Theoretical and Experimental Analysis of Building Model to Validate Seismic Simulation

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Abstract: **This paper compares the Linear Time History Analysis of a multi degree of freedom system using manual calculations and ETABS software analysis. The strong motion data of past three earthquakes are used for the analysis. The comparison is made for the response of the structure with respect to the time history motion of the ground acceleration record. The paper also considers the experimental investigation methods using the uniaxial horizontal shake table. The similitude laws are studied and models are designed such that they are similar to their proto type with respect to dynamic similitude. The scaled down models are tested on uniaxial horizontal shake table in three angles (0^o, 30^o and 60^o) of incidence for the seismic input motions. The seismic input motion is given in the form of displacement time history of three earthquake strong motion records considered throughout the study. Structures with different plan shapes having approximately same plan area are compared for the response to the ground motion excitation. This paper manifests the difference in response of structure to the given time history records of ground motion accelerations at various angles (at 30^o increment) of incidence of input seismic motion.**

Keywords: Time stepping methods, linear modal time history analysis, Similitude, Shake table experiments, Scale down models, irregular plan buildings, Seismic analysis.

I INTRODUCTION:

India being sensitive location, is vulnerable to many earthquakes. About 85% of country is susceptible to one or more disasters and seismicity of area is 57% high including the capital of the country [1]. For better design of the structures against earthquakes and economically viable location based solutions, Seismic Zonation Map of a country provides guidelines about seismic status and susceptibility of a region. The first map showing seismic zoning of India was putforth by the GSI (Geological Survey of India) in 1935 [2] after the massive Bihar-Nepal earthquake of 15 January 1934 having magnitude of 8.4. The seismic zoning map of India is regularly being updated and published along with the guidelines for earthquake resistant design of structures by BIS in IS-1893.

Many strong earthquakes are witnessed by India in recent history with large inter-plate earthquakes near to plate boundary in the Himalayas and in the mid region away from the plate boundaries in the shield region of Indian peninsula [3] . An apt region of very high seismicity in west of India appears to be caused by local convergence of plate at the Rann of Kachchh [4]. The Bhuj Earthquake of January 26, 2001 (magnitude 7.9 on Richter scale) in Gujarat too caused the destruction of a large number of modern 4 to 10 storied buildings as far as 350km away from the epicenter. The October 19, 1991 Uttarkashi earthquake occurred in the Indian Himalayan main thrust zone killed over a thousand people and caused important economic loss in the Garhwal, Himalaya region. An earthquake of magnitude 7.3 occurred in the Indo-Myanmar border on August 6, 1988 had its epicenter near Homalin and lasted for two minutes [5]. Tremors were felt in the entire Northeastern region, Myanmar, Bangladesh and Nepal during which Guwahati noticed a 20m subsidence. The three occurrences stated above are considered as time history records for the study. Information on magnitude and frequency of earthquakes is essential for proper assessment of the seismicity of a region. For this purpose a comprehensive and accurate database of past earthquakes is required [6].

Manual analysis of the equation of motion for a system of single-degree-of-freedom (SDOF) is usually tedious if the excitation is applied force or ground acceleration or varies arbitrarily with time. Such problems can be resolved by numerical time integration methods for integration of differential equations [7]. Experimental work can be carried out on either unscaled prototypes or scaled models of elements, subassemblies and complete structures[8]. The present study is related to dynamic model that is used to study vibration or loading effects on structures tested on a shake table under earthquake motion. Experimental techniques have always been a vital part of advanced engineering design. Whenever the current theoretical knowledge reaches its limit, an experiment provides an alternative in the evaluation of the adequacy of the proposed design. Study of behavior of structural systems under simulated loading conditions can be achieved through experimentation [9]. Considering the high cost of experimentation as compared to conventional or computer analysis, the scope of experimental work is usually limited to fundamental research and the study of complex input and response phenomena which cannot be modeled mathematically with confidence. Modern computing techniques and devices can play a vital role to make the life of a structural engineer easier [10]. Currently most of the structural engineers are using the traditional computing programs and techniques to solve their problems.

