Verification of irregularities in a reinforced concrete tall structure

Penunatcha Krishnam Raju\textsuperscript{1}, Vipparthy Ravindra\textsuperscript{2}

\textsuperscript{1}Professor, Department of Civil Engineering, Gayatri Vidya Parishad College of Engineering (A), Visakhapatnam - 530048, INDIA
\textsuperscript{2}Professor, Department of Civil Engineering, Jawaharlal Nehru Technological University Kakinada, Kakinada - 533003, INDIA
E-mail: drpkraju1962@gmail.com

Abstract. Building plans with simple, regular and compact arrangements are preferred to perform well during the occurrence of earthquakes. In practice, planning a regular layout may not be possible in all occasions due to irregular shape of building sites in the plan as well as in elevation due to uneven ground conditions. It is a challenge both for the architect and structural designer to plan and design such buildings. Further, the planning is to be made in compliance with the rules and regulations of the local approving authorities, which sometimes may lead to irregular shapes both in plan and elevation. Most of the times, the owner’s and / or builder’s requirement is to be fulfilled such that the project is viable to them. This is a challenge for the practising professionals designing the structures that are built in earthquake zones III, IV and V. The earthquake resistant design code i.e., IS 1893 (Part 1) was revised in the year 2016 and adopting the provisions of building irregularities with more restrictions on their allowable limits. This paper addresses the identification or verification of the existence of building irregularities in a 17 storey multipurpose tall structure with two parking, two commercial and 13 residential floors. From the results, it is opined that there is a need for a review of the procedure and some of the limits set on irregular building configurations particularly Stiffness, Excessive openings, Out-of-plane offsets, Strength, In-plane discontinuity and Irregular modes of oscillation.

Keywords: Irregular building configurations; Stiffness; Excessive openings; Out-of-plane offsets; Strength; In-plane discontinuity; Irregular modes of oscillation.

1. Introduction
According to IS 1893 (Part 1): 2016 (Code) [1] building irregularities are broadly classified into two types i.e., (a) Plan irregularities and (b) Vertical irregularities. The Code recommends that the buildings should be made with simple, regular geometry and uniformly distributed mass and stiffness both in plan and elevation. Limits on irregularities are also specified for irregular configurations indicating some special requirements that are to be followed for the buildings constructed in seismic zones III, IV and V. Specific reference is also made to certain irregularities that are to be avoided in seismic zone II in the Code.

Tso and Myslimaj [2] Myslimaj and Tso [3] and Mario and Barbara [4] studied the effects of interdependence between strength and stiffness irregularities. Magliulo and Ramasco [5] studied the seismic response of the design of RC frames with strength discontinuities in elevation. They have obtained irregularities by assigning over strengths either to the beams or to the columns of a regular frame. The reinforcements in beams or in columns at different floors were modified. The storey strengths are computed by two different methods i.e., (i) considering flexural resistance of columns...
only (ii) considering both flexural resistance of columns and beams. The methods of evaluation of strength are elaborated as given below.

1) storey strength is equal to the sum of the yielding bending moments at the ends of the columns belonging to the storey divided by the storey height;
2) evaluation of storey strength is same as above but, the yielding bending moment at each end of the storey columns is multiplied by the ratio between the sum of the yielding bending moments of the beams and the sum of the yielding bending moments of the columns converging into the same joint if such ratio is lower than one. Shreyasvi and Shivakumaraswamy [6] Pathan and Dhamge [7] and Livian et al. [8] investigated the irregularities due to “Re-entrant corners”, “mass” and “Non-parallel systems” respectively. Ismail et al. [9] studied the stress and vertical geometric irregularities.

2. Objective and scope of the study
This study is made to identify various irregularities in a seventeen storied multipurpose reinforced concrete tall structure with two parking, two commercial and 13 residential floors. The architectural plan of the residential floor is shown in Figure 1.

A schematic cross-section showing the floor heights of the building structure is presented in figure 2. The height of each residential floor, commercial floor and the lower parking floor is kept at 3.05m. However, the floor height of the upper parking floor is maintained to be 3.96m to facilitate entry of parking vehicles into basement floors. The beam layout for parking and commercial floors is shown in Figure 3 and of the typical residential floor in Figure 4. After several trials of analysis, the column and beam dimensions are finalized and adopted as shown in Table 1, Figure 3 and Figure 4.

