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Review of Performance of Existing Vertical Irregularity Indicators for Steel Framed Buildings

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Abstract

Due to architectural compulsions, buildings invite various types of irregularities due to which seismic performance of them is highly affected. With increase in such type of buildings, it is important to know the extent to which an irregularity could be introduced without causing any major damage to the structure. Different kinds of Irregularity indices are used by many previous studies for quantifying the vertical irregularities in buildings. This study discusses about the previous irregularity indicators and an attempt is made to evaluate their effectiveness to predict the seismic risk of irregular buildings. Steel buildings having various kinds of vertical irregularities such as mass, stiffness and/or strength are considered in this study and their seismic risks is evaluated. Pearson r correlation methodology is considered for correlating the irregularity indicators and the associated seismic risks and conclusions are drawn from them.

Keywords: Irregularity index; seismic risk; correlation coefficient

Introduction

Multi-storey buildings are being generally constructed with unequal distribution of mass, stiffness and strength due to functional and architectural reasons. The buildings having unequal distribution of irregularity of mass/stiffness/strength individually or in combination across the height are called vertically irregular buildings. It has been reported by many previous studies [1-5] that the performance of these types of buildings is poor as compared to that of regular buildings.

Seismic design criteria have been provided for vertically irregular buildings in various inter-national codes. However, many studies report the parameters mentioned in the codes for the quantification of irregularity exists in a building needs improvement. Previous studies [4-7] have proposed the regularity indices for quantifying the vertical irregularity based on the modal parameters or geometric parameters. It is to be noted that all the previous studies on the parameters used for quantification of irregularity in buildings were focussed on the seismic performance of vertical irregular RC buildings.

The purpose of this paper is to check whether the existing irregularity indices can capture the vertical irregularities in the steel framed buildings. This research focusses on the performance of existing vertical irregularity indices by checking the correlation of them with the seismic risk of the selected vertically irregular buildings. The seismic risk is evaluated by following the procedure proposed by [8].

Detailing of the building considered

A seven storey steel framed building having uniform distribution of mass and stiffness considered as a regular building is taken for reference. The steel framed building is assumed to be situated in a location of seismic zone with PGA = 0.16g (Zone- III). Plan and elevation of the selected buildings are shown in Fig. 1. The sections of beams and columns are design according to [9] and details of those sections are mentioned in Table-1. Thickness of the floor slab is assumed to be concrete of 120 mm [10] which is resting on the steel beams.

Typical buildings with mass and a stiffness/strength irregularity are considered in this study. Mass irregular buildings are modelled by considering a swimming pool or a storage place at the top and intermediate storeys. The seismic weight of the additional mass at a selected floor in a building is taken to be in the range of 500%-700% of the seismic weight of a typical floor. A mass irregular building with a mass of 5 times of mass of typical floor level, at 4th floor level is denoted as M5-4. Similarly, M7-4 frame indicates a mass irregular frame having 7 times of the typical mass at 4th (intermediate) floor level. The performance of mass irregular buildings is evaluated with reference to a regular building (M-R) having uniform masses in all storeys.

For studying the behavior of stiffness/strength irregular buildings, a regular reference building (SI- R) is taken in which the lateral stiffness/strength at each storey (cross bracings are provided on each storey) is equal (uniform in all storeys). Stiffness/strength irregularity or discontinuity in vertical direction is introduced by considering a bays without any bracings in a particular storey. SI-1-O represents a stiffness/strength irregular building frame having ground storey (index '1' stands for first storey) as an an open ground storey (index 'O' for open storey). SI-M-O depicts the frame with no bracings at 3rd and 4th storeys, SI-4-O depicts frame with no bracings at 4th storey and SI-7-O depicts the frame with no bracings at 7th storey. Fig. 2 shows detailing of all the vertical irregular buildings.

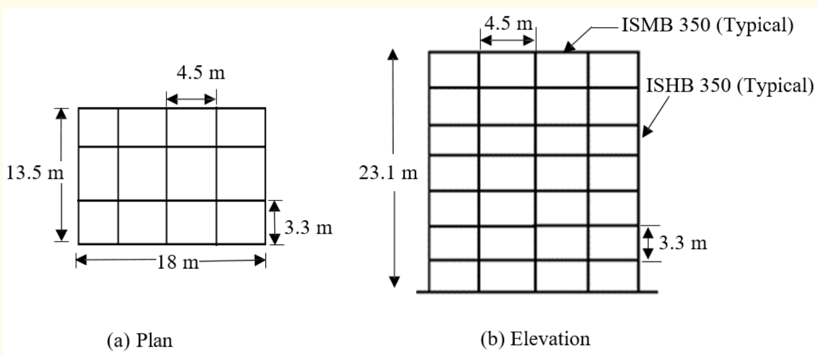
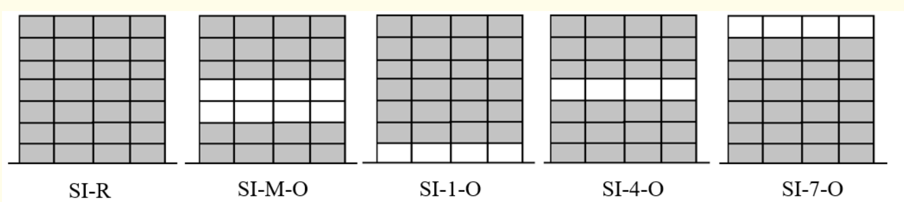


Figure 1: (a) Plan of building considered (b) Elevation of building considered.



