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Research Article

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Posted Date: December 9th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-1141410/v1

Evaluation of Seismic Response Modification Factor (R) for Moderate-Rise RC Buildings with Vertical Irregular Configurations

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Abstract: Most international design codes consider the nonlinear seismic performance of a structure by the concept of reduction/modification factor (R). Then, an elastic static force-based method can be normally used for seismic design to create earthquake resistant RC buildings. The response modification factor (R) is sensitive to many aspects such as overall ductility, over-strength, damping, and redundancy levels. Indeed, these factors are severely affected by geometric irregularity of the structural system. So, R-value does not become a constant number for the all types of structures with the same lateral load resisting system, as many standard codes noted. It depends on types, combination, and degrees of geometric vertical irregularity. This research assesses the actual values of R for regular and familiar vertical irregularity cases in RC buildings with moment-resisting frames (MRF) systems. Also, it takes into account the reduction percent that may occurs in R-value due to these studied vertical irregularities. The vertical irregularity cases, such as set-back and soft story, are essentially needed to be studied greater than ever due to the wide propagation of these types of buildings in Egypt, recently. In addition, the potential analytical methods that may be used to calculate R-value in comparison with Egyptian code's value. Nonlinear static pushover analysis is carried out using ETABS via three-dimensional numerical models. The findings prove that vertical irregular models have poor seismic capacities, in comparison with regular one, due to their sudden change in lateral stiffness than that with regular aspect. So, the response modification factor (R) must be re-calculated or even scaled-down before design stage with 15% and 25% for single and combined vertical irregularity, respectively. In addition, this investigation derives a vital equation between R values with vertical irregularity ratios in each studied model. This equation shall be a guide for seismic design codes, structural design engineers, and researchers. Accordingly, the response modification factor R does not become a fixed value regardless vertical irregularity aspects of the buildings, but it has a variable value that depend on their inelastic seismic performance of the lateral load resisting systems.

Keywords: Pushover nonlinear analysis, Vertical geometric irregularity, Response reduction/modification factor (R)

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1 Introduction

The main concept of earthquake-resistant design is that a structure should resist strong seismic event without sudden collapse, although it may be subjected to some structural and nonstructural damages. That is achievable because the structure is designed via seismic force which is less than the required due to its inelastic performance and energy dissipation [1-3]. Recent earthquakes indicate that elastic analysis is not an appropriate tool to evaluate the real seismic performance of RC buildings. While, the nonlinear time history analysis (NTHA) is capable to estimate the probable inelastic response of structures, but it is complex and the results are depending on ground motion contents [4]. So, various seismic codes namely Eurocode-8 [5], ECOL-201 [6], ASCE-7 [7], and IS [8] incorporate response reduction, modification, or behavior factor (R), respectively in their seismic analyses. Other performance-based seismic evaluation methods are used instead of NTHA such as nonlinear pushover analysis (NPA). Many approaches are considered NPA to assess the inelastic performance of structures such as displacement coefficient method of **FEMA-440** [9], capacity spectrum method of **ATC-40** [10], N2 method by **Fajfar and Fischinger** [11], and modal pushover analysis (MPA) [12].

Architectural requirements of building systems often impose the structural systems to have many irregularities in geometry; either horizontal or vertical plane. Vertical irregularities are characterized by vertical discontinuities in the geometry, distribution of mass, rigidity, and strength along the building's elevation. A common two forms of vertical irregularity occurs when there is a reduction in the lateral dimension of the building along its height and change in story's height [13-15]. Such irregularities are known as 'set-back' and soft story irregularities, respectively. Past experiences prove that when vertical irregular buildings locate in an active region, the structural system exhibits poor inelastic performance. So, reliable guidelines are needed for the seismic design regarding these irregularities' effect [16-18].

The main objectives of this paper is to investigate the effects of vertical geometric irregularity on R values of RC structures with moment resisting frame (MRF) systems. This is carried out for many vertical irregularity cases such as: set-back and soft story whether individual case or combined cases. The vertical irregularities alter global ductility and over-strength of the buildings. While, plastic hinges early occur at the weak story with combined vertical irregularity aspect. Subsequently, the response reduction factor (R) should be scaled-down to create dependable earthquake resistant buildings. Most of the past researchers focused on finding the ductility component of the response reduction factor for single-degree-of-freedom (SDOF) systems, 2D frames, or even simple regular buildings neglecting geometric irregularities combination effect. In addition, comparisons between methods of R-value calculations and code are not included in most previous researches.

2 Response Modification/Reduction Factor (R)

The first well-known researches on response reduction factor (R) were conducted by **Newmark and Hall** [19-21]. The proposed formulas for response modification factor (R) is a function of the vibration period, underneath soil, and inelastic displacement [22]. The R factor is a principal seismic design tool, which specifies the level of inelasticity in the lateral load resisting system (LLRS) during the seismic event. As per national earthquake hazard reduction program (NEHRP) [23]; the definition of R factor is "factor depends on both damping and ductility inherent in structural systems which are sufficient enough to approach the inelastic lateral deformation of the LLRS". As such, response modification/reduction factor is used to scale-down the elastic response of the structure [24]. During inelastic seismic performance of a structure, R factor shows the capability of structure to dissipate seismic energy, then reduce the seismic forces in earthquake resistant design of the structure [25, 26]. Also, there are many differences in the response reduction factor's (R) values which specified in different international codes for different types of LLRS. The concept of response reduction factor is the same; to reduce the seismic force and incorporate nonlinearity with the aid of damping, ductility, over-strength, and redundancy aspects [27]. Many researchers in **ATC-40 (1996)** [10] have investigated formulas for calculating the R-factor. The response modification factor (R) is computed as a product of the following four parameters [28, 29]:

$$R = R_{\mu} \times R_{\Omega} \times R_{R} \times R_{\xi} \tag{1}$$

Where; R_{μ} is the ductility, R_{Ω} is the over-strength, R_R is the redundancy, and R_{ξ} is the damping factors [30, 31]. These behavior parameters can be estimated from the nonlinear static pushover (NSP) curve as presented in **Figure 1**.

