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Study of Torsion Effects on Building Structures Having Mass and Stiffness Irregularities

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***Abstract*: Irregular buildings constitute a large portion of the modern urban infrastructure. The group of people involved in constructing the building facilities, including owner, architect, structural engineer, contractor and local authorities, contribute to the overall planning, selection of structural system, and to its configuration. This may lead to building structures with irregular distributions in their mass, stiffness and strength along the height of building. When such buildings are located in a high seismic zone, the structural engineer's role becomes more challenging. Therefore, the structural engineer needs to have a thorough understanding of the seismic response of irregular structures. In recent past, several studies have been carried out to evaluate the response of irregular buildings. This paper presents the details of the non-linear dynamic analysisperformed on mass and stiffness irregular buildings.It is established that irregular buildings are subjected to largedisplacements compared to regular buildings and localized damages nearthe regions of irregularity. Special care needs to be taken while designing such buildings.**

Keywords:Torsional response; Seismic behaviour; Irregular structures; Dynamic analysis; Design lateral foces; Linear static analysis; Non linear time history analysis; Mass irregularity; Stiffness irregularity; Setbacks; Ultimate yielding; Torsional effects

I. INTRODUCTION:

It would be ideal if all buildings have their lateral-load resisting elements symmetrically arranged and earthquake ground motions would strike in known directions.Due to scarcity of land in big cities, architects often propose irregular buildings in order to utilize maximum available land area and to provide adequate ventilation and light in various building components. However, it is quite often that structural irregularity is the result of a combination of both types. Most buildings have some degree of irregularity in the geometric configuration or the distribution of mass, stiffness, and/or strength. Due to one or more of these asymmetries, the structure's lateral resistance to the ground motion is usually torsionally unbalanced creating large displacement amplifications and high force concentrations within the resisting elements which can cause severe damages and at times collapse of the structure. Eccentric arrangement of non-structural components, asymmetric yielding, presence of rotational component in ground motions and the variations in the input energy imparted by the ground motions also contribute significantly to the torsional response of buildings.In India, failure of two most famous apartments during the 2001 Bhuj earthquake was reported due to torsional response.

I. 1 Design considerations in seismic codes:

An asymmetric building structure (torsionally-unbalanced) can be defined as one in which for a purely translational motion, the resultant of the resisting forces does not pass through the centre of mass (Humar and Kumar, 1999) [12]. When strained into the inelastic range, torsional motions in such structures will lead to displacements and ductility demands much larger than those in symmetric buildings (torsionally-balanced) which have similar characteristics.

In general, the torsion arising from eccentric distribution of mass and stiffness can be taken into account by describing an incremental torsion moment (T) in each storey equal to the shear (V)in that storey multiplied by the eccentricity (e), measured perpendicular to the direction of applied ground motion. A precise evaluation of the torsion response is quite complicated because the coupled lateral torsion vibration modes of the entire structure are to be considered by performing a two or three dimensional response calculations.

Torsional effects may significantly modify the seismic response of buildings. These effects occur due to different reasons, such as no uniform distribution of the mass, stiffness and strength, torsional components of the ground movement, etc. As a result, the lateral ductility capacity of the system may be smaller than the lateral ductility capacity of the elements. Design codes incorporate special requirements to take into account the torsional effects, which usually imply the amplification of eccentricity and the consideration of an accidental eccentricity.

These are static responses should be amplified for dynamic response using the response spectrum amplification factor for the fundamental torsion frequency of the structure.Most current codes use accidental eccentricity value of 5% of the plan dimension of the storey perpendicular to the direction of applied ground motion. The accidental torsion may be considered as an increase and also as a decrease in the eccentricity.The eccentricity of the centre of stiffness from the centre of mass is found from

$$e_{Rx} = \frac{\sum_{i=1}^{n} k_{yi} x_i}{\sum_{i=1}^{n} k_{yi}} \text{ and } e_{Ry} = \frac{\sum_{j=1}^{m} k_{xj} y_j}{\sum_{j=1}^{m} k_{xj}} \qquad (1)$$

wherek_{yi} andk_{xj} are the stiffness of frames in the *y*- and *x*-directions respectively, and $x_i$andy_j , the respective distances measured from the centre of mass.

