EVALUATION OF SEISMIC BEHAVIOR OF VERTICAL GEOMETRIC IRREGULAR RC MOMENT RESISTING FRAME STRUCTURES

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ABSTRACT

Now-a-days many buildings are designed with vertical geometric irregularity due to architectural, aesthetic or funtional reasons. However, during an earthquake, there is a possibility of damage of the building at the point of weakness induced by the vertical geometric irregularity at any storey level. In this paper, a comprehensive numerical study has been conducted to assess the seismic behavior of reinforced concrete (RC) moment resisting frame structures with vertical geometric irregularity. Regular 4, 6 and 10-storied RC moment resisting buildings were designed as Intermediate Moment Resisting (IMR) frames considering the response reduction factor (R) value of 5 as per BNBC 2020. Irregularity cases were considered due to presence of setback at top floor and mid floor level of the each building. Base shear vs. roof displacement curves were generated from the results of pushover analysis. From the obtained result, it shows that storey drifts of the irregular buildings were within the code specified allowable limit. Fundamental periods by modal analysis of the regular buildings were shown higher than that of the vertical geometric irregular buildings. No significant change in overstrength factors were found due to geometric irregularity. The values of ductility factor of geometric irregular buildings were found always lesser than that of the regular building. R values in vertical geometric irregular buildings were found lesser than that of the regular one. However, those obtained values also satisfied code recommended R values except 4 and 10-storied upper setback buildings. These two buildings result R values 3.14 and 3.92, respectively.

Keywords:*Vertical geometric irregularity, intermediate moment resisting frame, pushover analysis, ductility factor, response reduction factor*

1. INTRODUCTION

Earthquake is one of the deadliest forms of natural hazards as observed from the previous events. Bangladesh is located at seismically active region. Global seismic hazard maps indicate that Bangladesh is located in moderate to high seismic hazard zone with a maximum peak ground acceleration of 0.25g with 10% probability of exceedance in 50 years (Giardini et. al., 1999). During an earthquake, failure of a building may be triggered at the point of weakness in lateral load resisting system occurred by irregularity of the structure. The weaknesses in a RC moment resisting frame structure may be created by discontinuities in stiffness, strength or mass between adjacent storeys. Such weakness may also be found due to sudden variation in the frame geometry along the height. This type of building is known as setback building (Mouhine & Hilali, 2022). This type of vertical irregular building is becoming popular in modern building construction. Many researchers from previous to till now have worked particularly with the seismic behaviour and safety issues concerned with the vertical geometric irregular structures. An experimental study was conducted for a six storied building having a 50% setback at mid-height of the moment resisting frame structure by Shahrooz & Moehle (1990). They studied the influence of setbacks on the dynamic response and the adequacy of current equivalent static and dynamic design requirements for the setback buildings and found that the conventional dynamic and static design methods were inadequate to prevent concentration of damage in members near the setback for certain configurations. Wong & Tsu (1994) studied the elastic response of setback structures by response spectrum analysis and found that the modal weights of higher order modes for setback structures were large and the seismic load distributions by response spectrum analysis were different from that of the static code procedures. Valmundsson & Nau (1997) evaluated the Uniform Building Code (UBC) limits for vertical irregular buildings. Three RC moment resisting frame buildings with five, ten and twenty stories were considered in their study. They concluded that the mass and stiffness vertical irregularities had a minor impact on the ductility demand compared to the strength vertical irregularity. Athanassiadou (2008) conducted an assessment for two-dimensional plane frames with two and four large setbacks in the upper floors, respectively and another one which was regular in elevation. The study concluded that the seismic performances of geometrically irregular structures were satisfactory. Most plastic hinges in the irregular frames were generated in beams at the design earthquake, which was consistent with the strong columns–weak beams design approach. Varadharajan et al. (2013) examined the behaviour of irregular buildings subjected to 27 natural seismic excitations. A total of 195 frames with different geometrical arrangements of setbacks were considered. The study concluded that the fundamental periods and inter-story drift ratios were affected by the setback irregularity configuration and proposed equations that can estimate realistic periods of setback frames incorporating the cracking effects. Therefore, the main objective of the current paper is to assess the seismic response of vertical geometric irregular structures designed as per BNBC 2020. The presence of setback was considered at top floor and mid floor level of 4, 6 and 10-storied RC moment resisting frame structures. Equivalent static and nonlinear static or pushover analysis were conducted. Seismic performance in terms of ductility factors, overstrength factors and response reduction factors were evaluated.

