JOURNAL OF THE CIVIL ENGINEERING FORUM

Journal of Civil Engineering Forum, January 2020, 6(1): 49-60
DOI 10.22146/jcef.49387
Available Online at https://jurnal.ugm.ac.id/jcef/issue/archive

The Effect of Horizontal Vulnerability on the Stiffness Level of Reinforced Concrete Structure on High-Rise Buildings

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SUBMITTED 28 October 2019 **REVISED** 29 November 2019 **ACCEPTED 23** January 2020

ABSTRACT Buildings have an essential function; they are a place for people to carry out various activities, such as social, economic, and religious activities. In a building construction plan, considering multiple factors from strength to architecture is necessary. The issue of limited land in some areas has resulted in the construction of vertical buildings, often known as high-rise buildings. High-rise building construction requires paying attention to various levels of vulnerabilities, especially for projects in earthquake-prone areas. In this study, the levels of vulnerability and vertical irregularity of high-rise buildings were analyzed based on structural rigidity for reinforced concrete structures. Building models including a cube-shaped model, L-shaped model, and U-shaped model were investigated. The STERA 3D program was used to determine the strength values of the structures by providing earthquake loads on each structure model using the time-history analysis method. The El Centro and Kobe earthquakes were tested in these structural models because the earthquakes are known to contribute the most exceptional damage value in the history of earthquake-caused disasters. The assessed parameters of the tested structural models include structural stiffness, the most significant displacement in the structure, the maximum displacement and load relations experienced by the construction, and the hysteretic energy exhibited by the structure. Therefore, the best performed structural model in resisting the load could be obtained. The results showed that the U-shaped building model had the highest stiffness value with an increase in stiffness of 7.43% compared with the cube-shaped building model and 3.01% compared with the L-shaped building model.

KEYWORDS High-rise Building; Horizontal Vulnerability; Stiffness; STERA 3D; Time history

1 INTRODUCTION

Buildings are essential because they support the function of various human activities, such as economic, social, and housing activities. According to FEMA-426 (2011), the architecture of Buildings and Infrastructure Protection can be divided into several main groups based on the layout, and buildings can be grouped into several forms so that the strength of structures with variations in horizontal cross section can be studied. The horizontal system includes horizontal stiffeners (commonly called horizontal diaphragms) in the form of the story and deck framing systems (Majore, 2015).

According to Weningtyas (2017), beam-column joints in precast concrete are used to determine the values of elasticity, energy dissipation, stiffness, strain stress, and crack patterns based on variations in column dimensions to assess the strength of the structure due to the forces gradually acting on each dimensional change. The existence of effects that occur at these levels will result in displacement and deviation (Cornelis and Umbu, 2014).

One of the essential requirements in constructing an earthquake-resistant building is knowing the peak ground acceleration by determining the highest acceleration value produced by an earthquake on the surface of a particular area and at a particular time (Massinai et al., 2016). Kapojos et al. (2015) stated that in earthquake-resistant buildings, the ground velocity value could be calculated using earthquake time-history data. Saito (2016) investigated the characteristics of high-level buildings under long-period ground motion using a 37-story building simulation and the STERA 3D software by analyzing the time history of the structure.

The behavior of reinforced concrete structures has been studied by several researchers, including Louzai and Abed (2014), who researched the behavior of multilevel reinforced concrete structures, considering three-, seven-, and nine-story buildings. The results for the dynamic incremental analysis method showed that the seismic behavior factor was 2.32 for the three-story building, 2.43 for the seven-story building, and 2.48 for the nine-story building. Meanwhile, Pavel (2018) studied reinforced concrete that was designed in seismic conditions considering 5- to 11-story buildings. The results showed that the building collapse rate for the four structural models analyzed was in the range of 4×10^{-4} to 4×10^{-5} cm.

Li et al. (2016) researched the optimization of high-rise buildings at collapsing capacity for seismic designs. The results showed that the reduction in the building collapse reached the range of 23.75%–44.18% for reinforced concrete structure building framework of 4 to 10 stories. Brunesi et al. (2016) conducted a seismic analysis in high-level repetitive buildings with the addition of mega-cores. The results showed peak displacement in the highest cases of 0.77 m and 1.83 m. Lu et al. (2015) investigated shear wall elements by non-linear analysis in high-rise buildings. The displacement experienced by the peak of the structure was found to be 1,791 m for the X-direction and 1,580 m for the Y-direction.

In this study, three types of building construction plan variations, namely cube-shaped, L-shaped, and U-shaped building models, were analyzed, with each building having a height of 60 m and the same area. The levels of stiffness and displacement were measured using earthquake time-history records from the El Centro and Kobe earthquakes. This study aims to compare the results of stiffness and displacement from the variations of high-rise buildings that have been subjected to the same type of earthquake. It is expected that this research can provide information about the level of building vulnerability due to the irregularity of the building construction plan used.

2 METHODS

2.1. Building Information

This study used three building models that vary in horizontal planes, namely a cube-shaped model, L-shaped model, and U-shaped model. The building has 12 stories and a total height of 60 m. Table 1 presents the general data of each building model. Meanwhile, Figure 1 shows the beam cross section and column cross section, which have the same size. By using the STERA application, only a small amount of material data is required to facilitate the modeling process. The building data used are general data that have been previously surveyed.