There have been many researches carried out for investigating the behavior of various irregularities of the structures subjected to seismic forces with the help of software computing tools. Very less work is seen to be done using major Indian earthquakes (of those with strong motion data available). This gap of available studies motivated the present study to investigate various irregularities in plan configuration using Indian earthquake strong motion acceleration records as seismic input and use shake table as an investigating tool along with computer software and further comparing the ETABS software with theoretical computation method for time history analysis of structures.

II OBJECTIVES OF PROJECT WORK

A. To study the theoretical method of vibration analysis for calculating response of MDOF to time history excitation at base and validate the computer simulation.
B. To study the response of building models to base motions through experimentation techniques using Horizontal Shaking Table and validate the prototype simulation using software.
C. To study the effect of orientation of building plan with respect to direction of base ground motion using experimental techniques.
D. To study the effect of irregular plan shapes having re entrant corners on the response of the building to the time history excitation.

III SCOPE OF WORK

With 57% of India being major earthquake prone, and the development of multistory buildings as per its required usage and aesthetics that induces need for irregular plan shape buildings, seismic analysis of building plays vital role in its structural design. The present study performs (i) dynamic analyses of six story shear building theoretically and validates with ETABS software; and (ii) experimental investigation of irregular plan shape structures for earthquake strong motion acceleration time series records by shake table using laws of similitude and similar prototype buildings are compared in ETABS software to validate the experimental investigation; also (iii) the models are tested at three angles of incidence (0^o, 30^o and 60^o) for all three time history motion inputs to understand the effect of angle of incidence towards dynamic response of the scaled down models; (iv)the structures to various angle of incidences (at 30^o increment) with computer simulation through ETABS software to investigate the effect of plan shape irregularity in the response of building.

IV. METHODOLOGY

A. Time History Record for Base Excitation

Strong motion records are selected out of records contributed for the earthquake events occurred across India.

TABLE NO. I
TIME HISTORY RECORDS

Sr. No	Event	PGA (m/s/s)	PGV (m/s)	PGD (mm)
1	Bhuj (Ahmedabad, N78E) 26.01.2001	1.038	0.111	88.21
2	Uttarkashi (Bhatwari, N85E) 20.10.1991	2.480	0.179	37.50
3	India-Myanmar Border (Bokajan, N34E) 06.08.1988	1.480	0.086	19.90

B. Six Story Shear Building

In this paper a simple six story building is considered; not more than six stories are considered to facilitate manual calculation. The six story shear building will have six degrees of freedom in translation, one at each floor. There are four columns per story spaced at 3m grid and floor to floor height is 4m. The columns are 400mm x 400mm concrete M20 grade columns and slab is 125mm thick of same material property with damping ratio of the system as 0.05. The six story building is subjected to horizontal earthquake ground motion acceleration. The mathematical idealization of the six story shear building is as shown in fig. no. 1

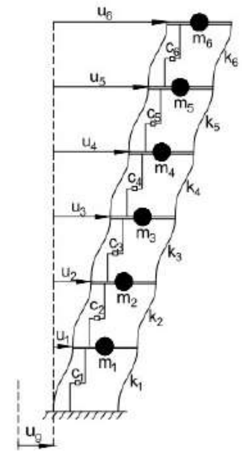

Fig No: 1 Single bay representation of six story shear building

Modal analysis is done using transformation of coordinates. The decoupled equation of motion is:

$$\ddot{q}_n + 2\zeta\omega_n\dot{q}_n + \omega_n^2 q_n = -\Gamma \ddot{u}_g(t) \qquad \text{Eq.1}$$

The problem of ascertaining the eigenvalues frequencies in MDOF systems is analysed with SDOF systems assuming undamped conditions, thus solving the characteristic equation.

$$\left|\mathbf{K} - \omega^2 \cdot \mathbf{M}\right| = 0 \qquad \text{Eq.2}$$

The eigenvalue problem is solved to find the mode shapes and corresponding frequencies. The modes are then checked for orthogonality and orthonormality.

C. Time Stepping Methods

The response of the structure subjected to ground acceleration $\ddot{u}_g(t)$ that varies arbitrarily with time can be tackled by numerical time-stepping methods of integration of differential equations. Many approximate procedures implemented numerically are based on three important requirements: (a) Convergence – as the time step decreases, the numerical solution should approach the exact solution. (b) Stability – the numerical solution should be stable in the presence of numerical round –off errors. (c) Accuracy – the numerical procedure should provide results that are close enough to the exact solution.

