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Case Study on the Effects of Plan Irregularities on Seismic Performance of Structures

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Abstract: Geometric configurations, such as large openings, re-entrant corners, and discontinuity in diaphragms, are very common in architectural design but are seen as undesirable for structural performance during earthquakes. The lateral systems in a structure resist the strong forces induced during an earthquake, preventing damage or collapse of the structure. If these systems fail, the structural integrity of the building may fail, which may lead to injury or loss of life. Configuration irregularities also tend to develop torsion in structures, contributing to much uncertainty in structural performance. These conditions often combine, working together to bring down the seismic performance of the building. In order to investigate, two steel mid-rise structures will be carefully designed using the U.S. building codes and RAM. Both structures will have the same square footage and lateral resisting systems, with differences only in geometric configurations so that accurate analysis of the effects of the irregularities may be achieved. Utilizing SAP2000, dynamic responses of two structures were performed and the drift values for both structures were determined. This study intends to present these findings so that a more integrative earthquake-resistant design process may be implemented, creating a safer world. With this in mind, it is important to evaluate the impact that the architectural design of a structure has on the performance during a seismic event, highlighting the importance of incorporating a more integrative earthquake-resistant design.

Keywords: Steel Structures, Plan Irregularities, Time-History Analysis, Seismic Performance, Response Assessment

Introduction

In areas of high seismic activity, it is necessary to design a structure to resist damage and collapse when subjected to a seismic event. As earthquakes can’t be predicted, it is the job of the structural engineer to design the structure to resist the large lateral forces that can be induced during a seismic event. As the form and geometry of the structure are factors that contribute to the seismic performance of a building, it is important to have an integrative design where the structural engineer and architect work together to increase the performance of a structure to resist damage and collapse during an earthquake. As per ASCE7-22 section 12.3.2, structures are classified as having two main types of configuration irregularities: Horizontal irregularities and vertical irregularities. This study considers the effects of a horizontal irregularity, the reentrant corner irregularity, which is described in ASCE7-22, reentrant corner irregularity exists when both plan projections of the structure beyond a reentrant corner are greater than 20% of the plan dimension of the structure.

Architectural design choices play a big role in the effect that plan irregularity has on this performance. Past research studies have evaluated the impact of structural irregularity on seismic performance. Monish (2015) performed a study and found that buildings with irregular structural configurations are more severely affected by seismic events, experiencing larger maximum displacements. The study also revealed that the results of the fundamental natural periods do not take into consideration the irregularity of buildings. Rajalakshmi *et al.* (2015) revealed that irregular buildings experience larger displacements due to torsional unbalances that are caused by one or more asymmetries in the structural configuration. Plan irregularities can cause the forces that a structure experiences during seismic events to be distributed unevenly throughout the building's lateral resisting systems, whereas Sultan and Peera (2015) revealed that

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buildings that have more severe irregularities are more severely affected during seismic events and experience more deformation than those with less irregularity. This irregular distribution of forces can also lead to concentrations of stresses, as Ahmed *et al*. (2016) performed research on re-entrant corners and showed that these geometric irregularities cause stress concentration, and the buildings with more severe irregularities are more vulnerable than those with regular configurations. They also found that the building codes underestimate the actual fundamental period compared to the actual models, revealing that the fundamental period is a function of a building's height and shape. Shah (2018) showed that buildings become more vulnerable with more irregularities, where setbacks and soft stories in buildings contribute to the most drastic effects when considering variations in capacities. Noorifard and Mehdizadeh Saraj (2018) revealed that architects play an important role in many factors that affect the seismic performance of a building. In order to create the most optimal seismic-resistant buildings, engineers should have more responsibility from the beginning. Yavari *et al*. (2019) showed that architectural openings can increase stresses in columns up to 6.5 times due to progressive failure, leading to the destruction of the building. Naveen *et al*. (2019) performed a study that showed buildings with single irregularities show an increase in response. They also revealed that configurations with stiffness and vertical irregularities resulted in the maximum displacement responses. Khanal and Chaulagain (2020) showed that an increase in plan irregularity correlated with an increase in earthquake excitation, larger inter-story drifts, shear force demands in vertical resisting elements, and overturning moments at the foundation level. Mouhine and Hilali (2022) showed that the performance of mid-rise structures is significantly reduced when the vertical irregularity passes from the bottom to the upper levels. Singh Rathore *et al*. (2022) performed a study in which maximum displacement values were experienced in L-shaped building models when compared to regular case models.

