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Seismic Performance of Multi-Story Reinforced Concrete Frame Structures Due to Vertical and Horizontal Irregularities

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Time History;
Seismic Performance.

Abstract
The irregularities in structures affect their seismic performance, particularly in earthquake-prone areas, such as Indonesia. This study evaluates the seismic performance of multi-story reinforced concrete frame structures with vertical and horizontal irregularities. The building has 12 floors and features two different plans and vertical irregularities, namely the L and H buildings. Each horizontal irregularity has five variations of vertical irregularity. Th-e frame structure is analyzed using STERA 3D software for non-linear dynamic time-history analysis. El-Centro, Kobe, and Parkfield earthquake time history data were used in this study. The seismic behavior investigated in this study consisted of base shear force, lateral deformation, stiffness, displacement, drift ratio, maximum acceleration, and capacity curve. Numerical simulation results indicate that each model performs differently when subjected to the same seismic load and material properties. It can be concluded that vertical irregularity significantly affects the seismic performance of high-rise reinforced concrete structures. The maximum shear force with vertical irregularity is 133% higher for the L-Shape and 169% higher for the H-Shape compared to a building without vertical irregularities.

INTRODUCTION

Earthquakes are among the world most destructive natural disasters. Numerous countries with dense populations live in areas with a relatively high rate of earthquake occurrence. Earthquake is one of the natural disasters caused by tectonic activity resulting from plate movement in the lithosphere layer. Because earthquakes cannot be foreseen or prevented, it frequently has substantial consequences, such as damage to buildings or infrastructure, which cause fatalities. Geographically, Indonesia is located above the ring of the fire zone, surrounded by three extremely active plates, the Eurasian, Australian, and Pacific plates. As a result, this increases the chances of an earthquake (Prayuda et al., 2017). Numerous field studies indicate that structures and housing continue to sustain the majority of damage after an earthquake in Indonesia, which is a significant issue because it can result in death for building users (Saputra et al., 2017; Idris et al., 2019; Pujianto et al., 2019; Maidiawati & Sanada, 2008).

When an earthquake occurs, several factors contribute to building damage, including the seismicity of the building location, the user population, the type of soil, non-structural elements, the type of building, the number of floors, the irregularity of the building in the horizontal and vertical directions, and the building service life (FEMA, 2015). Due to the limited land area, vertical construction is one of the best options. However, the irregular shape of the building in the vertical direction affects its stability, particularly during an earthquake. Vertical irregularity occurs due to significant changes in stiffness, strength, mass, or dimensions, resulting in an in-plane discontinuity in the structure (Mwafy & Khalifa, 2017). The design method for buildings with structural irregularities has been documented in various codes, including ASCE/SEI 7-10 (ASCE, 2010), Eurocode 8 (CEN, 2004), the Canadian National Building Code (NBCC, 2010), and the Indonesian National Standard (BSN, 2019a).

The interest in investigating the seismic behavior of irregularly shaped structures continues to grow. Several studies have discovered the seismic performance of plan (horizontal) irregularly shaped buildings (Monika et al., 2020; Jereen et al., 2016; Alecci et al., 2019; Stefano et al., 2014; Raheem et al., 2018; Haque et al., 2016). All previous analyses used numerical analysis with various earthquake analysis techniques, such as response spectrum and time history analysis. Those studies reveal that when a seismic load is applied, plan irregularity has a significant effect on the stiffness of the building. The seismic performance of buildings has also been evaluated of the influence of vertical irregularities, including high-rise steel frame structures (Azghandi et al., 2020; Wang et al., 2018; Homaei et al., 2017; Trung et al., 2012) and high-rise concrete frame structures (Mondal & Tesfamariam, 2014; Mohsenian & Nikkhoo, 2019; Elnashai & Mwafy, 2002; El-Kholy et al., 2012; Barbosa et al., 2017). It demonstrates that while design coefficients for buildings with mild irregularities are sufficiently conservative, they significantly affect the seismic response of multi-story buildings. Although a substantial amount of material has been published on the effect of vertical and horizontal irregularities on seismic performance, various types of vertical irregularities have not been completely and systematically studied. This study discusses in detail the factors to consider when evaluating the seismic performance of multi-story buildings.

This study aims to evaluate the effect of vertical irregularities on multi-story reinforced concrete frame buildings. The analysis in this study examined the seismic performance of structures using STERA 3D numerical simulation software. The STERA 3D is a seismic analysis computer program to evaluate seismic performance in reinforced concrete and steel buildings. This software can perform elastic modal analysis, nonlinear lateral static pushover, nonlinear lateral static cyclic analysis, and nonlinear earthquake response analysis (Tanjung et al., 2019). This software was introduced by T. Saito, a professor from Toyohashi University of Technology (Saito, 2017). Research on the response of high-rise buildings with long earthquake periods using the STERA 3D application was also reported by Saito in 2016 (Saito, 2016). Additionally, numerous studies have evaluated the performance of this STERA 3D software in studying the influence of seismic loads on the behavior of multi-story reinforced concrete buildings in various regions with an earthquake history (Cao et al., 2013; Nabeel, 2016; Afifuddin et al., 2017; Naqi & Saito, 2017; Pavel et al., 2018; Maulana et al., 2019; Olteanu et al., 2016). In addition, the application of STERA 3D has also already been validated in several experiments, so this software can produce reliable results on building seismic performance (Maulana et al., 2021).

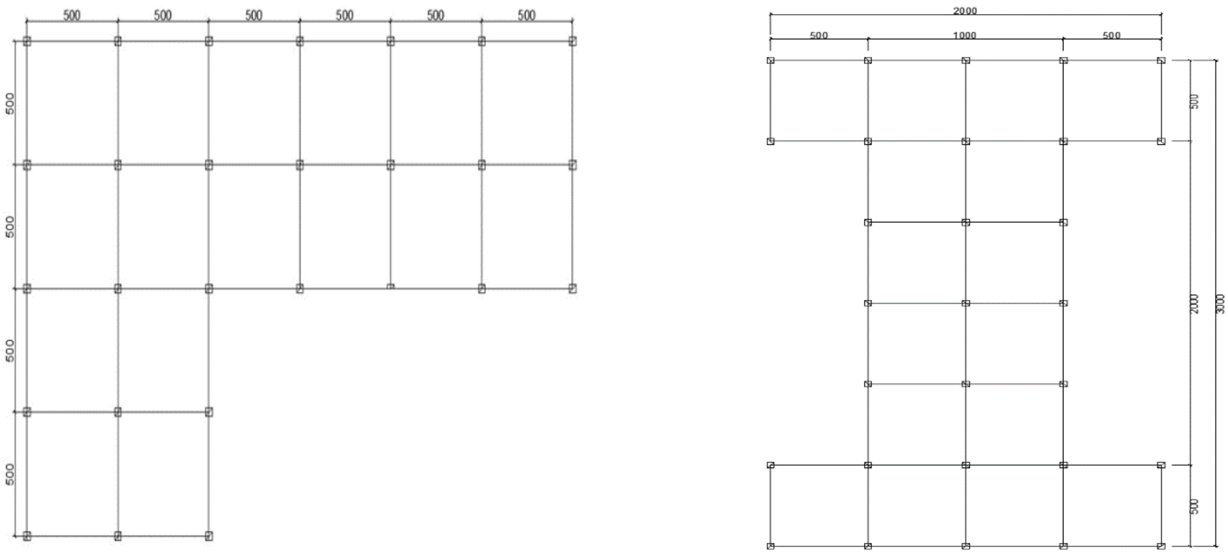
This study investigates the types of buildings with horizontal irregularities in the shape of L and H. Each of the horizontal irregularities has five variations of vertical irregularities, resulting in ten different structural frames being evaluated. Three types of earthquake history data were used, including El-Centro, Kobe, and Parkfield. This study discusses the seismic performance of the building, which consists of shear forces, lateral deformation, displacement, drift ratio, structural stiffness, maximum acceleration response, and capacity curve.

METHODS

Design of the Buildings

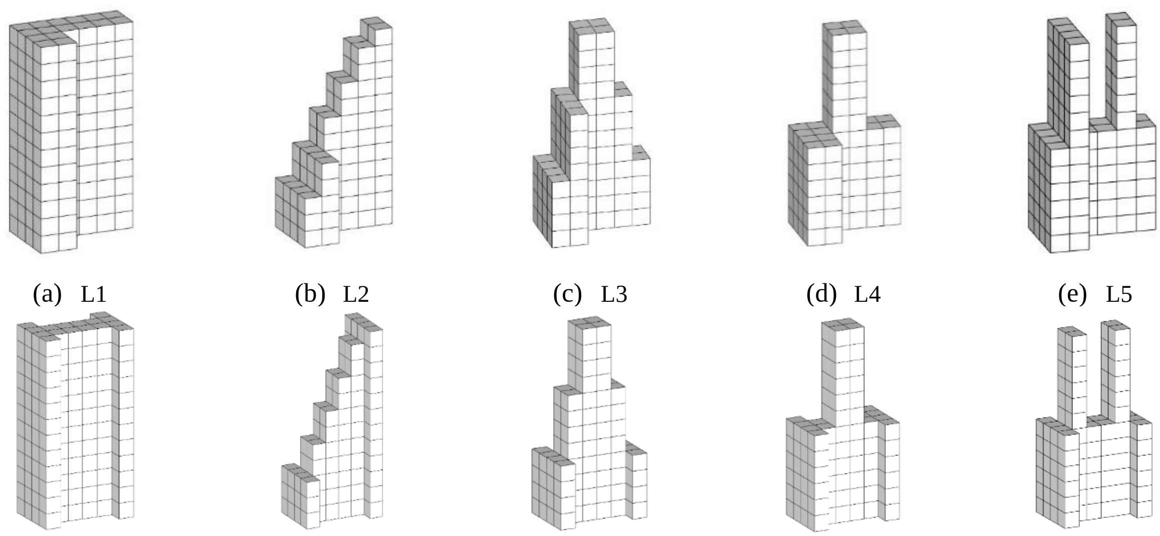
There are two types of buildings with different plan irregularities, namely L and H-shaped, as shown in Figure 1. Figure 2 shows the variation of the vertical irregularities of each horizontal irregularity. The ground floor area is the same for plans L and H, while the other story is altered to accommodate the vertical irregularities specified. Table 1 shows the information on material properties used in this study, while Table 2 and Table 4 shows each dimension of the structure and reinforcement requirements, such as columns, beams, and slabs. In this study, only the frame structure is modeled, with the wall behaving as a dead load. The structural design used in this study adhered to Indonesian standards, specifically SNI 1729: 2019 (BSN, 2019a) and SNI 2874:

2019 (BSN, 2019b). The position of stairs and voids is not considered in this study. The analytical method to obtain seismic performance parameters of the building is using STERA 3D software.



