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Evaluation of Seismic Response of Irregular Buildings Subjected to Near-Field Earthquakes

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Abstract

This study deals with the evaluation of the seismic performance of irregular buildings by comparing various seismic responses of six types of building, namely regular building, setback building, stepped building, mass irregular building, stiffness irregular building, and building with floating columns which are constructed of Reinforced Cement Concrete (RCC) subjected to extreme earthquake loads. The nonlinear time history analysis (NTHA) method is carried out to obtain different seismic response parameters for all considered irregular and regular buildings. The structural response results are compared by applying real earthquake records of different near-field & Far-field earthquakes and were compared for four different seismic response parameters which include top storey displacement, inter-storey drift, top base shear, and pattern of plastic hinges formation. This research concludes that the storey displacement, storey drift, and top base shear is significantly less for stepped and setback buildings, and significantly high for mass irregular, stiffness irregular, and floating columns buildings as compared to a regular building. Stepped buildings yield less responses and high responses are yielded in the building with floating columns.

Keywords: Set-back building; strength irregularity; mass irregularity; vertical irregularity; floating columns; plastic hinge

1. Introduction

Earthquake is the most precarious and destructive of devastation, it is very difficult to save life and engineering structures. Through various investigation procedures to ensure the buildings resist during periodic minor earthquakes, there is a need to recognize the seismic performance of the structures and take adequate precautions when a disaster occurs**.** There are several such procedures all around the world which have been updated frequently on this subject [1]. The performance of a building during a seismic activity effect is subject to various factors such as sufficient lateral strength, rigidity, plasticity, and simple and uniform configuration. On several earthquake response parameters which include base shear, inter-storey drift, and top-storey displacement, the effectiveness of the buildings subjected to seismic loads depends on sufficient lateral strength, plasticity, stiffness, and simple & uniform configuration. The structure with orderly geometry, uniformly distributed stiffness, and mass in elevation and plan to suffer much less damage than an irregular configuration structure. Near-field earthquakes occur between 20Km to 50Km. These types of earthquakes are more destructive than distant earthquakes. Near-field earthquakes are linked with two important effects known as the fling phase effect and the directivity effect. Far-field earthquake occurs above the range of 50km [2]. But nowadays due to the demand of population and rapid development taking place all over the world, engineers have to be convinced of irregular configuration buildings, and these are also built quite regularly in every country [3]. When the configuration of the structure around the entire axis is approximately symmetrical, that type of structure is known as a regular structure and when the building is irregular and there is an irregularity in the plan, load-bearing members, and elevation then it shall be treated as an irregular structure. For irregular buildings discontinuity in the plan, elevation, and load bearing members are to be considered as irregularity. Buildings that are similar in appearance, either in the plan or in height, are regular buildings. Along the storey height of the structure with varying distribution in their stiffness, strength, mass, etc. are irregular buildings [17]. But nowadays as per architectural design requirement, most of the area is covered with irregular buildings. These types of irregularities are mainly classified as irregularity along with width i.e., Plan irregularity (horizontal) and along with height i.e., vertical irregularity. Fig. 1 shows the classification of irregularities & fig. 3 shows the different models of vertical irregularity.

Plastic hinges are formed whenever the beam has a plastic bending. It doesn't permit free rotation. It gives a warning before the beam collapse which is an important mechanism of the plastic hinge.[4] have obtained a plastic hinge pattern by applying lateral forces using SAP2000 software. The author considered 3 different storeys level buildings i.e, G+5, G+8, and G+12 stories buildings, and evaluate that the plastic hinge pattern of all three types of buildings is broadly similar. At the joint (at the end) of beams, the plastic hinges are formed and at the bottommost of the column other the lower storey. The formation of the plastic hinges is shown in fig.2.

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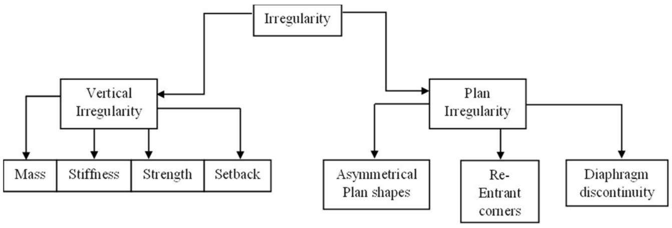