In areas of concentrated seismic activity, understanding the effects that structural irregularities have on seismic performance is paramount in designing a safe structure. The structural engineer is responsible for designing the structure to safely resist the large forces incurred during an earthquake. Major factors that contribute to the stability, such as building geometry, are dependent on the architect's design decisions while structural integrity is dependent on the structural engineer. With this in mind, it is important to evaluate the impact that the architectural design of a structure has on the performance during a seismic event, highlighting the importance of incorporating a more integrative earthquake-resistant design approach.

Materials and Methods

Methodology

As the design of a structure may have limitations in area, it is essential to compare two structures in this regard. To this end, two steel mid-rise residential structures are carefully designed as per the U.S. building codes. The structural design of the building followed the architectural design in order to imitate the design-build approach that is common in new construction projects. The two 5-story structures are Building 1 designed with a regular, square plan configuration, whereas Building 2 will have a plan irregularity, in the form of an L-shaped structure (Fig. 1). The structures are designed with the same area of 1,936 square feet, with Moment Resisting Frames (MRFs) along the perimeter of each. The two structures will have differences in their plan configurations, allowing a focus on the effect that plan irregularity has on seismic performance when subjected to an earthquake.

Modeling

Modeling in RAM Structural Systems (RAM SS) was done to achieve an integrative member and connection check to ensure that the building's structural elements are up to code standards. ASCE7-22 chapters 2 through 4 were utilized to determine the minimum loads and criteria required for structural design. As per ASCE7-22 chapter 4, a live load of 40 psf is considered for floors 1-4, and a roof live load of 20 psf was considered for the 5th floor. Typical dead loads included a floor dead load of 75 psf and a roof dead load of 25 psf. The dead load of the building elements, including a 3.5" concrete deck with a unit weight for concrete of 145 pcf and a self-weight of the steel deck of 3 psf, were modeled using RAM SS.

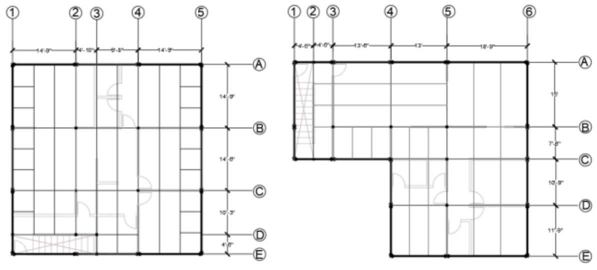


Fig. 1: Structural design imposed over architectural plans: Building 1 (left) and Building 2 (right), with MRFs shown along each perimeter

Modeling in RAM Structural Systems was also done to achieve optimized member design (Fig. 2). Design assumptions followed ASCE7-22: Where $S_{DS} = 1.625$ was determined through the USGS seismic design geodatabase, site location in Los Angeles, with the structure as risk category II, soil class C as per section 11.4.3; and an over strength factor $\Omega_0 = 3$ as per section 12.2.1. Through steel and seismic provisions, RAM SS yielded optimized member selections, shown in Tables 1-2.

Dynamic Analysis

In this study, a general-purpose finite element analysis utilizing SAP2000 was done. The structures were modeled with the same member elements and loads as in the RAM structural systems models, and each floor slab is modeled as a rigid diaphragm (Fig. 3).

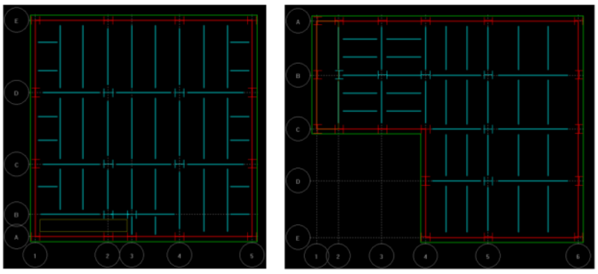


Fig. 2: RAM structural models: Regular structure (left) and irregular structure (right), with MRFs shown in red

