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Effects of Planar Irregularities on Seismic Responses of Building Under Bi-directional Ground Motions

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Abstract

The structural performance assessment of a building subjected to ground excitation needs realistic predictions of the ground motion and the form structure. This paper aims to study the seismic performance of buildings with a planar irregularity. It also focused on the effects of bi-directional ground motions on the seismic performance of irregular-shaped buildings. An irregular building called a C-shape is taken into consideration, along with a square-shaped building. The ground motions are modeled based on the target response spectrum according to the Bangladesh National Building Code-2020 (BNBC-2020) specifications. The assessment of the buildings is done in terms of interstorey drift, storey displacement, storey shear, and acceleration, which were predicted using modal and non-linear time history analysis (NTHA). It has been found that building response under bi-directional ground motion is greater than that under uni-directional ground motion. The irregular buildings are more critical and display high amplification in structural response compared to the buildings with regular shapes. Therefore, it is claimed that irregular-shaped buildings require special consideration in design, and additional precautions should be taken considering the effect of bi-directional ground motion.

Keywords: *Regular and irregular building, Bi-directional ground motion, NTHA, Structural Response.*

1 Introduction

In the last decades, earthquakes have caused major damage to infrastructure and claimed thousands of lives. In order to reduce the loss caused by earthquakes, a proper evaluation of the seismic response of a structure, which is dependent on the realistic prediction of the material behavior, the accuracy of the finite element model, and the prediction of the ground motion, is necessary. A structure with an irregular shape has many more uncertainties regarding its behaviour and response under earthquakes than a structure with a regular shape. As modern architecture increasingly favours irregularly shaped buildings, it is essential to comprehend the seismic behaviour of such structures for safe building design. According to the current codes and standards (UBC, 1997; IS, 2002; EC8, 2004; ASCE 7-10, and BNBC, 2020), building irregularities are primarily categorized as horizontal and vertical abnormalities. The existing design guidelines propose that the normalized overhanged ratio or re-entrant corner should not be greater than 15% for these buildings with planar irregularities.

The effect of planar irregularities on the seismic response of structures has been studied by several researchers (Bozorgnia et al., 1986.; Sadek and Tso, 1989; Tso and Sadek, 1985). These studies were done using a simple model of single-story irregular buildings, in which the irregularity is defined as the eccentricity between the center of mass and the center of stiffness. The impact of planar irregularities on the seismic performance of tall structures was also explored by Zhang et al. (2007). It was claimed that a building with planar irregularity responds to torsion, drift ratios, and inter-story drift much differently than a regular-shape structure. Shakib & Ghasemi (2007) and Aziminejad & Moghadam (2010) studied the impact of near-field and far-field earthquakes on the responses of structures with various types of plan irregularities. Anagnostopoulos et al. (2010) compared the inelastic torsional responses of single- and multi-story buildings. Fujii et al. (2004) studied the response of irregular buildings with both SDOF and MDOF systems. The building models used in these studies were very simple. Also, these studies considered only unidirectional earthquake motion.

Several researchers considered the complex building model to investigate the effects of planar irregularities. Alashker et al. (2015) studied the seismic responses of a rectangular-shape building and claimed that a rectangular building with an aspect of 1.5 has the lowest base shear. Naveen et al. (2019) studied a nine-story regular frame to investigate the impact of irregular mass, stiffness, and both planar and vertical irregularity. Alam et. al. (2020) conducted a comprehensive study on the effects of various plan irregularities on the seismic performance of buildings and concluded that irregularities significantly increase the seismic response, especially in tall buildings. Haque et al. (2021) analyzed different kinds of irregular buildings with different shapes, viz., C, L, I, and T shapes with different aspect ratios, to investigate the effect of planar irregularities.

All of the aforementioned studies concentrated on the effect of mass, stiffness, and geometry irregularities on structural responses of a building. Most of this research took into account a straightforward and elastic model for the structure. The above-mentioned research works considered only unidirectional ground. It is crucial to take into account both the bi-directional ground motions and the inelastic model of the building since irregular constructions are extremely susceptible to torsional deformation. Therefore, taking into account the behavior of inelastic materials, the current study concentrated on the effect of bidirectional ground motion on planar irregular buildings.

