geometric irregular structure with basement. It has 12 bays of 5 m in both *X* and *Y* directions. After each two consecutive stories, the size of model is reduced by 5 m in both directions as shown in Figure 2. The typical storey height is 3.0 m, ground storey height is 3.5 m, and foundation height below the plinth level is 2.0 m. Table 2 shows the geometric, structural, seismic, loading and material data of building.

Model-2: base model with mass irregularity

The structural configuration of this model is the same as model 1. Imposed load is 5 kN/m^2 on all the floors,

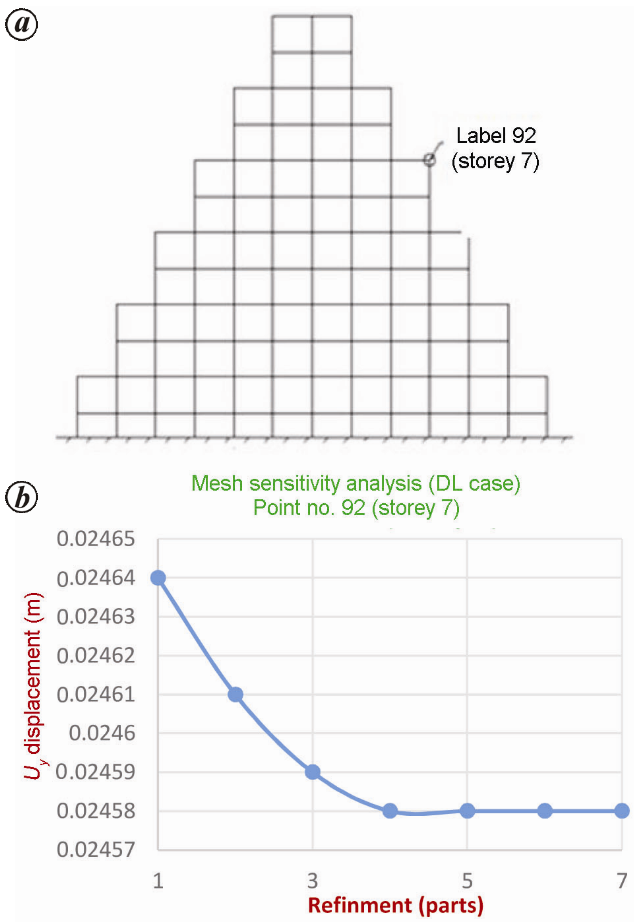

Figure 1. ***a***, Model 2 – elevation; ***b***, Displacement versus meshing plots.

Table 2. Geometric, structural, seismic, loading and material data for all models

Specification	Model-1	Model-2	Model-3	Model-4
Type of structure	SMRF	SMRF	SMRF	SMRF
Seismic zone	V	V	V	V
Zone factor	0.36	0.36	0.36	0.36
Importance factor	1.00	1.00	1.00	1.00
Response spectra	As per IS 1893 (Part-1): 2002	As per IS 1893 (Part-1):2002	As per IS 1893 (Part-1): 2002	As per IS 1893 (Part-1):2002
Type of soil	Medium soil	Medium soil	Medium soil	Medium soil
Number of storeys	G + 10	G + 10	G + 10	G + 10
Dimension of building (m × m)	60 × 60	60 × 60	60 × 60	60 × 60
Floor height (typical) (m)	3.0	3.0	3 and 5 at fourth floor	3.0
Base floor height (m)	3.5	3.5	3.5	5.0
Impose load (kN/m^2)	5	32 third and seventh floor	5	5
Materials	M30 and Fe415	M30 and Fe415	M30 and Fe415	M30 and Fe415
Sp. weight of infill (kN/m^3)	20	20	20	20
Size of column (mm × mm)	C700 × 300	C700 × 300	C700 × 300	C700 × 300
Size of beam (mm × mm)	300 × 700	300 × 700	300 × 700	300 × 700
Depth of slab (mm)	150	150 and 200 at third and seventh floor	150	150
Sp. weight of RCC (kN/m^3)	25	25	25	25

Table 3. Summary of base shear

Models	Height (m)	Time period (T_a; sec)	Sa/g	Ah	Swismic Wt (W kN)	Base shear (VB; kN)
1	35.5	1.0907	1.2469	0.0449	251621.67	11297.812
2	35.5	1.0907	1.2469	0.0449	301549.86	13539.588
3	37.5	1.1365	1.1966	0.0431	264140.12	11384.439
4	37	1.1251	1.2087	0.0435	284346.51	12369.073

Sa/g, Average response acceleration coefficient; Ah, Seismic response coefficient.