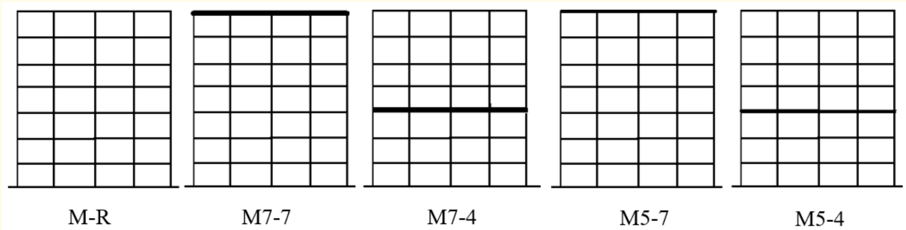


Figure 2: Selected Stiffness and Mass irregular steel framed buildings.

Frame	***Column Section***	***Beam Section***
M-R	ISHB 350	ISMB 350
M7-7	ISHB 400	ISMB 300
M4-7	ISHB 400	ISMB 300
SI-R	ISHB 350	ISMB 350
SI-I-O	ISHB 250	ISMB 300
SI-7-O	ISHB 350	ISMB 350
SI-4-O	ISHB 250	ISMB 300
SI-1-O	ISHB 300	ISMB 300

Table 1: Different type of sections.

Regularity Index

Various regularity indices have been proposed by many previous studies to quantify the irregularity of a building as shown in Table 2. Out of selected approaches, [4] proposed the index which was focussed on steel setback framed buildings. Indices proposed by [5] and [6] was based on modal participation factor and the frequency of the building respectively. [7] proposed the regularity index based on the ratio of maximum inter - storey drift of an irregular and regular building from elastic analysis. The regularity index proposed by [4] is not included in this study as it deals with only geometric irregular buildings. It can be noted that regularity index of a regular frame will be unity and as the irregularity increases the regularity index decreases.

References	***Building type***	***Proposed regularity indices***
[5]	RC stepped frame	$\eta = \frac{\Gamma_1}{\Gamma_{ref}}$
[6]	RC setback frame	$\lambda_r = \sum_{k=1}^{N} \frac{\omega_{k,ir}}{\omega_{k,r}}$
[7]	RC framed building	$SVI = \frac{Max(ISD_{IR})}{Max(ISD_R)}$

Table 2: Proposed irregularity indicators from previous studies.

Probabilistic Seismic Risk Assessment Methodology and Modelling for non-linear dynamic analysis

The current study evaluates the vulnerability of the selected vertically irregular frames by following an accepted methodology proposed by [8]. It uses a Probabilistic seismic demand model (PSDM), which is a relationship between PGA and median of the maximum inter-storey drifts (ISD) recorded fromthe nonlinear dynamic time history analysis.

The beams and columns of all the selected frames were modelled in OPENSEES laboratory tool [11] using the fiber element modelling approach for performing nonlinear time history analysis. An ensemble of 44 ground motions whose PGA ranging from 0.1g to 1.0g was used for the time history analysis. The parameters, yield strength of steel and global damping ratio, were taken as random variables. Values of mean and coefficient of variation of the random variables are shown in Table-3. An accepted methodology Latin hypercube sampling method (LHS) considered by [3], [7] and [12] was used to generate 44 samples of random variables and accordingly computational models are developed using these realizations of the random samples representing the building frames. Nonlinear dynamic time history analyses of the computational models are done to record the maximum inter- storey drift from each of the building models. A graph between the parameters, PGA and ISD is plotted to obtain the PSDM model as shown in Fig. 3. It can be seen that SI-1-O shows the highest inter-storey drift whereas the SI-R is having the lowest one. The PSDM obtained from all the models is shown in Table 4.

Material	***Mean***	***COV (%)***	***Source***
Yield Strength of Steel	250 MPa	10	Ranganathan (1999)
Global Damping Ratio	5%	40	Davenport and Carroll (1986)

Table 3: Random variables considered.

