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Preliminary communication

Seismic Performance Evaluation of RC Buildings Using Irregularity Based Indices

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Abstract: Earthquakes may cause structural and non-structural severefig damage and failure during seismic excitations. These collapses and damages start from the weak points of the structures. The reason for these weak points in structures is the mass, rigidity, and discontinuity in the geometry of the structure. These vertical irregularities are one of the major reasons for the failure of structures during earthquakes. Fifteen models are considered in this project to examine the behavior of the building with different heights and vertical irregularities. The seismic response of these selected setback frame structures have been compared with regular frame structures using finite element method-based software SAP2000 v22. In this work regular and setback models of 5 storey, 9 storey, and 13 storey RC frames are considered for modal and dynamic analysis by considering earthquake loads. Furthermore, irregularities indexes comparisons are carried out and discussed in detail for models. The methods used for the analysis are the static method and time history method.

Keywords: discontinuity; R/C building; setbacks; time history analysis; vertical irregularity

1 INTRODUCTION

Today, many buildings are designed with multiple irregularities for serviceability, aesthetic or economic reasons. So, it can be stated that the concept of the regular building is an idealization, and in practice many structures are irregular. Major seismic codes classify structural irregularities as plan and façade irregularities, but the structural irregularities are often available in buildings as a combination [1].

A building can be classified as vertically irregular due to the unequal distribution of structural properties, mass, stiffness, strength, and structural form in the vertical direction individually or in combination. Previous earthquakes (2005 Islamabad earthquake; 2011 South Island earthquake and 2015 Nepal earthquake) have repeatedly demonstrated the vulnerability of vertically irregular building frames. Hence, the seismicity of vertically irregular buildings has been attracted by considerable research attention [2].

Vertical irregularities are caused by instantaneous changes in stiffness, strength, or mass between sequential Storeys. The sudden changes in stiffness and strength are expressed through changes in the structural system along the height of the building, through changes in the height of the floors, changes in plan along the height of the building, changes in the material, etc. Many buildings have suffered significant and unlikely damage due to their irregularities, and thus irregularities can be considered an important parameter for disproportionate collapse resistance or durability [3].

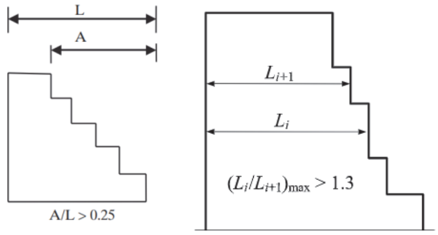
Recent area study shows that majority of the RC building does not meet the building code provisions. The majority of the buildings lack gradual reduction of the stiffness as well strength reduction due to the load path discontinuity. These structural deficiencies increase the seismic vulnerability of the buildings [4].

Therefore, a substantial amount of research noted has been received to appraise the performance of vertical irregular buildings. Valmundsson and Nau 1997 [5]; Rutenberg 2002 [6]; Chintanapakdee and Chopra 2004 [7] Alba et al. 2005 [8]; Fragiadakis et al. 2005 [9]; Karavasilis et al. 2008 [10]; Sadasiva et al. 2009 [11]; Le-Trung et al. 2010 [12]; Gerasimidis et al. 2012 [3]; Pirizadeh and Shakib 2013 [13]; Georgoussiset al. 2015 [14]; Farsangi et al. 2015 [15]; Sudharasana Murthy and Balachandran 2016 [16]; Farsangi et al. 2016 [17]; Priyanka et al. 2018 [18]; Kassem et al. 2019 [19]; Nazri et al. 2019 [20]; Kassem et al. 2020 [21]; Rathnasiri et al. 2020 [22]; Akhil and Sajebb 2020 [23]; Kassem et al. 2021 [24] are some of the past studies that evaluate the performance of the irregular buildings against the earthquake loading.

This study investigates the seismic risk effect over buildings that have vertical irregularity. The different types of vertically irregular buildings that are commonly encountered in urban construction are considered in the present study.

2 STUDIED STRUCTURES AND EARTHQUAKE GROUND MOTIONS

The setback building form is identified by several design codes, such as IS 1893:2002 [25] and ASCE 7:2005 [26] as a typical form of vertical geometric irregularity. As per IS1893:2002, such building forms are to be treated as vertically irregular when the lateral dimension of the maximum offset (A) at the roof level exceeds 25% of the lateral dimension of the building at the base (L), as shown in Fig. 1a. As per ASCE7:2005, when the horizontal dimension of the building in any story (L_i) is more than 130% of that in an adjacent story ($L_i + 1$) this building will be considered as vertically irregular as shown in Fig. 1b [27].



a) IS1893:2002 b) ASCE7:2005.

Figure 1 Vertical irregularity

The plan of the model is shown in Fig. 2. All selected models have the same total height storey of 3.2 meters and the bay length of 6 meters of 3 of them is regular and of the other ones is irregular with different arrangements of setbacks. More detailed information about element dimensions are given in Fig. 3. The buildings are modelled as three-dimensional configurations by SAP2000 V22 [28] software.

