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DETERMINATION OF THE OPTIMUM SHEAR WALL AREA TO FLOOR AREA RATIO FOR REINFORCED CONCRETE BUILDINGS

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MUSTAFA KHALID ABDULLAH AL-AGEEDI

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Approval of the Graduate School of Natural and Applied Sciences, Atilim University.

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ABSTRACT

DETERMINATION OF THE OPTIMUM SHEAR WALL AREA TO FLOOR AREA RATIO FOR REINFORCED CONCRETE BUILDINGS

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Due to the abundance and severity of earthquakes, there is an urgent need to study the seismic analysis and design of buildings. In this thesis, a structural analysis was conducted to determine the optimum ratio of shear wall areas in a reinforced concrete building. For this purpose, a total of 20 models were generated with varying building and wall dimensions. Twenty and thirty story buildings were selected to understand the effect of varying building heights on their structural behavior. A parametric study on shear wall areas was conducted using different shear wall area to floor area ratios. Building models, therefore, included no wall and some walls with 0.5%, 1% and 1.5% area ratios applied in both x and y directions. Each of these models were subjected to response spectrum analysis using the forces generated according to 2019 dated Turkish Earthquake Code (TEC 19) and 2016 dated American Building Code (ASCE 7-16). The buildings were assumed to be all office buildings located in a severe seismic zone, Avcilar, Istanbul. The thirty story building due to its total height had to be considered tall as per the requirements in TEC 19. The additional requirements were also included in the analysis to understand the impact of tall buildings on optimum shear wall determination. The following parameters were investigated for the optimum shear wall area to floor area ratio: (a) building periods, (b) base shear and shear force resisted by all shear walls, and (c) deflection and story drifts. The results indicated that the ratio of shear wall equal to 1.5% produces the optimum solution.

Keywords: Shear Wall Ratio, Reinforced Concrete Buildings, Earthquake Engineering, Seismic Codes

ÖZ

BETON BİNALARDA OPTİMUM PERDE DUVAR ALANININ KAT PLANI ALANINA ORANININ BELİRLENMESİ

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Depremlerin sayıca fazla olması nedeniyle, binalar için sismik analiz ve tasarımın incelenmesi önemli bir ihtiyaç haline gelmektedir. Bu tez çalışmasında, betonarme binalarda en uygun perde duvar alanının kat planı alanına olan oranını belirlemek için yapısal analizler yapılmıştır. Bu amaçla farklı bina ve duvar ölçülerinde toplam 20 bina modeli paket program kullanılarak üretilmiş. Farklı bina yüksekliklerinin yapısal davranışlarına etkisini anlamak için sırası ile yirmi ve otuz katlı iki tür bina seçilmiştir. Perde duvarlar üzerinde farklı perde duvar alanının kat alanına olan oranları değiştirilerek parametrik bir çalışma yapılmıştır. Bu amaç doğrultusunda, bina modelleri perde duvar içeren ve içermeyen binalar olmak üzere hazırlanmıştır. Perde duvar içeren modellerde hem x hem de y yönlerinde sırası ile % 0.5, % 1 ve % 1.5 oranlarına sahip perde duvar kullanımı sağlanmıştır. Bu modellerin her biri, Türkiye Bina Deprem Yönetmeliği 2019 (TBDY 19) ve Amerikan Bina Yönetmeliği 2016 (ASCE 7-16) yönetmeliklerine göre belirlenen kuvvetler kullanılarak mod birleştirme yöntemine (response spectrum method) deprem analizine tabi tutulmuştur. Binaların, deprem tehlikesi en yoğun olan Avcılar, İstanbul'da konumlandırıldığı ve tamamının ofis türü bina olduğu varsayılmıştır. Toplam yüksekliği nedeniyle otuz katlı olan bina, TBDY 19'daki koşullara göre yüksek bina olarak tasarlanmış ve analizi yapılmıştır. Böylelikle, yüksek binaların optimum perde duvar alanı oranına olan etkisi yapılan analizlerle anlaşılmaya çalışılmıştır. Bu kapsam dahilinde optimum perde duvar alanının toplam kat alanına oranı belirlenirken şu parametreler detaylı olarak incelenmiştir: (a) bina periyotları, (b) taban kesme kuvveti ve perde duvarların karşı koyduğu kesme kuvveti miktarı ve (c) yatay deplasmanlar ile kat öteleme miktarları. Sonuç olarak, perde duvar alanının kat alanına olan oranı şayet %1.5'a eşit ise yapısal açıdan optimum çözümün üretildiği görülmüştür.

Anahtar Kelimeler: Perde Duvar Alan Oranı, Betonarme Binalar, Deprem Mühendisliği, Deprem Yönetmelikleri

To

My father "Khalid Abdullah"

My mother "Maha Shaker"

My brother "Mohanad"

my sister "Shahad"

and my friends

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Shear walls are structural elements that resist horizontal or lateral loads acting on buildings (such as earthquakes and wind loads). Buildings have to also resist gravity loads such as self-weight, live loads and dead loads. Both lateral and gravity loads are resisted by structural elements consisting of slabs, beams, columns and foundation. Specifically, for horizontal loads, it is necessary to incorporate other elements to strengthen the lateral resistance of a building. For this purpose, shear or structural walls are used.

Previous studies conducted on building that have been subjected to earthquakes have shown that these building with shear walls performed better than those without shear walls from safety and damage perspective. Shear walls can obviously provide high lateral strength to a building, and therefore resist most of the seismic forces. Due to this critical significance of shear walls in resisting seismic loads, there is an increasing demand to study the factors that control seismic energy dissipation, and to adequately resist most of the lateral and vertical loads. Shear walls should be carefully placed in a floor layout in order to prevent any additional loads or moments that might result otherwise. The center of gravity of shear walls should be located near the gravity center of a building in order to reduce the torsional moments resulting from the eccentricity or the distance between the two gravity centers.

Shear walls are often made of reinforced concrete. The connection between the structural elements of a building and wall is generally achieved through a solid connection. Shear walls provide building a large stiffness to reduce its horizontal movement and flexibility.

The aim of this study is to investigate the effect of varying shear wall area to floor area ratio in a reinforced concrete building. It is also intended to investigate the optimum ratio of shear wall ratio to resist earthquakes to ensure that the building is safe and stable.

It should be noted that seismic waves result in both horizontal and vertical (gravity) forces. However, vertical forces are often not considered during structural design since the stability of a building in its vertical direction is invariably more rigid than the one in its horizontal direction. Forces resulting from a sudden earth movement can cause permanent damages to a building. Therefore, all earthquake design codes somewhat include specifications regarding adequate energy absorption properties. This property is called elasticity and can be defined as the structural ability to absorb seismic energy through inflexible changes in a structural element without the member losing its ability to withstand these forces. In order to achieve this principle, one of the best solutions is to add shear walls specifically to high buildings that are exposed to severe earthquake or winds loads.

1.2 Problem Statement

A good understanding of earthquake-resistant building relies on determining the priorities to reduce the damage caused by earthquakes, to save the lives of people from a seismic hazard, and to minimize any structural losses. The destruction and damage experienced by a building when an earthquake happens require extensive study to understand and explain the reasons that lead to such destruction in addition to finding appropriate solutions to avoid them. Also finding the most suitable solution for the renovation of a building or of an industrial facility to their original status with the least possible effect is another goal in addition to the development of building codes and recommendations. Under the influence of repeated vibration causing horizontal and vertical forces none of the structural members of a building should be damaged or destroyed. However, architectural members (nonstructural components) may experience a controlled damage since their failures will not jeopardize the structural integrity of a building.

The purpose of this study is to investigate the effect of varying ratios of shear wall area to floor area in a reinforced concrete building and to determine the optimum one. In the previous building codes shear walls were used in large proportions, since the codes did not have any requirements regarding the maximum shear wall usage (except for the tunnel formwork type buildings commonly used in Turkey). There has been numerous researches conducted in this area to find the best solution so that earthquake damage would be tolerable and non life threating. In this study, a total of 20 models were used to determine the optimum shear wall to floor area ratio by evaluating different number of floors and building dimensions.

1.3 Conclusion

This study was conducted on 20 different building models all built with reinforced concrete. The differences between each building models lay in their height and in their shear walls ratios, which were calculated according to TEC 19 and ASCE 7-16 building codes. A commercial software package, ETABS, was used to analyze the buildings based on response spectrum method. Also, in this study, the ratio of base shear to shear forces resisted by the walls was calculated to understand how this varying ratio of shear wall area affect the amount of forces carried by walls and frames. Lateral deflections and story drifts were also evaluated to determine the impact of varying walls.

This study contains four chapters. The first chapter is the introduction that provides brief information about the research topic. In the second chapter, a literature review is provided specifically to the topic. In the third chapter, building models are described in terms of their dimensions, areas and heights. Also, in the same chapter, parametric studies conducted on the prototype buildings are explained along with a discussion. In the fourth and final chapter, conclusion, recommendations and suggestion for future work are given.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Based on the shear wall ratio and its impact on buildings earthquake performance, in the past many researches have been carried out. In this chapter, a brief information about the past research will be provided in chronological order.

2.2 Literature Review

2.2.1 M. Fintel, 1995

In his paper, Fintel studied the performance of different types of shear walls based on earthquakes from 1960 to 1988. He examined the structural behaviors of shear walls and compared them to the earthquake codes, and concluded that using appropriate wall to floor area ratios would improve the performance of shear walls during earthquakes.

2.2.2 E. Miranda, 1999

In this article, the continuum approach was used to approximate the lateral drift of high-rise buildings when exposed to lateral loads. A basic model was applied in this study to calculate the ratio between the displacement of the roof and the spectral displacement. Also, he studied the effect of the number of floors and shear deformations on the maximum roof displacement. He concluded that the associated earthquake loads had a slight effect on the ratio of the roof displacement to the spectral displacement.

2.2.3 R. Kanit and E. Atimtay, 2006

In this paper, they studied the effect of earthquakes on masonry structures. Masonry structures, like reinforced concrete structures, susceptible to seismic failure. This is one of the reasons for failure of upper floor walls that were subjected to out of plan accelerations. In the end, they concluded that the collapse of a masonry wall made the structure extremely susceptible to lateral loads.

2.2.4 O. Esmaili S. Epackachi M. Samadzad and S.R. Mirghaderi, 2008

This paper studied the design of a fifty-six story tower. The shear wall structure resisted both gravity and lateral loads with irregular openings. The building had three primary walls and there were multiple secondary walls that were perpendicular to the main walls. The primary walls were the shear walls with overlapping openings. Secondary walls were linked by connecting beams to the primary ones. Some of the secondary walls contained continuous columns while the others did not. They used the trial and error approach to design the tower because there was no straight forward design procedure. In this study, this paper will be used as an example to study the structural behavior of shear wall.

2.2.5 O. Soydas 2009

The object of this study was to examine the impact of shear wall ratio on a buildings seismic response and compare it to the results from the approximate methods. They constructed a total of forty-five building models in a commercially available software package, SAP2000, with 2, 5 and 8 floors. In this study, they use analyzed the models with various ratios of shear walls. In their models, the ratio of shear wall area to floor area changed from 0.52% to 3.6%. They also studied the elastic and inelastic change in story drifts based on different shear wall ratios. The analysis results were compared to those from the approximate methods. Based on this comparison, they concluded that the change in the story drift was almost negligible if the shear wall ratio was larger than 2. It was concluded that the height of the building had impact on drift while the building type had an impact on the story drift.

2.2.6 R. Malik, S. K. Madan and V. K. Sehgal, 2011

In this study, they investigated the effect of shear walls with various heights on a building's seismic response during an earthquake. They analyzed three different types of buildings, low-rise, medium-rise, and high-rise building. The study concluded that the story shear was higher in a building with shear wall and exterior frames. The shear was greater for the mid-rise height and then reduced in a high-rise building. It was concluded that the shear walls up to 65% of the building height were adequate to resist the lateral forces effectively.

2.2.7 S. Charkha and A. Agrawal, 2012

They studied the effect of varying shear wall location in a building. A commercially available program package specific to buildings, ETABS was used to analyze the buildings. The study concluded that changing the shear wall location had an impact on the building's dynamic response. If the walls were located near the gravity center the displacements in the top floor were reduced. If the wall located away from the center of gravity, then the nonuniform motion was observed specially at the top of the building due to the resulting torsional moment.

2.2.8 M. Madhuri and N, Abidi, 2012

In this study, they discussed the structural behavior of shear walls based on the previous studies that dealt with the addition of new walls in varying locations. In order to reduce the soft story effect on a building where building was subjected to lateral loads, they found that the number and location of shear walls provided the building more ductility. The behavior of the building for soft story during an earthquake was better than the one without shear walls.

2.2.9 A. Gunel, 2013

In this study, they examined the performance of the impact ratio between the shear wall area to the floor area. They used twenty-nine building with a different number of stories, heights and material properties. The shear wall ratio in this study varied from zero to 2.5%. They concluded that as the ratio of shear wall increased, plastic deformations and roof drifts decreased. The wall with 1% ratio resulted lower drift when compared to the 0.0% or 0.5%. After the 1.5% wall ratio the effect of the ratio was reduced since any ratio beyond 1.5 did not have any major impact on the drifts under lateral loads.

2.2.10 M. Nollet and B. S. Smith, 2014

In this paper, they studied the optimum height of a shear wall that could effectively perform during an earthquake by neglecting the shear walls for the upper floors that were used to reduce the deflection at the top. Based on the analyses results, they concluded that for the building with uniform height shear wall, if the wall was shortened at the level of contra-flexure, the top deflection was negligible. However, during an earthquake, the lateral deflection from the shortened shear wall building would be slightly higher than the one with full height shear wall from the base to the top.

2.2.11 M. Hosseini, H. Hosseini, T. Naqvi and S. Olounabadi, 2015

The purpose of this paper was to study the importance of shear walls that would resist the lateral and wind loads on a building. They used the rectangular shear walls in a 20-story building, and the shear walls were located at the center of mass. Based on their analysis and discussion, they concluded that the shear walls were effective in resisting the lateral forces when compared to a building system without shear walls. They also observed that the column near the shear wall would take less moment when compared to a column far from the shear wall.

2.2.12 S. Gupta, S. Akhtar and A. Hussain, 2016

The aim of this study was to study the most effective location for shear walls based on their linear structural behavior. They used 10 story reinforced concrete buildings and modeled them using a commercially available software package, STAAD pro. In their analysis, they used two different locations for shear walls, one in the corner and one in the center with regular and irregular geometry. In this study, they also used a frame structure without any shear walls. Based on their analyses results, they compared the shear and moment values resulting from the building with varying wall locations to the one without any shear walls.

2.2.13 S. Foroughi and S. B. Yüksel, 2016

In this paper they studied 7 story buildings with three different types of framing system, wall equivalent dual system and coupled shear wall system. They modeled the building in ETABS, and compared the results of the shear, moment and lateral displacements generated from the three different framing systems.

CHAPTER 3

PARAMETRIC STUDIES AND RESULTS OF ANALYSES

3.1 Introduction

In this section, building modeling process followed in ETABS program will be discussed. A total of 20 building models were constructed in ETABS. Out of 20 models, four of them were the ones without any shear walls. The remaining 16 models had shear walls but with varying locations and quantities. In this study, number of floors were also used as an additional parameter by constructing buildings with 20 and 30 stories. All buildings were assumed to be located in Avcilar, Istanbul. This location was selected specifically since it has a potential to generate high seismic forces as described in the seismic maps of TEC19. The purpose of this study is to determine the optimum ratio of shear wall area to floor area. This ratio was calculated by dividing the individual floor areas to the corresponding wall areas for each the floor under consideration. In order to achieve this good, four shear wall area ratios were considered, one with no wall (the ratio is zero), the other three with 0.5%, 1% and 1.5% ratios. Due to the proposed layouts, 1% and 1.5% ratios were not exactly achieved. The exact value of the two ratios were calculated as 1.04% and 1.44%. As discussed before, four building layouts with 20 and 30 story were selected. The 20 story buildings total height was 64 meters and the 30 story buildings total height was 96 meters each with 3.2 meter floor-to-floor height dimension. These buildings floor dimensions in the x and y directions were all 40 meters. The Turkish Earthquake Code that is in effect (TEC19) and the American Building Code (ASCE16) were used to determine the effect of earthquakes on these models. In buildings seismic analyses stage, response spectrum method was used.

3.2 Building Information

In this section, building information is provided for all 20 models, including their, dimensions, layouts and material properties. 3.2.1 Layout Information

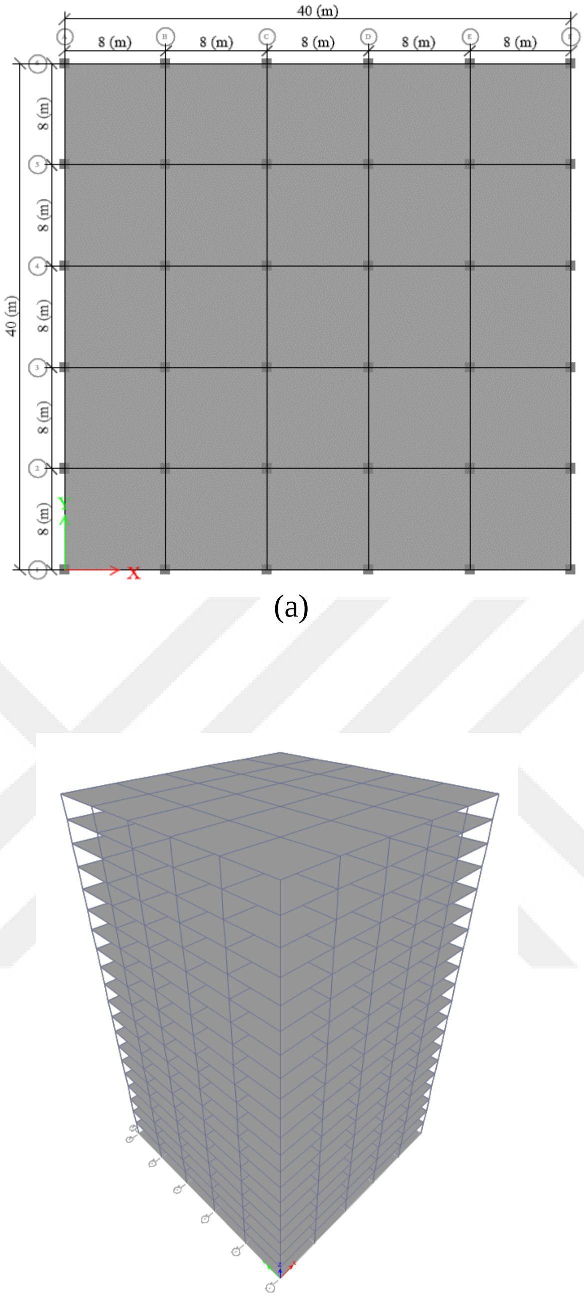
In this section, building models will be described by providing their dimensions, areas, heights and structural members. Two types of building layouts were selected. Type I is used to define a building without shear wall and Type II is used to define building with shear walls.