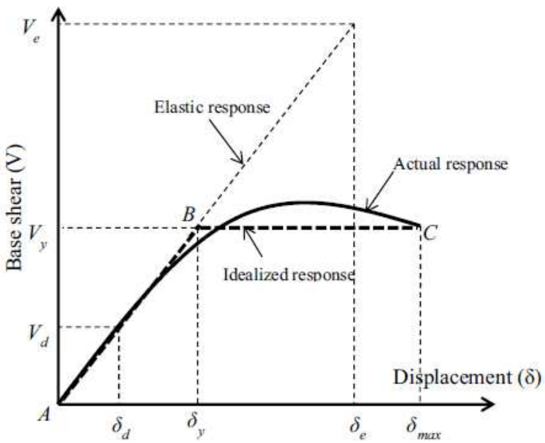


Figure 1 The concept of response modification/reduction factor (R) [32]

Where; Vy and δy are yield base shear and yield displacement, respectively. Ve and δe are elastic base shear and elastic displacement, respectively. Vd and δd are design base shear and design displacement, respectively.

2.1 Ductility Factor (Rμ)

Seismic force reduction occurs as a result of ductility (R_{μ}) that incorporated in the structural system, reinforcement details of elements, and the period of vibration of the structure. This factor is used to reduce the elastic force demand to the level of yield force of the structure. Ductility is classified according to the nature of deformation being considered, whether it is a strain, curvature, rotation or displacement [33].

$$R\mu = \frac{V_e}{V_y} \tag{2}$$

According to another approach of ductility factor (Rμ) which presented by **Uang** [34], Rμ can be determined approximately from the structural ductility ratio (μ) with the help of the fundamental period of vibration (T) as follows:

$$R\mu = 1, \qquad \text{for } T < 0.2 \text{ Sec} \tag{3}$$

$$R\mu = \sqrt{2\mu - 1}, \qquad \text{for } 0.2 \text{ s} < T < 0.5 \text{ Sec} \tag{4}$$

$$R\mu = \mu, \qquad \text{for } T > 0.5 \text{ Sec} \tag{5}$$

The structural ductility ratio (μ) according to **ATC-19** [35] can be defined as:

$$\mu = \frac{\delta_{max}}{\delta_y} \tag{6}$$

Mirenda et al. [36] evaluated the ductility factor (Rμ) with respect of soil coefficient (Φ) as the following equations:

$$R\mu = (\mu - 1) / (\Phi + 1) \tag{7}$$

Where Φ depends on soil conditions and time period.

For rock soil,

$$\Phi = 1 + \frac{1}{10T - \mu T} - \frac{1}{2T} \exp\left(-\frac{3}{2}\left(lnT - \frac{3}{5}\right)^2\right) \tag{8}$$

For medium soil,

$$\Phi = 1 + \frac{1}{12T - \mu T} - \frac{2}{5T}\exp(-2(lnT - \frac{1}{5})^2) \tag{9}$$

For soft soil,

$$\Phi = 1 + \frac{T_g}{3T} - \frac{3T_g}{4T}\exp(-2(ln\frac{T}{T_g} - \frac{1}{4})^2) \tag{10}$$

Where; T, and T_g is the predominant periods of the structure and ground motion, respectively.

2.2 *Over-strength Factor (R_Ω)*

This factor specifies the ratio between the real seismic force dominating in the structural system and the required force demand. Over-strength factor presents the amount of the residual resistant force in the structural system. The main sources of the structural over-strength results from sequential yielding of critical regions, material over-strength, strain hardening, capacity reduction factors, member size, and nonstructural elements [37-39]. In addition, the over-strength is generated because of load factors in various design load combinations and reduced design strength of materials by factor of safety. The over-strength factor (R_Ω) can be estimated as the following equation:

$$R_\Omega = \frac{V_u}{V_d} \tag{11}$$

Where, V_u is the actual ultimate force that will be obtained from the nonlinear pushover analysis, and V_d is the design base shear calculated according to the code [40]. As per the pre-mentioned formulation, the over-strength factor is suggested to be a combination of actual over-strength factor (Ωo) and redundancy factor (RR) as the following.

$$R_\Omega = Vu/Vd = (Vu)/(Vy) \times (Vy)/(Vd) = \Omega o \times R_R \tag{12}$$

Where, Ωo is the actual over-strength ratio of Vu/Vy and R_R is the redundancy factor of Vy/Vd.

2.3 *Redundancy Factor (R_R)*

The local yielding of a certain structural element does not cause the sudden failure of the overall structure. This is because of the excess load in specific elements, which do not reach to a reserve resistance. This is called redundancy. If the failure of a component of a structure leads to sudden failure of the structural system, thus it is termed as non-redundant structure. The redundancy /reliability of any structural system occurs when the system has multiple load paths with correlated characteristics [30, 41]. From past researches, a redundancy factor $R_R = 1.0$ is used in this study.

2.4 *Damping Factor (Rξ)*

Damping factor (Rξ) is used for structures which are provided with additional energy dissipating devices. The damping factor is assumed as 1 for buildings without any devices [42].