(a) L-plan irregularity (b) H-plan irregularity

Figure 1. Plan irregularity



(a) L1 (b) L2 (c) L3 (d) L4 (e) L5

(f) H1 (g) H2 (h) H3 (i) H4 (j) H5

Figure 2. Case study of vertical irregularity commonly used in real construction

Table 1. Material properties

No	Materials	Quality
1	Concrete for column	30 MPa
	Concrete for beam and slab	20 MPa
2	Young’s modulus for column	25.743 MPa
	Young’s modulus for beam and slab	23.500 MPa
3	Force yield steel reinforcement	450 MPa

The quality of the concrete used in this study is normal concrete, often used in general in the field, with compressive stress of 25 MPa to 30 MPa, as shown in Table 1. Two types of columns are used, namely K1 with dimensions of 850 × 850 mm for floors 1 to 5 and K2 with 750 × 750 for floors 6 to 12. The details of the reinforcement used for K1 and K2 can be seen in Table 2. This study also used two types of beams with different dimensions, as shown in Table 3. B1 uses 800 × 400 mm dimensions and is installed on floors 1 to 5, while for floors 6 to 12, it uses B2 beams with 600 × 300 mm dimensions. The details of the dimensions and the reinforcement slab used can be seen in Table 4. The dimensions of the reinforcement steel used vary from D10 to D13, with the steel quality referring to the standards applicable in Indonesia (BSN, 2017). The number of rebar reinforcements used is based on the results of an analysis of a typical office building.

Table 2. Dimension and reinforcement details for column structures

Column	Story	Dimension (mm)	Main reinforcement	Shear reinforcement	
				at joint (mm)	At center (mm)
K1	1-5	850 × 850	28 D25	4 D10-100	4 D10-150
K2	6-12	750 × 750	24 D25	4 D10-100	4D10-150

Table 3. Dimension and reinforcement details for beam structures

Beam	Story	Dimension (mm)	Bending reinforcement		Shear reinforcement	
			Top	Bottom	At joint (mm)	At center (mm)
B1	1-5	800 × 400	10 D25	5 D25	3 D13-100	3 D13-150
B3	6-12	600 × 300	7 D25	4 D25	3 D13-100	3 D13-150

Table 4. Dimension and reinforcement details for slab structures

Type	Story	Thickness (mm)	Reinforcement top and bottom (mm)
2-way slab	1-5	150	D13-150
2-way slab	6-12	150	D13-100

Earthquake Records

This study used three types of earthquake time history data: El-Centro, Kobe, and Parkfield. Each data used as input is time history in the direction of X, Y, and Z, as shown in Figure 3. This earthquake data was chosen because its characteristics are relatively similar to earthquakes that occurred in several regions in Indonesia. Several studies in Indonesia have also investigated the seismic performance of Indonesian buildings using the same time series data approach as this study (Masrilayanti et al., 2021; Wijaya et al., 2019; Setiawan & Nakazawa, 2017; Safarizki et al., 2013). Due to this analysis, the seismic performance of each frame structure comprises shear force, lateral deformation, displacement, drift ratio, structural stiffness, maximum acceleration response, and capacity curve. In addition to the dynamic earthquake load, gravity loads in the form of dead loads and live loads are also provided that adapt to the geometry and function of the building.

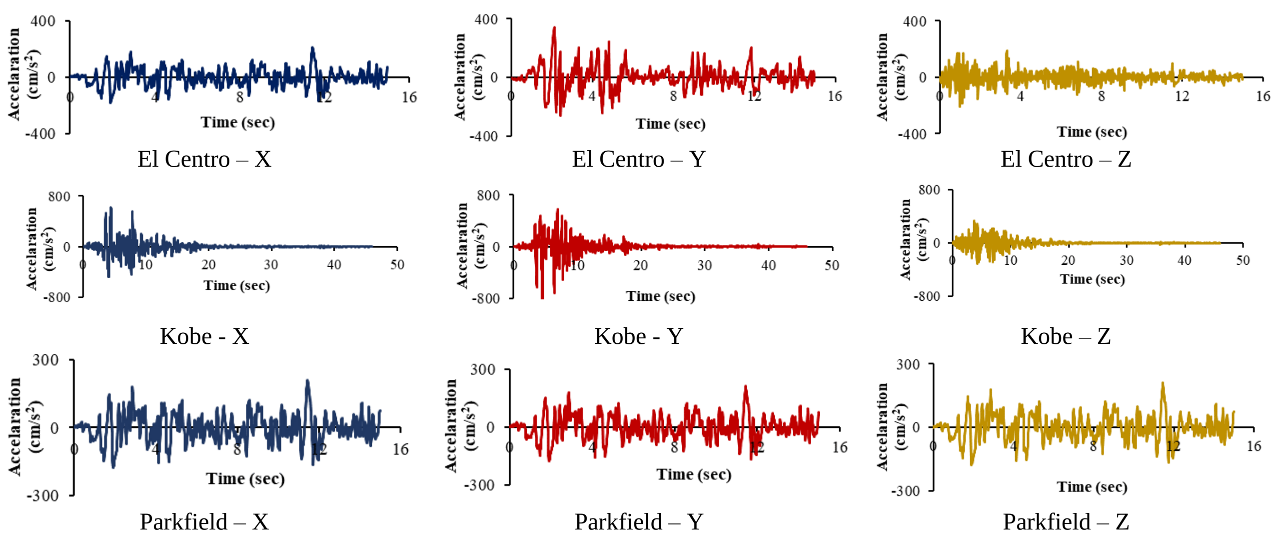
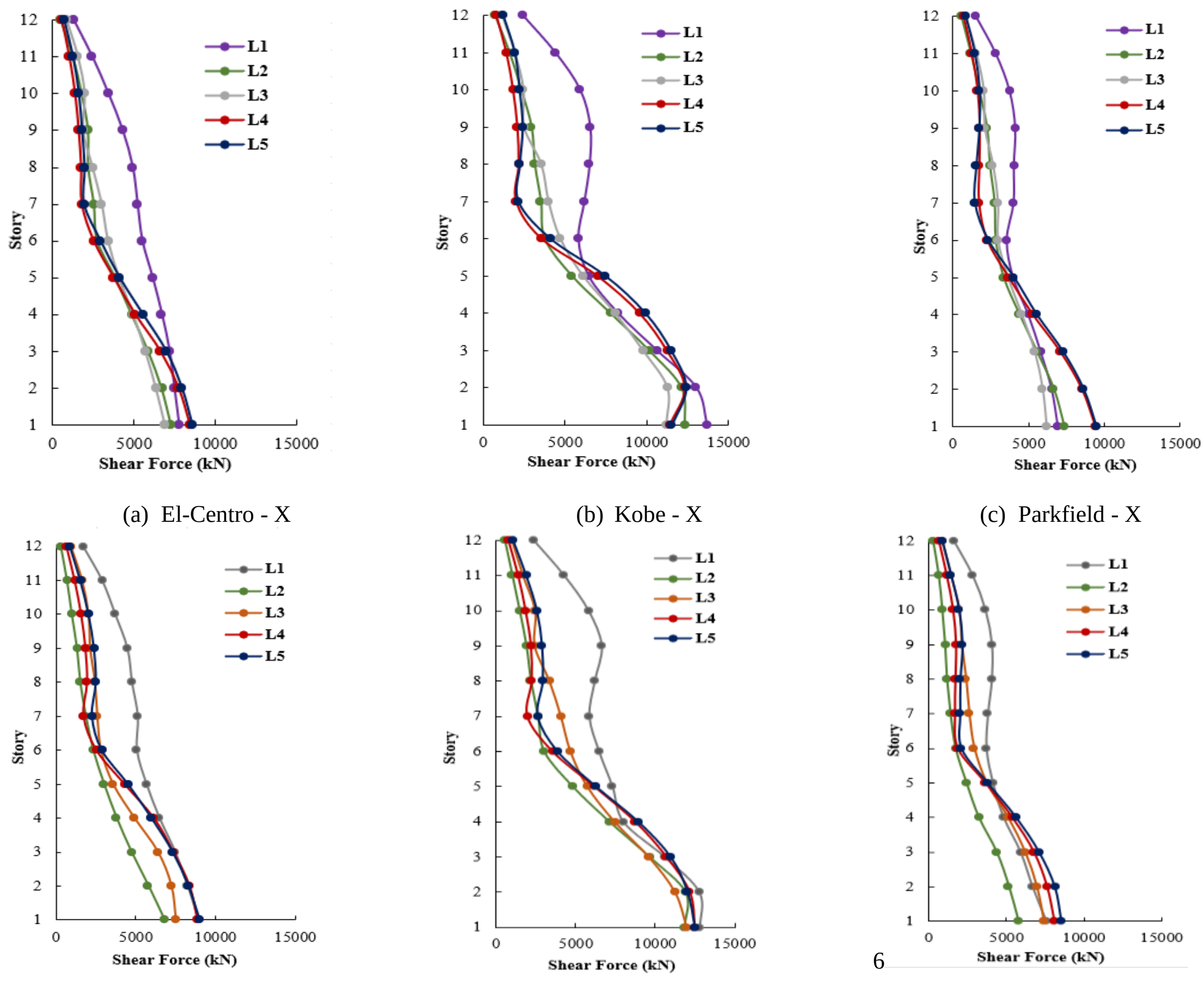


