Non-linear Response of Two-way Asymmetric Multistorey Building Under Biaxial Excitation

Nishant K. Kumar [#1], Rajul K. Gajjar [*2]
[#]Applied Mechanics, L.D.C.E.
Ahmedabad, Gujarat, India
[1] nishant.nitr2006@yahoo.co.in
[*] Govt. Engg. College,
Gandhinagar, Gujarat, India
[2] rkgajjar@yahoo.com

***Abstract*—Seismic analysis is generally performed by creating a structural model which is excited with forces in two orthogonal directions separately i.e. they are subjected to uniaxial excitation. But an actual earthquake will have its effect in both the directions simultaneously. Limited research has been carried out on effect of such biaxial excitation. This paper deals with the non-linear performance of multi-storey buildings under biaxial excitation using various time-histories. The angle of incidence of earthquake forces will be varying between 0 to 360 degrees. Three building plans, with eccentricity along each of x and z directions in plan and a third with eccentricity in both the orthogonal direction, have been studied. Time history analysis has been carried out using SAP2000 after validating a preliminary model with experimental results available in reference literature.**

Keywords- bi-axial excitation, time history analysis, multi-storey building

I. INTRODUCTION

In last decade, the investigations on asymmetric buildings under dynamic forces have been carried out on a large scale because asymmetric buildings are more vulnerable to earthquake forces. Particularly, much effort has been spent in studying the effect of seismic behaviour of the design eccentricities already adopted by Indian Standard code IS: 1893. For example, study of influence of vertical irregularity by J. H. Cassis and E. Cornejo (1996), estimation of accidental torsion effects for seismic design of buildings by Juan C. de la llera and Anil K. Chopra (1995) which was then included in code as 5% of lateral dimension, behaviour of beam column under uniaxial excitation by Christos A. Zeris and Strephen A. Mahin (1988), behaviour of rcc frame under biaxial excitation by Christos A. Zeris and Strephen A. Mahin (1991).

Most of the above mentioned literature basically focussed on issues related with design problems, numerous studies on analytical aspects have also been carried out. These studies aim to identify parameters which govern the non-linear response of asymmetric-plan building. It also helped in developing analysis methods to achieve a certain level of efficacy. For example, effect of plan configurations of the seismic behaviour of structure using response spectrum method by Rucha S. Banginwar, M. R. Vyawahare and P. O. Modwani (2012), non-linear seismic response on asymmetric plan buildings by Andrea Lucchini, Giorgio Monti and Enrico Spacone (2009), influence of bidirectional seismic motion on the response of asymmetric building by Julio J. Harnandez and Oscar A. Lopez (2000), non-linear response of two way asymmetric single storey building under biaxial excitation by Andrea Lucchini, Giorgio Monti and Sashi Kunnath (2011). These literatures brought light on several gray regions of analytical understanding of structures. However, final conclusions of earthquake forces in biaxial excitation on plan-symmetric and asymmetric multi-storey structures and other significant parameters are still lacking.

Although, the emphasis had been put on reducing the torsional effect and several provisions have been made in different codes, building a structure perfectly as per these criteria is not always viable. This may occur due to certain constraints like, architectural constraints, purpose of building, etc.

Also the current practices for analysis and design of multistorey structures follow the IS:1893-2002 clause 6.3.2.1 while doing dynamic analysis i.e. "When the lateral load resisting elements are oriented along orthogonal horizontal direction, the structure shall be designed for the effects due to full design earthquake load in one horizontal direction at time". [15]

The main aim of this paper is to overcome these deficiencies by providing the results of parametric investigations carried out by the authors on two-way asymmetric multi-storey building excited by bidirectional ground motions. A basic ground + five storey building plan is considered having 18 columns with beams and rigid diaphragm. From this plan, a total of four sub-plans are generated to create four different structures; i) totally symmetric building; ii) building symmetric about x-axis; iii) building symmetric about y-axis; iv) building asymmetric about both the axes. The size of column is same for all the 18 columns and the support is considered hinged. The effects on the seismic response of orthogonal components, the angle of incidence and intensity of earthquake are studied. In order to cover the non-linearities in response, time history analysis is carried out for 4 different accelerograms.