3 Codes' values for Response Modification Factor (R)

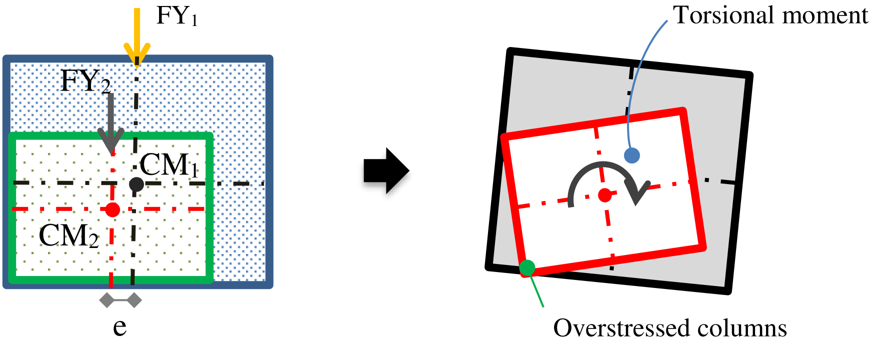
The response modification factor's symbols and magnitudes for any structural system might be significantly different from one design code to another. For example, in the European code (EC8) [5], this parameter is called the behavior factor (q). The American design codes ASCE-7 [43], international building code (IBC) [44], and Indian standard (IS) [8] present it as a response reduction factor (R). In addition, The Iranian standard[45] and Egyptian code (ECOL-201) [6] prescribe it as a response modification factor (R). **Table 1** summarizes the response modification factor (R) in most international codes for RC moment resisting frame system according to its assumed ductility classification.

Table 1 Response modification factor (R) in the international codes

Code	Structural system	Response modification factor (R)
EC8 (2004) [5]	Medium ductility class	3.00
	High ductility class	4.50
ASCE-7 (2010) [43], IBC (2003) [44]	Ordinary moment-resisting frame	3.00
	Intermediate moment-resisting frame	5.00
	Special moment-resisting frame	8.00
NBCC(1994) [46]	Intermediate moment-resisting frame	3.50
	Ductile moment-resisting frame	6.80
IS (2002) [8]	Ordinary moment-resisting frame	3.00
	Special moment-resisting frame	5.00
UBC 97 [47]	Ordinary moment-resisting frame	3.50
	Intermediate moment-resisting frame	5.50
	Special moment-resisting frame	8.50
ECOL 201 (2012) [6]	Sufficient ductility	7.00
	Limited ductility	5.00

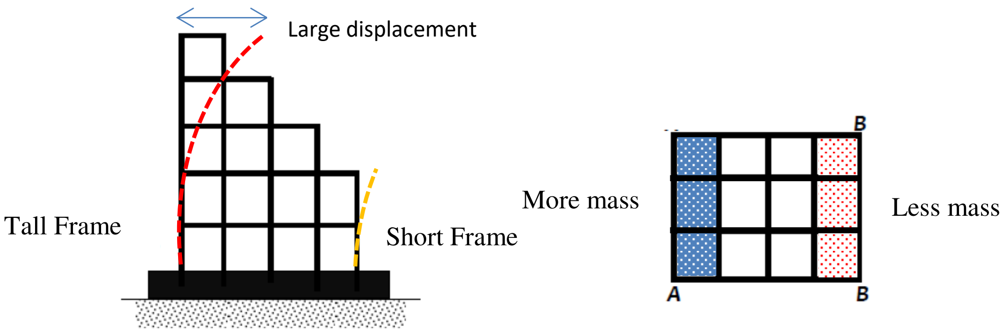
4 Vertical Geometric Irregularity

The regular configuration is an essential indication to strong seismic performance of the structures. The main aspects affecting the dynamic characteristics of structures are overall geometry, structural systems type, and available load paths [48-50]. The difference in usage of a specific floor with respect to the adjacent floors results in irregular distributions of mass, stiffness, and lateral resistance along the building height. Thus, poor seismic performance may be generated and need to be re-checked or additional structural elements must to be added [51]. The building may have irregular distributions of mass, strength, and stiffness along its elevation. In such cases, it can be said that the building has a vertical irregularity. When the center of mass of different stories do not lie along the same vertical line, this results in severe twisting of structures [52], as shown in **Figure 2**. Hence, overstressed columns will be generated and a special concern is required from the structural design engineers. **Figure 3** illustrates that set-back irregularity creates lateral deformation of tall (flexible) part is larger than that of short (stiff) part. So, the seismic force demand imposed on taller frame is greater than that on shorter stiffer one, because of the participating mass source is different in each part [53]. **Figure 4** presents two examples of different failures for vertical irregular buildings with two different vertical irregularity cases. **Figure 4 (a)** and **(b)** present failure mechanism of soft story and set-back irregularity cases, respectively. Where, FY_1 and FY_2 are the seismic force in Y-direction for example of the lower and upper part, respectively. CM_1 and CM_2 are the center on mass of the lower and upper part, respectively. The (e) is an accidental eccentricity due to set-back.



a) Eccentricity in plan b) Accidental twisting

Figure 2 Torsional moment in vertical irregular buildings



a) Elevation b) Plan

Figure 3 Characteristics of buildings with vertical (mass/set-back) irregularity [53]

a) Olive view hospital, San Fernando earthquake (1971)

b) Damaged building, Kobe earthquake, Japan (1995)

Figure 4 Examples of vertical irregular buildings' failure [54]

According to ECOL-201 (2012) [6], there are various cases of vertical irregularities. If any of them occurs, the structure can be classified as vertical irregular structure, therefore traditional equivalent static force method cannot be used:

1. Any story has lateral stiffness less than 75% of the previous one.
2. Change in mass of the story is more than 50% of that in next the story.
3. For gradual set-back structure, set-back in any story is more than 20% of that in adjacent story.
4. For one side set-back with 15% of height, set-back increases with 20% from the previous story's length.
5. For unsymmetrical set-back, total set-backs exceeds 30% of the first story length or 10% of the previous story.

It is unfortunate that no condition in the Egyptian code for response modification factor R is determined for these vertical irregular cases, while its value depends directly on ductility and over-strength ratios.