2. RESPONSE REDUCTION FACTOR (R)

The basic principle of earthquake resistance design of any structure is that the structure should not be collapsed but small damage to the structural and non-structural elements is permitted. By allowing some structural and non-structural damage, a high level of life safety can be economically achieved in structures. Structural members are designed to resist the effects of loads including the earthquake. Inelastic deformations may be utilized to absorb certain levels of energy leading to reduction in the forces for which structures are designed. This leads to the idea of response reduction factor (R) which reflects the capability of the structure to dissipate energy through inelastic behaviour (Mahmoudi & Zaree, 2013). National Earthquake Hazards Reduction Program (NEHRP) provision defines R factor as "R factor is intended to account for both damping and ductility inherent in structural systems at the displacements great enough to approach the maximum displacement of the systems". As per report ATC 19 (1995) a new formulation for R in which R was expressed as the product of overstrength factor, ductility factor and redundancy factor were presented. The equations were as follows:

$$R = R_S . R_\mu . R_R$$

where, R_S is overstrength factor, R_μ is period dependent ductility factor and R_R is redundancy factor.

Overstrength factor (R_S) is the ratio between the yield base shear to design base shear as provided in below:

$$R_S = \frac{V_y}{V_d}$$

where, V_y is the yield base shear and the V_d is the design base shear force.

Ductility factor R_μ is defined as a function of the period of the structure, the damping, the type of behaviour and the displacement ductility ratio. It is primarily influenced by the period of vibration and the level of inelastic deformation, and to a much lesser degree by the damping and the hysteretic behaviour of the system (Mahmoudi & Zaree, 2013). Proposed equations for ductility factor by Newmark and Hall, 1982 were as follows:

For structures having periods (T) below 0.03 second:

$$R_{\mu} = 1$$

For structures having periods (T) between 0.12 second and 0.5 second:

$$R_{\mu} = \sqrt{2\mu - 1}$$

For structures having periods (T) exceeding 1 second:

$$R_{\mu} = \mu$$

Base shear vs. roof displacement curve or pushover curve is found from nonlinear static or pushover analysis. Bi-linear idealization of pushover curves provides the key components, which are the significant yield strength, the significant yield displacement as well as the predetermined design strength and the ultimate displacement. Equal-energy method is widely used for bilinear approximations to extract the relevant information from pushover curve proposed by ATC 19. A generic illustration of the bi-linear approximation using equal energy concept is given in Figure 1. This approach is utilized in the current study.

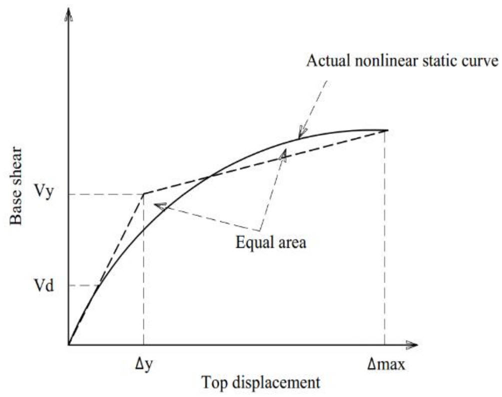


Figure 1: Bi-linear approximation of pushover curve

3. ANALYSIS OF CONSIDERED BUILDING MODELS

In this study, regular 4, 6 and 10-storied RC moment resisting frame structures were designed as Intermediate Moment Resisting (IMR) frames considering the response reduction factor (R) value of 5 as per BNBC 2020 and then vertical geometric irregularity cases were imposed on them. All the studied structures had the same symmetric plan configuration with 4 nos. of bays along each direction as shown in Figure 2. Bay width was considered 5m and typical storey height was 3m. Grade beams were provided at 1m height from the base. Fixed supports were considered at the base of the considered buildings.

Column sizes for 4, 6 and 10-storied buildings were 375 x 375 mm, 450 x 450 mm and 550 x 550 mm, respectively and reinforcement percentage was varied from 1% to 2.48%. Floor beam sizes were considered as 250 x 375 mm, 300 x 450 mm and 300 x 450 mm.