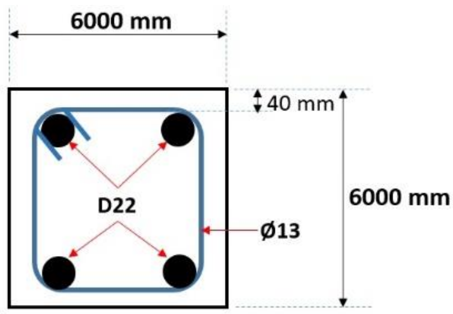


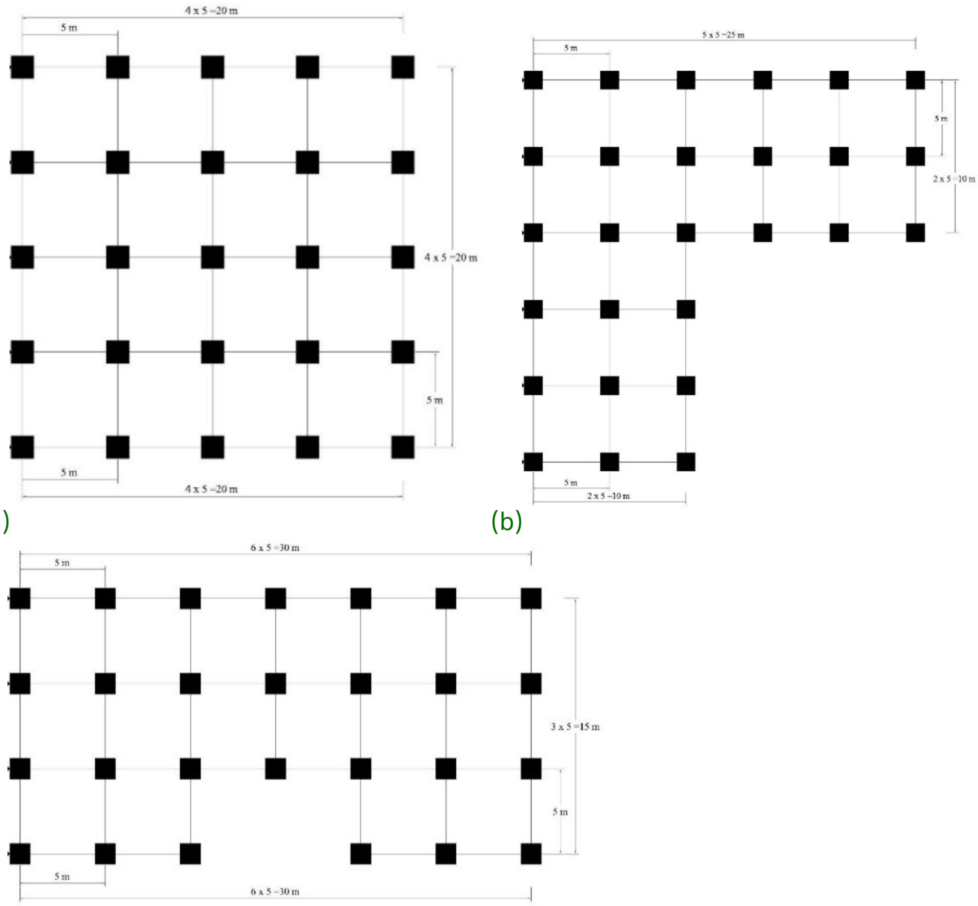
Figure 1. Beam cross section and column cross section

Table 1. Data structure model

Building Description	Dimensions of Structure Models		
	Cube-shaped Model	L-shaped Model	U-shaped Model
The number of stories	12 stories	12 stories	12 stories
Total building height	60 m	60 m	60 m
Story height	5 m	5 m	5 m
Total building width	20 m	25 m	30 m
Total building length	20 m	25 m	15 m
Total building area	400 m2	400 m2	400 m2

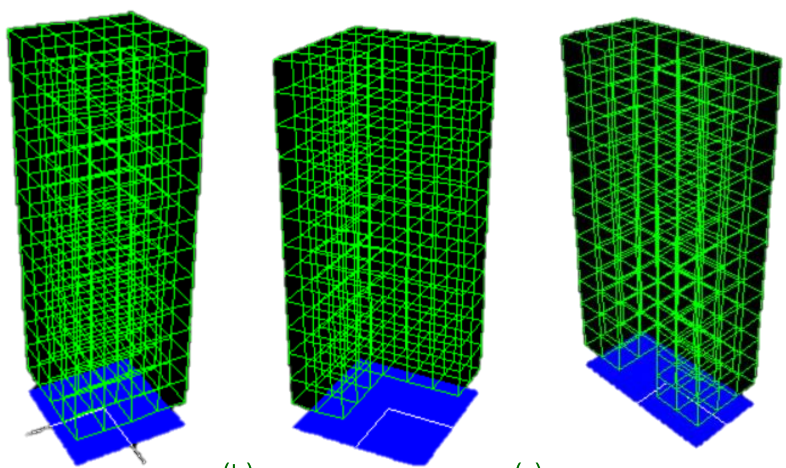
2.2. Structure Modeling

Figure 2 depicts the building dimensions used. Different building dimensions were used in this study, but the total building areas of the three variations were the same. The test was conducted by modeling; this method can allow a comparison for each test. The structure was modeled with an open structure frame system with force derived from the structure's weight and earthquake. The program used in this study is STERA 3D v9.6.