Fig.1 Classification of irregularities

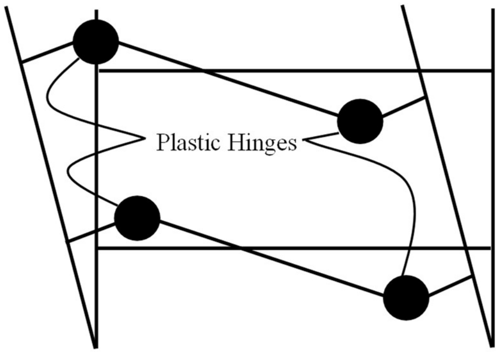


Fig.2 The Formation of the plastic hinges

1.1 Various types of vertical irregularity: -

a) *Stiffness Irregularity (Soft Storey):-* As per IS 1893:2016 (Part 1) stiffness irregularity is considered when the regular configuration with a height of ground storey level is larger(40%) as compared to other storey levels.

b) *Mass Irregularity: -* When the mass of one storey is 3 times (150%) greater than the mass of other storey levels.

c) *Vertical Geometric Irregularity: -* This irregularity occurs when more than 125% of the lateral force opposing horizontal length is greater than its adjacent storey.

d) *Floating Columns irregularity: - The* floating column must not be a primary load-bearing element. Floating columns cause concentrated structural damage.

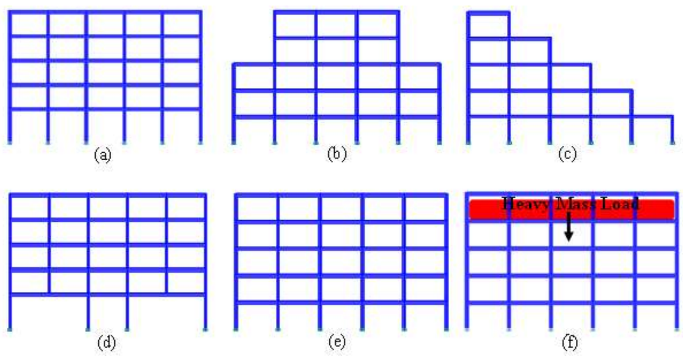


Fig.3 2-D models of regular and different irregular buildings (a) Stiffness irregular building (b) Setback building (c) Stepped building (d) Floating columns building (e) Regular building (f) Mass irregular building

So far, numerous researchers have studied the performance of buildings under seismic effect on structures with vertical and plan irregularities. [5] study that the seismic vulnerability indicator (SVI) gives accurate results or it is well correlated with seismic risk. [6] concluded that the linear analysis result for the modal participating ratio was greater than the irregular structure with 85% The NTHA was an efficient scheme to perform on the irregular structures.

[7] found that the building has a setback and soft storey irregularity more damage as compared to other irregularities, but with the discontinuous beam, it should be less damage. [8] analyzed that the displacement was reduced up to 35% in static analysis and up to 40% in dynamic analysis. The time period is also reduced when the position of shear walls at corners of the irregular mass frame.

[9] studied that the response of vertical geometric irregular building is evaluated with respect to different time periods, base shear & lateral drift. The load-carrying capacity of the building is reduced if there is irregularity present throughout the height of the building. [10] conclude study that the irregularities are harmful to the structures. The yield force is more in the case of regular structure and less in case of irregular and the same with the displacement value. Therefore, it has been concluded that the regular structures are weak compared to the irregular structure. [11] studied that the mass irregular buildings irregularity does not downgrade the level of building performance for the seismic event of DBE under different scenarios for the intensity of the input motions and irregular distribution of mass, the system managed to exhibit satisfactory performance.

In the present research work, a vertical irregular building with the seismic response having different configurations of 5-storey is used to evaluate different types of response parameters of NF earthquake. The present models are evaluated by performing NTHA to extract the earthquake response parameters.

2. Review of Past Research works

The research studies carried out by the various authors related to the performance of the irregular building under seismic behavior have been summarized are:

[12] evaluated the seismic response of vertical irregular building frames to seismic excitation. 7 frame models of 10-storey buildings with mass irregularities, soft storey, and floating columns were analyzed by an equivalent static method using ETABS. The result is that frames with irregularity of floating column had the maximum storey drift value and storey shear was maximum for the mass irregular frame and was maximum for soft storey displacement. Also, it was indicated that irregularities are harmful to the building.

[13] observed the seismic performance having stiffness irregularity on the 4th floor in a vertically irregular reinforced concrete frame. A G+10-storey of vertical irregular frames with one frame having equal floor height and the other frame having more height at the fourth floor as compared to the other floor. Frames were analyzed by a linear static method using ETABS software. It was held that stiffness was irregular with vertical extreme in the earthquake-prone area.