Table 4. Storey displacement (U_x) in the x-direction (m)

	Model-1	Model-2	Model-3	Model-4
Storey	U_x			
Roof	0.092815	0.104726	0.118881	0.105871
Tenth	0.089327	0.101178	0.115687	0.102367
Ninth	0.82156	0.094116	0.109095	0.095375
Eighth	0.074495	0.086706	0.101981	0.087991
Seventh	0.063778	0.076171	0.091971	0.077649
Sixth	0.054715	0.064721	0.083409	0.068848
Fifth	0.043792	0.051499	0.07295	0.058179
Fourth	0.03501	0.041348	0.063706	0.049515
Third	0.025377	0.030459	0.026005	0.039927
Second	0.01786	0.021315	0.017976	0.032342
First	0.010113	0.012045	0.010136	0.024209
Plinth	0.001783	0.002127	0.001786	0.002014
Base	0	0	0	0

except the third and seventh; irregularity is introduced in model 2 by increasing imposed load to 32 kN/m^2 for these two storeys (Figure 2 *b*).

Model-3: base model with stiffness irregularity at the fourth floor

This is vertically irregular model. Stiffness irregularity in the vertical direction is introduced by increasing the fourth floor height to 5 m. All the remaining floors except ground floor are of 3 m height. The remaining data are the same as model 1 and as mentioned in Table 2. Figure 2 *c* shows the elevation of model 3.

Model-4: base model with stiffness irregularity at the ground floor

This is vertically irregular model having stiffness irregularity at the ground floor. Stiffness irregularity is introduced by increasing height of ground floor to 5 m. All the remaining floors are of 3 m height. The remaining data are shown in Table 2 and Figure 2 *d* shows the elevation.

Analysis of results

Manual calculation has been done for the four models and base shear is calculated as per IS 1893 (Part-1):2002, as shown in Table 3; these results are compared with the ETABS result.

The four models with stiffness and mass irregularity have been analysed using equivalent lateral load and response spectra method. Results in the form of storey displacement, storey drift and storey shear by linear static method have been evaluated and tabulated (Tables 4–6). Figure 3 shows the deflected shapes of irregular model