![Typical floor plan of residential floor](image-url)
Figure 2. Schematic cross-section

Table 1. Dimensions of columns

| Sl. No | Storey No. | Grids A1 to A6 (mm×mm) | Grids B1 to B6 (mm×mm) | Grids C1 to C6 (mm×mm) | Grids D1 to D6 (mm×mm) | Grids E1 to E6 (mm×mm) | Grids F1 to F6 (mm×mm) |
|--------|------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| 1      | 17, 16, 15, 14 | 760×380                | 760×380                | 760×380                | 760×380                | 760×380                | 760×380                |
| 2      | 13, 12      | 760×380                | B1, B6 = 760×380       | C1 to C5 = 910×380     | D1 to D5 = 910×380     | E1, E6 = 760×380       | 760×380                |
|        |             |                        | B2 to B5 = 910×380     | C6 = 760×380            | D6 = 760×380           | E2 to E5 = 910×380     | 760×380                |
| 3      | 11, 10, 9   | 910×380                | B1, B6 = 910×380       | C1 to C5 = 910×460     | C6 = 910×380           | E1, E6 = 910×380       | 910×380                |
|        |             |                        | B2 to B5 = 910×460     | C6 = 910×380            | E2 to E5 = 910×460     | E1, E6 = 910×380       | 910×380                |
| 4      | 8, 7        | 910×380                | 910×460                | 910×380                | 910×460                | 910×460                | 910×380                |
| 5      | 6, 5        | 910×460                | 910×460                | 910×530                | 910×460                | 910×460                | 910×460                |
| 6      | 4, 3        | 910×460                | 910×530                | 910×460                | 910×530                | 910×460                | 910×530                |
| 7      | 2, 1        | 910×460                | 910×530                | 910×610                | 910×460                | 910×530                | 910×610                |
The ETABS Evaluation Version is used for analysis and design of the building structure considered for the study. The study also covers all the seismic zones of India i.e., Zone II to Zone V.
The dead loads are considered as per IS 875 (Part 1): 1987 [10]. The live loads on parking, commercial and residential floors are taken as 4, 5 and 2 kN/m² respectively as per IS 875 (Part 2): 1987 [11]. The structure is analyzed for all the possible load combinations that include both Limit state of collapse and Limit state of serviceability as per IS 456: 2000 [12]. However, the load combinations with wind are not included in the analysis as the study is specific to earthquake-resistant design. The results of the earthquake analysis are so arrived duly considering the strong column-weak beam effect as per cl. 7.2 of IS 13920: 2016 [13]. However, the presentation of results is limited to building irregularities only in this paper. The Importance factor and Response reduction factor are taken as 1.2 and 5 respectively. The structure adopted is assumed to be founded on medium soil as classified in Table 2 of IS 1893 (Part 1): 2016 [1].

3. Study on Plan irregularities

The Plan irregularities that cover (i) Torsional irregularity, (ii) Re-entrant corners, (iii) Floor slab having excessive cut-outs or openings, (iv) Out-of-plane offsets in vertical elements and (v) Non-parallel lateral force system are discussed as follows.

3.1. Torsional irregularity

This irregularity can only be identified after obtaining the results of post-analysis for the building considered. The building Rules permit constructions for the accommodation of commercial activity in some of the lower floors and with the remaining upper floors for residential purpose. However, the parking is normally allowed in basement floors in a multipurpose tall building structure. Depending upon the configuration, the building is to be analyzed several times by modifying the positions of vertical elements to bring the torsional irregularity within the specified limit. The plan aspect ratio is arrived less than 3 as per the requirement of the code. Two specifications are given defining the Torsional irregularity in Table 5 of IS 1893 (Part 1): 2016 [1].

a) If $\Delta_{\text{max}} > 1.5 \Delta_{\text{min}}$

Then, Torsional irregularity is present in the building.

Where,
$\Delta_{\text{max}}$ = Maximum horizontal displacement at the one end
$\Delta_{\text{min}}$ = Minimum horizontal displacement at the far end

The $\Delta_{\text{max}}$ and $\Delta_{\text{min}}$ values in both X and Y directions of the building for all seismic zones are tabulated in Table 2. It can be seen from this table that the ratios of $\Delta_{\text{max}}$ and $\Delta_{\text{min}}$ are less than 1.5 in both the directions and hence Torsional irregularity is not present. Figure 5 shows the checks for Torsional irregularity in X and Y axis respectively for Zone II.

b) If TR > TTX and TR > TTY

Then, Torsional irregularity exists in the building.

Where,
TR = Natural time period corresponding to the fundamental torsional mode
TTX = Natural time period corresponding to translational mode in X-direction
TTY = Natural time period corresponding to the translational mode in Y-direction

| Zone  | X-direction (mm) | Y-direction (mm) | Translationa l | Rotationa l |
|-------|-----------------|-----------------|----------------|-------------|
|       | $\Delta_{\text{min}}$ | $\Delta_{\text{max}}$ | $\Delta_{\text{min}}$ | $\Delta_{\text{max}}$ | TTX | TTY | TR |
| Zone - II | 18.94 | 19.43 | 1.03 | 17.70 | 18.58 | 1.05 | 2.33 | 2.29 | 2.10 |
| Zone - III | 30.12 | 30.52 | 1.01 | 27.50 | 28.55 | 1.04 | 2.33 | 2.29 | 2.10 |
| Zone - IV | 45.02 | 45.30 | 1.00 | 40.50 | 41.85 | 1.03 | 2.33 | 2.29 | 2.10 |
| Zone - V | 67.37 | 67.48 | 1.00 | 60.03 | 61.79 | 1.03 | 2.33 | 2.29 | 2.10 |
It can be seen from the Table 2, that the values of TR are less than the values of both TTX and TTY in all seismic zones and hence no torsional irregularity is present in any of the floors of the building.