3.2.1.1 Type I: This type is used for the building with no shear wall. This type is used for both 20 and 30 story buildings.

i. 20 story building: This building model, as mentioned above, contains only columns, beams and slab (no shear walls). Floor to floor height for this building is 3.2 meters, and the total buildings height is 64 meters. Figure 3.1 presents the floor layout model and the 3D view of the building in ETABS. Each span in the x and y direction is 8 meters and all the columns are connected through beams. Columns size were changed at every five floors. Both slabs and beams dimensions were kept the same for all floors. Table 3.1 lists the dimensions of all structural elements. In determining column, beam and slab size, a slightly overconservative approach was used to prevent members failure in the response spectrum analysis stage.

Table 3.1 Dimensions of Structural Elements

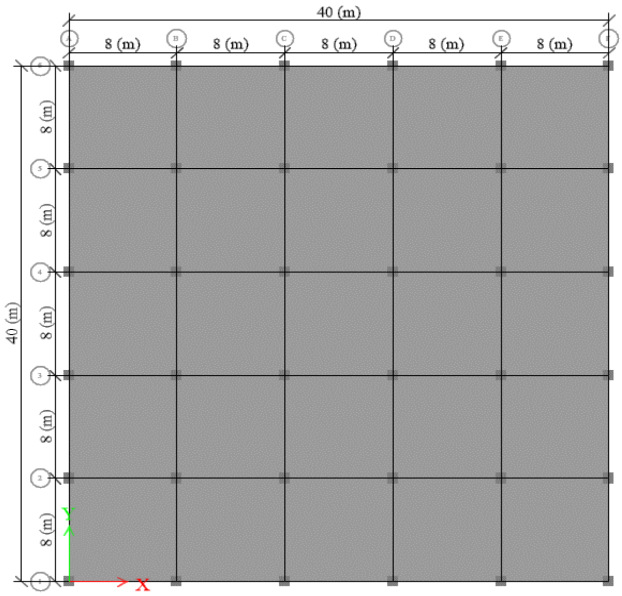
Floor number	Columns (cm)		Slab (cm)	Beams (cm)
	20 Floors	30 Floors		
1-5	95 x 95	115 x 115	22	40 x 75
6-10	80 x 80	105 x 105	22	40 x 75
11-15	70 x 70	95 x 95	22	40 x 75
16-20	50 x 50	80 x 80	22	40 x 75
21-25	—	70 x 70	22	40 x 75
26-30	—	50 x 50	22	40 x 75



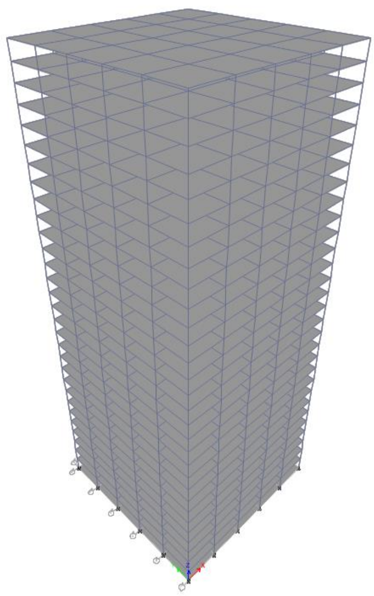
(b)

Figure 3.1 20 Story Building: (a) Floor layout, (b) 3D view

ii. 30 story building: Similar to the 20 story building model, this one contains columns, beams and slabs only. This building model has a floor to floor height of 3.2 meters, and a total building height of 96 meters. Figure 3.2 shows the layout and 3D view of the building in ETABS. Buildings in plan dimensions are the same as those for the 20 story one. However, due to the additional 10 story, column sizes were changed. Table 3.1 lists the dimensions of columns, beams and slabs.



(a)



(b)

Figure 3.2 30 Story Building: (a) Floor layout, (b) 3D view

3.2.1.2 Type II: Building in this type contains shear walls, columns, beams and slabs. Similar to the building in Type I, 20 and 30 story buildings were modeled with the same floor to floor height of 3.2 meters. The total height of the 20 and 30 story buildings are 64 and 96 meters respectively.

i. 20 story building with 0.5% ratio: The total height of this building model was 64 meters. The shear wall area ratio was 0.5% of the floor area. The shear walls in this model were intentionally located at the four corners of the building. The length of the walls was constant with 5 meters, and the thickness was 0.4 meters for all. Figure 3.3 presents the layout and the 3D view of this building model

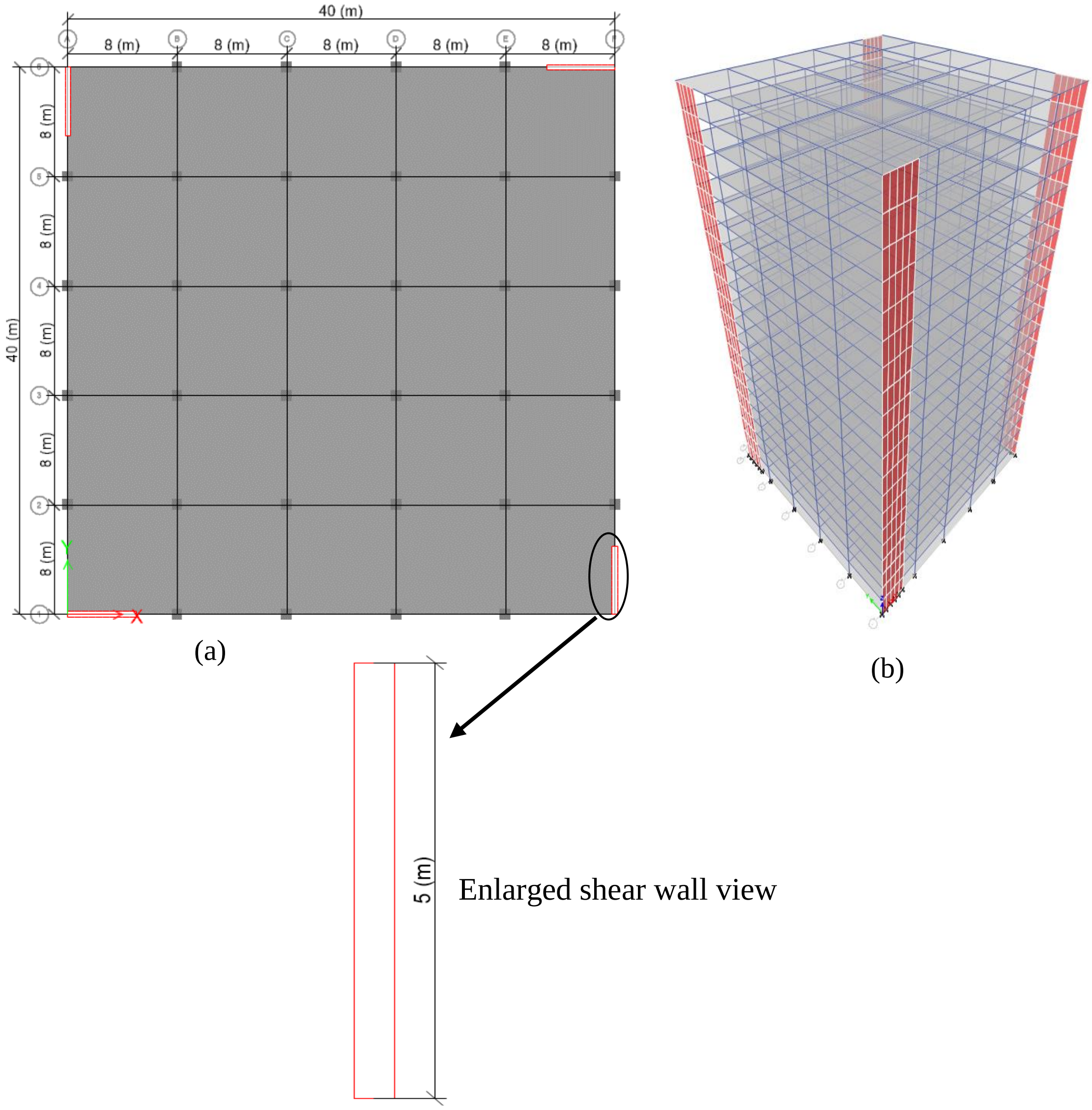


Figure 3.3 20 Story Building with 0.5% ratio: (a) Floor layout, (b) 3D view

ii. 20 story building with 1% ratio: The total height of this model was 64 meters with equal story heights and the shear walls to floor area ratio was approximately 1.0% (the exact number is 1.04%). In this model, the shear walls were located both in the center and in the midspans around the perimeter of the building. The thicknesses of all walls were 0.4 meters (See Figure 3.4).

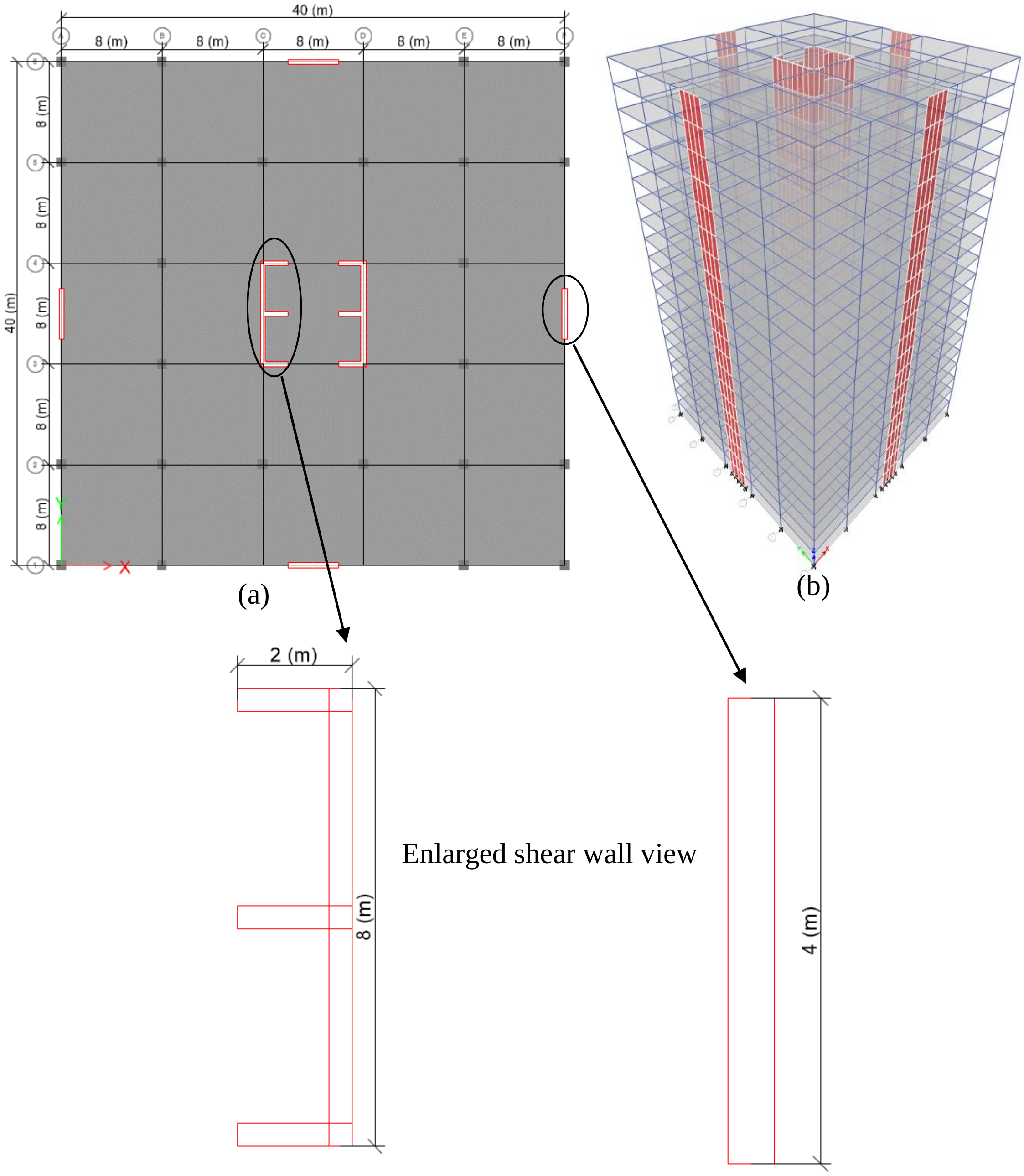


Figure 3.4 20 Story Building with 1.0% ratio: (a) Floor layout, (b) 3D view

iii. 20 story building – 1.5% ratio: The total height of this model was 64 meters with equal story heights, and the shear walls were approximately 1.5 % of the floor area (the exact ratio is 1.44%). In this model, walls were located in the center and in the midspans around the perimeter of the buildings. The thicknesses of all walls were 0.4 meters. Figure 3.5 illustrates the layout and 3D view of this model.

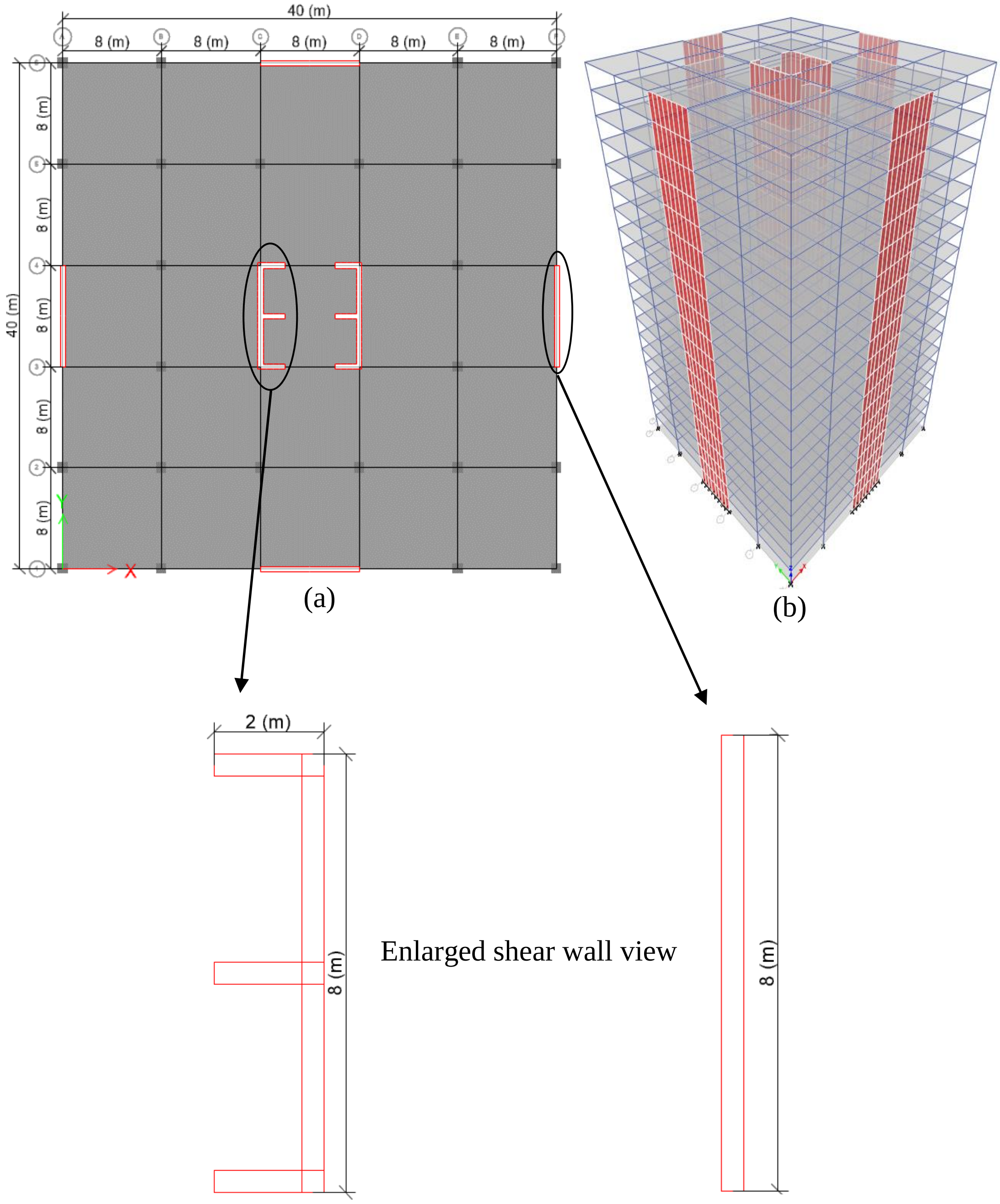


Figure 3.5 20 Story Building with 1.5% ratio: (a) Floor layout, (b) 3D view

iv. 30 story building with 0.5% ratio: The total height of this model was 96 meters with equal story heights of 3.2 meters. The ratio of the shear wall to floor areas for each floor was 0.5%. The thickness of all walls were 0.4 meters. The walls were located around the four corners of the building. Figure 3.6 illustrates the layout and 3D view of this model.

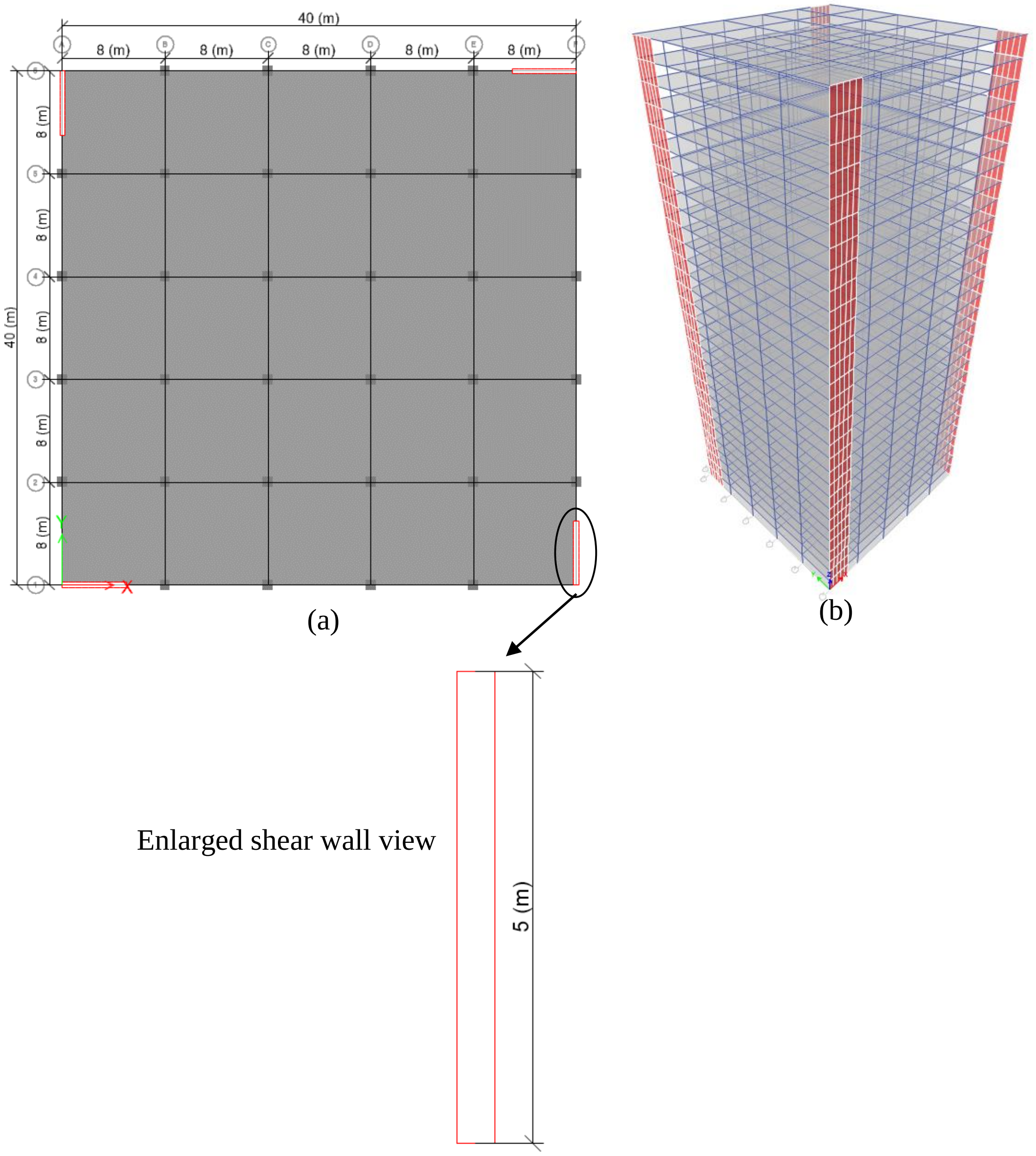


Figure 3.6 30 Story Building with 0.5% ratio: (a) Floor layout, (b) 3D view

v. 30 story building with 1.0% ratio: The total height of this model was 96 meters with equal story heights. The ratio of the shear wall area to floor area was 1.0% (the exact ratio was 1.04%). The thickness of all walls were 0.4 meters. The walls in this model were both located in the center and in the midspans of all four perimeter lines. Figure 3.7 shows the layout and the 3D view of this building model.