Three types of time stepping methods presented in this study are as follows: (a) Piecewise Exact Solution – Method based on interpolation of the excitation function (b)Central Difference Method – Method based on finite difference expressions of velocity and acceleration, (c)Newmark's Linear Acceleration Method – Method based on assumed variation of acceleration (linear).[11][12][13].

Linear modal time history analysis using theoretical time integration methods is performed and pseudo spectral accelerations are obtained to ascertain the top story displacement.

D. Experimental Method of Seismic Simulation

Three prototype six story RC building frames (G+5) of different shapes with same plan area and column grid spacing are considered. The building frames are of plan shape (i) Regular square shape, (ii) L shape, (iii) Plus shape. The geometry of building frames are decided based on the feasibility of experimental study on scale down steel model. Similitude between the prototype and model is attempted by using the scaling rules[14] and considering the payload capacity of the shake table. The model properties are shown in table no. II

TABLE NO. II
Scaled down model geometric properties

S. No	Contents	Description		
1	Structure	Regular	L Shape	Plus Shape
2	No. of stories	G+5	G+5	G+5
3	Storey Height	160 mm	160 mm	160 mm
4	Grade of Steel	Fe250	Fe250	Fe250
5	Bay width	120 mm	120 mm	120 mm
6	Slab thickness	3 mm	3 mm	3 mm
7	Size of Column	8 x8mm	8 x8mm	8 x 8mm
8	Model Mass	26.9 kg	29.3 kg	29.3 kg
9	Mass with base	45 kg	67.5 kg	67.5 kg

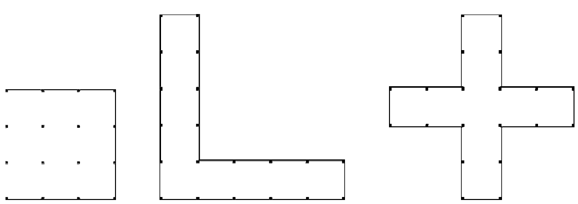
Fig No: 2 Plan Shapes of Experimental Models


Fig No: 3 Experimental Setup

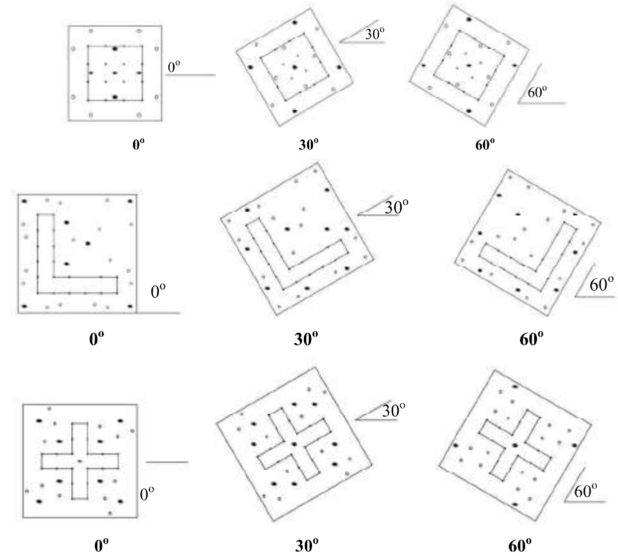

Fig No: 4 Scaled Model Testing Angles of Incidence

The test runs of input base motions are given in 3 directions namely 0°, 30° and 60° by rotating the model. With same model, base plate holes to be made such that it matches the shake table bolt positions for all three directions. For this reason only three directions are considered so that number of holes is not too much to crack the base plate.