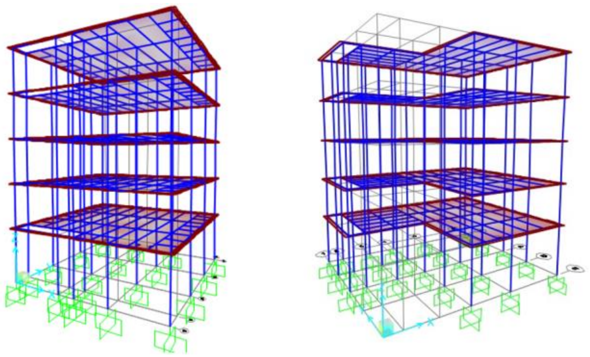


Fig. 3: SAP200 models: Building 1 (left) and Building 2 (right)

Table 1: Column sizes

	Building 1		Building 2	
Level	MRF	Gravity	MRF	Gravity
1st	W21×122	W8×31	W21×122	W8×31
2nd	W21×111	W8×31	W21×111	W8×31
3rd and 4th	W21×68	W6×25	W21×68	W6×20
5th	W16×31	W4×13	W14×26	W6×12

Table 2: Beam sizes

	Building 1			Building 2		
		Gravity			Gravity	
Level	MRF (stair frame)	Girder	Joist	MRF	Girder	Joist
1-4th	W12×96 (W14×132)	W14×22	W10×22	W12×96	W16×26	W10×15
5th	W12×96 (W14×132)	W12×14	W8×10	W12×96	W12×19	W8×15

The structures are then subjected to three seismic events: Imperial Valley (1940), landers (1992), and Northridge (1994) earthquakes. Details of the selected earthquake records are shown in Table 3. The ground motions are selected in a manner to cover earthquakes with various Peak Ground Velocity (PGV) and Peak Ground Acceleration (PGA) values within 10/50, i.e., 10% probability of exceedance in 50 years, hazard level.

The time histories of each of the earthquakes are applied to the two major plan axes (u_x, u_y) of the buildings. Drift criteria are specified in ASCE7-22 table 12.12-1: For a 5-story, risk category II structure, the maximum allowable drift, Δ_a, is determined by $\Delta_a = 0.020\, h_{sx}$, where h_{sx} is the height of the story below level x. The seismic performance criteria under investigation, the allowable story drift limit, as well as the velocities and accelerations experienced during a seismic event, were determined from analysis run for each of the seismic events. The typical 5th-story displacement time histories of the two building models are shown in Fig. 4.

Table 3: Selected ground motions

Record	Earthquake magnitude	PGV (mm/s)	PGA (mm/s^2)	Probability of exceedance
Imperial Valley, El centro, 1940	6.9	599.0	6628.8	10% in 50 years
Landers, yermo, 1992	7.3	603.5	3533.5	10% in 50 years
Northridge, sylmar, 1994	6.7	1189.3	8014.4	10% in 50 years

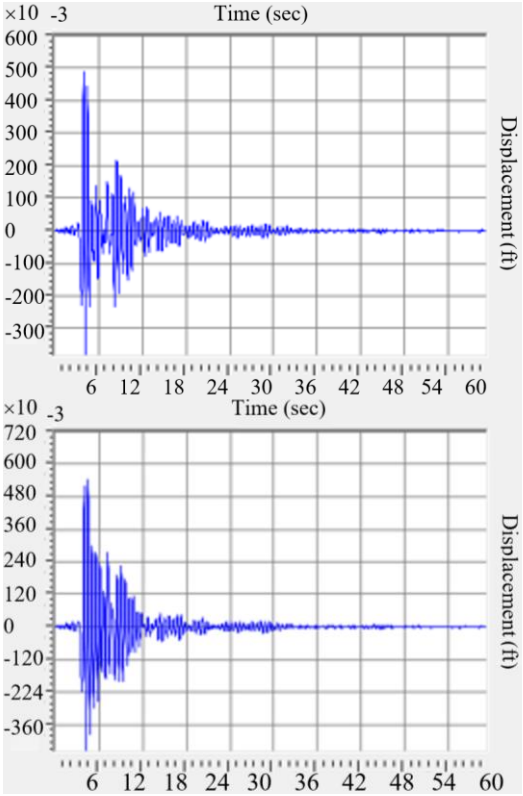


Fig. 4: Displacement vs. time responses of Building 1 (top) and Building 2 (bottom)