II. Background

To initialize the study, the investigations, carried out under the reference literature "non-linear response of two way asymmetric single storey building under biaxial excitation", are considered which was published in Journal of Structural Engineering in January 2011 by Andrea Lucchini, Giorgio Monti and Sashi Kunnath. In this paper, numerical study has been carried out on a single storey building having 6 columns and rigid diaphragm. Time history analysis and incremental dynamic analysis have been performed. Time history analysis has been performed for the Kobe earthquake and Erzincan earthquake having Peak Ground Acceleration (PGA) value 0.51g. The incremental dynamic analysis is performed for PGA value 0.1g, 0.5g and 0.9g. The evolution of the maximum displacement demand in the different resisting elements of the system and of corresponding global restoring forces has been investigated for earthquakes of increasing intensities characterized by different angle of incidence. The major conclusions [1] derived in this literature are;

- When response in nonlinear zone is increased then the different global forces acting on the system that produce the maximum demand in the resisting elements tends to converge toward a single distribution;
- This distribution is related to resistance distribution only and not to the elastic properties of the system. In particular, it has been found that the nonlinear response is governed by specific points of that surface known in the literature as Base Shear Torque surface. Such points denoted as CRs by the authors corresponding to the BST combinations with each fixed β-direction to the maximum lateral strength of the building;
- The direction of the pushing force, whose identification is not the focus of this study, dependent on the type of seismic analysis considered. In this only those buildings are studied whose Base-Shear Torque (BST) surface does not depend on the excitation i.e. structures with columns whose resistances are not affected by hardening or softening behaviour are studies;
- The convergence of the response toward the CR may not occur in those cases where low intensities of the seismic excitation or premature brittle failures of some resisting elements of the structure do not result in sufficient inelastic behaviour of the system.

III. Model validation

Time history analysis is carried on the similar model prepared in SAP2000 platform for different PGA i.e. 0.1g, 0.5g and 0.9g. The result in form of graph showing maximum displacement in the y-direction normalized with respect to the storey height is considered for model validation in SAP2000. The graph shows that the results occurred in the reference literature and in SAP2000 are almost similar with a little difference. These differences might have occurred due to certain difference in assumptions of parameters.

