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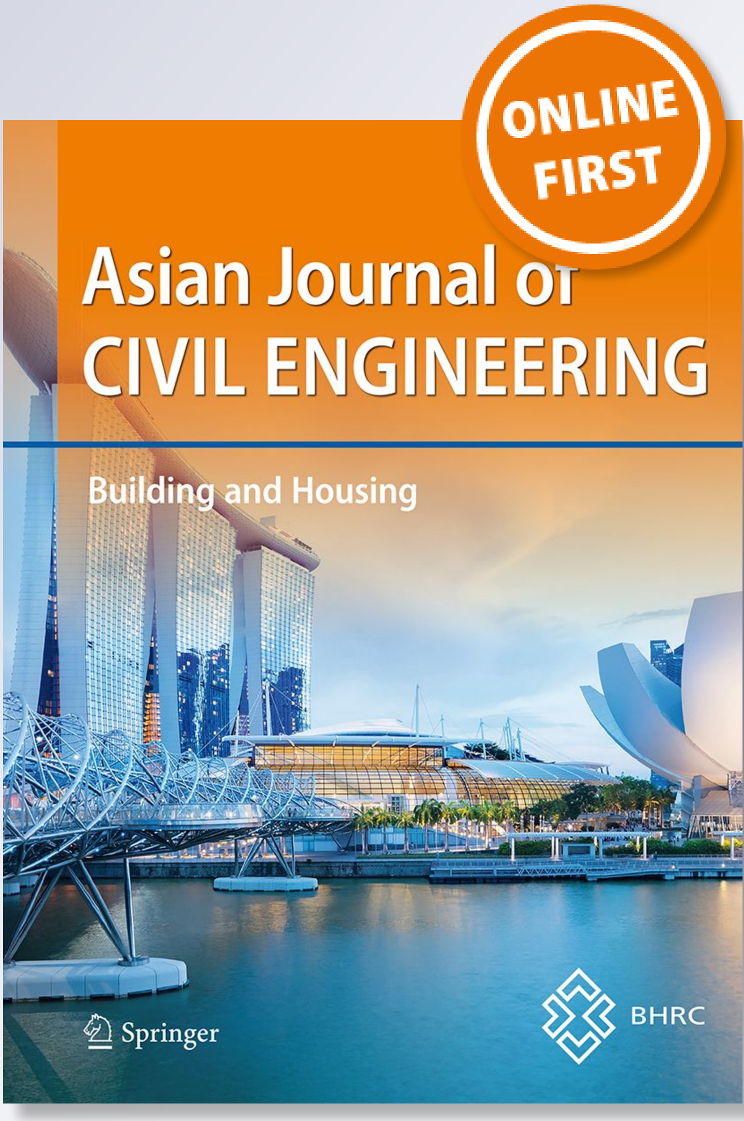

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ORIGINAL PAPER

Effect of in-plan eccentricity in vertically mass irregular RC framed buildings under seismic loads

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Abstract
Multi-storey buildings with complicated geometry and structural systems are common due to various possibilities offered by advanced construction methods. When these irregular buildings are subjected to lateral loads such as wind or earthquake, torsional effects become significant. The present study aims to evaluate the seismic response of vertically irregular multi-storey RC buildings of varying aspect ratios with different location of masses along the height and also with a stipulated amount of in-plan eccentricity. For this, building frames up to 15 storeys height incorporating an integration of vertical and in-plan eccentric masses are subjected to earthquake loads. Transient analysis is carried out by subjecting the three dimensional finite element models of building frames to El-Centro ground motion and the torsional behavior is evaluated in terms of variation in base shear, fundamental natural period, roof deflection and floor rotation. The results show that the in-plan eccentricity of the mass irregularities has least influence on the seismic response when irregularities are present in the lower half of the frames. The study proposes a parameter to quantify mass irregularity with respect to its location and in-plan eccentricity in the vertically irregular building.

Keywords Mass irregularity · Torsional behavior · Transient analysis

Introduction

The presence of irregularities in mass, stiffness, strength or geometry along the elevation of the building is categorized as vertical irregularity. These irregularities along the building height may either exist singly or in combination with plan irregularities which arise due to the non-coincidence of the positions of centre of mass and the centre of stiffness. The latter accentuates the seismic response of the buildings under earthquake loading due to the development of torsion. The ill effects of torsion in seismically actuated buildings have been studied extensively in the past several decades and are perceivable from the various relevant provisions in different codes. Generally, earthquake induced torsion in buildings is due to asymmetric arrangement of the load resisting elements leading to stiffness eccentricity or due to asymmetric distribution of masses along the plan or elevation of the buildings. Torsional effects are also caused due to ground motion incoherency, non-structural elements such as brick infill walls, asymmetric yielding of the elements and so on. The former reason for occurrence of torsion is approximately accounted for in design as accidental eccentricity in most of the building codes. The torsional response of asymmetric buildings under seismic loading makes the design of such buildings considerably more complicated in comparison to that of the symmetric ones with completely translational response. For the last 60 years, since the development of earthquake engineering as a separate research area in civil engineering, the analysis and design of asymmetric buildings under earthquake loading is an open field of study with varying definitions as per different code provisions. Most of the related research work were primarily on elastic models but were then substituted by inelastic models, since building response becomes inelastic under the action of severe earthquake loading. The present code provisions on irregular buildings are mainly based on analysis of single-story inelastic models and few on the analysis of multistory models.

The literature pertaining to the torsional behavior of buildings under various categories of irregularities is available in abundance. It is important to understand the significance of torsion in the serious damages of the vast majority

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of earthquake affected buildings, with different types of eccentricity. In the recent past, realistic multi-storey models have been employed to analyse the torsional response in the inelastic range, also based on the evaluation of results of simplified one story models as per studies by Stathopoulos and Anagnostopoulos (2003, 2005). It is also reported by Anagnostopoulos et al. (2010) that if the element stiffness and strength of the real buildings, as well as their three lowest periods of vibration is not comparable with that of the one story models, it may not give the accurate trend and behavior of the asymmetric buildings. These conclusions lead to further queries and in-depth analysis of the various existing code provisions on torsion based on simplified, one-story models.

Hejal and Chopra (1989) evaluated the effects of torsional coupling in buildings with both mass and stiffness asymmetry for an extended range of parameters like base shear, overturning moment, top floor displacement, base torque and so on. Valmundsson and Nau (1997) studied the response of vertically irregular multistory buildings of five, ten and fifteen storeys under earthquake loading. Mass, stiffness and strength were varied along the building height and it resulted in the increase in storey drifts and ductility demands. Das and Nau (2003) studied the various vertical irregularity effects on a large group of buildings of heights varying from 5 to 20 storeys.

The seismic parameters computed by Equivalent Lateral Force (ELF) method and Time History (TH) analysis were compared for the symmetrical and asymmetric buildings. Ductility demand and storey drifts at the location of the combined irregularities showed abrupt increase with respect to the limits as per Uniform Building Code (UBC) 1997. Through several studies, dynamic analysis approach was found to be more realistic and valid with respect to the modal pushover analysis procedure. Chintanapakdee and Chopra (2004) studied the seismic demands of vertically regular and irregular frames using Modal Pushover Analysis (MPA) and Response History Analysis (RHA) and concluded that RHA is more accurate in estimating the seismic demands of irregular buildings with strong/stiff lower half. Tremblay and Poncet (2005) and Ayidin (2007) examined the seismic response of mass irregular multistory buildings according to National Building Code of Canada 2005 (NBCC) and Turkish Seismic Code 1997 (TSC) respectively. The analytical study concluded that change in mass ratio affects the storey shear and that the time history procedure gives the accurate estimation of the seismic response of the multistory models in comparison with the ELF procedure.

Karavasilis et al. (2008) studied the responses of steel moment resisting frames with vertical mass irregularities and derived expressions to define the seismic response using regression analysis techniques. Sadasiva et al. (2008) studied the effect of location of mass eccentricities on nine storey frames designed as per New Zealand Building Code (NZS 2004) by carrying out inelastic time history analysis. It was concluded that the interstorey drift recorded is the highest when mass irregularity is present on the top storey of the building. Rizwan and Singh (2012) classified buildings into mass symmetric systems with stiffness and strength irregularities and mass asymmetric systems and carried out dynamic time history analysis and concluded that torsion resulted in the significant increase in beam ductility demands of the frames. Varadharajan et al. (2012) discussed the applicability of proposed equations based on regression analysis for estimating the fundamental period, roof deflection and inter-storey drift of mass and stiffness irregular 2D as well as 3D frames. Varadharajan et al. (2015) suggested an irregularity index to quantify the magnitude and location of the mass irregularity in the building frame and suggested modification for the expression for natural period as per IS 1893:2002. Generally the limits for mass irregularity range from 1.5 to 2 in different codes.

