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Review of Mitigation Measures for Vertical Stiffness-Strength Irregularities

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Abstract: Complex shaped and irregular buildings are getting popular in the present times, but they carry a high risk of sustaining damages during earthquakes. Past earthquakes has proven that the vertical structural irregularities tend to affect the seismic response of the structures. The study investigates these irregularities inherent in the buiding designs owing to the aesthetic and functional utilities. Studies show that the seismic performance can be regularized with the provision of suitable mitigation measures, analysis techniques and appropriate seismic design. The presence of these irregularities causes a significant increase in the structural costs and these may be optimized by introduction of suitable structural elements (e.g. shear walls, transfer girder etc.). The study focuses on the vertical stiffness-strength irregularities, and the several features in the buildings which induce these irregularities. The suggestions provided by the Indian seismic codes and different mitigation techniques for each of the features are discussed.

***Index Terms* - Vertical structural irregularity, Stiffness-strength irregularity, Seismic response, Mitigation measures, Building design, Seismic design**

1. INTRODUCTION

Structural irregularities are incorporated in the building design for both aesthetic and functionality benefits. The seismic response of the structure is varied by different irregularities. This difference in response is determined by the type and location of the irregularity in the structure (Naveen E, et al., 2019).

"An irregular structure can be any structure with non-uniform distribution of mass, strength, stiffness and structural configuration along elevation and plan, individually or in combination" (Sadashiva, et al., 2008). This causes sudden changes in the structural properties and irregular distributions of forces and deformations (Raja & Preetha, 2017).

"A building is termed as vertically irregular where the ratio of mass to stiffness in adjacent stories differs significantly." (FEMA, 2015).

The several types of vertical irregularities as defined by the Indian seismic code, IS 1893 Part I (2016), are listed in Table 1.

Most seismic design provisions were derived for buildings that have regular configurations, but earthquakes have shown repeatedly that buildings that have irregular configurations suffer greater damage (FEMA, 2015). Also, majority of the researches on irregular structures have concluded that irregularities are vulnerable to damages in seismic events and it is important to have simple and regular configurations as well as uniform load transmission along the building.

The term 'regularity' referred to in the seismic codes targets to obtain the appropriate solution to the seismic performance of the structures rather than to restrict the structures to uniform and monotonous buildings (Mezzi, et al., 2004).

The codes imposes regulations and penalties for the irregular buildings for the designs to be safe and the structure to withstand the earthquakes. These mitigation techniques may be increasing the size and reinforcement, adding new structural elements and increasing material strength etc. (LERİSOY, 2019).

The study aims to identify the several mitigation techniques practiced for different features inducing vertical irregularities in the buildings. In this direction, the probable seismic damages and vulnerability of the irregular structure can be identified and rectified earlier in the design phase. Hence, these irregularities can be easily incorporated in the structure without compromising seismic behaviour as well as structural costs (Naveen E, et al., 2019).

Table 1 Definition of Types of Vertical Irregularities
Adapted from (IS1893, 2016)

Sl. No.	Type of Vertical Irregularity	Parameter considered	Limit	
1.	**Strength Irregularity**	Storey Lateral Strength	< 80 %	Than that of the storey above.
2.	**Stiffness Irregularity**	Storey Lateral Stiffness		
	Soft Storey		< 70 %	Than that of the storey above.
	Extreme Soft Storey		< 60%	Than that of the storey above OR
			< 70 %	Average stiffness of the three storeys above
3.	**Mass Irregularity**	Seismic Weight	> 150 %	Than that of the storey above.
4.	**Vertical Geometric Irregularity**	Horizontal dimension of lateral force resisting system	> 125 %	Than that of the storey below.

2. SEISMIC VULNERABILITY OF VERTICAL IRREGULARITIES AND CODAL REQUIREMENTS

Majority of the past earthquake events across the globe have proven the vulnerability of the vertically irregular building frames (Bhosale, et al., 2018; Raja & Preetha, 2017), which increased the research attention on these structures.