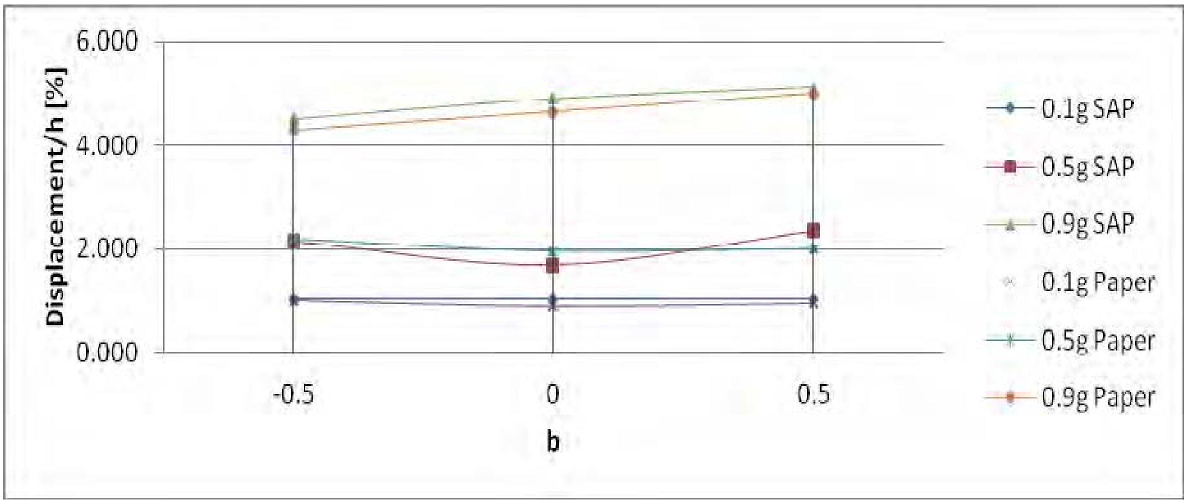

Fig 1. Comparison graph of results in reference literature and SAP2000

IV. Analysis of multistorey building

A G+5 building was considered whose autoCAD plan is shown in fig 2. From this plan four different structural plans were generated having different eccentricities. These eccentricities were brought by changing the alignment of lateral resisting elements i.e. columns. To carry out the biaxial excitation, the angle of incidence of earthquake was varied from 0 degree to 360 degree with interval of 22.5 degree. The y axis direction is taken as 0 degree and the angle is varied counter-clockwise. Building was analysed for following data;

- Dimension of beam : 230mm x 560mm
- Dimension of column : 300mm x 600mm
- Concrete : M20 for beam and M25 for column
- Steel : fy415

The columns are placed at all the beam intersection shown in SAP plan in fig 2. Different time history was used whose details are provided in table II.

Nonlinear and direct integration method (Hilber-Hughes-Taylor) has been used to record the response of structure during time history analysis. The geometric non-linearity parameters are not introduced in this study.