The eccentricity of the centre of strength from centre of mass is given by

$$e_{Vx} = \frac{\sum_{i=1}^{n} V_{yi} x_i}{\sum_{i=1}^{n} V_{yi}} \text{ and } e_{Vy} = \frac{\sum_{j=1}^{m} V_{xi} y_i}{\sum_{j=1}^{m} V_{xi}} \qquad (2)$$

where$V_{yi}$and V_{xj} are the design base shear strengths of frames in the *y*- and *x*- directions, respectively. Torsional response of asymmetric structures responding to seismic excitation is complex involving both strength and stiffness eccentricities as well as torsional mass inertia (Priestley et al., 2007)[11]. The displacements Δ_1 and Δ_2 of the stiff and flexible sides can be obtained by knowing the translational displacement of $C_M$and the twist angle θ which is given by

$$\theta = \frac{V_{By} e_{Rx}}{J_{R,eff}} \qquad (3)$$

where

$$J_{R,eff} = \frac{1}{\mu_{sys}} \cdot \sum_{i=1}^{n} k_{el,yi} (x_i - e_{Rx})^2 + \sum_{j=1}^{m} k_{el,xj} (yj - e_{Ry})^2$$

II. LATEST RESEARCH WORKS ON ASYMMETRIC BUILDINGS

N. P Modakwan, S. S Meshram and D. W. Guwatre (2014) [1] studied the different irregularity and torsional response due to plan and vertical irregularity in buildings and analyzed cross shape and L shape buildings while earthquake forces acts and calculated the additional shear due to torsion in the columns.It is concluded that the re-entrant corner columns are needed to be stiffened for shear force in the horizontal direction perpendicular to it as significant variation is seen in these forces. Significant variation in moments, especially for the higher floors about axis parallel to earthquake direction, care is needed in design of members near re-entrant corners.

A number of parameters govern the response of asymmetric buildings, but the one that has the most significant effect is the torsional stiffness (M/θ) (Humar and Kumar, 1999) [11]. It is to be noted that all in-plane structural elements (both parallel and perpendicular to the earthquake motion) contribute to the torsional stiffness. On the basis of analytical studies on elastic and inelastic behaviour, they concluded that the most important parameter governing the torsional response is the ratio of uncoupled elastic torsional frequency to the uncoupled elastic translational frequency or equivalently, the ratio of torsional to translational stiffness in the elastic range.

The uncoupled elastic translational frequency and the uncoupled elastic torsional frequency are defined as

$$\omega_y = \sqrt{K_y / m}$$
$$\omega_\theta ' = \sqrt{K_{\theta R} / mr^2} \qquad (4)$$

whereK_y is the sum of the elastic stiffness of planes in the *y*-direction and $K_{\theta R}$is the torsional stiffness about the centre of stiffness. The uncoupled frequency ratio is defined as

$$\Omega_R = \frac{\omega_\theta '}{\omega_y} = \sqrt{\frac{K_{\theta R}}{r^2 K_y}} \qquad (5)$$

If Ω_R is greater than 1, the response is mainly translational and the structure is considered as torsionally stiff; on the other hand, if Ω_R is less than 1, the response is affected by torsion and the structure is treated as torsionally flexible.

Various researchers conducted analytical and experimental studies on stepped and set-back buildings (where a narrow tower projects from a wide base) and came up with contradictory results which are specific to the building models they had selected. As per Priestley (2007) [11], in buildings which are stepped along one direction only, the stepped frames are not much influenced by the irregularity and only the frames in the perpendicular direction will have some effect due to the stepping.

The regularity of building can be quantified using regularity/ irregularity indices, based on the geometry of the building. Karavasilis et al. (2008) [10] had proposed two irregularity indices (Φ_s , storey-wise and Φ_b , bay-wise) as follows:

$$\Phi_s = \frac{1}{n'_s - 1} \sum_{1}^{n_s - 1} \frac{L_i}{L_{i+1}}$$
$$\Phi_b = \frac{1}{n_b - 1} \sum_{1}^{n_b - 1} \frac{H_i}{H_{i+1}} \qquad (6)$$

Where n'_s is the number of storeys of the frame and n_b is the number of bays at the first storey of the frame. H_i and L_i are the height and width of the i^{th}storey. However, this does not give a measure of the overall irregularity in the building.