[14] analyzed the response of mass irregularity on RC structure. A 10-storey building with mass irregularity at the third and sixth storey and a structure with no mass irregularity

were analyzed on ETABS and wind load was applied in accordance with IS 875 part III, it was held that a mass irregular building has a 67% moment increase in comparison to a non-irregular building but the drift was more in without mass irregularity. The load-resistant shape of the structural part is also increased when mass irregularities are included.

[15] analyzed the seismic response of regular and vertical geometric irregular RC frame building. The four-story regular and four irregular setback buildings were analyzed by a seismic coefficient method using STAAD Pro. The shear force, top storey displacement, and top storey drift are high, the irregular frame having maximum bending moment was higher than that of regular building for all heights, and with an increase in the number of bays of building the seismic response of regular & setback irregular building will be improved.

[16] studied the response of vertical irregular and plan irregular RC building models. A 15 -storey E-shape building with stiffness irregularity, mass irregularity, and vertical geometric irregular models were analyzed by response spectrum method using ETABS. It was concluded that a building with mass irregularities experiences small base shear and has a high storey drift ratio. Lower stiffness results in higher displacement.

[17] focused on the response of RC structures with incorporated vertical irregularities as per IS code 1893(part 1): 2002. A comparative study of eighteen models with mass irregularity, soft storey, setback, and the sloping ground is considered. The linear static result was greatly on their traditional side and doesn't take the accurate effect. Higher the irregularity chances of vulnerability also higher. Setback and soft storey give a higher drastic effect but mass irregularities show less or negligible effect.

[18] compared the seismic response for the reinforced concrete building having stiffness and mass irregularities. Six storeys' buildings with mass irregularities provided on different floors and stiffness irregularities on the first floor were analysed by pushover analysis method, linear dynamic method (RSM), and nonlinear dynamic method (THM) using SAP2000. The conclusion shows the at frame has mass irregularity in the top storey and having a soft storey on the first floor shows poor performance.

[19] presented an invariable study of the vertical irregular building having stiffness and mass irregularities at different storeys. All models were evaluated by using equivalent static analysis & linear dynamic method using ETABS at zone III. The author summarised that lateral displacement increases with the increase of irregularities.

3. Objectives of the Research Work

1. To evaluate the seismic performance of irregular buildings subjected to NF and FF earthquakes.
2. To compare the seismic response parameters like top base shear, top storey displacement, and inter-storey drift of various types of regular buildings and vertical irregular buildings.
3. To evaluate inelastic seismic demands on irregular buildings by comparing the formation of plastic hinge patterns.
4. To identify the most vulnerable type of irregularity in terms of seismic damage.

4. Building Modelling and Designing

In this study, five types of 2-D irregular buildings and one type of 2-D regular building are considered, namely mass irregular building, stiffness irregular building, stepped building, setback building, and floating columns building, and modeled of RCC material. All the buildings are taken of 5 storey level. Modeling and designing of all buildings are done in commercial ETABS software, this software is used for the purpose of designing and analysis. All buildings are modeled in the X and Z axis direction, 5 numbers of bays are taken for all building models except the floating column building model.

The section properties of columns and beams for all types of buildings referenced from A. S. Bhosale et.al. and the sections of RCC building are assumed. For RCC building rectangular columns and beams are used. The elevation dimension of the ground floor of the all building models is 5m of equal lengths in X-direction. For all building models, a uniform height is taken for all 5 storeys i.e., 3.2m except in stiffness irregular building the height of GF (ground floor) is taken as 4.5m & for the rest of the above storeys as 3.2 m. In the stepped building, a single no. of reduction of the bay is carried out on each storey until the top storey of the building model (length of the top storey is 5m) & the height of this building model is uniform for all storey, i.e., 3.2m. The height of all the storeys in a setback building is taken as same as of a regular building but the length differs on the fourth storey.The height of the 1st three storeys is taken to be equal, i.e., 25m and for the fourth and top storey length is taken as 15m. In the floating column building, 2 columns have been discontinued at the ground storey level to create a floating column building effect.

The nonlinear material model for concrete is considered as Takeda model. The modeling of the building frames is done by assuming uncracked sections. All RCC buildings have to comply with IS-456. Seismic loads are taken and followed from the Indian Earthquake Code, IS 1893. Zone V is taken for the location of the building which is a high seismic zone, with a zone factor equal to 0.36 and soil of moderate type. When designing buildings, for seismic coefficients 1.5 importance factor is considered. The reduction factor is assumed to be 5. For the design of the seismic-resistant building, as per the IS code, the mass source is to be taken into consideration. The multipliers for live and dead loads are considered to be 0.5 and 1 (100% dead load).