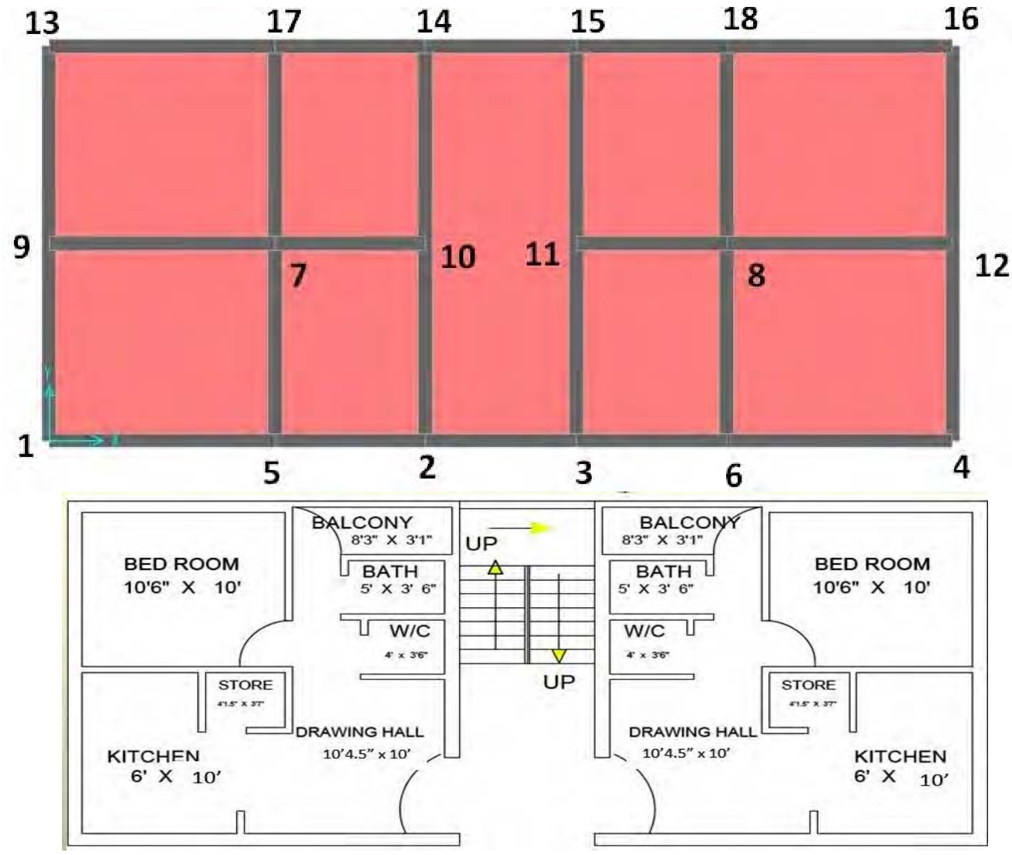

Fig 1 Plan of building and position of columns in SAP model

All the four models were then subjected to time history analysis with different angle of incidence and different PGA. Certain parameters are there on which the response for different angle can be compared. For this study, forces at the support in X and in Y directions are recorded and compared.

TABLE I
Type of Symmetricity in Different Column

Sl.no.	Plan geometry symmetry	Stiffness symmetry about x-axis	Stiffness symmetry about y-axis
1	√	√	√
2	√	X	√
3	√	√	X
4	√	X	X

TABLE II
Earthquake Time History Details

Name	Loma Prieta	Kobe	Loma prieta	San Farnando	Nahanni
Station	UCSC station 16	Takatori 000	LGPC 000	Pacoima Dam	Site 1, 010
Date of eq.	10/18/1989	10/18/1989	10/18/1989	02/09/1971	23/12/1985
PGA	0.56g	0.65g	0.76g	1.16g	0.9g

TABLE III
Eccentricity in Different Models

	Model 1		Model 2		Model 3		Model 4	
S.N.	Ex (m)	Ey (m)	Ex (m)	Ey (m)	Ex (m)	Ey (m)	Ex (m)	Ey (m)
1	0	0	1.875	0	0	-0.93	-1.5	-0.65

Where Ex is eccentricity along x-direction and Ey is eccentricity along y-direction

Comparison of forces in two orthogonal directions for uniaxial excitation and biaxial excitation is done as per the following formula.

$$\%\Delta F_i = \frac{max(F_{bi}) - max(F_{ui})}{max(F_{ui})} \times 100$$

Where F_i is the force in i^{th} direction,
F_{bi} = base forces due to biaxial excitation in i^{th} direction
F_{ui} = base forces due to uniaxial excitation in i^{th} direction

V. Results

For all the models, variation of base forces in x and y direction with change in angle of incidence of earthquake is calculated for all the columns. Overall difference in forces for all the models is shown in table IV.

TABLE IV
Percentage Difference Between Base Forces Due to Uniaxial and Biaxial Excitation

	Model 1		**Model 2**		**Model 3**		**Model 4**	
	ΔFx (%)	**ΔFy (%)**	**ΔFx (%)**	**ΔFy (%)**	**ΔFx (%)**	**ΔFy (%)**	**ΔFx (%)**	**ΔFy (%)**
Column 1	-7.74	-7.62	17.74	-7.54	-7.58	5.00	9.21	28.04
Column 2	-7.82	-7.60	19.88	-7.63	-7.54	-5.59	9.37	13.85
Column 3	-7.40	-7.61	19.70	-7.57	-7.54	-2.72	9.31	1.59
Column 4	-7.48	-7.60	17.82	-7.59	-7.58	6.59	9.63	8.46
Column 5	-7.67	-7.61	18.44	-7.68	-7.59	21.00	9.56	17.19
Column 6	-7.54	-7.61	19.54	-7.62	-7.59	27.28	9.50	-0.43
Column 7	-7.61	-7.61	-7.61	-7.61	-7.60	20.86	-0.25	17.25
Column 8	-7.61	-7.61	-7.61	-7.61	-7.60	27.36	0.15	-0.17
Column 9	-7.61	-7.61	-7.61	-7.61	-7.57	5.77	0.01	28.11
Column 10	-7.61	-7.61	-7.61	-7.61	-7.57	-5.72	-0.34	13.93
Column 11	-7.61	-7.61	-7.61	-7.61	-7.57	-3.06	-0.54	2.08
Column 12	-7.61	-7.61	-7.61	-7.61	-7.57	6.64	0.63	8.87
Column 13	-7.48	-7.60	17.74	-7.68	-7.60	5.74	2.22	27.96
Column 14	-7.40	-7.61	19.88	-7.60	-7.60	-5.87	1.82	14.06
Column 15	-7.82	-7.60	19.70	-7.65	-7.60	-3.11	1.81	2.43
Column 16	-7.74	-7.62	17.82	-7.64	-7.60	6.74	1.94	9.47
Column 17	-7.54	-7.61	18.44	-7.54	-7.60	21.22	1.68	17.49
Column 18	-7.67	-7.61	19.54	-7.60	-7.60	27.58	1.90	-0.16