Figure 3. Earthquake time history for dynamic load

RESULTS AND DISCUSSION

Base Shear Forces

Shear force is the vertical distribution of the gap throughout the height of the structure, which acts as a horizontal force on each level. When the structure is subjected to an additional earthquake load, this force can result in the shear of one beam cross-section. Figure 4 shows the maximum shear force per floor for a reinforced concrete frame with an L-shaped plan irregularity (L1 to L5). The results include shear forces in the X and Y directions for each dynamic load applied, specifically the time histories of El-Centro, Kobe, and Parkfield. While Figure 5 shows the maximum inter-story shear force for H-shaped plan irregularity (H1 to H5). The result of each graph shows different vertical irregularities. The results indicate that the most significant shear force is always on the floor close to the base of the building in both the X and Y directions.

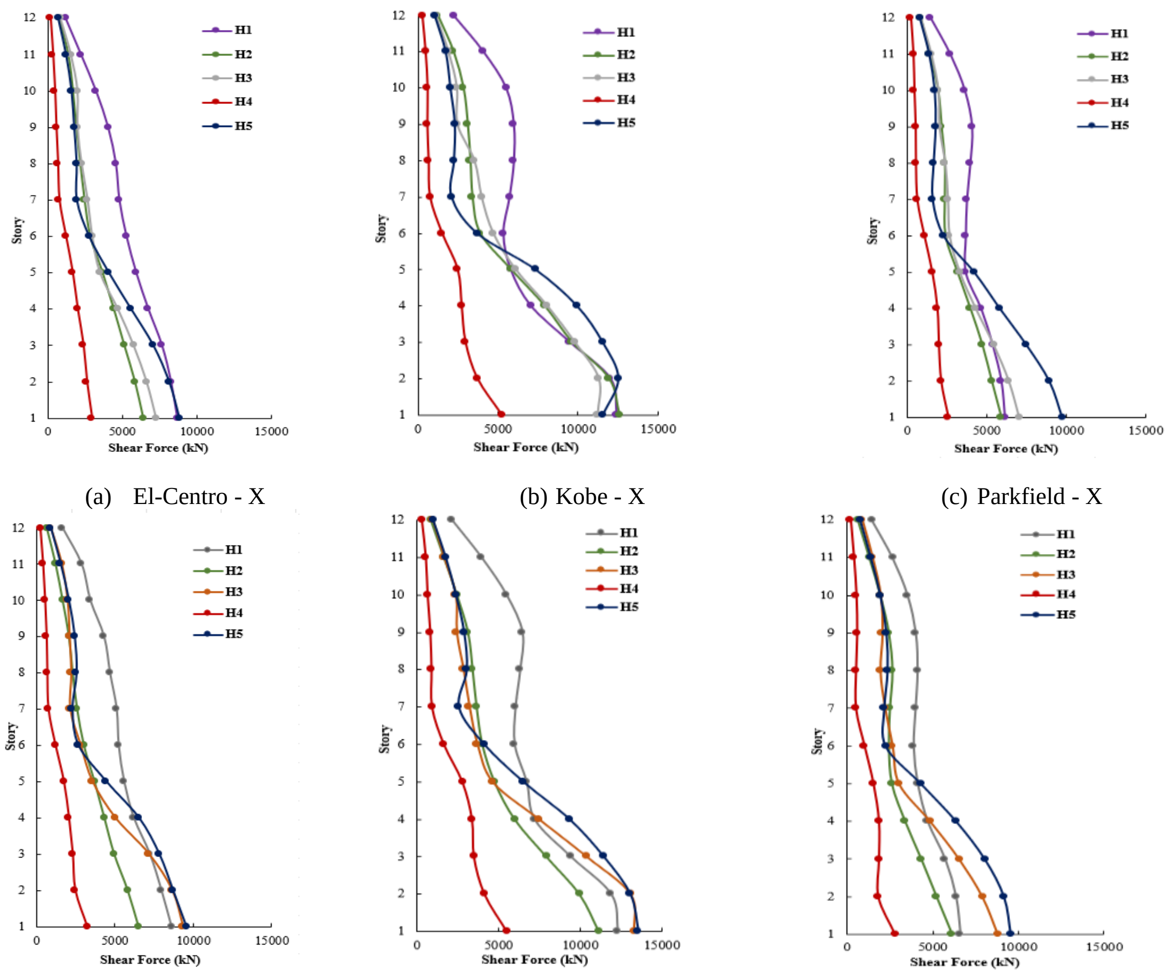


(a) El-Centro - X (b) Kobe - X (c) Parkfield - X

(d) El-Centro - Y (e) Kobe - Y (f) Parkfield - Y

Figure 4. Distribution of inter-story shear force for L-shape

Simulation results with El-Centro earthquake data show that the L5 and H5 models have the most significant shear forces for the X and Y directions. The model with Kobe Earthquake data shows that the largest shear force is seen in the L1 and H5 models, both in the X and Y directions. Meanwhile, the Parkfield earthquake data showed that L5 and H5 obtained the largest shear forces. Meanwhile, the shear force pattern for each floor shows that the data from the Kobe earthquake causes the greatest difference between floors. This can be demonstrated by comparing the shear force differences across floors 1, 6, and 12. The variation in shear force between the 12th and 6th floors is insignificant. However, a significant disparity exists between the first and sixth floors. According to the results of this shear force investigation, the vertical irregularity model 5 has the largest range for producing the highest shear force. While model 4 produces the lowest shear force in some cases of L-shaped plan irregularity, all cases for H-shaped plan irregularity. It is noted that the results of based shear forces are also similar with previous research (Prayuda et al., 2023; Maulana et al., 2023). However, those previous studies focus on different discussion of building performance due to earthquake load.



(a) El-Centro - X (b) Kobe - X (c) Parkfield - X

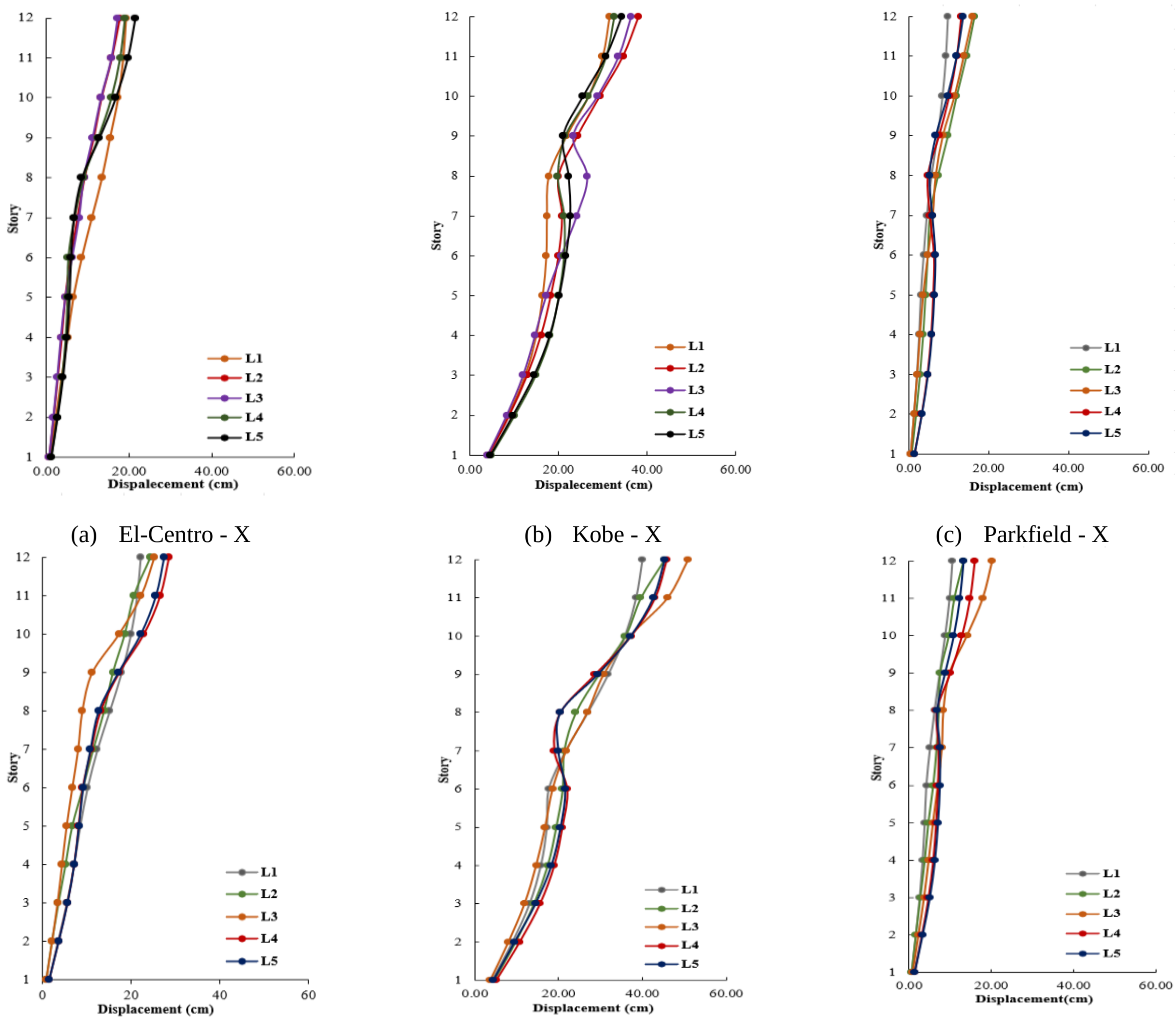
(d) El-Centro - Y (e) Kobe - Y (f) Parkfield - Y