5 Nonlinear Pushover Analysis (NPA)

Pushover analysis is nonlinear static analysis carried out to determine the capacity of the structure. In this procedure, a predefined lateral load pattern is distributed along the building height. The lateral forces are monotonically increased with lateral displacement till certain level of deformation and plastic hinge modeling as shown in **Figure 5**. For this nonlinear analysis, plastic hinges have been assigned to all of the structural resistant elements [55, 56]. The capacity spectrum method (CSM) allows for a graphical comparison between the structural capacity and the seismic demand. Pushover curve represents the lateral resisting capacity while response spectrum curve represents the seismic demand. Building performance level can be determined by target displacement using the capacity spectrum method according to **ATC-40** [10]. The intersection of the demand spectrum and the capacity spectrum is considered the performance point of the structure. If the base shear at performance point is greater than the design base shear then the structure is safe [55, 57].

The force-deformation behavior of the plastic hinge is labelled **IO** (immediate occupancy), **LS** (life safety) and **CP** (collapse prevention). These labels are used to define the acceptance criteria for the hinges. The procedure of classic nonlinear static pushover (NSP) analysis is only applicable to those structures whose response is dominated by the fundamental vibration mode. Therefore, the nonlinear static procedure is not suitable for tall or irregular buildings as in this research, where the higher modes' effects are significant [58]. To overcome the above limitation; **Chopra and Goel (2001)** [59, 60] proposed a practical seismic evaluation procedure called modal pushover analysis (MPA) procedure. It involves the pushover analysis of all significant participated vibration modes of the irregular structure. For each mode, the pushover forces are made proportionally to the corresponding modal inertia forces.

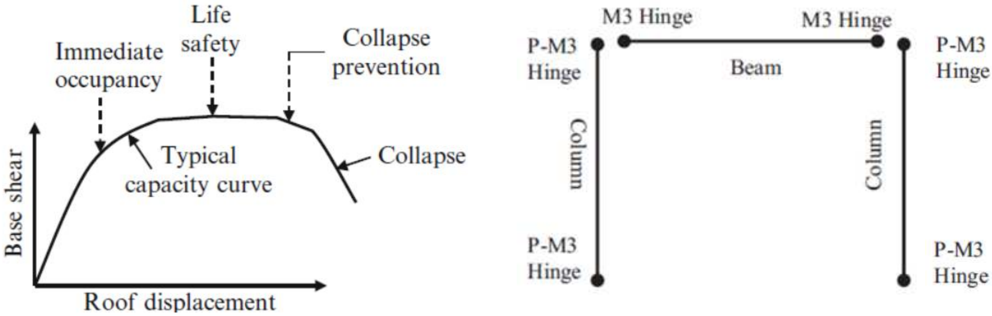


Figure 5 Qualitative capacity curve with performance levels (Limit states) [33] and plastic hinge's location [61]

6 Description of Studied Buildings

Three-dimensional models of the studied buildings are constructed using ETABS [62]. Material properties are assumed to be 30 MPa for the concrete compressive strength, 400/600 MPa for the yield/ultimate strength for longitudinal reinforcement, and 240/350 MPa for transverse one. The presented loads are combined, structural members are designed in accordance with the ECP-203 (2017) [63] specifications. The total dimensions for the plan of the building = 25x20 m, consisting of 5x4 bays of 5m for each one, as depicted in **Figure 6**. The whole height of the structures = 24 m, with 8 typical story of 3 m height. The buildings are solid-slab type with 0.14 m slab thickness and 0.25x0.60m for beams with 4 Ø 16 for longitudinal rebar (bottom and above supports). The loads considered for designing the frames are given in **Table 2**. Seismic characteristics of models are presented in **Table 3**.

Table 2 Summary of vertical loads on floors

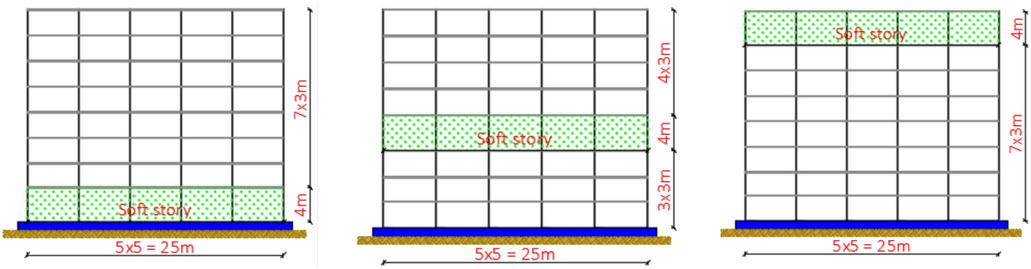
Dead (own weight)	Calculated depending on elements' dimensions	
Live load (Hotels' room)	Typical	2.50 kN/m^2
	Accessible roof	1.00 kN/m^2
Floor covering	Typical	1.50 kN/m^2
	Roof	3.00 kN/m^2
Partitions of 12 cm thickness	Typical only	5.12 kN/m

Table 3 The seismic characteristics of the studied buildings

Building location (zone)	5A	Damping ratio (ζ)	0.05
PGA	0.25g	Response modification factor (R)	5.00
Response Curve	I	Soil type (S)	C
Importance factor (γ)	1.20	Live load % for mass source (Ψ)	0.50

