

SEISMIC ASSESSMENT OF A CODE-DESIGNED PLAN IRREGULAR RC BUILDING USING NONLINEAR TIME HISTORY ANALYSIS

Md. Abdul Adol¹, Sohel Rana^{2*}, Ankan Barua³, and A. H. M Shahidul Islam⁴

¹ Former UG Student, Department of Civil Engineering, Chittagong University of Engineering & Technology, Bangladesh, e-mail: abduladol10@gmail.com

² Assistant Professor, Institute of Earthquake Engineering Research, Chittagong University of Engineering & Technology, Bangladesh, e-mail: ranasohel@cuet.ac.bd

³ Research Assistant, Institute of Earthquake Engineering Research, Chittagong University of Engineering & Technology, Bangladesh, e-mail: ankan.barua.16@gmail.com

⁴ Research Assistant, Institute of Earthquake Engineering Research, Chittagong University of Engineering & Technology, Bangladesh, e-mail: enr.ahmshahidul@gmail.com

***Corresponding Author**

ABSTRACT

Though code-designed buildings are typically analyzed for the life safety performance level corresponding to the Design Basis Earthquake (DBE), their actual performance needs to be checked through reliable analysis and assessment. The building, designed according to code guidelines, exhibits plan irregularities that may lead to concentration of stresses and torsional responses under earthquake loading. Moreover, results from the equivalent static analysis (ESA) sometimes don't provide an accurate response and performance of the building due to irregularity, level of seismicity, and other complexities or scenarios. This paper deals with the seismic performance assessment of a plan-irregular C-shaped reinforced concrete (RC) building designed by a code-based ESA approach, satisfying the requirements of the Bangladesh National Building Code (BNBC) 2020. In this regard, nonlinear dynamic analyses have been performed using selected code-compatible earthquake ground motion records. For the performance assessment, storey drift ratio (SDR) and peak floor acceleration (PFA), which are considered as indicators of buildings' structural and non-structural damage, respectively, have been selected as the engineering demand parameters (EDP). In addition, the base shear of the building under different earthquakes is also compared. This study will help the structural engineers, architects, and decision-makers by illustrating the performance of code-designed buildings with the effects of plan irregularity.

Keywords: *Seismic performance, nonlinear time history analysis, life safety performance level, plan-irregular building*

1. INTRODUCTION

Nowadays, building owners and users prefer irregular buildings in urban areas for aesthetic purposes, user requirements, etc. These structures are more prone to damage during earthquakes, due to their increased vulnerability to the existence of vulnerable parameters, e.g., soft-storey configurations, plan or vertical irregularity, etc. as experienced in previous earthquakes. It is more complex to predict the behaviour of such structures compared to regular buildings. As nonlinear dynamic analysis can capture the realistic behaviour of irregular structures under strong seismic excitations, such type of analysis is preferred to get a better understanding of their seismic safety and performance-level.

Seismic performance of irregular buildings is a topic of discussion due to probable inferior performance due to the presence of irregularity. Post-earthquake damage reports and several research works validates poor performance of such complex and irregular building. Research articles, guidelines and standards recommend advanced analysis of such buildings over conventional methods to accurately assess their performance. Mahdi & Soltan Gharai, (2011) conducted pushover and nonlinear time history analyses to evaluate the performance of the RC buildings with re-entrant corners. The findings for the frames showed that pushover methods still need further improvement to produce a reliable assessment of the dynamic response of three-dimensional asymmetrical structures. Karimiyani et al. (2015) tested a series of symmetric and asymmetric 6, 9, and 12-story RC ordinary moment frame buildings to investigate the effects of irregularity on seismic progressive collapse potential of the building. When the mass eccentricity of RC symmetric and asymmetric mid-rise and tall structures increases, the decrement in the drifts of the stiff edges becomes closer. Koçak et al. (2015) studied the effects of frame-wall irregularities in existing reinforced concrete (RC) buildings during the 1999 Kocaeli Earthquake in Turkey. The analysis showed that irregularities caused by basement shear walls significantly reduced the buildings' structural capacity. Badri et al. (2016) investigated how the response of asymmetric buildings is affected by various deteriorating hysteretic model parameters. They studied the impact of decreasing strength and stiffness on the performance of lateral-load resisting components in asymmetric structures. Marušić & Fajfar, (2005) and Peruš & Fajfar, (2005), found that the inelastic torsional response of building structures is influenced by many ground motions and structural characteristics. In comparison with elastic analysis, inelastic torsional response analysis usually shows larger dispersion.

