Structural Monitoring and Maintenance, *Vol. 11, No. 2 (2024) 101-126*
https://doi.org/10.12989/smm.2024.11.2.101

A novel approach for the definition and detection of structural irregularity in reinforced concrete buildings

S.P. Akshara*[1], M. Abdul Akbar[1a], T.M. Madhavan Pillai[1b],
Renil Sabhadiya[2c] and Rakesh Pasunuti[3d]

[1]Department of Civil Engineering, National Institute of Technology Calicut, Kozhikode-673601, India
[2]KEC International, RPG centre, 30, Forjet street, near Bhatia hospital, Tardeo, Mumbai, India
[3]L&T Construction, Mount Poonamallee road, Manapakkam, P.B. No. 979, Chennai, India

(*Received May 4, 2024, Revised June 12, 2024, Accepted June 18, 2024*)

Abstract. To avoid irregularities in buildings, design codes worldwide have introduced detailed guidelines for their check and rectification. However, the criteria used to define and identify each of the plan and vertical irregularities are specific and may vary between codes of different countries, thus making their implementation difficult. This short communication paper proposes a novel approach for quantifying different types of structural irregularities using a common parameter named as unified identification factor, which is exclusively defined for the columns based on their axial loads and tributary areas. The calculation of the identification factor is demonstrated through the analysis of rectangular and circular reinforced concrete models using ETABS v18.0.2, which are further modified to generate plan irregular (torsional irregularity, cut-out in floor slab and non-parallel lateral force system) and vertical irregular (mass irregularity, vertical geometric irregularity and floating columns) models. The identification factor is calculated for all the columns of a building and the range within which the value lies is identified. The results indicate that the range will be very wide for an irregular building when compared to that with a regular configuration, thus implying a strong correlation of the identification factor with the structural irregularity. Further, the identification factor is compared for different columns within a floor and between floors for each building model. The findings suggest that the value will be abnormally high or low for a column in the vicinity of an irregularity. The proposed factor could thus be used in the preliminary structural design phase, so as to eliminate the complications that might arise due to the geometry of the structure when subjected to lateral loads. The unified approach could also be incorporated in future revisions of codes, as a replacement for the numerous criteria currently used for classifying different types of irregularities.

Keywords: axial load; plan irregularity; structural irregularity; tributary area; unified identification factor; vertical irregularity

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*Corresponding author, Ph.D. Student, E-mail: akshara_p210035ce@nitc.ac.in
[a] Assistant Professor, E-mail: maa@nitc.ac.in
[b] Professor, E-mail: mpillai@nitc.ac.in
[c] Assistant Manager, E-mail: sabhadiyar@kecrpg.com
[d] Senior Design Engineer, E-mail: pasunuti.rakesh@lntecc.com

http://www.techno-press.org/?journal=smm&subpage=7 ISSN: 2288-6605 (Print), 2288-6613 (Online)

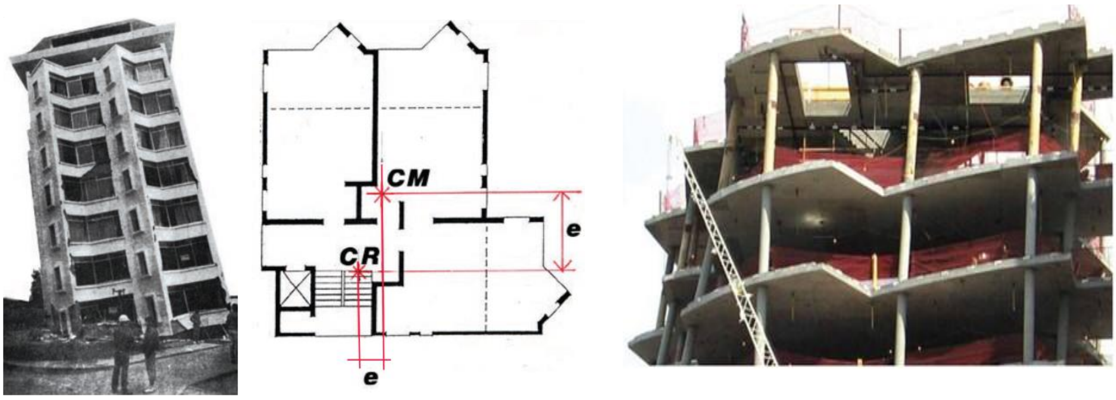
1. Introduction

There is an increasing demand for asymmetric/irregular buildings due to obvious reasons such as aesthetic and utility considerations. However, seismic codes across the world insist on eliminating irregularities by modifying architectural planning and structural configurations. According to reports on past earthquakes such as the 1985 Mexican earthquake by Esteva (1987) and the 1994 Northridge earthquake by Mitchell *et al.* (1995), large portions of the structures that failed were characterized by significant irregularities. Moreover, the collapse probability of buildings with plan or vertical irregularities has been found to be higher than that of regular buildings (Mouhine and Hilali 2022a, 2022b, Ghanem *et al.* 2024). A few buildings with structural irregularity, including those that were severely damaged during past earthquakes are shown in Figs. 1 and 2.

The design and response of asymmetric buildings under earthquake excitations has been an active area of research for long. Initially, most studies considered only the elastic response of buildings. However, studies shifted from elastic to inelastic response of systems following the contributions made by Goel and Chopra (1991) who evaluated the inelastic response of one-storey systems. Valmundsson and Nau (1997) studied the seismic behaviour of two-dimensional multi-storied buildings having mass, stiffness and strength irregularities, and observed that reducing the strength of the first storey by 20% increased the ductility demand by 100-200%. Even though numerical studies have expanded to multi-storey structures with the aid of finite element software capable of non-linear modelling, the predicted results are greatly influenced by the modelling assumptions. Researchers have carried out numerical and experimental studies on various types of irregularities (Chunyu *et al.* 2012, Bosco *et al.* 2015, Haque *et al.* 2016, Abdel Raheem *et al.* 2018, Firoj and Singh 2018, Habibi *et al.* 2019, Ahmed *et al.* 2021, Vielma-Quintero *et al.* 2024) and it has been concluded that during an earthquake, damage/failure starts from the weakest points that arise due to the irregularities in the structure (Ravikumar *et al.* 2012).

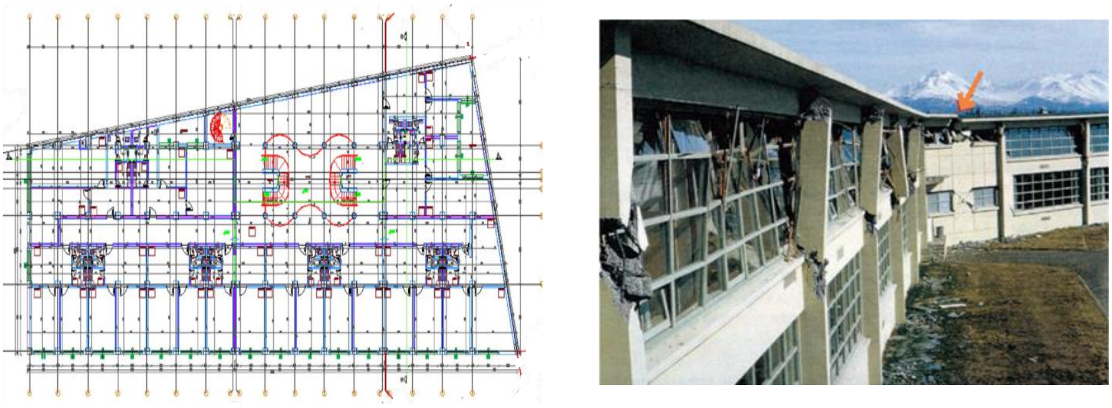
Although a structure may possess a combination of irregularities, most studies in the past have focussed on a single irregularity, which may not result in an accurate prediction of seismic response. In this regard, Naveen *et al.* (2019) studied the seismic response of reinforced concrete structures possessing single irregularity/various combinations of irregularities. It was observed that although the presence of a single irregularity amplified the seismic response, a combination of certain irregularities such as re-entrant corners and vertical geometric irregularities showed less displacement response. Wang *et al.* (2018) carried out seismic risk analysis on an industrial building and identified that a combination of mass and vertical irregularities increased the collapse risk. Hence, the influence of a particular irregularity on the seismic response of a building may be attributed to several factors including the size or proportion of the irregularity, its location in the building, presence of other irregularities, etc. (Nady *et al.* 2022). Experiences from past earthquakes have prompted design codes to incorporate separate provisions on structural irregularity. However, the parameters considered for plan and vertical irregularities by various codes across the world may be same or different, as shown in Table 1. In certain codes like the European seismic code, EN 1998-1 (2004), most of the criteria for classifying buildings as regular are qualitative (Alecci *et al.* 2019).

The current guidelines on structural irregularity across the world consider a building model to be simple and assume one irregularity at a time. Moreover, frequent revisions and amendments of the guidelines and their lack of clarity have made it difficult for engineers and analysis software to check for each of the irregularities and avoid them in real projects. For instance, the torsional



Failure of apartment building in Vina del Mar, Chile due to torsional irregularity, 1985 Mexican earthquake (Wood *et al.* 2002)

Building with excessive cut-outs (Portland Cement Association 2006)



Plan with non-parallel lateral force system, damaged during 2011 Van earthquake (Bikçe and Celik 2016)

Concrete roof of a high school damaged due to stress concentration at re-entrant corner, 1964 Alaska earthquake (FEMA 454 2006)

Fig. 1 Examples of plan irregularity

irregularity guidelines of IS 1893-Part 1 (2016) are defined in terms of the maximum and minimum displacements at the two ends of a building. However, for buildings without definite edges, the criterion may not be appropriate. Similarly, buildings with excessive cut-outs are defined using a single cut-out which is regular in shape. In actual scenario, the shape of the cut-out may vary in addition to being scattered in plan. Furthermore, researchers have pointed out the inadequacy of seismic codes with respect to the provisions of structural irregularity. For example, the validity of torsional irregularity provisions of different seismic codes has been controversial for quite long and researchers have pointed out deficiencies associated with the drift-based and displacement-based torsional irregularity criteria (Ozhendekci and Polat 2008, Ozmen *et al.* 2014, Anagnostopoulos *et al.* 2015, Zhang *et al.* 2016, Alecci *et al.* 2019, Athanatopoulou and Manouka 2021, Alaa *et al.* 2022, Akshara *et al.* 2024). Nevertheless, most seismic codes continue with the existing formulations.