E. Analytical Method of Seismic Simulation

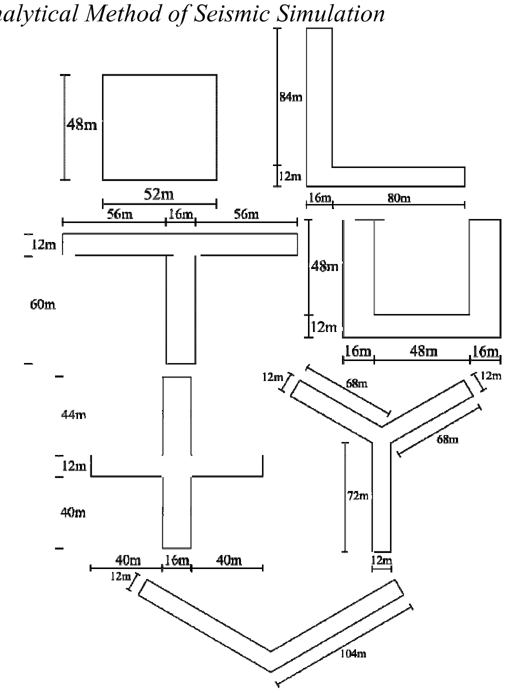

Fig No: 5 Irregular plan shape models

Plan Irregular buildings[15] with ten story (G+9 floors) are modeled using ETABS computer software. Each building plan shape model is having same column grid spacing of 4m in both directions and floor to floor height of 3m each. All the building plan shape models are having approximately same floor area of about 2496 m^2. The various plan shapes considered are subjected to three strong motion records discussed earlier with various angles of incidence of input ground motion varying at 30^o each

The various plan shapes modeled in ETABS are namely 1) Regular square shape, 2) L shape plan, 3) T shape plan, 4) U shape plan, 5) Plus shape plan, 6) Y shape plan and 7) V shape plan. All the re-entrant corners considered for a particular plan shape are of same percentage for that particular plan shape.

V. RESULTS AND DISCUSSIONS

A. Linear Modal Analysis Time History Analysis

The six story shear building subjected to ground acceleration time history for three different input records is analyzed theoretically by time integration methods and with ETABS, the results are discussed hereinafter.

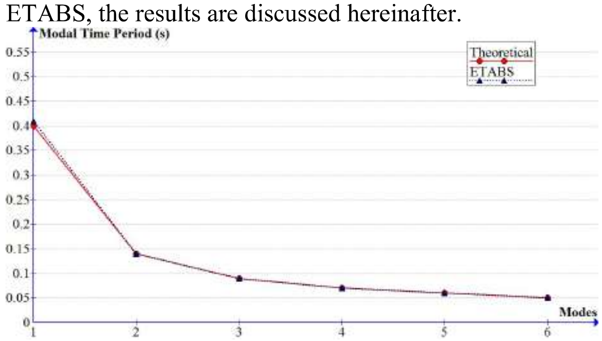

Fig No: 6 Modal Time Periods

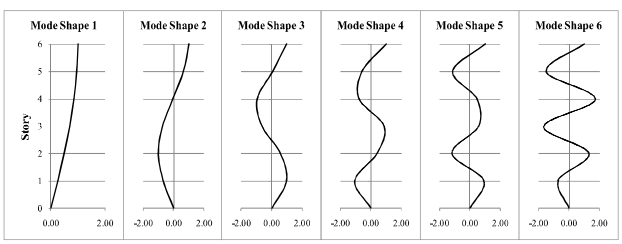

Fig No: 7 Mode Shape Vectors

The modal time periods of theoretical and software results are in well agreement with each other. The mode shape vectors match for both the methods of analysis.

The response of the six story shear building subjected to time history of base motion acceleration is obtained theoretical with the help of modal analysis and time stepping methods. The fig. no.8 shows response for Bhuj data input.

The maximum story response for Bhuj time history motion pertaining to six story shear building is shown in fig. no.9, that compares the time integration methods which shows that results are in agreement with each other. Similarly, results are obtained for other time history inputs that show results inline with each other.