In addition to the above provisions, if the ratio of $\frac{\Delta_{\text{max}}}{\Delta_{\text{min}}}$ is in the range of (1.5 to 2.0), the building configuration shall be revised to ensure that the natural time period of the fundamental torsional mode of oscillation shall be smaller than those of the first two translational modes. Even though the code recommended 3D dynamic analysis for the above case, it is not possible to assess the torsional irregularity in the building without 3D dynamic analysis. The building configuration shall be revised also in case of $\frac{\Delta_{\text{max}}}{\Delta_{\text{min}}}$ more than 2.0 to ensure that the natural time period of the fundamental torsional mode of oscillation is less than those of the first two translational modes along with each principle plan directions. In the present study, the above situation does not arise.

3.2. Re-entrant corners

It is a pre-determined irregularity based on the planning of the structure. If irregularity due to Re-entrant corners exists, IS 1893 (Part 1): 2016 [1], recommends the adoption of 3D dynamic analysis. If the ratio of $\frac{A}{L} > 0.15$ in any plan direction, then it is said to be irregularity due to Re-entrant corner.

Where $A =$ length of Plan projection in the direction considered
$L =$ Overall plan dimension in the same direction

In the present study, Re-entrant corners are identified as shown in Fig. 6 that cannot be eliminated in this plan configuration particularly along Y-axis. However, along X-axis, no such irregularity is present as the $\frac{A_1}{L_1}$ the ratio is less than 0.15.

Along X-axis
Ratio of $\frac{A_1}{L_1} = \frac{3.0}{29.4} = 0.102 < 0.15$, Irregularity due to Re-entrant corner does not exist
Along Y-axis

Ratio of \( \frac{A_2}{L_2} \) = \( \frac{5.20}{33.6} \) = 0.155 > 0.15, Irregularity due to Re-entrant corner marginally exists

Ratio of \( \frac{A_3}{L_2} \) = \( \frac{7.20}{33.6} \) = 0.214 > 0.15, Irregularity due to Re-entrant corner exists

Where, \( A_1, A_2 \) and \( A_3 \) are plan projections and \( L_1 \) and \( L_2 \) are overall plan dimensions in X and Y directions as shown in Figure 6.

As residential flats are planned with at-least three sides ventilation and also acceptable as per building bye-laws such irregularities do exists in many of the structures. However, code recommends 3D dynamic analysis for such buildings and the same is carried out for the present structure.

![Figure 6. Check for Re-entrant corners](image)

3.3. Floor slabs having excessive cut-outs or openings

It is a plan irregularity that can be determined based on the planning of the structure. This irregularity can be verified based on plan dimensions before actual analysis is carried out. In the present case, hardly any openings or cut-outs both in commercial and parking floors except lift and staircases present. However, openings or cut-outs are present in the residential floors of the building as shown in Figure 7. According to IS 1893 (Part 1): 2016 [1] the building is said to have a discontinuity in their in-plane stiffness and is considered as “Flexible diaphragm” behaviour if the area of cut-outs or openings is more than 50% of the total floor area of the slab. In respect of openings located along any edge of the slab, the above provision is restricted to 10% only to consider the “Rigid diaphragm” effect.

This provision is verified for the study under consideration.

Area of Total openings \( (m^2) \), \( \Delta \text{O} = (a_1+a_2+a_3+a_4+a_5+a_6+a_7+a_8+a_9+a_{10}+a_{11}) \)

\( = (15.6+24.3+17.4+21.6+15.6+17.7+3.8+17.4+21.6+8.16+2.16) \)

Where, \( a_1, a_2, a_3 \) etc., are areas of openings as marked in Figure 7.

Total floor area

\( A_1 = \text{Floor area surrounded by grids A1, A6, F6, F1 and A1} = 29.4 \times 33.6 = 987.84m^2 \)

Ratio = \( \frac{\Delta \text{O}}{A_1} = \frac{165.32}{987.84} = 0.167 < 0.5 \) (Hence, rigid diaphragm effect can be considered)
Therefore, the irregularity due to “Excessive openings or cut-outs” is not present in this structure and the floor acts as a rigid diaphragm.

In this building, there are no openings in individual floor slab panels close to the edge of the slab and hence, the check for the ratio of \( \frac{A_o}{A_t} > 0.1 \) does not arise. It is not clear in the code, whether the portions of openings extended beyond column line and up to edge of balconies are to be taken into consideration while calculating the “opening area”. According to cl. 5.6.2.2 of IS 16700: 2017 [14], the maximum area of openings in any floor diaphragm is limited to 30% of the plan area of the diaphragm, probably to achieve Rigid diaphragm behaviour. Hence, this provision of IS 1893 (Part 1): 2016 [1] needs further review.