Sarkar et al. (2008)[8] proposed a single regularity index (η) which is based on the dynamic behaviour of the structure and is given below:

$$\eta = \frac{\Gamma_1}{\Gamma_{1,ref}} \qquad (7)$$

where Γ_1 is the first mode participation factor for the stepped frame and $\Gamma_{1,ref}$ is the first mode participation for the regular frame without steps. Even though this approach seems to be more logical, one has to do a modal analysis to obtain the regularity index.

Sarkar et al. had also proposed a correction factor (κ) for the code proposed empirical formula for fundamental period of regular building to get that of stepped frame. It is given by,

$$\kappa = \frac{T_{stepped}}{T_{regular}} = \left[1-2(1-\eta)(2\eta-1)\right] \text{ for } 0.6 \le \eta \le 1.0 \quad (8)$$

S. G. Maske and P S Pajgade (2013)[2] studied the influence of the torsion effects on the behavior of the structure. Two cases are considered for the study. Case one is without considering torsion and case two is considering torsion. The Indian standard code of practice IS-1893 (Part I: 2002) guidelines and methodology are used for analysis and design. Results are compared in terms of % Ast in columns. They conducted the structural analysis and design of four storey reinforced concrete asymmetric frame building with the help of Etab software.

S.A. A. A. Rahman and G. Deshmukh (2013)[3] studied the proportional distribution of lateral forces evolved through seismic action in each storey level due to changes in stiffness of frame on vertically irregular frame. As per the Bureau of Indian Standard (BIS) 1893:2002(part1) provisions, a G+10 vertically irregular building is modeled as an simplified lump mass model for the analysis with stiffness irregularity at fourth floor. They studied the response parameters like story drift, story deflection and story shear of structure under seismic force under the linear static & dynamic analysis. The analysis focused on the base shear carrying capacity of a structure and performance of structure. They concluded that a building structure with stiffness irregularity provides instability and attracts huge storey shear. A proportionate amount of stiffness is advantageous to control over the storey and base shear.E Tab was used for modeling and analysis.

Q. Z. Khan, A. Tahir and S. S. Mehboob (2013)[4] studied theperformance evaluation of reinforced concrete buildings with vertical irregularities (i.e., setbacks). A five story vertically regular building is designed by equivalent static load method of seismic analysis by using UBC (Uniform Building Codes) 1997. Nine vertically irregular models are derived from the regular building by omitting different stories at different heights creating setbacks. For numerical solution ETABs nonlinear version software is used. The study as a whole is a slight attempt to evaluate the effect of vertical irregularities on RC buildings, in terms of dynamic characteristics such as story displacement, overturning moment, base shear, story drift and participating mass ratio. They concluded that the irregularity established due to setbacks, that even very large variation of irregularity distribution in elevation causes reasonable modifications of the seismic response with respect to the reference regular case. Maximum story drift and story displacement will increase as the vertical irregularities increase in models.

B.G.N. Kumar and A. Gornale (2012)[5] studied the performance of the torsionally balanced and unbalanced buildings also called as symmetric and asymmetric buildings subjected to pushover analysis. The buildings have unsymmetric distribution of stiffness in storeys. Also studies are conducted on the effect of eccentricity between centre of mass (CM) and centre of story stiffness (CR) and the effect of stiffness of infill walls on the performance of the building. It is concluded that the analytical natural period depends on the mass and stiffness of each model and is therefore different for models with different amounts of eccentricity and where stiffness of infill walls is considered or ignored. It can be observed that models where stiffness of infill walls is considered to have significantly lower fundamental natural period as compared to models where stiffness of infill walls ignored.

III. DETAILS OF BUILDING MODELS

A 30-storeyed regular reinforced concrete moment resisting frame building model(R1) is prepared in SAP 2000 and preliminary dimensioning of structural members is done (Table 1).Shear walls are provided as a lateral load resisting system as shown in Figure 1. The structure is designed as per the various load combinations as givenin IS 456:2000. Both linear and non-linear analyses are performed. Moment-rotation relation (hinge properties) are generated using Modified Mander model for stress-strain curves of concrete (Panagiotakos and Fardis, 2001) and Indian Standard IS 456:2000 stress-strain curve for reinforcing steel.