Gokdemir et al. (2013) compared static and dynamic nonlinear analysis methods, as per Eurocode 8, through analyzing three reinforced concrete buildings that represent typical RC structures in Italy: a rectangular plan shape, an L-shaped plan, and a rectangular plan with a courtyard building. They found that nonlinear dynamic analysis yields lower safety factors for low-intensity seismic levels. Kosmopoulos & Fardis, (2007) studied the estimation of inelastic chord rotations in four 3-6 storey RC buildings. Elastic response spectrum analysis provides generally unbiased and reasonable estimates of member chord rotations, which usually have natural periods in the velocity-sensitive region. Bhasker & Menon, (2020) evaluated the efficiency and adequacy of a diverse spectrum of non-structure specific seismic intensity measures (IMs) and structure specific IMs in predicting the inter-storey drift of an irregular RC building which was analyzed with bi-directional earthquakes. It showed that vector IMs that are based on non-structure-specific IMs are not as good at predicting the highest inter-storey drift needs as those that are based on structure-specific measures. Arslan et al. (2018) explored the torsional irregularity effect and also the effect due to the discontinuity of the beam on the seismic performance of buildings. They used performance evaluation methods suggested by the Turkish Earthquake Code, TEC (2007). Haque et al. (2021) carried out a research to perform comparative assessment of four common plan irregular buildings and compared their responses subjected to two (2) ground motions records. However, those are some hypothetical archetype buildings which needs to be analyzed with larger ground motion suits.

This study aims to check the performance of irregular buildings that meet code requirements during realistic earthquake conditions, finding important parameters of engineering requirements, i.e., storey drift ratio (SDR), base shear, and the peak floor acceleration. Comparative performance assessment of various plan-irregular buildings is yet limited in literature. In this regard, nonlinear time history analysis

of a real case study building is used to assess the seismic performance of the plan-irregular reinforced concrete academic building based on the requirements of the Bangladesh National Building Code (BNBC 2020). The study will provide practical knowledge to the structural engineers, architects, and decision-makers. It explains the performance of code-designed irregular buildings during a seismic event to improve design and assessment methods for seismic situations in Bangladesh.

2. METHODOLOGY

The present study investigates a five-story reinforced concrete (RC) academic building located on the Chittagong University of Engineering & Technology (CUET) campus. The building has a C-shaped layout with additional middle sections on the ground and first floors. According to the Bangladesh National Building Code (BNBC 2020), this building is plan-irregular because the projections beyond the re-entrant corner exceed 15% of the plan dimension in the specified direction. Figure 1 shows typical irregular buildings with re-entrant corners. This geometric irregularity causes torsional responses and non-uniform lateral force distribution during earthquakes.