![Diagram](https://via.placeholder.com/150)

**Figure 7.** Check for irregularity due to Floor slabs having excessive cut-outs or openings

### 3.4. Out-of-plane offsets in vertical elements

According to the code, a building is considered to be out of plane offset in the vertical direction, when the structural walls or frames are moved out of the plane in any storey along the height. The amount of out-of-plane offset is not quantified. Instead, it was advised to refer specialist literature for all seismic Zones of II to V. However, for the buildings located in Zone III, IV and V, it is recommended that the lateral drift should be less than 0.2% in the storey having the offset and in storeys below them. Whereas, no such provision is included for Zone II. Post analysis verification is only possible to identify this irregularity.

In the present study, the above provision is verified with the columns in residential floors and Parking and Commercial floors. Even though the sizes of columns in the upper floors are reduced with respect to the lower floors, the centroid of the column is maintained throughout the height of the
building. Hence, the above irregularity is not present in this case. In case, where the irregularity is present, specialist literature is to be referred as recommended in IS 1893 (Part 1): 2016 [1]. The code should also refer to such specialist literature to follow uniformly by the practising structural designers.

3.5. Non-parallel lateral force system

If vertically oriented structural systems resisting lateral forces are not oriented along the two principal orthogonal axes in the plan, the code recommends to carry out analysis of such systems for load combinations as mentioned in cl. 6.3.2.2 or 6.3.4.1. However, Non-parallel lateral force system does not exist in the present building under consideration.

4. Study on vertical irregularities

The vertical irregularities such as Stiffness irregularity (Soft storey), Mass irregularity, Vertical geometric irregularity, In-Plane discontinuity in vertical elements resisting lateral force, Strength irregularity (Weak storey), Floating or Stub columns and Irregular modes of oscillation in two principal plan directions are discussed below with respect to the structure under verification.

4.1. Stiffness irregularity (soft storey)

According to the code, if the lateral stiffness of the storey considered is less than that of the storey above, then stiffness irregularity exists and is to be eliminated. The lateral stiffness of the storey can be assessed only through 3D analysis and hence this type of irregularity can only be established after obtaining analysis results. One of the controlling factors in stiffness is storey height. Considering a uniform horizontal diaphragm in all the floors with varying height even in any lower or intermediate floor causes the stiffness irregularity. But in practice, the basement floors or lower floors of the building are catered for parking or commercial purposes and the upper floors are catered for residential or other purposes. Higher floor height is needed for basement and commercial floors compared to residential floors particularly in multipurpose buildings.

The other aspect is the consideration of diagonal strut action due to Un-Reinforced Masonry (URM) infills for internal and external walls. As per the clause 7.9 of IS 1893 (Part 1): 2016 [1], the advantage due to the infills for thickness 230mm, 200mm, 150mm and 115mm (to match with standard brick size) is limited compared to the regular spacing of columns that are maintained for residential buildings. The same is demonstrated below for most commonly adopted unreinforced masonry infill with a sample calculation.

4.1.1. Check for the advantage of URM infill. The following two limits are set for calculation of thickness of “equivalent diagonal strut” and both these limits should satisfy to consider the infill effect.

\[
\left( \frac{h}{t} \right) < 12 \text{ and } \left( \frac{l}{t} \right) < 12
\]

Where,

- \( h \) = Clear height of the URM infill wall between the top beam and bottom floor slab
- \( l \) = Clear length of the URM infill wall between the columns/walls
- \( t \) = Thickness of unreinforced masonry infill

a) For 230mm thick wall (maximum infill thickness that is being considered in practice)

(i) The spacing of columns, \( l < 12t \)

\[
l < 12 \times 230 = 2760\text{mm} = 2.76\text{m}
\]

Hence, this restricts maximum spacing of columns to 2.76m, and same is not practically being followed.

(ii) The clear height of the URM in-fill wall, \( h < 12t \)

\[
h < 12 \times 230 = 2760\text{mm} = 2.76\text{m}
\]

This limit may be satisfied for residential buildings with regular beam depths. Even if one of the above two limits are not satisfied, the contribution of URM infill wall for improvement of storey stiffness is not achieved.

4.1.2. Check for soft storey effect.
From the results of the study, the lateral stiffness of different storeys as obtained in the 3D dynamic analysis are tabulated for both X and Y axes in Tables 3. The soft storey effect is observed in second (upper parking) and third (lower commercial) floors in X - direction as the storey stiffness of these floors is less than that of its upper floors. But, as per cl. 7.1 (Table 5) of IS 1893 (Part 1): 2002 [15], the above two storeys do not fall under soft storey effect as explained below.