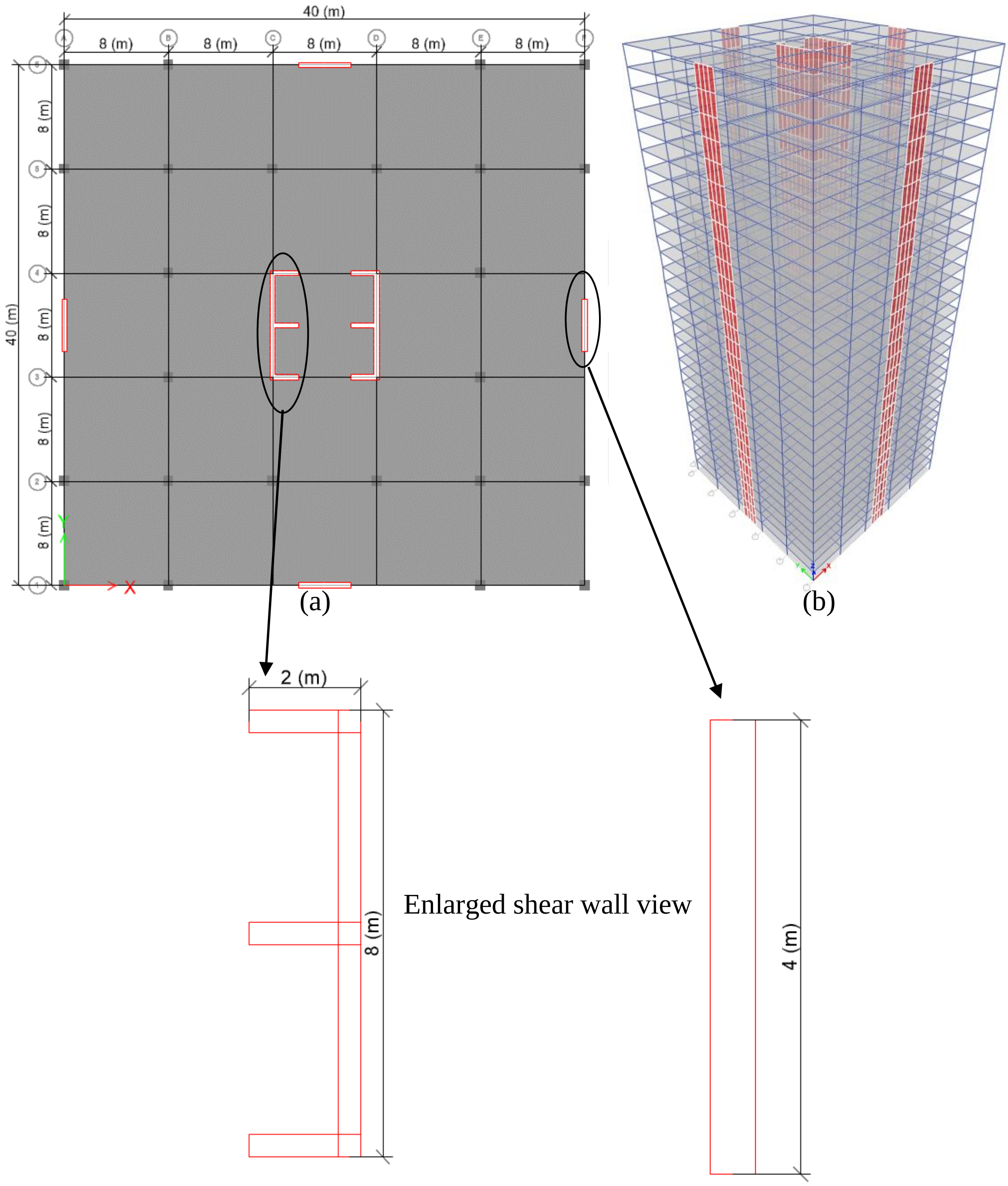


Figure 3.7 30 Story Building with 1.0% ratio: (a) Floor layout, (b) 3D view

vi. 30 story building with 1.5% ratio: The total building height of this model was 96 meters with equal story heights. The ratio of shear wall areas to floor areas was 1.5% (the exact ratio 1.44%). In all models, the wall thickness were the same, 0.4 meters. The walls in this model were located both in the center and in the midspans of all four edges. Figure 3.8 illustrates the floor plan and the 3D view of the building.

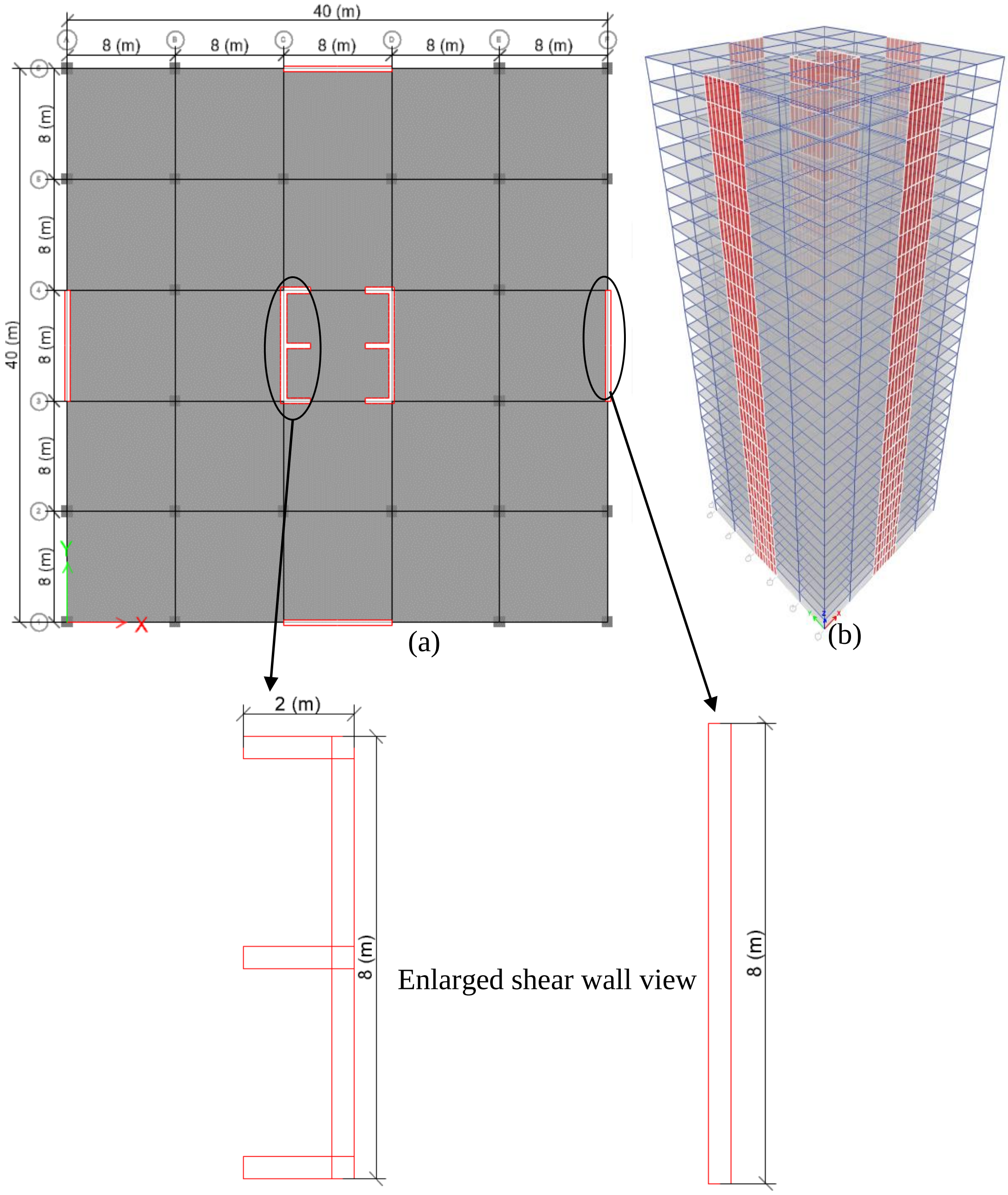


Figure 3.8 30 Story Building with 1.5% ratio: (a) Floor layout, (b) 3D view

3.2.2 Material Properties

Concrete class C40 is used for all the structural members of the buildings. As defined in the Turkish Standards 500 (TS 500), the poison's ratio for concrete is 0.2. The modulus of elasticity for C40 concrete is 34,000 MPa. In the self weight calculation of structural members, the unit weight of reinforced concrete was selected to be 2,500 kg/m^3. Since the focus of this study was not the structural design of the members, no material properties for rebars were needed.

3.2.3 Earthquake Loads

In this study, two structural codes and a guideline were used to apply lateral loads to a total of twenty building models. These structural codes as follows:

(a) TEC 2019, Turkish Earthquake Code 2019

(b) ASCE 7-16, Minimum Design Loads for Buildings and Other Structures

(c) TBI 2017, Tall Buildings Initiative (guideline)

3.2.3.a TEC 19

In this study, all the buildings were assumed to be office buildings. Since the location of all models assumed to be in a sever earthquake region, Avcilar, a district in Istanbul, was chosen. In this study, Response Spectrum Analysis method was used for all models. For response spectrum analysis, important factors need to be specified, which are (a) local site classes and (b) importance factor. In the following section, these factors will be described in detail.

3.2.3.a.1 Local Site Classes

Table 16.1 in TEC 19 shows the site classes from rock to loose soil. In this study, the site class was defined as slightly weathered rocks as mentioned in the table. Therefore, site class ZB with V_S = 760 to 1500 m/s was selected as the soil for all buildings. By selecting this soil, a need for piles was eliminated.

3.2.3.a.2 Importance Factor

Table 3.1 of TEC 19 list the importance factors for different types of buildings. In this study, all the models were assumed to be office buildings. As mentioned in Table 3.1, the importance factor was equal to one for all office type buildings. The same table also includes a list for buildings occupancy class (BKS), which is used to determine its earthquake design class. Based on this information the BKS value for all the buildings was 3.

3.2.3.a.3 Design stages (stage I, II and III)

- Design stage I is completed based on an earthquake with a return period of 475 years (DD2 type earthquake). The short and 1 second periods for mapped spectral acceleration coefficients, S_S and S_1, respectively are provided on the government website: http://tdth.afad.gov.tr. In this study, the S_S and S_1 values for Avcilar, Istanbul are 1.21g and 0.33g respectively. For this design stage, the concrete assumed to be cracked. Table 3.2, which is also a copy of the table in TEC 19 lists the stiffness values for various structural members. Stage I, the R and D value were obtained from TEC 19 as 7 and 2,5, respectively. These values correspond to the high ductile lateral resisting system and are specifically used for the framing system entitled "Earthquake forces resisted both by frames with high ductility and by high ductile shear walls with no openings."

Table 3. 2 Effective Stiffness Values for DD2 in TEC 19 [14]

Component	Effective Stiffness Values	
Shear wall – slab (in plan)	Axial	Shear
Shear wall	0.50	0.50
Basement walls	0.80	0.50
Slabs	0.25	0.25
Shear wall- slab (off plan)	Flexural	Shear
Shear wall	0.25	1.00
Basement walls	0.50	1.00
Slabs	0.25	1.00
Structural members	Flexural	Shear
Coupling beams	0.15	1.00
Beams	0.35	1.00
Columns	0.70	1.00
Shear wall (equivalent column)	0.50	0.50

- Design stage II is performed based on an earthquake with a return period of 43 years (DD4 type earthquake). Based on the government's website S_S and S_1 for various types of earthquake ground motion levels, for DD4 are obtained as 0.278g and 0.072g, respectively. For design stage II, according to in TEC 19, both the R and the D values are equal to one. In this stage, concrete is assumed to be cracked. Table 3.3, which is also a copy of the table in TEC 19 includes a list of stiffness values. This stage is used only for tall buildings. In this study, the 30 story buildings were the only tall building with their 96 meter heights. As a result of this requirement, DD4 design stage was used for this model. However, the 20 story buildings with its 64 meter heights was not a tall building, and therefore the requirements for DD4 analysis were not used.

Table 3. 3 Effective Stiffness Values for DD2 in TEC 19 [14]

Component	Effective Stiffness Values	
Shear wall – slab (in plan)	Axial	Shear
Shear wall	0.75	1.00
Basement walls	1.00	1.00
Slabs	0.50	0.80
Shear wall- slab (off plan)	Flexural	Shear
Shear wall	1.00	1.00
Basement walls	1.00	1.00
Slabs	0.50	1.00
Structural members	Flexural	Shear
Coupling beams	0.30	1.00
Beams	0.70	1.00
Columns	0.90	1.00
Shear wall (equivalent column)	0.80	1.00

- Design stage III is required only for tall buildings. In this study, the response spectrum method was decided to be used for all buildings. Therefore, the requirements of design stage III were not included in this study.

3.2.3.b ASCE 7-16

The short and 1 second periods for mapped spectral acceleration coefficients, S_S and S_1, respectively are provided based on an earthquake with a return period of 2475 years (DD1 type earthquake) on the government website: http://tdth.afad.gov.tr. In this study, the S_S and S_1 values for Avcilar, Istanbul are 2.118g and 0.589g respectively. ASCE 7-16 divides the risk category of a building into four groups. In this study, all models were assumed to be office buildings. According to ASCE 7-16, the risk category for an office building falls into the second group (II) as shown in Table 3.4.

Table 3.4 Risk Category of Buildings and Other Structures for

Flood, Wind, Snow, Earthquake, and Ice Loads in ASCE 7-16 [15]

Use or Occupancy of Buildings and Structures	Risk Category
Buildings and other structures that represent low risk to human life in the event of failure	I
All buildings and other structures except those listed in Risk Categories I, III, and IV	II
Buildings and other structures, the failure of which could pose a substantial risk to human life Buildings and other structures not included in Risk Category IV, with potential to cause a substantial economic impact and/or mass disruption of day-to-day civilian life in the event of failure Buildings and other structures not included in Risk Category IV (including, but not limited to, facilities that manufacture, process, handle, store, use, or dispose of such substances as hazardous fuels, hazardous chemicals, hazardous waste, or explosives) containing toxic or explosive substances where the quantity of the material exceeds a threshold quantity established by the Authority Having Jurisdiction and is sufficient to pose a threat to the public if released[a] Buildings and other structures designated as essential	III
Buildings and other structures designated as essential facilities Buildings and other structures, the failure of which could pose a substantial hazard to the community Buildings and other structures (including, but not limited to, facilities that manufacture, process, handle, store, use, or dispose of such substances as hazardous fuels, hazardous chemicals, or hazardous waste) containing sufficient quantities of highly toxic substances where the quantity of the material exceeds a threshold quantity established by the Authority Having Jurisdiction and is sufficient to pose a threat to the public if released[a] Buildings and other structures required to maintain the functionality of other Risk Category IV structures	IV
[a]Buildings and other structures containing toxic, highly toxic, or explosive substances shall be eligible for classification to a lower Risk Category if it can be demonstrated to the satisfaction of the Authority Having Jurisdiction by a hazard assessment as described in Section 1.5.3 that a release of the substances is commensurate with the risk associated with that Risk Category.	

After determining the risk category, the seismic design category needs to be identified. In order to identify the seismic design category, S_{DS} and S_{D1} values should be calculated according to Equations 3.1 and 3.2 using the values of S_S and S_1. The S_{DS} and S_{D1} are defined in ASCE 7-16 as follows:

S_{D1}: design, 5% damped, spectral response acceleration parameter at a period of 1 second.

S_{DS}: design, 5% damped, spectral response acceleration parameter at short periods.

$$s_{DS} = \frac{2}{3} S_{MS} \tag{3. 1}$$

$$s_{D1} = \frac{2}{3} S_{M1} \tag{3. 2}$$

Where the definitions of S_{MS} and S_{M1} are as follows:

S_{M1}: the MCE_R (Risk-Targeted Maximum Considered Earthquake) 5% damped, spectral response acceleration parameter at a period of 1 second adjusted for site class effects.

“$S_{MS:}$ the MCE_R, 5% damped, spectral response acceleration parameter at short periods adjusted for site class effects.

S_{MS} and S_{M1} can be calculated using Equations 3.3 and 3.4.

$$S_{MS} = F_a S_S \tag{3. 3}$$

$$S_{MS} = F_V S_1 \tag{3. 4}$$

Where F_a and F_v in these equations are described as follows:

F_a: the short-period site coefficient at 0.2 second period (See Table 3.5).

F_v: the long-period site coefficient at 1.0 second period (See Table 3.6).

In order to calculate the values of F_a and F_v, a site class selection is made. In ASCE 7-16, there are six soil classes depending on the type of soil as listed in Table 3.5. In this study, site class B was selected, which will be similar to the soil properties in TEC 19.

Table 3.5 Short-Period Site Coefficient, F_a, in ASCE 7-16 [15]

Mapped Risk-Targeted Maximum Considered Earthquake (MCER) Spectral Response Acceleration Parameter at Short Period						
Site Class	$S_S \leq 0.25$	S_S =0.5	S_S =0.75	S_S =1.0	S_S =1.25	SS ≥ 1.5
A	0.8	0.8	0.8	0.8	0.8	0.8
B	0.9	0.9	0.9	0.9	0.9	0.9
C	1.3	1.3	1.2	1.2	1.2	1.2
D	1.6	1.4	1.2	1.1	1.0	1.0
E	2.4	1.7	1.3	See Section 11.4.8	See Section 11.4.8	See Section 11.4.8
F	See Section 11.4.8	See Section 11.4.8	See Section 11.4.8	See Section 11.4.8	See Section 11.4.8	See Section 11.4.8
Note: Use straight-line interpolation for intermediate values of Ss.						