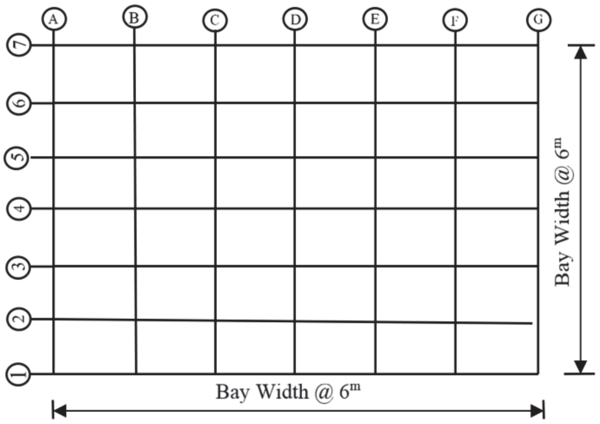


Figure 2 Plan of the Building model

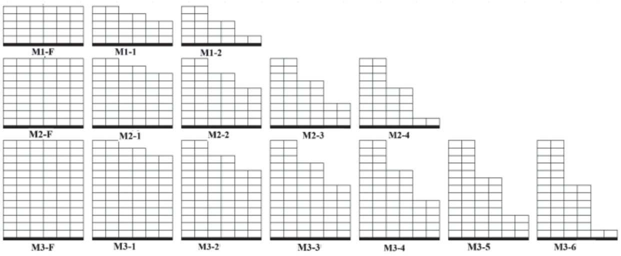


Figure 3 Different structural configurations of the buildings studied

The frame elements, as well as floor and roof slabs, are assumed to be normal weight concrete of class C30-B420C. Columns are defined as 0.85 × 0.85 meters, from the first floor to the fifth, 0.70 × 0.70 meters from the sixth floor to the ninth, and 0.50 × 0.50 meters from the tenth floor to the thirteenth. Dimensions of the columns are defined as 0.30 × 0.60 meters for each story. Slab thickness is defined as 0.18 meters. The width of the retaining walls is defined as 0.50 meters. The dead loads applied on the slab were defined as 1,5 kN/m^2. For the roof, live loads applied on the slab were defined as 3,5 kN/m^2 and for the rest of the stories live loads are defined as 5 kN/m. A rigid diaphragm is defined for each floor. The live load participation coefficient is 0.3, the effective ground acceleration coefficient is 0.3, the building importance coefficient is 1.0, the structural system behavior coefficient is 7.0, and the local soil class is Z3. Wall loads were defined as 3.7 kN/m^2 and 2.7 kN/m^2 for the outer beams and inner beams, respectively. The self-weights of the elements are defined in the SAP2000 finite element program. Beams and columns are modeled as frame elements while floors and shear walls as shell elements.

11 ground acceleration records adapted to the Earthquake level 2 design (DD2) spectrum, defined in the Turkish building earthquake code, were used for the time history analysis. The records are taken from the Pacific Dep. Eng. Res. The Center [29] is given in Tab. 1.

Spectral acceleration graphs obtained according to earthquake level 2 are shown in Fig. 4.

Table 1 Earthquake Data

ID	Earthquake	Year	Station Name	Magnitude	Mechanism	R_{jb} / k	R_{rup} / km	$Vs30$/ m/sec
1	RSN15	1952	"Taft Lincoln School"	7.36	Reverse	38.42	38.89	385.43
2	RSN164	1979	"Cerro Prieto"	6.53	Strike slip	15.19	15.19	471.53
3	RSN313	1981	"Corinth"	6.6	Normal Oblique	10.27	10.27	361.4
4	RSN549	1986	"Bishop - LADWP South St"	6.19	strike slip	14.38	17.17	303.47
5	RSN570	1986	"SMART1 C00"	7.3	Reverse	56.01	56.01	309.41
6	RSN571	1986	"SMART1 E01"	7.3	Reverse	53.31	53.31	308.39
7	RSN574	1986	"SMART1 I07"	7.3	Reverse	55.82	55.82	309.41
8	RSN576	1986	"SMART1 M07"	7.3	Reverse	55.11	55.11	327.61
9	RSN581	1986	"SMART1 O07"	7.3	Reverse	54.17	54.17	314.33
10	RSN582	1986	"SMART1 O08"	7.3	Reverse	54.8	54.8	357.43
11	RSN584	1986	"SMART1 O12"	7.3	Reverse	58	58	303.36