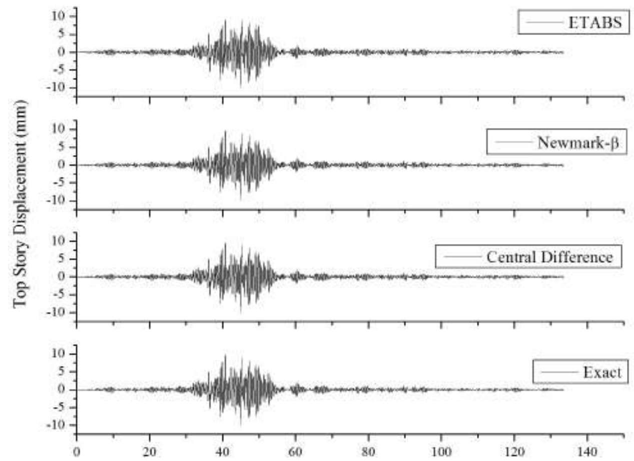

Fig No: 8 Top Story Displacement Response of Shear Building

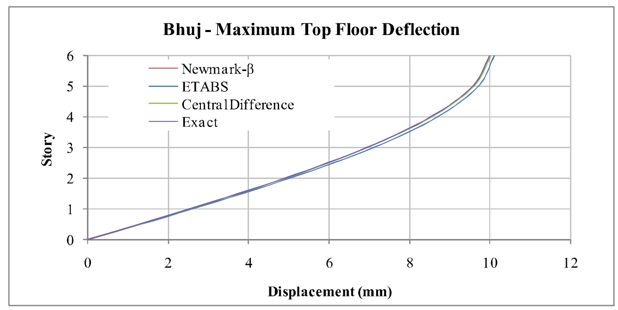

Fig No: 9 Maximum Story Displacements

B. Shake Table Experiments on scaled models.

The experiments are performed on scaled models and the results are compared for 0^o angle of incidence among the models.

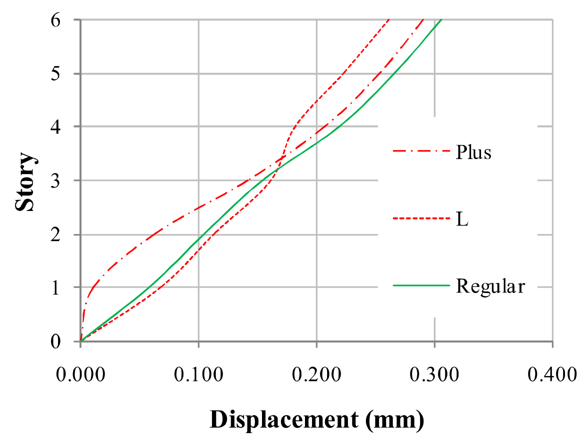

Fig No: 10 Scaled Model Response to Bhuj data

The scaled model displacement response to Bhuj time history is shown in fig. no. 10. which shows that regular plan shape model with less no. of columns than other shapes perform similar in terms of story displacements thus showing economy. Results for Uttarkashi and IndoBurma time history as shown in fig. no. 11 and 12 indicate that the L shape model shows maximum displacement. Plus shape model being symmetric and more number of columns than regular model show less displacement. The tests show that the irregular shape models without symmetry deflect more when subject to base motion excitation. The L shape model shows more deflection as compared to regular shape model and plus shape model.