Collapse of half portion of Mansi complex due to presence of massive swimming pool at 10th floor, 2006 Bhuj earthquake (Agarwal and Shrikhande 2011)

Failure of Olive View Hospital due to vertical geometric irregularity, 1971 San Fernando earthquake (FEMA 454 2006)

Damage of apartment due to floating columns, 2006 Bhuj earthquake (Agarwal and Shrikhande 2011)

Collapse of ground floor of apartment due to soft storey, 2006 Bhuj earthquake (Agarwal and Shrikhande 2011)

Fig. 2 Examples of vertical irregularity

In order to reduce the complexity associated with the numerous parameters and criteria for the seismic analysis and design of irregular buildings, Archana and Akbar (2021) pointed out that similar to permissible range of values existing for vital signs in a human body (such as body temperature, pulse rate, respiratory rate, blood pressure), a range of values could be identified after the finalization of vital signs in buildings (Fig. 3). Nevertheless, common parameters to define and detect irregularities in buildings have not yet been established. Therefore, the purpose of this paper is to propose a simplified approach for the definition and detection of structural irregularity in buildings, which could be adopted by seismic codes across the world as a replacement of the numerous guidelines that exist at present. A parameter named as unified identification factor (UIF) is defined to distinguish columns that are in close proximity of irregularities, which may result in unfavourable seismic behaviour. As a result, columns with extreme values of UIF can be identified

Table 1 Parameters considered for structural irregularity by different codes

		Type of irregularity and parameter	ASCE 7-16/ USA	BNBC: 2017/ Bangladesh	EN 1998-1: 2004/ Europe	GB 5001: 2010/ China	IS 1893 (Part 1): 2016/ India	KBC: 2009/ Korea	NBC 105: 2020/ Nepal	NBC: 2020/ Canada	NEHRP 2020/ USA	NSCP: 2010/ Philippines	SI 413: 1995/ Israel	TSC: 2007/ Turkey	UBC: 1997/ USA
Plan irregularity	a.	Torsional irregularity													
		Displacement	-	✓	-	-	✓	-	✓	✓	-	-	✓	-	-
		Storey drift	✓	✓	-	✓	-	✓	-	-	✓	✓	-	✓	✓
		Torsional frequency	-	-	-	-	✓	-	-	-	-	-	-	-	-
		Eccentricity and torsional radius	-	-	✓	-	-	-	-	-	-	-	-	-	-
	b.	Re-entrant corners													
		Dimension of projection	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	✓	✓
	c.	Cut-out irregularity (diaphragm discontinuity)													
		Area of openings	✓	✓	-	✓	✓	✓	✓	-	✓	✓	-	✓	✓
		Diaphragm stiffness	✓	✓	-	✓	-	✓	✓	-	✓	✓	-	✓	✓
	d.	Out of plane offsets in vertical elements													
		Out of plane offsets of walls/ frames along building height	✓	✓	-	-	✓	✓	✓	✓	✓	✓	-	-	✓
	e.	Non-parallel lateral force system													
		Orientation of lateral force resisting systems	✓	✓	-	-	✓	✓	✓	✓	✓	✓	-	-	✓
Vertical irregularity	a.	Stiffness irregularity (soft storey)													
		Lateral stiffness	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	-	✓
		Storey drift	-	-	-	-	-	-	-	-	-	-	-	✓	-
	b.	Mass irregularity													
		Effective mass of storey	✓	✓	-	-	-	✓	✓	-	-	✓	✓	-	✓
		Seismic weight	-	-	-	-	✓	-	-	✓	-	-	-	-	-
	c.	Vertical geometric irregularity													
		Horizontal dimension of lateral force resisting systems	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	-	✓
	d.	In-plane discontinuity in vertical elements													
		In plane offset of lateral force resisting elements	✓	✓	-	-	✓	✓	✓	✓	✓	✓	-	✓	✓
		Lateral stiffness	-	-	-	-	-	✓	-	✓	-	-	-	-	-
	e.	Strength irregularity (weak storey)													
		Lateral strength of storey	✓	✓	-	-	✓	✓	✓	-	✓	✓	-	-	✓
		Inter-storey shear capacity	-	-	-	✓	-	-	-	✓	-	-	✓	-	-
		Effective shear area	-	-	-	-	-	-	-	-	-	-	-	✓	-
	f.	Irregular modes of oscillation													
		Mass participation factor	-	-	-	-	✓	-	-	-	-	-	-	-	-
		Fundamental lateral natural period	-	-	-	-	✓	-	-	-	-	-	-	-	-

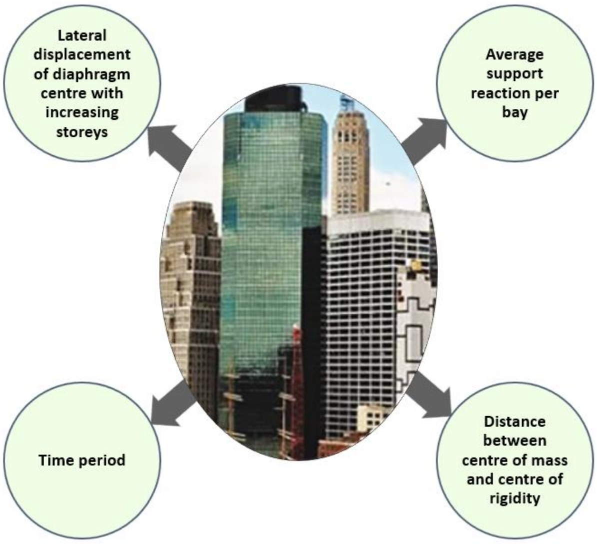


Fig. 3 Vital signs proposed by Archana and Akbar (2021) for quantifying irregularities in buildings

and subsequently, the designer can modify the structural configuration in those locations, in order to bring the UIF values to the desired range. The proposed parameter will thus help in eliminating critical irregularities prior to detailed design.

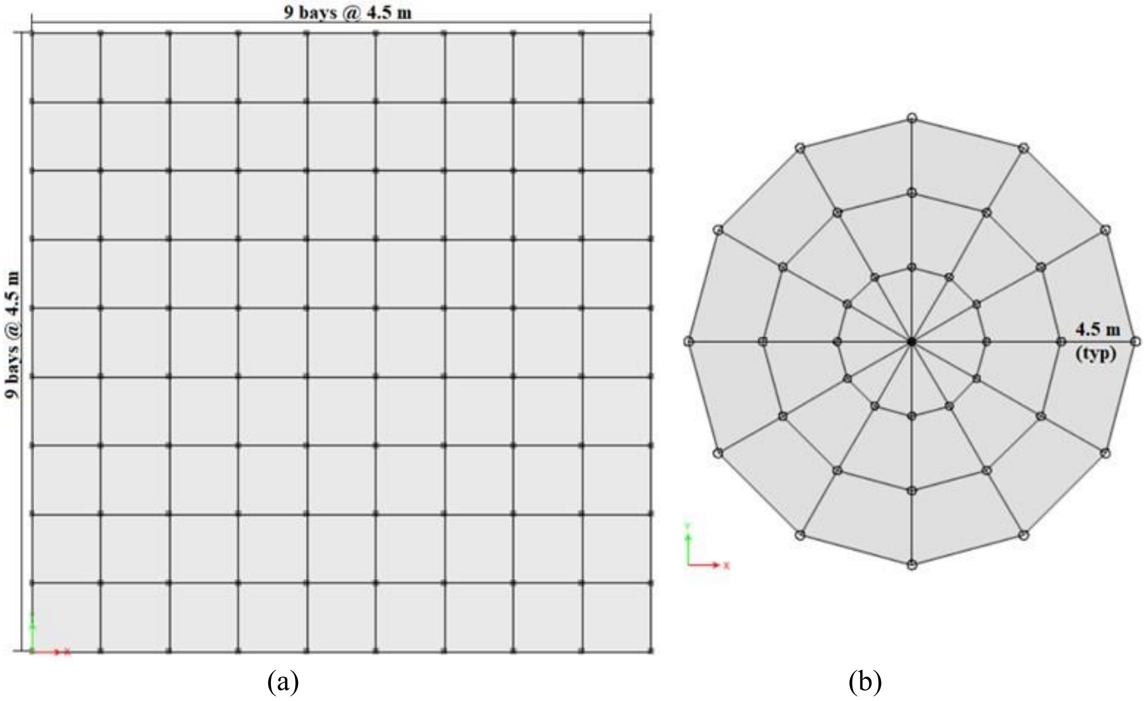
2. Numerical modelling

The concept of the unified identification factor (UIF) is demonstrated through the analysis of a series of irregular reinforced concrete building models, carried out using ETABS v18.0.2. The 3D models are generated using rectangular beams and columns modelled as frame elements, with rigid beam-column joints. Slabs are modelled as four-noded thin shell elements. The other modelling assumptions are shown in Table 2. A rectangular model of grid size 4.5 m×4.5 m (BM 1) and a circular model with 4.5 m long beams along the radial direction (BM 2) are defined as base models. The plan and 3D views of the base models are shown in Figs. 4 and 5 respectively. In addition to self-weight, a superimposed dead load (SDL) of 1 kN/m^2 and live load (LL) of 4 kN/m^2, as per IS 875-Part 2 (1987) are applied on all floors. The irregular models are obtained by modifying the base models and by maintaining symmetry about X axis. Since the plan aspect ratio is less than 3 for all the models, they are considered to provide rigid diaphragm action as per 1893-Part 1 (2016). Three plan irregularities (torsional irregularity, cut-out in floor slab and non-parallel lateral force system) and three vertical irregularities (mass irregularity, vertical geometric irregularity and floating columns) are considered in this study. Further, it is ensured that the models are irregular as per conditions of IS 1893-Part 1 (2016) presented in Fig. 6.

To generate torsional irregularity, the live load on one side of the base models is maintained as 4 kN/m^2, whereas the live load on the other side is increased to 15 kN/m^2 for all the floors, as shown in Fig. 7. This induces an eccentricity (distance between the centre of mass and centre of rigidity) of 2.3 m and 1.2 m for the rectangular (TI 1) and circular (TI 2) models respectively.