Table 3.6 Long-Period Site Coefficient, F_v, in ASCE 7-16 [15]

Mapped Risk-Targeted Maximum Considered Earthquake (MCER) Spectral Response Acceleration Parameter at 1-s Period						
Site Class	$S_S \leq 0.25$	S_S =0.5	S_S =0.75	S_S =1.0	S_S =1.25	SS ≥ 1.5
A	0.8	0.8	0.8	0.8	0.8	0.8
B	0.8	0.8	0.8	0.8	0.8	0.8
C	1.5	1.5	1.5	1.5	1.5	1.4
D	2.4	2.2[a]	2.0 [a]	1.9 [a]	1.8 [a]	1.7 [a]
E	4.2	See Section 11.4.8	See Section 11.4.8	See Section 11.4.8	See Section 11.4.8	See Section 11.4.8
F	See Section 11.4.8	See Section 11.4.8	See Section 11.4.8	See Section 11.4.8	See Section 11.4.8	See Section 11.4.8
Note: Use straight-line interpolation for intermediate values of S1. [a]Also, see requirements for site-specific ground motions in Section 11.4.8.						

Table 3.7 Site classification, in ASCE 7-16 [15]

Site Class	$\tilde{v}_s$	Ñ or $\tilde{N}_{ch}$	$\hat{s}_u$
A. Hard rock	>5,000 ft /s	NA	NA
B. Rock	2,500 to 5,000 ft /s	NA	NA
C. Very dense soil and soft rock	1,200 to 2,500 ft /s	>50 blows /ft	>2,000 lb /ft2
D. Stiff soil	600 to 1,200 ft /s	15 to 50 blows /ft	1,000 to 2,000 lb /ft2
E. Soft clay soil	Any profile with more than 10 ft of soil that has the following characteristics — Plasticity index PI > 20, — Moisture content w ≥ 40%, — Undrained shear strength $\hat{s}_u$ < 500 lb /ft2		
F. Soils requiring site response analysis in accordance with Section 21.1	See Section 20.3.1		
Note: For SI: 1 ft=0.3048 m; 1 ft /s=0.3048 m/s; 1 lb /ft2 =0.0479 kN /m2.			

According to the values of S_{DS} and S_{D1}, the seismic design category can be selected (see Tables 3.8 and 3.9). In this study, a seismic design category D was used.

Table 3.8 Seismic Design Category Based on Short-Period

Response Acceleration Parameter in ASCE 7-16 [15]

Value of S_{DS}	Risk Category	
	I or II or III	IV
$S_{DS} < 0.167$	A	A
$0.167 \leq S_{DS} < 0.33$	B	C
$0.33 \leq S_{DS} < 0.50$	C	D
$0.50 \leq S_{DS}$	D	D

Table 3.9 Seismic Design Category Based on 1-s Period

Response Acceleration Parameter in ASCE 7-16 [15]

Value of S_{D1}	Risk Category	
	I or II or III	IV
$S_{D1} < 0.067$	A	A
$0.067 \leq S_{D1} < 0.133$	B	C
$0.133 \leq S_{D1} < 0.20$	C	D
$0.20 \leq S_{D1}$	D	D

Table 3.10 is used to determine the values of Response Modification Coefficient (R), Overstrength Factor (Ω_0) and Deflection Amplification Factor (C_d).

Table 3.10 Desıgn Coeffıcıents And Factors For Seısmıc Force–Resıstıng Systems in ASCE 7-16 [15]

Seismic Force–Resisting System	ASCE 7 Section where Detailing Requirements are Specified	Response Modification Coefficient, R^a	System Overstrength Factor, $\Omega_0{}^g$	Deflection Amplification Factor, $C_d{}^b$	Structural System Limitations and Building Height (ft) Limit^c Seismic Design Category				
					B	C	D^d	E^d	F^e
C. MOMENT-RESISTING FRAME SYSTEMS									
1. Special steel moment frames	14.1 and 12.2.5.5	8	3	5½	NL	NL	NL	NL	NL
2. Special steel truss moment frames	14.1	7	3	5½	NL	NL	160	100	NP
3. Intermediate steel moment frames	12.2.5.6, 12.2.5.7, 12.2.5.8, 12.2.5.9, and 14.1	4.5	3	4	NL	NL	$35^{h,i}$	NP^h	NP^i
4. Ordinary steel moment frames	12.2.5.6, 12.2.5.7, 12.2.5.8, and 14.1	3.5	3	3	NL	NL	NP^h	NP^h	NP^i
5. Special reinforced concrete moment frames	12.2.5.5 and 14.2	8	3	5½	NL	NL	NL	NL	NL
6. Intermediate reinforced concrete moment frames	14.2	5	3	4½	NL	NL	NP	NP	NP
7. Ordinary reinforced concrete moment frames	14.2	3	3	2½	NL	NP	NP	NP	NP
8. Special composite steel and concrete moment frames	12.2.5.5 and 14.3	8	3	5½	NL	NL	NL	NL	NL
9. Intermediate composite moment frames	14.3	5	3	4½	NL	NL	NP	NP	NP
10. Composite partially restrained moment frames	14.3	6	3	5½	160	160	100	NP	NP
11. Ordinary composite moment frames	14.3	3	3	2½	NL	NP	NP	NP	NP
D. DUAL SYSTEMS WITH SPECIAL MOMENT FRAMES CAPABLE OF RESISTING AT LEAST 25% OF PRESCRIBED SEISMIC FORCES	12.2.5.1								
1. Steel eccentrically braced frames	14.1	8	2½	4	NL	NL	NL	NL	NL
2. Special steel concentrically braced frames	14.1	7	2½	5½	NL	NL	NL	NL	NL
3. Special reinforced concrete shear walls	14.2	7	2½	5½	NL	NL	NL	NL	NL
4. Ordinary reinforced concrete shear walls	14.2	6	2½	5	NL	NL	NP	NP	NP
5. Composite steel and concrete eccentrically braced frames	14.3	8	2½	4	NL	NL	NL	NL	NL
6. Composite steel and concrete concentrically braced frames	14.3	6	2½	5	NL	NL	NL	NL	NL
7. Composite steel plate shear walls	14.3	7½	2½	6	NL	NL	NL	NL	NL
8. Special composite reinforced concrete shear walls with steel elements	14.3	7	2½	6	NL	NL	NL	NL	NL

[a]Response modification coefficient, R, for use throughout the standard. Note that R reduces forces to a strength level, not an allowable stress level.
[b]Where the tabulated value of the overstrength factor, Ω_0, is greater than or equal to 2½, Ω_0 is permitted to be reduced by subtracting the value of 1⁄2 for structures with flexible diaphragms.
[d]NL = Not Limited, and NP = Not Permitted. For metric units, use 30.5 m for 100 ft and use 48.8 m for 160 ft.
[e]See Section 12.2.5.4 for a description of seismic force-resisting systems limited to buildings with a structural height, hn, of 240 ft (73.2 m) or less.
[g]In Section 2.3 of ACI 318. A shear wall is defined as a structural wall.
[h]In Section 2.3 of ACI 318. The definition of “special structural wall” includes precast and cast-in-place construction.
[i]An increase in structural height, h_n, to 45 ft (13.7 m) is permitted for single-story storage warehouse facilities.

3.2.3.c TBI 2017

TBI 2017, Seismic Design Guidelines provide solutions to earthquake resistant design of buildings. This guideline is prepared for structures capable of attaining the ASCE 7 seismic performance requirements. In this study, Table 3.9 is used for the effective stiffness values of reinforced concrete members. TBI 2017 is a guideline for the tall buildings, therefore, the effective stiffness values will only be used for the 30 story building with a height of 96 meters.

Table 3.11 Reinforced concrete effective stiffness values in TBI 2017 [16]

Component	Service-Level Linear Models			MCE_R-Level Nonlinear Models		
	Axial	Flexural	Shear	Axial	Flexural	Shear
Structural walls[1] (in-plane)	$1.0E_cA_g$	$0.75E_cI_g$	$0.4E_cA_g$	$1.0E_cA_g$	$0.35E_cI_g$	$0.2E_cA_g$
Structural walls (out-of-plane)	--	$0.25E_cI_g$	--	--	$0.25E_cI_g$	--
Basement walls (in-plane)	$1.0E_cA_g$	$1.0E_cI_g$	$0.4E_cA_g$	$1.0E_cA_g$	$0.8E_cI_g$	$0.2E_cA_g$
Basement walls (out-of-plane)	--	$0.25E_cI_g$	--	--	$0.25E_cI_g$	--
Coupling beams with conventional or diagonal reinforcement	$1.0E_cA_g$	$0.07\left(\frac{\ell}{h}\right)E_cI_g \le 0.3E_cI_g$	$0.4E_cA_g$	$1.0E_cA_g$	$0.07\left(\frac{\ell}{h}\right)E_cI_g \le 0.3E_cI_g$	$0.4E_cA_g$
Composite steel / reinforced concrete coupling beams	$1.0(EA)_{trans}$	$0.07\left(\frac{\ell}{h}\right)(EI)_{trans}$	$1.0E_sA_{sw}$	$1.0(EA)_{trans}$	$0.07\left(\frac{\ell}{h}\right)(EI)_{trans}$	$1.0E_sA_{sw}$
Non-PT transfer diaphragms (in-plane only)[3]	$0.5E_cA_g$	$0.5E_cI_g$	$0.4\ E_cA_g$	$0.25E_cA_g$	$0.25E_cI_g$	$0.1E_cA_g$
PT transfer diaphragms (in-plane only)[3]	$0.8E_cA_g$	$0.8E_cI_g$	$0.4E_cA_g$	$0.5E_cA_g$	$0.5\ E_cI_g$	$0.2E_cA_g$
Beams	$1.0E_cA_g$	$0.5E_cI_g$	$0.4E_cA_g$	$1.0E_cA_g$	$0.3E_cI_g$	$0.4E_cA_g$
Columns	$1.0E_cA_g$	$0.7\ E_cI_g$	$0.4E_cA_g$	$1.0E_cA_g$	$0.7\ E_cI_g$	$0.4E_cA_g$
Mat (in-plane)	$0.8E_cA_g$	$0.8E_cI_g$	$0.8E_cA_g$	$0.5E_cA_g$	$0.5\ E_cI_g$	$0.5E_cA_g$
Mat[4] (out-of-plane)	--	$0.8E_cI_g$	--	--	$0.5E_cI_g$	--

3.3 Modeling in ETABS

ETABS is a commercially available software package that deals with building analysis and design. In this study, ETABS program was used for all building analyses. Since the program had already Turkish and US codes installed, they were used in the analysis stage. A total of 20 models were constructed and analyzed using the response spectrum method according to both Turkish and US codes that was applied in the x and y directions. In this study, the concrete assumed cracked for the earthquake DD2 and DD4 design categories as described in TEC 19. For the earthquake in DD1, which was used for the analysis conducted according to ASCE 7-16 and the TBI 2017, the concrete was assumed cracked only for the 30 story buildings since this building was the only tall one. Table 3.3 was used for the DD4 as described in TEC 19, Table 3.2 was used for DD2 and Table 3.11 was used only for the 30 story buildings as described in TBI 2017. The concrete in the 20 story buildings was assumed uncracked since this building with 64 meters heights was not a tall building. The load combinations used in this study are given in Table 3.12. The load combinations were only used for deflections, wall shear forces, periods, and story drifts. Since ETABS automatically calculates the self weight, no additional loads were applied to the buildings.

Table 3.12 Load combination

No. of Load Combinations	Load Combinations
1	D
2	L
3	D+0.3L
4	1.2D+1.6L
5	$D+L+0.2S+E_X +0.3 E_Y$
6	$D+L+0.2S+E_X -0.3 E_Y$
7	$D+L+0.2S-E_X -0.3 E_Y$
8	$D+L+0.2S-E_X +0.3 E_Y$
9	$D+L+0.2S+0.3E_X +E_Y$
10	$D+L+0.2S+0.3E_X -E_Y$
11	$D+L+0.2S-0.3E_X -E_Y$
12	$D+L+0.2S-0.3E_X +E_Y$

In the Table 3.12, “D” is used for dead loads, “L” is used for live loads, “S” is used for snow loads, and “E_X” and “E_Y” are used for the response spectrum loads in the x and y directions, respectively. In this study, 0.75 kN/m^2 of snow load, 0.35 kN/m^2 of uniformly distributed live loads and 1.5 kN/m^2 of superimposed dead loads were used [17].

The notation chosen for each model includes the following logic. For the building models analyzed according to ASCE 7-16 code, the first letter in the model name refers to the ASCE 7-16. The second and thirds numbers in the model name, refer to the number of floors. The fourth number and the final number refers to the ratio of shear wall area to floor area. Similar notation is also used for the building models analyzed according to TEC 19. In these model names, unlike the 4 digit names that were used for ASCE code, 6 digits were preferred. The first letter in the model name refers to TEC 19, the second and third letters are for the earthquake design category. The fourth and fifth numbers refer to the number of floors. The last number in the building model name is used for the percentage of shear wall area to floor area ratio. As listed in the Table 3.13, shear wall area ratios are represented by integer numbers from 1 to 4, 1 is for 0.5%, 2 is for 1.0%, 3 is for 1.5% and 4 is for no wall. For example, the model name TD2201 is used for a 20 story building that has a shear wall to floor area ratio of 0.5% which is subjected to earthquake in DD2 design category which is derived from TEC 19. Table 3.14 has listed of 20 building model names sorted by the earthquake code used in their analyses.

Table 3.13 Shear wall ratios

Corresponding number	Shear wall ratio (%)
1	0.5
2	1.04
3	1.44
4	No walls

Table 3.14 Names of the models

Number of floors	Name of the model		
	TEC 19		ASCE 7-16
	D2 Design Category	D4 Design Category	——
20 story	TD2201		A201
	TD2202		A202
	TD2203		A203
	TD2204		A204
30 story	TD2301	TD4301	A301
	TD2302	TD4302	A302
	TD2303	TD4303	A303
	TD2204	TD4304	A304

3.4 Results

In this study, ETABS is used to analyze the building models. A total of twenty models were analyzed. The results of the twenty models will be discussed in this section. First, the fundamental periods will be investigated for each model, then the base shear results will be examined, and then the wall shear will be used to determine the percentage of their resistance to the total base shear. Finally, lateral displacements of the top floor and story drifts will be investigated.

3.4.1 Fundamental periods

In this section, the fundamental periods will be investigated for all models. As the shear wall ratios change as well, the building periods vary. A buildings period is specifically used to classify the possible resonance phenomena between the building and the soil. Building periods are affected by many parameters, such as structural height, the ratio of shear wall area to floor area, in-plan dimensions of floor, and the number of floors. Table 3.15a through Table 3.15e list the first three periods for all building models acting in the x, y and rotational direction.

Table 3.15a Fundamental periods for 20 story building: TEC 19

(DD2, 5% damping ratio)

Model Names	Building periods (sec)		
	T_1	T_2	T_3
TD2201	3.284	3.260	2.950
TD2202	2.783	2.530	2.389
TD2203	2.894	2.650	2.485
TD2204	3.554	3.530	3.518

Table 3.15b Fundamental periods for 30 story building: TEC 19-DD2

(DD2, 5% damping ratio)

Model Names	Building periods (sec)		
	T_1	T_2	T_3
TD2301	4.978	4.950	4.605
TD2302	4.289	4.032	3.667
TD2303	4.573	4.299	3.960
TD2304	5.825	5.780	5.751

Table 3.15c Fundamental periods for 30 story building: TEC 19

(DD4, 2.5% damping ratio)

Model Names	Building periods (sec)		
	T_1	T_2	T_3
TD4301	4.493	4.484	3.781
TD4302	3.849	3.606	3.114
TD4303	4.767	4.464	3.872
TD4304	4.754	4.742	4.285

Table 3.15d Fundamental periods for 20 story building: ASCE 7-16

(5% damping ratio)

Model Names	Building periods (sec)		
	T_1	T_2	T_3
A201	2.671	2.671	2.155
A202	2.403	2.017	1.850
A203	2.240	2.031	1.776
A204	2.964	2.964	2.602

Table 3.15e Fundamental periods for 30 story building: ASCE 7-16

(2% damping ratio)

Model Names	Building periods (sec)		
	T_1	T_2	T_3
A301	4.374	4.335	3.898
A302	3.801	3.502	3.253
A303	2.861	2.655	2.416
A304	4.628	4.606	4.427

According to the building periods, the building models with 20 story generated less period values than those with 30 story (see Tables 3.15a and 3.15b). When the periods of 20 story building model from TEC 19 were compared to those from ASCE 7-16, the periods from TEC 19 were as high as 30% more due to the change in the total weight of the buildings and cracked properties of structural members (see Table 3.16a). The total seismic weight of the building was calculated using the following equation:

$$W_{seismic} = G + nQ \qquad 3.5$$

In this equation "G" is used for total dead load and "Q" is used for total live load. "n" is a coefficient called live load participation factor. In TEC 19, "n" is 0.3 since the buildings were office and in ASCE 7-16, "n" is zero. Therefore, the building has less seismic weight in ASCE 7-16 compared to TEC 19. In addition to this difference between TEC 19 and ASCE 7-16, uncracked properties were used for the building analyzed according to ASCE 7-16 while cracked properties were used for the building in TEC 19 (see Table 3.2).

As described before, two design stage were used in analyzing the buildings according to TEC 19. In the first design stage DD2 design category was used while DD4 design category was used for the second design stage. Both design categories had different damping ratios and cracked properties (see Table 3.2 and 3.3).

In DD2 5%, and in DD4 2.5% damping ratios were used. As a result of these differences in the ratios, the building periods from DD2 were slightly larger than those from DD4 (see Table 3.16b).

The fundamental periods of DD2 from TEC 19 were compared to those from ASCE 7-16. Both the total seismic weight and the cracked properties were different for the buildings analyzed according to TEC 19 and ASCE 7-16 (see Table 3.16c).

The total seismic weights of buildings in TEC 19 were more than those in ASCE 7-16 which make the building periods of TEC 19 larger than those of ASCE 7-16. However, in cracked concrete properties, the effective stiffnesses of structural members in TEC 19 and ASCE 7-16 were either large or small when they were compared to each other. Therefore, it was difficult to withdraw a general conclusion based on this parameter.

As a result of these findings in the building periods and cracked concrete properties, the building periods of TEC 19 in DD4 were very close to those of ASCE 7-16. However, in the building models TD4303 and A303, the average ratio of the periods from TEC 19 to ASCE 7-16 was around 1.67 since the walls were a lot more dominant in determining the fundamental periods.