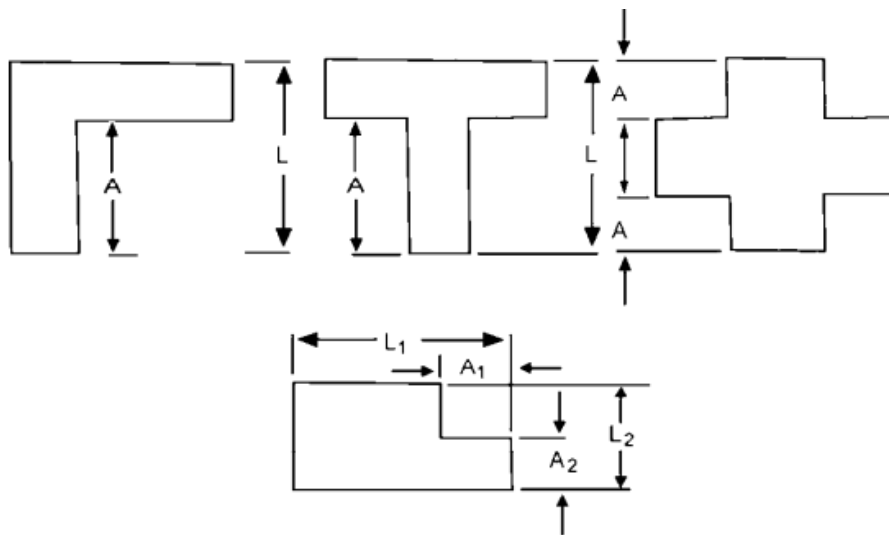


Figure 1: Irregular Buildings with Re-Entrant Corners (BNBC, 2020)

Model Development and Material Properties

The building is 47.0407 m long, 37.6428 m wide, and 3.048 m in height from floor to floor. The building has four above-ground floors and a 150 mm-thick slab. The structural system is a Special Moment Resisting Frame (SMRF) made of M28 grade concrete and high-yielding strength deformed (HYSD) (Fe420) grade steel. To perform the nonlinear analyses, an accurate mathematical model of the building was developed using SeismoStruct (version 25), providing the material properties, geometric properties, and other details. The parameters in Table 1 were used to develop the analytical model. This building is located in Seismic Zone III, which has MCE-based mapped seismic zone factor (Z) of 0.28, as per BNBC 2020. A damping ratio of 5 percent was used for this reinforced concrete structure. The foundation consists of medium-density sand.

Plan and 3D view of the developed analytical model is shown in Figure 2. Various types of loads on the building were considered according to the BNBC 2020 code requirements. Classrooms and ground-floor corridors have live loads of 4 and 4.8 kN/m², while upper-level corridors have 3.8 kN/m². Dead loads include floor finish (0.5 kN/m²), slab self-weight (3.66 kN/m²), partition walls (6.4 kN/m), and railing (2.3 kN/m). The roof had a live load of 1 kN/m² and a floor finish load of 1.13 kN/m². As per ASCE 7-10 (ASCE 2010) guideline, the load combination DL+ 0.25LL was utilized for seismic analysis to properly account for gravity loads during seismic events.

Table 1: Parameters considered for modelling the structure

Parameters	Description
Plan Area	47.0407 m x 37.6428 m
Floor height	3.048 m
No. of storey	G +4
Slab thickness	150 mm
Concrete	28 MPa
Reinforcing Steel	420 MPa
Seismic Zone	Zone-III
Zone Factor	0.28
Response Reduction Factor (R)	8
Importance factor (I)	1.25
Damping Ratio	5%
Soil Type	Medium-Dense Sand
Type of building frame	RC Special Moment Frame (SMF)
Classroom (Live Load)	2 KN/m ²
Ground floor Corridor (Live Load)	4.8 KN/m ²
Corridors above (Live Load)	3.8 KN/m ²
Floor Finish (Dead Load)	0.5 KN/m ²
6" Slab self-weight (Dead Load)	3.66 KN/m ²
Partition wall (Dead Load)	6.4 KN/m
Roof (Live Load)	1 KN/m ²
Floor Finish (Dead Load)	1.13 KN/m ²
6" Slab self-weight (Dead Load)	3.66 KN/m ²
Railing (Dead Load)	2.3 KN/m