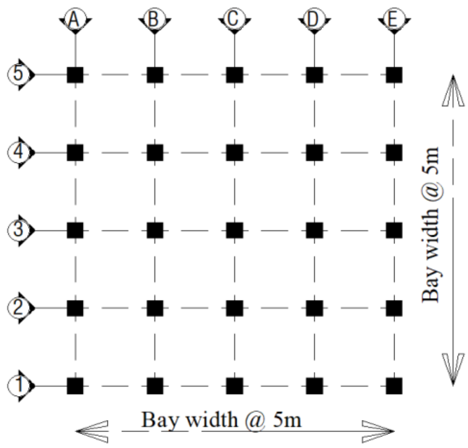


Figure 2: Plan view of 4, 6 and 10-storied buildings

According to BNBC 2020, in case of one-stepped setback building, geometric irregularity will be considered when the horizontal dimension of lateral force resisting system in any storey is more than 1.3 times of that in the adjacent storey. In this study, ratio of horizontal dimension for 1 bay setback was used as 1.325 times of the in the adjacent storey. Two types of geometric irregularity configurations: B1-upper and B1-mid were considered. Upper means the setback was provided at the roof level and mid means the setback was provided at the mid storey level. All the setbacks were provided at the same number of bay and at the same storey level from both horizontal directions. A typical figure of upper and mid geometric irregular building has been shown in Figure 3.

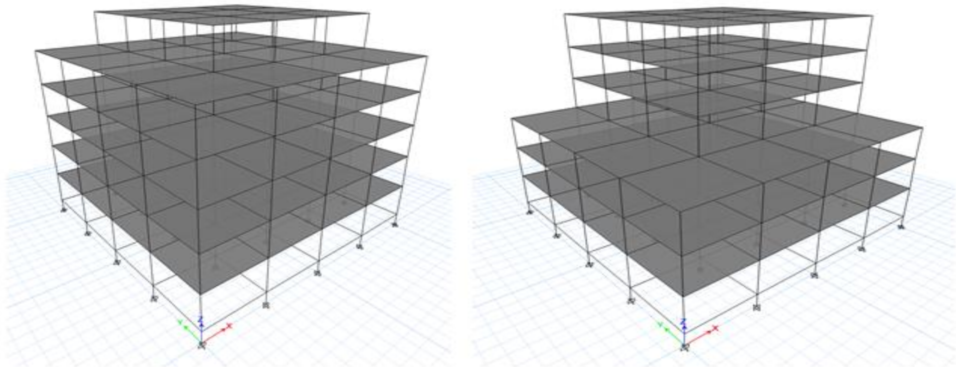


Figure 3: 3D views of 6-storied upper and mid geometric irregular buildings

Total vertical load for floor finish applied on the structure was 1.5 kN/m^2. Live load applied on the floor levels was 2 kN/m^2 and on the roof was 1 kN/m^2. Thickness of the slabs was 150 mm. Earthquake load (EQ) has been considered as per BNBC 2020. Equivalent static load method was used with response reduction factor, R = 5 and associated other factors. In determining seismic weight, a 25% of live load was considered. Other parameters used in seismic load calculation are Z = 0.2, I = 1.00 and S = 1.15 as per BNBC 2020. Compressive strength of concrete and yield strength of rebar were 27.6 MPa (4 ksi) and 414 MPa (60 ksi), respectively.

Nonlinear static or pushover analyses were performed and corresponding curves were generated. The uniform and triangular lateral load patterns are recommended by the FEMA 356. In this study, triangular lateral load pattern consistent with the fundamental mode shape of the building was used. Axial force biaxial moment interaction hinges (P-M2-M3) were assigned for the columns and moment hinges (M3) were assigned for the beams. The plastic hinges were assigned to the end of the members.

4. RESULTS AND DISCUSSIONS

In this section, results of the analyses for different regular and irregular building models are presented and discussed with an aim to assess the seismic response of vertical geometric irregular structures. Figure 4 shows the storey drifts of 4, 6 and 10-storied regular and geometric irregular frames. Storey drifts of geometric irregular frames were found within allowable drift limit as per BNBC 2020.