A. Model 1

In this model, the centre of mass is coinciding with the centre of stiffness. Hence there are no eccentricities as shown in below figure.

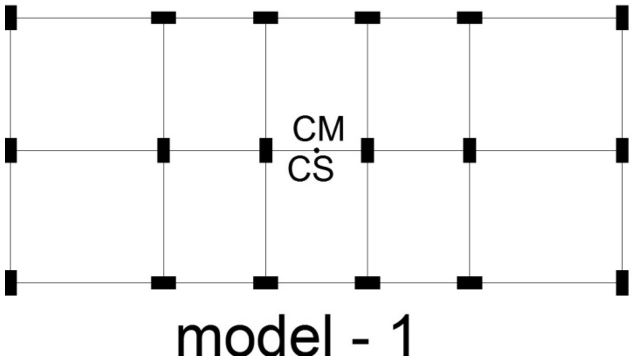

Fig 3. Layout showing column orientation in model - 1

The base forces for all the columns is giving maximum value at 0 degree and 90 degree which shows that the absence of eccentricities causes the base forces to be smaller for any angle other than 0 and 90 degree. That means, when the angle of incidence is 0 degree then Fx for all the column will be zero and for 90 degree Fy for all the column will be zero.

B. Model 2

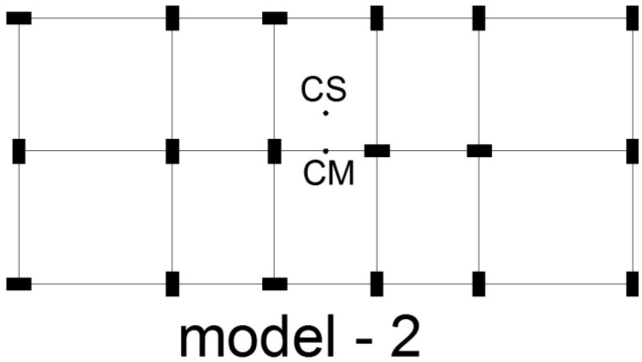

Fig 4 Layout showing column orientation in model - 2

This model has the eccentricity in y direction i.e. it is symmetric along y-direction as shown in figure above. When the angle of incidence is 0 degree then the eccentricity is not taking part. For all the other angles, the eccentricity will come into action and causes torsion. This will induce more forces and thus increase the value of Fy. Due to no eccentricity along x-direction, the Fx for all columns will have maximum value at 90 degree as expected. As the angle of incidence in changing from 0 to 90 degree, the value of Fy due to direct forces will reduce and the torsion will increase in that range. At a certain angle, the combined value of direct force and torsion induced force will reach its maximum for biaxial excitation. Depending upon the position of column with respect to the centre of stiffness, some column will show greater forces for biaxial excitation and vice-versa.

C. Model 3

This model has the eccentricity in x direction i.e. it is symmetric along x-direction as shown in figure given below. When the angle of incidence is 90 degree then the eccentricity is not taking part. For all the other angles, the eccentricity will come into action and causes torsion. This will induce more forces and thus increase the value of Fx. Due to no eccentricity along y-direction, the Fy for all columns will have maximum value at 0 degree as expected. As the angle of incidence in changing from 0 to 90 degree, the value of Fx due to direct forces will reduce and the torsion will increase in that range.