Lateral stiffness (LS) of sixth storey = 1171069 kN/m
Lateral stiffness (LS) of fifth storey = 1306403 kN/m
Lateral stiffness of fourth storey = 1460919 kN/m
Lateral stiffness of third storey = 1438802 kN/m
Lateral stiffness of second storey = 1004628 kN/m

4.1.2.1. Verification of soft storey effect for second storey (as per IS 1893 (Part 1): 2002) [15].

a) As $1004628 > 0.6 \times 1438802 > 863281$ kN/m and
b) As $1004628 > 0.7 \times \left( \frac{1460919 + 1306403 + 1171069}{3} \right) > 981429$ kN/m,
it is to be considered that the Stiffness irregularity is not present in the second storey as the building is planned with stilts.

4.1.2.2. Verification of soft storey effect for third storey (as per IS 1893 (Part 1): 2002) [15].

a) As $1438802 > 0.6 \times 1460919 > 876551$ kN/m and
b) As $1438802 > 0.7 \times \left( \frac{1460919 + 1306403 + 1171069}{3} \right) > 918958$ kN/m,
it is to be considered that the Stiffness irregularity is not present in the third storey also as the building is planned with stilts.

Similarly, the soft storey effect found exists from second to the sixth storey in Y- direction as per IS 1893 (Part 1): 2016 [1] as shown in Table 3. But such an effect is not found as per IS 1893 (Part 1): 2002 [15]. The above situation calls for further review on Stiffness irregularity provisions.

### Table 3. Check for Stiffness irregularity in X and Y directions

| Type   | Storey | Storey height | X-direction | Y-direction | Soft Storey IS 1893 (Part-1): 2016 | Soft Storey IS 1893 (Part-1): 2002 |
|--------|--------|---------------|-------------|-------------|----------------------------------|----------------------------------|
|        |        |               | X          | Y           |                                  |                                  |
|        |        |               | Diff. (%)  | Diff. (%)   |                                  |                                  |
|        |        |               | Storey Stiffness (kN/m) | Storey Stiffness (kN/m) |
| Residential | 17 | 3.05 | 324068 | 165.71 | 535310 | NA | No | No | No | No |
|          | 16 | 3.05 | 537012 | 117.56 | 955676 | 114.18 | No | No | No | No |
|          | 15 | 3.05 | 631327 | 110.48 | 1042352 | 109.07 | No | No | No | No |
|          | 14 | 3.05 | 697501 | 110.63 | 1134823 | 108.87 | No | No | No | No |
|          | 13 | 3.05 | 771670 | 110.46 | 1179321 | 103.92 | No | No | No | No |
|          | 12 | 3.05 | 844698 | 110.63 | 1179321 | 103.92 | No | No | No | No |
|          | 11 | 3.05 | 913283 | 110.48 | 1179321 | 103.92 | No | No | No | No |
|          | 10 | 3.05 | 977674 | 110.63 | 1179321 | 103.92 | No | No | No | No |
|          | 9 | 3.05 | 1002363 | 107.05 | 1179321 | 103.92 | No | No | No | No |
|          | 8 | 3.05 | 1039985 | 106.46 | 1179321 | 103.92 | No | No | No | No |
|          | 7 | 3.05 | 1107218 | 105.77 | 1179321 | 103.92 | No | No | No | No |
|          | 6 | 3.05 | 1171069 | 104.89 | 1179321 | 103.92 | No | No | No | No |
|          | 5 | 3.05 | 1306403 | 111.56 | 1179321 | 103.92 | No | No | No | No |
|          | 4 | 3.05 | 1460919 | 111.83 | 1179321 | 103.92 | No | No | No | No |
|          | 3 | 3.05 | 1438802 | 98.49 | 1179321 | 103.92 | Yes | Yes | No | No |
|          | 2 | 3.06 | 1004628 | 69.82 | 842794 | 74.39 | Yes | Yes | No | No |
| Parking | 1 | 3.05 | 1616927 | 160.95 | 1498875 | 177.85 | No | No | No | No |
4.2. Mass irregularity
The structure considered at present has three different types of occupation i.e., Residential, Commercial and Parking purposes. Different live loads are considered for these occupations i.e., 2 kN/m², 5 kN/m² and 4 kN/m² respectively. The code considers that the mass irregularity exists when the seismic weight of any floor is more than 150 % of that of the floors below. The code further recommended that the earthquake effects are to be estimated by adopting 3D dynamic analysis for the buildings located in Zone III, IV and V. In the present building, the seismic weights are estimated for Residential floor, Commercial floor and Parking floors and Mass irregularity is calculated and shown in Table 4. It is found that there is no Mass irregularity present in the building.

| Storey                  | Seismic weight (kg×1000) | Difference (%) | Limit (%) |
|-------------------------|--------------------------|----------------|-----------|
| Residential             | 1247                     | 91.3           | <150      |
| Residential-Commercial  | 1365                     | 121.7          | <150      |
| Commercial -Parking     | 1122                     | 104.3          | <150      |
| Parking                 | 1077                     |                |           |

4.3. Vertical geometric irregularity
The Vertical geometric irregularity of the building under consideration is verified as follows.
The parking and commercial floors occupy the total area of the building whereas the residential towers are projected above fourth slab and up to 17th slab with a gap (A) of about 3.0m maintained between towers as shown in figure 2.