Table 3.16a Comparison of the Fundamental Periods: TEC 19 / ASCE 7-16 for 20 Story Building

$T_1^{(1)}$	$T_2^{(1)}$	$T_3^{(1)}$
1.23	1.22	1.37
1.16	1.25	1.29
1.30	1.30	1.40
1.20	1.19	1.35

(1)The values in this table are obtained by dividing the results in Table 3.15a to those in Table 3.15d

Table 3.16b Comparison of the Fundamental Periods: TEC 19-DD2 / TEC 19-DD4 for 30 Story Building

$T_1^{(1)}$	$T_2^{(1)}$	$T_3^{(1)}$
1.11	1.10	1.22
1.11	1.12	1.18
0.96	0.96	1.02
1.22	1.22	1.34

(1)The values in this table are obtained by dividing the results in Table 3.15b to those in Table 3.15c

Table 3.16c Comparison of the Fundamental Periods: TEC 19-DD4 / ASCE 7-16 for 30 Story Building

Table 3.13 c / 3.13 e		
$T_1^{(1)}$	$T_2^{(1)}$	$T_3^{(1)}$
1.03	1.034	0.97
1.01	1.03	0.96
1.67	1.68	1.60
1.027	1.02	0.97

(1)The values in this table are obtained by dividing the results in Table 3.15c to those in Table 3.15e

3.4.1.1 Mode shapes

Figures 3.9 through 3.29 illustrate mode shapes of the top three fundamental periods of the buildings. As shown in these figures, the first period was always in the x direction. However, for the second period, the deflected shape was almost always in the “y” direction except for the model TD2204. For the third period, the deflected shape was almost always rotational around the z direction.