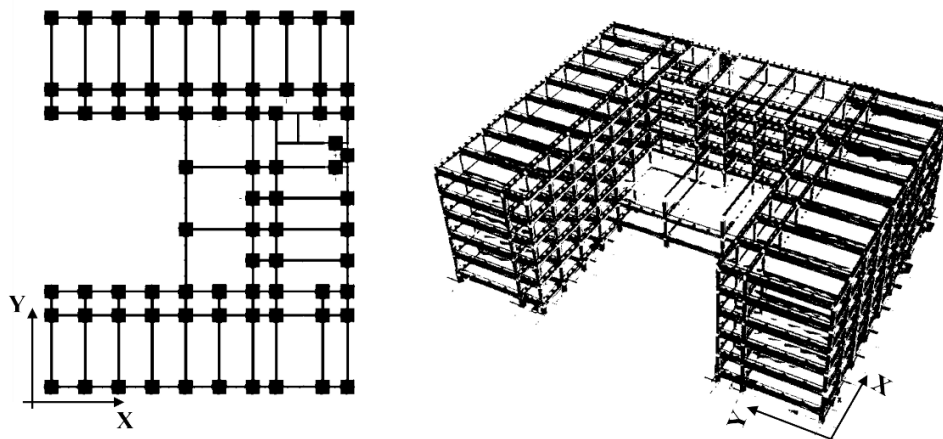


Figure 2: Plan and 3D View of Model

Method of Analysis

Nonlinear time history analyses have been used to consider how the structure will behave during the actual earthquake ground movements. This analysis method gives a clear picture of structural behavior compared to linear elastic methods due to the gradual loss of stiffness and strength in structural elements as plastic deformation is induced in them. The method incorporates equations of motion on a very small-time step by using the actual seismic acceleration records at the foundation level. Material nonlinearity has been incorporated in the model to represent the inelastic response characteristics of the reinforced concrete frame. The approach is useful in evaluating the seismic performance of irregular structures where redistribution of forces and localized damages are likely, as it is used to determine the extent of damage at the member level, permanent deformations, and the integrity of the structure in general.

2.3 Selection of Ground Motions

In the nonlinear time history analysis, two horizontal ground-motion components (H1 and H2) were used, as per the recommendations of BNBC 2020 and ASCE 7-16 (ASCE 2016). The ground motions were selected from various regions to ensure code-compatible requirements. When selecting the records, local fault types, earthquake magnitude, intensity, soil types, site location, etc., were considered. The ground motions were collected from the PEER NGA-WEST ground motion database. The details of the selected motions are given in Table 2.

Table 2: Details of selected ground motions

ID	1	2	3
RSN	580	1082	4860
Earthquake			
Name	"Taiwan SMART1(45)"	"Northridge-01"	"Chuetsu-oki_ Japan"
Year	1986	1994	2007
Station Name	"SMART1 O06"	"Sun Valley - Roscoe Blvd"	"Sanjo Shinbori"
Magnitude	7.3	6.69	6.8
Mechanism	Reverse	Reverse	Reverse
Scale Factor	0.9349	0.4588	0.5384
Unscaled PGA (g)	0.171	0.277	0.323
Scaled PGA (g)	0.160	0.127	0.174

Three recorded pairs of ground motion acceleration were selected and scaled using the square-root-of-sum-of-squares (SRSS) approach, as outlined below. Pair of each record was scaled in such a way to ensure that the mean SRSS spectrum of all horizontal pairs, throughout the period range of 0.2T to 1.5T (where, T represents the period of the structure), was at least 1.3 times the 5% damped acceleration design response spectrum (ADRS) of BNBC 2020. The SRSS spectra of three earthquake records (RSN 580, RSN 1082, and RSN 4860), along with the mean spectrum is shown in Figure 3. The figure also presents the acceleration design response spectrum (ADRS) and 1.3 times of ADRS as per the code-required benchmark for Bangladesh. From the figure, it is clear that the average of SRSS spectra exceeds the 1.3 times ADRS, confirming their suitability of use as per the BNBC requirement for seismic analysis of 3D structures.