The length of the building (L) in X-axis is 29.4m. Accordingly, the ratio of \( \frac{A}{L} = \frac{3.0}{29.4} = 0.102 \), and the same is less than 0.125 and hence no vertical geometric irregularity exists in the building. The code recommends estimation of earthquake effects by adopting dynamic analysis for the buildings located in Zone III, IV and V in case Vertical geometric irregularity exists.

4.4. In-Plane discontinuity in vertical elements resisting lateral force
The code does not permit the buildings with In-plane discontinuity particularly in seismic Zones III, IV and V. However, the buildings with in-plane discontinuity are permitted in zone II with a limitation of the lateral drift of the building under-designed lateral force to be less than 0.2% of the building height. It is considered that the in-plane discontinuity in vertical elements resisting lateral force exists when the offsets are greater than 20% of the plan dimension of those elements. In the present case, the column sizes are reduced in upper floors by maintaining centroid throughout the height of the building. Therefore, the above irregularity is not present in this case. In practice, the size of the peripheral column in upper floors are normally reduced in tall structures concerning the outer side and thereby the above irregularity may sometimes exist. Further research in this area is necessary.

4.5. Strength irregularity (Weak Storey)
The strength irregularity is said to exist when the lateral strength of the storey considered is less than that of the storey above. The code does not specify the method of estimation of lateral strength. However, two methods are referred in ‘Magliulo and Ramasco’ [5], for estimating the lateral strength of the storey. In the first method, flexural resistance of columns is only considered and in the second method, both flexural resistance of columns and beams are considered. A typical column at grid C2 (refer Figure 3 or 4) is considered for estimation of column strength in 3rd and 4th storeys and the details are presented in Figure 8 and Appendix.

It can be seen from the Appendix that the column strength (C2) in 3rd storey is more than the column strength in 4th storey according to both the methods. Hence, Strength irregularity is not present in this case.

The storey strengths of 3rd and 4th are also estimated adopting the Method 1 procedure and the summary is tabulated in Table 5. As can be seen from the table that the lateral strength of 3rd storey is more than the lateral strength of 4th storey in both X and Y directions. Hence, no Strength irregularity
(weak storey) is present in the structure. However, the procedure is to be extended to other floors also to ascertain the storey strengths. The manual calculations for estimation of storey strength are very tedious and hence the software should directly provide the results of strength like storey stiffness.

### Table 5. Check for Storey strength

| Storey No. | Storey Height (m) | X-Direction | Y-Direction |
|------------|-------------------|-------------|-------------|
| Storey 4   | 3.05              | 6966        | 7091        |
| Storey 3   | 3.96              | 7409        | 7166        |

![Figure 8](image)

**Figure 8.** Estimation of storey strength

4.6. **Floating or Stub columns**

Floating columns as a part of supporting the primary lateral load resisting system shall be avoided as recommended by the code. In practice, Floating columns or Stub columns are being adopted widely particularly in duplex houses and also where the columns of upper floors obstruct the parking in residential buildings.

The code does not specify any limit in height or any other parameter to be followed for adoption of Floating columns. In the present study, no Floating columns were provided in the structure.
4.7. Irregular modes of oscillation in two principal plan directions
The above irregularity is related to mass participation of the structure and limitation of difference in Time period in mode 1, 2 and 3. The mass participation factor and time periods both in X and Y axes are obtained from the analysis and the same are reported in Table 6.

| Zone-II and Zone-III | Zone-IV and Zone-V |
|----------------------|--------------------|
| Mass participation (%) | Time Period T (sec) | Diff with Max T (Sec) | Difference w.r.t Max. T (%) | Irregularity |
| Mode | X | Y | Check | Irregularity | T | X-2.332 | 0.047 | 2 < 10 | Present |
| 1 | 80.10 | - | > 65 % | Not Present | Y-2.285 | - | - | - | |
| 2 | 80.11 | 84.37 | > 65 % | Not Present | - | - | - | - | |
| 3 | 80.11 | 84.75 | > 65 % | Not Present | - | - | - | - | |

As the mass participation factor for all the three modes is greater than 65% for all seismic zones, it is considered that there is no irregularity present in the structure.

For Zones IV and V, in addition to the mass participation factor, the difference of time periods along X and Y axes with respect to the maximum time period either X or Y directions should be more than 10% and same is not satisfied in the present case. This limit may need a review by experts as the buildings with square shape may have the same time period.