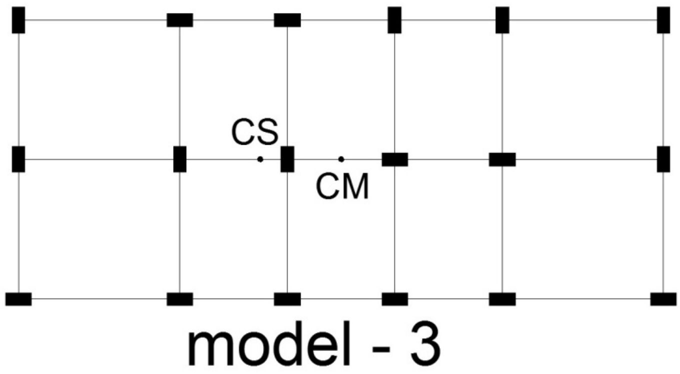

Fig 5. Layout showing column orientation in model - 3

At a certain angle, the combined value of direct force and torsion induced force will reach its maximum for biaxial excitation. Depending upon the position of column with respect to the centre of stiffness, some column will show greater forces for biaxial excitation and vice-versa.

D. Model 4

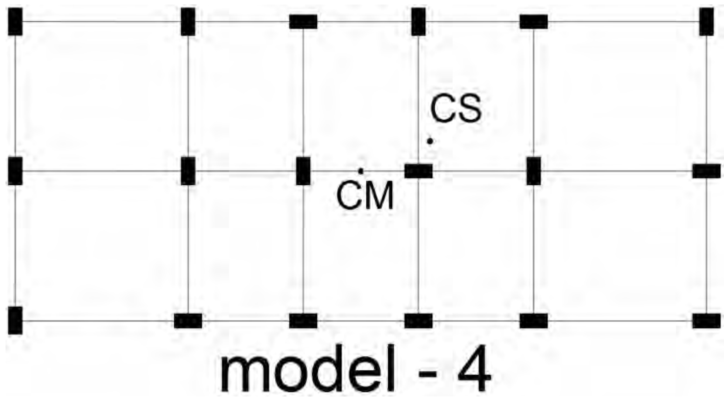

Fig 6. Layout showing column orientation in model - 4

There is asymmetricity along both the orthogonal directions as shown in above figure. Due to this condition, when the angle of incidence of earthquake is 0 or 90 degree then eccentricity in other orthogonal direction doesn't come into picture. However, while biaxial excitation asymmetricities along both the direction take part in generating base forces due to which forces due to biaxial excitation exceeds the forces due to uniaxial excitations for almost all the columns. For every column, there exists a particular angle for which Fx and Fy reaches it maximum value. It's worth noting that none of the columns in this model is having more forces Fx and Fy simultaneously due to uniaxial excitation as compared to forces due to biaxial excitation.

VI. CONCLUSIONS

When the dynamic is applied in one of the orthogonal directions then it doesn't include eccentricity along the other orthogonal directions. When the angle of incidence of earthquake changes then the direct force reduces sinusoidally; however the torsion increases which ultimately increases the forced induced in columns due to torsion. So there exists an angle at which the summation of these forces reaches its maximum value.

- With the change in angle of incidence of earthquake, the direct forces reduces and since there is no eccentricity in the building, there won't be any base force generated due to torsion. Since base forces for uniaxial excitation in both the orthogonal directions in a symmetric building are lesser than the forces due to bi-axial excitation; biaxial excitation is not required for symmetric building.
- For the x-symmetric plan, when the angle of incidence of earthquake changes from 0 to 90 degree, then Fy changes sinusoidally. Due to eccentricity, at a certain angle, the summation of direct force and force induced due to torsion reaches its maximum value. It was observed that force in y direction due to biaxial excitation exceeds the forces due to uniaxial excitation by 28% in 3 out of 18 columns, ~21% in another 3 out of 18 columns. Hence, the biaxial excitation is necessary to get adequate design forces.
- Similarly, for the y-symmetric plan, force in y direction due to biaxial excitation exceeds the forces due to uniaxial excitation by ~18%-20% in 12 out of 18 columns.
- For the asymmetric plan, force in x direction due to biaxial excitation exceeds the forces due to uniaxial excitation by ~10% in 6 out of 18 columns.