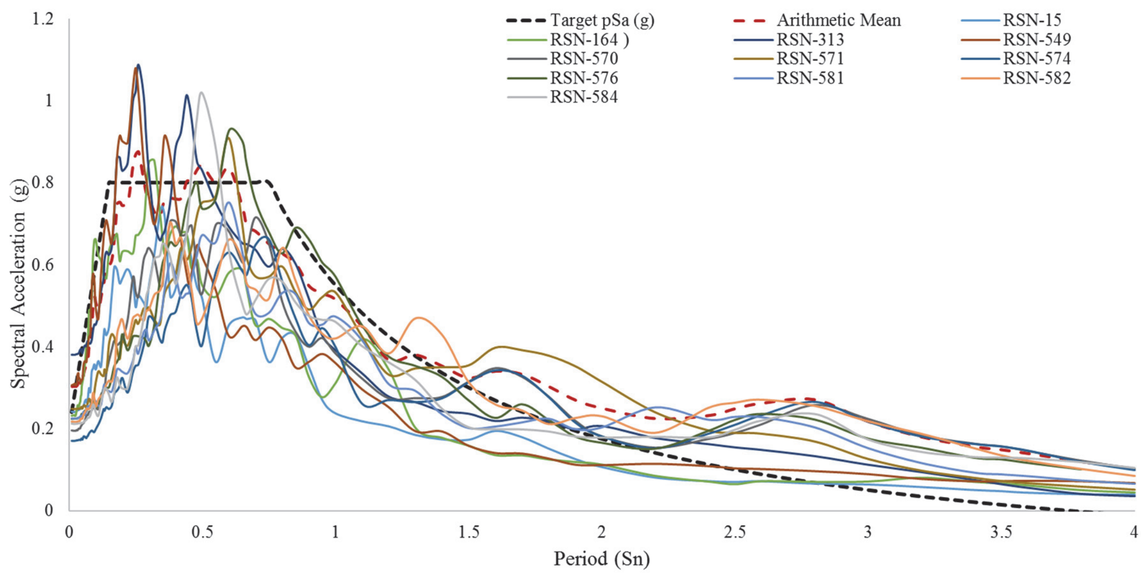


Figure 4 Spectral acceleration graphs

3 IRREGULARITY INDEXES

There are a number of past studies on quantifying the degree of irregularity in irregular building frames. Past studies and published articles have quantified the degree of irregularity in vertically irregular reinforced concrete and steel buildings based on the geometric configurations and using dynamic parameters [22]. In all indexes in the literature, the configuration of the geometric building frame and dynamic properties such as the first mode participation factor, natural vibration frequency, and modal mass of the frame are used. The geometry definition for geometrical irregularity indices is shown in Fig. 5. a summary of the current irregularity indices proposed by past studies to measure the degree of irregularity in vertically irregular buildings is given in Tab. 2.

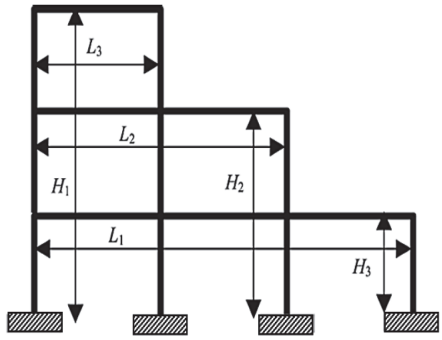


Figure 5 Geometry definition for geometrical irregularity indices [10]

Table 2 Published literature on the vertical irregularity indexes

Index Type	Reference	Formulate
Geometric	Karavasilis et al. (2008) [10]	$\Phi_s = \frac{1}{n_s - 1}\sum_1^{n_s - 1}\frac{L_i}{L_i + 1}$ $\Phi_b = \frac{1}{n_b - 1}\sum_1^{n_b - 1}\frac{H_i}{H_i + 1}$
	Roy and Mahato (2013) [30]	$\Phi_{avg} = \frac{\Phi_s - \Phi_b}{2}$
Dynamic	Sarkar et al. (2010) [27]	$\eta = \frac{\Gamma_1}{\Gamma_{1,ref}}$
	Varadharajan et al. (2013) [31]	$\lambda = \sum_1^k \frac{\omega_{ir}}{\omega_r}$
φ_s and φ_b are geometric irregularities in different setback configurations, η, λ are Dynamic Parameters in different setback configurations, n_s is number of stories; n_b is number of bays; Γ_1 is the 1st mode participation factor of stepped frame and $\Gamma_{1,ef}$ is the 1st mode participation factor for a similar regular frame; ω_{ir} and ω_r are the modal combinations of the frequency of vibration of the irregular and regular building frames from 1st mode to kth mode.		

4 ASSESSMENT OF SEISMIC PERFORMANCE
4.1 Variations in Fundamental Period

The vibration time of the building in the first mode or the time it takes for one vibration cycle of the building in the first mode is defined as the Fundamental natural period [1]. The fundamental natural period of vibration is an intrinsic property of a structure, the fundamental periods of regular and vertically irregular buildings were obtained from finite element (FE) analysis with and without considering the different setback ratio effect. The variation of the fundamental natural period of 5, 9, and 13 setback storey buildings as compared to that of the regular building frames are shown in Fig. 6.

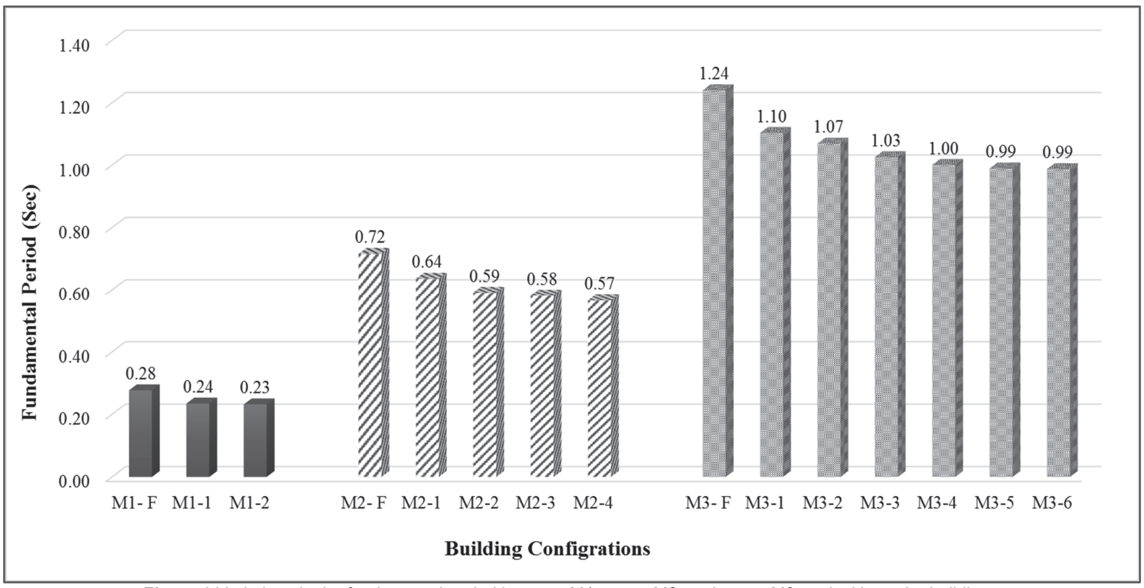


Figure 6 Variations in the fundamental period in group M1, group M2, and group M3 vertical irregular buildings

From the above graphs, it can be observed that the regular buildings have the maximum periods value, whereas the Setback buildings have the minimum periods value for M1, M2, M3 buildings in all setback model types.