The present study aims to identify the variation in seismic responses of three dimensional building frames due to varying locations as well as eccentricity of mass considering mass ratios up to 5 along the height of the building. The effects of torsional in-plan irregularity on vertically mass irregular multistory RC buildings of varying heights of 5, 10 and 15 storeys subjected to EL-Centro (1940) seismic ground motion are studied. A new irregularity index has been proposed considering the eccentricity of mass along height as well as in-plan and the power equations based solely on this irregularity index are introduced to predict the natural period and base shear ratio of irregular buildings.

Structural idealization

In the present study, seismic response of reinforced concrete building frames of height below 50 m is considered. Three dimensional finite element models of building frames of 5, 10 and 15 storeys (aspect ratio 0.937, 1.875 and 2.813) with storey height of 3 m and length of each bay as 4 m were modeled. The number of bays was taken as 4 in each direction. The dimensions of building components were adopted based on structural design as per Indian standard codes for design of reinforced concrete structures IS 456:2000 and IS 13920:2016. The loading for the residential building was considered on the basis of IS 875(Part 1):1987. Live loads of 3.0 kN/m^2 on floor and 1.5 kN/m^2 on roof were provided. The beam and column dimensions were taken as 300 mm × 400 mm and 400 mm × 400 mm respectively. The thickness of floor slab and foundation slab were adopted as 0.15 m and 0.5 m respectively. M25 grade concrete and Fe415 grade steel were considered as the materials for structural elements.

The buildings were idealized as 3D frames in finite element software LS DYNA using resultant Hughes-Liu beam elements with six degrees of freedom at each node. Four-noded Hughes-Liu shell elements with bending and membrane capabilities and six degrees of freedom at each node were used for modeling the roof, floor and foundation slab. MAT_CONCRETE_EC2 was used as the material for the Hughes-Liu elements for representing a smeared combination of concrete and reinforcing steel. This material model includes concrete cracking in tension and crushing in compression, and reinforcement yield, hardening and failure as per Eurocode 2. The input data required for the material model includes mass density, compressive strength, tensile stress of concrete, Young's modulus, ultimate stress, Poisson's ratio of reinforcement and the fraction of reinforcement along both the directions. Type 6 Mander model (Mander et al. 1988) has been used to represent the material non-linearity of the reinforced concrete sections Mesh size of 1 m was used to discretize the building components.

In the initial set of buildings considered in this study, mass irregularities were provided in a single storey, adjacent two storeys and adjacent three storeys at a time correspondingly in the 5, 10 and 15 storey building frames. Mass ratios of 1.5, 2, 3, 4 and 5 were considered at the bottom, middle and top floor levels of the buildings. Mass ratio is defined as the ratio of the seismic weight of the floor considered to the seismic weight of the floor below. The highest mass ratio of 5 was considered such that even the distributed mass in three adjacent storeys together also causes vertical irregularity as per IS 1893:2016 code provisions. The mass density of concrete was taken as 2500 kg/m^3. The mass density of the slab was varied at different floor levels as well as at different locations in plan, to represent different mass ratios along the plan without any variation in stiffness.

Two major sets of buildings with uniformity and non-uniformity of distributed mass in a floor (without and with in-plan eccentricity) were studied. The Fig. 1 schematically represents the first set of buildings showing the location of mass irregularity in the elevation of the buildings by dark solid lines. Similarly Fig. 2 represents the second set of buildings showing the distribution of this mass irregularity in plan of the corresponding storey with filled up areas. The 5, 10 and 15 storey building frames were categorized as Group A, Group B and Group C and the regular buildings in each group were designated as 5R, 10R and 15R respectively. In groups B and C, mass irregularities at the top,

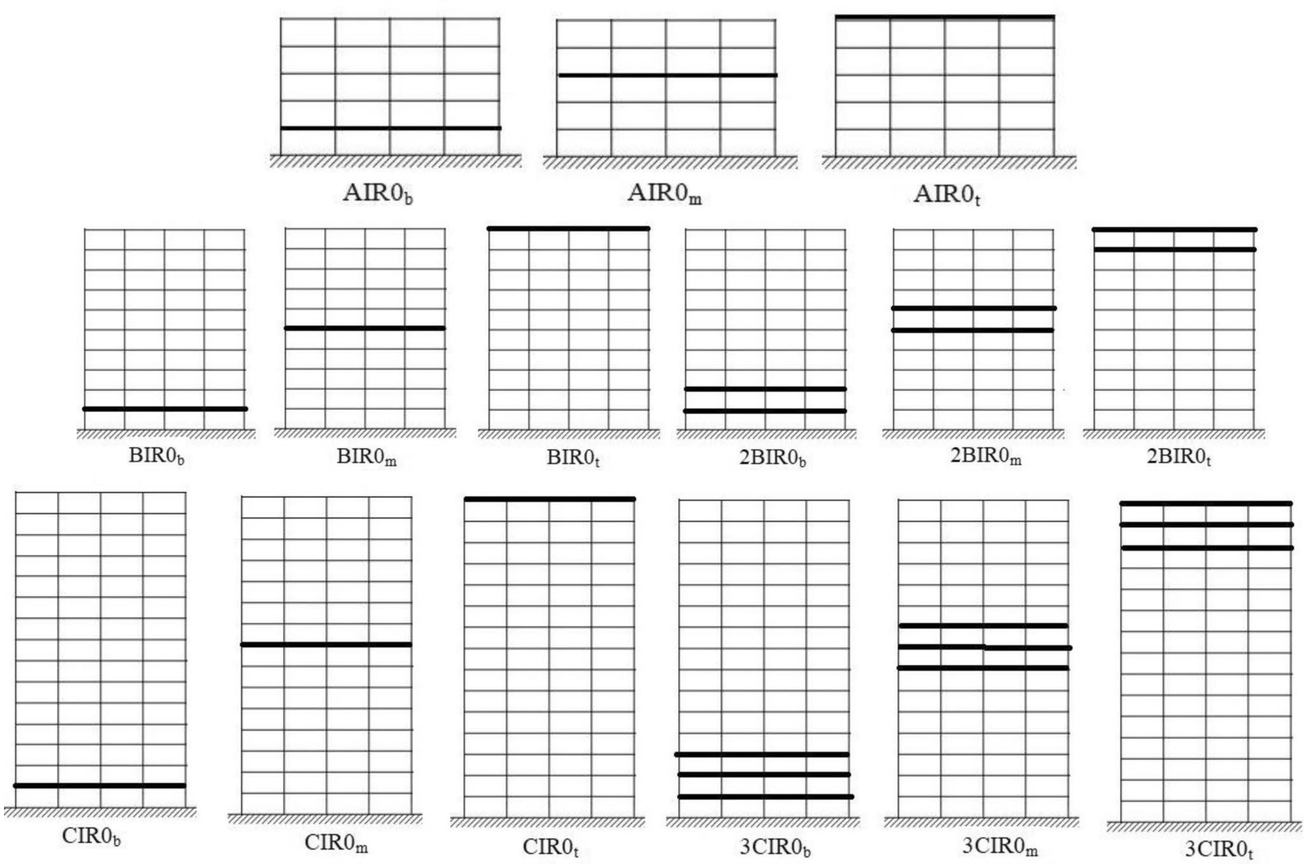

Fig. 1 Elevation of Group A, Group B and Group C buildings with mass irregularities at the bottom, middle and top floor levels