Figure 5. Distribution of inter-story shear force for H shape

Lateral Deformation

Lateral deformation is determined by the displacements caused by the lateral applied load to the structure due to earthquake loading. Only lateral displacement in the X and Y directions was investigated using three different earthquake time history data types. The maximum lateral displacement of each story in the X and Y directions for a concrete frame structure with an L-shaped horizontal irregularity is displayed in Figure 6. Figure 7 shows the maximum lateral displacement of each floor in a concrete frame structure with H-shaped horizontal irregularity. Each figure compares the results of the lateral deformation with five vertical irregularities. In general, the data indicates that the taller the building or the more floors, the higher the lateral deformation.

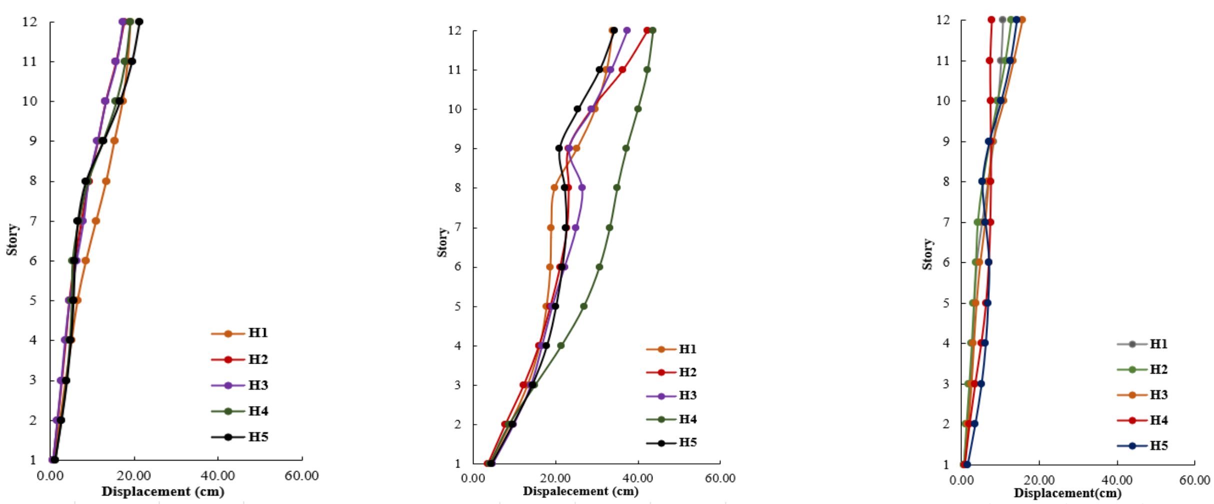
The model with L-shaped plan irregularity shows that model L5 (El-Centro), model L2 (Kobe), and model L2 (Parkfield) produce the largest deformation in the X direction on the 12th floor. The model that produces the largest displacement in the Y direction is L4 for the El-Centro earthquake and L3 for the Kobe and Parkfield earthquake. Meanwhile, the model with H-shaped irregularity shows that the H5 (El-Centro), H2 (Kobe), and H3 (Parkfield) models produce the largest deformation in the X-direction. The H3 model for the El-Centro earthquake, the H2 model for the Kobe earthquake, and the H3 model for the Parkfield earthquake generate the highest lateral deformation in the Y direction. The results of this maximum displacement indicate that the ensuing deformation is highly reliant on the type of earthquake and the building design, both in terms of plan and elevation irregularities. Based on this investigation, it can be concluded that the Kobe earthquake always produces a larger displacement than the El-Centro and Parkfield earthquakes.



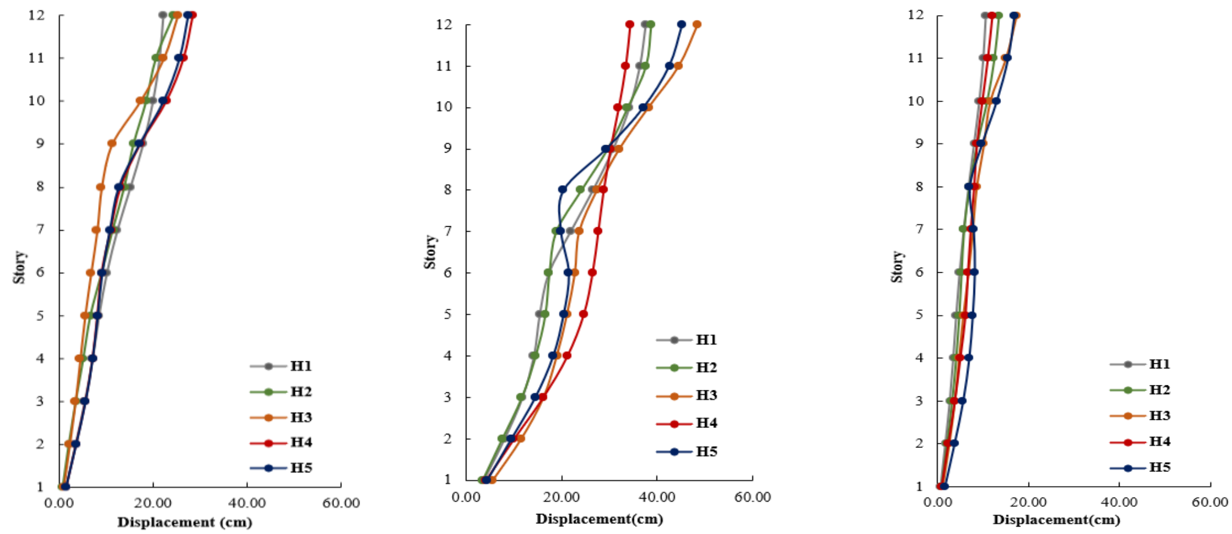
(a) El-Centro - X (b) Kobe - X (c) Parkfield - X