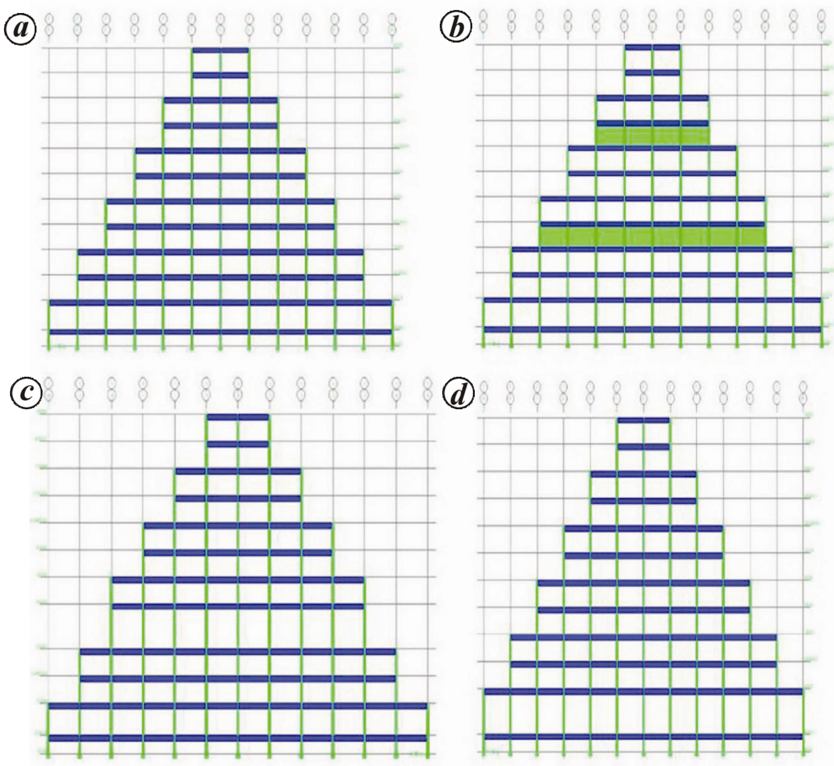

Figure 2. Model elevation. ***a***, Base model (model-1); ***b***, model-2; ***c***, model-3; ***d***, model-4 elevation view.

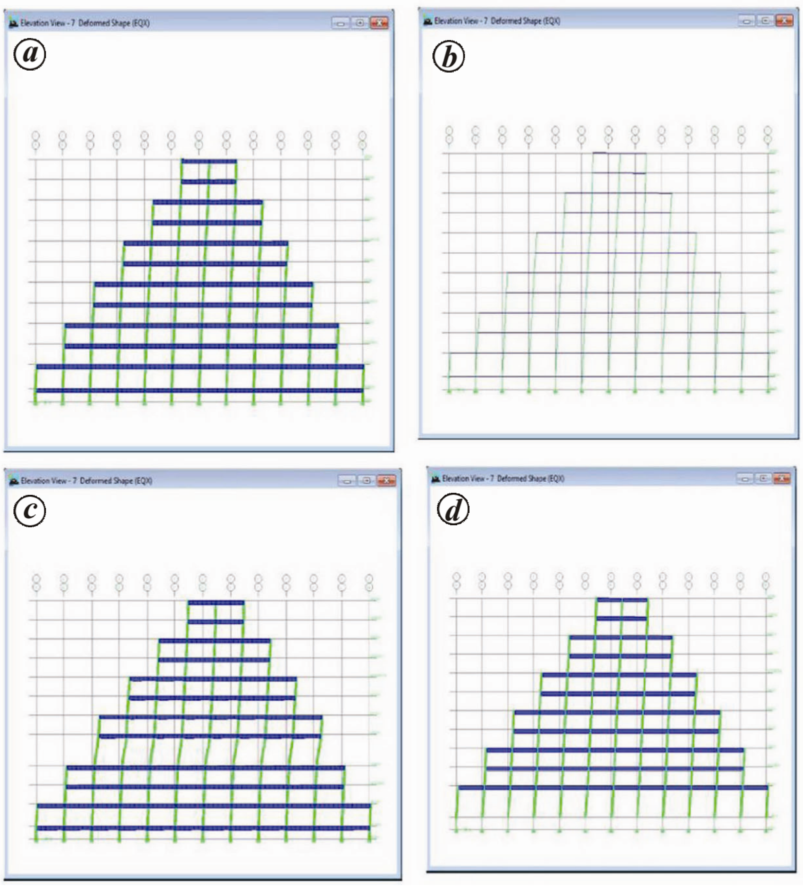

Figure 3. Deflected shape of irregular models. ***a***, Model 1; ***b***, Model 2; ***c***, Model 3; ***d***, Model 4.