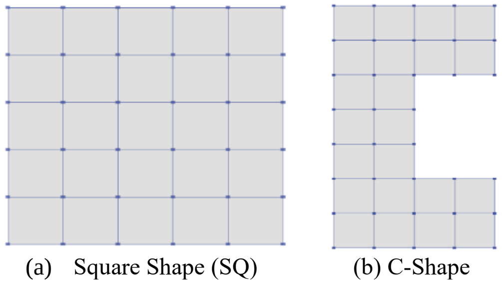
2 Structural Modelling of Buildings

In the present study, one irregular-shape building called C-shape and one square-shape reinforced concrete building located in Chattogram, Bangladesh, are considered. Both are six-story buildings. Two buildings have comparable geometric dimensions, such as a beam and column that are 12"×16" in size, a beam span length of 16 ft, and a total floor area of approximately 5600 ft^2. The total number of panels in a square-shape building is 25 and in a C-shape building is 22. Figure 1 shows the geometry of the assumed buildings. The modeling and analysis are done using ETABS version 18.1.1. Table 1 describes the dimensions of the members, material properties, and loading conditions. Bidirectional ground motion is the loading condition where two components of ground acceleration are acting simultaneously.

Table 1. Description of material properties, dimension of members and load assignments.

Basic Consideration	Load Consideration
Beam Dimension: 12" × 16"	Dead Load- Self Weight
Column Dimension: 12" × 16"	Floor Finish- 20 lb/ft^2
Slab Thickness: 6 in	Live Load- 80 lb/ft^2
Span length: 16 ft (approx.)	Earthquake acceleration:100% of a_y in Y-direction+ 30% of a_x in X-direction
Concrete Strength: 3000 psi	Steel Strength: 60 ksi

Non-linear time history analyses have been used to extract the seismic responses of buildings with various irregularities. To simulate the pile foundation, a fixed boundary condition was assigned. All the members were modeled as RC members.

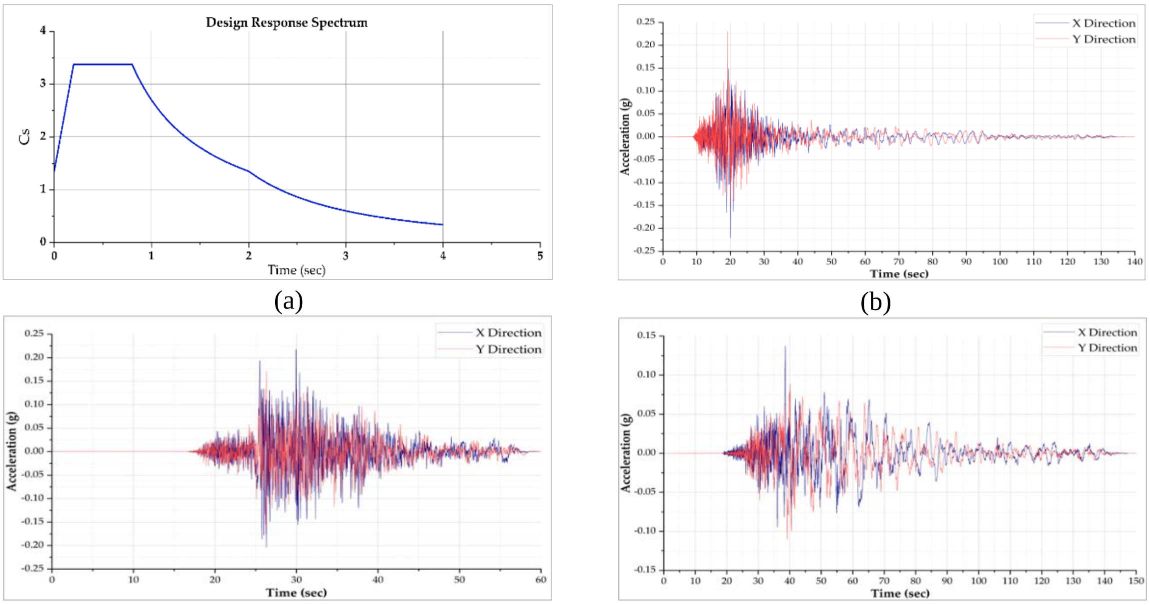


(a) Square Shape (SQ) (b) C-Shape

Figure 1. Different types of building shapes

3 Ground Motion Modelling

The studied buildings are assumed to be located in Chattogram, where the seismic zone is 0.28, representing a probable PGA of 0.28g. It is also assumed that the shear wave velocity of soils beneath the building site will be in the range of less than 180 m/s, representing soil type S_D with a soil factor of S = 1.35 according to BNBC-2020. For inelastic (nonlinear) analysis, the response spectrum curve is derived according to BNBC-2020 guidelines. A response modification factor, R = 1, and a structural importance factor, I=1 = 1, are assumed. The components of ground motions (X and Y) as shown in Figs. 2(b), 2(c), and 2(d) are matched with the design acceleration response spectrum curve as shown in Fig. 2(a).