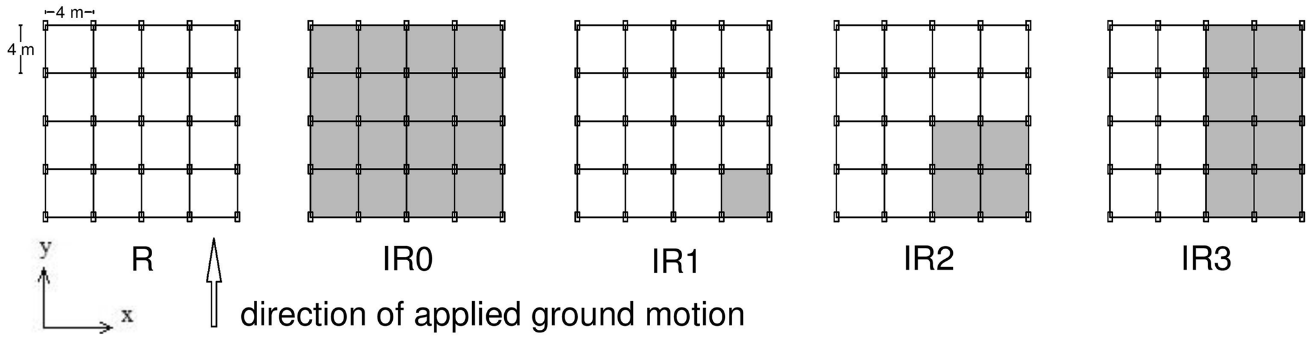

Fig. 2 Plan layout of the building frames depicting the placement of masses

middle and bottom of the building frames were also distributed among two and three floors (2B and 3C) respectively keeping the total mass ratio constant with that of the single floor levels cases as shown in Fig. 2. The groups designated as 2B and 3C refer to the buildings with the same mass ratio as B and C itself but the same mass being distributed among two adjacent floors (2B) and three adjacent floors (3C) respectively, maintaining the same total seismic weight in each category. 'R' corresponds to the regular frame buildings without eccentricity; 'IR0' corresponds to the frame with vertical mass irregularity without any in-plan mass eccentricity i.e. mass distributed uniformly throughout the entire area of floor slab. In the designation of buildings, 'b', 'm', 't' corresponds to the bottom, middle and the top location floor levels along the height of the building.

The second set of buildings in which the mass is concentrated at different locations in plan for all the above groups of buildings were considered. Herein the irregularities were generated along the plan, in the initial set of buildings as shown in Fig. 1 having vertical irregularities. Masses of varying mass ratios from 1.5 to 5 were provided in different patterns with varying eccentricity keeping the total seismic weight of the entire configurations belonging to a particular mass ratio as constant. The initial mass density of 2500 kg/m^3 in the floor slab was increased in portions along the floor slabs in three different patterns as shown in Fig. 2 to generate in-plan eccentricity. The configurations IR1 to IR3 correspond to the three different patterns with decreasing in-plan eccentricities 'AIR1$_b$' indicates a 5 storey building (Group A) with the mass irregularity provided at the bottom level having in-plan eccentricity pattern IR1. M1.5 to M5 represent mass ratio of 1.5–5.

Methodology

As per IS 1893:2016, ASCE 7-10:2010 and FEMA 450:2003, the criterion of vertical mass irregularity is considered to exist when mass of a storey is more than 1.5 times the mass of the storey below. This study essentially attempts to study the response of vertically irregular frames with varying mass ratios along the height and to identify the effects of torsional coupling on them. Three different plan configurations IR1, IR2 and IR3 as in Fig. 2 with torsional irregularities as per IS 1893:2016 were considered. As per 1893:2016, in-plan torsional irregularity is said to exist only when the irregularity coefficient which is the ratio of the maximum displacement in the direction of the lateral force at one end of a floor to the minimum horizontal displacement at the far end of the same floor in the same direction is more than 1.5. The torsional irregularity coefficient values of the different configurations of varying heights, mass ratios and irregularity locations considered in this study range from 1.457 to 1.788. The static eccentricities (e_s) of the configurations are obtained from the difference of the center of mass and center of stiffness of the considered floor level. Under the application of dynamic loading, the effect of eccentricity in irregular buildings is higher as compared to the static load case. Therefore, a dynamic amplification is considered over the static eccentricity as per IS 1893:2016 to calculate the design or dynamic eccentricity (e_d) at any floor level i as in the Eq. (1) given below:

$$e_{di} = \left\{ \begin{array}{c} 1.5e_{si} + 0.05b_i \\ e_{si} - 0.05b_i \end{array} \right\} \tag{1}$$

where, b represents the floor plan dimensions perpendicular to the direction of the force. The design eccentricities (e_d) of the buildings were calculated as per IS 1893:2016 and are represented in terms of the total plan width (L) for the buildings of mass ratios varying from M1.5 to M5 as shown in Table 1.

A total of 375 three-dimensional building models with mass irregularities, were generated using finite element software LS DYNA and were analysed for their eigen values. Time history analysis was carried out on these 375 space frames by subjecting them to El-Centro ground

Table 1 Dynamic eccentricity of the building configurations

Building configuration	Dynamic eccentricity ratio (e_d/L)				
	M1.5	M2	M3	M4	M5
IR1	0.119	0.173	0.252	0.307	0.347
IR2	0.096	0.132	0.185	0.221	0.248
IR3	0.096	0.132	0.185	0.221	0.248

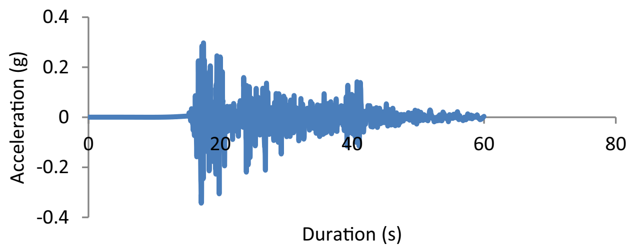

Fig. 3 Acceleration time history of El-Centro earthquake ground motion

motion (Imperial Valley, Southern California on May 18, 1940) with a PGA of 0.343 g, magnitude of 6.9 and duration of 30 s. The acceleration time history plot of El-Centro earthquake data is given in Fig. 3. The results of the time history analysis been employed to assess the effect of the vertical irregularities with in-plan eccentricity on the seismic response of the frames in terms of fundamental natural period, base shear, roof deflection and roof rotation. Further, based on the results of time history analysis, an irregularity index is developed to quantify the vertical mass irregularity with in-plan eccentricity and equations are developed through regression analysis to predict the natural period and base shear of irregular buildings.

Results and discussions

Building models with various aspect ratios and mass irregularities along the height as well as within each floor were analysed and the transient analysis responses in 375 building frames were studied. The variations in dynamic responses of the buildings due to the inclusion of mass irregularities were evaluated and are expressed in terms of absolute maximum responses of fundamental natural period, base shear, roof deflection and roof rotation. The variations in responses of irregular buildings with respect to that of the regular frames were also computed. A new irregularity index 'α' which incorporates the effect of in-plan eccentricity as well as vertical irregularity of mass has been proposed to predict the natural period and base shear of an irregular building with reference to that of a regular one.

Variation in natural period of buildings

Fundamental natural period of vibration is determined by carrying out Eigenvalue analyses on building frames. Figures 4, 5 and 6 represent the variation of fundamental lateral natural period of the 5, 10 and 15 storey frames represented as A, B and C group buildings with respect to the regular building frames for mass ratios 1.5, 2, 3, 4 and 5. The natural period of the regular buildings, 5R, 10R and 15R are in the range of 0.586 s - 2.105 s and that of the IR0 configurations are in the range of 0.59 s to 3.18 s. 2BIR0 and 3CIR0 configurations have higher natural period in comparison to BIR0 and CIR0 although the same mass is evenly distributed in two or three floors. Among the first set of buildings, it can be observed that with the increase in height of the location of irregular masses from the base of the buildings, the natural period increases. Buildings of group C with mass ratio of 5 have the highest variation in time period of 44% due to the shift of the vertical mass center (the center of distribution of mass along the direction of elevation) upwards by 1.5 m.