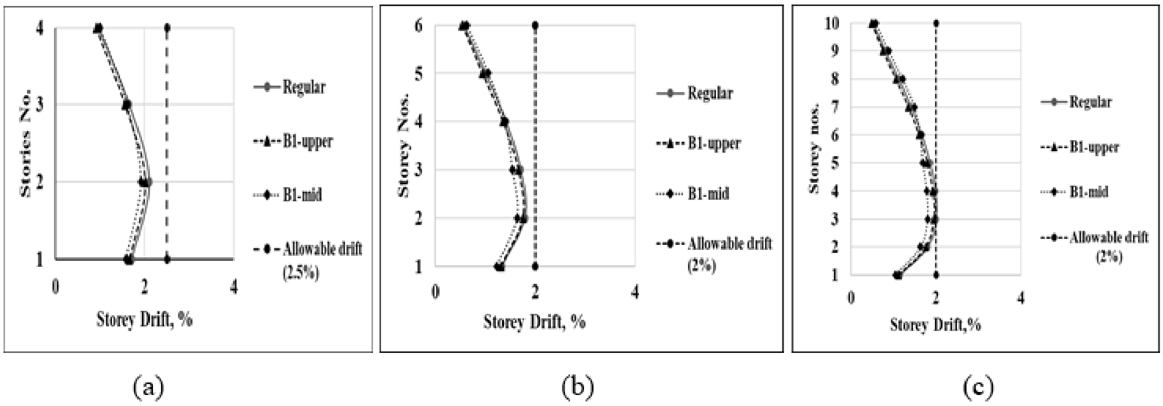


Figure 4: Storey drifts of 4, 6 and 10-storied regular and vertical geometric irregular buildings

The fundamental period (T) of any building can be determined by the following BNBC 2020 code equation:

$$T = C_t \left(h_n\right)^m$$

For the concrete moment resisting frame structures, the value of C_t and m are 0.0466 and 0.9, respectively. The main parameter in estimation of T in accordance with code equation is the building height. Presence of any vertical geometric irregularity in the building does not affect the period of that building. Table 1 shows the T of regular and vertical geometric irregular buildings by code equation.

Table 1: Fundamental period of regular and vertical geometric irregular buildings by BNBC 2020 code equation

Model	Period by code equation, sec		
	Regular	B1-upper	B1-mid
4 storied	0.47	0.47	0.47
6 storied	0.66	0.66	0.66
10 storied	1.02	1.02	1.02

In case of estimation of time period, T by modal analysis procedure mass, stiffness and angular frequency of the structure are taken in consideration. The equation of T of the building is as follows:

$$T = \frac{2\pi}{\omega_n}$$

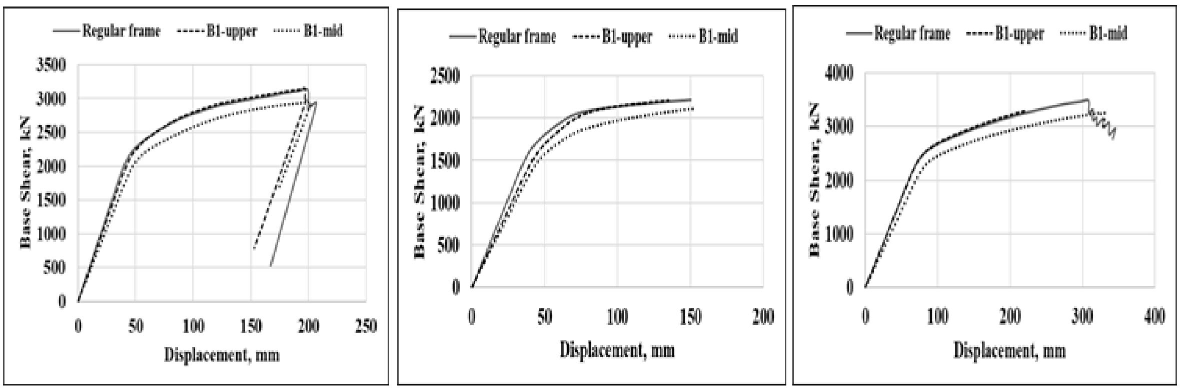
where, ω_n is the angular frequency of the building.

In this study, values of T by modal analysis for first three modes were obtained directly from finite element analysis software ETABS (2016).Table 2 shows the modal period (T) of 4, 6 and 10-storied regular and vertical geometric irregular frames for the first three modes. It was observed that, modal period of regular frames was higher than that of the geometric irregular frames. It was also found that, T by modal analyses were always larger than that of by code equation for both regular and vertical geometric irregular buildings.