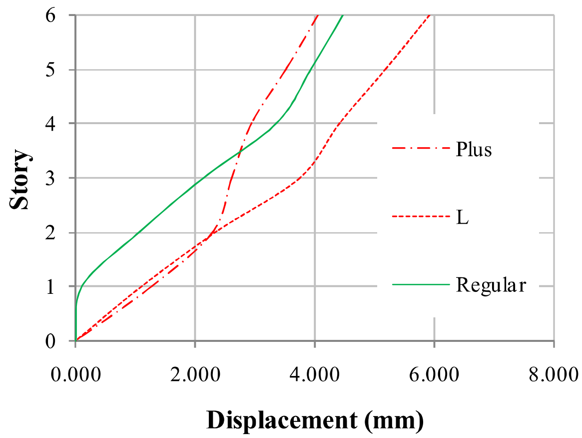

Fig No: 11 Scaled Model Response to Uttarkashi data

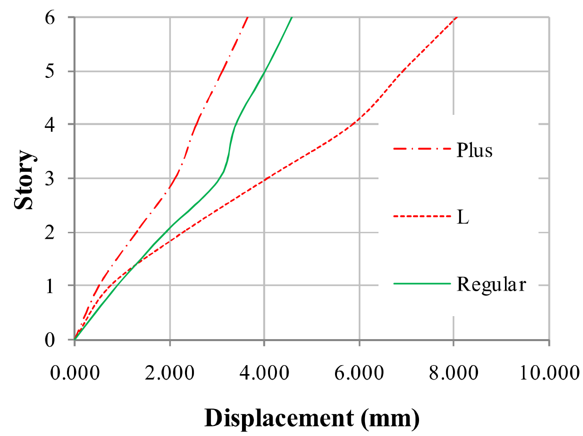

Fig No: 12 Scaled Model Response to IndoBurma data

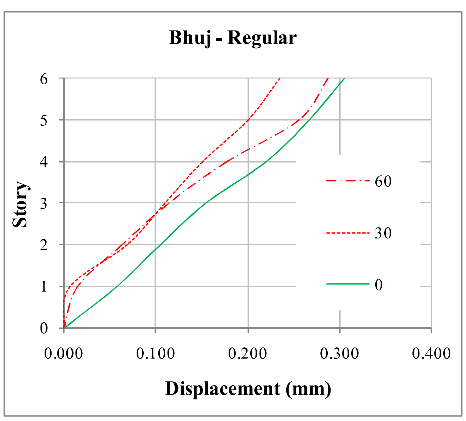

Fig No: 13 Response to input angles for Bhuj data

The testing of scaled models with varying angles of incidence shows that the response of the building changes with change in direction of earthquake motion. The regular building shows 6% less displacement in 60° whereas L and Plus models show 17% and 15% less respectively.

C. Software Simulation of Irregular Plan Shape buildings.

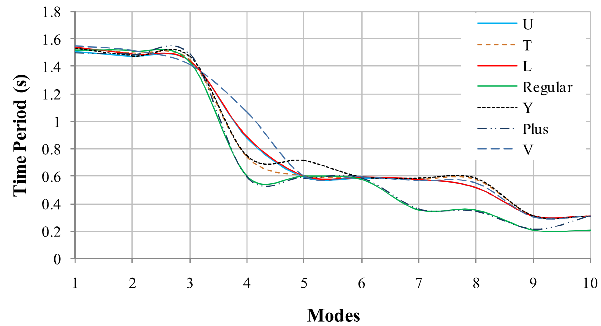

Fig No: 14 Modal time periods of irregular plan buildings

The irregular plan shape G+9 buildings are analyzed for linear time history analysis. The modes of vibration are also observed for various models and shown in fig. 14. Modal time periods and mode shape varies with the plan shapes of the buildings. Torsion is observed in early modes for irregular plan shapes as compared to the regular and also more torsional modes are observed.

The maximum story displacement response in X & Y direction for Bhuj time history data is shown in table no. III

TABLE NO. III

Maximum Displacement for Bhuj data

Story	X-direction Displacement of Plan Shapes (mm)						
	Regular	L	T	U	Plus	Y	V
10	67.19	68.47	70.01	66.33	69.46	71.05	71.87
9	59.87	63.24	64.62	61.27	62.65	65.16	66.69
8	52.23	54.39	55.79	52.70	51.67	56.57	57.43
7	47.17	49.65	50.72	47.45	46.06	49.49	50.49
6	40.19	42.67	43.49	40.42	39.29	42.22	42.57
5	33.38	35.26	35.91	33.22	32.64	34.81	35.03
4	25.19	26.23	26.72	24.60	24.68	25.89	26.08
3	17.18	18.77	19.04	18.56	16.75	18.98	18.73
2	9.23	11.61	11.78	11.43	8.98	11.64	11.77
1	3.24	4.30	4.36	4.23	3.08	4.28	4.35
Story	Y direction Displacement of Plan Shapes (mm)						
	Regular	L	T	U	Plus	Y	V
10	0.017	23.93	23.76	8.03	2.13	4.31	29.79
9	0.013	21.88	21.66	7.36	1.53	3.42	27.56
8	0.009	19.03	18.61	6.22	1.71	2.46	24.31
7	0.01	17.80	16.76	5.62	1.59	2.39	22.42
6	0.008	15.74	14.25	4.79	1.07	2.32	19.54
5	0.011	13.36	11.94	3.99	0.92	2.10	16.43
4	0.008	10.32	9.13	3.04	1.14	1.82	12.58
3	0.007	7.13	6.28	2.12	1.07	1.33	8.65
2	0.01	3.88	3.42	1.16	0.71	0.76	4.69
1	0.012	1.26	1.12	0.38	0.26	0.26	1.52