(d) El-Centro - Y (e) Kobe - Y (f) Parkfield - Y

Figure 6. Distribution of inter-story lateral displacement for L shape



(a) El-Centro - X (b) Kobe - X (c) Parkfield - X

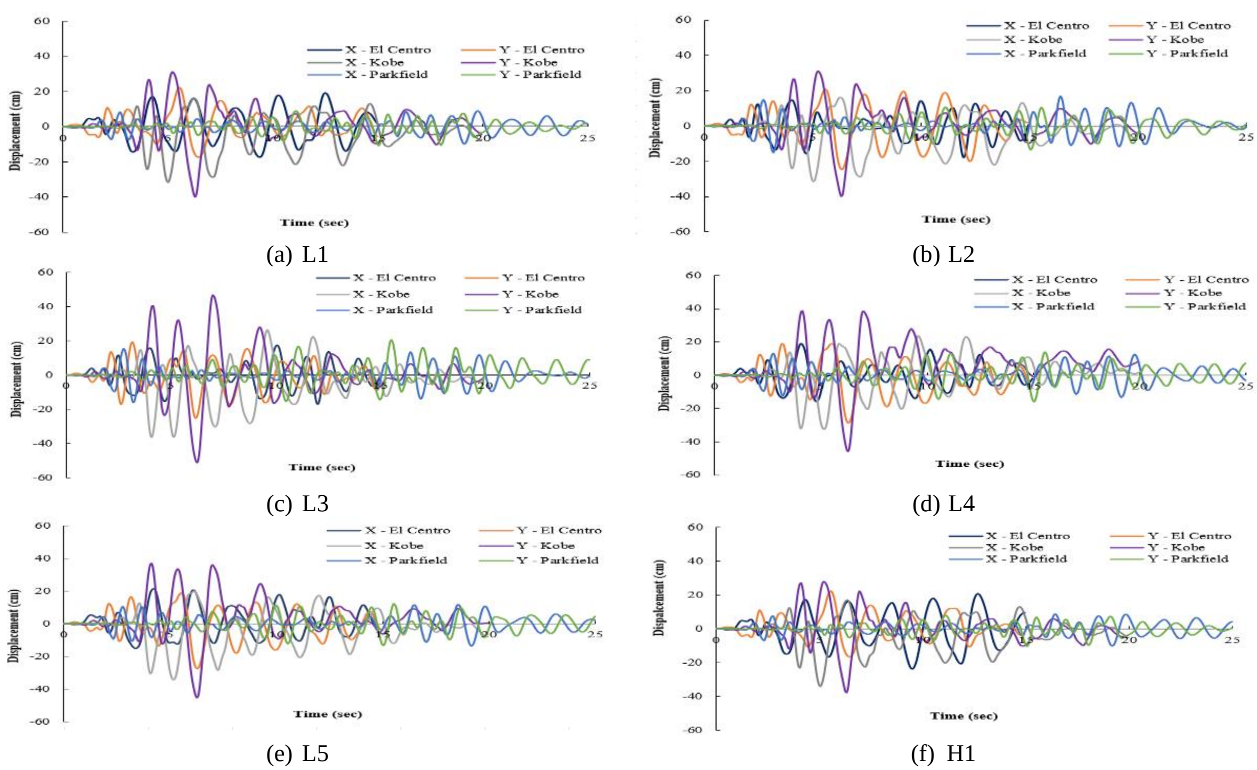


(d) El-Centro - Y (e) Kobe - Y (f) Parkfield - Y

Figure 7. Distribution of inter-story lateral displacement for H-shape

Top Displacement Versus Times

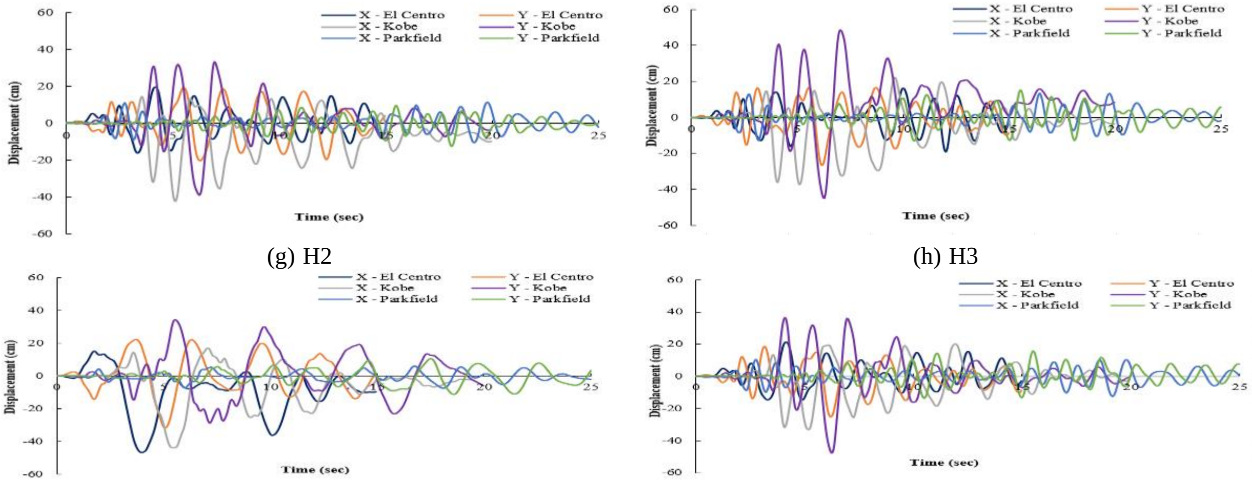
Displacement happens as a result of a load of the structure. The displacement value is essential and should be considered when assessing the safety level of a building. When an earthquake occurs, the displacement induced by force acting on the building is compared to the displacement target set as the maximum displacement. Figure 8 shows the displacement results for each building using three variations of earthquake data. The displacement direction is determined by the X and Y directions of the earthquake. The simulation results demonstrate that the Kobe earthquake data consistently provides the highest displacement when all vertical irregularities are considered, followed by the El-Centro and Parkfield earthquake data. The highest displacement occurred in the Y-direction L1 model for L-shaped plan irregularity and the Y-direction H1 model for H-shaped plan irregularity when time history data for the El-Centro earthquake were used.



(a) L1 (b) L2

(c) L3 (d) L4

(e) L5 (f) H1



(g) H2 (h) H3

(i) H4 (j) H5

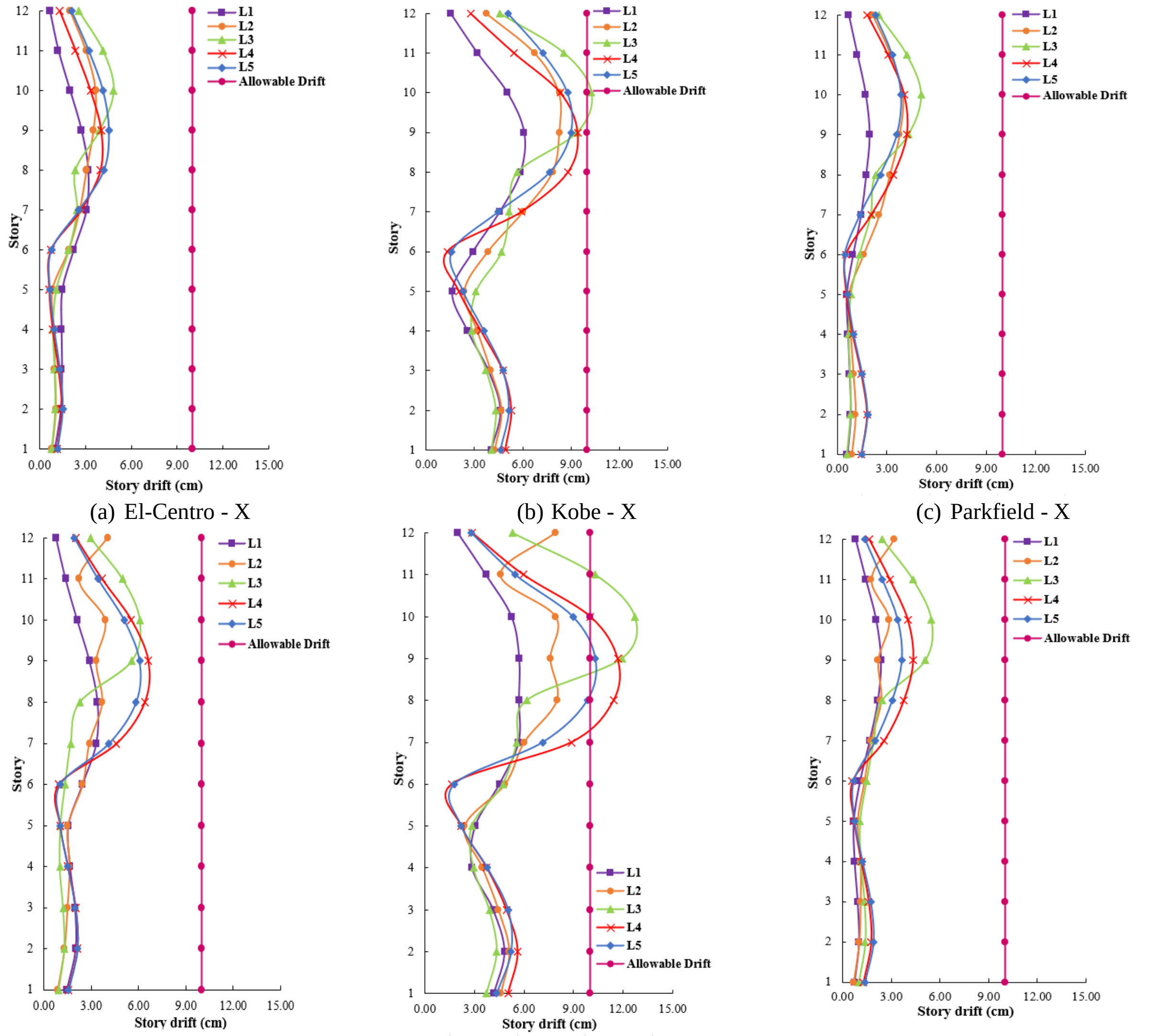
Figure 8. Relationship between top displacement and time

Kobe earthquakes always produce the most significant displacement compared to other earthquakes. This also proofed by previous studies show the similar patterns when utilized Kobe time history data as earthquake load for building simulation due to earthquake (Prayuda., et al 2023; Wang et al., 2020). In the L-shaped and H-shaped irregularity variations, the maximum displacement occurs in the L3 model in the Y direction with a displacement of 46.79 cm and the H3 in the Y direction with a displacement of 48.46 cm. The highest displacement occurred in the Y-direction L1 model for L-shaped plan irregularity and the Y-direction H1 model for H-shaped plan irregularity when time history data for the El-Centro earthquake were used. It can be concluded from the investigation of the relationship between top displacement and the duration of an earthquake that the Kobe Earthquake data produced the most significant displacement. L3 and H3 models get a larger displacement value than other models. The increase in the displacement in the L3 and H3 models occurs due to the irregularity of the building in the vertical direction.

Inter Story Drift

Story drift refers to the deviation at each building level, the relative lateral displacement between two adjacent building levels, or the horizontal deviation of each building level. The results obtained in this analysis have different values for each reinforced concrete frame model. The story drift value can be used as an indicator of the damage level of a building. The results of an inter-story drift investigation for a structure with an L-shaped plan irregularity are shown in Figure 9. The results of an inter-story drift investigation for a building with an H-shaped plan irregularity are shown in Figure 10. The results of story drift analysis using El-Centro time history data indicate that the L3 model generates the highest result of 4.85 cm in the X-direction. The L4 model produces the largest value of 6.62 cm in the Y direction. Based on the Ko-be earthquake data, the L3 model produces the largest value for the X-direction, which is 10.26 cm, and the Y-direction is 12.71 cm. While using Parkfield data, the L3 model has the highest drift ratio of 5.08 cm in the X direction and 5.47 cm in the Y direction. It can be concluded that the L3 model has the highest story drift value compared to other models. One of the most critical aspects of the seismic performance of story drift inquiry is comparing each story drift of building results to the allowable story drifts. From the results of the Kobe earthquake, several models exceed the theoretical allowable story drift capacity to endanger the safety of the building and its users. As can be seen, buildings with vertical irregularities exhibit increased story drift.