As per IS 1893:2016, load cases are considered. The restraint joints are considered as fixed support. The Dead load for building design is 20 kN/m and the live load is 8 kN/m are considered for all types of buildings model, except the mass irregular building model. For mass irregularity building, the dead load on the 4th storey is considered as 60 kN/m which 3times more and the load for the rest of all storeys is kept the same as of all building models. The plastic hinges for columns and beams are assigned at a 0.5% distance from the ends of beams and columns. For defining plastic hinges ASCE 41-17 code is used. Far-field earthquakes and near-field earthquakes are abbreviated as FF eq. and NF eq.

Table 1 Details of reinforcement of regular building

Frame Element	Breadth (mm)	Depth (mm)	Reinforcement	
Columns				
C1	500	500	12 bars@16mm dia.	
C2	500	500	14 bars@16mm dia.	
C3	500	500	12 bars@20mm dia.	
Beams			**Top**	**Bottom**
B1	300	500	5 bars@12mm	4 bars@12mm
B2	300	500	4 bars@16mm	4 bars@12mm
B3	300	500	4 bars@20mm	5 bars@12mm
B4	300	500	4 bars@20mm	4 bars@16mm

Table 2 Details of reinforcement of Mass irregular building

Frame Element	Breadth (mm)	Depth (mm)	Reinforcement	
Columns				
C1	500	500	18 bars@20mm dia.	
C2	500	500	14 bars@25mm dia.	
C3	500	500	14 bars@28mm dia.	
C4	500	500	18 bars@28mm dia.	
Beams			**Top**	**Bottom**
B1	350	550	6 bars@20mm	4 bars@20mm
B2	350	550	8 bars@20mm	6 bars@16mm
B3	350	550	10 bars@25mm	6 bars@20mm
B4	350	550	10 bars@25mm	8 bars@20mm

The details of reinforcement of regular and mass irregular buildings are given in Tables 1 and 2. The building material properties for designing are considered as follows: -

- For RCC Building, M30 grade of concrete is used for modeling which has a high compressive strength of $30N/mm^2$.
- For RCC building, Fe 415 grade of steel is used for steel bars in modeling which have a yield strength of $415N/mm^2$.

4.1. Numerical study:

This research evaluates the performance of irregular buildings by comparing 2 types of earthquakes for 6 types of RC buildings which include mass irregular buildings, stepped buildings, setback buildings, floating columns buildings, stiffness buildings and regular buildings.

For comparison, NTHA is done for all types of RC models with variations of irregularity in the frames. NTHA is selected due to the fact that it is a dynamic analysis and it is the most preferred method for analysis. As per the IS 1893:2016, the analysis is done keeping in the view of zone V. For the present study, we have taken 2 types of earthquakes for analysis i.e., NF eq. and FF eq. and we have taken 3 time-histories of each type of earthquake. The different earthquakes that are taken into consideration are given in Table 3. The earthquake records are scaled to a peak ground acceleration (PGA) level of 0.4g for perfuming NTHA.

5. Discussion of results:

After performing NTHA on all 6 types of irregular RC buildings, comparisons are made considering various seismic response parameters which include inter-storey drift, top storey displacement, and top base shear. In Tables 4 and 5 significant results are given. The results evaluated by analyzing specific models show that a stepped and setback building performs better as compared to a regular building. The results obtained from the simulation in terms of different response parameters are presented in the form of a table and figures in the below sections.