Comparing the second set of irregular buildings which have in-plan eccentricity of mass, fundamental natural

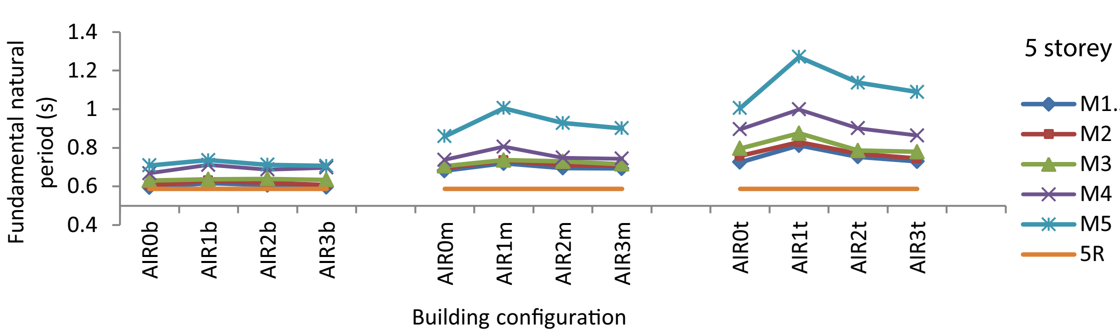

Fig. 4 Variation of fundamental natural period in group A buildings

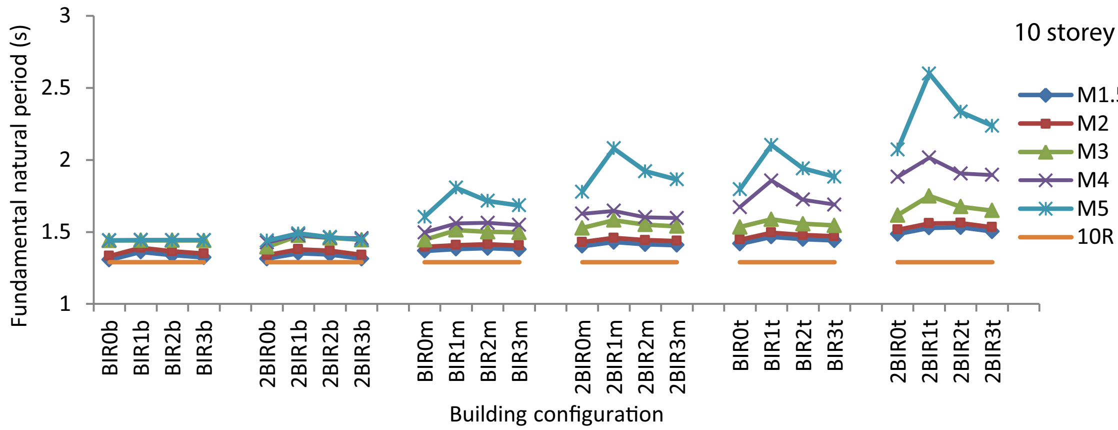

Fig. 5 Variation of fundamental natural period in group B buildings

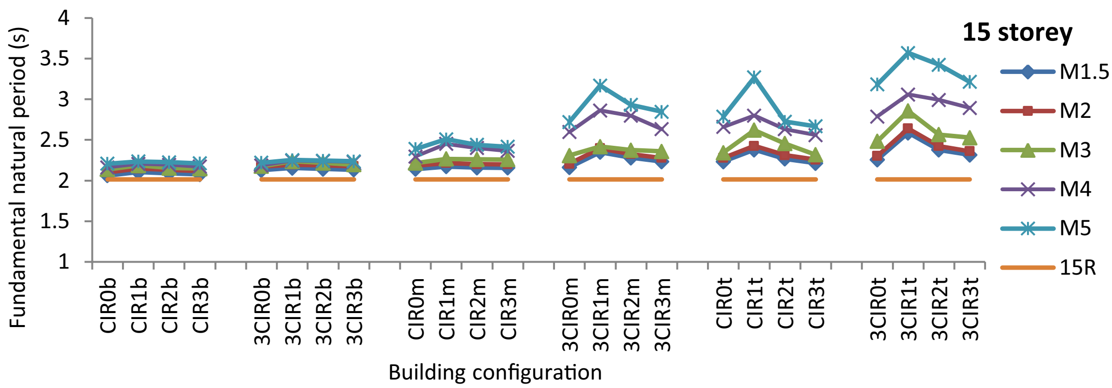

Fig. 6 Variation of fundamental natural period in group C buildings

periods obtained for torsionally irregular buildings are higher compared to the regular frame buildings. The percentage variation in natural period with respect to the regular buildings also increases with increase in eccentricity. The natural periods of buildings with irregularity $IR1_b$-$IR3_b$ are very close to that of the regular frames in all the three groups indicating that masses placed at the lower floor do not cause much variation in natural period. When the masses of ratio 1.5 and 2 are at the lower floor levels there is only a very nominal variation in natural period of 1.2–7.2% in Group A, 1.3–7.7% in Group B and 2.2–8.9% in Group C. But when the masses are located at the top of the frame elevating the vertical mass centre, natural period increases and becomes highest in $IR1_t$ with mass ratio 5. Provision of irregularity at the top level of the buildings increases the natural period by 30.5% in comparison to IR0 due to maximum torsional coupling. IR1 with highest e_d/L ratio has the highest natural period in all groups. In the irregular frames with mass ratios from 1.5 to 3, the variation of natural period with change in e_d/L is also nominal. $AIR1_t$, $2BIR1_t$ and $3CIR1_t$ buildings with a mass ratio of 5 has the highest increase in percentage of 116.5%, 101.5% and 77% in natural period among A, B and C group buildings. It can thus be interpreted that with the inclusion of heavy masses on the floors of the building, the natural period increases and to a maximum when placed at the top floors. The increase in seismic masses in a building increases the fundamental natural period. When a building has non-uniform distribution of masses along its height and masses vibrate at different heights from the base, it simulates the changes in the effective stiffness and hence, natural period varies. This increase is amplified when masses are placed with in-plan eccentricity which further enhances the structure's flexibility. Even in buildings of mass ratio M1.5, which is within the code prescribed limits for mass irregularity, in-plan eccentricity at the upper levels causes a variation of 38% in natural period with respect to regular frame buildings and 18% with respect to IR0 buildings.

The important parameters that affect the torsional response of the irregular buildings are the eccentricity ratio and the torsional to lateral frequency ratio. The frequency ratio is defined as:

$$\Omega = \frac{\omega_\theta}{\omega_y} \tag{2}$$

where ω_θ is the uncoupled elastic torsional frequency and ω_y is the uncoupled elastic translational frequency of the building given by:

$$\omega_y = \sqrt{\frac{K_y}{m}}, \quad \omega_\theta = \sqrt{\frac{K_\theta}{mr^2}} \tag{3}$$

where K_y is the sum of elastic stiffness of frames in y direction, K_θ is the sum of torsional stiffness about the centre of stiffness, m is the mass and r is the radius of gyration of the floor. As per IS 1893:2016, a building can be categorized as a torsionally flexible or irregular one if the natural period corresponding to the torsional mode is greater than that in the translational modes of vibration or value of Ω is less than 1. The building response is mainly translational if Ω is more than 1. According to Kan and Chopra (1981), buildings with very small eccentricities or $\Omega \geq 2$, exhibit planar behaviors. Buildings with smaller eccentricities can be torsionally sensitive for $\Omega = 1$ but with a lesser dynamic response amplification than buildings with larger eccentricities. The frequency ratio, Ω decreases in all the three groups of buildings in the order of increasing e_d/L. IR1 with the highest e_d/L has the least Ω ratio among all the groups and Table 2 lists the frequency ratios of buildings of IR1 configuration of the three groups of buildings. Frequency ratio, Ω is less for higher eccentricity ratio of the configurations and hence the buildings with the maximum torsional coupling are AIR1$_t$, 2BIR1$_t$ and 3CIR1$_t$ with mass ratio 5 with frequency ratios of 0.905, 0.879 and 0.756 respectively. Furthermore, the general pattern is that the Ω values of the buildings tend to decrease with increase in the aspect ratio of the buildings, though there isn't any evident variation between the mass ratios especially in buildings with low eccentricity.