According to IS 1893 Part I (2016), buildings of regular configurations along plan and elevation, perform better in the seismic events than the irregular buildings. Hence the code suggests to avoid the irregularities by varying the design and configurations in buildings located in highly seismic areas (IS1893, 2016 and FEMA, 2015).

If the irregularities are unavoidable in any cases, they must be designed as per the provisions provided in the IS 1893 Part I (2016) and IS 456 (2000), and the detailing should be according to IS 13920 (2016) (Kumar & Chakraborty, 2017).

Simple analysis methods, such as the Equivalent Lateral Force method, are not allowed to be used for the design of structures if the structure is irregular (Sadashiva, et al., 2012).

The collapse and failure of irregular buildings can be avoided by following two considerations in structural proportioning.

i. To avoid the irregularities.
ii. Designing the structure with special design provisions using dynamic analysis if the irregularity is unavoidable. The code also suggests to scale up the base shear obtained from the analysis (Sarkar, et al., 2010).

Dynamic analysis is required to be performed in the following conditions as per IS1893 (2016).
In case of regular buildings,

- If height > 40m in seismic zones IV and V
- If height > 90m in seismic zones II and III.

In case of irregular buildings,

- If height >12m in seismic zones IV and V.
- If height > 40m in seismic zones II and III.

It is also recommended for irregular buildings when height is less than 40m in seismic zones II and III, though not mandatory.

Design Based Earthquake is used to design the regular and uniform structures. Since the forces acting on the irregular structures can be greater than that of the Design Based Earthquake, ductility based design is more preferred (Bansal & Gagandeep, 2012). Earthquake resistant design of structures ensure that the building has required ductility to withstand the forces of earthquake.

3. VERTICAL STIFFNESS-STRENGTH IRREGULARITIES

The study of available researches on seismic performance of vertically irregular structures shows that different types of irregularities may be generated by similar features found in buildings. For example, presence of open ground storeys or difference in floor heights generate both stiffness and strength irregularities (Murty, et al., 2012; Sadashiva, et al., 2012; Rahman & Deshmukh, 2013). Kalibhat, et al. used setbacks to generate stiffness irregularity. Hence it can be inferred that presence of such features generate a difference in lateral stiffness and strength in the structure.

A comparative study of previous works on vertical irregularities concludes that changes in stiffness and strength cause detrimental increases in the seismic forces. Effect of combined stiffness-strength irregularities is found to be the most significant while strength irregularity is more dangerous than stiffness irregularity.

A change in a structural property is often accompanied by a change in any other properties. Hence stiffness and strength irregularities are often found together than individually in the structure.

Some of the most common features contributing to stiffness-strength irregularities in high-rise buildings are discussed in Table 2.

Table 2 List of features and irregularities induced

Sl. No.	**Contributing features**	**Discription/ Identification**	**Examples**	**Properties varying along vertical direction**		
				Stiffness	**Strength**	**Mass**
1.	Open storeys	Occurs due to absence/reduction in masonry infills in the particular floor	Stilt floors, Floors for car parking, Office Floors	✓	✓	
2.	Storey Height modification	Occurs due change in slenderness ratio of vertical elements in the particular floor	Lobbies, Service floors, Banquet Halls	✓	✓	
3.	Change in member properties	Occurs due to abrupt changes in member sizes (columns and shear walls) and material properties	Reduction in column sizes along height	✓	✓	
4.	Discontinous structural walls and floating columns	Occurs due to vertical members in the structure being discontinuous at particular floor	Stilt floors for car parking, Banquet Halls	✓	✓	
5.	Short Column Effect	Occurs due to restriction of movement of vertical members of particular floor	Mezzanine floors, Duplex floors, Plinth beams, Buildings on slope, Partial infills	✓	✓	
6.	Change in vertical configuration	Occurs due to changes in vertical geometric configurations	Setbacks and Stepbacks	✓	✓	✓

4. SUGGESTED MITIGATION MEASURES

The primary mitigation technique to eliminate the irregularities is to transpose the occurrence of plastic hinges on the beams instead of the columns during earthquakes (LERİSOY, 2019). The precautions for each of the features are as follows.