Table 2 Modelling assumptions

Property	Description
Grade of concrete	M 30 (IS 456 (2000))
Grade of steel	Fe 500 (IS 1786 (2008))
Slab thickness	150 mm
Number of stories	5
Storey height	3 m
Floor diaphragm	Rigid
Support condition	Fixed at base
Seismic zone factor, Z	0.36 (zone V)
Importance factor, I	1
Response reduction factor, R	3
Soil type	II (medium stiff)
Damping ratio	5%



(a) (b)

Fig. 4 Plan of base models (a) BM 1 and (b) BM 2

Further, a building is classified as torsionally irregular when

$$\frac{\Delta_{max}}{\Delta_{avg}} > 1.2 \tag{1}$$

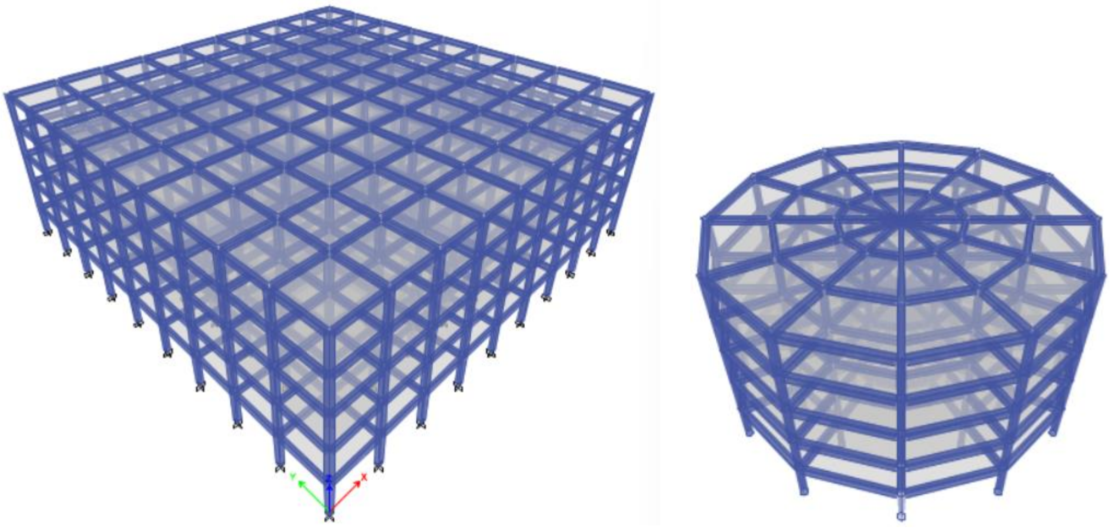

(a) (b)

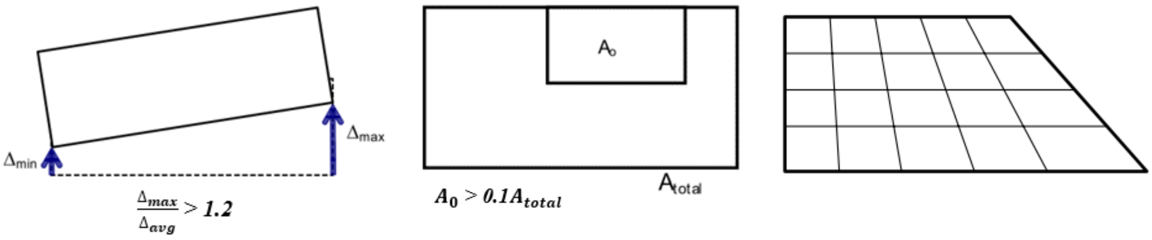
Fig. 5 3D view of base models (a) BM 1 and (b) BM 2

where $\Delta_{avg} = \frac{\Delta_{max}+\Delta_{min}}{2}$, Δ_{max} and Δ_{min} are the larger and smaller horizontal displacements (in the direction of lateral force) at the two ends of the floor diaphragm respectively. The floor displacements obtained from dynamic analysis are used to calculate the torsional irregularity coefficient (TIC) defined in Eq. (1) The results are furnished in Table 3, and it may be seen that for both the rectangular (TI 1) and circular (TI 2) models, the TIC values are greater than 1.2 and hence they are torsionally irregular.

A building is said to have cut-out irregularity when the floor slabs have openings of area (located near the centre of the slab) more than 50% of the full area of the floor slab. However, the percentage opening is limited to 10% when it is located along any edge of the slab. In this study, cut-out irregularity is introduced by providing an opening near the edge of the floor slab (in all floors) of the base models, as shown in Fig. 8. The percentage opening is approximately 18.5% and 11.1% for the rectangular (CO 1) and circular (CO 2) models respectively.

When the lateral force resisting systems are not oriented along two plan directions that are orthogonal to each other (non-parallel lateral force system), it results in instability and torsion in the event of an earthquake. To obtain such an irregularity, the base model (BM 1) is modified by reducing the bay width at top of the plan to 2.5 m and maintaining the bay width at bottom and left portion of the plan as 4.5 m. Plan of the model with non-parallel lateral force system (NP 1) is shown in Fig. 9.

Mass irregularity shall be considered to exist, when the seismic weight of any floor is more than 150% of that of the adjacent floor. To induce mass irregularity, the live load on the 1st, 3rd and 5th floors of the base models is increased to 15 kN/m^2, as shown in Fig. 10. The increased seismic weight is thus 375% of that of the adjacent floors, on which the live load is 4 kN/m^2. The assumed higher live load of 15 kN/m^2 for the torsional and mass irregular models is intended to accommodate various functional demands such as heavy equipment storage, plant rooms or swimming pools.

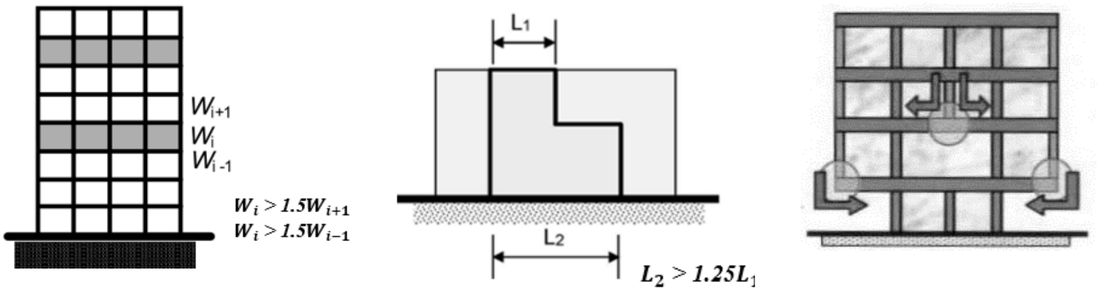


Torsional irregularity

Cut-out irregularity

Non-parallel lateral force system

Horizontal irregularity (plan view)



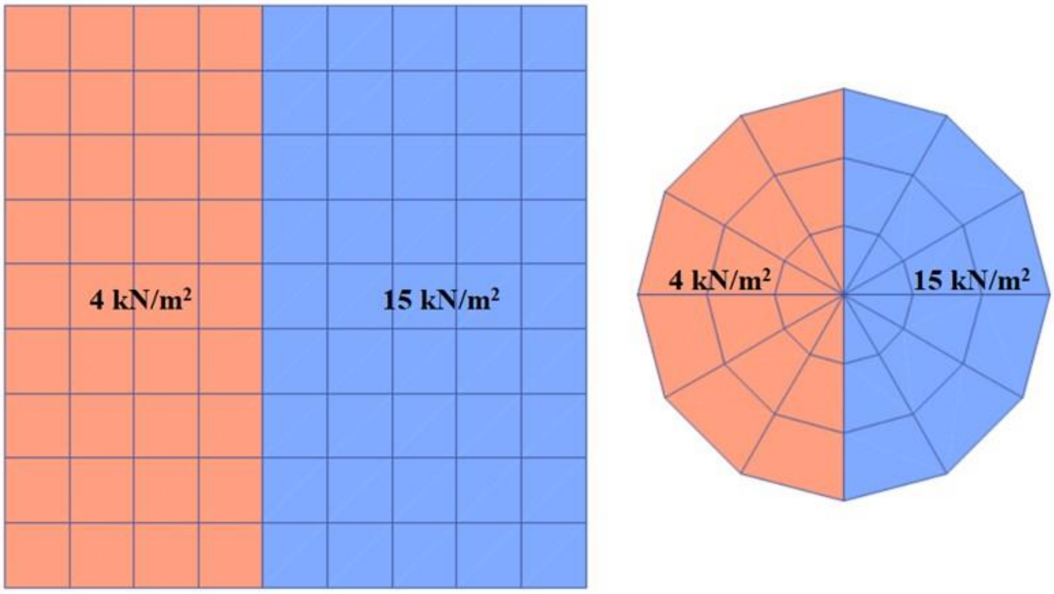
Mass irregularity

Vertical geometric irregularity

Floating columns (Murty 2005)

Vertical irregularity (elevation view)

Fig. 6 Conditions for irregularity as per IS 1893-Part 1 (2016)



(a)

(b)