(c)

Figure 2. Blueprints of (a) cube-shaped model; (b) L-shaped model; (c) U-shaped model



(a) (b) (c)

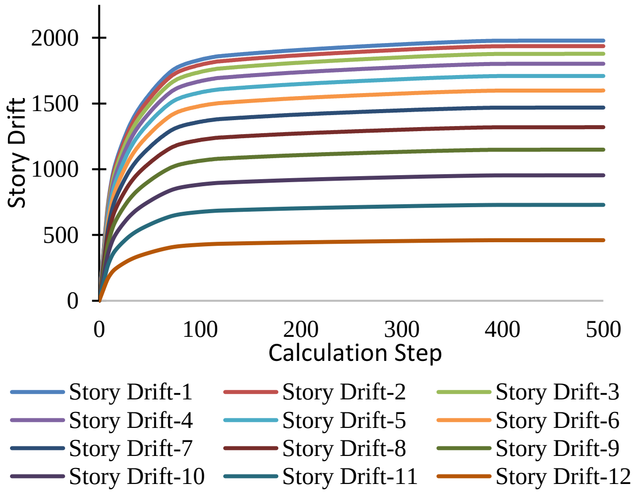
Figure 3. Three-dimensional diagrams of (a) cube-shaped model; (b) L-shaped model; (c) U-shaped model

The earthquake speed was estimated using data from the El Centro earthquake in 1940 and Kobe in 2015 because it is the largest earthquake that has ever occurred. Figure 3 depicts three-dimensional views taken from the STERA application. These models have the same area for each story; thus, the variations are given only on the building plan. Time-history earthquake loads are used in this study. The north–south part of the building is vertically burdened, and in the east–west part, the El Centro and Kobe loads are used; thus, effects that are close to real conditions will be known. The El Centro earthquake has an increased acceleration: 210.1 cm/s2 in the east–west direction, 314.7 cm/s in the north–south direction, and 206.3 cm/s2 in the vertical direction. The Kobe earthquake has a much greater acceleration than the El Centro earthquake: 617.1 cm/s2 in the east–west direction, 817.8 cm/s2 in the north–south direction, and 332.2 cm/s2 in the vertical direction. The loading is done by providing a three-way earthquake model in the cube-shaped, L-shaped, and U-shaped building models vertical irregularity; then, the properties shown by each structural building model can be seen directly.

3 RESULTS AND DISCUSSIONS

3.1 Building Stiffness

Stiffness is modeled by providing load in stages to show the damage in certain calculations. Figure 4 illustrates the relationship between step calculations and the story drift produced by each story. Each story from the modeling method showed different results. For each model tested, a significant difference existed in the stiffness of the first story of each model. Figure 5 is the stiffness result for each model, and Figure 5 (a) depicts the stiffness produced on each story, while Figure 5 (b) depicts the highest stiffness obtained. The U-shaped building model showed the greatest stiffness value, i.e., 2125 kN, compared with other models. That stiffness value is 7.43% higher than that of the cube-shaped building model and 3.01% higher than that of the L-shaped building model. This phenomenon occurred because the U-shaped building model had a greater cross section in the X-direction.



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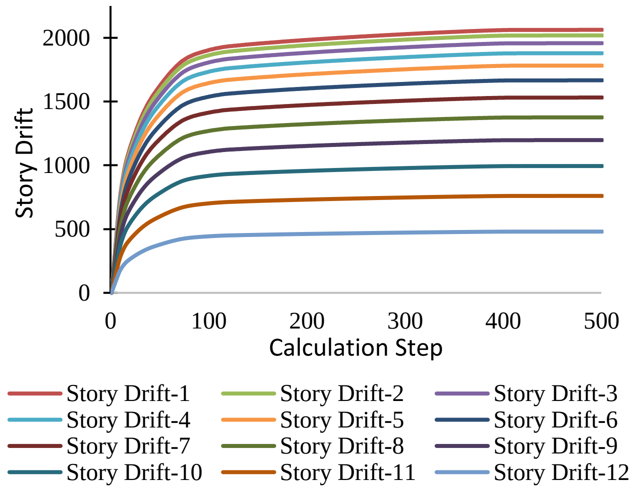

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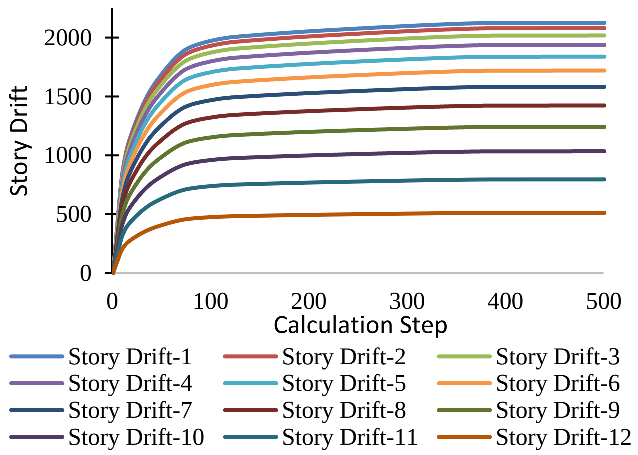


(c)

Figure 4. The relationship between story drift and step calculation in terms of stiffness for the (a) cube-shaped, (b) L-shaped, and (c) U-shaped building models