4.1 Open Storeys

The open floor configuration is an architectural design feature which is recognized to result in both soft and weak storey irregularities. The rigid non-structural components like the masonry, restrict the deformations of the columns (Guevara-Perez, 2012). When all unreinforced masonry (URM) infills are removed, the building is significantly weakened in that particular storey, but is strong in the other storeys owing to large contribution to lateral stiffness by the URM infills. Hence the absence of masonry infills induces a stiffness and strength irregularities in the elevation.

Figure 1 Damages to open/weak/soft storeys due to earthquakes
Source: (Khan & Rawat, 2016)

Methods suggested by Kumar & Chakraborty (2017) to avoid irregularities through open ground storeys are as follows.

- Provision of shear walls at open ground storey level without affecting the functionality, i.e., vehicle parking.
- Selection of alternative structural systems to provide earthquake resistance. A ductile frame is not an adequate choice when the number of panels in the ground floor which can be masonry filled is insufficient to offer required lateral stiffness and strength. In such cases, alternatives like RC shear wall is prefered.

Two of the measures are shown in Figures 1 and 2.

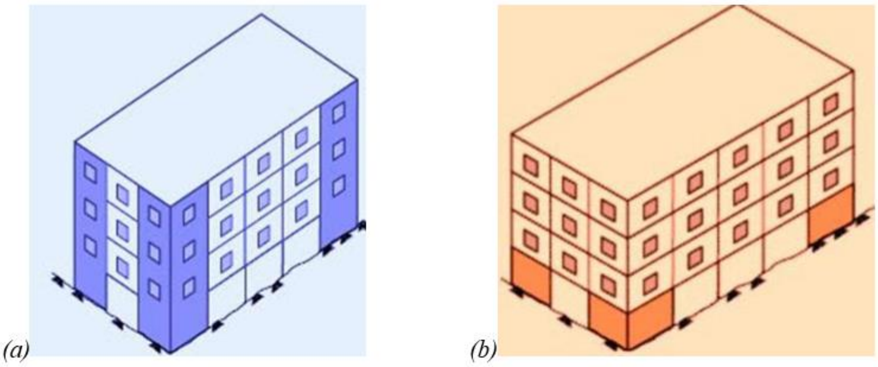

Figure 2 (a) Shear wall system, (b) Masonry wall system
Source: (Kumar & Chakraborty, 2017)

The special design provisions for the building structures with open storeys are as follows.

i. Conducting a dynamic analysis of the structure including the effects of masonry and the inelastic deformations;
ii. Analysing the structure without infills and the dynamic forces obtained in the elements of the open storey to be scaled up 2.5 times the storey shear and moments;
iii. Shear walls, which are designed for 1.5 times the storey shear, to be introduced in the open storey in both directions of the structure (Kumar & Chakraborty, 2017).

A summary of few solutions suggested by Guevara, L. T. and M. Paparoni, (1996) to deal with the weak/soft/open first storeys are as follows,

i. use of stiff and strong cores in the structure for elevators and staircases, to bear the base shear so that open story columns will have to take up only the axial loads;
ii. use of diagonals to increase the stiffness of the open story;
iii. designing the open story for larger value of loads and smaller displacements than the rest of the storeys;
iv. by making "transitions" where the "softness" is distributed in several stories (this is very delicate and needs careful tuning).

In case of existing buildings, the open storeys should be strengthened suitably so as to prevent collapse during earthquakes (Murty, et al., 2005).