- For the asymmetric plan, force in y direction due to biaxial excitation exceeds the forces due to uniaxial excitation by 28% in 3 out of 18 columns, ~18% in another 3 out of 18 columns and ~10% for the other 3 columns. Hence, the biaxial excitation is necessary to get adequate design forces. From the results, it can be concluded that for torsionally coupled building biaxial excitation is generating more forces in comparison to uniaxial excitation.

REFERENCES

[1] Lucchini Andrea, Monti Giorgio and Kunnath Sashi. "*Non linear response of two way asymmetrical single storey building under bi-axial excitation." Journal of structural engineering, ASCE (January, 2011)*

[2] Julio J HERNÁNDEZ, Oscar A LÓPEZ, "*Influence of Bidirectional Seismic Motion on the Response of Asymmetric Building*" by 12th World Conference on Earthquake Engineering, 2000

[3] Dorde Ladinovic, "*Nonlinear seismic analysis of asymmetric in plan building*" by FACTA UNIVERSITATIS: Architecture and Civil Engineering Vol. 6, No 1, pp. 25 – 35, 2008

[4] Raúl González Herrera1, Consuelo Gómez Soberón, "Influence of Plan Irregularities of Buildings" by 14th World Conference on Earthquake Engineering, 2008

[5] Andrea Lucchini, Giorgio Monti, Enrico Spacone, "Asymmetric-Plan Building: Irregularity Levels and Nonlinear Seismic Response" by E. Cosenza (ed), Eurocode 8 Perspectives from the Italian Standpoint Workshop, pg 109-117, Doppiavoce, Napoli, Italy, 2000

[6] N. Özhendekci, Z. Polat, "Torsional Irregularity of Buildings" by 14th World Conference on Earthquake Engineering, 2008

[7] Rucha S. Banginwar, M. R. Vyawahare, P. O. Modani, "Effect of Plan Configurations on the Seismic Behaviour of the Structure by Response Spectrum Method" by International Journal of Engineering Research and Applications(IJERA), May-June 2012

[8] Christos A. Zeris, Stephen A. Mahin, "Behaviour of Reinforced Concrete Structures Subjected to Biaxial Excitation" by Journal of Structural Engineering (ASCE), Sept 1991

[9] Christos A. Zeris, Stephen A. Mahin, "Behaviour of Reinforced Concrete Beam-Columns under Uniaxial Excitation" by Journal of Structural Engineering (ASCE), April 1998

[10] H. P. Hong, "Torsional Responses under Bi-Directional Seismic Excitations: Effects of Instantaneous Load Eccentricities" by Journal of Structural Engineering (ASCE), March 2012

[11] Juan C. De La Llera, Anil K. Chopra, "Estimation of Accidental Torsion Effects for Seismic Design of Buildings" by Journal of Structural Engineering (ASCE), Jan 1995

[12] Czeslaw Bajer, "Time Integration Methods – Still Questions" by Theoretical Foundations of Civil Engineering, Warsaw, 2002

[13] Deierlein, Gregory G., Reinhorn, Andrei M., and Willford, Michael R. (2010). "Nonlinear structural analysis for seismic design," NEHRP Seismic Design Technical Brief No. 4, produced by the NEHRP Consultants Joint Venture

[14] "Applicability of Non-linear Multiple-degree-of-freedom modelling for design" by NEHRP joint venture

[15] IS 1893:2002 "Criteria for Earthquake Resistant Design of Structures