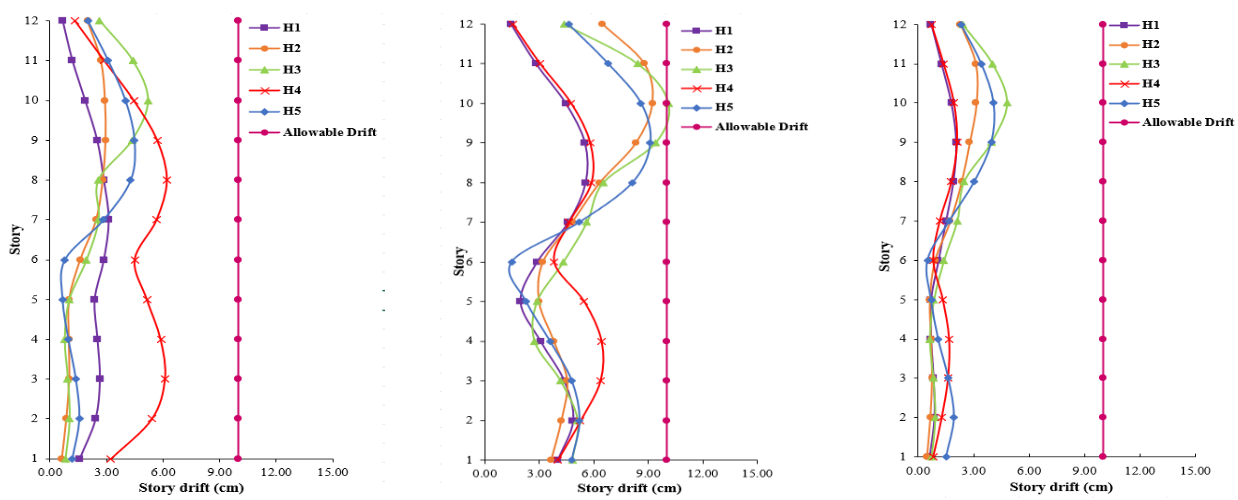
According to the simulation results for the H-shaped plan irregularity using El-Centro data, the highest story drift in the X direction is 6.22 cm in the H4 model and 6.04 cm in the H3 model. In the Kobe earthquake, the largest story drift in the X direction in the H3 model is 10.12 cm, and the Y direction is 6.53 cm. Meanwhile, in the Parkfield earthquake, the most significant story drift produced by the H3 model in both X and Y directions was 4.81 cm and 4.57 cm. The variation of vertical irregularity with H-shaped plan irregularity shows that the H3 model has a higher level of vulnerability than other models. This can be seen from the simulation results with Kobe earthquake data. It can be seen that models 3 and 5 tend to exceed the allowable story drift limit. It can be concluded that model 3, with vertical irregularity, produces a higher vulnerability to damage when viewed from the story drift.



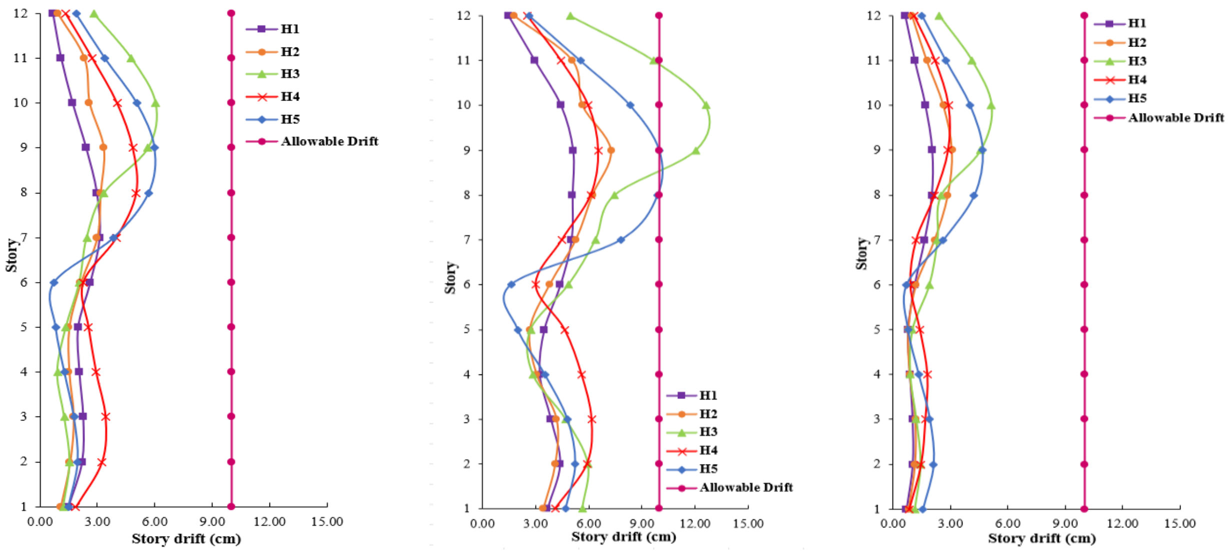
(a) El-Centro - X (b) Kobe - X (c) Parkfield - X

(d) El-Centro - Y (e) Kobe - Y (f) Parkfield - Y

Figure 9. Distribution of inter-story drift for L-shape



(a) El-Centro - X (b) Kobe - X (c) Parkfield - X



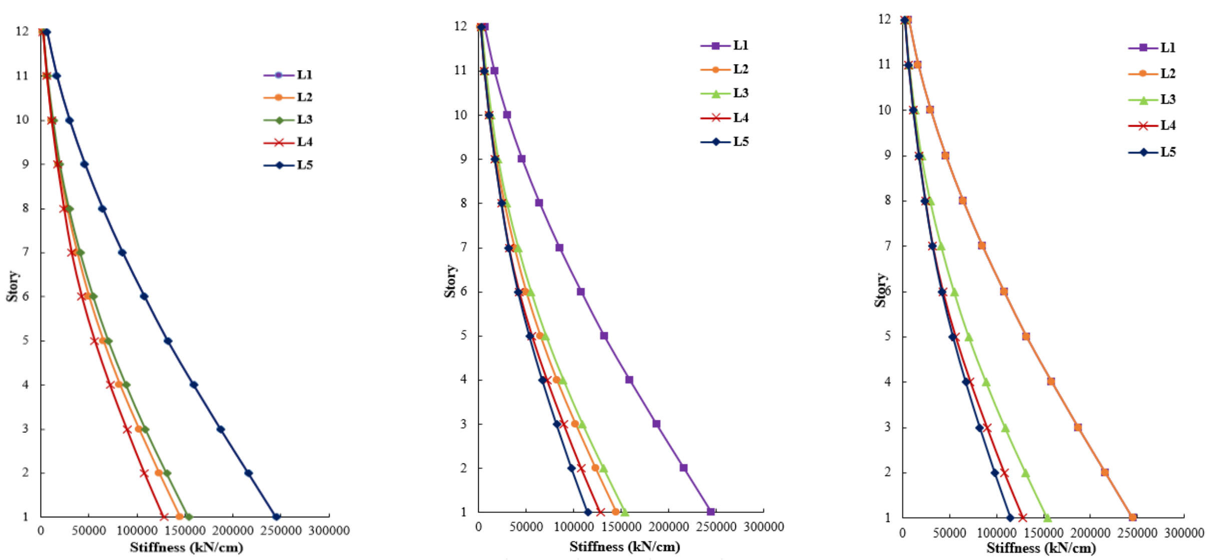
(d) El-Centro - Y (e) Kobe - Y (f) Parkfield - Y

Figure 10. Distribution of inter-story drift for H-Shape

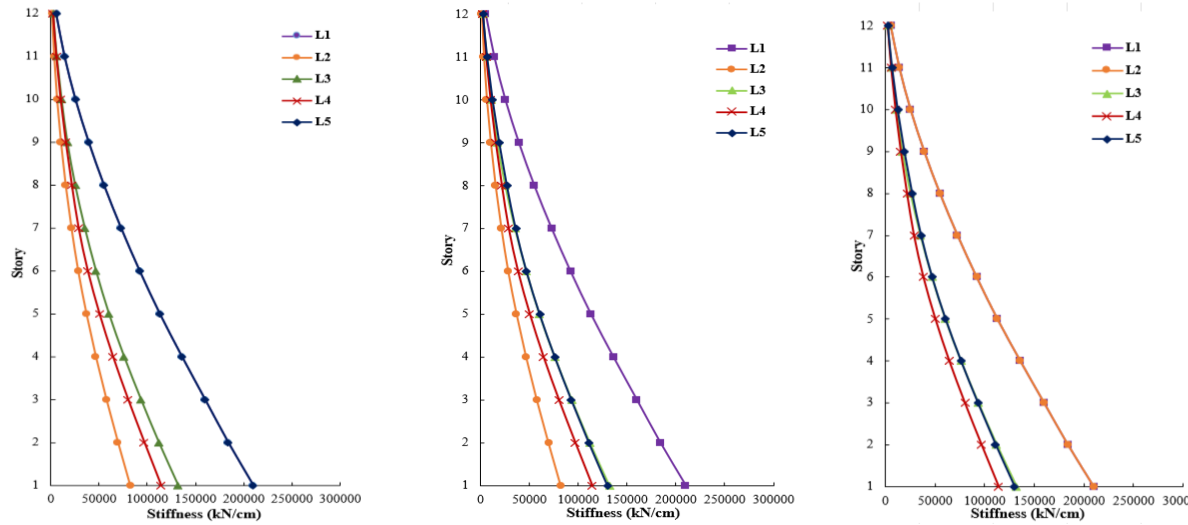
Stiffness of Structures

The stiffness of the building is one of the factors that affect the response due to vibrations during an earthquake. The building stiffness is obtained from the relationship between shear force and displacement on each floor. The load on the structure is applied stepwise for the X, Y, and Z-axis direction until the structure model shows the damage. Figure 11 shows the stiffness of each floor in the X and Y directions for the L-shaped plan irregularity, whereas Figure 12 shows the stiff-ness between floors for the H-shaped plan irregularity. Each figure displays the stiffness value of each type of vertical irregularity with different earthquakes.