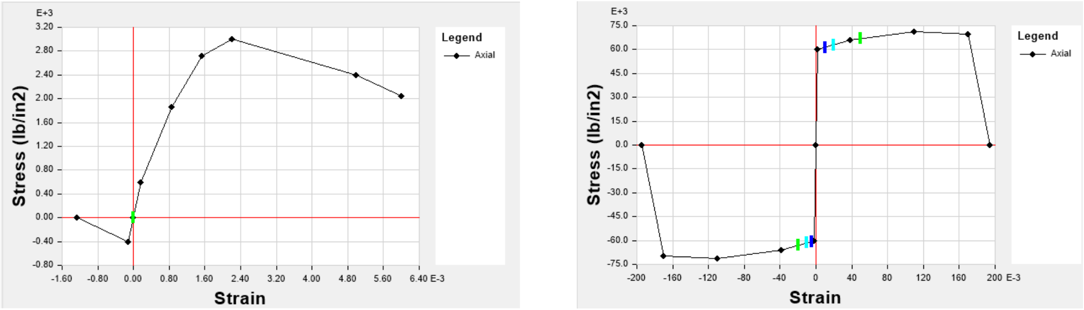
(a) (b) (c) (d)

Figure 2. (a) Design acceleration response curve, (b) Kobe earthquake, (c) Miyagi earthquake, (d) Chi-Chi earthquake

The ground acceleration of the Kobe earthquake (1995) was taken at Albeno station with a magnitude of 6.9. The same is true for the Miyagi earthquake (2008), which was taken at Miyagi Great Village station and had a magnitude of 6.95. The Chi-Chi earthquake (1999) ground acceleration is taken from CHY002 station, which has a magnitude of 7.62. In each analysis, both components of the earthquake are applied simultaneously in the X and Y directions. According to the guidelines of BNBC-2020, 100% of ground acceleration (a_x) and 30% of ground acceleration (a_y) are simultaneously applied in the X and Y directions.

4 Non-linear Material Modelling

Figure 3 shows the material curves for concrete and steel. The compressive strength of the concrete is assumed to be 3000 psi, and the yield strength of steel is 60 ksi. The nonlinearity of concrete is modeled using the concrete hysteresis force model. The steel is assumed to be an isotropic material, and a kinematic force-displacement relationship is considered for the same. In the structural modeling, M3 (considering only flexure action) plastic hinges are assumed for beams, and P-M2-M3 (axial force and flexure action about two axes) plastic hinges are applied for columns. The properties of the plastic hinge at different performance levels are assumed according to the ASCE 41-17 guidelines as given in Table 2 (Structural Engineering Institute). By using the balanced steel ratio that is used in the analysis, these hinges show the appropriate nonlinear material property.



(a) (b)

Figure 3. Stress-strain curve for (a) concrete and (b) steel material

Table 2. Nonlinear Modelling Parameters and Performance Criteria (ASCE 41-17; Table-10-17)

Conditions	Modelling Parameters			Acceptance Criteria		
	Total Strain		Residual Strength Ratio	Total Strain Performance Level		
	d	*e*	*c*	IO	LS	CP
i. Columns modelled as compression chords. Columns confined along entire length	0.02	0.04	0.4	0.003	0.03	0.04
All other cases	0.003	0.01	0.2	0.002	0.01	0.01
ii. Columns modelled as tension chords. Columns with well-confined splices or no splices	0.05	0.05	0.0	0.01	0.04	0.05
All other cases	See note *d*	0.03	0.2	See note *d*	0.02	0.03

[d] Potential for splice failure shall be evaluated directly to determine the modelling and acceptance criteria. For these cases, refer to the generalized procedure of Section ASCE 41-17-10.6.3.2

5 Results and Discussions

Both X and Y components of the structural response of the building at each instant of time are calculated. Then the SRSS (Square Root of the Sum of the Squares) of the displacement, drift, acceleration, and storey values is calculated from both directional components for the simultaneous and non-simultaneous action of an earthquake application. In the following figures, the dashed line represents the structural response without simultaneous action, i.e., both components of an earthquake act independently. The solid line represents the structural response due to the simultaneous action of the earthquake components. Also, C stands for irregular-shaped building, and SQ stands for regular-shaped building.