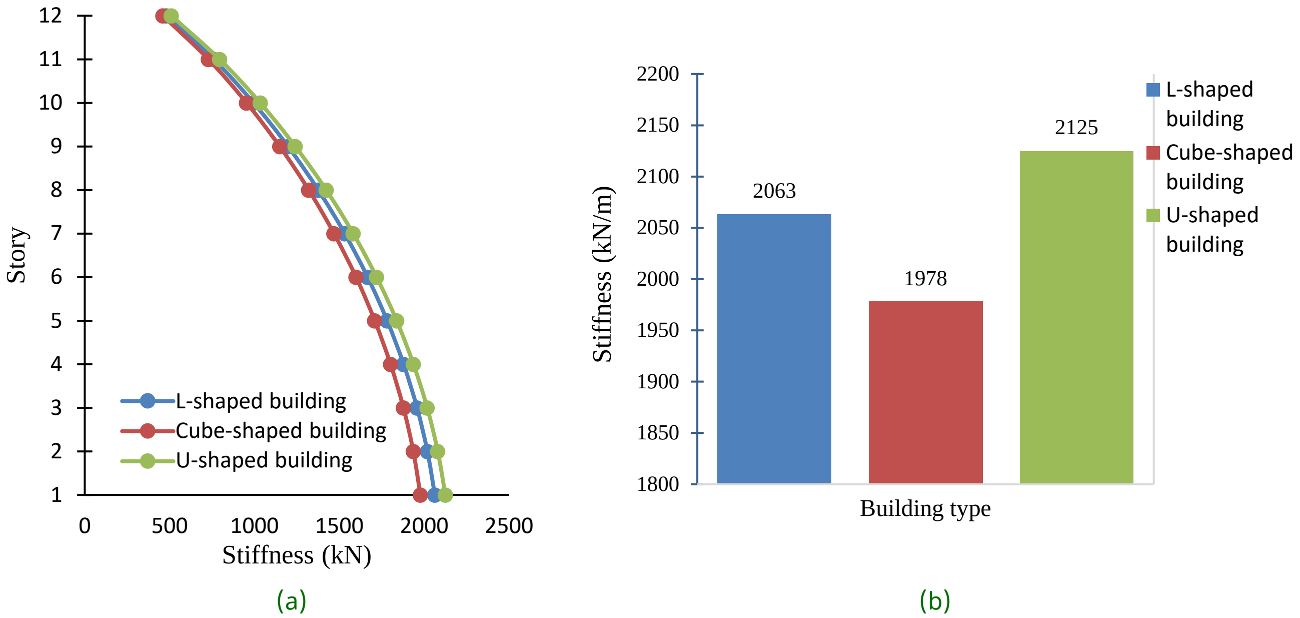


Figure 5. (a) Stiffness values on each story; (b) the value of maximum stiffness

3.2 Displacement Value

Displacement is one of the requirements used to know building security and building stiffness. The displacement that resulted from the force received from the structure is calculated based on a certain displacement from the control point, called the displacement target, as the maximum displacement that can occur in the structure at the time the planned earthquake occurs. The displacement provides information about the maximum natural distance by the structure model; therefore, the smallest displacement can be known. The results of the study show the displacement value of the top story of the building due to the force exerted on the ground by the existence of the earthquake; the displacement will indicate the maximum value of displacement experienced by the model.

The most significant displacements that occurred from the three models after being given the same earthquake force are as follows: For the El Centro earthquake, in the X-direction, the cube-shaped model exhibited the most significant displacement (15.85 cm), while the U-shaped model exhibited the smallest displacement (15.15 cm). Meanwhile, in the Y-direction, the U-shaped model exhibited the most significant displacement (19.5 cm), while the cube-shaped model showed the smallest displacement (18.97 cm), as shown in Table 2. Table 2, which presents the displacement due to the Kobe earthquake, shows a significant difference in the displacement due to the Kobe earthquake from that due to the El Centro earthquake; the maximum displacement due to the Kobe earthquake is higher than that due to the El Centro earthquake. For the Kobe earthquake, the L-shaped model produced the most significant displacement in the X-direction, which was 23.81 cm, and the U-shaped model produced the most significant displacement in the Y-direction, which was 36 cm.

The results of this study show the value of the top story displacement of the building and the base shear forces generated by the earthquake force applied to each model. The same earthquake force was applied to the three models, and the U-shaped model exhibited the most significant displacement in the X-direction (15.98 cm), with a base shear force of 1825 kN, and the L-shaped model exhibited the smallest displacement (15.72 cm), with a base shear force of 1934 kN. As for the Y-direction, the U-shaped model exhibited the most significant displacement (20.17 cm), with the base shear force being 1974 kN, and the cube-shaped model exhibited the smallest displacement (18.97 cm), with the base shear force being 2020 kN.