Table 2 Frequency ratios of buildings of IR1 configuration

Frequency ratio (Ω)					
Building configurations	Mass ratios				
	M1.5	M2	M3	M4	M5
AIR1$_b$	0.980	0.985	0.984	0.983	0.981
AIR1$_m$	0.940	0.945	0.935	0.930	0.925
AIR1$_t$	0.913	0.918	0.915	0.910	0.905
BIR1$_b$	0.937	0.942	0.924	0.912	0.906
2BIR1$_b$	0.919	0.924	0.921	0.911	0.899
BIR1$_m$	0.912	0.917	0.908	0.899	0.892
2BIR1$_m$	0.903	0.908	0.900	0.890	0.885
BIR1$_t$	0.892	0.896	0.891	0.885	0.881
2BIR1$_t$	0.883	0.887	0.882	0.880	0.879
CIR1$_b$	0.951	0.956	0.927	0.904	0.895
3CIR1$_b$	0.893	0.897	0.886	0.875	0.863
CIR1$_m$	0.906	0.911	0.903	0.883	0.856
3CIR1$_m$	0.797	0.801	0.801	0.802	0.803
CIR1$_t$	0.887	0.877	0.852	0.831	0.822
3CIR1$_t$	0.865	0.869	0.842	0.796	0.756

Variation in maximum seismic base shear

Seismic base shear of buildings with mass irregularity in plan as well as elevation, subjected to El-Centro ground motion is as shown in Figs. 7, 8 and 9. The seismic base shears of the buildings are expressed in terms of their total seismic weight (W) as the 'base shear ratio'. Base shear ratio decreases with increase in the aspect ratio of the buildings. The base shear ratios of the 15R, 10R and 5R are obtained in the range of 0.051 W to 0.115 W. Buildings with lower mass ratios of range 1.5–2 do not show much variation in base shear ratios wherein the total mass is divided among two or three storeys (i.e. 2B, 3C). Base shear is directly dependent on the total mass of the building and hence with increase in mass ratios, base shear increases. It can also be observed that

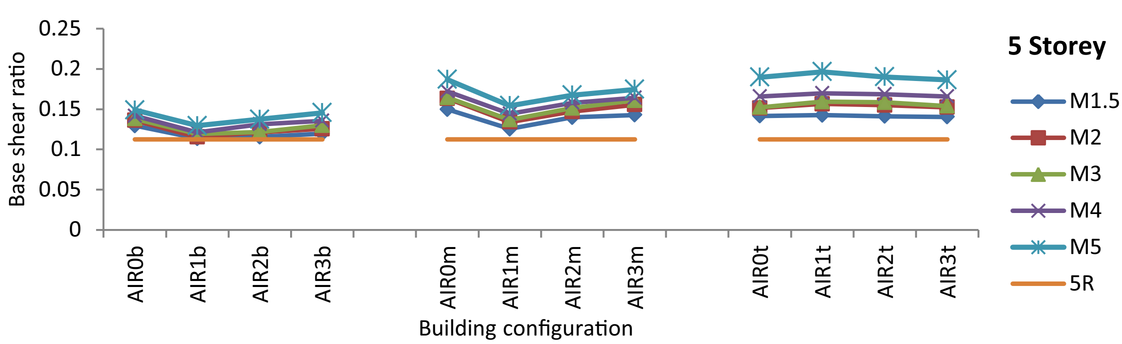

Fig. 7 Variation of base shear ratio in group A buildings

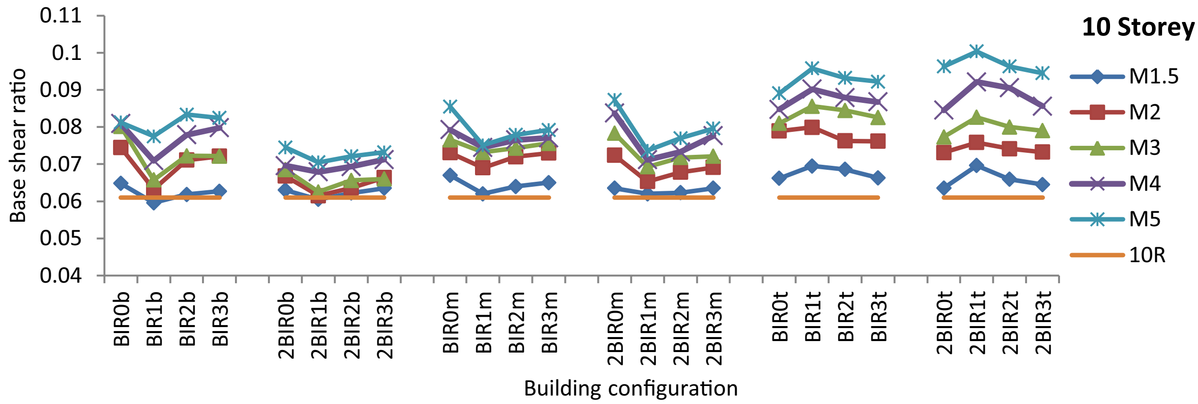

Fig. 8 Variation of base shear ratio in group B buildings

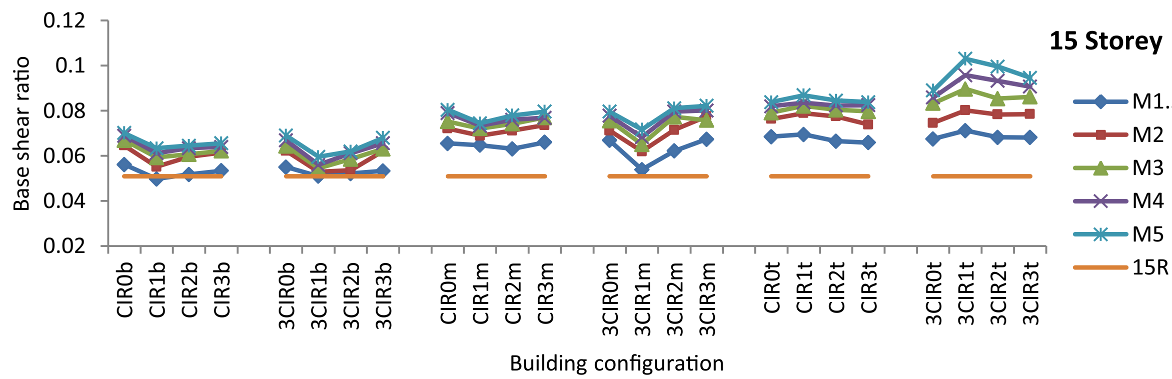

Fig. 9 Variation of base shear ratio in group C buildings

base shear demand varies with the location of irregularity along the height of the buildings and the shift of irregularity location from the bottom storey to heights above the vertical mass centre of the building frame increases the base shear ratio. While considering the initial set of buildings without eccentricity, due to the shift of the masses to the upper levels of the buildings, base shear ratio increases by a maximum of 29% in Group C buildings. The base shear demand of irregular buildings is lower than that of the regular frame buildings in few cases with mass ratio 1.5 placed at the bottom level implying that smaller eccentricities do not cause much variation in base shear unless located along higher floor levels of the frame.

It is observed that the seismic base shear demand increases with increase in eccentricity when the irregularity is located at the top level of the building frame. Whereas, with irregularities positioned along the bottom half height of the frames, the increase in eccentricity leads to a reduction in base shear ratio in comparison to the regular frames. The decrease in base shear with increase in eccentricity when the irregularities are located at the bottom half of the frames may be attributed to the increase in natural period. Further when the mass irregularities are present in the upper floor levels with higher in-plan eccentricities, effects of increasing base overturning moments becomes significant and hence base shear ratio increases. Therefore it can be observed that the building configuration with the highest dynamic eccentricity (IR1) has the highest base shear ratio when the additional mass is placed at the top level of the frame and has the least value when the additional mass is placed at the middle and bottom level of the frames. Hence eccentric masses located in the upper half of the frames amplify the effect of vertical irregularity remarkably, but if located in the lower half tend to stiffen the building frames. This variation can be observed in all mass ratio and aspect ratio variants. The lowest base shear demand is observed in $CIR1_t$ configuration with mass ratio 1.5 as 0.0498 W and the highest base shear in $AIR1_t$ configuration with mass ratio 5 as 0.1965 W. The highest variations of base shear demand of irregular frames with respect to the regular frames are observed in $AIR1_t$, $2BIR1_t$ and $3CIR1_t$ building frames of the M5 variants as 74.6%, 64.5% and 101.9% respectively. The maximum variation of base shear in buildings with in-plan eccentricity with respect to the plan regular ones is obtained in $3CIRI_m$

as 34.6%. Among buildings of mass ratio 1.5, due to in-plan eccentricity at the upper levels, maximum increase of base shear ratio by 22% with respect to regular frames and 14% with respect to IR0 frames is observed.