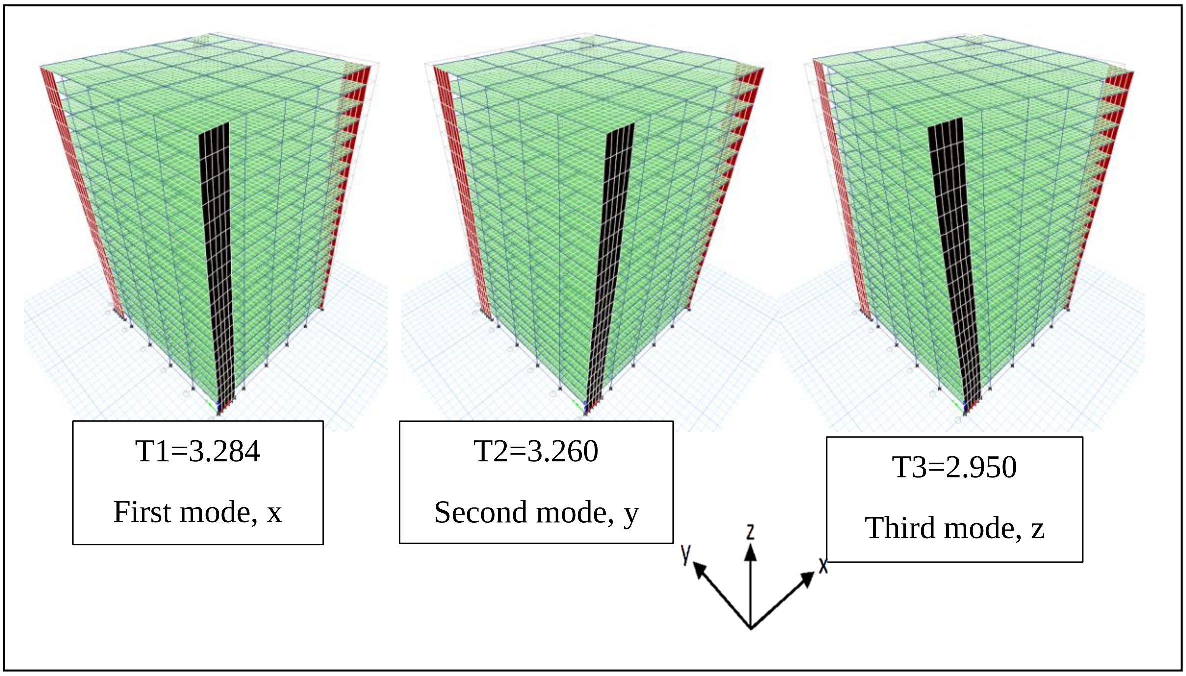


Figure 3.9 TD2201: First three modes shape

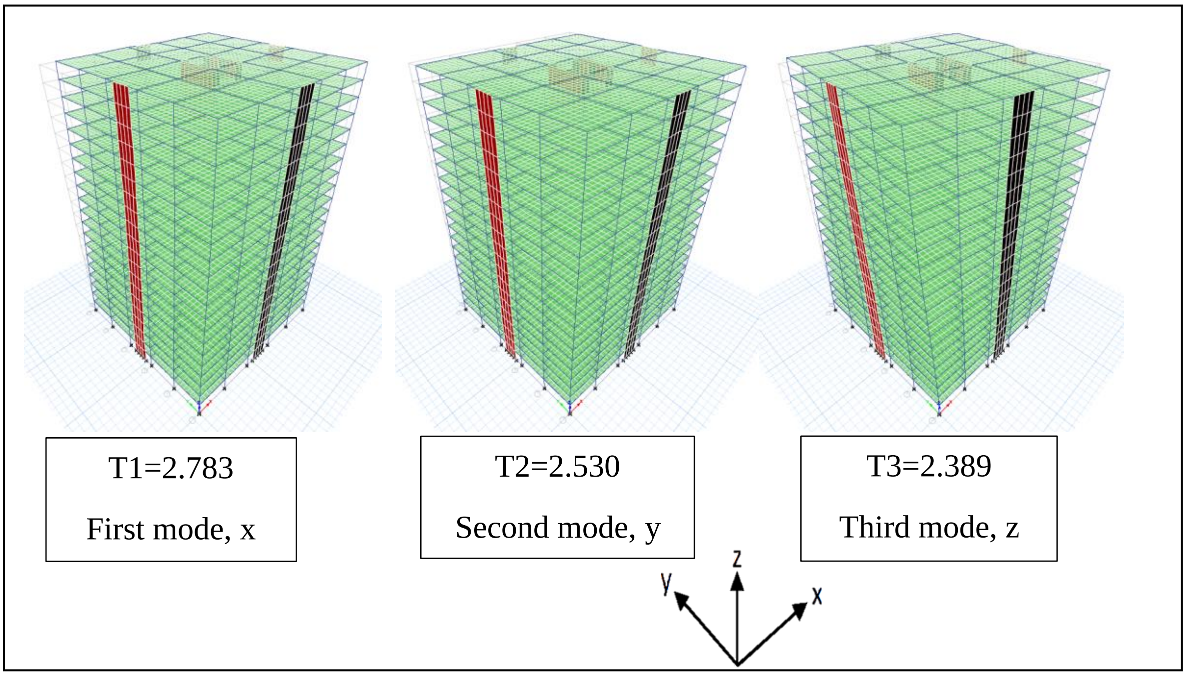


Figure 3.10 TD2202: First three modes shape

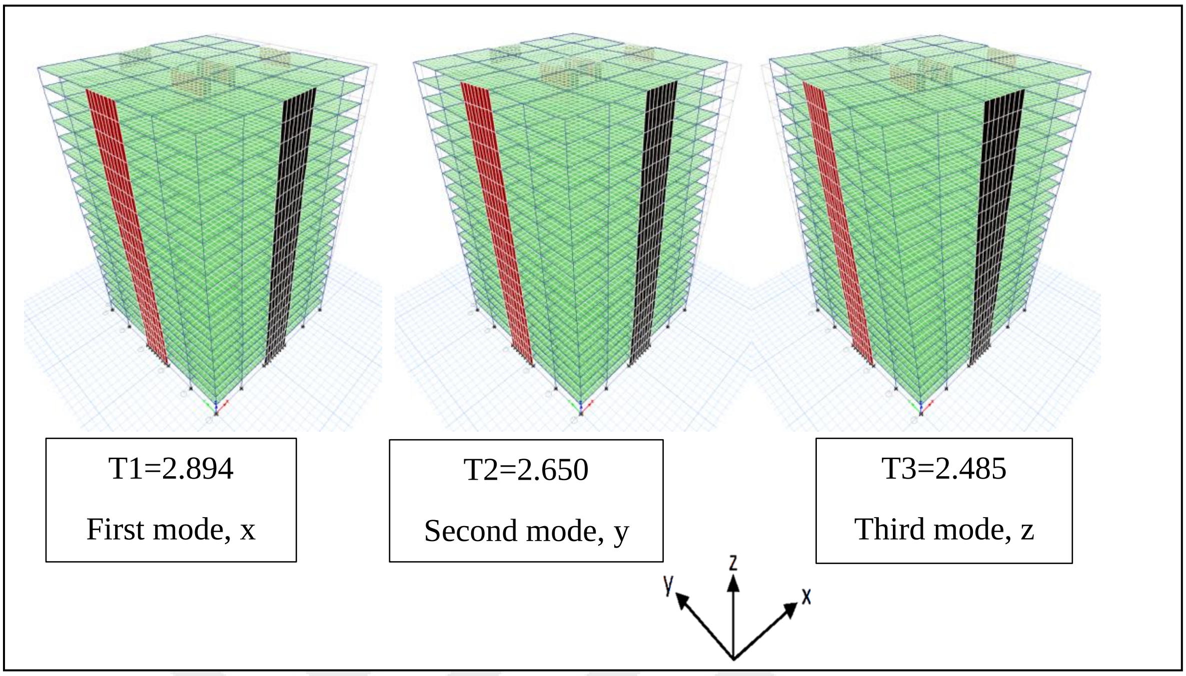


Figure 3.11 TD2203: First three modes shape

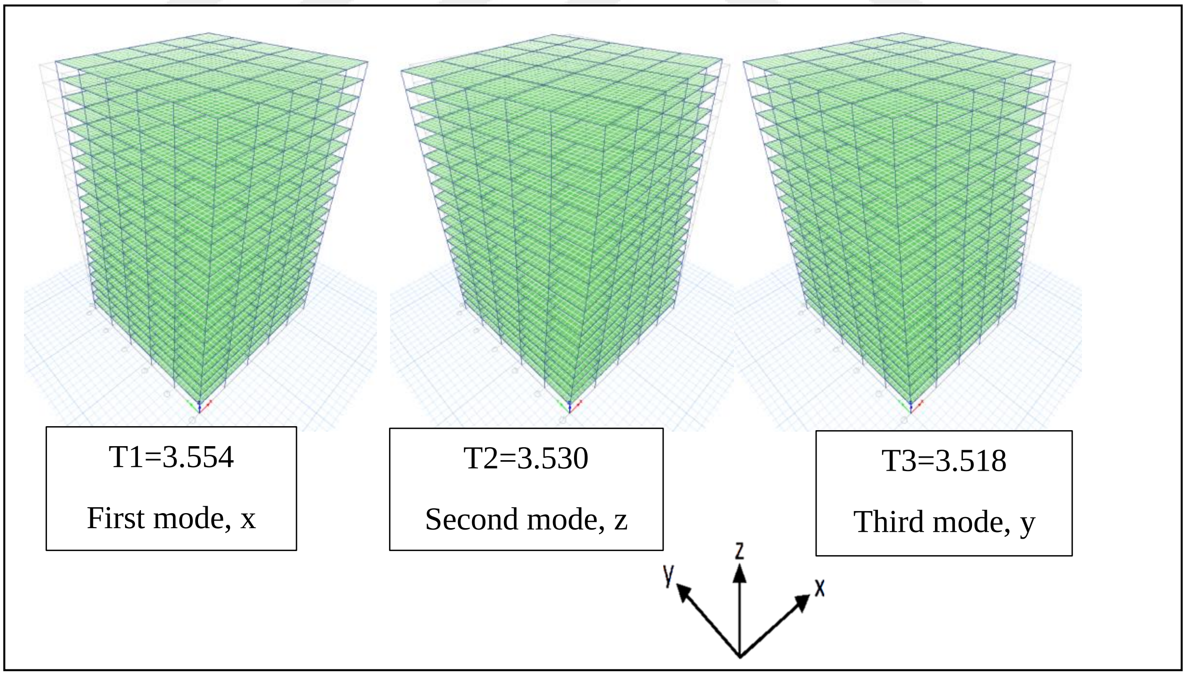


Figure 3.12 TD2204: First three modes shape

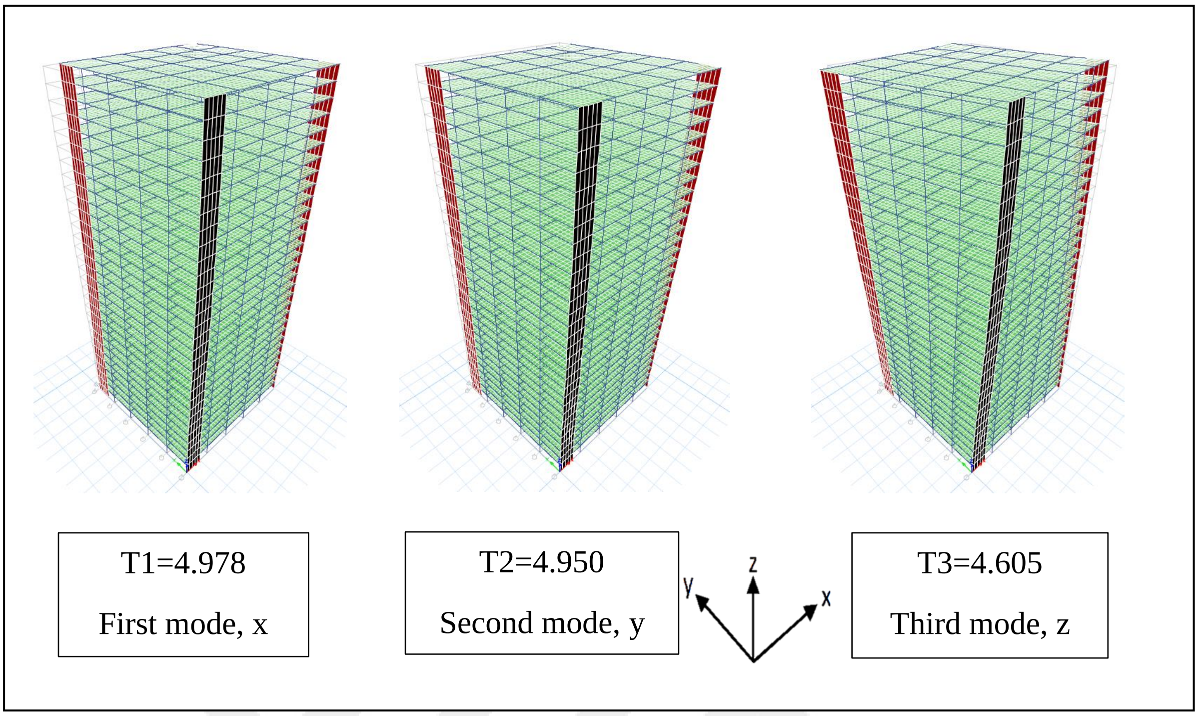


Figure 3.13 TD2301: First three modes shape

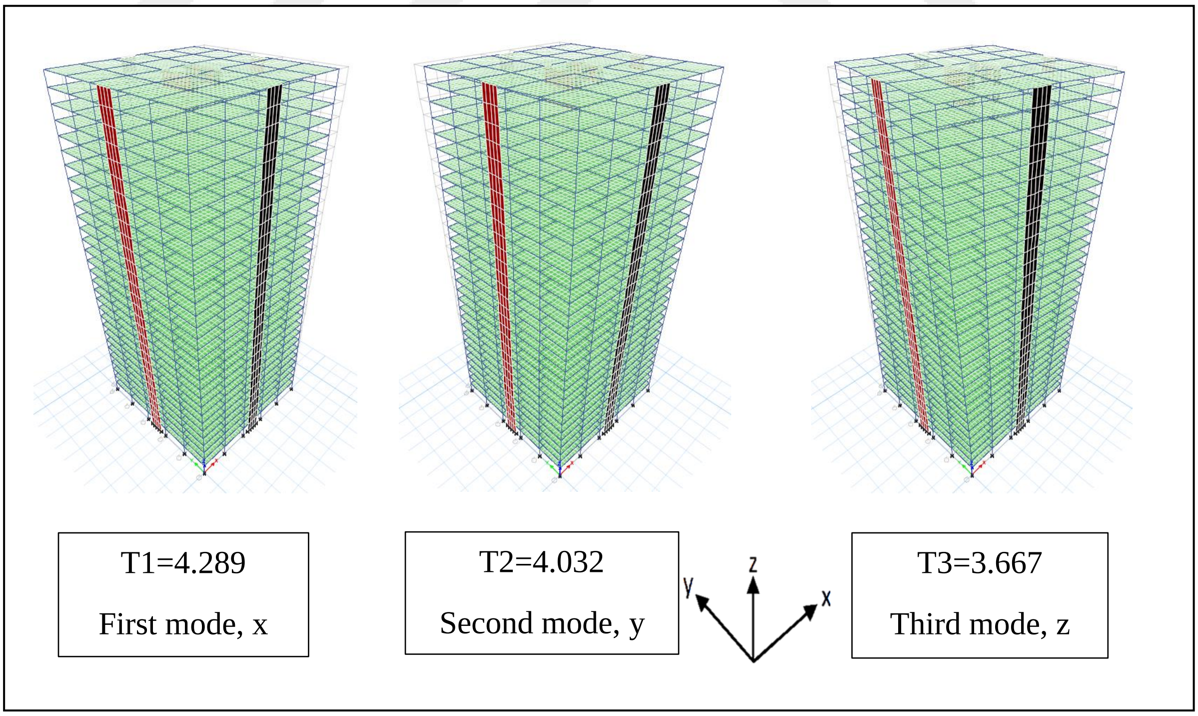


Figure 3.14 TD2302: First three modes shape

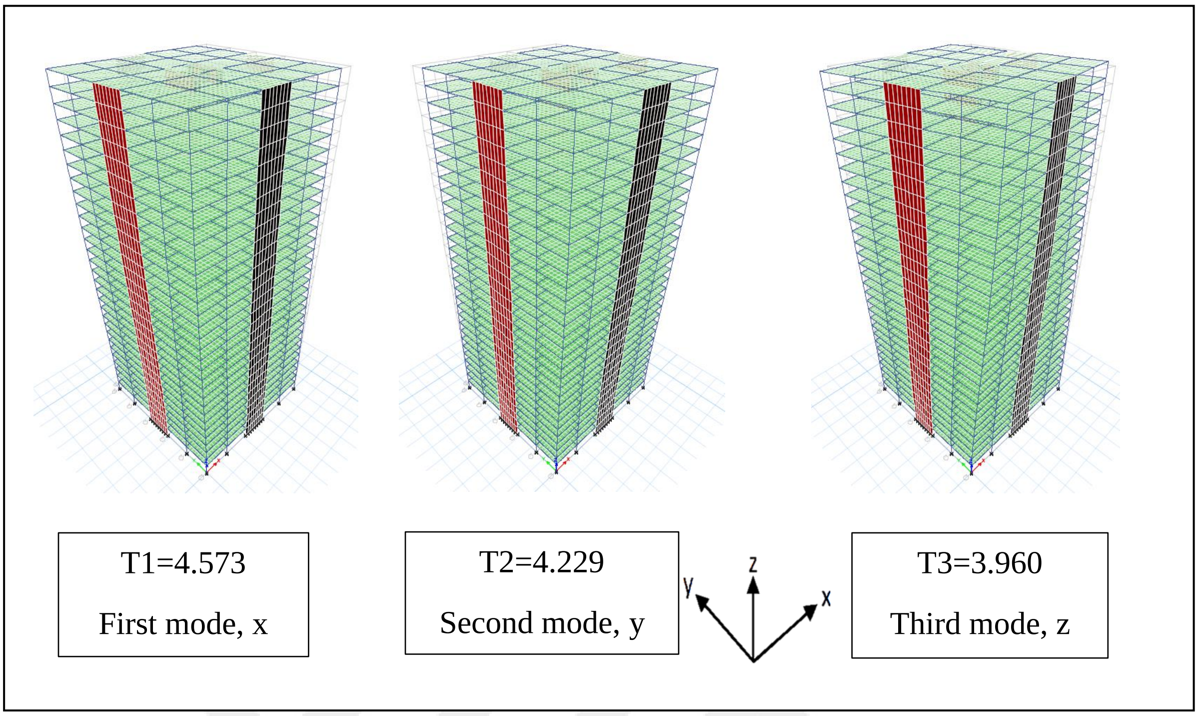


Figure 3.15 TD2303: First three modes shape

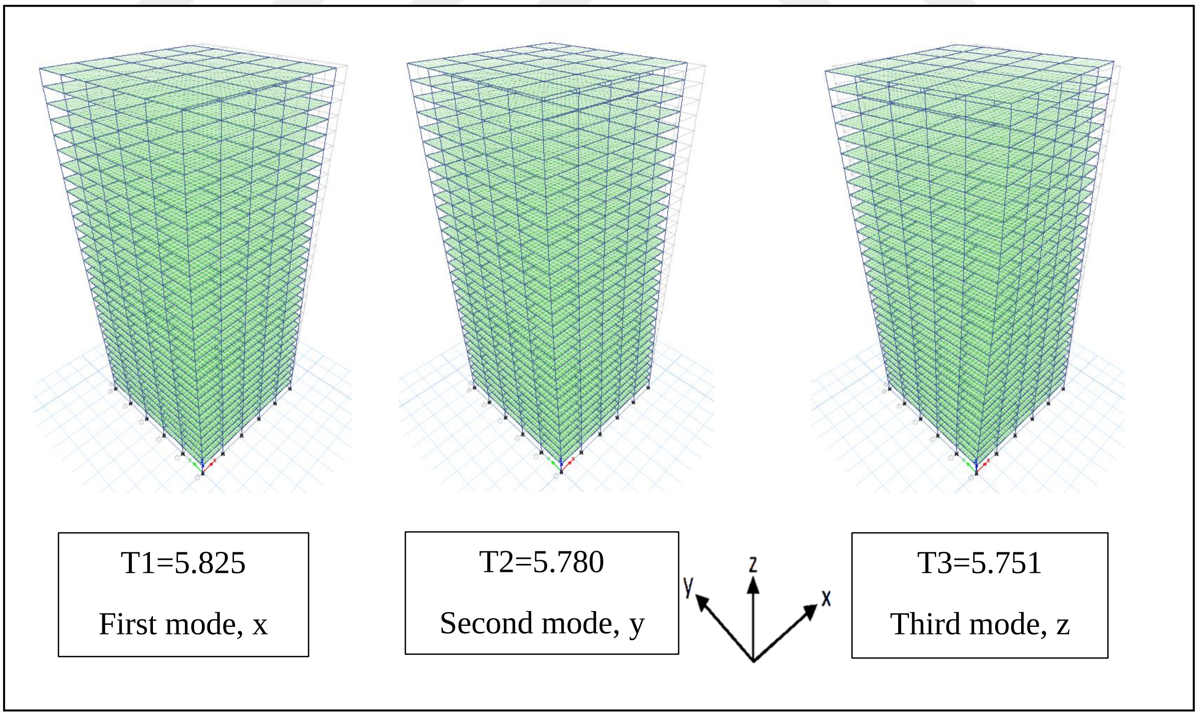


Figure 3.16 TD2304: First three modes shape

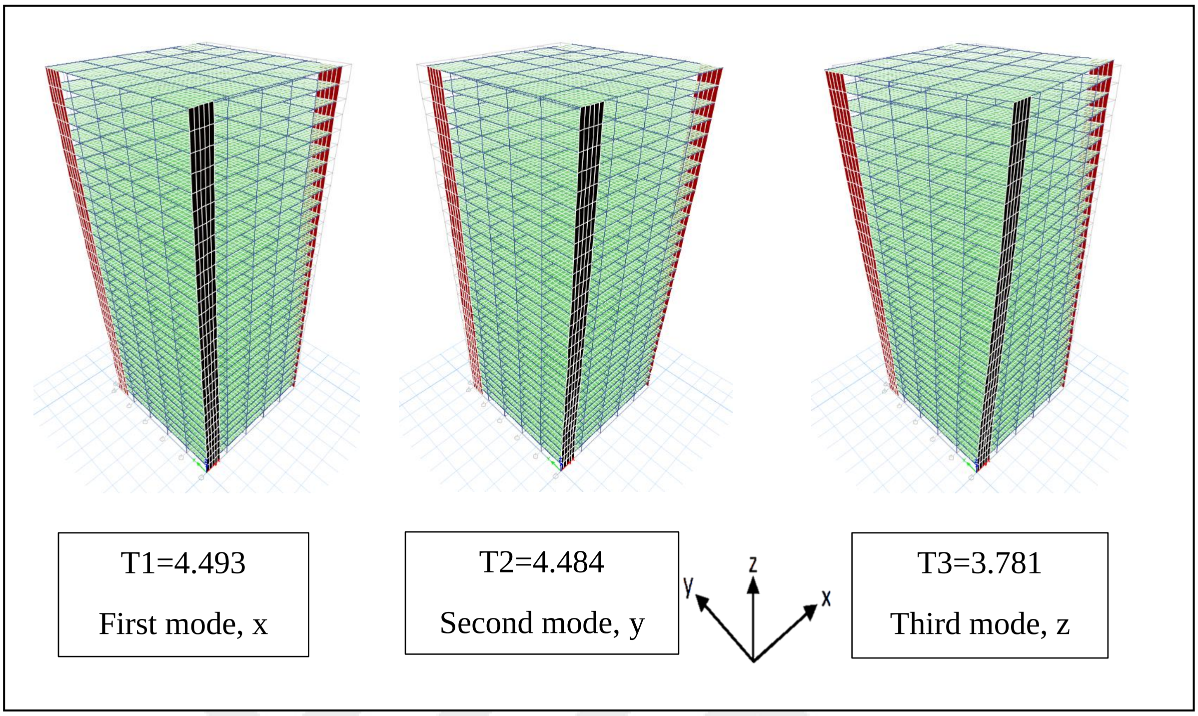


Figure 3.17 TD4301: First three modes shape

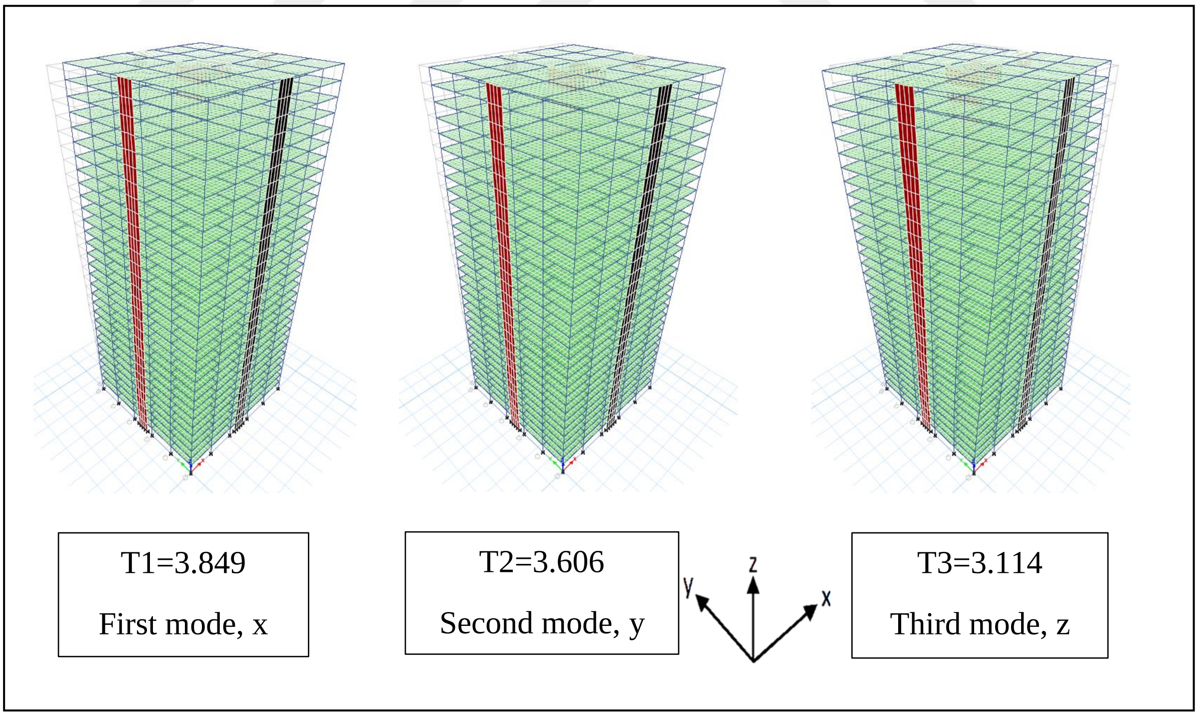


Figure 3.18 TD4302: First three modes shape

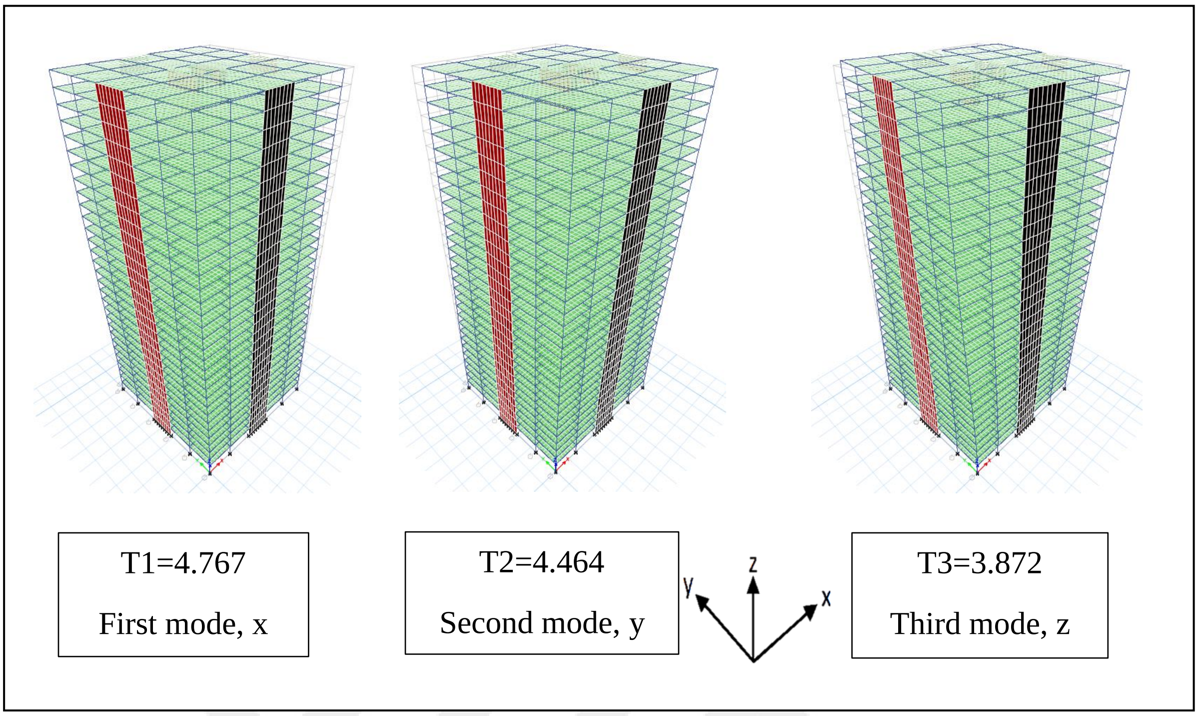


Figure 3.19 TD4303: First three modes shape

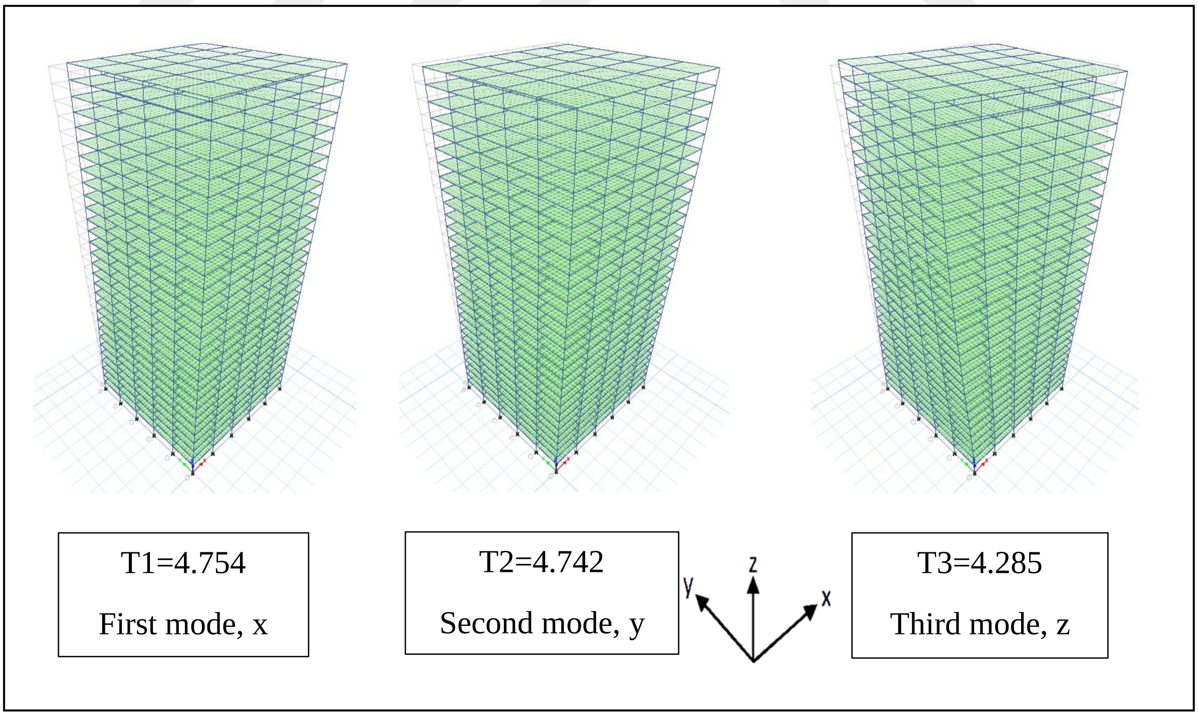


Figure 3.20 TD4304: First three modes shape

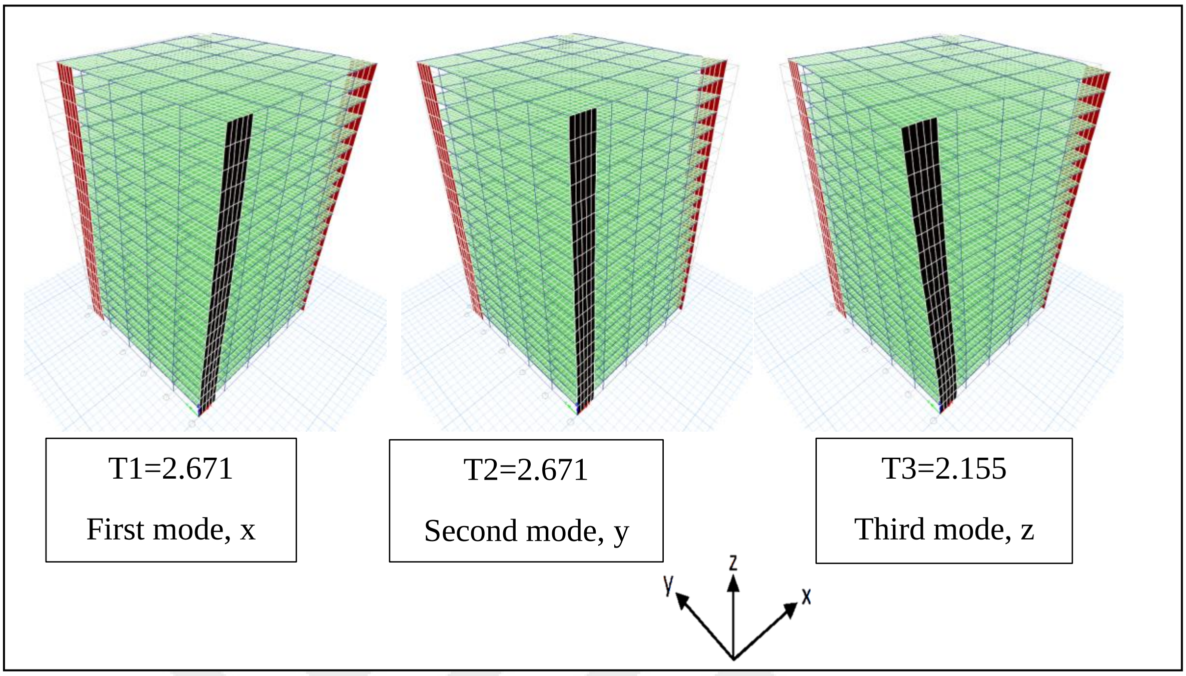


Figure 3.21 A201: First three modes shape