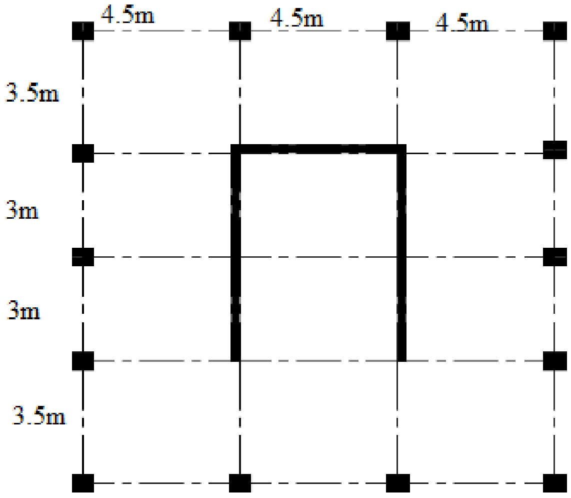

Figure 1: Column layout of the building model R1

TABLE 1: STRUCTURAL ELEMENT SIZES

Structural elements	Sizes(mm)
Beams	350 x 600
Columns	800 x 800, 700 x 700, 600x 600
Slab	120 mm thick
Shear walls	400, 350, 300 thick at various levels

Three types of irregular buildings are considered in the present study, viz., mass irregular, stiffness irregular and setback buildings. Table 2 shows the details of irregular buildings generated from the regular building (R1).

Mass irregularity is generated by increasing the live load on half the portion of the building plan from 2 kN/m^2 to 5 kN/m^2 at 5,10,15,20,25thstorey (Figure 2).

TABLE 2: TYPE OF BUILDING MODELS

Type of building model	Model designation
Mass irregular building model	M1
Stiffness irregular building model	L1
Setbacks	S1

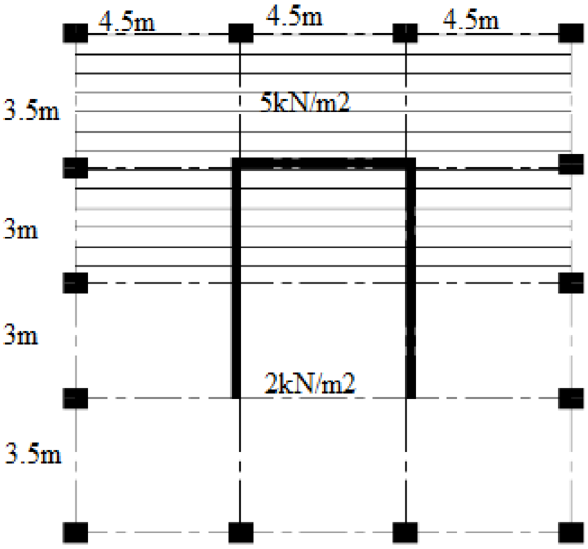

Figure 2: Mass irregular building model plan

Lateral stiffness irregularity is generated in the elevation of the structure by increasing the height of the columns to 4.5m at 4,9,14 and 19th floors.h1=3m,h2=4.5m. (Figure 3)

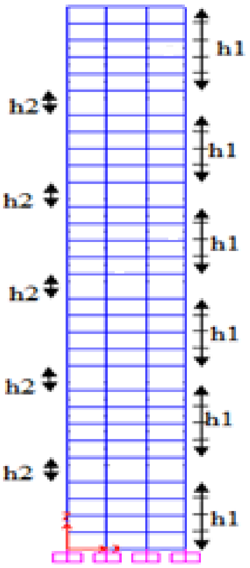

Figure 3: Elevation of the stiffness irregular building model L1

Setbacks are generated in the regular building model at 15,20, and 25th floors (Figure 4).

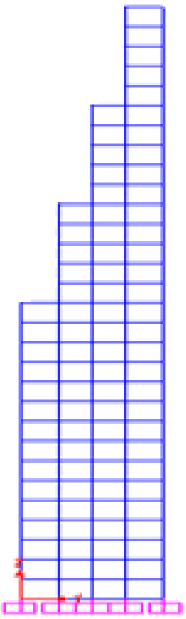

Figure 4: Elevation of the setback generated building model S1

IV. ANALYSIS OF BUILDING MODEL

Non-linear time history analysis will give the response of the structure at various time instants during the application of ground motion accelerogram.The minimum number of records required for time history analysis is three and the maximum response shall be used for design purpose. However, when a set of at least seven ground motions is used, the structural engineer canuse the mean structural response (FEMA P695,2009).
Three accelerograms are taken from the strong motion database(http://www.strongmotioncenter.org/)of Centre for Engineering Strong Motion Data, USA.The records are made consistent with IS 1893:2002 spectrum using the program SEISMOMATCH and were scaled to have a PGA of 0.3g. The maximum of the responses obtained from the three analyses is reported as the response of each building model.