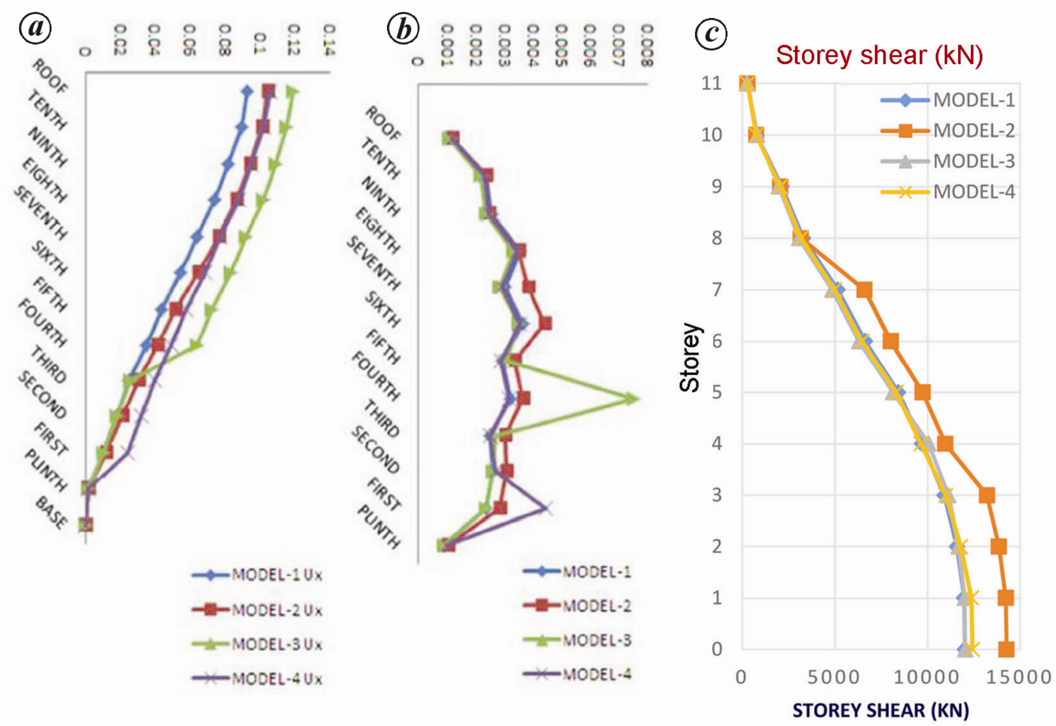

Figure 4. Response of various frames with irregularities. ***a***, Displacement (m); ***b***, Storey drift; ***c***, Storey shear (kN).

Table 5. Storey drift in the *X*-direction

Storey	Model-1	Model-2	Model-3	Model-4
Roof	0.001162	0.001183	0.001065	0.001168
Tenth	0.002390	0.002354	0.002197	0.002331
Ninth	0.002554	0.002470	0.002371	0.002461
Eighth	0.003572	0.003512	0.003337	0.003447
Seventh	0.003021	0.003816	0.002854	0.002934
Sixth	0.003641	0.004408	0.003486	0.003556
Fifth	0.002927	0.003384	0.003081	0.002888
Fourth	0.003211	0.003630	0.00754	0.003196
Third	0.002505	0.003048	0.002677	0.002528
Second	0.002582	0.003090	0.002613	0.002711
First	0.002380	0.002834	0.002386	0.004439
Plinth	0.000892	0.001063	0.003337	0.003447

Table 6. Storey shear (V_x) in the X direction (kN)

	Model-1	Model-2	Model-3	Model-4
Storey	V_x			
Roof	279.8094	288.9388	255.0791	284.262
Tenth	766.9844	754.826	808.7402	746.0453
Ninth	2121.592	2050.242	1965.4	2041.597
Eighth	3283.746	3161.614	3063.568	3162.297
Seventh	5146.129	6596.34	4855.083	4990.77
Sixth	6625.345	8010.92	6310.863	6466.243
Fifth	8427.288	9734.125	8138.716	8305.889
Fourth	9705.725	10956.7	10057.51	9654.061
Third	10908.04	13206.54	11128.14	10984.73
Second	11582.64	13851.66	11679.27	11793.4
First	11981.04	14232.66	12004.68	12374.24
Plinth	12016.64	14266.69	12031.73	12417.65

and Figure 4 *a–c* shows a plot of the results of storey displacement, storey drift and storey shear.

Storey displacement

From Table 4 and Figure 4 *a*, it can be observed that maximum lateral displacement at the top floor is observed in model-3, and minimum in model-1. This is because there is reduction in lateral stiffness at storey-4 in model-3, which provides overall less stiffness for lateral loads compared to model-1. Also in Figure 4 *a*, there is sudden increase in lateral displacement in model-3 at storey 4 due to sudden change in lateral stiffness at storey 4. Also due to the same reason, sudden increase in lateral displacement is observed in model-4 at the first storey. There are no kinks in storey displacement graph of model-1 above the first storey due to uniform distribution of mass and stiffness throughout the height of the building.