Modeling using the Kobe earthquake as a force on the ground of the structure provided a large enough displacement and force, which had a significant impact on each structural model; the force of the Kobe earthquake resulted in a greater displacement than that of the El Centro earthquake. The maximum displacement due to earthquake in the cube-shaped model in the X-direction was 23.4 cm, and the maximum base shear force was 2877 kN; in the Y-direction, the displacement was 35.64, and the maximum base shear force was 2774 kN. The L-shaped model produced a displacement in the X-direction of 23.81 cm and a maximum base shear force of 3062; and in the Y-direction, a displacement of 35.44 cm and a maximum base shear force of 2937 kN. The U-shaped model produced a displacement in the X-direction of 23.71 cm and a maximum base shear force of 2897 kN; and in the Y-direction, a displacement of 35.87 cm and a maximum base shear force of 2802 kN. Figure 6 to 8 illustrate the relationship between displacement and vibration time for each type of model. The deviation was from the X and Y-directions of the El Centro and Kobe earthquakes.

Table 2. The result of displacement and base shear force for the El Centro and Kobe earthquake models

Building	Direction	Maximum Displacement (cm) El Centro	Maximum Base Shear Force (kN) El Centro	Maximum Displacement (cm) Kobe	Maximum Base Shear Force (kN) Kobe
Cube-shaped model	X	15.85	1869	23.40	2877
	Y	18.97	2020	35.64	2774
L-shaped model	X	15.72	1934	23.81	3062
	Y	19.20	2126	35.44	2937
U-shaped model	X	15.98	1825	23.71	2897
	Y	20.17	1974	35.87	2802

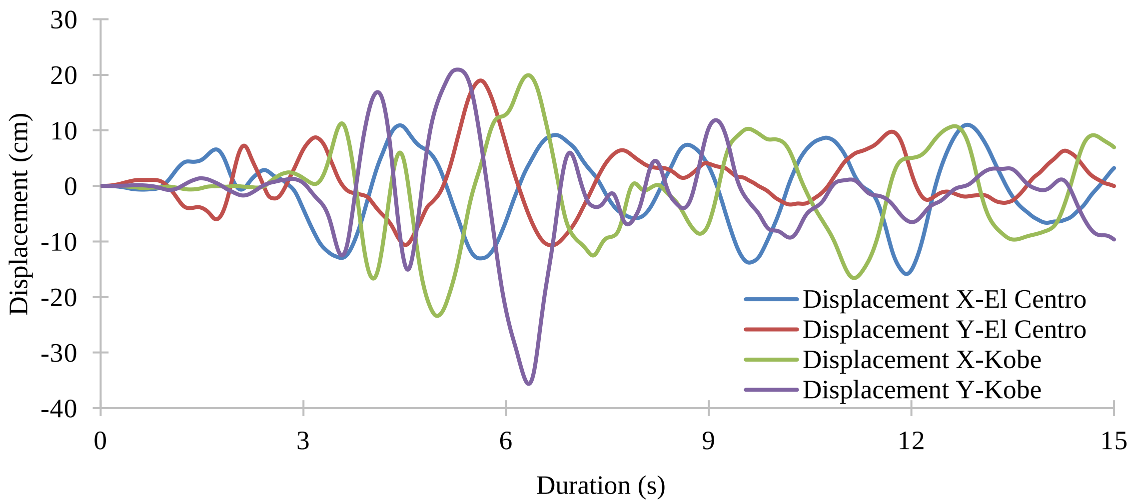


Figure 6. Relationship between the earthquake displacement and earthquake vibration time of the cube-shaped model

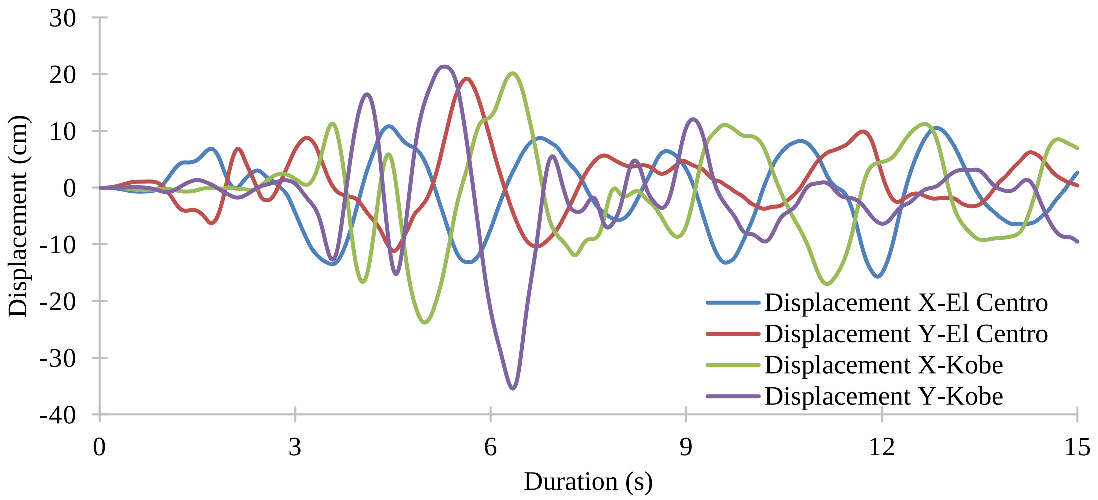


Figure 7. Relationship between the displacement and earthquake vibration time of the L-shaped model