V. RESULTS AND DISCUSSIONS

Figure 5 shows the displacement of building model (R1) for the three time histories. It is clear from the figure that ALTADENA gives the maximum response. A maximum displacement of 180mm is observed for the 30th floor level. The combination of inelastic hinges at the ends of beams and columns which when formed in a building eventually makes it unstable and causes it to collapse and is called collapse mechanism. Good ductility is achieved in a building when the collapse mechanism is of the desirable type. In such a case, the hysteretic loops of its load deformation curve are stable and full. This type of hysteretic loops imply good energy dissipation in the building through each of the inelastic hinges at the beam ends. Such a behaviour is observed in buildings that fail in sway mechanism,which ensures that beam yields before failure, and ductile flexural damages occur at beam ends. This happens when the building has **strong column – weak beam** design (in which the beams are made to be weaker in bending moment capacity and ductile links, and columns stronger in bending moment capacity).

Hinge formation in building model R1 at the end of time history is shown in Figure 6. It is found that hinges corresponding to yield level are formed in beams and at ground floor column base. This is a desirable mechanism.

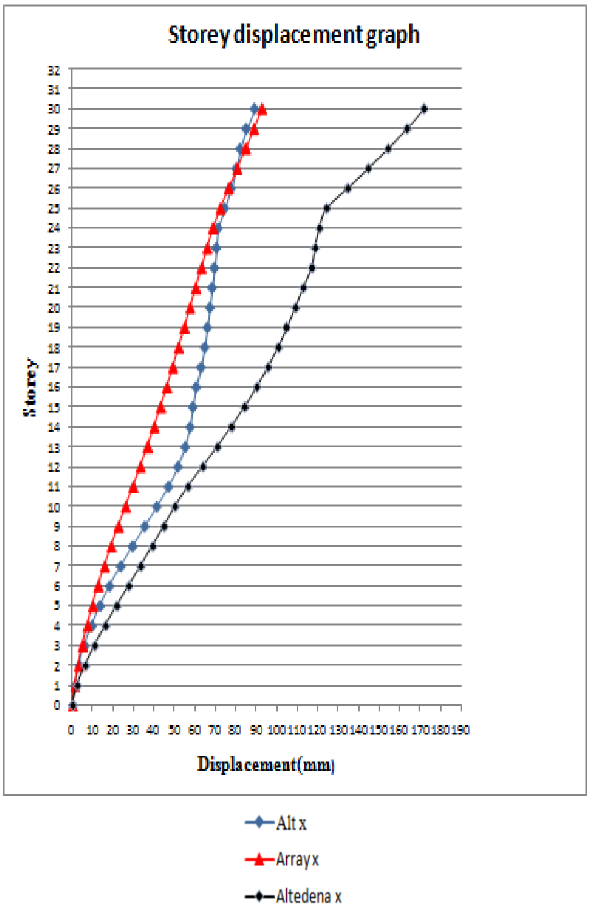

Figure 5: Comparison of storey displacement from Alt,Altedena and *Array for building model R1*