Fig. 7 Plan of torsional irregular models (a) TI 1 and (b) TI 2

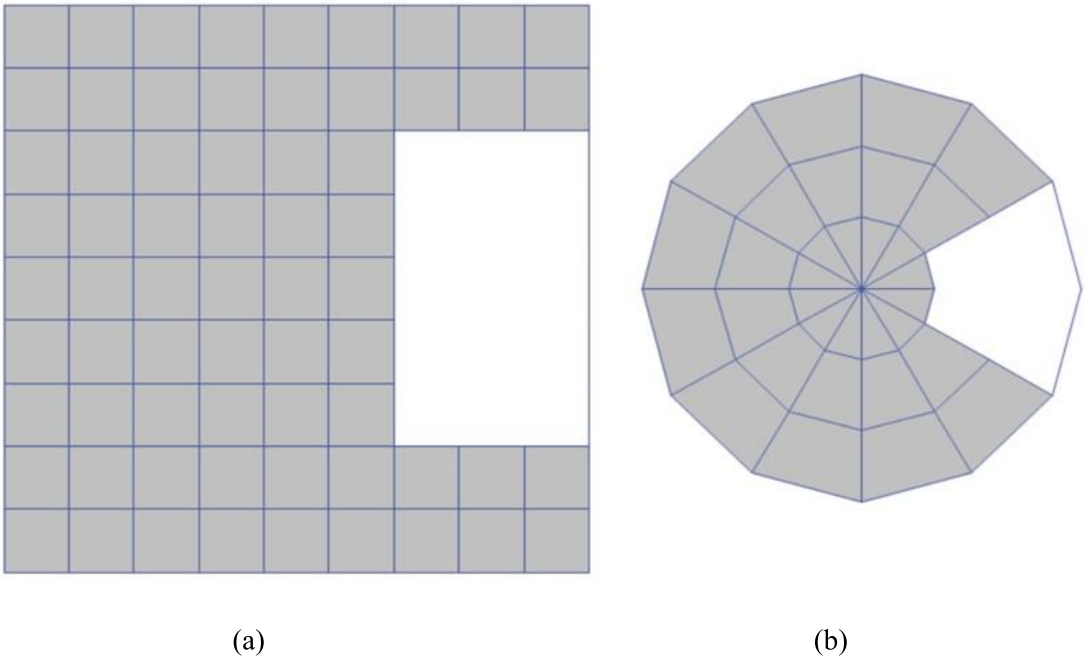


Fig. 8 Plan of cut-out irregular models (a) CO 1 and (b) CO 2

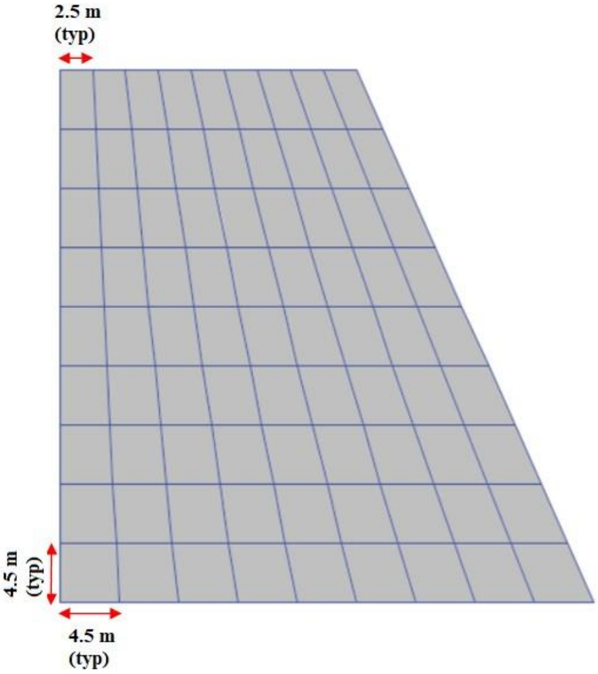
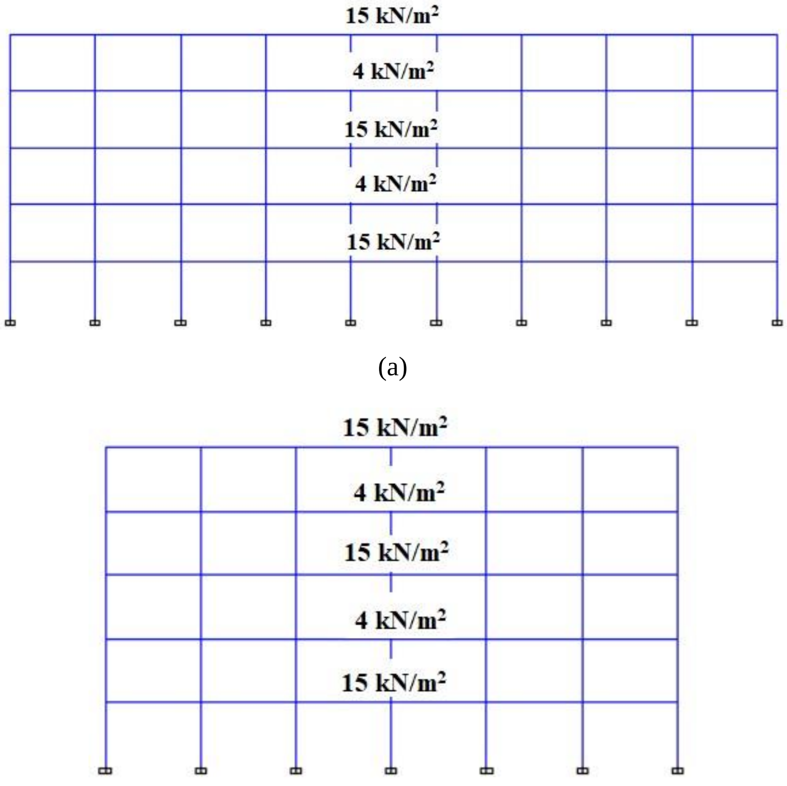


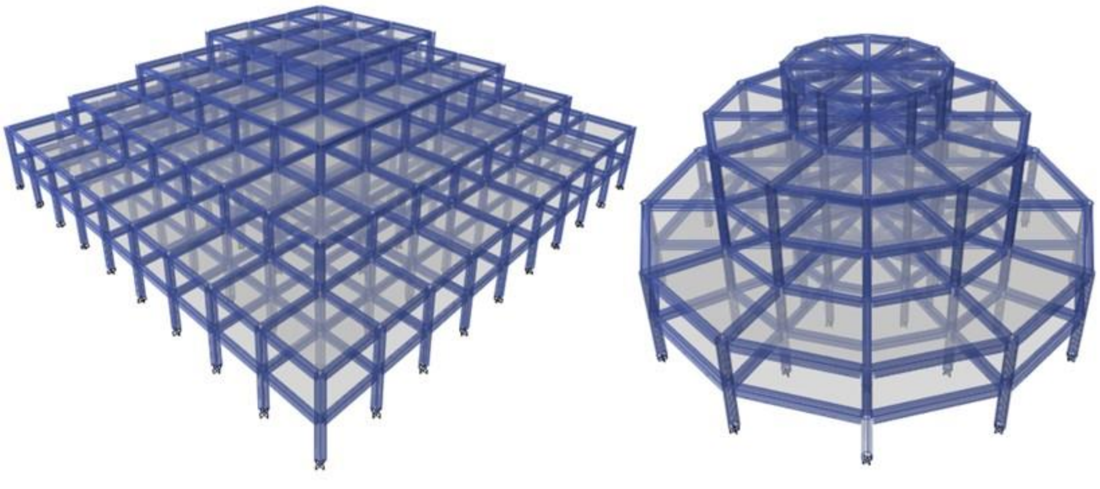
Fig. 9 Plan of model with non-parallel lateral force system (NP 1)



(a)

(b)

Fig. 10 Elevation of mass irregular models (a) MI 1 and (b) MI 2



(a) (b)

Fig. 11 3D view of models with vertical geometric irregularity (a) GI 1 and (b) GI 2

Table 3 Calculation of torsional irregularity coefficient

Model	Storey	Load combination	Δ_{max} (mm)	Δ_{min} (mm)	Δ_{avg} (mm)	*TIC* ($\Delta_{max}/\Delta_{avg}$)
TI 1	5	DL+SDL+EQ$_Y$	35.34	21.66	28.50	1.24
	4		32.02	19.63	25.83	1.24
	3		25.96	15.92	20.94	1.24
	2		17.63	10.80	14.22	1.24
	1		7.82	4.79	6.31	1.24
	5	DL+SDL+0.8LL+0.8EQ$_Y$	28.27	17.33	22.80	1.24
	4		25.61	15.71	20.66	1.24
	3		20.77	12.74	16.76	1.24
	2		14.10	8.64	11.37	1.24
	1		6.26	3.83	5.05	1.24
TI 2	5	DL+SDL+(EQ$_Y$+0.3EQ$_X$)	37.67	23.15	30.41	1.23
	4		33.86	20.81	27.33	1.23
	3		27.08	16.66	21.87	1.23
	2		17.86	11.02	14.44	1.23
	1		7.39	4.56	5.98	1.23
	5	DL+SDL+0.8LL+0.8(EQ$_Y$+0.3EQ$_X$)	30.13	18.50	24.32	1.23
	4		27.08	16.63	21.86	1.23
	3		21.68	13.31	17.50	1.23
	2		14.28	8.78	11.53	1.23
	1		5.91	3.64	4.78	1.23

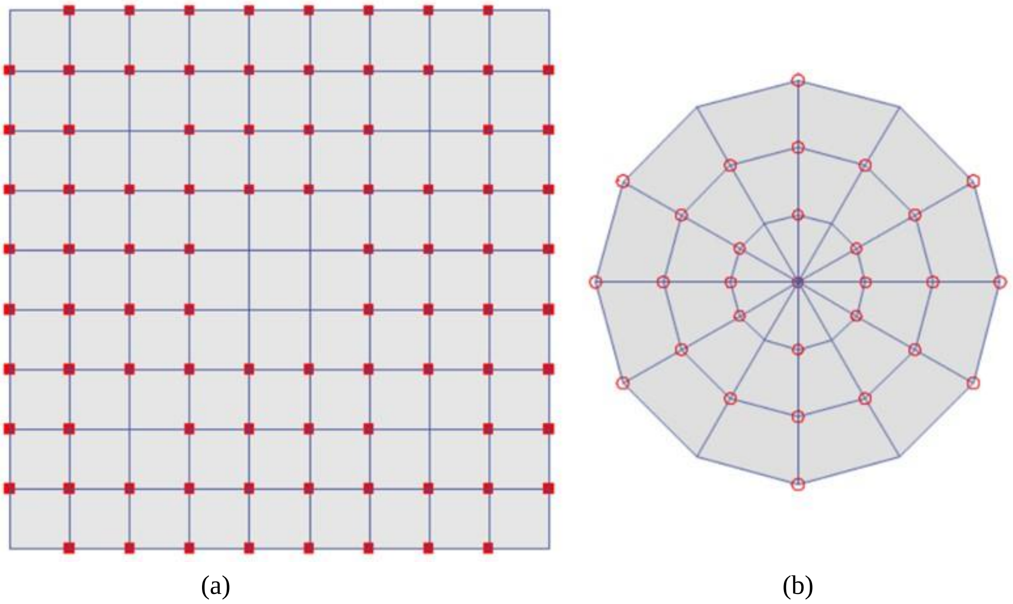

(a) (b)

Fig. 12 Plan (at storey 1) of floating column models (a) FC 1 and (b) FC 2

Vertical geometric irregularity is defined to exist when the horizontal dimension of the lateral force-resisting system in any storey is more than 125% of that of the adjacent storey. In this study, the geometric irregular models are obtained by removing certain bays symmetrically from all sides of the base models (Fig. 11). For NP 1, the lateral dimension of the 4th floor (22.5 m) is 166.7% of that of the 5th floor (13.5 m). Similarly, for NP 2, the lateral dimension of the 4th floor (18 m) is 200% of that of the 5th floor (9 m).

Floating columns cause sudden deviations in the load path and hinder the transfer of lateral forces to the foundation. Such columns are usually discontinued at the ground storey, resulting in an increased demand on the surrounding columns that are continuous till the foundation. Certain columns are removed from the ground floor of the base models, as shown in Fig. 12, to produce the rectangular (FC 1) and circular (FC 2) models with floating columns.

3. Results and discussions

The unified identification factor (UIF) is developed in order to identify and eliminate any undesirable irregularity during the planning stage of a building. Since the factor is aimed to be used as an initial check, it is developed based on gravity load analysis. Column numbering (which is used for interpretation of results) is consistent for all models, as shown in Fig. 13.