5. Conclusions
An attempt was made to identify and verify the existence of various irregularities present in a 17 storey tall structure. Based on the results and discussion, the following conclusions have arrived.

5.1. Plan irregularities
1. There is no “Torsional Irregularity” present in 50m high Tall structure in both principal plan directions and all seismic Zones, even though the Building system is planned only with “Special moment resisting frames”.
2. Building Irregularity due to Re-entrant corners is found to be in existence in this structure along Y-axis only. However, 3D dynamic analysis is adopted as recommended in IS 1893 (Part 1): 2016 to take care of such irregularity.
3. In respect of Excessive Cut-outs or Openings, there is no such Irregularity present in the building. However, it is recommended to review the limits set in the code to this irregularity to consider rigid diaphragm effect compared to the provision given in cl. 5.6.2.2 of IS 16700: 2017.
4. There are no “Out-of-plane offsets” present in any of the Columns of the structure considered as the centroid of all upper columns are coinciding with the lower columns and hence such Irregularity does not exist. Code is silent on quantification of Out-of-plane offsets and hence there is a scope for further research in this area.
5. As the structure considered for the study is rectangular with certain openings, no “Non-Parallel lateral forces” arise on the system.

5.2. Vertical irregularities
6. The advantage of equivalent diagonal strut action due to un-reinforced masonry infill of even for 230mm thick is very less as the limits of (l/t) and (h/t) (cl.7.9 of IS 1893 (Part 1): 2016) is restricting the maximum spacing between columns not more than 3m. The same is not desirable in most of the residential buildings.
7. No Strength irregularity (weak storey) is present in the structure as the lateral strength of 3rd storey is more than that of lateral strength of 4th storey in both X and Y directions. However, the procedure is to be extended for other floors also to ascertain all storey strengths. The structural designers are facing a lot of difficulty in the estimation of storey strength to verify the “Strength irregularity” (Weak storey) as IS 1893 (Part 1): 2016 is silent on the method of estimation of Storey strength. The
applicability of the methods as indicated in the Appendix is also to be confirmed by more rigorous studies.
8. The two methods that are available in the literature for estimation of lateral Story strength involves a lot of calculations and the regular structural analysis and design software is not directly providing the “Storey strength” unlike “Storey stiffness”. There is a scope for software developers to consider this aspect.
9. No Mass irregularity and Vertical geometric irregularity exists in the present structure.
10. There is no Irregularity present in the structure due to In-plane discontinuities in vertical elements. However, further research is needed in case of column offsets that are unavoidable in certain cases.
11. There is no Irregularity as the floating columns are absent in the structure. The code completely restricts the presence of floating columns that may not be avoidable in practice in certain cases.
12. Irregular modes of oscillation in two principal plan directions need a review by experts as the provision contradicts for the square-shaped building in respect of percentage of difference in time periods.

Future scope of Research
A similar study can be conducted on Irregular building configurations studied by Markandeya Raju et al. (2018), [16], Siva Bhanu et al. (2016) [17] and Markandeya Raju and Reddi Poornima (2020) [18].

Appendix

Methods of estimation of storey strength

**Method I**
a) Column location = C2, 4\textsuperscript{th} storey
Storey height, H = 3.05 m
Column moments:
4\textsuperscript{th} storey column moment at the top, $M_{ct-4} = 217$ kN-m
4\textsuperscript{th} storey column moment at the bottom, $M_{cb-4} = 400$ kN-m
Strength of the column = \(\frac{(M_{ct-4} + M_{cb-4})}{H} = \frac{(217+400)}{3.05} = 202\) kN-m/m
b) Column location = C2, 3\textsuperscript{rd} storey
Storey height, H = 3.96 m
Column moments:
3\textsuperscript{rd} storey column moment at the top, $M_{ct-3} = 316$ kN-m
3\textsuperscript{rd} storey column moment at the bottom, $M_{cb-3} = 593$ kN-m
Strength of the column = \(\frac{(M_{ct-3} + M_{cb-3})}{H} = \frac{(316+593)}{3.96} = 241\) kN-m/m

**Method II**
a) Column location = C2, 4\textsuperscript{th} storey
Storey height, H = 3.05 m
Column moments at the top joint:
4\textsuperscript{th} storey column moment at the top, $M_{ct-4} = 217$ kN-m
5\textsuperscript{th} storey column moment at the bottom, $M_{cb-5} = 416$ kN-m
Column moments at bottom joint:
4\textsuperscript{th} storey column moment at the bottom, $M_{cb-4} = 400$ kN-m
3\textsuperscript{rd} storey column moment at the top, $M_{ct-3} = 361$ kN-m
Beam moments at the top joint of 4\textsuperscript{th} storey:
4\textsuperscript{th} storey beam, $M_b_{4-4} = 467$ kN-m, $M_b_{4-2} = 407$ kN-m, $M_b_{4-3} = 288$ kN-m and $M_b_{4-4} = 353$ kN-m
Beam moments at bottom joint of 3\textsuperscript{rd} storey:
3\textsuperscript{rd} storey beam, $M_b_{3-1} = 487$ kN-m, $M_b_{2-3} = 456$ kN-m, $M_b_{3-3} = 433$ kN-m and $M_b_{4-3} = 408$ kN-m
The ratio of the sum of beam moments to the column moments at the top joint is
\[\frac{\sum M_b}{\sum M_c} = \frac{(467+407+288+353)}{(217+416)} = 2.39 > 1\]
Consider the ratio 2.39 since it is more than 1 as outlined in the method.