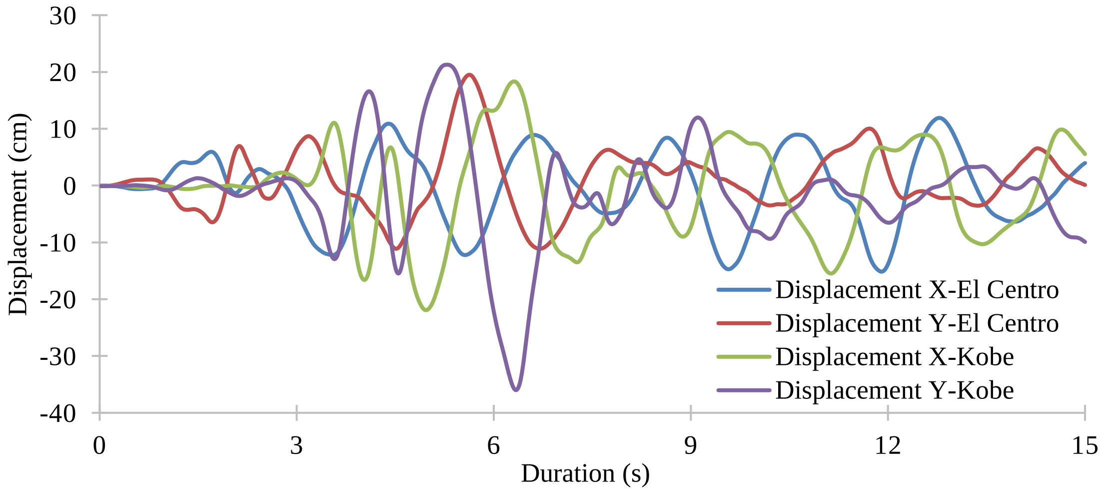
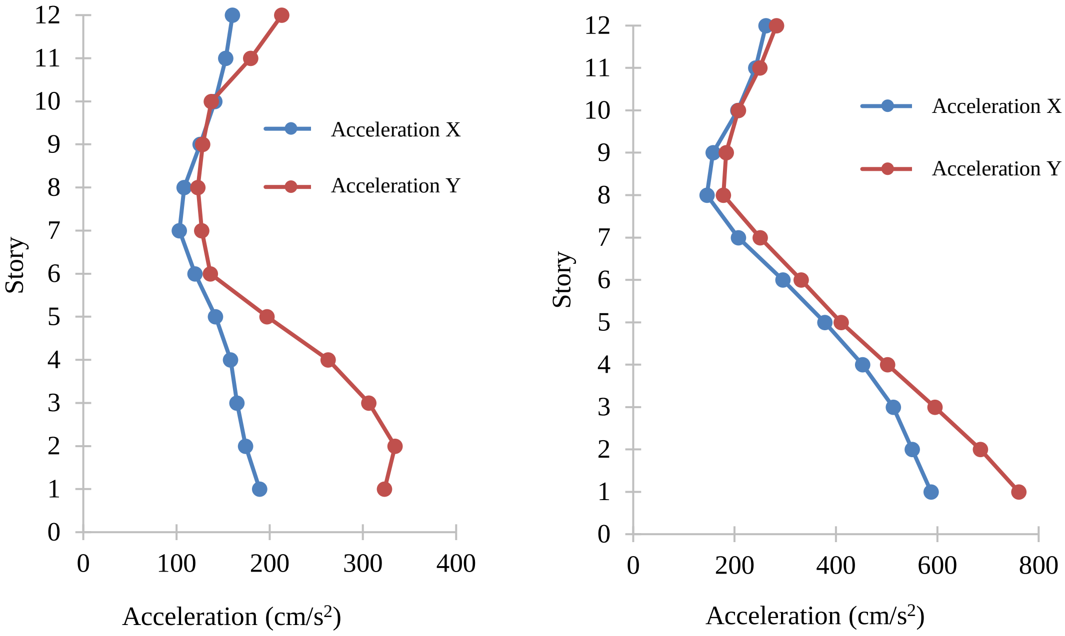


Figure 8. Relationship between the displacement and earthquake vibration time of the U-shaped model

3.3 Maximum Acceleration

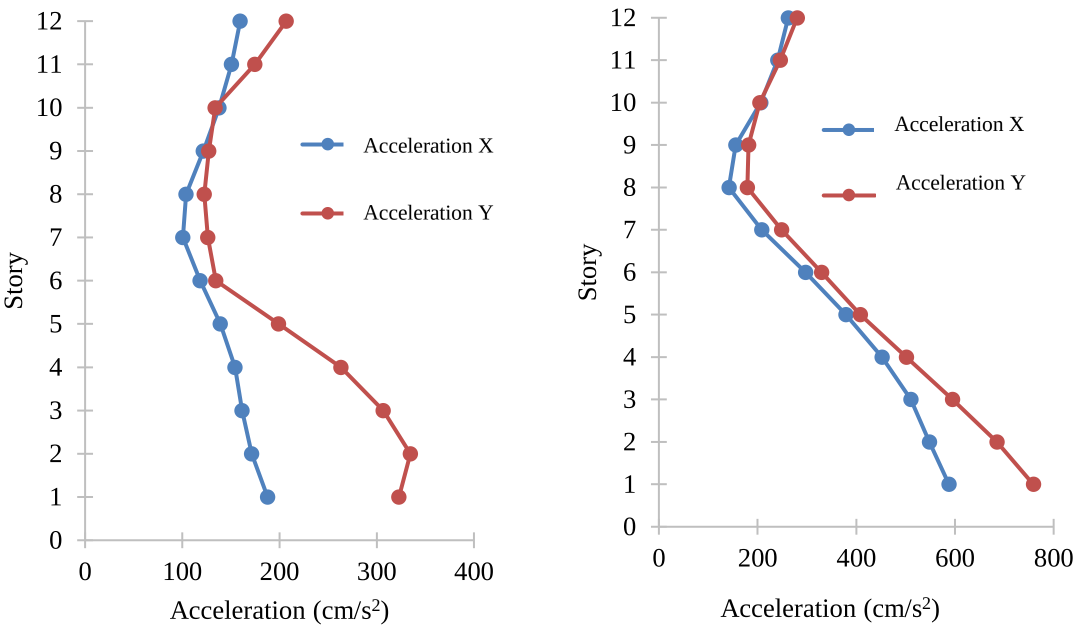
The acceleration of a structure is influenced by the ratio between the responses that occur in one story and the story below. The smaller the ratio between the stories, the greater the maximum acceleration value that the structure has before the structure is damaged. The relationship of the acceleration value with the number of stories can be seen in Figure 9 to Figure 11. Figure 9 illustrates the relationship between the maximum acceleration value and the number of stories for square-shaped buildings. Figure 10 illustrates the maximum acceleration relationship for L-shaped buildings, while that for U-shaped buildings can be seen in Figure 11.