3.1 Definition of UIF

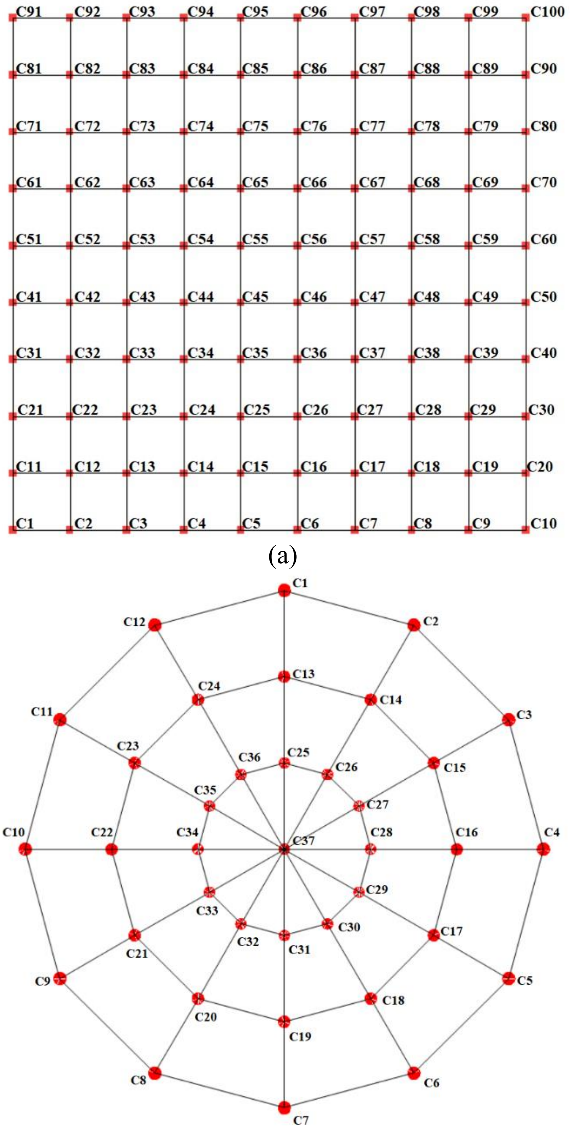
After analysis, the beams and columns are checked with respect to limit state of strength as per IS 456 (2000). Thereafter, the axial load (*P*) is extracted for the columns of all 5 stories, corresponding to the load combination 1.5 (DL+SDL+LL). The axial force diagrams obtained from ETABS, for a plan irregular model (TI 1) and a vertical irregular model (GI 1) are shown in Fig. 14. A parameter called unified identification factor (UIF) is defined as shown in Eq. (2).

$$UIF = \frac{P}{A \times n} \tag{2}$$

where *A* is the tributary area from which the column receives load and *n* is the number of floor slabs above the considered column. Tributary area for a column is the area of the floor that directly transfers its load to that specific column. For calculating the tributary area, the largest floor area amongst all floors of the building is considered without deducting any cut-out area within the slab. The total area is then distributed to the different columns supporting the floor using the tributary area approach. For accurate prediction of tributary areas, the ETABS models are imported into the BIM software, Visicon which displays the load path and subsequently calculates and reports the tributary area for each column. For illustration, Fig. 15 highlights the cumulative tributary area on the columns around the slab opening for the cut-out irregular models. The area marked in red has to be shared exclusively by the columns enclosing the opening (marked in yellow), resulting in large tributary areas for those columns.

3.2 Implementation using Python

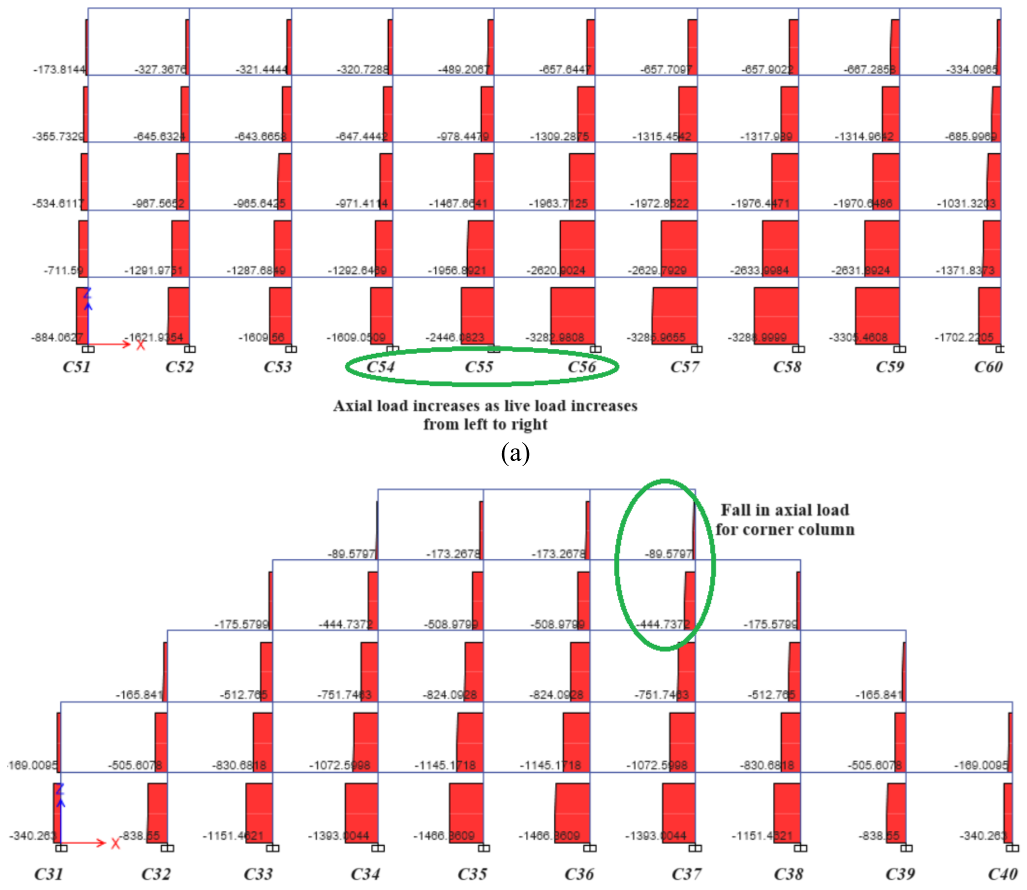
The calculation of UIF for all columns becomes laborious and time-consuming for large projects. Hence, a Python code is written using Jupyter Notebook for easy implementation of the



(b)

Fig. 13 Column layout in plan for (a) rectangular and (b) circular models

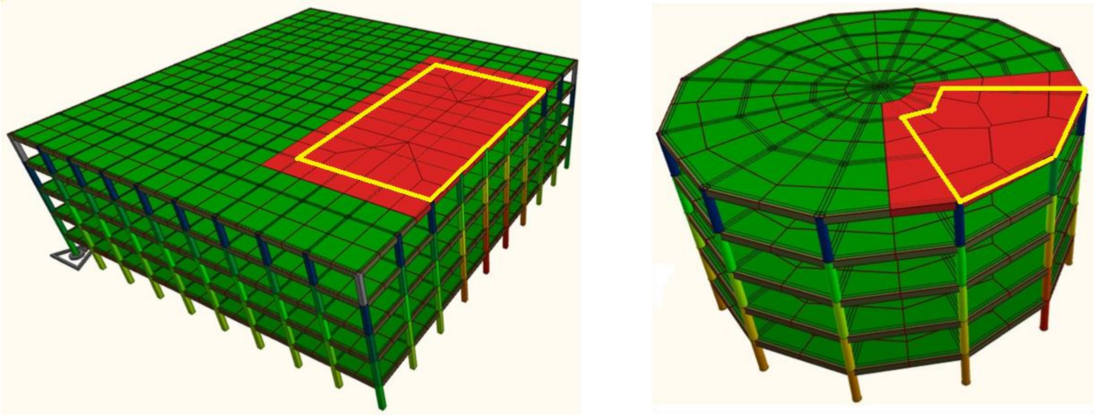
proposed methodology. The CSI ETABS API (Application Programming Interface which is a package available for interaction with ETABS) is connected to the running instance of the desired ETABS model. Further, the Python code is integrated with the ETABS model, which finally displays the interactive 3D model to view the UIF values of different columns. The output generated for the rectangular base model (BM 1) is shown in Fig. 16. The code can be modified for viewing the UIF values of one particular floor/column to obtain more insights. The authors are further working towards creating a plugin within ETABS for exporting tributary areas and UIF values.



(a)

(b)

Fig. 14 Axial force diagram of interior grid (in kN) for 1.5 (DL+SDL+LL) (a) TI 1 and (b) GI 1



(a) (b)

Fig. 15 Tributary areas from Visicon (a) CO 1 and (b) CO 2

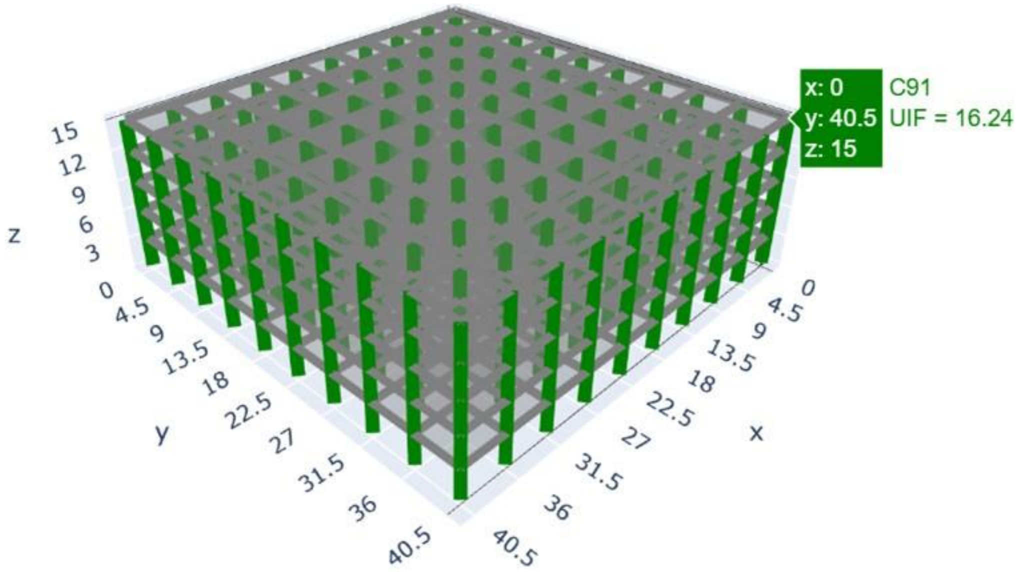


Fig. 16 Interactive 3D model to view UIF values

3.3 Range of UIF

Once the UIF is calculated for all the columns, the maximum and minimum values are identified for each model and plotted. Table 4 shows the computation of maximum and minimum values of UIF. The columns that produce maximum/minimum values of UIF and the corresponding storey in which these columns are present are also included in the Table.

As shown in Fig. 17, the values of UIF for the base models, which are regular in configuration, lie within a very narrow range, whereas for all other models which are irregular, the values are within a very wide range. This indicates that there is a strong relationship between the UIF range and structural irregularity. The extent of irregularity in a building can thus be understood from the range of values of UIF.

3.4 Comparison of UIF between columns

For additional insights on various irregularities, the UIF values of individual columns are examined for each irregular model and compared with the corresponding base model. The results for selected columns across the 5th floor (for plan irregular models) and elevation (for vertical irregular models) are summarized in Figs. 18 and 19 respectively. For the torsional irregular models, three columns of an interior frame are considered. As the live load increases from 4 to 15 kN/m^2, the axial load also increases, thus resulting in higher values of UIF for the columns on the right side. For cut-out irregularity, UIF values of the columns around the opening are plotted. Large tributary areas on these columns lead to exceptionally low values of UIF. In the non-parallel lateral force system, the UIF value of the top bay corner column is comparatively high as it has the lowest tributary area.