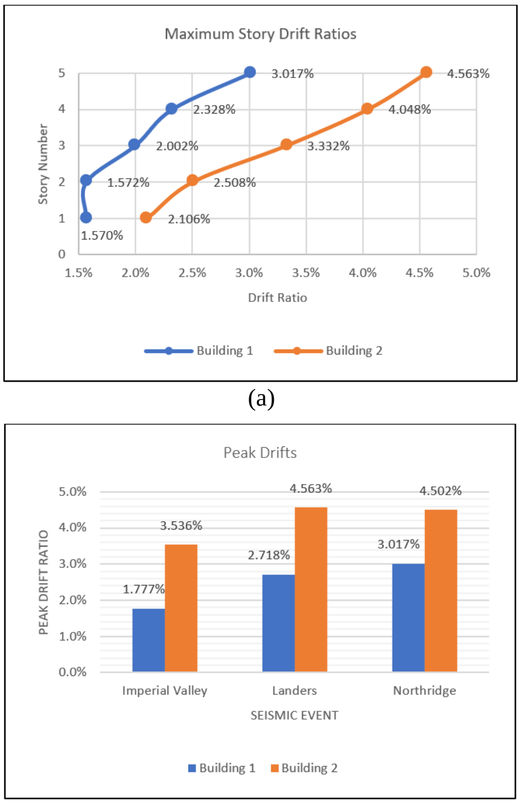
Results and Discussion

Drift

Figure 5 shows the drift response of the two structures. Figure 5(a) shows the maximum drift values of the seismic events for each story. It is observed that the Building 2 model experienced larger drift values relative to that of the Building 1 model for each story number. Figure 5(b) shows the peak drift values experienced for each seismic event. It is observed that Building 2 experienced larger peak values relative to Building 1, with the largest variation in the Imperial Valley earthquake, where the peak drift value for Building 2 is 2 times larger than that of Building 1.

Velocity

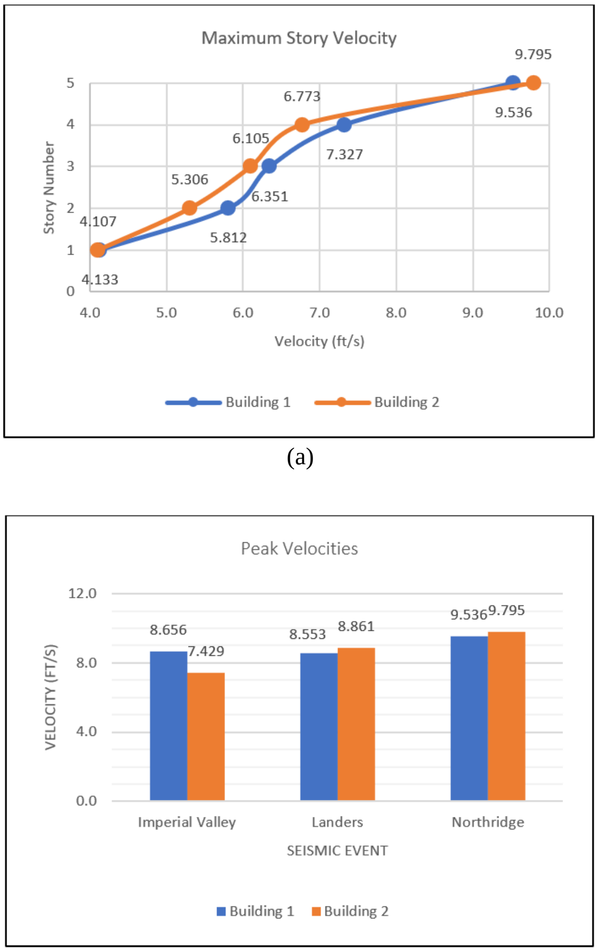
Figure 6 shows the velocity response of the two structures. Figure 6(a) shows the maximum velocity values of the seismic events for each story. It is observed that the irregular building model experienced the largest velocity relative to Building 1 on the 5th floor, but smaller values on the floors 1-4. Figure 6(b) shows the peak velocity values experienced for each seismic event. It is observed that Building 2 experienced larger peak values for the landers and Northridge earthquakes, with the largest value of 9.795 ft/s. The largest variation response is found in the Imperial Valley earthquake.