The results of the acceleration of each structural model for the El Centro earthquake show that the lowest acceleration values always occur in the middle of the stories, that is, the seventh story for the X-direction and the eighth story for the Y-direction. The highest acceleration value always occurs on the lower stories of each model, that is, the first story for the X-direction and the second story for the Y-direction. For the Kobe earthquake, it can be seen that the greatest acceleration occurs on the first story, with the value of each model not significantly different. The largest acceleration (760.8 cm/s^2) occurs in the first story of the cube-shaped model in the Y-direction, and the smallest acceleration (141.8 cm/s^2) occurs in the eighth story of the L-shaped model in the X-direction.



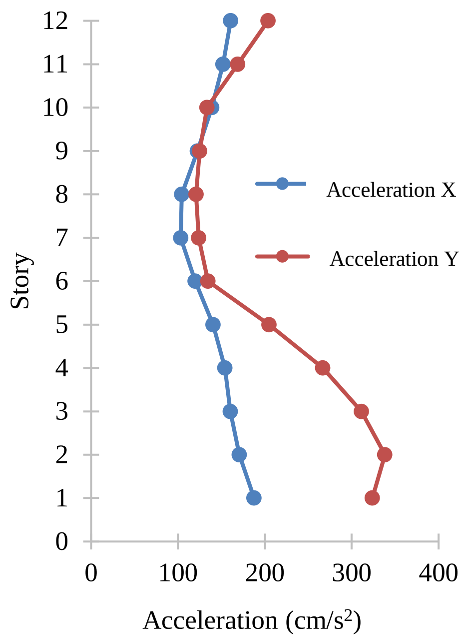
(a) (b)

Figure 9. (a) Acceleration of the cube-shaped model for the El Centro earthquake; (b) Acceleration of the cube-shaped model for the Kobe earthquake



(a) (b)

Figure 10. (a) Acceleration of the L-shaped model for the El Centro earthquake; (b) Acceleration of the L-shaped model L for the Kobe earthquake



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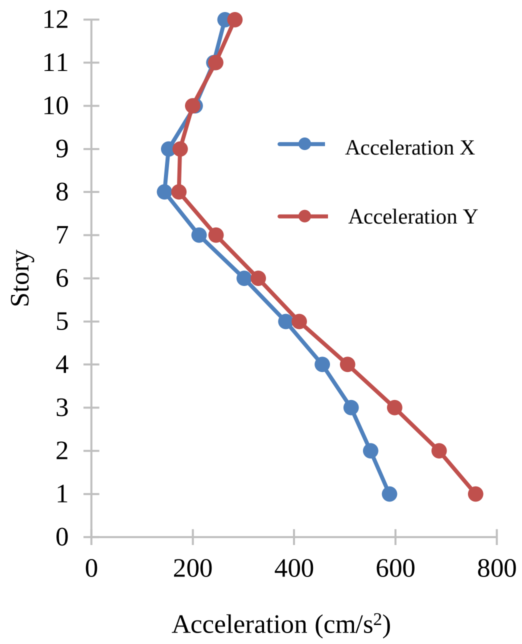


(b)

Figure 11. (a) Acceleration of the U-shaped model for El Centro earthquake; (b) Acceleration of the U-shaped model for Kobe earthquake