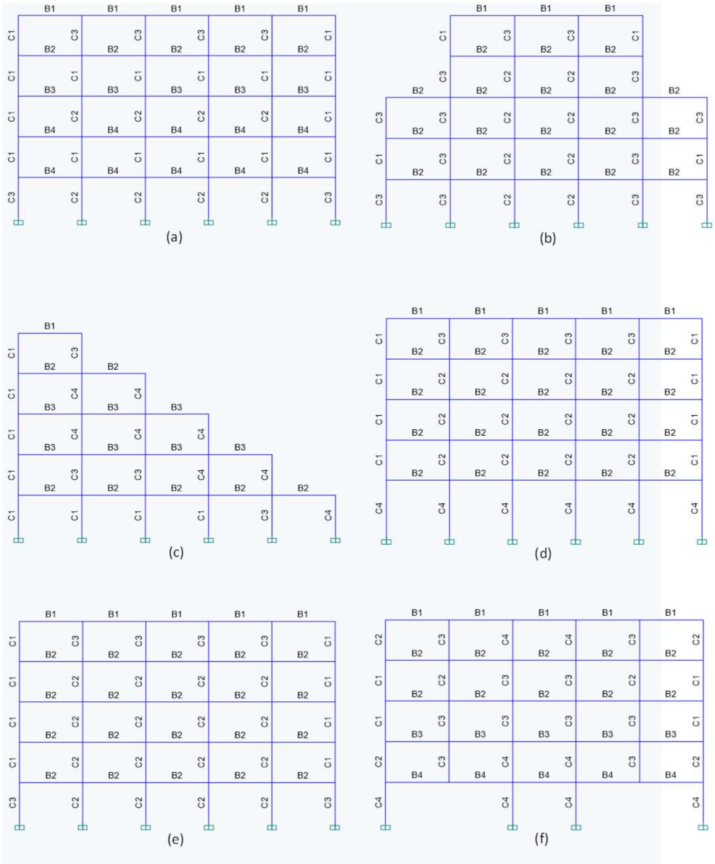


Fig.4 Shows reinforcement of various types of models; (a) Regular Building; (b) Setback Building; (c) Stepped Building; (d) Stiffness Irregular Building; (e) Mass Irregular Building; (f) Floating columns Building

Table 3 Shows the different earthquake records

S.No	Earthquake (Year)	Magnitude (M_w)	Station	PGA (g)	R_{jb} (km)
1	Kobe (1995)	6.9	KJMA	0.84	0.94
2	Morgan hill (1984)	6.19	Gilroy Array #6	0.29	9.85
3	Coyote Lake (1979)	5.7	Gilroy Array #6	0.42	0.42
1	Whittier Narrow-01 (1987)	5.99	Hemet Fire	0.031	102.88
2	Big bear (1992)	6.46	Mecca-CVWD	0.029	104.03
3	Northridge (1994)	6.69	Santa Barbara-UCSB Goleta	0.039	107.2

Table 4 Response parameters of NF earthquake

Type of building	FF earthquake response parameter (average of the maximum value obtained)		
	Base Shear (KN)	Displacement (mm)	Story Drift (%)
Regular Building	765	27	0.236
Mass irregular building	824	26	0.216
Stepped building	941.	26	0.172
Setback building	622	23	0.199
Floating Columns building	683	30	0.261
Stiffness irregularity building	900	32	0.219

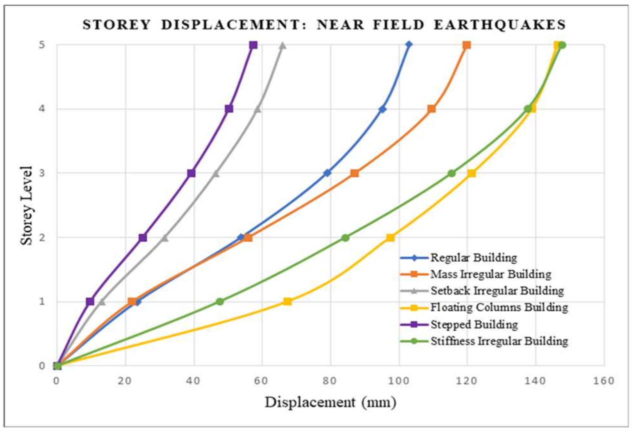
Table 5 Response parameters of FF earthquake

Type of building	NF earthquake response parameter (average of the maximum value obtained)		
	Base Shear (KN)	Displacement (mm)	Story Drift (%)
Regular Building	1728	103	0.577
Mass irregular building	2958	120	0.906
Stepped building	1784	57	0.447
Setback building	1956	66	0.464
Floating Columns building	3191	146	1.40
Stiffness irregularity building	2795	148	1.04

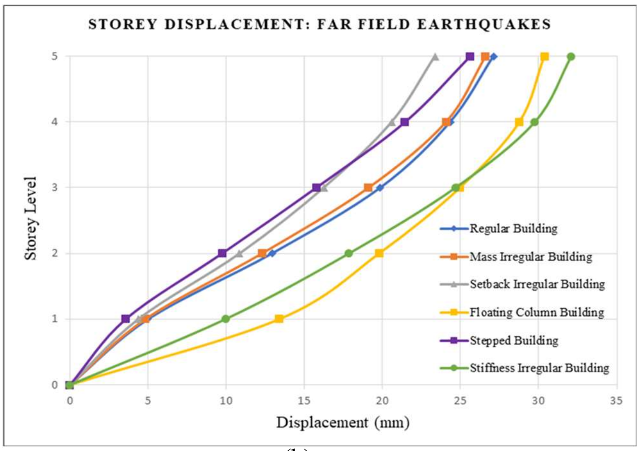
5.1 Displacement:

The trend of results obtained from the graphical representation (as shown in fig. 5) depicts that the value that comes out of storey displacement for the stepped and setback building is less than for regular buildings.