(a)

(b)

Fig. 5: Response diagrams for (a) Maximum story drift and (b) Peak drift



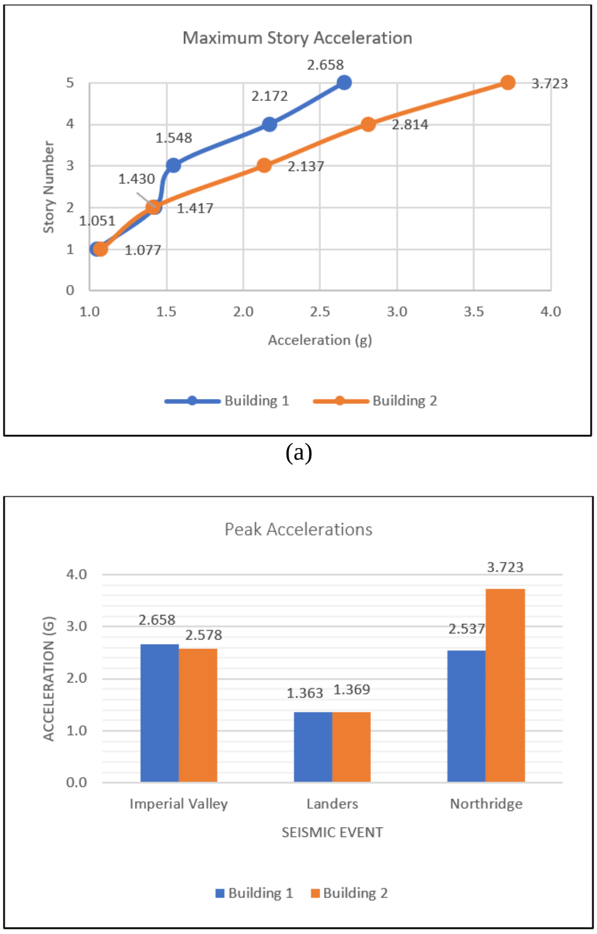
(a)

(b)

Fig. 6: Response diagrams for (a) Maximum story velocity and (b) Peak velocity

Acceleration

Figure 7 shows the acceleration response of the two structures. Figure 7(a) shows the maximum acceleration values of the seismic events along with the corresponding story. Figure 7a shows that the maximum acceleration response on each floor was found in Building 2, with the largest value of 3.723. Figure 7(b) shows the peak acceleration values experienced for each seismic event, where it is observed that Building 2 experienced the largest peak value relative to Building 1, with the largest variation in the Northridge earthquake, where the peak drift value for Building 2 being 1.47 times larger than that of Building 1. It is also important to note that the percent difference of the peak values for the Imperial Valley and Landers earthquakes is less than 3.06%, while those of the Northridge earthquake are 37.89% different.



(a)

(b)

Fig. 7: Response diagrams for (a) Maximum story accelerations and (b) Peak acceleration

Conclusion

This study aims to study the effects of architectural design choices on the seismic performance of a building. The results of the analysis are discussed in the parameters of drift, velocity, and acceleration. It was found that Building 2 (with irregularities) experienced the largest drift responses for each seismic event; moreover, it had larger peak drift values for all stories for each ground motion. Building 2, also, had the largest velocity response, while Building 1 (with no irregularities) had larger velocity responses in stories 1 through 4. In addition, Building 2 experienced larger acceleration responses in each story and had larger acceleration responses in the landers and Northridge earthquakes. When comparing the responses of the two building models, it is evident that the largest impact that the architectural design choice of a plan irregularity is on the drift response. As drift is a measure of the relative displacement a story experiences during a seismic event, this study revealed that the irregular structure was more vulnerable to a seismic event. Damage sustained during earthquakes is attributed to lateral displacements, which can be amplified when plan irregularities are present.

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Author's Contributions

Eduardo Flores: Design, analysis, data collection and processing and preparation of the first draft.

Tadeh Zirakian: Conceptualization, supervision, interpretation of results, finalization of manuscript.

Ethics

This article is original and contains unpublished material. All authors have read and approved the manuscript and no ethical issues are involved.

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