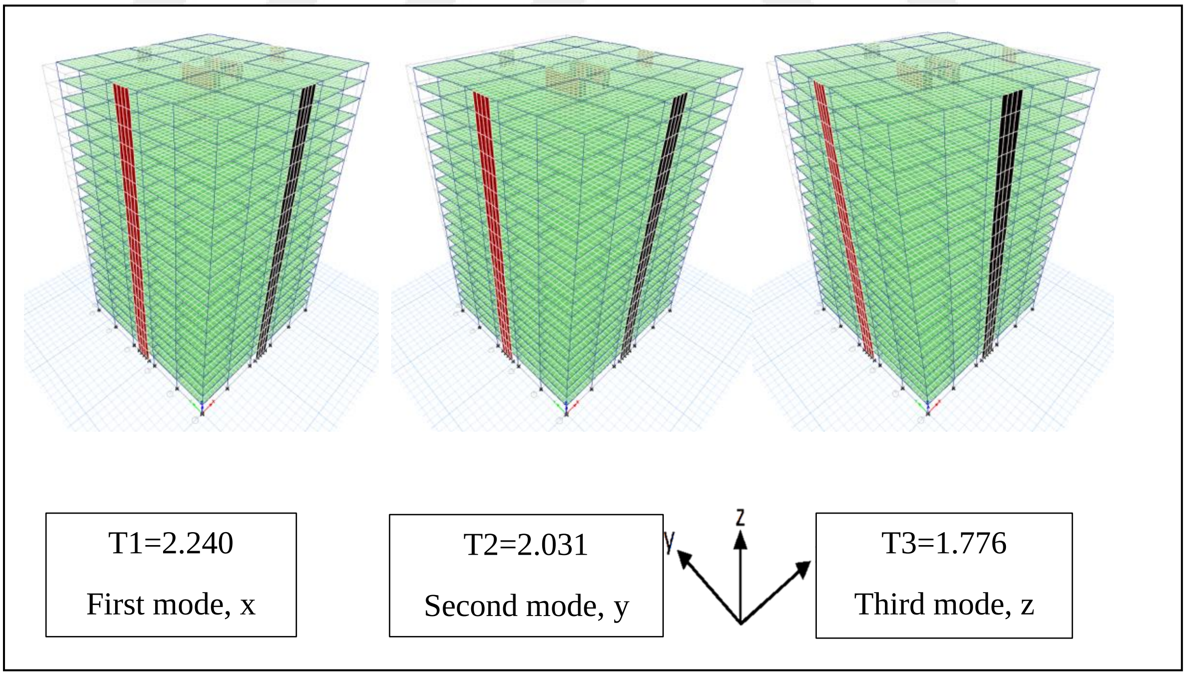


Figure 3.22 A202: First three modes shape

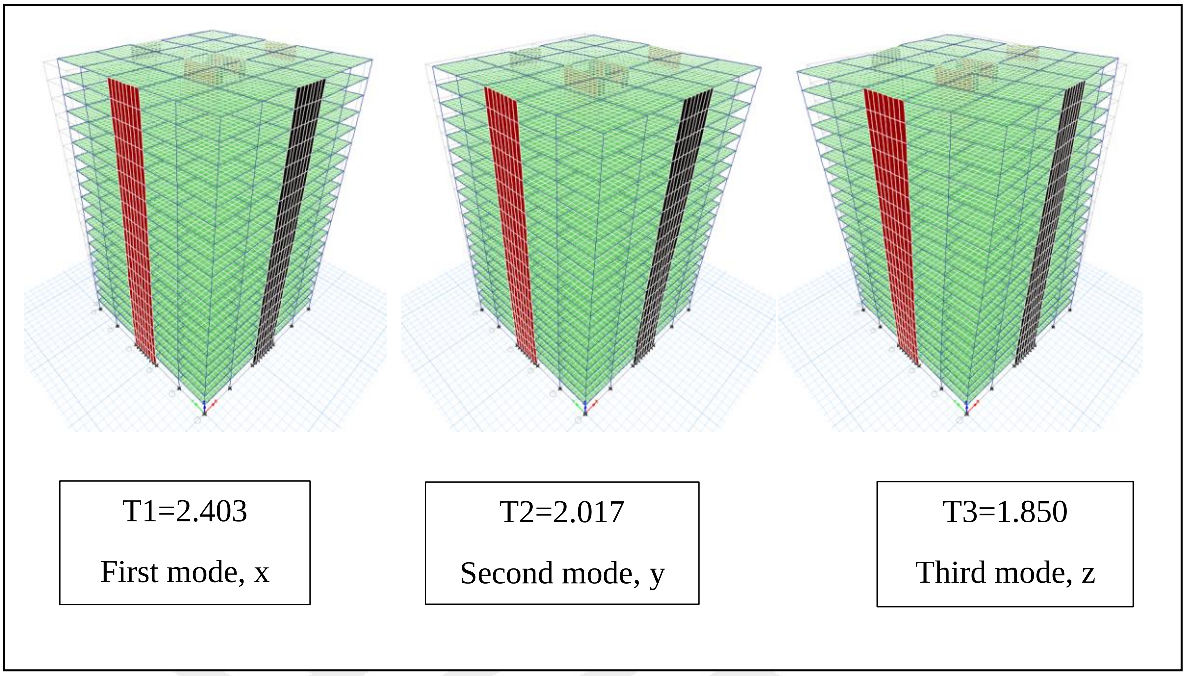


Figure 3.23 A203: First three modes shape

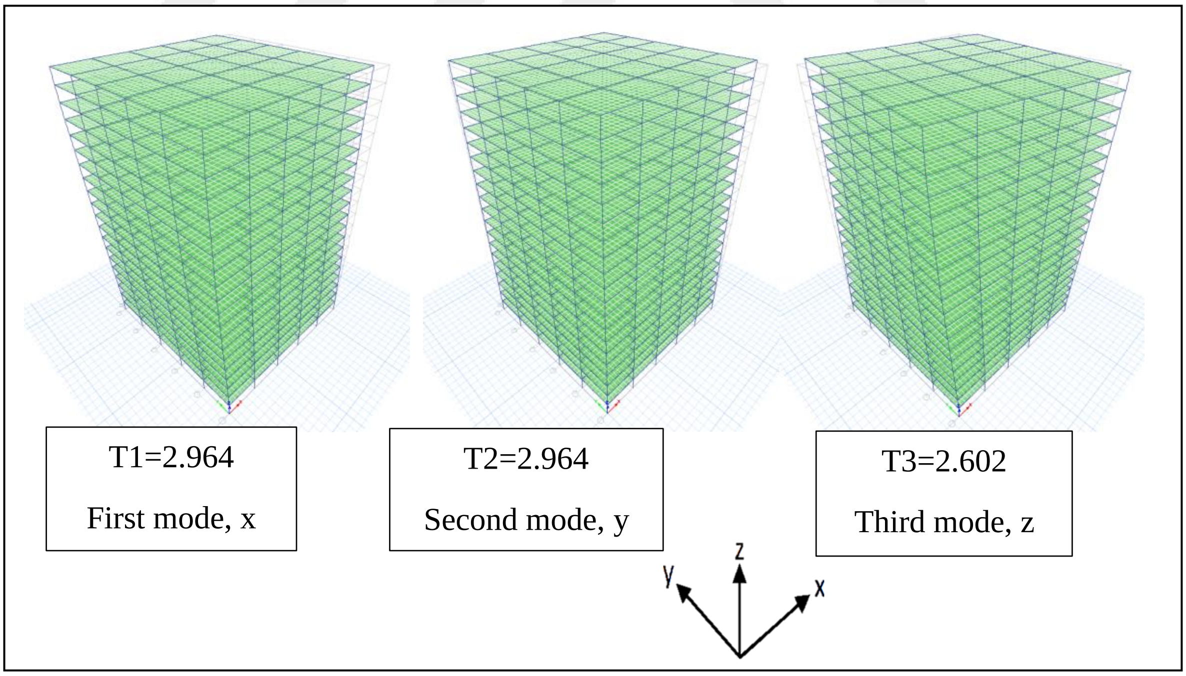


Figure 3.24 A204: First three modes shape

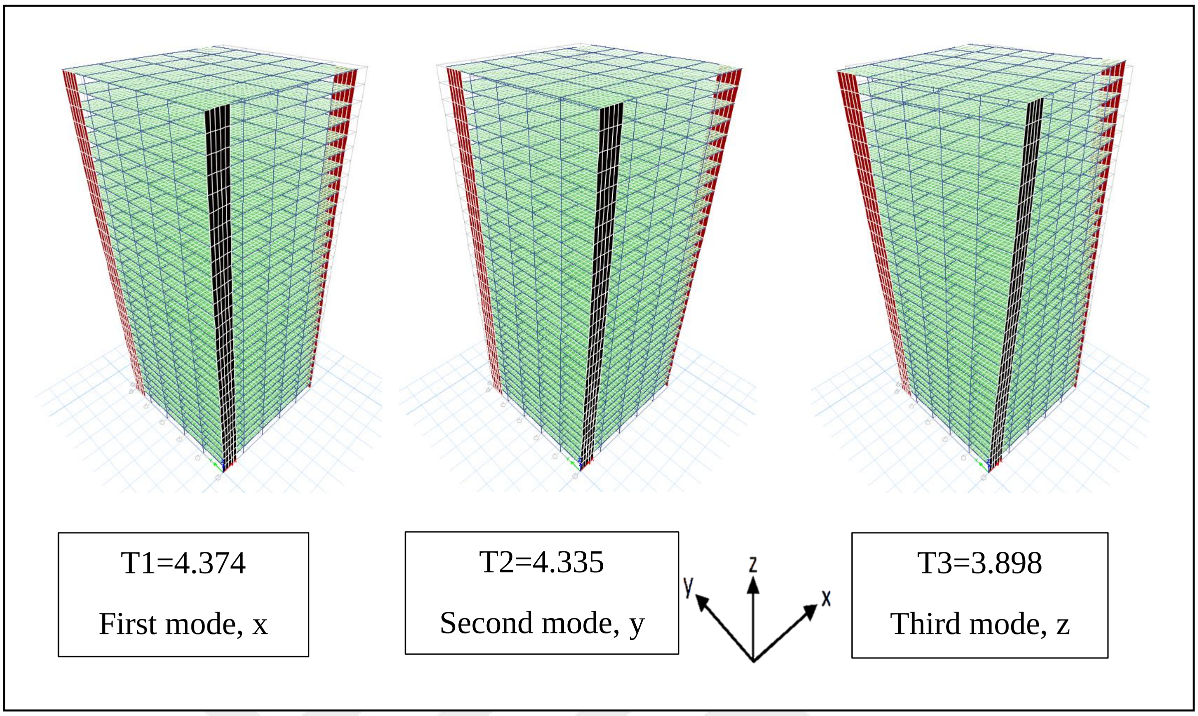


Figure 3.25 A301: First three modes shape

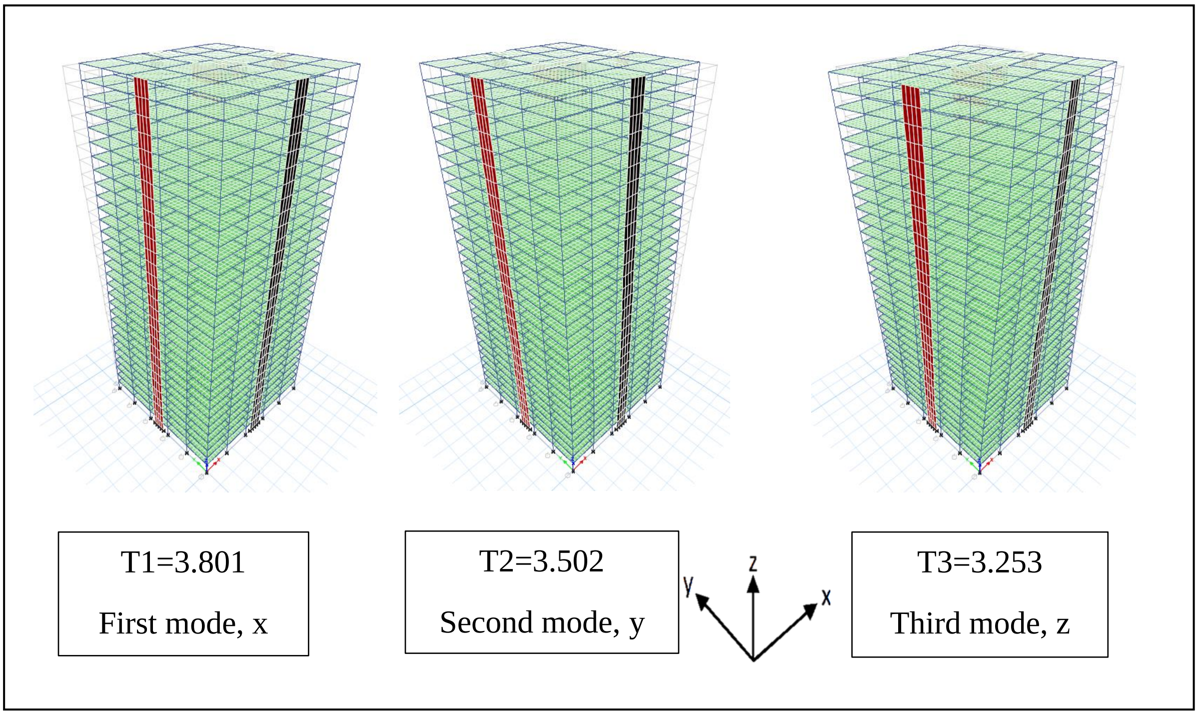


Figure 3.26 A302: First three modes shape

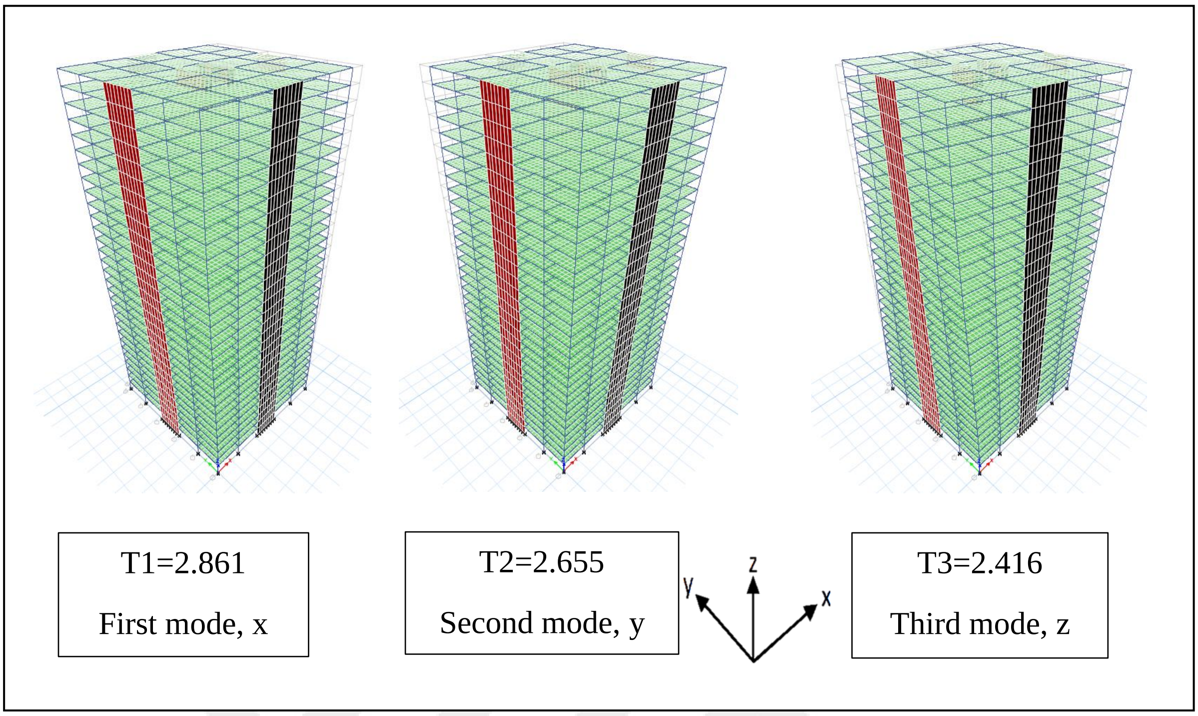


Figure 3.27 A303: First three modes shape

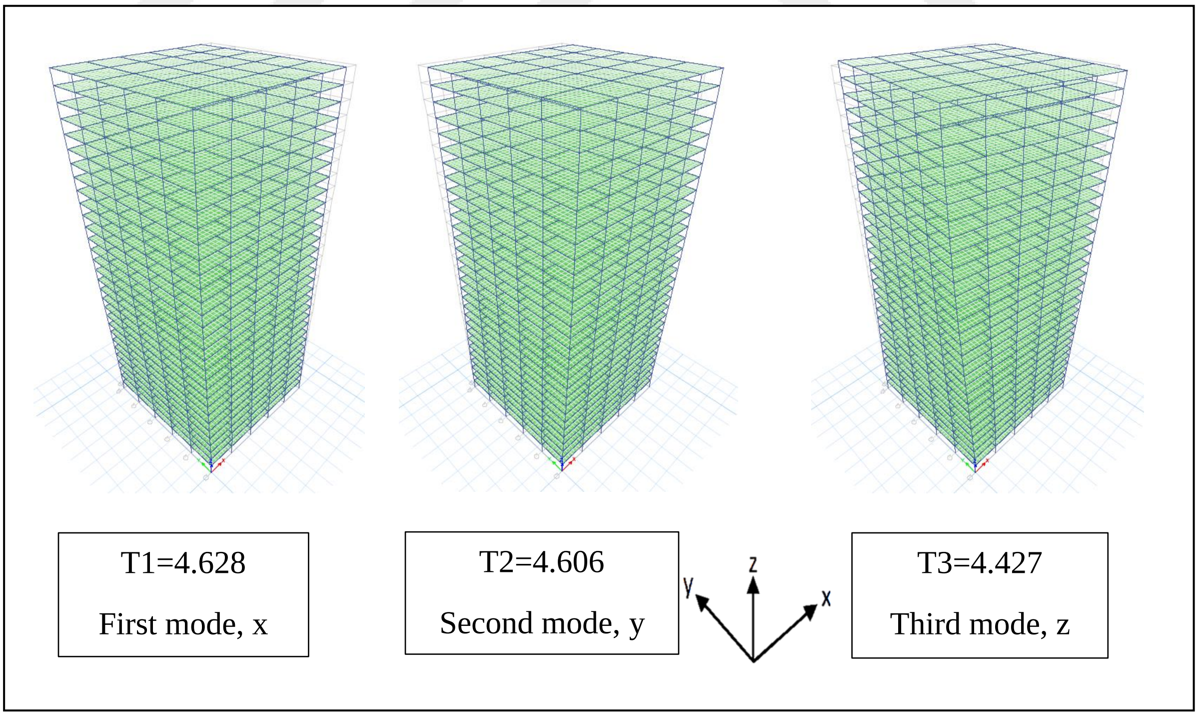


Figure 3.28 A304: First three modes shape

3.4.2 Base Shear Resisted by Shear Walls

Base shear approximates the maximum predictable earthquake force that will occur due to seismic ground motion at the base of a building. The base moment is the moment produced at the base of a building due to different loading conditions. In this study, the focus will be on the ratio of the shear forces resisted by shear walls. Tables 3.17a through Table 3.17e list the base shear, the shear forces resisted by shear walls, and the ratio of shear force in percentage resisted by the wall.