The reduction in the storey displacement is 44.47% for NF eq. and 5.5% for FF eq. in the case of the stepped building as compared to that of regular building, and for setback building, the reduction in the storey displacement is 36.03% for NF eq. and 13.82% for FF eq. as compared to that of a regular building. The setback and stepped building are effective to counter loads. In stepped and setback buildings, it is evident from graphs that abrupt reduction of storey floor areas at different storeys of buildings models which is reducing the storey displacement, it is more pronounced in the case of NF eq. In setback and stepped building stiffness reduction is directly affected by a decrease in the regularity index. The storey displacement of a mass irregular building has increased by 16.23% for NF eq. and 1.9% for FF eq., for the floating columns building increased by 42.01% for NF eq. and 12.01% for FF eq., for the stiffness irregular building 43.23% is increased subjected to NF eq. and 18.28% for FF eq. compared to a regular building. The variation in the different types of irregularities in buildings has led to an increase in storey displacement.



(a)



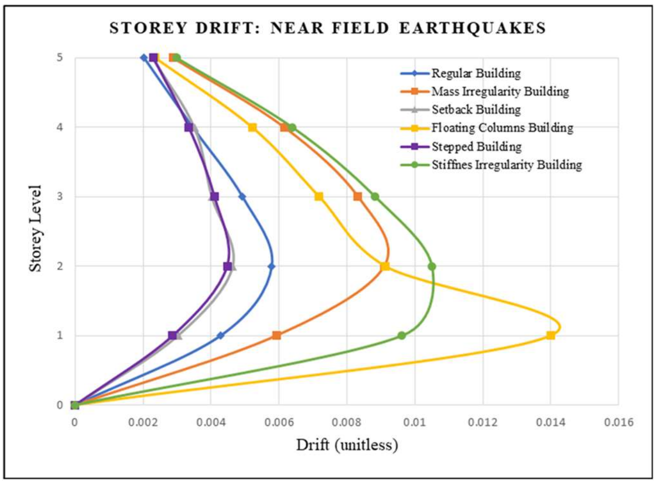
(b)

Fig.5 Graphical representation of storey displacement (a) Storey displacement corresponding to NF earthquakes (b) Storey displacement corresponding to FF earthquakes.

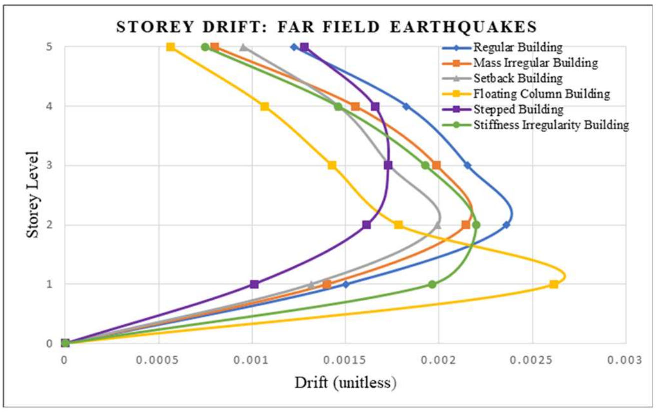
The results obtained in graphical representation show that sudden increase in storey displacement in the building consisting of floating columns, due the presence of floating columns at the ground floor the overall stiffness of the building is decreased, leading to a decrease in the strength of the building and an increase in flexibility. In the mass irregular building, the increase in mass at the fourth storey level of the building causes the building to become weaker which causes considerable variation in storey displacement. Due to increase in the height of the ground storey of stiffness irregular building causes a decrease in stiffness which have to suffer higher storey displacements. The graphical representation is evident that the value of storey drift in NF eq. is significantly high as compared to FF eq. The graphical representation is evident that the value of storey displacement in NF eq. is significantly high as compared to FF eq.