The L1 model produces the L-shaped plan view model with the El-Centro earthquake in the X and Y directions, whereas the L4 model produces the lowest stiffness in the X and Y directions. The simulation using the Kobe earthquake data shows that the L1 model has the highest stiffness in both the X and Y directions, while the L5 model has the lowest stiffness in the X direction and the L2 model has the lowest stiffness in the Y direction. The L1 model produces the highest stiffness in the X and Y directions for Parkfield earthquake data, while the L5 model produces the lowest stiffness in the X and Y directions. The simulation results on the variation of L-shaped plan irregularity show that the L1 model always produces the highest stiffness because there is no vertical irregularity in this model. While other models have different vertical irregularities so that the resulting stiffness is decreased.

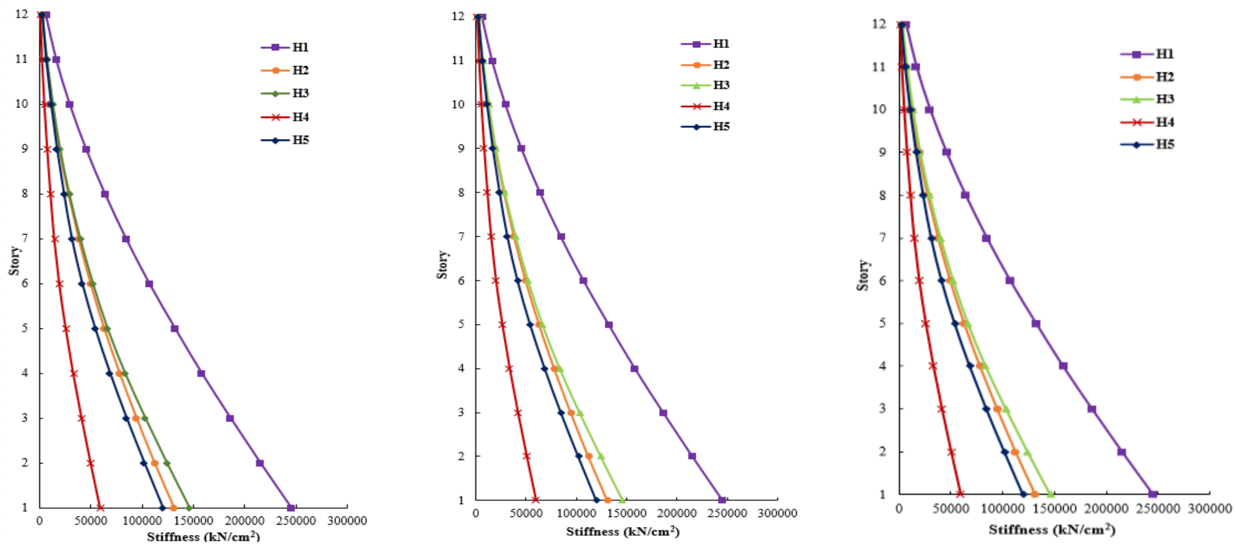


(a) El-Centro - X (b) Kobe - X (c) Parkfield - X

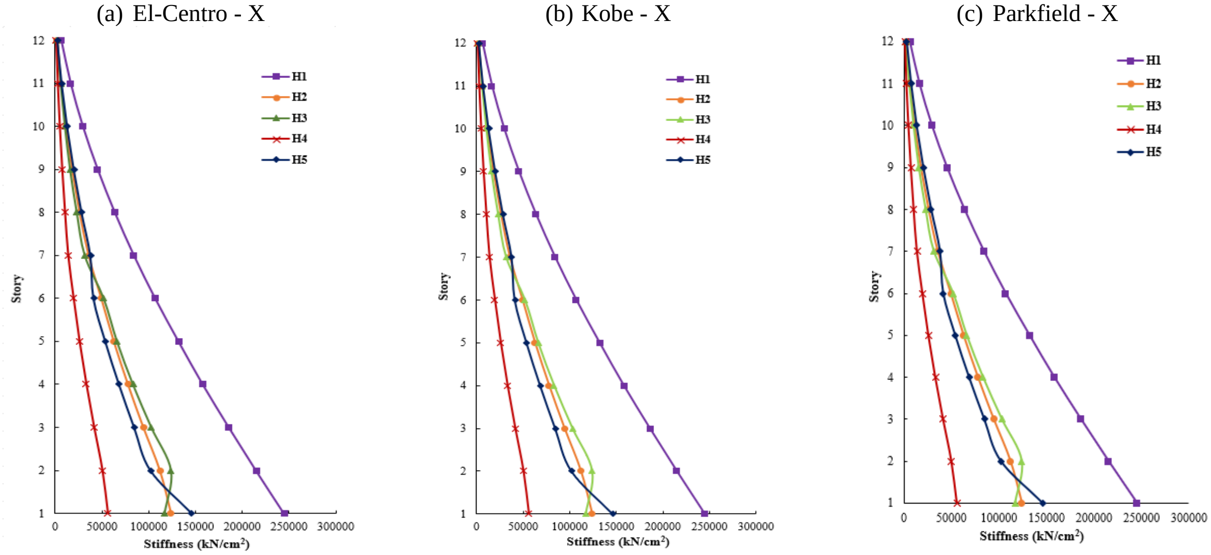


(d) El-Centro - Y (e) Kobe - Y (f) Parkfield - Y

Figure 11. Distribution of inter-story stiffness for L shape



(a) El-Centro - X (b) Kobe - X (c) Parkfield - X



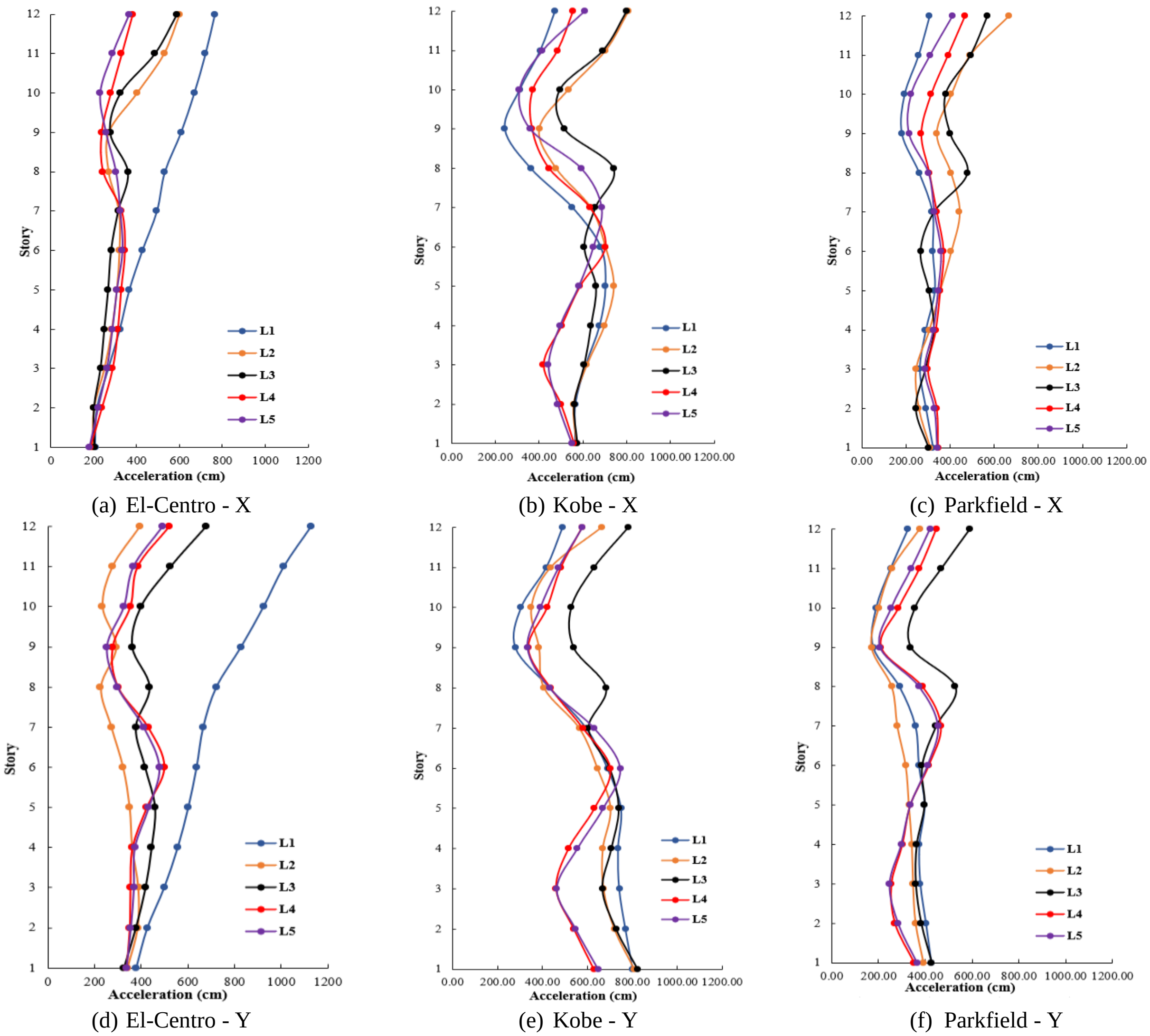
(d) El-Centro - Y (e) Kobe - Y (f) Parkfield - Y

Figure 12. Distribution of inter-story stiffness for H shape

Figure 12 shows the stiffness with an H-shaped plan irregularity for three earthquake types. The results of this simulation show that the H1 model produces the highest stiffness in both the X and Y directions for all variations of the earthquake used. This demonstrates that the model without vertical irregularities produces a stiffer frame than those with vertical irregularities. The H4 model produces the lowest stiffness compared to other models in both the X and Y directions for all earthquakes. This shows that the H4 model has the smallest level of stiffness, so it has a higher level of vulnerability than other models. From this stiffness investigation, it can be concluded that vertical irregularity plays an important role in the level of stiffness.