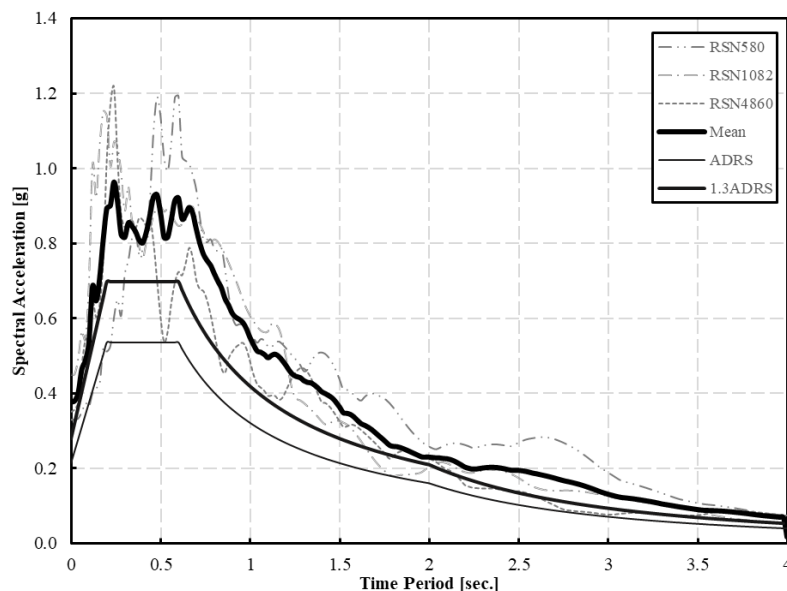


Figure 3: Spectral acceleration of the selected ground motions

3. RESULTS AND DISCUSSIONS

Storey Drift Ratio (SDR)

Storey drift ratios obtained from the nonlinear time history analyses under three ground motion records (RSN 580, RSN 4860, and RSN 1082) are presented in Figure 4 for both horizontal directions. The results indicate that all three ground motion records produce drift distributions that progressively increase from the base toward the upper stories, with the maximum drift values generally concentrated in the mid-to-upper-height zones of the structure.

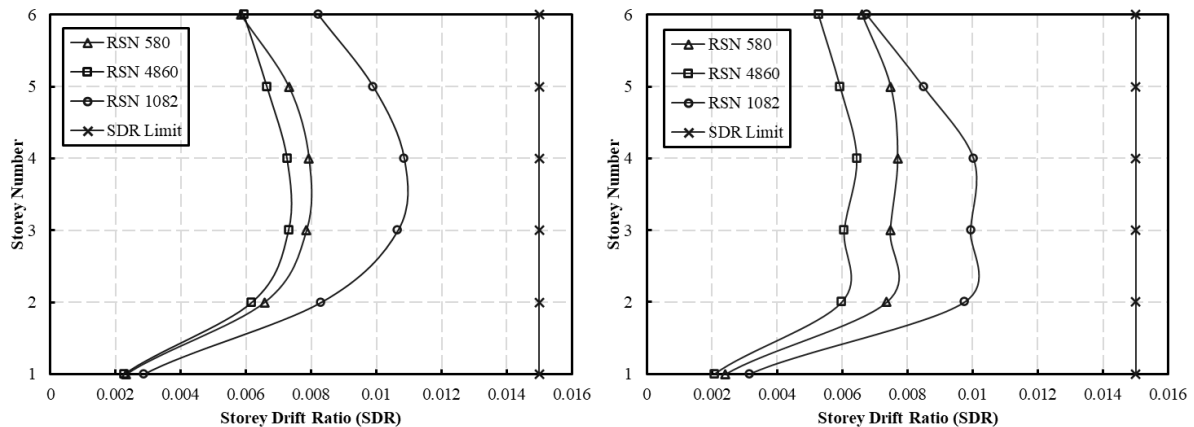


Figure 4: Storey drift ratio-X direction (*left*) and storey drift ratio-Y direction (*right*)

In the X direction, RSN 1082 shows the largest storey drift ratios, reaching approximately 0.011 at the upper floors, followed by RSN 4860 and RSN 580, which show comparatively lower drift ratios. The same thing happens in the Y direction, where RSN 1082 again has the biggest drift response, but the magnitudes have been slightly lower than in the X direction. The storey drift ratios for all three ground motion scenarios remain below the BNBC 2020 restriction of 0.015 for all story levels and in both directions. The nonlinearity is shown by the curves between storey number and drift ratio, where the slope of the curve becomes steeper in the lower stories and gradually becomes less steep in the upper parts. The directional comparison indicates slightly different drift patterns in the X and Y directions, where the X direction has always slightly higher drift values, which is associated with the difference in structural response under seismic excitation due to the geometry configuration and stiffness distribution of the building.