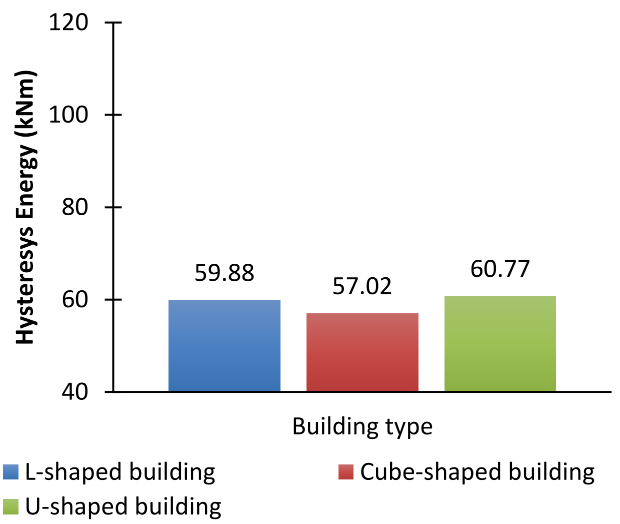
3.4 Hysteretic Energy

Hysteretic energy is the total energy that occurs in each cycle. The ability of the structure to absorb the energy becomes a basis to determine the structure resistance ability. The trapezoidal method with many piles is used to calculate hysteretic energy based on the total energy area and using numerical integration. The load applied and the lateral displacement of the structure in the L-shaped model, the cube-shaped model, and the U-shaped model can be seen in Table 3. In Figure 12, structural modeling with the El Centro earthquake shows that the U-shaped model has the highest hysteretic energy value of 60.77 kNm, followed by the L-shaped model structure, which has a value of 57.02 kNm, and the cube-shaped model has the smallest hysteretic energy, 57.02 kNm. The differences owned by each structural model are quite large due to the burden not being well distributed throughout the model.

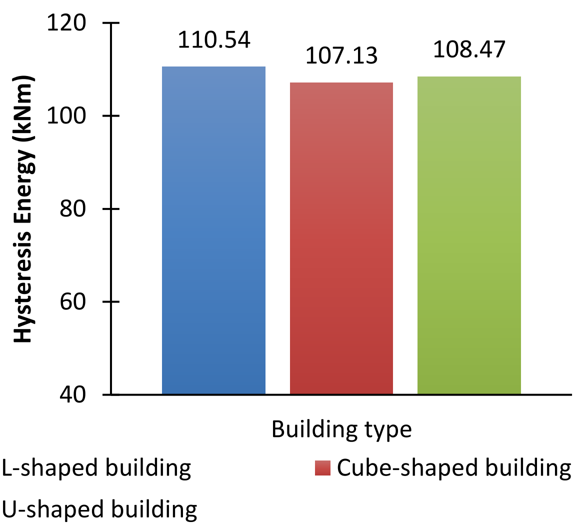
For the Kobe earthquake, the results of the modeling with earthquake load show that the L-shaped model exhibited the greatest hysteretic energy value, 110.54 kNm. The greater the hysteretic energy that occurs in the structural model, the lower the structure collapse rate and the greater the structure rigidity; moreover, the structure would have a large lateral displacement; conversely, the smaller the hysteretic energy value, the higher the structural collapse rate and the lower the stiffness. Differences exist in the hysteretic energy produced by the models with the El Centro and Kobe earthquake loadings. It can be seen that in the El Centro earthquake loading, the L-shaped model generated the largest hysteretic energy value, while in the Kobe earthquake, the U-shaped model generated the largest hysteretic energy value. Figure 12 depicts a comparison between the hysteretic energy values produced as a result of the El Centro and Kobe earthquake forces

Table 3 Load and lateral displacement of building

Objects	El Centro 1940		Kobe 2015	
	Loading (kN)	Lateral Displacement (m)	Loading (kN)	Lateral Displacement (m)
L-shaped model	311.90	0.19	311.90	0.35
Cube-shaped model	300.60	0.19	300.60	0.36
U-shaped model	301.30	0.20	301.30	0.36



(a)



(b)

Figure 12. Comparison of hysteretic energy values of the L-shaped, cube-shaped, and U-shaped models for (a) the El Centro earthquake and (b) the Kobe earthquake

4 CONCLUSIONS

Based on the modeling of horizontal cross section variations using the STERA 3D software, the L-shaped model was found to have the highest stiffness value of 2063 kN; the cube-shaped model, a stiffness value of 1978 kN; and the U-shaped model, a stiffness value of 2125 kN. Considering the El Centro earthquake, the U-shaped model produced the largest displacement of 20.17 cm, while for the Kobe earthquake, the U-shaped model produced the largest displacement of 35.87 cm. The relationship between the force and displacement that occurred shows that for the El Centro earthquake, the L-shaped model exhibited the greatest stiffness in terms of the base shear force shown, which is a lateral deviation value of 19.20 cm and a load of 2126 kN, whereas for the Kobe earthquake, the L-shaped model exhibited stiffness by showing a lateral deviation of 23.81 cm and a load of 3062 kN. Moreover, the U-shaped model structure generated the greatest acceleration (338.3 cm/s^2) that occurred in the El Centro earthquake, and in the Kobe earthquake, the cube-shaped model structure generated the greatest acceleration (760.8 cm/s^2). In addition, for the El Centro earthquake, the cube-shaped model produced the smallest hysteretic energy (57023820 Nmm), while for the Kobe earthquake, the cube-shaped model also produced the smallest hysteretic energy (107133840 Nmm). The cube-shaped model had the most stable structure because it produced a relatively small lateral deviation in the El Centro earthquake, which is 15.85 cm with a loading of 1869 kN in the X-direction and 18.97 with the loading of 2020 in the Y-direction. Meanwhile, in the Kobe earthquake, the deviation was 23.4 cm with a loading of 2877 kN in the X-direction and 35.64 cm with a loading of 2774 kN in the Y-direction. The stiffness value exhibited by the structural model is 1978 kN, and the hysteretic energy value is 57.02 kNm in the El Centro earthquake and 107.13 kNm in the Kobe earthquake.

DISCLAIMER

The authors declare no conflict of interest.

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