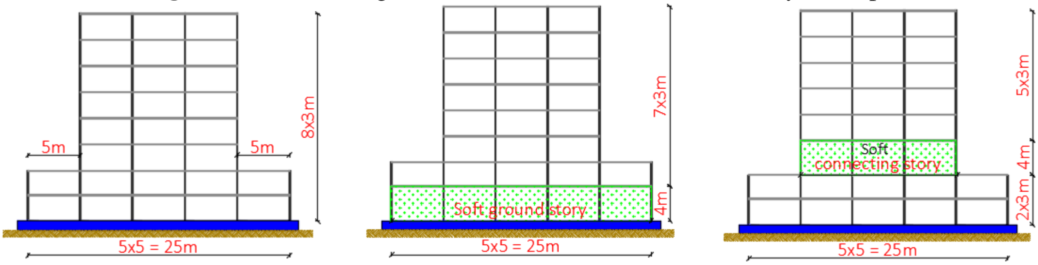
Two types of vertical irregularities are considered in this research. Firstly, stiffness irregularity (soft story) as presented in **Figure 7**, with relative lateral stiffness of the soft story and the following one**.** Secondly, symmetric and asymmetric set-back irregularities are studied with stiffness irregularity as described in **Figure 8** Figure **9**, respectively with 40% set-back in the buildings' length. **Figure 10** shows the three-dimensional for basic models of buildings under study before vertical irregularities' aspects. The nonlinear static pushover analysis is performed for these pre-mentioned sets of models. **Table 4** lists vertical irregularity cases with labels for different models under study. Also, it contains the percent of vertical irregularity percent in each model according to **ECOL [6]**. In addition, soft story ratios (SSr), setback ratios (SBr), and total vertical irregularity ratio (Vtotal) are calculated using inversed values of their relative stiffness for the adjacent stories. Four models (Group-1) are brought for Ref. (regular), Irr. (1, 2, 3) with soft stories in different levels (Ground, third, and Roof). Then, six models (Group-2 and 3) are brought for Irr. T (1, 2, 3) with combination of symmetric set-back with soft story irregularities and Irr. L (1, 2, 3) for combination of asymmetric set-back with soft story irregularities.

Figure 6 Plan of the studied models



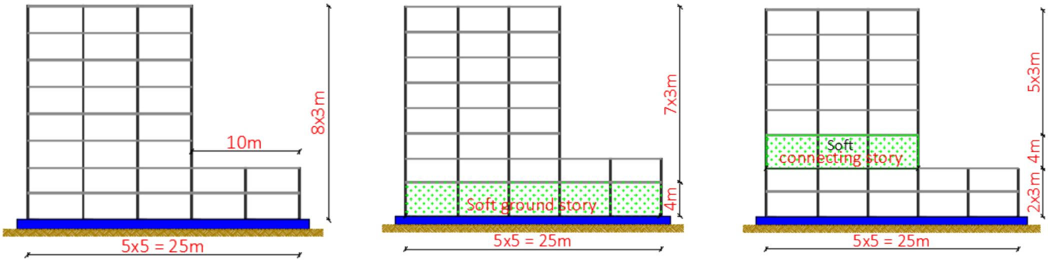
a) Irr.1 model b) Irr.2 model c) Irr.3 model

Figure 7 Vertical irregular models' elevations with soft story (Group-1)



a) Irr. T1 model b) Irr. T2 model c) Irr. T3 model

Figure 8 Vertical irregular models' elevations with combination of soft story and symmetric set-back (Group-2)



a) Irr. L1 model   b) Irr. L2 model   c) Irr. L3 model

Figure 9 Vertical irregular models' elevations with combination of soft story and asymmetric set-back (Group-3)

a) Ref. model   b) Irr. T model   c) Irr. L model

Figure 10 Three-dimensional models for basic buildings under study

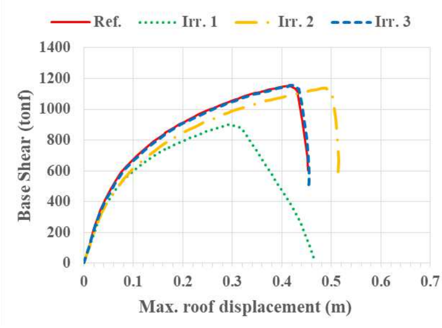
Table 4 Vertical irregularities' cases and percentages due to ECOL-2012 [6] for models

	Models	**Vertical irregularities' cases**	**Soft story ratio**		**Set-back ratio**		**Total Vertical irregularity (Vtotal)**
Group-1	Ref.	None	0	0	0	0	0
	Irr.1	Soft ground story	42 < 75 %	2.38	0	0	2.38
	Irr.2	Soft third story	42 < 75 %	2.38	0	0	2.38
	Irr.3	Soft roof story	42 < 75 %	2.38	0	0	2.38
Group-2	Irr.T1	Symmetric set-back	67 < 75 %	0	40 > 20%	4.63	4.63
	Irr.T2	Symmetric set-back with soft ground story	42 < 75 % 67 < 75 %	2.38	40 > 20%	4.63	7.01
	Irr.T3	Symmetric set-back with soft connecting story	28 < 75%	2.38	40 > 20%	4.63	7.01
Group-3	Irr.L1	Asymmetric set-back	67 < 75 %	0	40 > 30%	4.63	4.63
	Irr.L2	Asymmetric set-back with soft ground story	42 < 75 % 67 < 75 %	2.38	40 > 30%	4.63	7.01
	Irr.L3	Asymmetric set-back with soft connecting story	28 < 75 %	2.38	40 > 30%	4.63	7.01