Figure 3 shows the maximum lateral displacement of the building along its height. The lateral displacement of C-shape (C) and square-shape (SQ) buildings is comparable in Kobe and Chi-Chi earthquakes. The lateral displacement of the C-shape building is significantly higher than that of the square-shape building in the case of the Miyagi earthquake. It is found that in the Kobe, Miyagi, and Chi-Chi earthquakes, the lateral displacement of the C-shape building is 6.76% (Story 2), 251.65% (Story 1), and 4% (Story 2) higher than that of the square-shape building. Also, the effect of bidirectional ground motion on lateral displacement is higher than that of unidirectional ground motion.

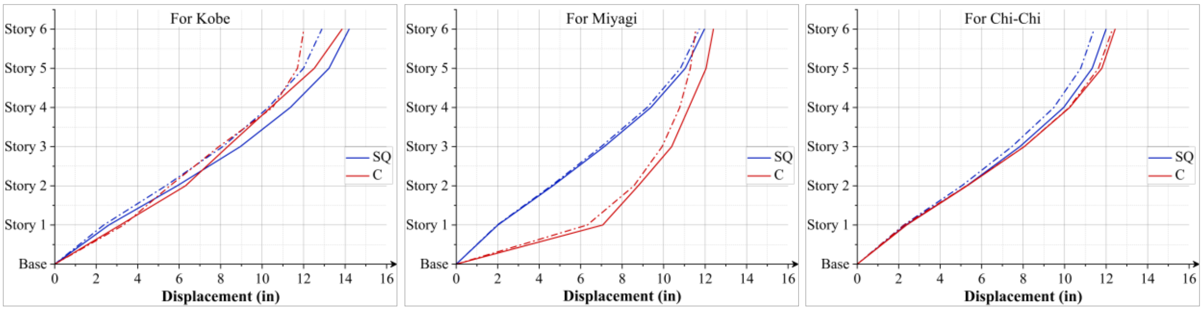


Figure 3. Maximum Displacement along the height of the building

The storey drift of the buildings along its height is given in Fig. 5. In general, storey drift in a C-shape building is higher than that in a square-shape building, and its magnitude in the case of bidirectional loading is significant, especially in the Miyagi and Kobe earthquakes. In some cases, the drift value of the C-shape building is almost double in bi-directional ground motion compared to uni-directional ground motion. A comparison shows that at level 5, the C-shape shows about 19.5% more drift than the square shape due to the Kobe earthquake, which is 4% and 2% for the Miyagi and Chi-Chi earthquakes, respectively.

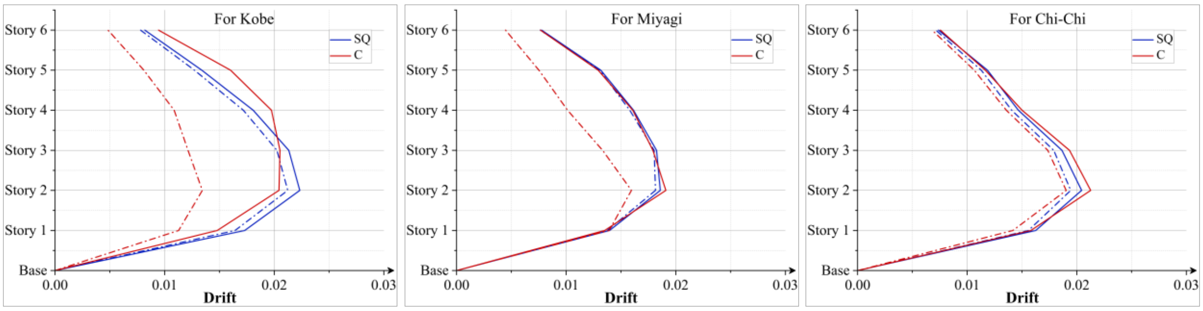


Figure 4. Maximum Drift along the height of the building

The acceleration along the height of the building is shown in Fig. 6. It is observed that the acceleration of the top floor is higher than the acceleration of the other floors. Floor accelerations of a C-shape building are found to be slightly larger than those of a square-shape building due to the Chi-Chi earthquake. In the other two loading cases, no specific relationship is observed. It is observed that floor acceleration due to the simultaneous action of the bidirectional components of ground acceleration is significantly higher than that of the non-simultaneous ground motions.