Variation in maximum roof rotation

The roof rotation is estimated by considering the highest storey displacements of the extreme corners of the roof of each model. The displacement time histories of the corner points with maximum displacements were considered and the highest value of the difference of the displacements gives the maximum relative displacement of the corners. Roof rotation in radians is obtained by dividing the relative displacement by the width of the building. From the initial set of vertically irregular buildings, it can be observed that maximum roof rotation increases with increase in the aspect ratio of the buildings and the 15 storey buildings have the highest roof rotation. It can also be seen from Figs. 10, 11 and 12 that when the location of irregularity is at the top level of the building, the rotation of the roof is the highest due to the increased flexibility with an exception in the case of the 5 storey buildings where the rotation values are higher when the irregularity is located at the middle of the frame.

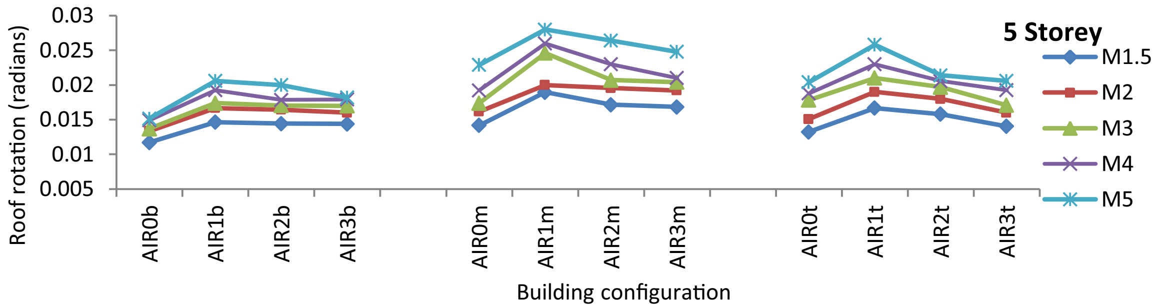

Fig. 10 Variation of roof rotation in group A buildings

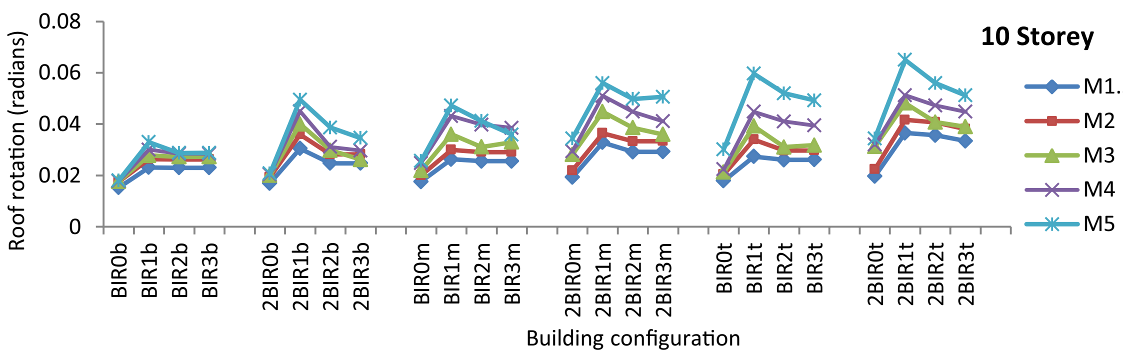

Fig. 11 Variation of roof rotation in group B buildings

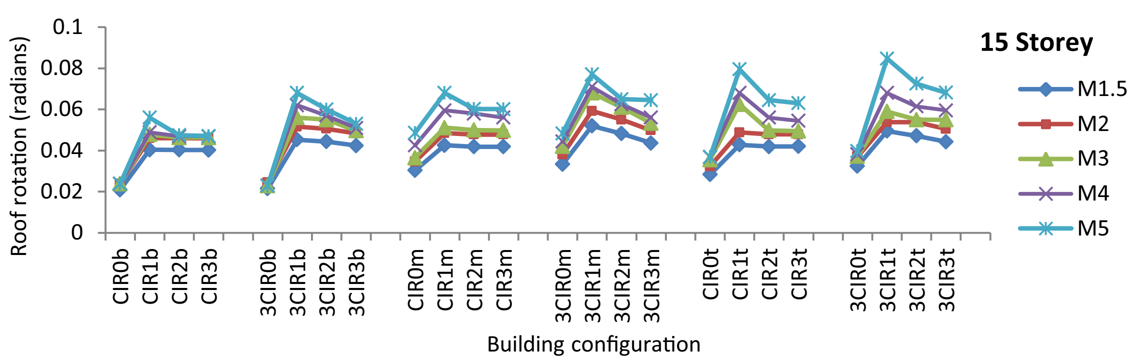

Fig. 12 Variation of roof rotation in group C buildings

In group 3C buildings with M5, the highest increase in roof rotation due to shift in masses from the bottom level to the top level is 67%.

Among the second set of buildings with in-plan eccentricity, IR1 has the highest roof rotation, and IR0 without eccentricity has minimal roof rotation in all variants. IR2 and IR3 with same e_d/L have almost equal rotation in most of the cases. 2B and 3C configuration have higher rotation in comparison to B and C configuration since the irregularities are provided as distributed in two and three floors respectively along the height. When irregularities are located at the upper levels with eccentricity, the storey drifts increases along with considerable increase in twisting moments, which leads to increase in maximum roof rotation. The pattern of floor rotation is very similar in 10 and 15 storey variants. The maximum roof rotation among all the cases is observed in 3CIR1_t with mass ratio 5 as 0.0847 rad. The minimum roof rotation is observed in AIR0_b with M1.5 as 0.0117 rad. Due to varying e_d/L, a maximum variation of 138.5% is observed in roof rotation in IR1 configuration with respect to the plan regular IR0 buildings. IR1_b of mass ratio 1.5 increases the roof rotation 22–72% implying that eccentrically placed smaller masses at lower floor levels can also lead to significant increase of roof rotation. When the masses of mass ratio 1.5 are placed at the upper levels, a maximum variation in roof rotation of 88% with respect to regular frame and 85% with respect to IR0 buildings is observed.

Variation in maximum roof deflection

The maximum roof deflection of buildings with various mass irregularity locations under the application of El-Centro ground motion are represented in Figs. 13, 14 and 15. Roof deflection values are expressed in terms of the height of the buildings (H) as 'roof deflection ratio'. The roof deflection ratios of the regular buildings from 5–15 storey are in the range of 0.0052 H to 0.0085 H. It is observed that, AIR0, BIR0 and CIR0 configuration without eccentricity has the least roof deflection in A, B and C groups of vertically irregular buildings respectively. Increase in roof deflection is proportional to the increase in aspect ratio as well as to the location of irregularity. It can be observed that roof deflections of the frames are less when the irregularity is located at the bottom of the frames in all the aspect ratio variants. The variation in maximum roof deflection between the regular and the vertically irregular buildings increases as the location of irregularity shifts upwards from the bottom to the top level. When the masses are located at the top level of the buildings, the B group buildings show a maximum variation of 35.5% in roof deflection as compared to mass located at the bottom storey. The variation of maximum roof deflection in buildings with mass ratio of 1.5–2 with respect to the regular ones is considerably low. A nominal variation of 3.1–12% in Group A, 1.5–10% in Group B and 1.4–14% in Group C are observed in irregular buildings with mass