Since the changing weights of the buildings affect the amount of horizontal load and stiffness period values, the building periods are different. The fundamental periods of the vertical irregular building are lower than the fundamental period of the regular buildings taken as reference. However, it can be stated that the location of setback and setback level reductions decreases the natural period. The natural periods of the 5, 9, and 13 storey buildings with vertical stiffness irregularity are in the range of 0.23 - 0.24 s, 0.57 - 0.64 s, and 0.99 - 1.1 s, respectively.

4.2 Interstory Drift Ratio

Inter-story drift ratio (IDR) is the maximum relative displacement of each floor divided by the height of the same floor. IDR is one of the most widely used parameters to determine the performance and damage status of buildings under earthquake loads. Fig. 7, Fig. 8, and Fig. 9 show the maximum relative story displacement rates resulting from the dynamic lateral load, Stiffness irregularity index (SII), and Setback effect factor (SEF) values calculated by normalizing according to IDR values for M1, M2, and M3, respectively. The values for the floors were calculated by taking the average of the results obtained for all ground accelerations.

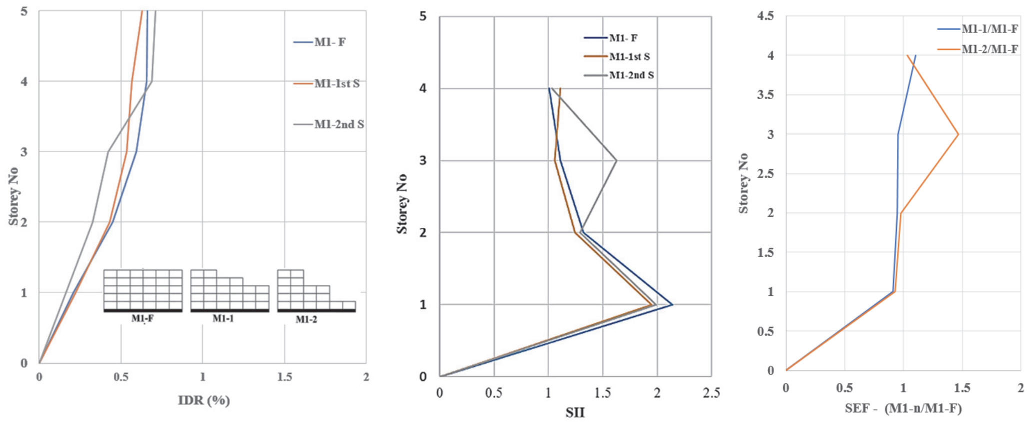


Figure 7 IDR, SII and SEF values of 5th buildings

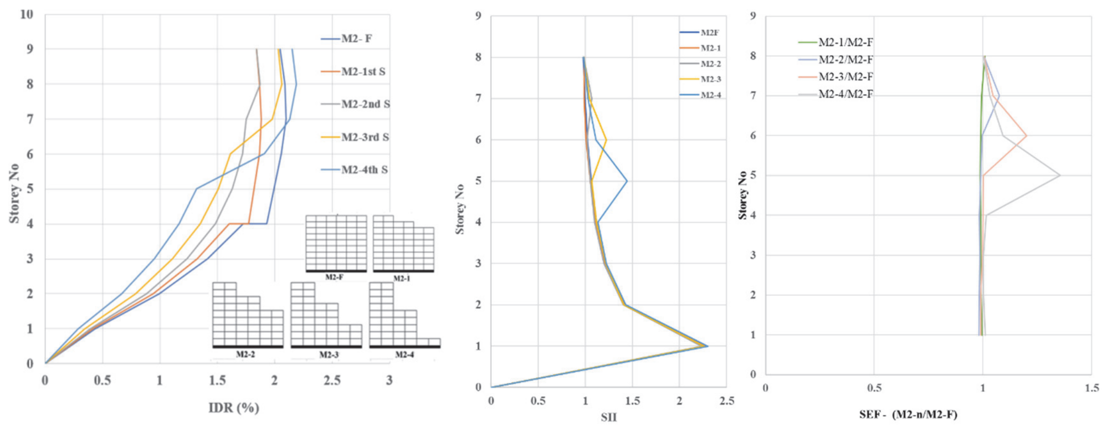


Figure 8 IDR, SII and SEF values of 9th buildings

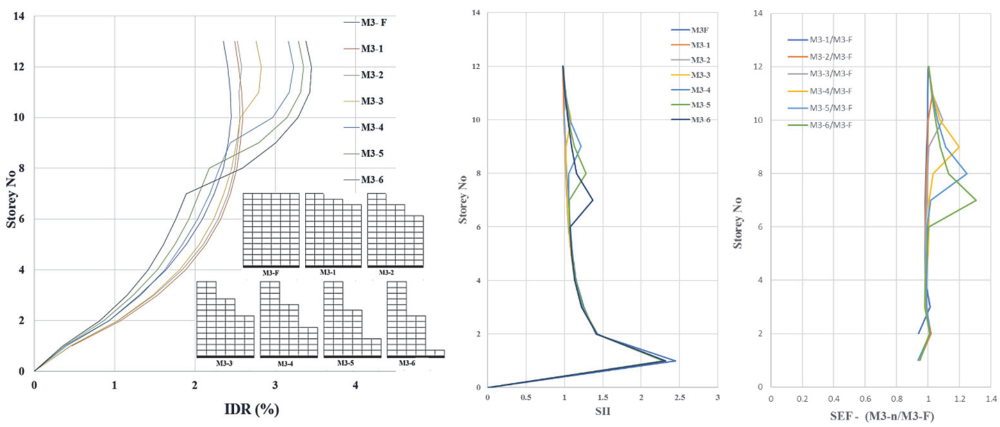


Figure 9 IDR, SII, and SEF values of 13th buildings

If there is a setback in the system, there is a sudden jump in SII values at the first setback level above. Therefore, the upper setback is more important in terms of IDR. When we normalize the SII values in the setback system by proportioning the SII values in the non-setback system, it is seen that there is an increase in the SII values at the upper setback level. The highest values of this increased rate were found as 19%, 47% for 5-storey systems, and 1%, 7%, 20%, and 36% for 9-storey systems, respectively. For 13-storey systems, it was found as 1%, 3%, 9%, 20%, 20% and 30%, respectively.

4.3 Storey Shear