4.2 Storey Height Modification

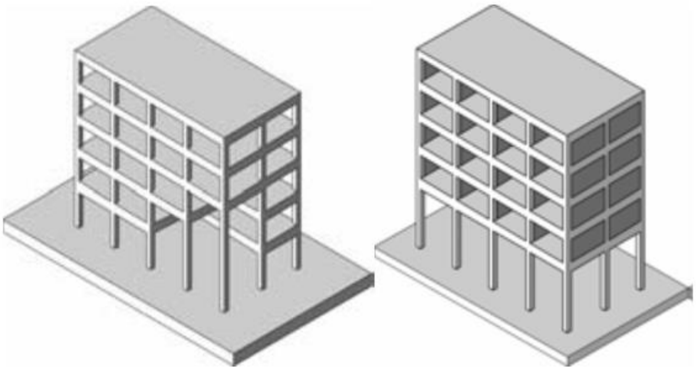

Figure 3 Modern building configuration with double height story
Source: (Guevara-Perez, 2012)

The modification in the floor height generates a difference in the flexibility and stiffness of the columns of that particular floor. Increase in height induces an increase in flexibility and decrease in height results in a decrease in flexibility (Guevara-Perez, 2012).

Large slenderness ratio is not desirable in buildings since they are expected to sway laterally during earthquakes and induces excessive lateral displacements (Murty, et al., 2012). Large lateral displacements causes significant structural and non-structural damages; also second-order P-Δ effects that lead to building collapse.

The seismic design code suggests the interstorey drift to be restricted to 0.4 percent of the height of the floor as a mitigation technique for this irregularity (IS1893, 2016; Murty, et al., 2012). Moreover, the reinforcements of the columns and shear walls in the open story can be rearranged to reduce horizontal loads (LERİSOY, 2019).

4.3 Change in Member Properties

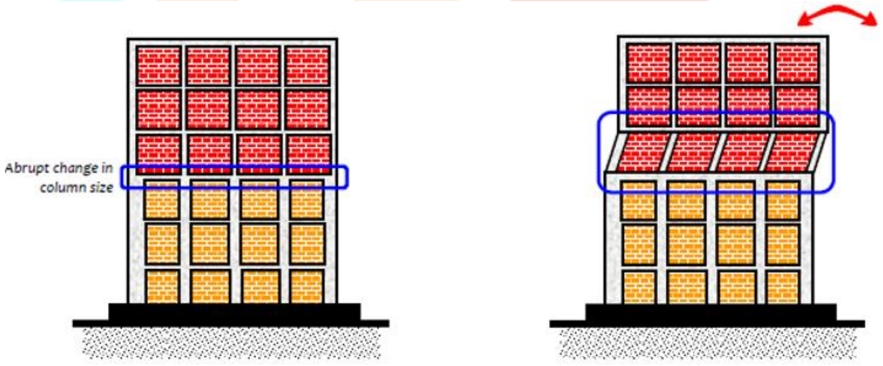

Figure 4 Stiffness-strength irregularity due to change in member sizes
Source: (Murty, et al., 2012)

A significant number of buildings are found to have changes in their member and material properties in the top storeys. Reduction in the column sizes is one of such features found in high-rise buildings. Member properties may also vary because of the composite structural systems adopted. The basic precaution to be taken is to ensure sufficient stiffness and strength at the storeys with the irregularity.

4.4 Short Column Effect

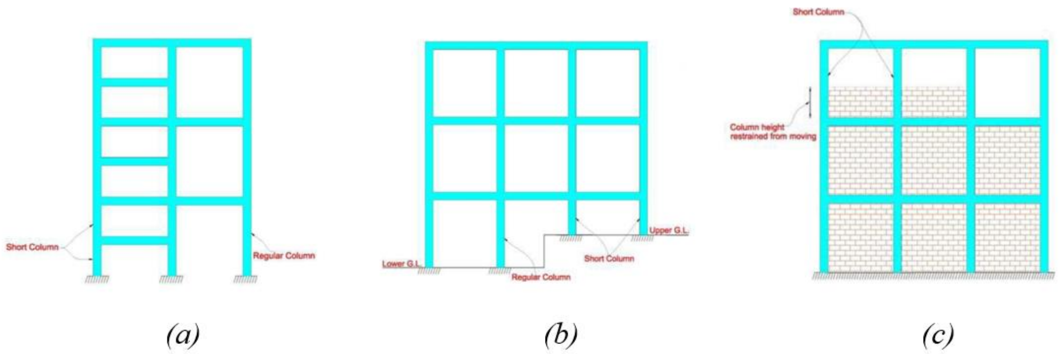

Figure 5 Short columns due to (a) staircase landing beams; (b) tructures in slopes; (c) partial masonry infills
Source: (Anon., n.d.)