Storey drift

Figure 4 *b* shows a plot of storey drift ratios for all models obtained by ETABS. IS 1893 (Part-1):2002 specifies that storey drift should not be greater than 0.004. From the storey drift plot it can be observed that for model-1 storey drift is within permissible limits at all storeys, while for model-2 drift ratio exceeds specified limit at the seventh storey (0.00441) due to sudden change in mass at that storey. Storey drift ratio of storey 4 of model-3 is very high, almost double the permissible limit (0.00754). This is due to sudden change in stiffness at the fourth storey. At the first storey of model-4, storey drift exceeds permissible limit due to sudden change in stiffness at the first storey.

Storey shear

Figure 4 *c* shows the storey shear plot for all models. Maximum storey shear is observed in model-2 due to heavy mass at storeys 3 and 7, because storey shear is directly proportional to seismic weight. Model-4 has slightly higher storey shear than model-1 and model-3. Storey shear plots of model-1 and model-3 almost overlap.

Conclusion

The behaviour of G + 10-storeyed building with mass and stiffness irregularity has been studied using four models. Model-1 is an irregular building which is considered as the base model and extra mass is applied at storeys third and seventh of the base model for mass irregularity in model-2. Model-3 and model-4 are formed by increasing height of the fourth storey and first storey columns of the base model respectively. Results in the form of storey displacement, storey drift and storey shear are evaluated and compared. The following conclusions can be made from the obtained results.

- When there is a sudden change in mass between two storey (mass irregularity) of a building, there will be a sudden change in storey displacement or storey drift at that level and if masses are heavy then drift ratio will go beyond the permissible limit.
- For a building with heavy mass at some storey, storey shear will be high compared to the same building having normal mass distribution.
- Vertical stiffness irregularity at a storey in a building causes increase in storey drift beyond specified limits at that storey, while buildings without stiffness irregularity perform well for lateral loads.
- Buildings having mass and stiffness irregularity should be analysed and designed properly. Special detailing and designing methodology should be utilized to keep the displacement and stresses within permissible limit.

1. Jack, P. and Moehle, A. M., Seismic response of vertically irregular structures. *ASCE J. Struct. Eng.*, 1984, **110**(9); ISSN 0733-9445/84/0009-2002, Paper No. 19161.
2. Bhattacharya, S. P. and Chakraborty, S. K., Estimation of storey shear of a building with mass and stiffness variation due to seismic excitation. *Int. J. Civil Struct. Eng.*, 2010, **1**(3); ISSN 0976–4399.
3. Valmundsson, E. V. and Nau, J. M., Seismic response of buildings frames with vertical structural irregularities. *ASCE J. Struct. Eng.*, 1997, **123**(1), 30–41.
4. Sadashiva, V. K., MacRae, G. A. and Deam, B. L., Determination of structural irregularity limits – mass irregularity example. *Bull. NZ Soc. Earthquake Eng.*, 2009, **42**(4).
5. Chintanapakdee, C. and Chopra, A. K., Seismic response of vertically irregular frames: response history and modal pushover analyses. *ASCE J. Struct. Eng.*, 2004, **130**(8), 1177–1185.
6. Ravikumar, C. M., Babu Narayan, K. S., Sujith, B. V., Venkat Reddy, D., Effect of irregular configurations on seismic vulnerability of RC buildings. *Architecture Res.*, 2012, **2**(3), 20–26.
7. IS: 456-2000 (Fourth Revision), Indian standard code for practice for plain reinforced concrete for general building construction, Bureau of Indian Standards, New Delhi, 2000.
8. IS 1893 (Part-I):2002, Criteria for earthquake design structures, general provisions on buildings, Bureau of Indian Standards, New Delhi, 2002.
9. Murty, C. V. R., Earthquake tips. Indian Institute of Technology Kanpur, September 2005.
10. Arun Solomon, A. and Hemalatha, G., Limitation of irregular structure for seismic response. *Int. J. Civil Struct. Eng.*, 2013, **3**(3), 579–590.
11. Dubey, S. K. and Sangamnerkar, P. D., Seismic behavior of asymmetric RC buildings. *Int. J. Adv. Eng. Technol.*, E-ISSN 0976-3945.

Received 6 February 2015; revised accepted 19 July 2016

doi: 10.18520/cs/v111/i10/1658-1663