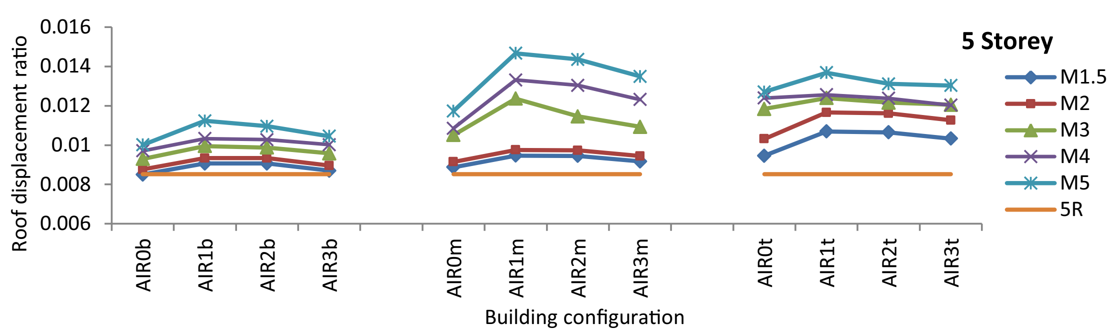

Fig. 13 Variation of roof displacement ratios in group A buildings

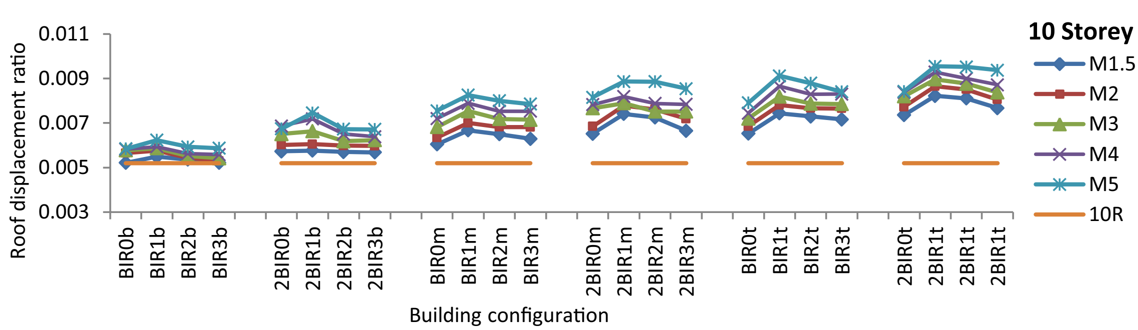

Fig. 14 Variation of roof displacement ratios in group B buildings

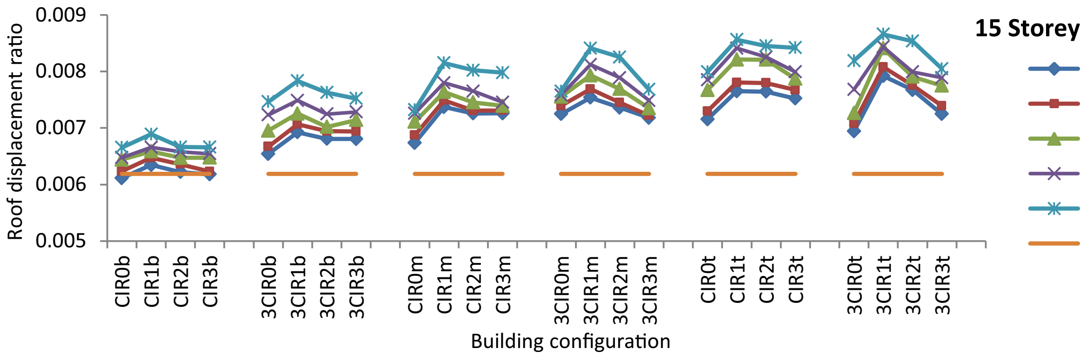

Fig. 15 Variation of roof displacement ratios in group C buildings

ratio of 1.5–2 at the lower storey with respect to the regular buildings.

Considering the second set of buildings, this variation is further amplified by the eccentricity of the masses along the plan of the floor up to a maximum of 28.9%. The highest roof deflection of 0.0866 H is observed in $3CIR1_t$ configuration of 15 storey for mass ratio 5. Among the 5 storey buildings, the highest roof deflection was obtained when irregularity was at the middle of the frame. But in buildings of higher aspect ratios, when irregularities are positioned at the upper levels, the buildings undergo maximum deflection under earthquake ground motion. It can also be observed that the 2B and 3C configuration have higher deflection ratio, in comparison to the B and C buildings among all cases of irregularity locations. The roof deflection ratio of buildings with in-plan mass irregularity even in M1.5 located at upper levels increases by a maximum of 14% with respect to IR0 and 57% with respect to regular frame buildings. The roof deflection or displacement pattern comprises the global deformation demand of a building. Therefore the variation due to the change in position and magnitude of mass irregularities causes variation in the storey drift demands and hence roof deflection is the highest when the mass irregularities are present at the upper floor levels with highest in-plan eccentricity.

Irregularity index

The quantification of mass irregularity with the inclusion of eccentricity is necessary to define the variation of the response parameters with respect to the location as well as the in-plan eccentricity of the vertical irregularity. An index was proposed for quantification of mass irregularity based on location of mass irregularity along the height by Varadharajan et al. (2015) as:

$$\eta_m = \frac{b}{L}\frac{H_i}{H}\frac{M_i}{M} \tag{4}$$

where M_i is the mass of the irregular floor, M is the total mass of the building, H_i is the height of the irregular floor from the base of the building, H is the total height of the building, b is the plan width along the direction and L is the plan dimension transverse to the direction of seismic excitation. The above equation for mass irregularity index (η_m) has been modified by the present authors and a new irregularity index 'α' has been proposed which includes the effects of in-plan eccentricity for buildings with equal dimensions along the direction of seismic excitation and the transverse direction as:

$$\text{Irregularity index, } \alpha = \frac{\sum_{i=1}^{n} M_{ri} H_i \frac{e_{si}}{L^2}}{n} \tag{5}$$

where M_{ri} is the mass ratio and e_{si} is the static eccentricity of the irregular floor considered and n denotes the number of floors with irregularity. This irregularity index 'α' is applicable for buildings with eccentric mass irregularity along 'n' number of floors located at any height from the base of the building. The irregularity index varies from a minimum of 0.0058 to a maximum of 2.788 for all the building configurations considered in the study and increases with increase in eccentricity as well as the change in position of irregularity from bottom level to the top level. The value of α is lowest for buildings with irregularity present at the bottom of the frames and the variation of α due to eccentricity becomes prominent when the irregularity location shifts from the bottom to the upper level of the frame. The irregularity indices are observed to get almost doubled when the location is shifted from the bottom to the top level of the buildings. α also varies remarkably with the height of the buildings and the magnitude of increase is same for all the mass ratios considered. α is obtained in the range of 0.0086–0.918 in group A buildings, 0.0065–1.818 in group B buildings, and 0.0058–2.788 in group C buildings.

The pattern of variation of α with respect to the eccentricity of the buildings is identical in all the three aspect ratio variants.

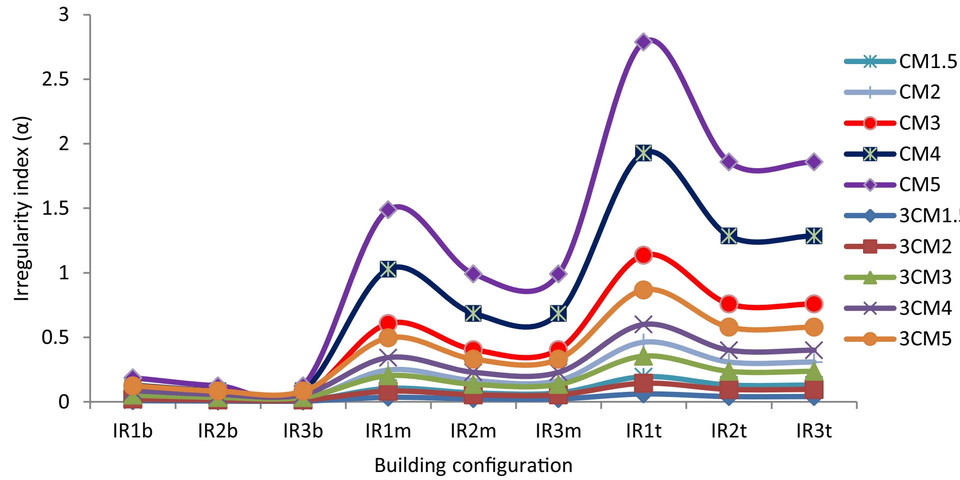

Fig. 16 Irregularity indices for different irregular building configurations

Figure 16 depicts the variation of irregularity indices of the building configurations in group C for various mass ratios of M1.5 to M5 which are placed in single (C) as well as distributed in three adjacent floor levels (3C). It can be observed that the higher mass ratios of 4 to 5 have very high α which is almost 10 times of that obtained for the mass ratio variants of 1.5-3. Buildings with nominal mass ratios of 1.5 to 3 even with highest in-plan eccentricity have the irregularity indices within a range of 0.5 and this is generally the case of real buildings. Within this range of α from 0 to 0.5, with respect to regular frame buildings, natural period, base shear ratio, roof deflection ratio and roof rotation are higher by 41%, 57%, 66% and 122% respectively with respect to that of the regular frame buildings. Furthermore, when the same masses are distributed in two or three adjacent floors as in 2B and 3C, α is lower in comparison to that of B and C configuration buildings. Figures 17 and 18 show the variation of ratios of natural period (T_i/T_r) and base shear (B_i/B_r) of irregular buildings to that of the regular ones with respect to the proposed index α where, T_i and B_i denote the natural period and base shear ratio of irregular building and T_r and B_r correspond to the natural period and base shear ratio of the regular building.