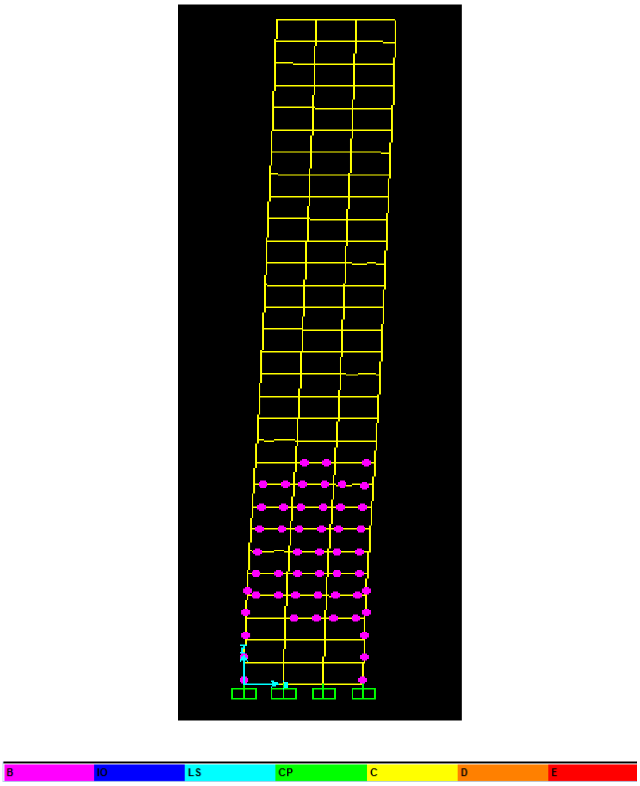

Figure 6: Elevation of building model R1 having hinge formation

For mass irregular building model (M1), (Figure 7), ALTADENA gives the maximum response.More number of hinges are formed on and near the irregularity applied floors (Figure 8), compared to regular building model (R1).

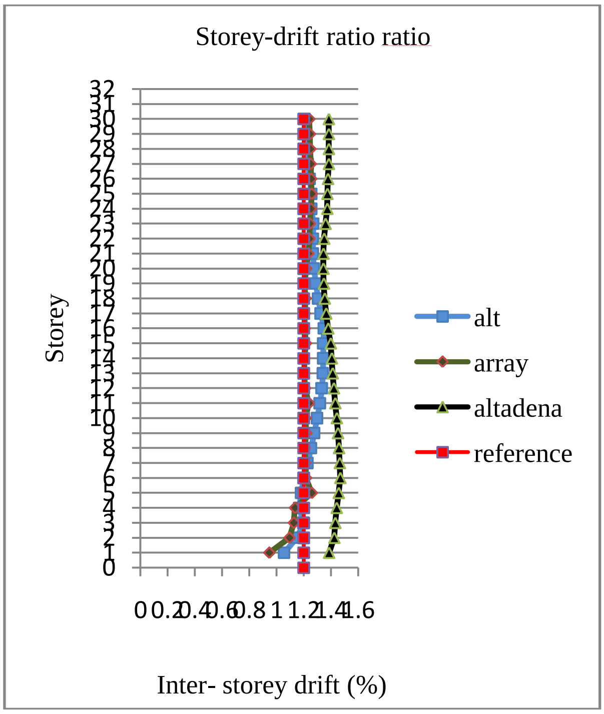

Figure 7: Comparison of storey-drift ratio ratio from Alt,Altedena,Array for building model M1

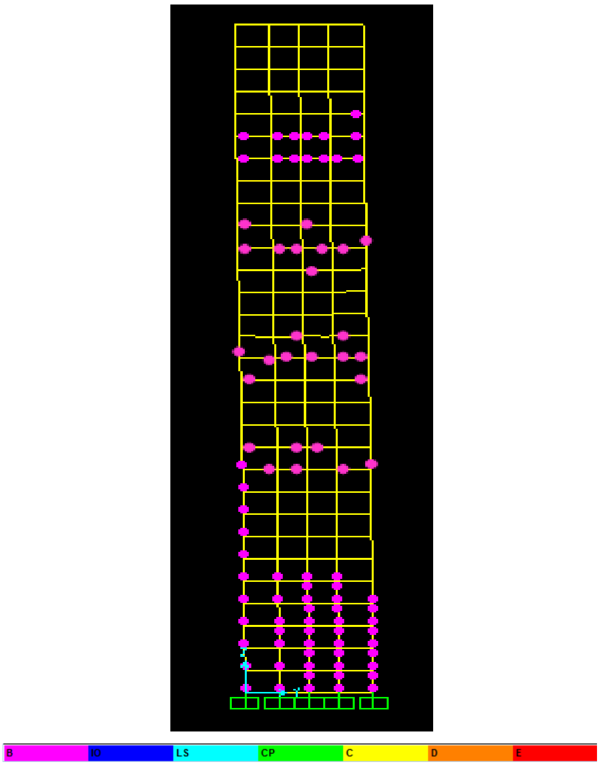

Figure 8:Hinge formation in model M1

For stiffness irregular building model (L1), (Figure 9), ALTADENA gives the maximum response.The displacement for stiffness irregular building model L1 is more as compared to the building model R1. More number of hinges are formed on and near the irregularity applied floors (Figure 10), compared to regular building model (R1).Confinementreinforcement have to be provided near and on the stiffness irregular floors.