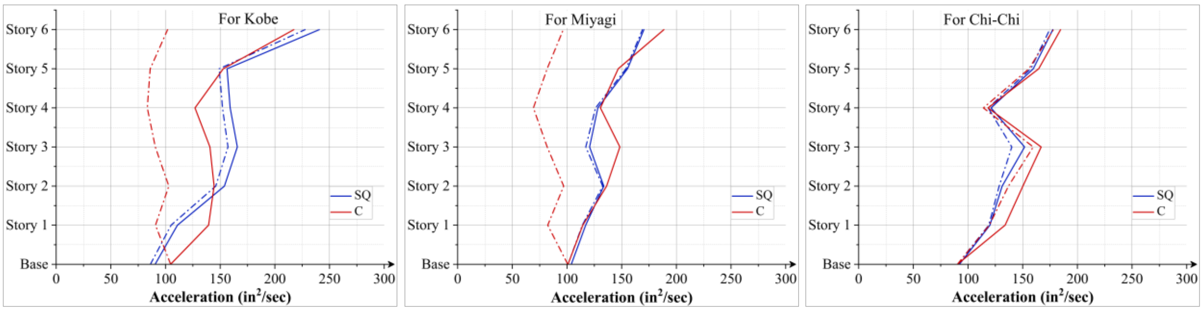


Figure 5. Maximum Acceleration along the height of the building

Figure 7 shows the variation of storey shear along the height of the building. The effect of planar irregularity on the seismic response of a structure can be clearly identified from the base shear. It is seen that storey-shear in a C-shape building is significantly higher than that of a square-shape building. The base-shear is equal to the shear fore at storey 1. The base share of C-shape buildings increases by 14.2% compared to square-shape buildings in the Kobe earthquake, which is about 29% and 32.2% in the Miyagi and Chi-Chi earthquakes, respectively. Again, simultaneous application of two components of earthquakes causes a significant increment in storey shear, which is highly noticeable in the Kobe and Miyagi earthquakes.

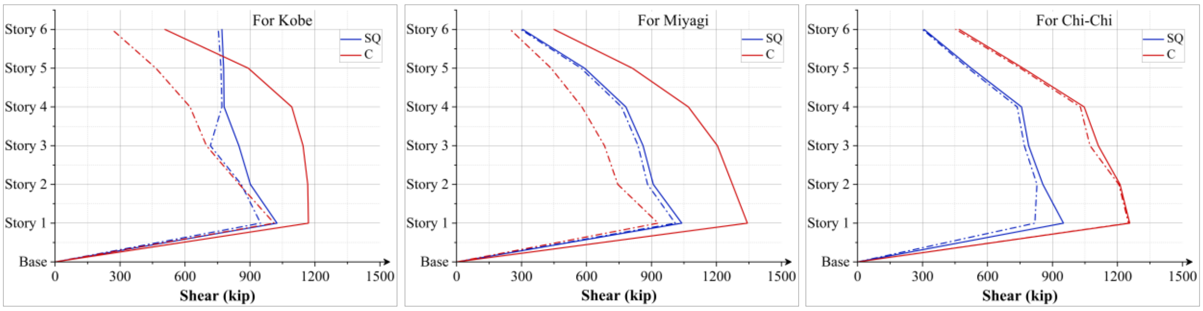


Figure 6. Maximum Shear along the height of the building

6 Conclusions

The primary objectives of this study are to investigate the impact of planar irregularities on the seismic response of buildings. It also focused on the impact of bidirectional ground motion on the seismic response of the building.

A nonlinear time history analysis is performed following the guidelines of BNBC-2020 to evaluate the structural response of the buildings.

It is concluded that the simultaneous action of bidirectional ground motion is more critical than that of non-simultaneous ground motion. The lateral displacement, storey-drift, storey-shear, and floor acceleration in an irregular building are higher than those in a regular building, and under bidirectional ground motion, an irregular building exhibits significant amplification of these responses. Therefore, to minimize the loss of life and failure of buildings, the simultaneous action of bi-directional ground motion should be considered in building design, and more attention should be paid in the case of irregular building designs.

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