Table 2: Time period of regular and vertical geometric irregular buildings by modal analysis

Buildings	**Mode number**	**Period by modal analysis, sec**		
		Regular	B1 upper	B1 mid
4 storied	1st mode	1.16	1.09	1.04
	2nd mode	1.16	1.08	1.00
	3rd mode	1.02	0.91	0.76
6 storied	1st mode	1.34	1.28	1.19
	2nd mode	1.34	1.27	1.15
	3rd mode	1.17	1.09	0.87
10 storied	1st mode	2.15	2.09	1.91
	2nd mode	2.15	2.08	1.84
	3rd mode	1.87	1.79	1.36

Nonlinear static or pushover analysis were conducted using the ETABS software for all the considered types of models. The pushover analysis consists of the application of the gravity loads and the code recommended lateral load pattern. For simplicity, P-Delta effects were not considered. Figure 5 shows the pushover curves (base shear vs. top displacement) for all types of considered models.



(a) (b) (c)

Figure 5: Pushover curves of 4, 6 and 10 storied regular and irregular buildings

Overstrength factor (R_s), ductility factor (R_μ) and response reduction factor (R) values of 4, 6 and 10-storied regular and geometric irregular frames were shown in Table 3. Overstrength factor of regular 4, 6 and 10-storied buildings were found as 1.58, 1.42 and 1.29 whereas 1.63, 1.42, 1.32 and 1.66, 1.52, 1.43 were found for B1-upper and B1-mid type geometric irregular buildings, respectively. No significant change in overstrength factor was found due to geometric irregularity. Ductility factor of regular 4, 6 and 10-storied buildings were found as 3.26, 4.00 and 4.11 whereas 1.93, 3.77, 2.97 and 2.94, 3.97, 3.58 were found for B1-upper and B1-mid type geometric irregular buildings, respectively. The values were found always lesser than that of the regular buildings. Minimum and maximum percentage of attenuated value in ductility factor for geometric irregularity were range from 6% to 41%.Response reduction factor (R) of regular 4, 6 and 10-storied buildings were found as 5.15, 5.67 and 5.29, respectively whereas 3.14, 5.35, 3.92 and 4.89, 5.58, 5.52 were found for B1-upper and B1-mid typed geometric irregular buildings, respectively. R value of 4, 6 and 10-storied buildings with B1-upper type geometric irregular frames were found 39%, 6% and 26% lesser than that of the regular frames, respectively. R values of 4, 6 and 10-storied buildings with B1-mid type geometric irregular frames were found 5%, 2% and 3% lesser than that of the regular frames, respectively.

Table 3: R_s, R_μ and R factors of regular and vertical geometric irregular frames

Building	**Frame Type**	**V_y (kN)**	**V_d (kN)**	**Overstrength factor (R_s)**	**Δ_{max} (mm)**	**Δ_y (mm)**	**Ductility factor (R_μ)**	**R**
4 storied	Regular	1950	1235	1.58	150	46	3.26	5.15
	B1-upper	1900	1165	1.63	135	70	1.93	3.14
	B1-mid	1750	1054	1.66	153	52	2.94	4.89
6 storied	Regular	2500	1763	1.42	200	50	4.00	5.67
	B1-upper	2400	1692	1.42	196	52	3.77	5.35
	B1-mid	2250	1480	1.52	202	55	3.67	5.58
10 storied	Regular	2600	2019	1.29	308	75	4.11	5.29
	B1-upper	2600	1970	1.32	223	75	2.97	3.92
	B1-mid	2400	1676	1.43	322	90	3.58	5.12

5. CONCLUSIONS

In this study, a comprehensive numerical analysis has been conducted to assess the seismic behaviour of vertical geometric irregular structures. Vertical geometric irregularity was considered due to the presence of setback at upper and mid storey levels. Storey drifts of geometric irregular frames were found within the allowable drift limit in accordance with BNBC 2020. Modal fundamental period of regular frames was higher than that of the geometric irregular frames. No significant change in overstrength factor was found for geometric irregularity. The values of ductility factor were found always lesser than that of the regular buildings. Response reduction factor in geometric irregular buildings was decreased in comparison to that of the regular one due to the presence of geometric irregularity. However, those obtained values satisfied code recommended R values except 4 and 10-storied upper setback buildings.

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