Floor Acceleration

Acceleration response at the floor, as represented in Figure 5, indicates that the lower to upper story amplification is high in all the studied ground motions, with the highest peaks recorded in the X direction, in which the accelerations at RSN 1082 get to a peak of about 14 ms^{-1} . The non-uniformity of these acceleration profiles is also very pronounced with regions of localized magnification particularly in the mid story and upper stories, showing the interaction of structural dynamic properties, modes, and input motion characteristics.

The highest floor acceleration is at the mid and upper storeys and is approximately 14 ms^{-2} in the X direction. However, the greatest acceleration occurs on the least to mid-storeys on the Y direction, with the values being slightly lower than on the X direction, approximately 11 ms^{-2} . This difference in the acceleration distribution of the three ground motions indicates that the inertial requirements of the building at various heights is highly influenced by certain attributes of the three individual inputs

including its frequency and intensity. As an example, the accelerations at a particular story may be higher due to the stronger and faster-shaking earthquakes and this significantly affects the response and possible vulnerability of nonstructural components at that story. These findings indicate the need to take into account the possibility of acceleration to differ at various building heights and in various directions in such a way that nonstructural elements are safeguarded in the most appropriate manner regardless of their positions within the structure.

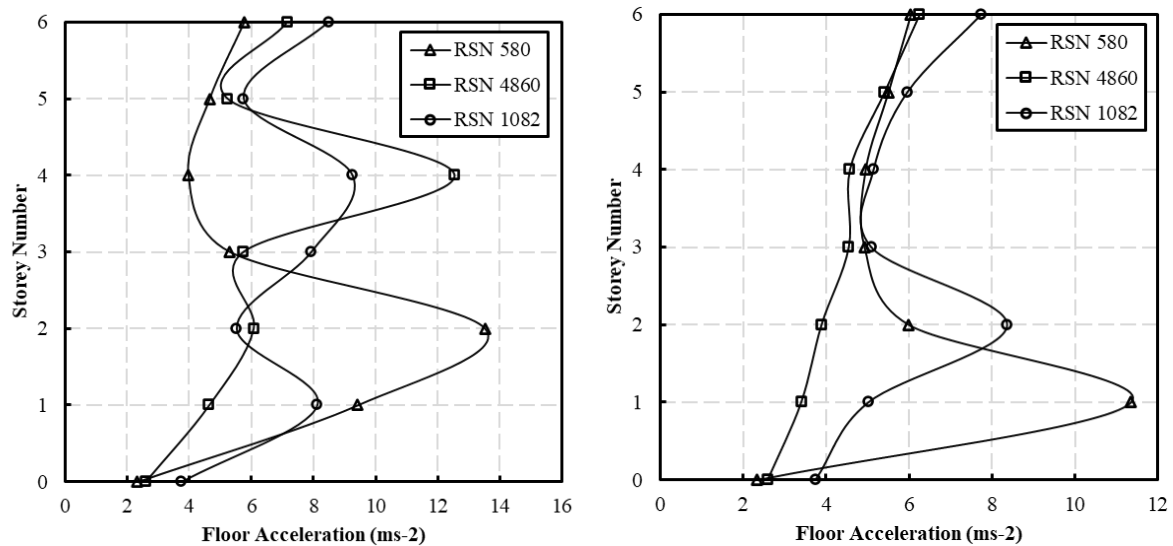


Figure 5: Floor acceleration-X direction (*left*) and floor acceleration-Y direction (*right*)

Base Shear

The base shear response from the nonlinear response history analysis using spectrum compatible three records in the X and Y directions is indicated in figure 6. The findings show that the largest base shear demand is due to RSN 1082 and this is around 16,500 kN in the X direction and 19,500 kN in the Y direction of the building.