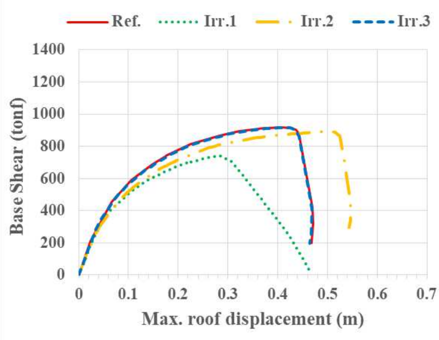
7 Results and Discussion

7.1 Capacity Curve

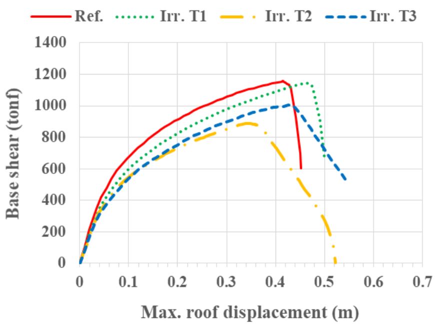
The capacity curves demonstrate the impact of vertical geometric irregularity on seismic capacity of studied numerical models. Then, how ductility and over-strength capabilities of the models will be deteriorated. The maximum capacity curves are plotted for each model in global x and y directions as presented in **Figure 11 (a-f)**. **Figure 11 (a, and b)** plots the capacity curves of the Ref. and Irr. (1, 2, 3) models (Group-1) in the x and y directions, respectively. It is shown that soft ground story of Irr. 1 provides minimum lateral displacement and base shear capability with around 10% and 30%, respectively. **Figure 11 (c-f)** exhibits the capacity curves for inverted T and L models. It is clear that combination of set-back and soft story irregularity reduces the target displacement and base shear with 20% and 40%, respectively. The connecting soft story model is the worst case in comparison with the ground soft story one for L models. There are severe differences between the capacity curves for the studied regular and irregular models due to sudden change in stiffness between adjacent stories. In spite of that, most of the standard design codes use the same value of the response reduction factor (R) for the same structural system regardless obvious variation in inelastic seismic performance.



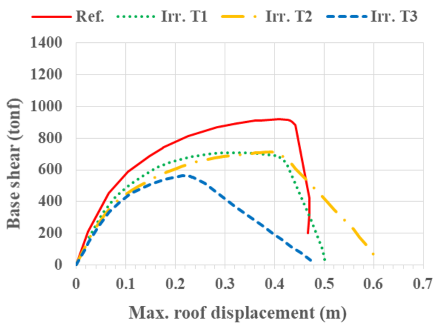
a) X-direction



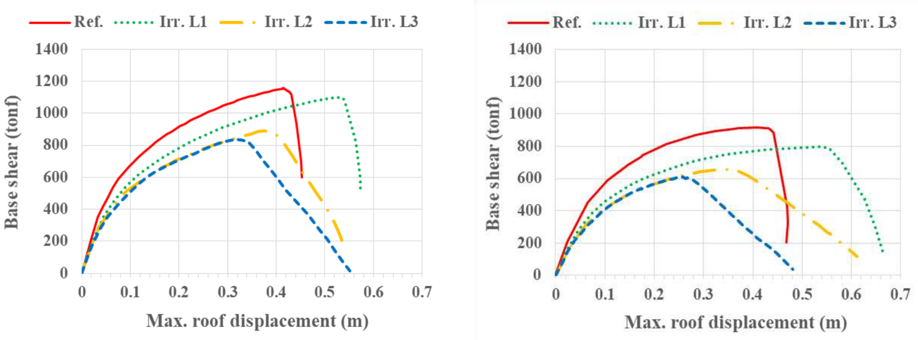
b) Y-direction



c) X-direction



d) Y-direction



e) X-direction f) Y-direction

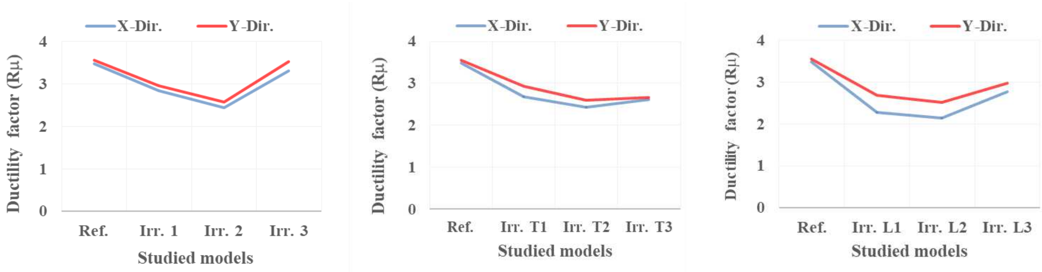
Figure 11 Capacity curve results of studied models

7.2 Ductility Ratio

Figure 12 (a, b, and c) show the obvious variation in the ductility ratios, μ, with vertical irregularity for all the measured models. It is observed that the ductility factors for the soft ground story buildings are lower than reference/regular one by 15-25%. In cases of buildings Irr. T (1, 2, 3) and Irr. L (1, 2, 3), it is observed that the ductility factor for Ref. model building exceeded by over 14-27% and 18-25% for Irr. T and Irr. L, respectively. Irregular buildings T and L with soft connecting story have more ductility than those buildings with soft ground story.

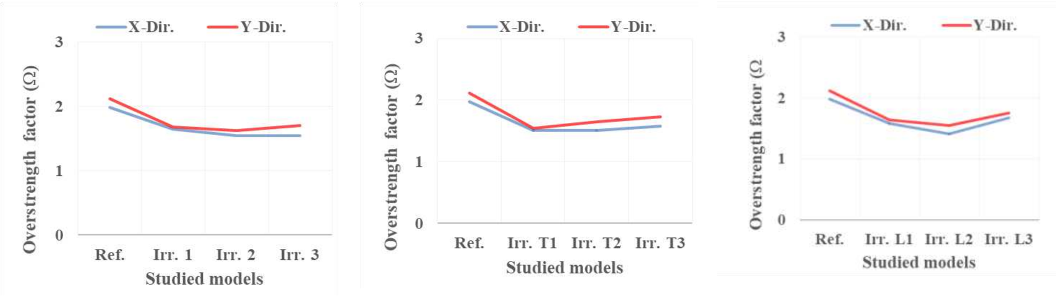
7.3 Over-Strength *Ratio*

Figure 13 (a, b, and c) show the variance of over-strength ratios values with irregular vertical configurations of buildings. It is seen that the irregular models show lower over-strength values in comparison with the regular ones. Where, over-strength factor of the regular Ref. model exceeds by over 20% than irregular models. The soft ground story is the worst case of studied vertical irregularity cases for Irr. L with 10% and 30% reduction in overstrength value compared with models without soft ground story irregularity and regular model (Ref.), respectively.