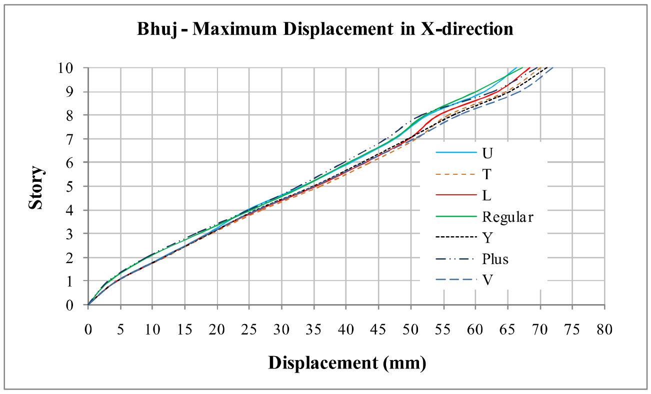

Fig No: 15 Building Displacement Response to Bhuj data – X Dir.

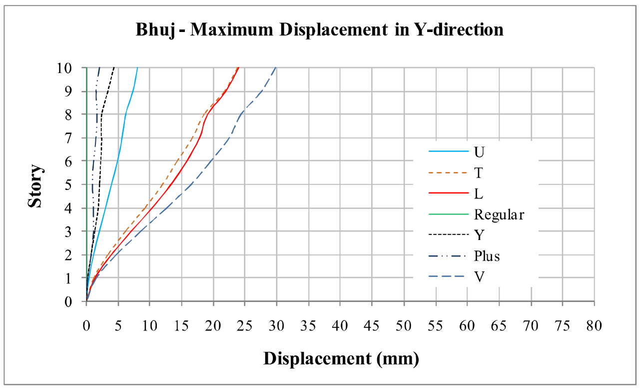

Fig No: 16 Building Displacement Response to Bhuj data -Y Dir.

The displacement response of irregular plan shape buildings is shown in the fig. no. 15 and 16 which manifests that the irregular building displacement is more in Y direction as well and the displacement varies with the different plan shapes. Similar response is observed with Uttarkashi and IndoBurma time history data. Displacement of V shape building is more and that of regular building is less.

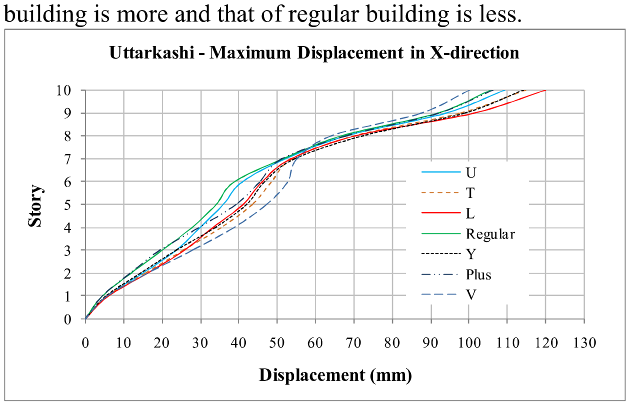

Fig No: 17 Building Displacement Response to Uttarkashi data -X Dir.

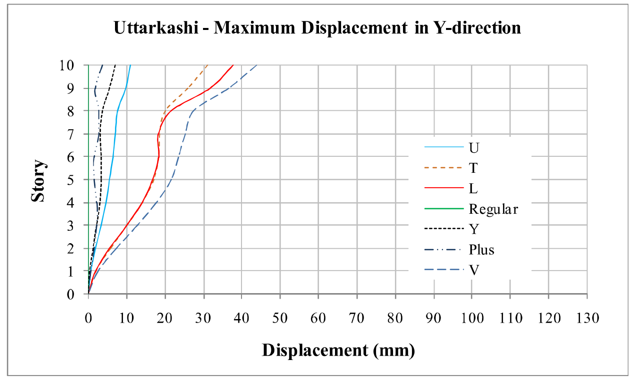

Fig No: 18 Building Displacement Response to Uttarkashi data -Y Dir.

The displacement response of irregular plan shape buildings subjected to time history base motion of Bhuj, Uttarkashi and IndoBurma data shows that the regular plan shape building performs better towards displacement response to earthquake motion considering overall effect in both directions.