Strength of the column at the top joint = \( \frac{M_{c,3}}{H} \times \sum M_b = \frac{217}{3.05} \times 2.39 = 170 \text{ kN-m/m} \)

The ratio of the sum of beam moments to the column moments at the bottom joint is

\[ \sum M_b = \frac{(487+433+456+408)}{(400+361)} = 2.34 > 1 \text{, Consider the ratio 2.34 since it is more than 1 as outlined in the method.} \]

Strength of the column at the bottom joint = \( \frac{M_{c,3}}{H} \times \sum M_b = \frac{361}{3.05} \times 2.34 = 307 \text{ kN-m/m} \)

**Total column strength** = (170+307) = 477 kN-m/m

Check for Column strength (C2) in 3\(^{rd}\) and 4\(^{th}\) Storey

| Floor height (H) | 3.05m | 3.96m |
|------------------|-------|-------|
| **Column No. (C2)** | **At top of the column** | **At bottom of the column** | **At top of the column** | **At bottom of the column** |
| **Beam moments** (kN-m) | M\(_{b,3}\) | M\(_{b,3}\) | M\(_{b,3}\) | M\(_{b,3}\) |
| M\(_{b,4}\) | 407 | 361 | 407 | 445 |
| M\(_{b,2}\) | 400 | 408 | 439 | 425 |
| M\(_{b,3}\) | 433 | 456 | 419 | 419 |
| M\(_{b,4}\) | 388 | 400 | 361 | 593 |
| **Column moments** (kN-m) | M\(_{c,3}\) | M\(_{c,3}\) | M\(_{c,3}\) | M\(_{c,3}\) |
| M\(_{c,4}\) | 217 | 361 | 361 | 223 |
| **Ratio** \( \sum M_b / \sum M_c \) | 2.34 | 2.34 | 2.34 | 2.34 |
| **Strength (kN-m/m)** | 170 | 307 | 213 | 317 |

Total Strength as method I = 202 (kN-m/m)
Total Strength as method II = 477 (kN-m/m)

b) Column location = C2, 3\(^{rd}\) storey
Storey height, H = 3.96 m

Column moments at the top joint:
3\(^{rd}\) storey column moment at the top, M\(_{c,3}\) = 361 kN-m
4\(^{th}\) storey column moment at bottom, M\(_{b,4}\) = 400 kN-m

Column moments at bottom joint:
3\(^{rd}\) storey column moment at bottom, M\(_{c,3}\) = 593 kN-m
2\(^{nd}\) storey column moment at the top, M\(_{c,2}\) = 223 kN-m

Beam moments at the top joint of 3\(^{rd}\) storey:
3\(^{rd}\) storey beam, M\(_{b,3}\) = 487 kN-m, M\(_{b,2}\) = 456 kN-m, M\(_{b,3}\) = 433 kN-m and M\(_{b,4}\) = 408 kN-m

Beam moments at bottom joint of 2\(^{nd}\) storey:
2\(^{nd}\) storey beam, M\(_{b,2}\) = 445 kN-m, M\(_{b,2}\) = 425 kN-m, M\(_{b,3}\) = 419 kN-m and M\(_{b,4}\) = 439 kN-m

The ratio of the sum of beam moments to the column moments at the top joint is

\[ \sum M_b = \frac{(487+433+456+408)}{(361+400)} = 2.39 > 1 \text{, Consider ratio 2.39 as it is more than 1 as outlined in the method.} \]

Strength of the column at the top joint = \( \frac{M_{c,3}}{H} \times \sum M_b = \frac{361}{3.96} \times 2.34 = 213 \text{ kN-m/m} \)

The ratio of the sum of beam moments to the column moments at the bottom joint is
\[ \frac{\sum M_b}{\sum M_c} = \frac{(445+425+419+439)}{(593+223)} = 2.12 > 1 \text{, Consider ratio 2.12 as it is more than 1 as outlined in method.} \]

Strength of the column at the bottom joint = \[ \frac{M_{b,\text{res}}}{H} \times \frac{\sum M_b}{\sum M_c} = \frac{593}{3.96} \times 2.12 = 317 \text{ kN/m} \]

Total column strength = (213+317) = 530 kN/m

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16