The variations of base shear ratio and natural period ratio with respect to the irregularity index for buildings of three different aspect ratios having $\alpha \leq 0.5$ give a well fit plot. In the case of group A buildings of M2 variant, when eccentric irregularity shifts from the bottom to the top level, α increases by 4 times and T_i/T_r ratio and B_i/B_r ratio increases by 32% and 25% respectively. Similarly, in the case of group B buildings of M1.5 variant, with shift in location of eccentrically placed mass irregularity from the bottom to the top level, α increase by 5 times, T_i/T_r ratio and B_i/B_r ratio increases by 35% and 33%. In group C buildings, α increase by 6 times, T_i/T_r ratio and B_i/B_r ratio increases by 40% and 44% respectively. Based on regression analysis, the best fit relations between the irregularity index α and the natural period (T_i)and base shear (B_i) of irregular buildings in terms of those of regular buildings (T_r and B_r) are obtained as:

$$\frac{T_i}{T_r} = 1.365\alpha^{0.062} \tag{6}$$

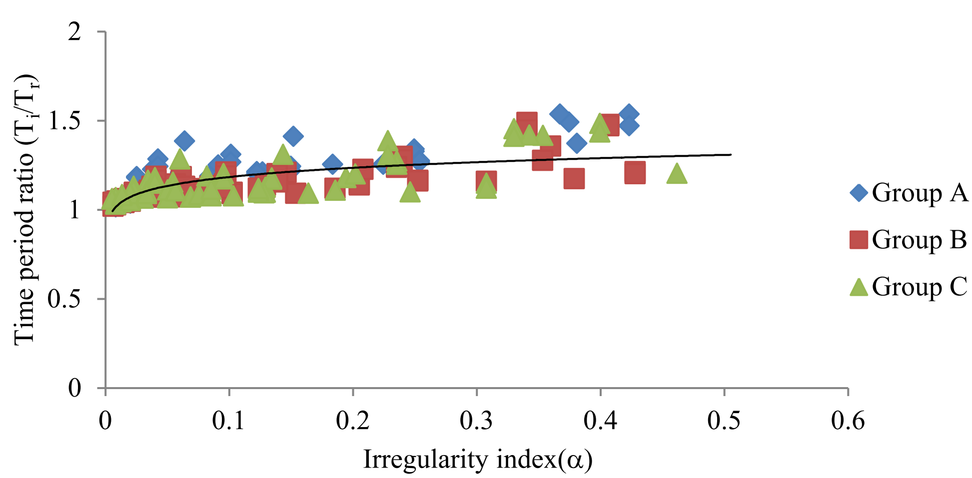

Fig. 17 Variation of irregularity index with natural period ratio

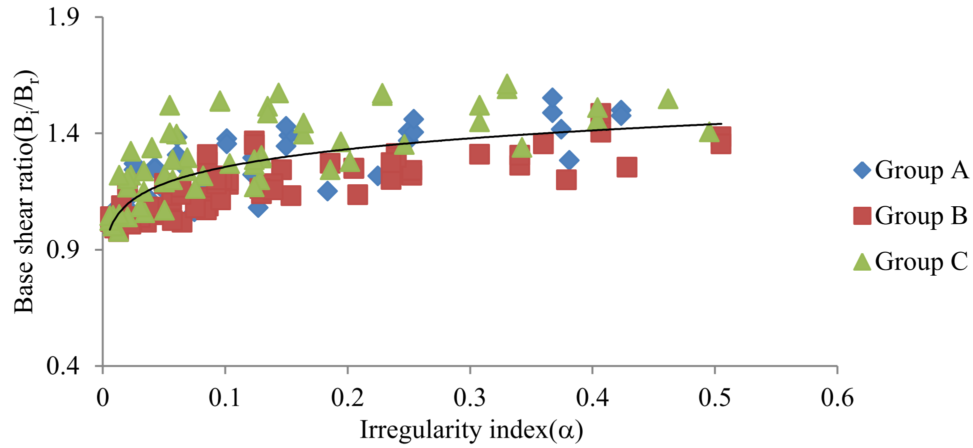

Fig. 18 Variation of irregularity index with base shear ratio

$$\frac{B_i}{B_r} = 1.527\alpha^{0.085} \tag{7}$$

It can be observed that the base shear ratio has a better fit for the developed power equation, with respect to α, in comparison to the natural period ratio. Within a range of values for α from 0 to 0.5, which generally covers the irregularity of real buildings, both T_i/T_r ratio and B_i/B_r ratio have good compliance with α index and the equations developed can be used to predict the response of the buildings accurately. The base shear values in mass irregular buildings (B_i) can be computed from the predicted values as per Eq. 7 and the structural system can be properly planned for the suitable location of irregular masses.

Conclusions

The vertically irregular building frames with eccentric location of masses along plan were analysed and parametric studies were conducted to determine the effect of in-plan eccentricity on mass irregular frames by considering different mass ratios at the bottom, middle and top level of the frames. The dynamic characteristics and seismic responses of structures are expressed in terms of fundamental natural period, absolute maximum responses of base shear, roof deflection and roof rotation. The effects of eccentricity in the considered building configurations were assessed and the following conclusions are drawn,

- Vertical mass irregularity at the top level of the frames increases the natural period by 8–44% in comparison to that of the frames with irregularity at the bottom. This effect is further amplified due to in-plan eccentricity in the building frames by a maximum of 30.5% with respect to the plan regular IR0 buildings. Even in buildings with a mass ratio of 1.5 at the upper level, there is an amplification of natural period by 38% in Group A, 18% in Group B and 28% in Group C buildings due to in-plan as well as vertical mass irregularity.
- Base shear ratio increases by 9–29% in all three groups of buildings due to positioning of the masses at the top levels in comparison to that at the bottom levels. Base shear demand is highest when the irregularities are provided at the top level of the frames. The base shear ratio increases by 34.6% due to the high in-plan eccentricity at the top with respect to IR0 buildings. Even a mass ratio of 1.5 placed as $3C1R1_t$ increases the base shear by 22%.
- Maximum roof rotation is more when the masses are placed at the upper levels of the frames by 16–67% as compared to placement of masses at bottom levels. In-plan eccentricity leads to an increase of 138.5% in roof rotation with respect to plan regular frames. The roof rotation increases by a maximum of 88.8% due to in-plan eccentricity even in the case of irregularity corresponding to a mass ratio of 150% (M1.5).
- Roof deflection ratio is more when the mass irregularities are at the top level of the frame, by 6.8–35.5%, as compared to the placement of the masses at the bottom levels. A maximum increase of 28.9% in roof deflection is observed in $3CIR1_t$ with respect to 3CIR0 due to in-plan eccentricity. Even though, mass ratio of 1.5 is permissible within the IS code limits, it leads to an increase of roof deflection by 57.7% due to in-plan eccentricity at the upper levels.
- The proposed irregularity index (α) can be applied to quantify irregularity in mass irregular buildings with in-plan eccentricity. The natural period and base shear ratio of the irregular buildings of mass ratio less than 3, has good correlation with α in the range of 0 to 0.5.

With respect to the response parameters evaluated in the study, it would be advantageous to place the heavy masses if any, at the bottom floor levels if the buildings are located in seismically intense regions. Even if the masses are of smaller ratio M1.5, if placed with eccentricity along the bottom half of the building, it can lead to increase of 10–22% in natural period and 14–20% in base shear with respect to the regular frame building. The proposed irregularity index can be employed to quantify the mass irregularity in asymmetric buildings with in-plan eccentricity and thus determine the suitable placement of heavy eccentric masses without inducing high torsional coupling in such buildings located in earthquake prone areas.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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