a) Irr. models b) Irr. T models c) Irr. L models

Figure 12 Ductility factor (μ) for studied models



a) Irr. models b) Irr. T models c) Irr. L models

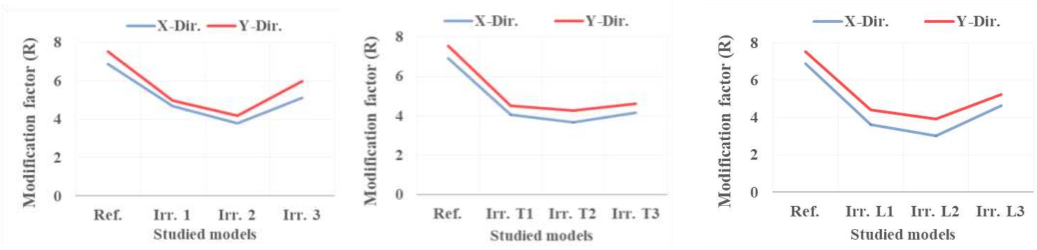
Figure 13 Over-strength factor (Ω) for studied models

7.4 Response Reduction Factor (R)

The response reduction factor (R) has been calculated for all three groups of vertical irregularity via **Mirenda et al.** [36] and **Newmark** and **Hall** [20] equations, in which response reduction factors (R) are sufficient for most design codes. **Figure 14 (a, b, and c)** and **Figure 15 (a, b, and c)** present the variation in R value for different studied models. Where, in case of combination of set-back and soft story irregularity, response reduction factor (R) becomes less value for less ductility and over-strength aspects with 40%. It decreases nearly with 30% for models with soft stories only. Mirenda equations give over-estimated values for response reduction factor than Newmark, which become more realistic values for bare moment resisting frames. Eurocode-8 (2004) [5] states that for vertical irregular buildings, the response behavior factor (R) shall be reduced by 20% as impact of these irregular configurations. Besides, ASCE (2010) [43] prevents these types of buildings with extreme vertical irregularity to be constructed in active seismic zones (E and F). For Egyptian Code ECOL 201-2012 [6], there are no clear provisions for these types of structures according to R value, while the structural system only is the dominating term regardless its configurations.

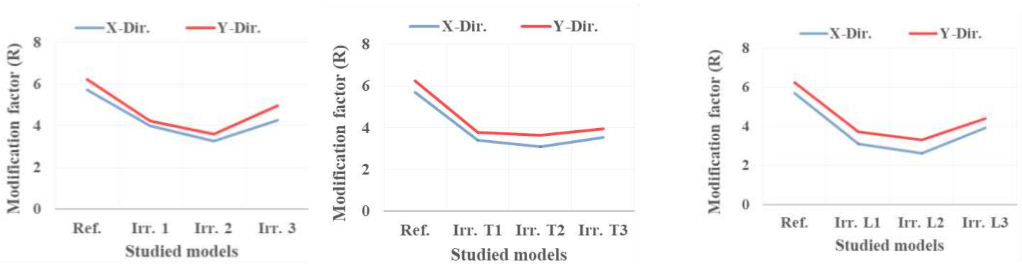
Figure 16 (a, b, c, and D) illustrate percentage of reduction in response modification factor (R) for models under study according to ECOL code's value that equals to 5 for moment resisting frame with limited ductility system. It is shown that Irr. L2 model with combination of asymmetric set-back and ground soft story has the worst value of R with 32% reduction in comparison with Ref. model. Most of reduction percentages in R for the vertical irregular models via Newmark equation are nearly corresponding to 20% reduction that approved via Eurocode as a precautionary step due to geometric irregularity. The differences in R values via Newmark and Mirenda are between 15 to 25% for models under study either in X or Y directions. In spite of that, both Newmark and Mirenda equations are overestimated for Ref. model in R value's calculation with 15 and 30%, respectively.

Figure 17 presents the relationship between the response reduction factor for Newmark and Mirenda with the vertical irregularity ratios as shown previously in **Table 4**. It is clear that vertical irregularity changes any value of R factor with polynomial relationship as list in equations from 13 to 16 with correlation factor equals to 0.75. These equations and charts can be used from seismic design codes as a guide to calculate R value before design stage. Also, Both Newmark and Mirenda have a significant trend with Vt ratios as a vertical irregularity indicator.



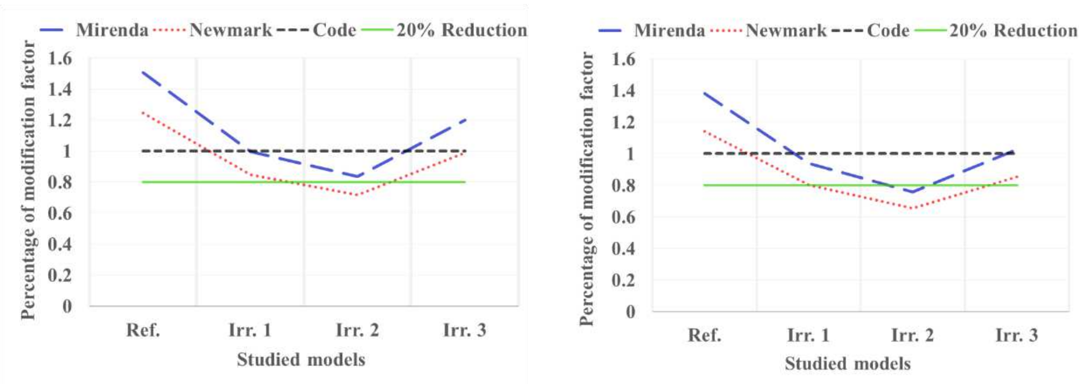
a) Irr. models b) Irr. T models c) Irr. L models