Same is the case with setback building model (S1). Figures 11 and 12.Hinges are developed in columns particularly near the setback portion. More damages can occur near the setback portion. Special care should be given in the design of components of the structure particularly near the setback regions.

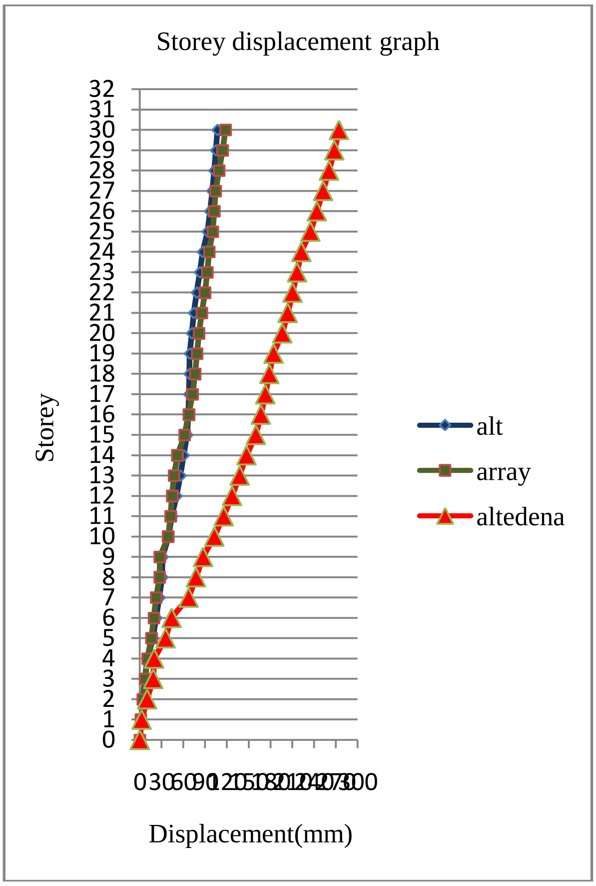

Figure 9:Comparison of storey displacement from Alt,Altedena,Array for building model L1