5.2 Storey drift:

It has been studied that the storey drift of mass irregular, stiffness irregular, and floating columns building storey drift has higher storey drift than a regular building. Graphical representation of storey drift of various models subjected to NF eq. and FF eq. are presented in fig. 6



(a)



(b)

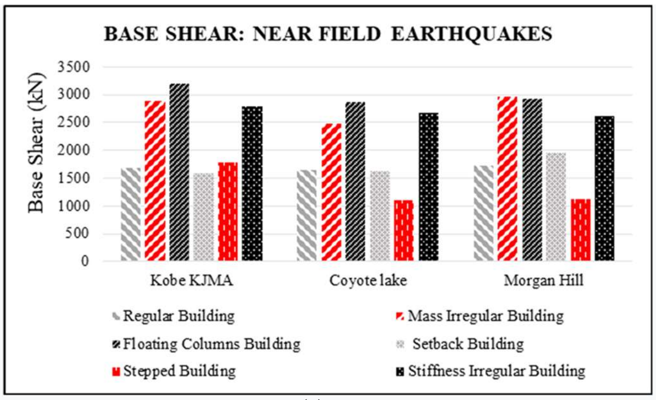
Fig.6 Graphical representation of storey drift; (a) For NF eq. (b) For FF eq.

The reduction in the storey drift is approximately 22.46% for NF eq. and 22.97 % for FF eq. in the case of the stepped building as compared to that of regular building and for setback building, the reduction of storey drift is approximately 19.58% for NF eq. and 15.31% for FF eq. as compared to a regular building. The stepped building and setback building performs well to counter the lateral drift produced by an earthquake due to less overall mass of the building. Due to the setbacks in stepped and setback building a sudden change occurs in the values of storey drift. The storey drift of mass irregular building is increased by 57.53% for NF eq. and for FF eq. 11.14% is reduced, for the floating columns building increased by 144.54% for NF eq. and 3.40% for FF eq., for the stiffness irregular building 116.63% is increased under NF eq. and for FF eq. 11.06% is reduced as compared to that of a regular building. With the height of the storey, the storey drift is changing due to variation of mass and stiffness irregularity of the building. In the graphical representation, it can be observed that the slope of values before a setback in a building tends to be low and after setback values increases after setbacks. Storey drift values tend to be higher in a stiffness irregular building due to increased flexibility in the building. The graphical representation is evident that the value of storey drift in NF eq. is significantly high as compared to FF eq.

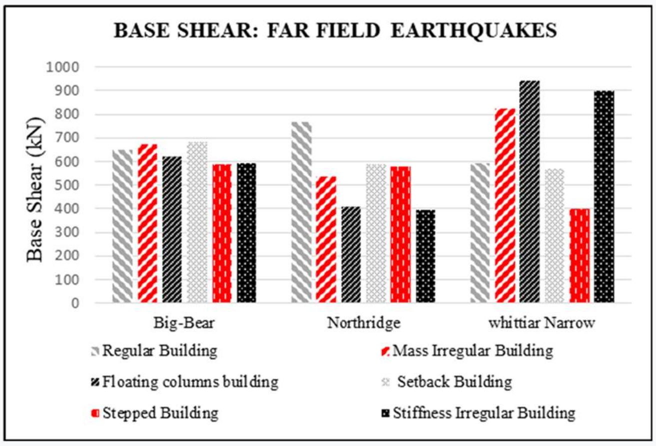
5.3 Base shear:

Evaluation of maximum expected horizontal force based on building due to seismic activity. Graphical representations of top base shear of various models subjected to NF eq. and FF eq. are shown in fig. 7.

Due to the earthquake, the value of base shear for mass irregular building, floating columns building NF eq. comes out to be significantly higher corresponding to the regular building. The value of base shear is reduced by 20.64% for NF eq. and 21.77 % for FF eq. in the case of the stepped building as compared to regular building and for setback building base shear is increased by 1.97% for NF eq. and for FF eq. 1.79% reduced as compared to a regular building. The base shear is changing due to variation of mass and stiffness occurs with a height of the storey. The base shear of the mass irregular building is increased by 64.62% for NF eq. and for FF eq. 1.21% is reduced, for the floating columns building increased by 77.70% for NF eq. and for FF eq. 1.79% is reduced, for the stiffness irregular building 59.7% is increased under NF eq. and for FF eq. 6.08% is reduced as compared to that of a regular building. The increment in the value of base shear is anticipated because the overall weight of the building is increased of the mass irregular building by increasing mass on the fourth floor of the building. The value of base shear is more in the case of the NF eq. as compared to the FF eq. because the NF eq. have pulse-type nature and the intensity of NF eq. is very high as compared to the FF eq.



(a)



(b)

Fig.7 shows the top base shear of various models (a) Top base shear of NF eq. (b) Top base shear FF eq.