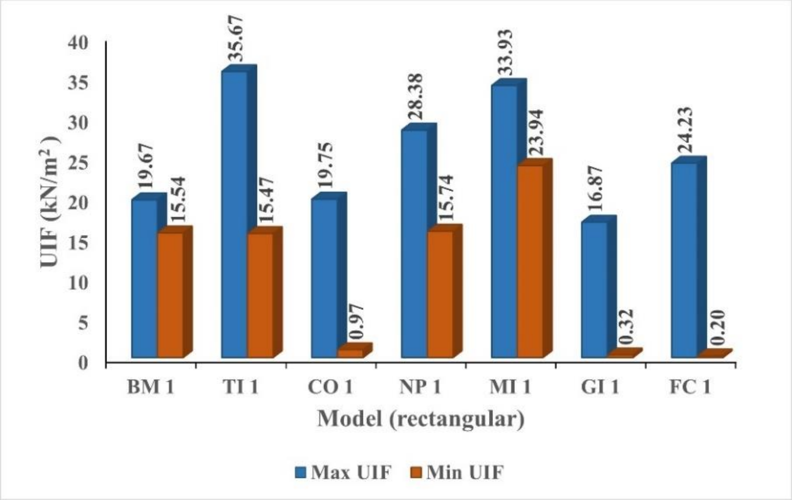
Table 4a Calculation of maximum and minimum values of UIF for rectangular models

Model name	Column number	Storey	P (kN)	A (m^2)	n	Max. UIF (kN/m^2)	Min. UIF (kN/m^2)
BM 1	C1, C10, C91, C100	2	398.27	5.06	4	19.67	
	C34, C37, C64, C67	5	314.61	20.25	1		15.54
TI 1	C10, C100	3	541.78	5.06	3	35.67	
	C34, C64	5	313.21	20.25	1		15.47
CO 1	C10, C100	2	399.92	5.06	4	19.75	
	C50, C60	5	29.36	30.38	1		0.97
NP 1	C100	2	333.49	2.94	4	28.38	
	C24	5	287.26	18.25	1		15.74
MI 1	C12, C19, C82, C89	5	687.00	20.25	1	33.93	
	C12, C19, C82, C89	4	969.74	20.25	2		23.94
GI 1	C45, C46, C55, C56	5	341.58	20.25	1	16.87	
	C23, C28, C73, C78	4	81.02	126.56	2		0.32
FC 1	C35, C36, C44, C47, C54, C57, C65, C66	2	1963.01	20.25	4	24.23	
	C45, C46, C55, C56	2	15.91	20.25	4		0.20

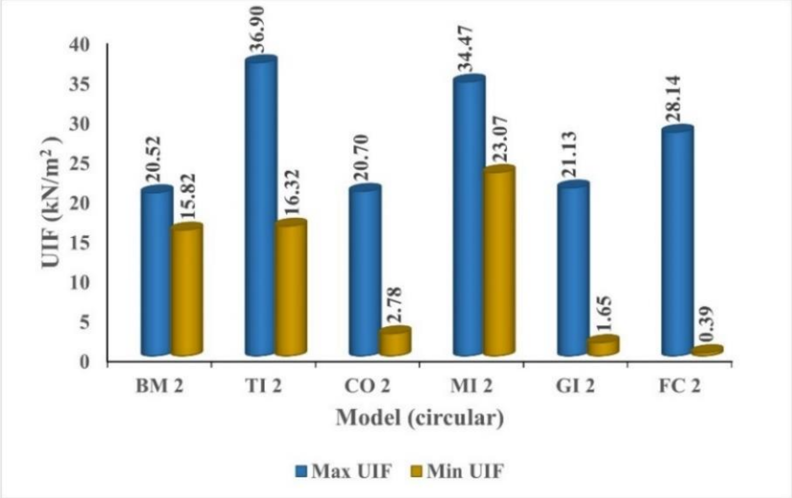
Table 4b Calculation of maximum and minimum values of UIF for circular models

Model name	Column number	Storey	P (kN)	A (m^2)	n	Max. UIF (kN/m^2)	Min. UIF (kN/m^2)
BM 2	C10	2	1078.86	13.14	4	20.52	
	C37	5	257.54	16.28	1		15.82
TI 2	C2	3	1454.78	13.14	3	36.90	
	C22	4	707.11	21.66	2		16.32
CO 2	C2	2	1087.83	13.14	4	20.70	
	C4	5	56.40	20.3	1		2.78
MI 2	C10	5	452.97	13.14	1	34.47	
	C37	4	751.07	16.28	2		23.07
GI 2	C37	5	343.93	16.28	1	21.13	
	C25	5	75.43	45.60	1		1.65
FC 2	C1	2	1479.20	13.14	4	28.14	
	C8	2	20.25	13.14	4		0.39

For mass irregularity, columns (typical) that give maximum values of UIF are examined. Since the axial load increases significantly, the UIF values are higher for columns across all stories. In models with vertical geometric irregularity, since the selected columns are corner/edge columns in the 5th storey alone, a sudden fall is seen in the UIF values from the 4th to 5th storey. In models with floating columns, the floating columns are seen to have very low UIF values in all stories. However, the UIF values of columns adjacent to the floating columns are significantly high. This is mainly because of the load redistribution due to the presence of floating columns. It is also found that for all the analysed models, columns away from the irregularity have UIF values nearly equal to that of the base models. The wide range of UIF values for the irregular models (discussed in section 3.3) can hence be attributed to the columns in close proximity to the irregularity.



(a)

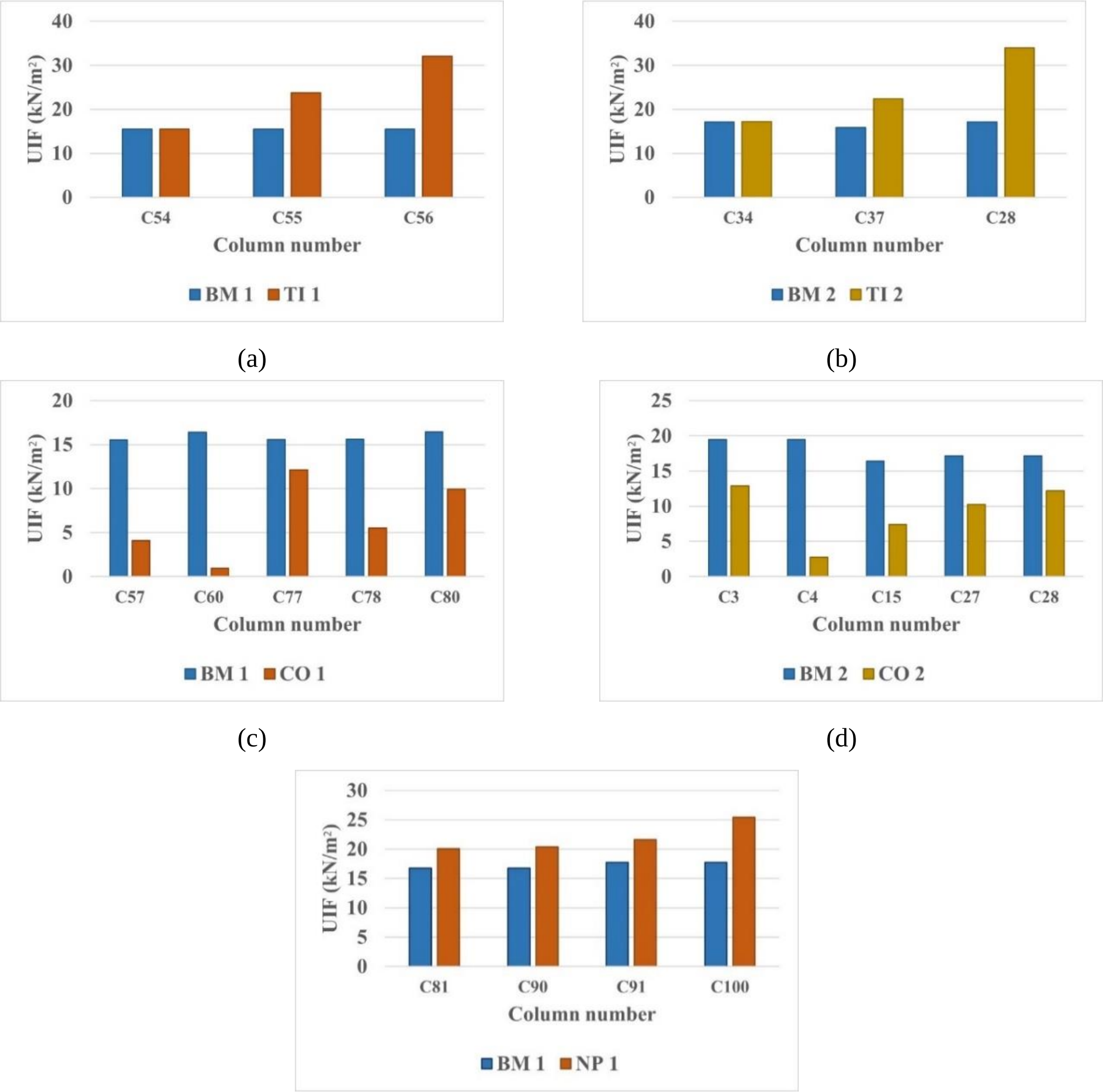


(b)

Fig. 17 Range of UIF values for (a) rectangular and (b) circular models

3.5 Proposed extension of UIF

In wake of the 2023 Turkey earthquakes (Garini and Gazetas 2023), novel techniques have been developed to identify irregularities in buildings and assess their seismic vulnerability, using image processing and artificial neural network methods (Akan *et al.* 2023, Saadati and Moghadam 2023). The motivation behind this paper is to envisage the need for a single parameter to define any type of structural irregularity in buildings. Although the proposed formula for the unified identification factor (UIF) may have its limitations, the aim is to introduce the concept of the unified approach to the research community. Consequently, the idea could be adopted by future researchers to rework on the UIF and develop a more refined formula. In order to extend the



(a) (b)