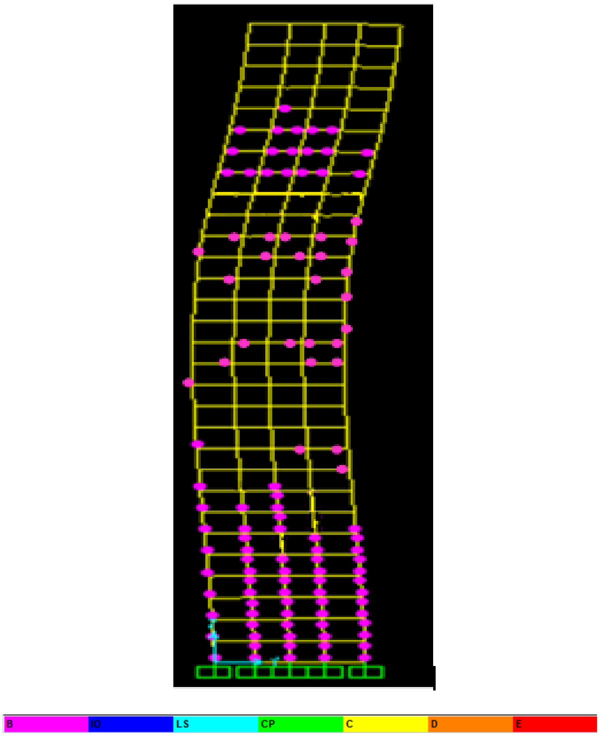

Figure 10: Hinge formation on building model L1

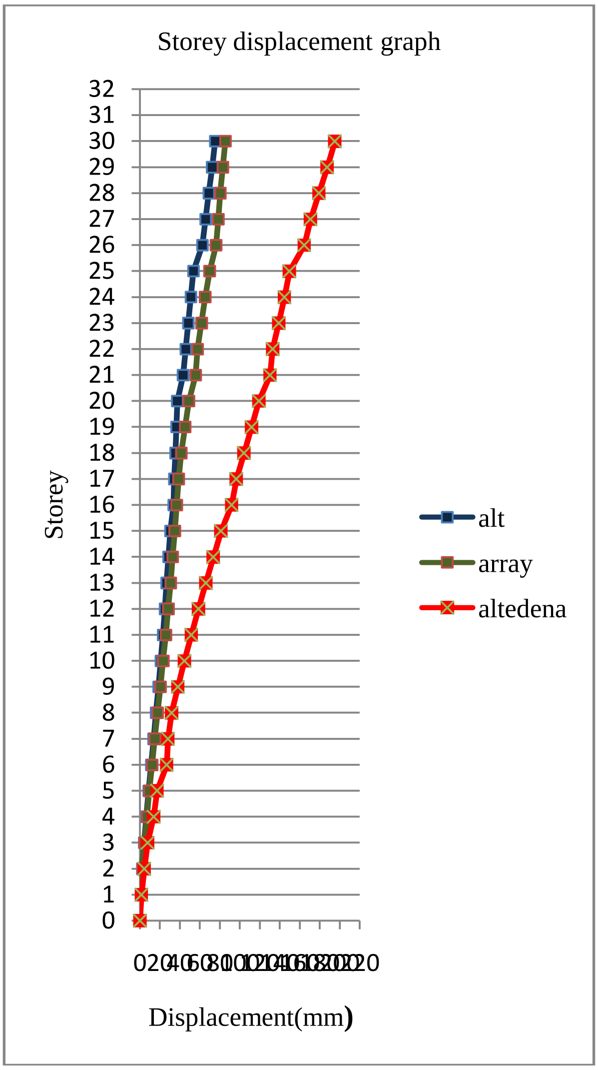

Figure 11:Comparison of storey displacement from Alt,Altedena,Array for building model S1

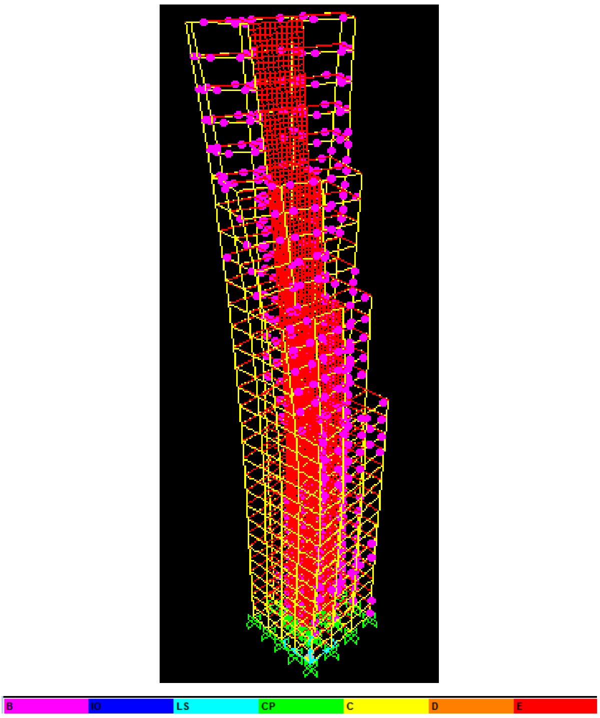

Figure 12: Hinge formation on setback building model S1

VI. SUMMARY

Review of literature on asymmetric buildings reveals that irregularities due to asymmetric distribution of mass, stiffness and strength are sources of severe damage because they result in floor rotations in addition to floor translations. A common form of vertical irregularity arises from reduction of the lateral dimension of the building along its height and such buildings are known as stepped buildings. This building form is becoming increasingly popular in modern multistorey building construction mainly because of its functional and aesthetic architecture. In particular, such a stepped form provides for adequate daylight and ventilation in the lower storeys in an urban locality with closely spaced tall buildings.

Vertically irregular buildings (like open ground storey and stepped buildings) are common in India, but are more vulnerable to earthquake shaking. The collapses of irregular buildings during recent earthquakes have raised many questions regarding the adequacy of current seismic provisions to prevent collapse of such buildings.

The present study confirms that the design of irregular buildings need special care and enhancement of member sizes are required at regions of irregularity. New design methods are needed which can improve the performance of such buildings under expected seismic shaking.

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