A column can be said to act as a 'short column' when its effective length is divided into smaller portions at the interface (Kheyroddin & kargaran, n.d.).

Short columns are more vulnerable in earthquakes due to the fact that the high stiffness in these columns attracts higher earthquake forces than the regular columns in structure (Anon., n.d.). Moreover, the displacements of a short column is same as that of a tall column with the same cross-sectional area (Murty, et al., 2005). Hence, the short columns require an adequate seismic design to sustain the increased earthquake forces and to avoid shear failure (Arjun, n.d.).

As per the seismic codes, short column effect should be eliminated during the design phase of the building. If the short columns are not avoidable, they must be considered in the structural and seismic design. IS 13920 (2016) recommends special confining reinforcement (closely spaced closed ties to be provided along the full height of the probable short columns, and they must extend vertically beyond the columns to a certain distance as shown in Figure 6 (Murty, et al., 2005).

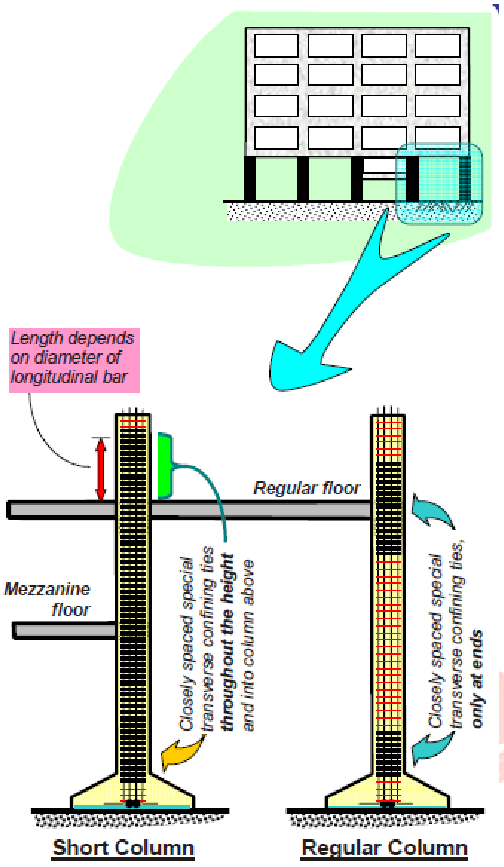

Figure 6 Short column detailing as per IS 13920:2016
Source: (Murty, et al., 2005)

Some practical recommendations to eliminate the short column effect due to partial infills, suggested by Cagatay, et al., (2010) are as follows,

- In cases where the short columns cannot be avoided, the modern seismic codes state that the shear force used for calculation of transverse reinforcement should be obtained by considering the short column effect.
- Short column effect due to partial infills may be eliminated by separating the walls from the bounding structural frame with an adequate gap to allow the column to bend (Cagatay, 2005). But this can lead to out of plane failure of the column because of the lack of rigidity along the axis perpendicular to the face of the wall (Kadsiewski and Mosalam 2008). Incorporation of a steel beam with U-shaped section between the frame and wall can avoid this failure as well as allow the bending of the columns (Cagatay, 2005).
- Another technique is to decrease the shear force in the columns by reducing the opening width adjacent to the short columns (Pineda, 1994).

The short columns in the existing buildings must be strengthened using any of the suitable retrofitting techniques (Murty, et al., 2005).