Figure 14 Resonse reduction Factor (R) via Mirenda et al. [36]

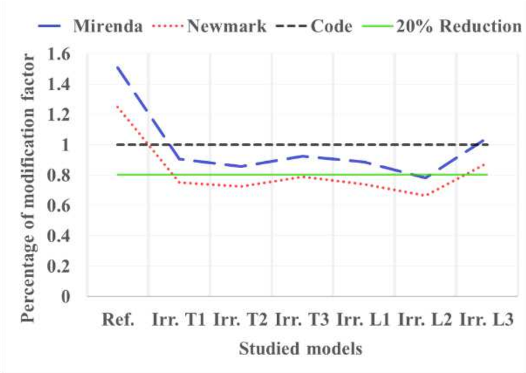


a) Irr. models b) Irr. T models c) Irr. L models

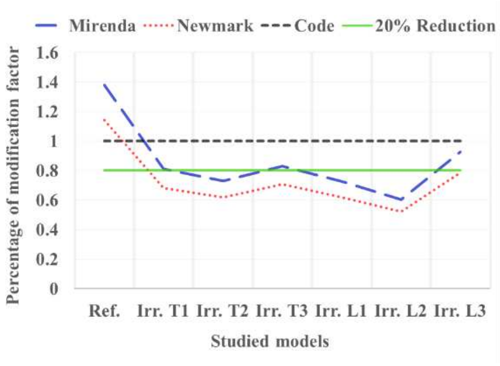
Figure 15 Resonse reduction Factor (R) via Newmark and Hall [20]



a) X-direction for soft story models b) Y-direction for soft story models

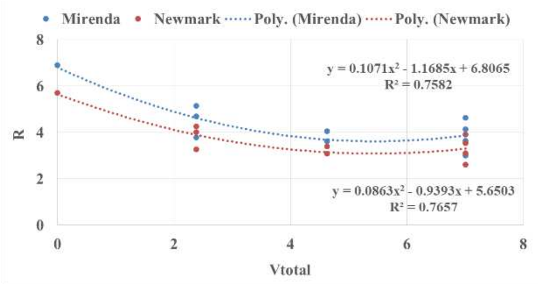


c) X-direction for set-back models

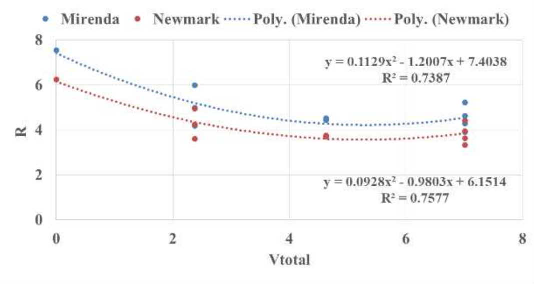


d) Y-direction for set-back models

Figure 16 Percentage of convergence in response modification factor (R) relative to value (R=5) of ECOL code [6]



a) X-direction



b) Y-direction

Figure 17 Relationship between reduction factor (R) and Vertical irregularity ratios

- For Newmark equation:

$$R = 0.086(Vt)^2 + 0.939\ (Vt) + 5.65, \text{ for X-direction} \quad (13)$$

$$R = 0.093(Vt)^2 + 0.980\ (Vt) + 6.15, \text{ for Y-direction} \quad (14)$$

- For Mirenda equation:

$$R = 0.107(Vt)^2 + 1.168\ (Vt) + 6.80, \text{ for X-direction} \quad (15)$$

$$R = 0.113(Vt)^2 + 1.200\ (Vt) + 7.40, \text{ for Y-direction} \quad (16)$$

8 Conclusions

The objective of this study is to identify an appropriate evaluation for response reduction factor (R) of vertical irregular RC moment resisting frame buildings. From the illustrated results, it can be concluded that many variations occur as a result of vertical irregular configurations. While most of international building codes provide many criteria to classify the vertical irregular structures. But without any specifications about their effect are mentioned on the R value.

Whereas, it is considered the main factor in equivalent elastic seismic force calculation. Soft story and set-back irregular buildings are leading to unsymmetrical stiffness and mass distributions. So, their reduction factors (R) need to be scaled-down through modal nonlinear static pushover analysis. Based on the obtained results, the following conclusions can be drawn for the studied models:

1) Vertical irregular buildings suffer from less top displacement and base shear capacity with 10% and 30%, respectively for soft story irregular buildings compared with regular one. Moreover, about 20% and 40% reductions occur in top displacement and base shear capacity, respectively, for buildings with combined set-back and soft story vertical irregularities.
2) The ductility and over-strength ratios are sensitive to vertical irregular configurations with 15% and 20% for building with soft story and combination of soft story and set-back irregularity, respectively.
3) The seismic force reduction using R factor become highly misleading value for vertical irregular buildings. Indeed, the calculated R value is reduced by 20-40% due to obvious defect in overall ductility and over-strength.
4) Newmark equation has more reliable approach to determine response modification factor (R) than Mirenda equation. While, both of them boost the reduction percent of 20% for R value of the vertical geometric irregular structures.
5) The seismic design codes need to be updated through additional precautions for buildings with vertical irregular configurations in case of one type of irregularity occurred or combination of some of them.
6) The response modification factor (R) in ECOL-201 2012 [6] needs to be scaled-down with sufficient percent as EC-8 [5] for vertical irregular buildings, especially for combined ones as T1, T2, L2, and L3 models.
7) There is a significant relationship between the response reduction factor (R) and vertical irregularity percentage (Vtotal) with correlation factor equals to 0.75. These equations may be vital guide for structural design engineers and researchers.

According to the above results, vertical irregularities in RC buildings have a significant voice to alter inherent properties of inelastic seismic performance such as ductility, over-strength. So, the response modification factor R does not become a fixed value regardless vertical irregularity aspects of the buildings.

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