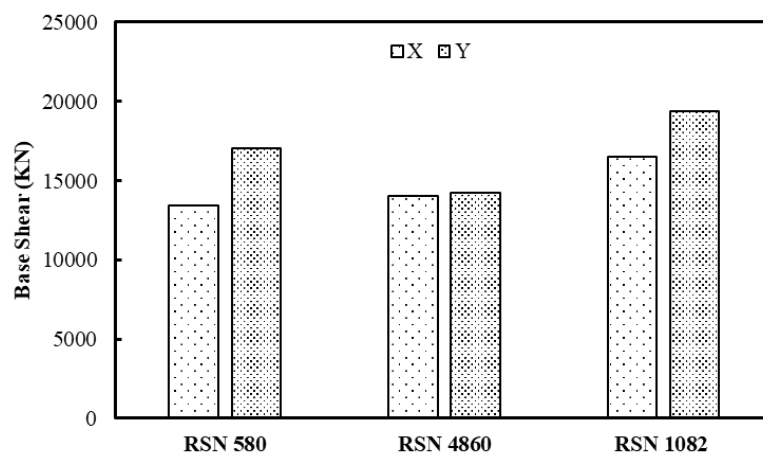


Figure 6: Base shear (X & Y direction)

RSN 4860 and RSN 580 have comparatively lower base shear forces of 13,500-14,500 kN in each direction. An important observation is that the base shear magnitudes on the Y direction are never less than the base shear magnitudes on the X direction in all three ground motions, showing that the plan irregularity of the building causes different capacities of the building to resist lateral forces on the two principal directions.

4. CONCLUSIONS

In this research, a code-designed plan irregular reinforced concrete building is assessed using nonlinear time history analysis. The investigation on structural response indicates that the storey drift ratios are within the regulation range (0.015) at all the levels in both directions but the X-directional response is always higher than the Y-directional response. This is due to the C-shaped architectural pattern that produces less stiffness in that direction of the building. Storey drift ratios of up to 0.011 at higher storeys are observed, indicating inelastic behaviour of the structure even when code specifications are followed. This inelastic response should be considered when evaluating the long-term integrity and serviceability of structural elements.

The responses of floor acceleration show amplification effects of lower to middle and upper sections of the building, with peak accelerations of about 14 m/s² in the longitudinal direction. The highest acceleration of the floor is in the X direction at the mid and high storeys but on the Y direction the highest acceleration of the floor is at the lowest to the mid-storey. This structure demonstrates the impacts of the geometric irregularity of the building, directional rigidity, modal action and the necessity of directional response analysis during seismic performance evaluations. The non-uniform vertical acceleration profile shows that nonstructural elements such as mechanical systems, architectural finishes, and interior contents can have considerably varied seismic requirements on the basis of the vertical location. As there is a difference in accelerations in the two horizontal directions, the single-direction earthquake analysis is not good in predicting the actual performance of irregular buildings.

The level of demand at the foundation level is strongly directional as longitudinal base shear is always greater than transverse values in all ground motions considered. The difference between the highest base shear in the transversal direction (which is about 19,500 kN) over the longitudinal direction (which is about 16,500 kN) is a clear indication that the distribution and magnitude of the inertial forces in various directions are controlled by geometry irregularity. This asymmetry clearly shows that static analysis method of models are insufficient.

This paper illustrates responses of a irregular building subjected to three earthquake records, assessed through nonlinear time history analysis. However, response or behavior from larger no. analysis results using at least eleven (11) or, if possible, with twenty (20) earthquake records may provide more reliable results on the performance of the building. Future works, may include advanced seismic analysis of various types of plan-irregular buildings with larger ground motion suits to assess their comparative seismic responses, fragilities, resilience, etc.