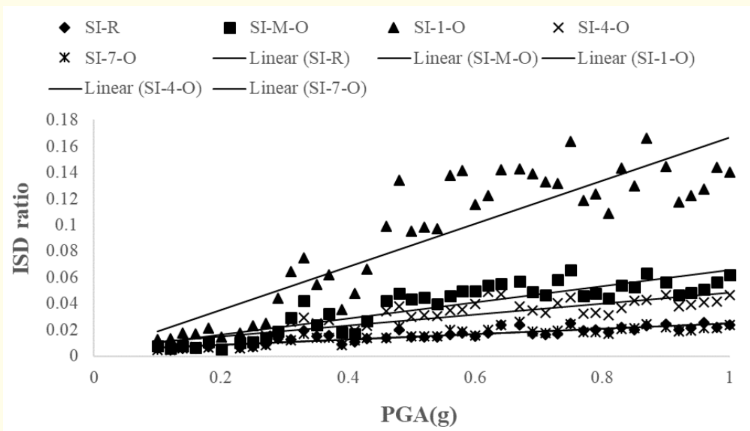


Figure 3: PSDMs for all models.

Frame	***PSDM***	R^2	***βD/PGA***
SI-R	$0.0248(PGA)^{0.7336}$	0.7854	0.1996
SI-M-O	$0.0715(PGA)^{1.1148}$	0.7788	0.2894
SI-1-O	$0.1857(PGA)^{1.2386}$	0.7882	0.2833
SI-4-O	$0.0508(PGA)^{0.8959}$	0.7597	0.2357
SI-7-O	$0.025(PGA)^{0.7519}$	0.7471	0.2014

Table 4: PSDM model and measure of dispersion.

Correlation of Proposed Regularity Indicators and Probability of Unacceptable Performance

As the vertical irregularity in a frame increases the irregular frame is more likely to perform poorly. In other words, probability of unacceptable performance (failure) of irregular frames also increases with amount of irregularity. In order to study the performance of the existing irregularity indicators, correlation of the existing indicators with the probability of unacceptable seismic performance (P_{PL} at various performance levels, IO, LS and CP) of the vertically irregular buildings has been calculated as shown in Table 5 and 6. It can be noted that the order the frames in the increasing value of P_{PL} respectively for stiffness irregular and mass irregular frames are SI-7-O < SI-R < SI-M-O < SI-4-O < SI-1-O and M-R < M7-4 < M5-4 < M5-7 < M7-7.

In case of stiffness irregular frames, the vertical irregularity increases in the order SI-1-O < SI-R < SI- 7-O < SI-4-O < SI-M-O for [5], SI-R-O < SI-7-O < SI-4-O < SI-M-O < SI-1-O for [6] and SI-R < SI-7-O < SI-4-O < SI-M-O < SI-1-O for [7].

In case of mass irregularity, the vertical irregularity increases in the order M-R = M5-4 < M7-7 < M7- 4 < M5-7 for [5], M-R = M5-7 < M7-7 < M5-4 < M7-4 for [6] and M7-4 < M5-4 < M7-7 < M5-7 < M-R for [7].

Figs. 4 and 5 show the correlation between the probability of failure and irregularity index for stiffness and mass irregular frames respectively. In case of stiffness irregular frames, it can be observed that correlation coefficient is positive for the indices proposed by [6] and [7] whereas it is negative for the index proposed by [5]. In case of mass irregular frames, correlation coefficient is negative for both [5] and [6] but positive for [7].

		Existing Irregularity Index as per			***Annual Probability of collapse PPL (x10^{-3})***	
Frame	[5]	[6]	[7]	IO	LS	CP
SI-R	1	1	1	6.16	1.52	0.97
SI-M-O	1.10	1.47	2.6	12.41	4.94	3.67
SI-1-O	0.925	1.85	6.6	29.14	12.72	9.74
SI-4-O	1.041	1.204	1.92	13.79	4.38	3.03
SI-7-O	1.01	1.030	1.04	5.93	1.51	0.97

Table 5: Comparison of existing irregularity indices with annual Probability of unacceptable performance, P_{PL} for stiffness irregular buildings.

		Existing Irregularity Index as per			***Annual Probability of collapse PPL (x10^{-3})***	
Frame	[5]	[6]	[7]	IO	LS	CP
M-R	1	1	1	2.3	1.13	0.9
M7-4	1.063	1.069	0.935	2.36	1.12	0.88
M7-7	1.010	1.02	0.979	6.94	2.53	1.83
M5-4	1	1.03	0.963	2.42	1.15	0.9
M5-7	1.123	1	0.98	3.14	1.4	1.08

Table 6: Comparison of existing irregularity index with annual Probability of collapse P_{PL} for mass irregular buildings.