Storey shear is the sum of the design lateral forces at all levels above that storey and base shear is the total design lateral force at the base of a structure. As the span size increases, the size of the coupling beam decreases, and accordingly the base shear decreases. The building with a solid shear wall has a higher base shear force than the combined shear wall because the weight of the structure is reduced due to the opening in the assembled Shear Wall [32].

Irregular buildings have less mass than normal buildings. For this reason, it is quite hard to predict whether irregularity in buildings will lead to an increase in base shear or not [33]. Storey shear is selected as one of the most important response parameters in seismic design practice. The inter-story shear values over height were taken into account for building types and average ground motions data. The average structural shear demands in comparison to fifteen building configurations are shown in Fig. 10 to Fig. 12.

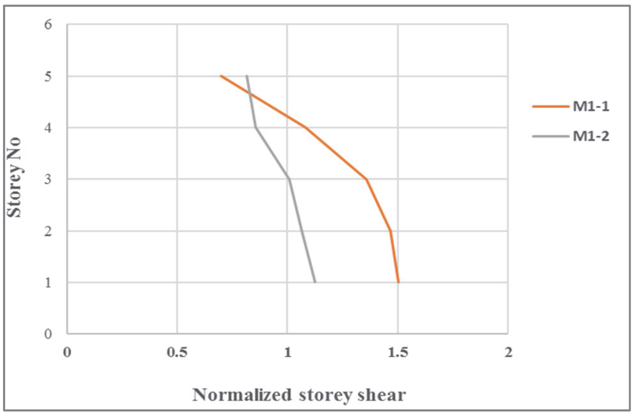


Figure 10 Normalized Storey of Five Storey Buildings

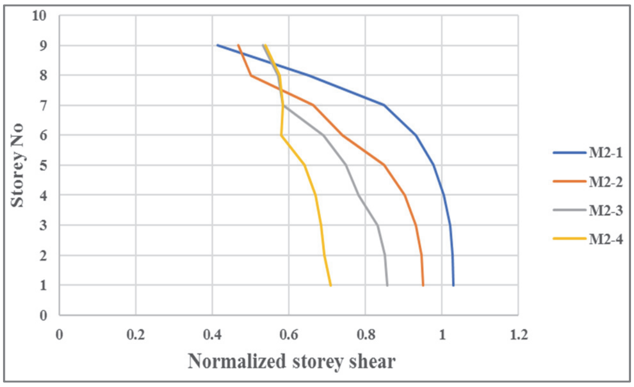


Figure 11 Normalized Storey of Five Storey Buildings

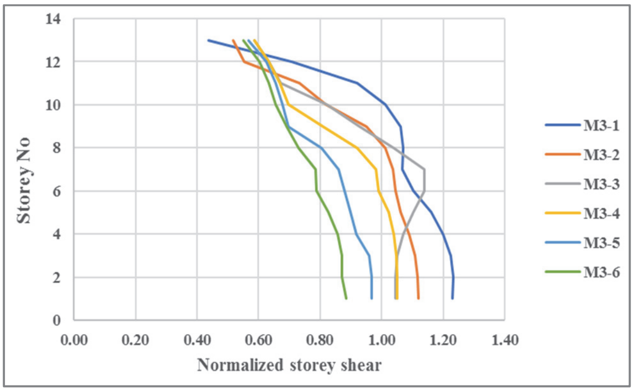


Figure 12 Normalized Storey of Five Storey Buildings

It is clear storey distribution conservatively shows the storey shear for all the frames. The storey shear is low near the top of the building where higher mode effects and variations due to stepping effects are predominant. This implies that the change in base shear is related to the change in the chosen setback structure. Depending on the results obtained, the base shear force in the rigid structure is higher than in the stepped structures, but as the number of storeys increases (on the stories where there is a setback), the storey shear force starts to decrease.

When the storey shear force values of the setback system are divided by the storey shear forces of the non-setback system, it is seen that the shear force ratio does not change much in storeys above the upper setback level.

4.4 Assessment of Irregularity Indexes and SEF Index

There are different regularity indices for quantifying the irregularity of buildings in the literature. Regularity indices of selected building frames are calculated using Karavasilis et al. (2008) [10], Roy and Mahato (2013) [30], Varadharajan et al. (2013) [31], and Sarkar et al. (2010) [27]for this study. Tab. 3 shows Irregularity indexes of the buildings.