REFERENCES

- Arslan, G., Borekci, M., Sahin, B., Denizler, M. I., & Duman, K. S. (2018). Performance Evaluation of In-Plan Irregular RC Frame Buildings Based on Turkish Seismic Code. *International Journal of Civil Engineering*, 16(3), 323–333. <https://doi.org/10.1007/s40999-016-0131-1>
- ASCE. (2010). *Minimum Design Loads for Buildings and Other Structures, ASCE 7-10*. American Society of Civil Engineers (ASCE), Reston, Reston, Virginia, US.
- ASCE. (2016). *Minimum Design Loads for Buildings and Other Structures, ASCE 7-16*. American Society of Civil Engineers (ASCE), Reston, Reston, Virginia, US.

- Badri, R. K., Moghadam, A. S., & Nekooei, M. (2016). The influence of deterioration parameters on the response of low-rise symmetric and asymmetric RC buildings. *International Journal of Civil Engineering*, 14(8), 547–560. <https://doi.org/10.1007/s40999-016-0038-x>
- Haque, M. N., Zisan, M. B., Kibria, M. G., & Dey, A. K. (2021). Influence of planar irregularities on seismic responses of RC building. *Asian Journal of Civil Engineering*, 22(5), 995-1009.
- Bhasker, R., & Menon, A. (2020). Characterization of ground motion intensity for the seismic fragility assessment of plan-irregular RC buildings. *Structures*, 27, 1763–1776. <https://doi.org/10.1016/j.istruc.2020.08.019>
- BNBC. (2020). *Bangladesh National Building Code (BNBC) 2020*. Housing and Building Research Institute (HBRI), Dhaka.
- Fajfar, P., Marušić, D., & Peruš, I. (2005). Torsional effects in the pushover-based seismic analysis of buildings. *Journal of Earthquake Engineering*, 9(6), 831–854. <https://doi.org/10.1080/13632460509350568>
- Gokdemir, H., Ozbasaran, H., Dogan, M., Unluoglu, E., & Albayrak, U. (2013). Effects of torsional irregularity to structures during earthquakes. *Engineering Failure Analysis*, 35, 713–717. <https://doi.org/10.1016/j.engfailanal.2013.06.028>
- Karimiyan, S., Moghadam, A., Husseinzadeh Kashan, A., & Karimiyan, M. (2015). Progressive collapse evaluation of RC symmetric and asymmetric mid-rise and tall buildings under earthquake loads. *International Journal of Civil Engineering*, 13(1), 30-44.
- Koçak, A., Zengin, B., & Kadioğlu, F. (2015). Performance assessment of irregular RC buildings with shear walls after Earthquake. *Engineering Failure Analysis*, 55, 157–168. <https://doi.org/10.1016/j.engfailanal.2015.05.016>
- Kosmopoulos, A. J., & Fardis, M. N. (2007). Estimation of inelastic seismic deformations in asymmetric multistorey RC buildings. *Earthquake Engineering and Structural Dynamics*, 36(9), 1209–1234. <https://doi.org/10.1002/eqe.678>
- Mahdi, T., & Soltan Gharai, V. (2011). Plan irregular RC frames: comparison of pushover with nonlinear dynamic analysis. *Asian Journal Of Civil Engineering (Building And Housing)*, 12 (6), 679-690.
- Marušić, D., & Fajfar, P. (2005). On the inelastic seismic response of asymmetric buildings under bi-axial excitation. *Earthquake Engineering and Structural Dynamics*, 34(8), 943–963. <https://doi.org/10.1002/eqe.463>
- Peruš, I., & Fajfar, P. (2005). On the inelastic torsional response of single-storey structures under bi-axial excitation. *Earthquake Engineering and Structural Dynamics*, 34(8), 931–941. <https://doi.org/10.1002/eqe.462>
- TEC. (2007). *Turkish code for buildings in seismic zones (TSC 2007)*. Turkish Earthquake Code (TEC), the Ministry of Public Works and Settlement, Ankara, Turkey.