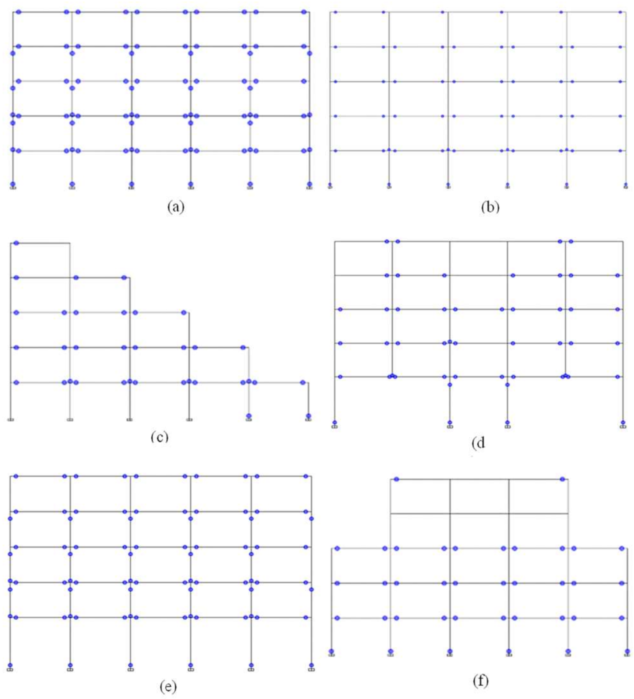


Fig. 8 Pattern of plastic hinges formation of all types of models subjected to Kobe KJMA eq. (a) Mass Irregular Building; (b) Regular Building; (c) Stepped Building; (d) Floating columns Building; (e) Stiffness Irregular Building; (f) Setback Building

5.4 Plastic Hinges:

Plastic hinges are formed whenever the beam has a plastic bending. It doesn't permit free rotation of the element. The pattern of plastic hinge formation, when subjected to Kobe KJMA earthquake, is shown in Figure 8.

The plastic hinges are formed, when all types of buildings are subjected to NF eq., But when subjected to FF eq. no building formed hinges. The maximum number of hinges are formed in a mass irregular building which means it is an unstable building due to its heavy mass load on its fourth storey which makes the building weak. The most stable building is a stepped building due to the minimum no. of hinges formed. Less no. of hinges formed is caused due to a less amount of overall mass of the building as compared to the regular building which causes better stiffness. The number of NF eq. hinges formed are summarized in table 6.

Table 6. Shows the number of hinges formed when subjected to a near-field earthquake

Types of building	**Kobe KJMA**	**Coyote Lake**	**Morgan Hill**
Regular Building	56	50	50
Floating columns Building	49	0	15
Mass irregular Building	80	46	84
Setback Building	38	26	40
Stepped Building	34	05	13
Stiffness Building	82	64	75

6. Conclusions

This study evaluates the performance of vertical irregular RC buildings. The earthquake response parameters are compared across all types of building models. The result outcomes of different building frame models are compared corresponding to various types of earthquake response parameters which include base shear, inter storey drift, and max. storey displacement by performing NTHA. The important conclusions that have been taken out from the current study are as follow:

1. The minimum storey displacement value comes out in stepped building which is approximately 44% subjected NF eq. and 6% subjected to FF earthquake.
2. The minimum storey drift value comes out in stepped building which is approximately 22% subjected NF eq. and 23% subjected to FF earthquake.
3. The maximum storey displacement value comes out in stiffness irregular building which is approximately 43% subjected NF eq. and 18% subjected to FF earthquake.
4. The maximum storey drift value comes out in floating columns building which is approximately 144% subjected NF eq. and 3% subjected to FF earthquake.
5. The maximum base shear value comes out in floating columns building which is approximately 78% subjected NF eq. and1.79% subjected to FF earthquake.
6. The minimum base shear value comes out in stepped building which is approximately 21% subjected NF eq. and 22% subjected to FF earthquake.
7. The most destructive earthquake is Kobe KJMA of NF eq. because it has maximum number hinges formation in buildings.
8. In FF earthquakes no hinges formed in any type of building.
9. According to the present study, the most stable (in terms of yielding of less responses) building model is stepped building as the plastic hinges formed in the type of model is comparatively less as compared to the regular model when subjected to NF earthquake.
10. When irregular type buildings were subjected to near-field earthquakes, the base-shear value tends to be higher than when compared to far-field earthquakes.

Disclosures

Free Access to this article is sponsored by SARL ALPHA CRISTO INDUSTRIAL.

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