M1-1, M1-2, M2-1, M2-2, M2-3, M2-4, M3-1, M3-2, M3-3, M3-4, M3-5, M3-6buildings models are found to be more than one when calculated with the index formulation given by Karavasilis et al. (2008) [10] and Roy and Mahato (2013) [30]. As per these works, the regularity index for regular buildings should be integrity (Bhosale et al., 2017) [34]. The regularity indexes decrease with the increase in the irregularity of the buildings for Karavasilis et al. (2008) [10] and Roy and Mahato (2013) [30] whereas for Varadharajan et al. (2013) [31], Sarkar et al. (2010) [27] it is the opposite. Tab. 3 shows that the regularity indexes for all irregular buildings are less than one according to Varadharajan et al. (2013) [31]. However, regularity indices for some buildings are found to be more than one when calculated with the index formulation given by Sarkar et al. (2010) [27].

Comparisons of the indices found in the literature and suggested in this study are calculated for the 5th, 9th, and 13th storey buildings and are given in Fig. 13 to Fig. 15, graphically.

Table 3 Building irregularities according to some existing indexes

	Amount of Irregularity		Irregularity Indices						
Building Type	Mode 1		IS1893 (2002) [25]	ASCE7 (2005) [26]	Karavasilis et al. (2008) [10]		Roy and Mahato (2013) [30]	Varadharajan et al. (2013) [31]	Sarkar et al. (2010) [27]
	T / Sec	Γ_1			Φ_s	Φ_b	Φ_{avg}	$1/\lambda_r$	$\eta = \frac{\Gamma_1}{\Gamma_{1,ref}}$
M1-F	0.28	0.36	1.00	1.00	1.00	1.00	1.00	1.00	1.00
M1-1	0.24	0.37	0.67	2.00	1.38	1.12	1.25	0.85	1.04
M1-2	0.23	0.43	0.67	2.00	1.38	1.53	1.45	0.84	1.19
M2-F	0.72	0.36	1.00	1.00	1.00	1.00	1.00	1.00	1.00
M2-1	0.64	0.32	0.67	2.00	1.19	1.05	1.00	0.89	0.90
M2-2	0.59	0.35	0.67	2.00	1.19	1.14	1.12	0.83	0.96
M2-3	0.58	0.36	0.67	2.00	1.19	1.30	1.16	0.81	1.00
M2-4	0.57	0.39	0.67	2.00	1.19	1.96	1.24	0.79	1.07
M3-F	1.24	0.36	1.00	1.00	1.00	1.00	1.57	1.00	1.00
M3-1	1.10	0.42	0.67	2.00	1.13	1.03	1.00	0.89	1.18
M3-2	1.07	0.33	0.67	2.00	1.13	1.08	1.00	0.86	0.93
M3-3	1.03	0.35	0.67	2.00	1.13	1.15	1.08	0.83	0.97
M3-4	1.00	0.35	0.67	2.00	1.13	1.25	1.10	0.81	0.99
M3-5	0.99	0.37	0.67	2.00	1.13	1.46	1.14	0.80	1.02
M3-6	0.99	0.38	0.67	2.00	1.13	2.37	1.19	0.80	1.06