4.5 Floating Columns

Floating columns and discontinous structural walls may be defined as those vertical members which are not connected to the foundation (Figure 7). Their lower ends rest on beam which is a horizontal member, this beam transfer the load of floating column to other columns below it (Maitra & Serker, 2018).

Floating or discontinous columns introduces sudden variations in the lateral stiffness and lateral strength along the elevation of RC buildings. The seismic response of such structures can be improved by either of the following methods,

i. Strengthening of the columns in the ground storey (local modification),
ii. Reducing the seismic demand by “supplemental energy dissipation mechanisms” (global modification) (Gowda & Tajoddeen, 2014).

Local modification methods like jacketing, steel caging and bracings can be used for dissipation of energy in the global modification methods.

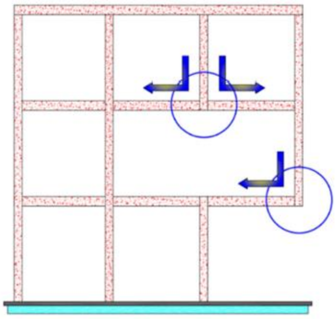

Figure 7 Discontinous structural walls and floating columns
Source: (B & K, 2014)

4.6 Change in Vertical Configurations

These buildings are characterised by “staggered abrupt reductions” or additions in floor area along the building height, with “consequent variations in strength, stiffness and mass” (at same or different rates) as in Figure 8 (Sarkar, et al., 2010).

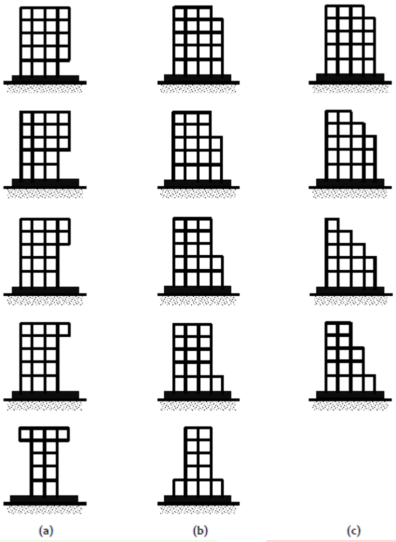

Figure 8 (a) Setback buildings; (b) and (c) Stepback buildings
Source: (Murty, et al., 2012)

The results from the literatures contradict in the case of changes in vertical configurations. While it is shown that it causes a maximum increase in the seismic parameters (Naveen E, et al., 2019), other researches (Md. Akberuddin & Mohd. Saleemuddin, 2013; Shelke & Ansari, 2017) state that lateral load capacity increases with reduction in number of bays. Hence it can be inferred that vertical geometric irregularities have a potential to improve the seismic response of the structure. This may be because of the reduction in stiffness and as well as floor mass along the elevation for vertically geometric irregular buildings when compared to similar regular buildings. Displacement increases with reduction in stiffness but reduction in mass attracts lesser forces and thereby reduces displacement.

Mitigation measures suggested for the feature is to analyse the structure using dynamic analysis and appropriate seismic design as per the codes.

5. CONCLUSION

The presence of irregularities in the building structures creates a gap, break or bending of the load transmission path. This causes localisation of stresses at these points and failure at that particular location. Major seismic codes as well as past earthquake events suggest to avoid the structural irregularities whenever possible so as to avoid damages and collapse of the buildings.

However, when these irregularities are unavoidable, the weak points in the structures should be predicted and proper mitigation techniques should be incorporated. In this paper, the various suggested measures for the features inducing vertical stiffness-strength irregularities are discussed. Performance evaluation and suitability of these mitigation measures are out of the scope of this paper.

The seismic vulnerability of the irregular features and their solution measures should be acknowledged early in the design phase, since it will not be possible to optimize the cost impact of these irregularities in the later phases. Structural irregularities, if considered properly, have a high scope in reduction of costs of structures in the high seismic areas.

The study concludes that the irregular structures should be addressed according to the codal provisions, integrating the practical engineering knowledge with the creative thoughts of architects.

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