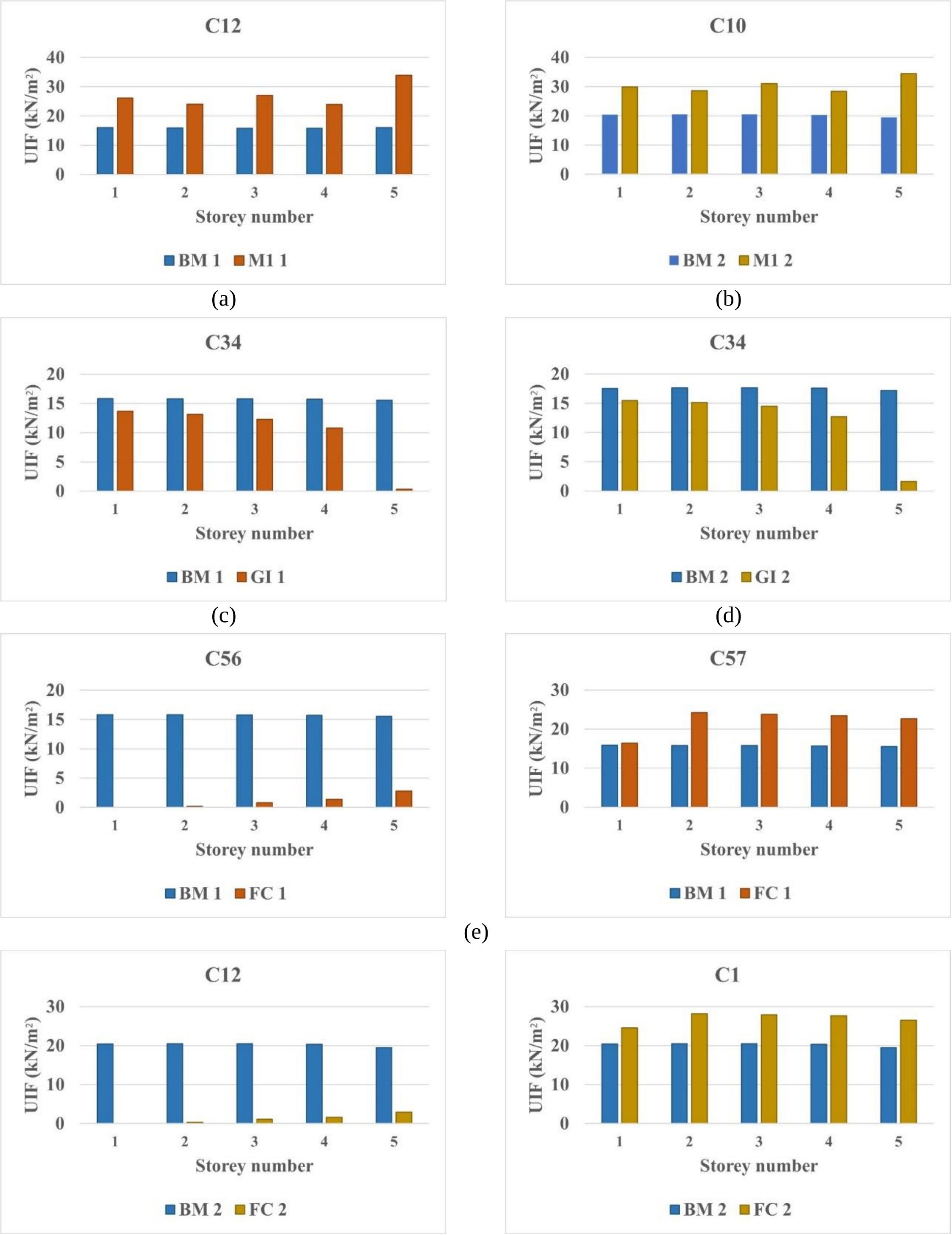
(c) (d)

(e)

Fig. 18 UIF for plan irregular models (a) TI 1, (b) TI 2, (c) CO 1, (d) CO 2 and (e) NP 1

applicability of UIF, the first three authors of this paper are continuing research taking into account certain key aspects which are illustrated in Fig. 20 and discussed below:

- The definition of UIF has been formulated by considering certain irregularities defined as per IS 1893-Part 1 (2016). Extension of the work, considering other plan and vertical irregularities, will give a better understanding of the relevance of UIF to systems that demonstrate any kind of irregular behaviour.
- As discussed in section 1, a combination of certain irregularities may increase/decrease the earthquake demands on the structure. Case studies considering buildings with combination of



(a) (b)

(c) (d)

(e)

(f)

Fig. 19 UIF for vertical irregular models (a) MI 1, (b) MI 2, (c) GI 1, (d) GI 2, (e) FC 1 and (f) FC 2

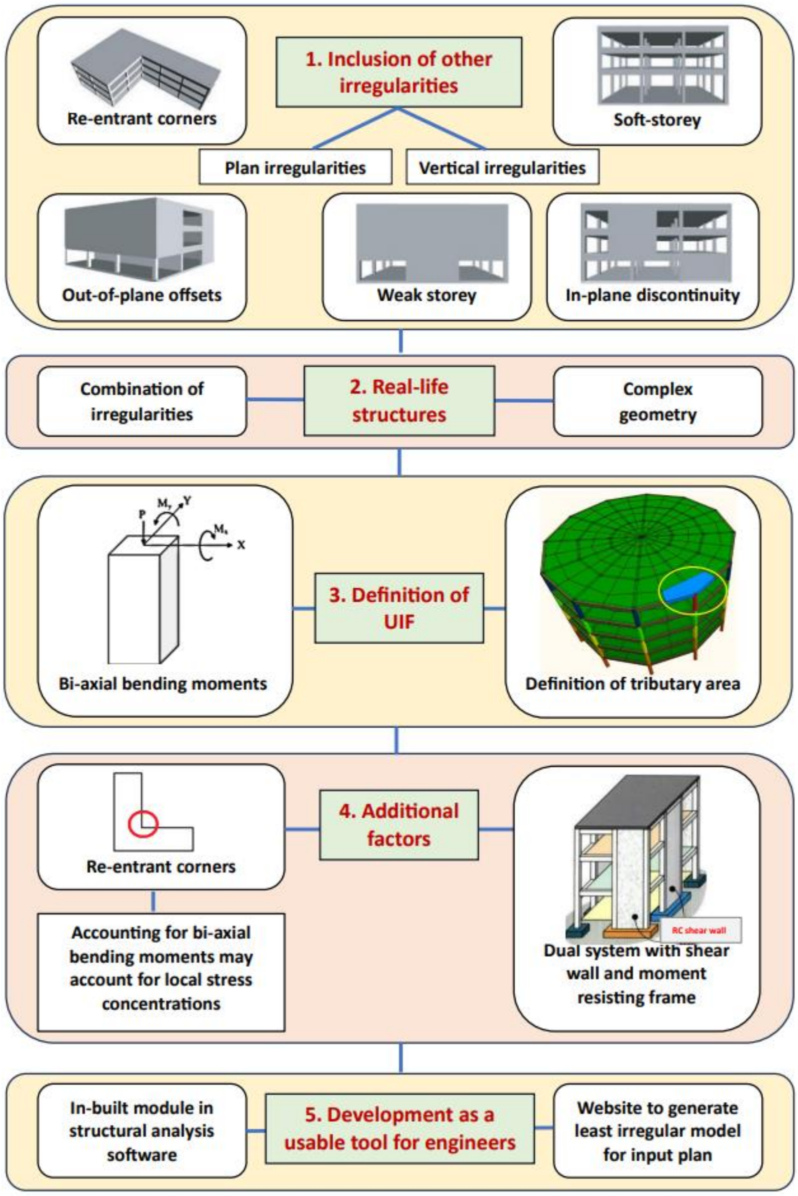


Fig. 20 Key aspects for extension of UIF

irregularities along with complex geometries will validate the suitability of UIF to real-life structures.

- The formula for UIF is defined using the axial load on columns under gravity loading. However, the effects of bi-axial moments are known to increase the vulnerability of columns when subjected to seismic loads (Marusic and Fajfar 2005, Gwalani *et al.* 2022). Hence, the formula can be further modified to incorporate bi-axial moments. Also, the definition of tributary area adopted by the authors can be refined by inputs from other researchers.

- Certain irregularities such as re-entrant corners cause local stress concentration and torsion-related problems during earthquakes, which have not been examined in this study. The inclusion of bi-axial moments may incorporate these effects. However, further investigation is required in order to arrive at conclusions. Similarly, buildings with dual systems (Murty 2005) commonly used in high seismic zones are to be explored.
- A website can be developed for use by design firms, to generate the least irregular model for an input architectural plan, using artificial intelligence techniques.

4. Conclusions

The fact that irregular buildings suffer higher levels of damage than their regular counterparts has been recognized in seismic codes across the world through specific guidelines on each of the plan and vertical irregularities. However, the complexities associated with these guidelines in addition to frequent revisions often tempt the designers to disregard the irregularity checks during the design stage. In this paper, a new parameter called unified identification factor (UIF) is defined so as to identify the presence of any irregularity within a floor or along the height of a building, during the planning stage. Based on the results, the most important conclusions of the study are as below:

- The proposed parameter is a strong indicator regarding the extent of structural irregularity in a building. The key aspect of the approach is that the UIF of columns of a regular building will be in a narrow range, when compared to that of an irregular building.
- As a practical application, for large projects, columns with high or low values of UIF can be identified, and such locations can be examined in detail. Necessary modifications like inclusion of additional columns, increasing the dimensions of beams/columns or revising the plan can be done, in order to bring the UIF values within the desired range. Consequently, the extent of structural irregularity can be minimized.
- The UIF can be used prior to detailed engineering in real projects, so as to eliminate large irregularities and the consequences associated with seismic behaviour. However, further investigations may be taken up by the research community in order to increase the scope of application of this simplified approach. The final outcome may be useful for incorporation in building codes.

Acknowledgments

The stipend provided to the first author by the Ministry of Education, Government of India for pursuing full-time Ph.D. is gratefully acknowledged.

References

Abdel Raheem, S.E., Ahmed, M.M.M., Ahmed, M.M. and Abdel-shafi A.G.A. (2018), “Evaluation of plan configuration irregularity effects on seismic response demands of L-shaped MRF buildings”, *Bull. Earthq.*

Eng., **16**(9), 3845-3869. https://doi.org/10.1007/s10518-018-0319-7.

Agarwal, P. and Shrikhande, M. (2011), *Earthquake resistant design of structures*, PHI Learning Private Limited, New Delhi, India.

Ahmed, M.M.M., Abdo, M.A.B. and Mohamed, W.A.E. (2021), "Vertical geometric irregularity effect on performance-based seismic design for moderate rise RC moment resisting frame buildings", *Arab. J. Sci. Eng*., **47**(10), 12333-12348. https://doi.org/10.1007/s13369-021-06376-y.

Akan, A., Bingol, K., Ormecioglu, H.T., Er., A. and Ormecioglu, T.O. (2023), "Towards an earthquake-resistant architectural design with the image classification method", *J. Asian Archit. Build. Eng*., **23**(1), 157-170. https://doi.org/10.1080/13467581.2023.2213299.

Akshara, S.P., Akbar, M.A., Madhavan Pillai, T.M., Pasunuti, R. and Sabhadiya, R. (2024), "Using an appropriate rotation-based criterion to account for torsional irregularity in reinforced concrete buildings", *Earthq. Struct.,* **26**(5), 349-361. https://doi.org/10.12989/eas.2024.26.5.349.

Alaa, K.M., El-Kashif, K.F. and Salem, H.M. (2022), "New definition for torsional irregularity based on floors rotations of reinforced concrete buildings", *J. Eng. Appl. Sci*., **69**(12), 1-35. https://doi.org/10.1186/s44147-021-00061-5.

Alecci, V., De Stefano, M., Galassi, S., Lapi, M. and Orlando, M. (2019), "Evaluation of the American approach for detecting plan irregularity", *Adv. Civ. Eng*., **2019**, 1. https://doi.org/10.1155/2019/2861093.