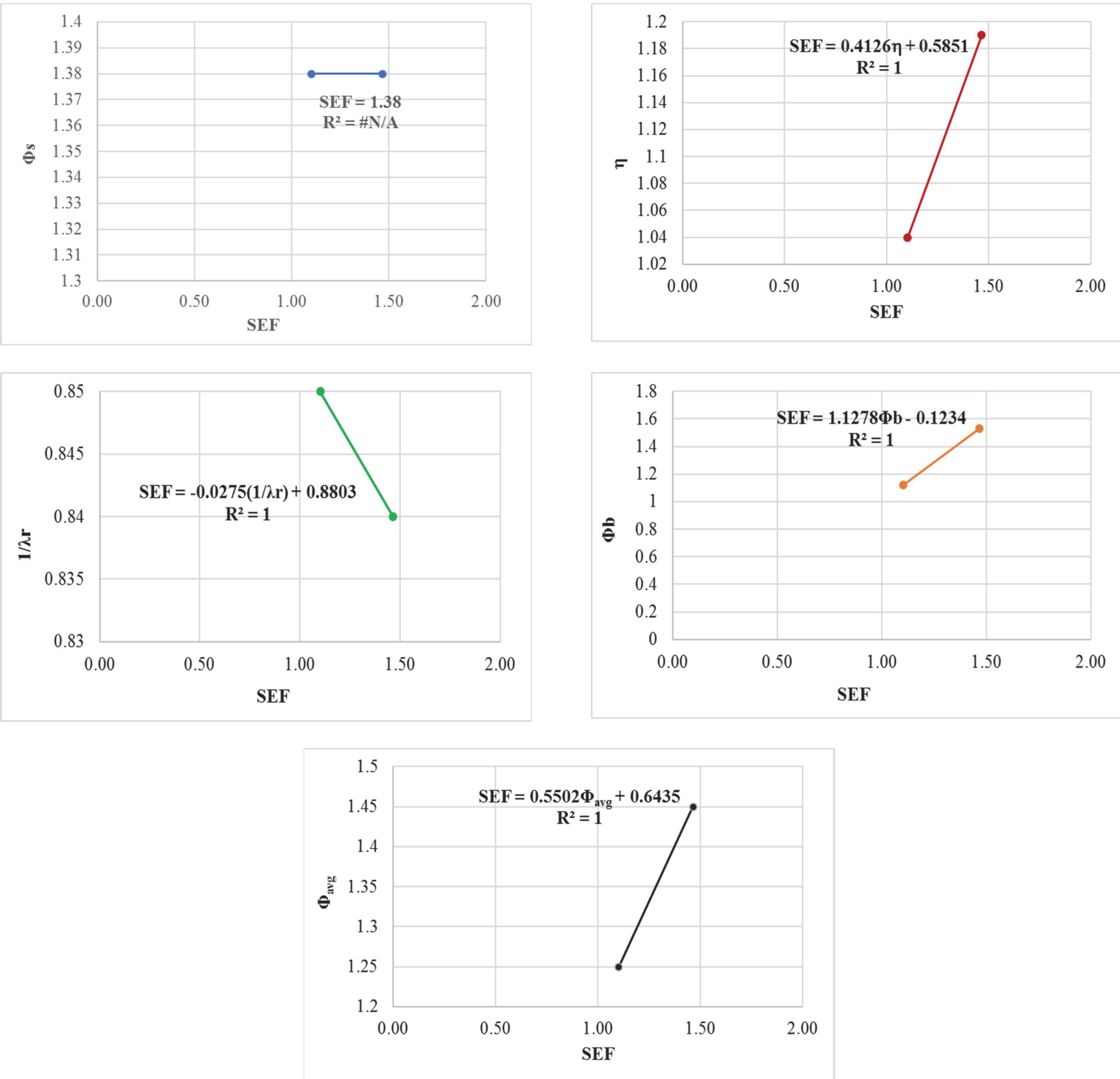


Figure 13 Indexes comparison for The 5th Storey Buildings

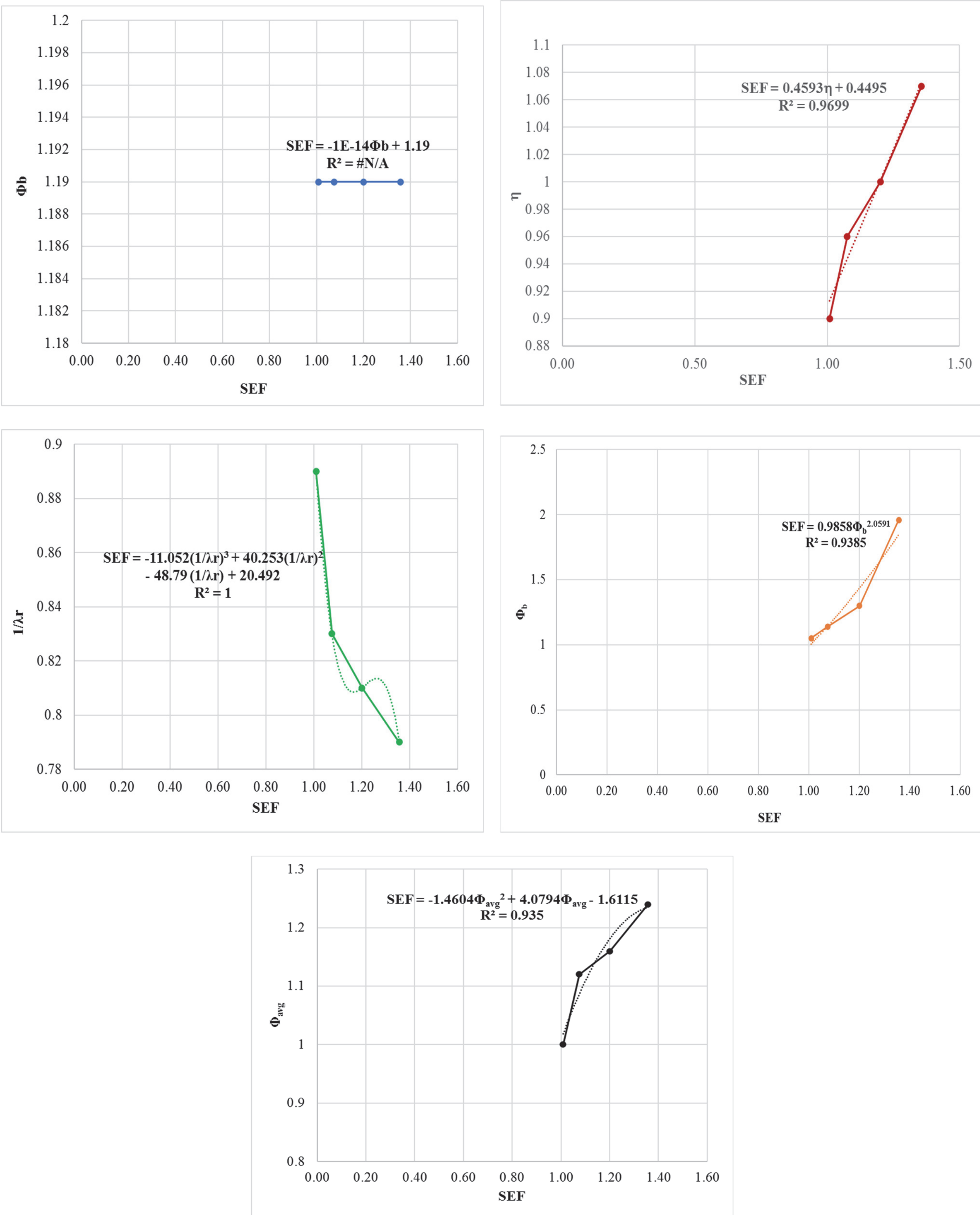


Figure 14 Indexes comparison for The 9th Storey Buildings

The above equations are proposed based on regression analysis and are valid for studied RC buildings in this paper. The proposed equations present the comparison of existing indexes with the SEF indexes that is obtained by dynamic analysis. It is very essential to check the equation proposed. When the correlation between the defined indexes in the literature and the max normalized SII, that is, SEF values, is made, it is seen that the fs index is insufficient to reflect the effect on the IDR that will occur due to the setback, while the other indexes have a certain correlation.