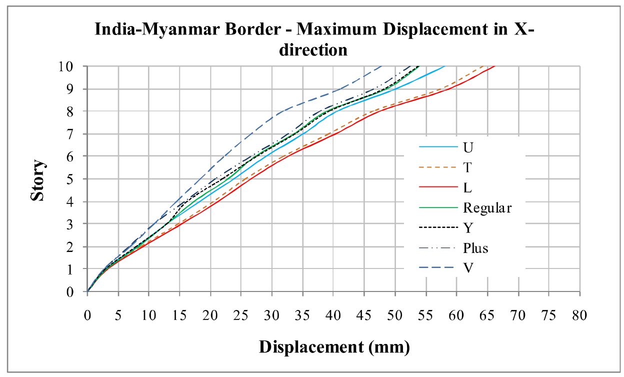

Fig No: 19 Building Displacement Response to IndoBurma data -X Dir.

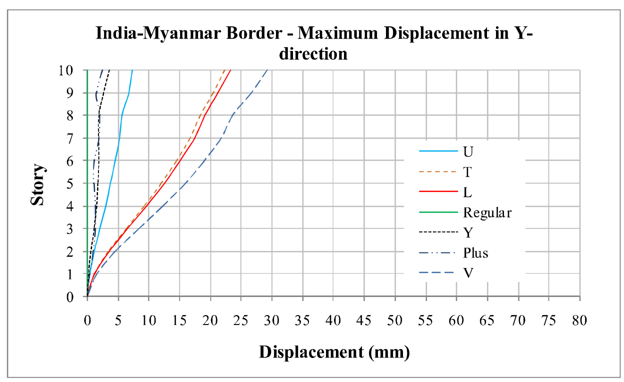

Fig No: 20 Building Displacement Response to IndoBurma data -Y Dir.

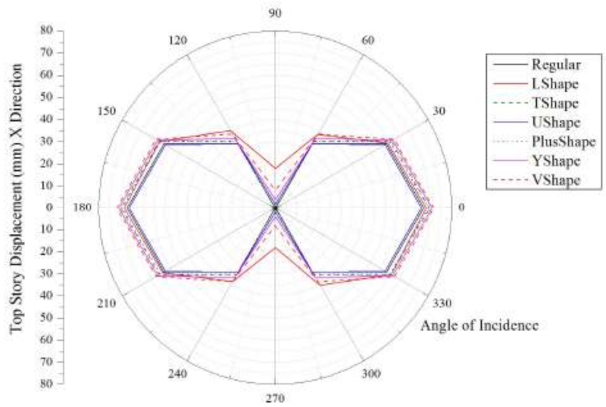

Fig No: 21 Displacement Response – X dir. For Angle of incidence

The plan irregular G+9 buildings are subjected to base ground motion with varying angles of incidence of input motion. The top story displacement response is shown in fig. 21 and 22. The displacement response in X and Y direction shows that the displacement varies with angle of incidence.

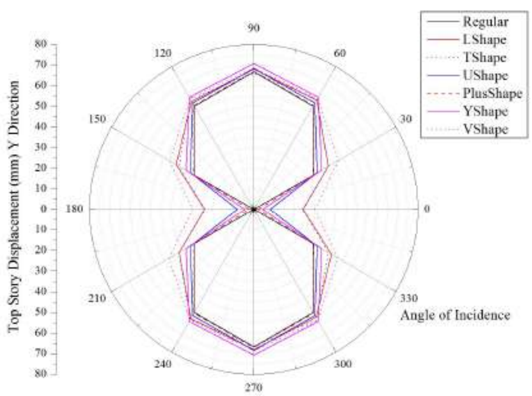

Fig No: 22 Displacement Response – Y dir. For Angle of incidence

VI. CONCLUSIONS

1) The theoretical time integration methods show similar results in their stability limits and are in agreement with ETABS results and show a variation of 3% in results.
2) The experimental studies shows that the scaled model of L shaped building gives average 30% more displacement response as compared to plus shape scaled building model that has least displacement.
3) The scaled building models show variation in displacement response with variation in angle of incidence of base motion. Regular model shows 6% less displacement at 60^{o} whereas L and Plus model show 17% and 15% less, respectively.
4) The irregular plan shape buildings show more displacement in Y direction due to early torsion modes as compared to regular building. Displacement of V shape building is highest with 7% more than regular shape in X direction. Irregular buildings show displacement in Y direction with 0^{o} angle of incidence whereas regular building shows negligible displacement. The response of the building varies with the change in angle of incidence of input motion.

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