Table 3.17a Base Shear and Wall Shear for 20 Story Building: TEC 19

(DD2, 5% damping ratio)

Building Models	Base Shear (kN)		Wall Shear (kN)		Percentage (%)	
	FX	FY	FX	FY	FX	FY
TD2201	44540.46	44895.99	29749.03	29178.85	66.8	65.0
TD2202	52992.64	64586.76	41239.85	49066.22	77.8	76.0
TD2203	55353.48	66473.41	53326.34	58821.29	96.4	88.5
TD2204	37902.50	38302.40	–	–	–	–

Table 3.17b Base Shear and Wall Shear for 30 Story Building: TEC 19

(DD2, 5% damping ratio)

Building Models	Base Shear (kN)		Wall Shear (kN)		Percentage (%)	
	FX	FY	FX	FY	FX	FY
TD2301	46196.35	46459.32	16897.80	16290.05	36.6	35.1
TD2302	54879.12	64276.10	36503.77	42505.02	66.5	66.2
TD2303	55552.14	64530.45	49101.58	52617.50	88.4	81.5
TD2204	36568.77	36838.23	–	–	–	–

Table 3.17c Base Shear and Wall Shear for 30 Story Building: TEC 19 (DD4, 2.5% damping ratio)

Building Models	Base Shear (kN)		Wall Shear (kN)		Percentage (%)	
	FX	FY	FX	FY	FX	FY
TD3041	10617.75	12776.96	4495.42	5307.05	42.4	41.5
TD3042	12931.21	15739.97	9523.91	11947.92	73.7	75.9
TD3043	11422.79	13685.24	10839.63	12180.90	94.9	89.0
TD3044	9322.62	9318.49	–	–	–	–

Table 3.17d Base Shear and Wall Shear for 20 Story Building: ASCE 7-16 (5% damping ratio)

Building Models	Base Shear (kN)		Wall Shear (kN)		Percentage (%)	
	FX	FY	FX	FY	FX	FY
A201	53135.21	53135.22	28285.33	28285.34	53.2	53.2
A202	60540.04	81558.12	51377.68	68006.36	84.9	83.4
A203	77590.37	95422.01	76325.20	89205.42	98.4	93.5
A204	43458.82	43336.96	–	–	–	–

Table 3.17e Base Shear and Wall Shear for 30 Story Building: ASCE 7-16 (2% damping ratio)

Building Models	Base Shear (kN)		Wall Shear (kN)		Percentage (%)	
	FX	FY	FX	FY	FX	FY
A301	54215.86	54746.45	21723.83	20938.32	40.0	38.3
A302	64774.53	77410.97	46913.67	49098.85	72.4	63.4
A303	47770.75	55370.85	43014.74	42858.79	90.0	77.40
A304	47653.73	47954.65	–	–	–	–

The base shear forces of the 20 story building obtained from TEC 19 were compared to those from ASCE 7-16. Based on the results, the forces from TEC 19 were about 80% of their counterparts from ASCE 7-16 (see Table 3.18a). As discussed for the periods of these buildings, ASCE 7-16 generated less periods than those from TEC 19. As a result of this conclusion for periods, the base shear forces from ASCE 7-16 were found to be higher.

Similar to the base shear forces, total wall show shear forces at the base were also compared both in x and y directions. According to the results, TEC 19 generated less shear forces than those from ASCE 7-16. This observation is similar to the one that were extracted from the base shear. However, as the ratio of wall area to the floor area increased, the ratio of total shear wall forces from TEC 19 to ASCE 7-16 decreased from 1.5 to 0.69 indicating that TEC 19 generated less forces as wall area increased.

The percentage of the base shear force resisted by shear walls for the 20 story building in TEC 19 was around 65% in both x and y direction when the ratio of the shear wall to base shear was 0.5%. This ratio increased to an average of 92% when the wall ratio increased to 1.5% (see Table 3.17a). These percentages were very similar to those generated by ASCE 7-16 except for the one with 0.5% ratio. In the 0.5% ratio case, the percentage in ASCE 7-16 were 53% as compared to 65% from TEC 19 (see Table 3.17d).

The base shear forces and total wall shear forces of the 30 story buildings that were obtained based on DD2 and DD4 design categories of TEC 19 were compared to each other. Based on the results, as expected, DD2 generated much larger forces than DD4. The ratios for both base shear and shear walls varied from a minimum of 3.0 to a maximum of 4.9 (see Table 3.18b). The percentages of the total base shear shared by the shear walls in DD2 were 35% for the building with 0.5% shear wall area ratio and it increased to an average of 85% for the building with 1.5% ratio (see Table 3.17b). The percentages were slightly higher in DD4. 35% ratio increased to 42% for the building with 0.5% shear wall area to floor area ratio as 85% increased to 92% for the building with 1.5% ratio (see Table 3.17c).

The base shear and shear wall forces of the 30 story building with DD2 were less than those from ASCE 7-16. This outcome is expected since the periods from ASCE 7-16 were less due to less weight resulting from no live load participation factor (see Table

3.18c). Also, the short and 1 second spectral acceleration values from ASCE 7-16 were larger than their counterparts from TEC 19. The average ratio of base shear forces from TEC 19 to ASCE 7-16 was around 0.85 with almost no difference between x and y directions (see Table 3.18c). Similar to the outcome of the base shear, wall shear forces generated by TEC 19 were less compared to those generated by ASCE 7-16. The average ratio of the total wall shear to wall shear forces from TEC 19 to ASCE 7-16 was 0.80 with almost no difference in x and y directions (see Table 3.18c).

Table 3.18a Comparison of Base Shear and Wall Shear Forces: TEC 19 / ASCE 7-16 for 20 Story Building

Base shear(1)		Wall shear(1)		Percentage (%)	
Fx	Fy	Fx	Fy	Fx	Fy
0.84	0.85	1.05	1.03	1.25	1.22
0.87	0.80	0.80	0.72	0.92	0.91
0.71	0.70	0.70	0.66	0.98	0.94
0.87	0.88	—	—	—	—

(1)The values in this table are obtained by dividing the results in Table 3.17a to those in Table 3.17 d

Table 3.18b Comparison of Base Shear and Wall Shear Forces: TEC 19-DD2 / TEC 19-DD4 for 30 Story Building

Base shear(1)		Wall shear(1)		Percentage (%)	
Fx	Fy	Fx	Fy	Fx	Fy
4.35	3.64	3.76	3.07	0.86	0.84
4.24	4.08	3.83	3.56	0.90	0.87
4.86	4.72	4.53	4.32	0.93	0.92
3.92	3.95	—	—	—	—

(1)The values in this table are obtained by dividing the results in Table 3.17b to those in Table 3.17c

Table 3.18c Table 3.18d Comparison of Base Shear and Wall Shear Forces: TEC 19-DD2 / TEC 19-DD4 for 30 Story Building

Base shear[1]		Wall shear[1]		Percentage (%)	
Fx	Fy	Fx	Fx	Fy	Fx
0.85	0.845	0.78	0.78	0.91	0.92
0.84	0.83	0.78	0.87	0.92	1.04
1.16	1.16	1.14	1.23	0.98	1.05
0.77	0.77	—	—	—	—

(1)The values in this table are obtained by dividing the results in Table 3.17b to those in Table 3.17e

3.4.3 Maximum Story Drift and Displacements

During the lateral motion of a building, maximum displacement and story drift become important parameters that need to be considered. In order to ensure the structural integrity of a building, both structural and non-structural components must comply with the existing building code requirements. Table 3.19a through 3.19e show the maximum displacement and story drifts for each model. The maximum displacement were obtained at the top floor of all buildings. It is important to note that load combinations 5 and 9 generated the maximum displacements (see Table 3.12).

Table 3.19a Maximum Displacements and Story Drifts for 20 story Building: TEC 19

(DD2, 5% damping ratio)

Building Models	Maximum Displacements (mm)		Maximum Drift (mm)	
	x	y	x	y
TD2201	255.7	253.3	16.7	16.7
TD2202	215.1	202.3	14.0	13.2
TD2203	225.1	213.3	14.5	13.9
TD2204	264.5	261.0	19.0	18.8

Table 3.19b Maximum Displacements and Story Drifts for 30 story Building: TEC 19

(DD2, 5% damping ratio)

Building Models	Maximum Displacements (mm)		Maximum Drift (mm)	
	x	y	x	y
TD2301	381.5	379.0	17.3	17.3
TD2302	331.0	318.2	14.4	13.6
TD2303	350.2	338.7	15.7	14.6
TD2304	434.9	431.0	21.0	20.8

Table 3.19c Maximum Displacements and Story Drifts for 30 story Building: TEC 19

(DD4, 2.5% damping ratio)

Building Models	Maximum Displacements (mm)		Maximum Drift (mm)	
	x	y	x	y
TD4301	83.0	98.3	3.7	4.3
TD4302	67.5	65.1	2.9	2.8
TD4303	82.8	79.9	3.7	3.4
TD4304	80.7	80.4	3.8	3.8

Table 3.19d Maximum Displacements and Story Drifts for 20 Story Building: ASCE 7-16

(5% damping ratio)

Building Models	Maximum Displacements (mm)		Maximum Drift (mm)	
	x	y	x	y
A201	230.8	230.8	15.4	15.4
A202	200.9	175.6	12.9	11.9
A203	218.8	203.7	13.9	13.6
A204	239.6	239.6	17.6	17.6

Table 3.19e Maximum Displacements and Story Drifts for 20 Story Building: ASCE 7-16

(2% damping ratio)

Buildings	Maximum Displacements (mm)		Maximum Drift (mm)	
	x	y	x	y
A301	416.0	411.3	17.9	17.8
A302	353.8	336.4	15.3	14.2
A303	267.6	256.4	11.7	10.8
A304	420.7	417.6	19.5	19.4

Similar to the comparisons made for the periods, the base shear and wall shear forces, displacements and story drift were discussed. First, the displacements and story drift of the 20 story building from TEC 19 were compared to those from ASCE 7-16. The displacement and drift results from the two codes were very close to each other (in other words not diverging based on different models). The displacements of the top floors from TEC 19 decreased to an average of 7% when the shear wall area to floor area ratio increased from 0.5% to 1.5% (see Table 3.20a). But for the model with no shear walls, the difference between the two codes were almost the same indicating the fact that as the wall ratio increased, the difference became more prominent. The maximum displacement, as expected, was obtained for the model with no shear wall while the minimum was obtained for the one with 1.5% shear wall ratio. The ratio of the maximum displacement from no shear wall case to 1.5% one was 1.2 for TEC 19 model and was 1.1 for the ASCE 7-16 one.

The results of the 30 story building from DD2 design category were compared to those from the DD4 using the same earthquake code of TEC 19. As expected, the DD2 generated a minimum of 3.9 times larger displacements and drifts for the building model with 1.5% shear wall area ratio while the maximum ones were 5.5 times larger for the model with no shear walls (see Table 3.20b).

The story drifts and displacements of the 30 story building models from the DD2 design category in TEC19 were compared to their counterparts from ASCE 7-16. As stated before the models from TEC 19 generated less forces than those from ASCE 7-16 except for the one with 1.5 % of shear wall area ratio (see Table 3.20c). The maximum displacements and drifts followed a similar pattern as well. The displacements and drifts of the models with 0.5% and 1% of shear wall areas ratios including the one with no shear wall produced results very close to each other for both DD2 in TEC 19 and ASCE 7-16. As the wall ratio increased to 1.5%, the result from TEC19 became as much as 30% higher than those from ASCE 7-16 (see Table 3.20c).

Table 3.20a Comparison of Maximum Displacements and Drift for: TEC 19 / ASCE 7-16 for 20 Story Building

Maximum Displacements Ratios		Maximum Drift Ratios	
x	y	x	y
1.11	1.10	1.09	1.08
1.07	1.15	1.08	1.11
1.03	1.05	1.04	1.02
1.10	1.09	1.08	1.07

(1)The values in this table are obtained by dividing the results in Table 3.19a to those in Table 3.19d

Table 3.20b Comparison of Maximum Displacements and Drift for: TEC 19-DD2 / TEC 19-DD4 for 30 Story Building

Maximum Displacements Ratios		Maximum Drift Ratios	
x	y	x	y
4.60	3.86	4.70	4.04
4.90	4.89	4.93	4.88
4.23	4.24	4.27	4.24
5.39	5.36	5.55	5.50

(1)The values in this table are obtained by dividing the results in Table 3.19b to those in Table 3.19c

Table 3.20c Comparison of Maximum Displacements and Drift for: TEC 19-DD2 / ASCE 7-16 for 30 Story Building

Maximum Displacements Ratios		Maximum Drift Ratios	
x	y	x	y
0.92	0.92	0.97	0.97
0.94	0.95	0.94	0.96
1.31	1.32	1.35	1.35
1.03	1.03	1.08	1.07

(1)The values in this table are obtained by dividing the results in Table 3.19b to those in Table 3.19e

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Introduction

The objective of this thesis is to determine the optimum ratio of the shear wall areas to floor areas in reinforced concrete buildings. For this purpose, buildings with different layouts, number of floors and shear wall areas were studied. Determining the optimum shear wall area is an important task for structural designers since the shear walls significantly affect the buildings dynamic behaviors. There are no written rules or guidelines with respect to how much wall area needs to be included in a building. The task here was to select buildings with no walls and buildings with some walls. The specifics of the word “some” used in the previous sentence were investigated by selecting a shear wall area to floor area equal to 0.5, 1.0 and 1.5%. In this study, walls were assumed to be continuous from the base up to the roof.

In this thesis, first, a literature review was provided. Then, the material properties, gravity and lateral loads were applied to the building modeled in ETABS. Two building codes were decided to be used in order to understand the effect of walls on the overall structural behavior of buildings. The current Turkish earthquake code, TEC 19, and the current American code of ASCE 7-16 were used. Two specific building heights were selected one with a height of 64 meters equivalent to 20 story building and one with a height of 96 meters equivalent to 30 story building. Two building heights were selected intentionally in order to understand the impact of tall buildings on the structural analysis. As per TEC 19, the 30 story building is considered a tall building and its design and analysis require special attention due to the additional requirements enforced by the same code. Three parameters were decided to be studied in depth. These parameters were: (a) building periods, (b) base shear and total shear force resisted by walls, and (c) displacements and story drifts.

4.2 Conclusions

In this study, the impact of the ratio of shear wall areas on buildings performances were studied. A total of 20 building models were constructed in ETABS. These models had different shear wall areas, floor numbers and lateral loads. The results were investigated based on the requirements of TEC 19 and ASCE 7-16. In the conclusion part of this study, first building periods then the base shear and shear in walls, and finally maximum displacements and drifts were studied to draw conclusions on determining the optimum shear wall areas. The findings of the research are summarized below:

(a) Building Periods:

- The comparison of the outcomes of TEC 19 code indicated that the periods generated from the buildings with 64 meter height (equivalent to 20 story) were less than the periods generated from the buildings with 96 meters height (equivalent to 30 story). This difference shows that the height of the buildings, as expected, played an important on the fundamental periods.
- The periods resulted from ASCE 7-16 with 20 story building were compared to those from TEC 19. The results showed that the TEC 19 generated 30% higher periods than those in ASCE 7-16. This difference between the two codes was due to the change in the seismic weight of the models and the different cracked properties used for the structural members.
- The periods of the 30 story building based on DD4 design category in TEC 19 were compared to those of DD2 design category in TEC 19. The periods generated from the DD2 case were slightly higher than those from DD4 due to the differences in the cracked properties and the damping ratio.
- For the 30 story building, due to the differences both in total seismic weight and in the effective stiffnesses of structural members that were analyzed according to TEC 19-DD2 and ASCE 7-16, there was no clear outcome as to which code generated higher or lower periods since the results were somewhat interchangeable.

- The periods of the 30 story building generated from TEC19-DD4 were compared to those from ASCE 7-16. The building periods of TEC 19-DD4 were very close to those of ASCE 7-16.

(b) Base Shear and Wall Shear:

- The base shear forces generated from the 20 story building in TEC 19 were 80% of the forces obtained from ASCE 7-16. Similar to the base shear, the wall shear forces from TEC 19 were also less than those from ASCE 7-16 since TEC 19 generated less base shear forces. The ratio of total shear wall forces of TEC 19 to ASCE 7-16 decreased from 1.05 to 0.7 when the wall area to floor area ratio increased from 0.5% to 1.5% indicating that TEC 19 generated less shear forces as the wall area increased.

- For the 20 story building, the percentage of the total wall shear forces to base shear for TEC 19 increased from 65% to 92% when the shear wall ratio increased from 0.5% to 1.5%. These ratios were similar to those from ASCE 7-16 except for the wall ratio of 0.5% which in ASCE was 53%.

- For the 30 story buildings, the results of DD2 and DD4 design categories in TEC 19 were compared to each other. The results showed that the DD2 case generated higher base shear forces than those from the DD4. In the DD2 design category, 35% of the total base shear was resisted by the walls when the shear wall area ratio was 0.5%. When this shear wall ratio increased to 1.5%, the 35% shear increased to 85%. In DD4 design category, the 35% and 85% ratios increased to 42% and 92% for the 0.5% and 1.5 % shear wall area ratios, respectively.

- For the 30 story buildings, both the base shear and the shear wall forces of the TEC 19-DD2 were less than those from ASCE 7-16 since the periods and the seismic weights were less in ASCE 7-16. This conclusion was expected since the short and 1-second spectral acceleration values from ASCE 7-16 were larger than those from TEC 19. The average ratio of base shear forces from TEC 19 to ASCE 7-16 was around 0.85 with almost no difference between x and y directions. Similar to this outcome for the base shear, wall shear forces from TEC 19 were found to be less when they were compared to those from ASCE 7-16. The average ratio of the total wall shear to wall shear forces of TEC 19 to ASCE 7-16 was around 0.80.

(c) Displacements and Drifts:

- According to the results of the 20 story buildings from TEC 19 and ASCE 7-16, the displacements and drift values were very close to each other. The relative top displacements of the building in TEC 19 with respect to ASCE 7-16 increased by an average of 8% when the shear wall area to floor area ratio increased from 0.5% to1.5%. For the models without shear walls, the difference between the two codes were almost the same.
- Based on the results of the 20 story buildings it was obvious that the displacements were reduced as the shear wall area ratios increased. The maximum displacement was obtained for the model with no shear walls while the minimum displacement obtained for the model with 1.5% shear wall ratio. The ratio between the maximum displacement to the minimum one was 1.18 for TEC 19 and 1.1 for ASCE 7-16.
- Both displacements and drift results of the 30 story buildings that were analyzed according to the DD2 and DD4 design categories were compared to each other for the same earthquake code of TEC 19. The DD2 generated a minimum of 3.9 times larger displacements and drifts for the model with 1.5% shear wall ratio while the maximum one was 5.5 times larger for the model with no shear walls.
- For the 0.5% shear wall ratio, similar to the results of the forces, the maximum displacements and story drifts of the 30 story building in TEC 19-DD2 were very close to those in ASCE 7-16. As the wall ratio increased to 1.5%, the results from TEC19 became as much as 30% higher than those from ASCE 7-16.
- For the TEC 19 models with heights of 64 meters (20 story) the optimum shear wall area to floor area was 1.5%. For the models with heights of 96 meters (30 story), the same ratio for TEC 19 was 1.0%. For ASCE 7-16 code, the optimum ratio for both 20 and 30 story buildings was 1.5%.

4.3 Recommendations

Based on this study, some recommendation are listed below. These recommendations are found to be useful for parametric study and might need to be verified for buildings with different configurations.

- Based on the 20 and 30 story building analyses, in order obtain the best structural performance by shear walls, the wall area ratio should be kept around 1.5%
- In order to prevent the impact of any accidental torsional moment resulting from an eccentricity between the wall and building centers, shears wall should be located as close as possible to the gravity center of a building.
- For the 20 story building, 1.5% wall area ratio was found to be adequate to resist the base shear resulting from an earthquake. The same observation was also valid for the 30 story building. Therefore, its recommended not to exceed 1.5% wall area ratio for the 20 and 30 story buildings. However, it is clear that as the number of floors increase, the wall area ratio should increase.

4.4 Suggestions for Future Research

The analytical studies in this thesis were performed for two specific building layouts. However, in order to understand the effect of varying wall locations different wall layouts might be selected. In this study, two different building heights were selected, one with 20 story and the other one with 30 story. Buildings with lees or a greater number of floors might also be investigated to better understand the impact of wall area ratios. Also, in this study the walls were continuous from the base to the top while the walls can be removed at certain elevations. Therefore, an optimum wall area might be studied by terminating walls at varying floor in order to determine the optimum floor levels where wall no longer needed.

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