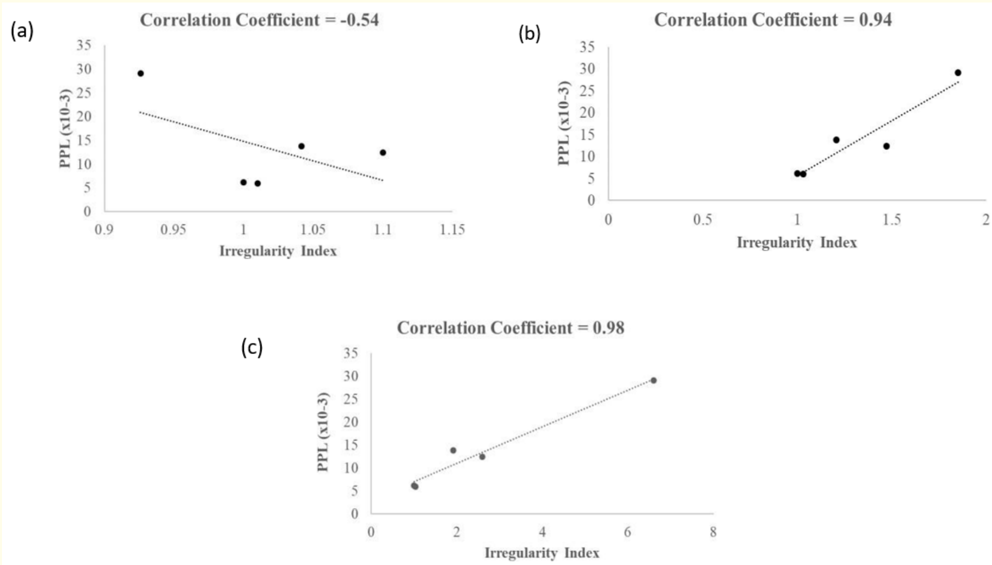


Figure 4: Correlation between Irregularity Index and PPL for: (a) [5]; (b) [6]; and (c) [6] at IO level.

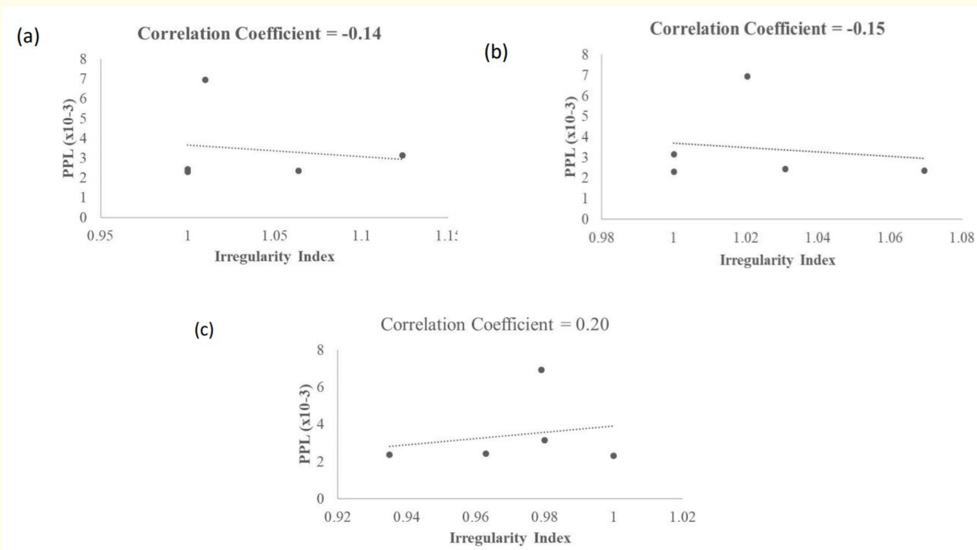


Figure 5: Correlation between Irregularity Index and PPL for: (a) [5]; (b) [6]; and (c) [6] at IO level.

Conclusions

Various indicators are used in existing literature to quantify the vertical irregularities in buildings. Focus of the present study is to evaluate the adequacy of the existing irregularity indicators to quantify the irregularity in selected vertically irregular steel framed buildings. Correlation between the existing indicators with the seismic risk of the selected buildings are considered and the following conclusions are made.

- Regarding seismic risk, the frames SI-1-O and M7-7 are found to be the most vulnerable when compared to respective regular buildings.
- In case of stiffness irregular framed buildings, it has been observed that the behavior of SI-7-O is very much similar to that of a regular building and hence irregularity caused by reducing the stiffness of a top storey is not much harmful during earthquake. In case of mass irregular building frame, it has been observed that the seismic risk is reduced to a far extent when swimming pool is provided at an intermediate storey rather than at top storey. The behavior of this frame is similar to that of a regular building.
- It is found that existing irregularity indicators proposed by [6] and [7] perfectly correlates with the seismic risk.
- In case of mass irregular framed buildings, the indicators proposed by [7] is correlating well with the seismic risk.

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