"An engineers guide to: openings in concrete floor slabs", *Portland Cement Association,* Skokie, Illinois, **2005**.

Anagnostopoulos, S.A., Alexopoulou, C. and Stathopoulos, K.G. (2010), "An answer to an important controversy and the need for caution when using simple models to predict inelastic earthquake response of buildings with torsion", *Earthq. Eng. Struct. D*, **39**(5), 521-540. https://doi.org/10.1002/eqe.957.

Archana, A.R. and Akbar, M.A. (2021), "Structural irregularity quantification in buildings using vital signs", *Structures*, **34**, 2592-2599. https://doi.org/10.1016/j.istruc.2021.09.026.

ASCE/ SEI 7 (2016), *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, American Society of Civil Engineers, Virginia, United States of America.

Athanatopoulou, A.M. and Manouka, G.E. (2021), "Torsional sensitivity criteria in seismic codes", *Earthquakes Struct*., **21**(1), 1-10. https://doi.org/10.12989/eas.2021.21.1.001.

Bikçe, M. and Çelik, T.B. (2016), "Failure analysis of newly constructed RC buildings designed according to 2007 Turkish seismic code during the October 23, 2011 Van earthquake", *Eng. Fail. Anal.*, **64**, 67-84. https://doi.org/10.1016/j.engfailanal.2016.03.008.

BNBC (2017), *Bangladesh National Building Code-part 6: structural design*, Housing and Building Research Institute, Bangladesh.

Bosco, M., Ferrara, G.A.F., Ghersi, A., Marino, E.M. and Rossi, P.P. (2015), "Seismic assessment of existing R.C. framed structures with in-plan irregularity by nonlinear static methods", *Earthq. Struct.*, **8**(2), 401-422. https://doi.org/10.12989/eas.2015.8.2.401.

Chunyu, T., Junjin, L., Hong, Z. and Jinzhe, C. (2012), "Experimental study on seismic behavior of an irregular high-rise building", *Proceedings of the 15th World Conf. Earthq. Eng*. Lisboa, Portugal.

Computers & Structures, Inc. Structural and Earthquake Engineering Software. https://www.csiamerica.com/products/etabs. 2016.

EN 1998-1 (2004), *Eurocode 8: Design of structures for earthquake resistance-Part 1: General rules, seismic actions and rules for buildings,* European Committee for Standardization, Brussels.

Esteva, L. (1987), "Earthquake engineering research and practice in Mexico after the 1985 earthquakes", *Bull. New Zeal. Natl. Soc. Earthq. Eng*., **20**(3), 159-200. https://doi.org/10.5459/bnzsee.20.3.159-200.

FEMA 454 (2006), *Risk management Series - Designing for earthquakes, A manual for architects.*

FEMA P-2082-1 (2020), *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures-volume 1*, Building Seismic Safety Council of the National Institute of Building Sciences, Washington, United States of America.

Firoj, M. and Singh, S.K. (2018), "Response spectrum analysis for irregular multi-storey structure in seismic zone V", *Proceedings of the 16th Symp. Earthq. Eng*. IIT Roorkee, India.

Garini, E. and Gazetas, G. (2023), "The 2 earthquakes of February 6th 2023 in Turkey: preliminary report", NTUA, Greece.

GB 50011 (2010), *Code for Seismic Design of Buildings*, Ministry of Housing and Urban-Rural Development of the People's Republic of China.

Ghanem, A., Lee, Y.J. and Moon, D.S. (2024), "Seismic vulnerability of reinforced concrete frame structures: obtaining plan or vertical mass irregularity from structure use change", *J. Struct. Eng.*, **150**(3), 1-13. https://doi.org/10.1061/jsendh.steng-12440.

Goel, R.K. and Chopra, A.K. (1991), "Effects of plan asymmetry in inelastic seismic response of one-story systems", *J. Struct. Eng.*, **117**(5), 1492-1513. https://doi.org/10.1061/(ASCE)0733-9445(1991)117:5(1492).

Gwalani, P., Singh, Y. and Varum, H. (2022), "Effect of bidirectional excitation on seismic performance of regular RC frame buildings designed for modern codes", *Earthq. Spectra*, **38**(2), 950-980. https://doi.org/10.1177/87552930211047879.

Habibi, A., Gholami, R. and Izadpanah, M. (2019), "Behavior factor of vertically irregular RCMRFs based on incremental dynamic analysis", *Earthq. Struct.*, **16**(6), 655–664. https://doi.org/10.12989/eas.2019.16.6.655.

Haque, M., Ray, S., Chakraborty, A., Elias, M. and Alam, I. (2016), "Seismic performance analysis of RCC multi-storied buildings with plan irregularity", *Am. J. Civ. Eng.*, **4**(3), 68–73. https://doi.org/10.11648/j.ajce.20160403.11.

IS 875 (1987), *Indian Standard Code of Practice for Design Loads (other than Earthquake) for Buildings and Structures-part 2: Imposed loads*, Bureau of Indian Standards, New Delhi, India.

IS 456 (2000), *Indian Standard for Plain and Reinforced Concrete-Code of Practice*, Bureau of Indian Standards, New Delhi, India.

IS 1786 (2008), *Indian Standard for High Strength Deformed Steel Bars and Wires for Concrete Reinforcement-Specification*, Bureau of Indian Standards, New Delhi, India.

IS 1893 (2016), *Indian Standard Criteria for Earthquake Resistant Design of Structures-part 1: general provisions and buildings*, Bureau of Indian Standards, New Delhi, India.

KBC (2009), *Korean Building Code*, Structural Korean Ministry of Land, Infrastructure and Transportation, Korea.

Marusic, D. and Fajfar, P. (2005), "On the inelastic seismic response of asymmetric buildings under bi-axial excitation", *Earthq. Eng. Struct. D.*, **34**(8), 943-963. https://doi.org/10.1002/eqe.463.

Mitchell, D., DeVall, R.H., Saatcioglu, M., Simpson, R., Tinawi, R. and Tremblay, R. (1995), "Damage to concrete structures due to the 1994 Northridge earthquake", *Can. J. Civ. Eng.*, **22**(2), 361-377.

Mouhine, M. and Hilali, E. (2022a), "Seismic vulnerability assessment of RC buildings with setback irregularity", *Ain Shams Eng. J.*, **13**(1), 101486. https://doi.org/10.1016/j.asej.2021.05.001.

Mouhine, M. and Hilali, E. (2022b), "Seismic vulnerability for irregular reinforced concrete buildings with consideration of site effects", *Mater. Today Proc.*, **58**, 1039-1043. https://doi.org/10.1016/j.matpr.2022.01.038.

Murty, C.V.R. (2005), *Earthquake tips - Learning earthquake design and construction*, Indian Institute of Technology Kanpur and Building Material and Technology Promotion Council, New Delhi, India.

Nady, O., Mahfouz, S.Y. and Taher, S.E.D.F. (2022), "Quantification of vertical irregularities for earthquake resistant reinforced concrete buildings", *Buildings*, **12**(8), 1-19. https://doi.org/10.3390/buildings12081160.

Naveen, E.S., Abraham, N.M. and Kumari, S.D.A. (2019), "Analysis of irregular structures under earthquake loads", *Procedia Struct. Integr.*, **14**, 806-819. https://doi.org/10.1016/j.prostr.2019.07.059.

NBC (2020), *National Building Code of Canada-volume 1*, National Research Council of Canada.

NBC 105 (2020), *Nepal National Building Code-seismic design of buildings in Nepal*, Ministry of Urban Development, Kathmandu, Nepal.

NSCP C101 (2010), *National Structural Code of the Philippines-volume 1: buildings, towers and other vertical structures*, Association of the Structural Engineers, Quezon City, Philippines.

Ozhendekci, N. and Polat, Z. (2008), "Torsional irregularity of buildings", *Proceedings of the 14th World Conf. Earthq. Eng.* Beijing, China.

Özmen, G., Girgin, K. and Durgun, Y. (2014), "Torsional irregularity in multi-story structures", *Int. J. Adv. Struct. Eng.*, **6**(4), 121-131. https://doi.org/10.1007/s40091-014-0070-5.

Ravikumar, C.M., Narayan, K.B.S., Sujith, B.V. and Venkat Reddy, D. (2012), "Effect of irregular configurations on seismic vulnerability of RC buildings", *Archit. Res.*, **2**(3), 20-26. https://doi.org/10.5923/j.arch.20120203.01.

Saadati, D. and Moghadam, A.S. (2023), "EZRVS: An AI-based web application to significantly enhance seismic rapid visual screening of buildings", *J. Earthq. Eng.*, **28**(3)**.** 689-706. https://doi.org/10.1080/13632469.2023.2217944.

SI 413 (1995), *Design Provisions for Earthquake Resistance of Structures*, The Standards Institution of Israel.

TSC (2007), *Specification for Buildings to be Built in Seismic Zones*, Ministry of Public Works and Settlement, Government of Republic of Turkey.

UBC (1997), *Uniform Building Code-volume 2: structural engineering design provisions*, International Conference of Building Officials, California, United States of America.

Valmundsson, E.V. and Nau, J.M. (1997), "Seismic response of building frames with vertical structural irregularities", *J. Struct. Eng.*, **123**(1), 30-41. https://doi.org/10.1061/(ASCE)0733-9445(1997)123:1(30).

Vielma-Quintero, J.C., Diaz-Segura, E.G. and Vielma, J.C. (2024), "Influence of the plan structural symmetry on the non-linear seismic response of framed reinforced concrete buildings", *Symmetry (Basel).*, **16**(3). https://doi.org/10.3390/sym16030370.

Visicon, Inc. Smart BIM Tools. https://visicon.com/calculate-tributary-loads/ 2019.

Wang, J., Dai, K., Yin, Y. and Tesfamariam, S. (2018), "Seismic performance-based design and risk analysis of thermal power plant building with consideration of vertical and mass irregularities", *Eng. Struct.*, **164**, 141-154. https://doi.org/10.1016/j.engstruct.2018.03.001.

Wood, S.L., Wight, J.K. and Moehle, J.P. (2002), "The 1985 Chile earthquake observations on earthquake-resistant construction in Vina Del Mar", UILU-ENG-87-2002; *National Science Foundation*, Alexandria, VA, USA.

Zhang, C., Alam, Z. and Samali, B. (2016), "Evaluating contradictory relationship between floor rotation and torsional irregularity coefficient under varying orientations of ground motion", *Earthq. Struct.*, **11**(6), 1027-1041. https://doi.org/10.12989/eas.2016.11.6.1027.

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Abbreviations

DL	Dead load
SDL	Superimposed dead load
LL	Live load
TIC	Torsional irregularity coefficient
UIF	Unified identification factor
P	Axial load
A	Tributary area
n	Number of floor slabs above a column
BM	Base model
TI	Torsional irregularity
CO	Cut-out in floor slab
NP	Non-parallel lateral force system
MI	Mass irregularity
GI	Vertical geometric irregularity
FC	Floating column