Responses of Maximum Acceleration

The response ratio between the structure floors controls this maximum acceleration response. This response ratio affects the maximum acceleration in the building before the structure receives the load-receiving damage. This response ratio is inversely proportional to the maximal acceleration. The maximum acceleration response for the L-shaped plan irregularity in the x and y directions was investigated using three different earthquake data sets, whereas the maximum acceleration response for the h-shaped plan irregularity in the x and y directions was investigated using three different earth-quake data sets, as shown in Figure 13 and Figure 14. The investigation results indicate that the maximum acceleration response varies significantly and depends on the type of earthquake used in the modeling and the design of the building itself. It can be concluded that the plan irregularity and vertical irregularity play an important role in producing the maximum acceleration response for each building floor. The irregularity of the building will create a different reaction.



(a) El-Centro - X (b) Kobe - X (c) Parkfield - X

(d) El-Centro - Y (e) Kobe - Y (f) Parkfield - Y

Figure 13. Distribution of inter-story maximum acceleration for L-shape

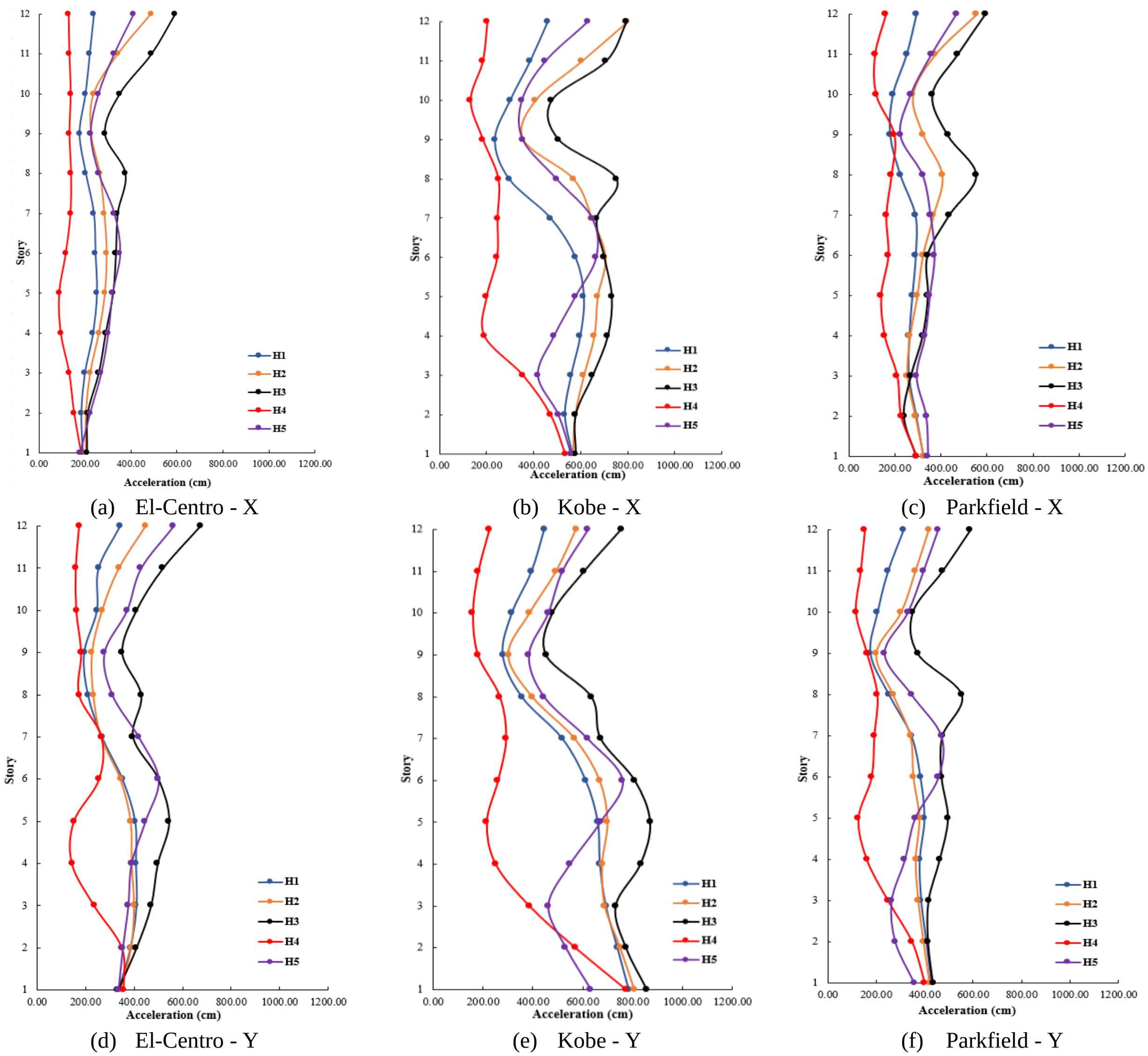
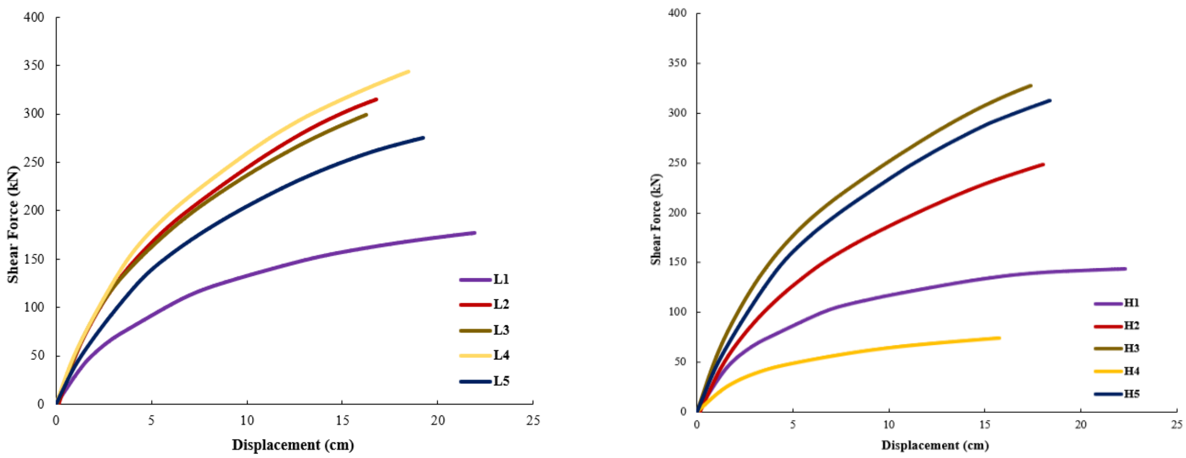


Figure 14. Distribution of inter-story maximum acceleration for H-shape

Capacity Curve

The capacity curve expresses the relationship between the lateral base shear force and the lateral displacement that occurs in the structural components of the building. The value of deformation that appears in each building element can affect the magnitude of the capacity curve. This curve is constructed using pushover analysis to determine the strength of a structure following deformation. The capacity curves for each model with L-shaped and H-shaped plan irregularities are shown in Figure 15. The results show that the L4 model produces the most significant shear force in the model with L-shaped plan irregularity, while the L1 model produces the smallest shear force. Meanwhile, the model with H-shaped irregularity shows that the H4 model produces the smallest shear force, and the H3 model produces the most significant shear force. The difference in the results between the L-shaped and H-shaped plan irregularities is caused by the different structural configurations found in each building, both vertical and horizontal. Some previous studies show that capacity curve of some buildings really depend on the shape of the buildings (Prayuda et al., 2022; Prayuda et al., 2023; Paudel et al., 2024). Building with the high irregularities usually produces high shear forces.



(a) L- shape irregularity (b) H- shape irregularity

Figure 15. Capacity curve

CONCLUSION

The concluded results are based on the analysis carried out using STERA 3D software on ten types of irregularities in building structures with L and H-shaped floor plans, and the addition of earthquake loads in the form of 3 earthquake time history data, namely Kobe, El Centro, and Parkfield. (1) Variations in plan irregularities produce different seismic performances even though the building does not have vertical irregularities. Plan irregularities play an essential role in producing better building performance. Based on these results, it shows that the Kobe earthquake has more impact on the buildings. (2) Vertical irregularity plays an important role in the seismic performance of a building. The stiffness results show that the building without vertical irregularity produces higher stiffness than the model with vertical irregularity. The maximum shear force with vertical irregularity is 133% higher for the L-Shape and 169% higher for the H-Shape compared to a building without vertical irregularities. (3) The simulation results show that model 4 tends to produce the lowest stiffness compared to other models for both L-shaped and H-shaped plan irregularities due to vertical irregularities.

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