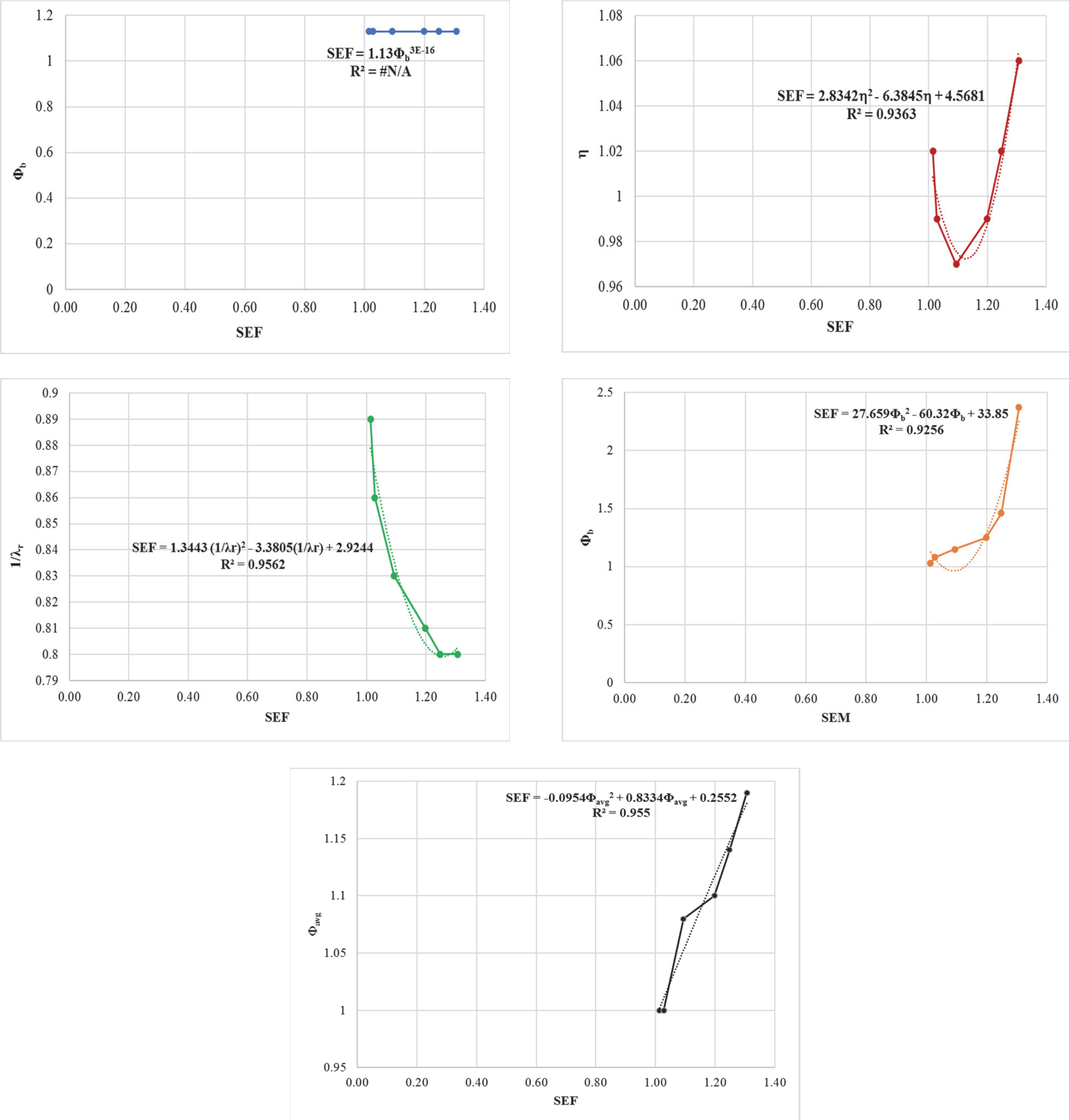


Figure 15 Indexes comparison for The 13th Storey Buildings

5 CONCLUSIONS

This paper represents the relation among seismic risk and degree of vertical irregularity as per existing setback irregularity buildings. It also evaluated the validity of irregularity indexes proposed in the literature. A study has been carried out to evaluate the seismic performance of Vertical setback buildings using time history analysis. The work presented has considered fifteen buildings, which are designed based on vertical irregularities. The accepted simplified indexes were used for the calculation of irregularity.

The major conclusion of the study presented here are as follows:

- It is concluded that vertical irregularity is one of the most important parameters to be considered when checking the irregularity of a building. It is also suggested that the assessment of irregularities in buildings matches with seismic codes of practice and the limitations to ensure that building systems with any irregularities in the lower levels of buildings are prevented.
- In buildings with vertical irregularities, a decrease in mass reduces the fundamental vibration period and a decrease in stiffness increases it.
- In buildings with vertical irregularities, the reduction in the mass decreases the fundamental period of vibration while the stiffness reduction increases it.
- Vertical Irregularity shaped buildings were showed greater displacement than regular-shaped buildings. While the difference in displacement values among all models was insignificant in the lower stories, it increased and reached a peak in the upper stories, especially in the setback-shaped stories.
- it is quite possible for maximum damage to occur over the elements near the setback, also experience proves this. Therefore, it is extremely important to pay attention to

these elements to ensure the level of life safety of the frames.

Therefore, it can be concluded that the performance of buildings with vertical irregularity is more sensitive to earthquake load than that of regular-shaped buildings.

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