EFFECTIVE POSITIONS AND OPTIMUM LEVEL OF THE CURTAILMENT OF STRUCTURAL WALLS IN HIGH-RISE WALL-FRAME REINFORCED CONCRETE STRUCTURES UNDER SEISMIC LOADING

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Civil, Transportation and Geo-resources Engineering

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ตำแหน่งประสิทธิผลและปริมาณที่เหมาะสมของผนังโครงสร้างในอาคารสูงคอนกรีตเสริมเหล็กภายใต้แรงแผ่นดินไหว

นายธิฤทธิ์ เจิน

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต

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Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

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ธิฤทธิ์ เจิน : ตำแหน่งประสิทธิผลและปริมาณที่เหมาะสมของผนังโครงสร้างในอาคารสูงคอนกรีตเสริมเหล็กภายใต้แรงแผ่นดินไหว (EFFECTIVE POSITIONS AND OPTIMUM LEVEL OF THE CURTAILMENT OF STRUCTURAL WALLS IN HIGH-RISE WALL-FRAME REINFORCED CONCRETE STRUCTURES UNDER SEISMIC LOADING) อาจารย์ที่ปรึกษา : ผู้ช่วยศาสตราจารย์ ดร. มงคล จิรวัชรเดช, 127 หน้า.

ผนังโครงสร้าง (ผนังเฉือน) เป็นผนังที่รู้จักกันทั่วโลกว่าสามารถรับแรงด้านข้างในระนาบอย่างมีประสิทธิภาพโดยเฉพาะแรงลมและแรงแผ่นดินไหว วิทยานิพนธ์ฉบับนี้จะนำเสนอการศึกษาเกี่ยวกับการหาตำแหน่งที่มีประสิทธิภาพมากที่สุดและก็จะพูดถึงการกำหนดปริมาณที่เหมาะสมของผนังโครงสร้างในอาคารสูงคอนกรีตเสริมเหล็กภายใต้แรงแผ่นดินไหว ในเรื่องของอาคารสูงนั้นผู้ออกแบบสามารถลดความหนาหรือตัดผนังโครงสร้างจากชั้นบนบางส่วนของอาคาร โดยไม่มีผลกระทบรุนแรงต่อพฤติกรรมการรับแรงด้านข้างของอาคาร อย่างไรก็ตามขั้นตอนในการลดปริมาณผนังโครงสร้างนั้นจะต้องทำอย่างระมัดระวังและถูกต้องที่สุด มิฉนั้นจะส่งผลเสียต่อประสิทธิภาพในการรับแรงด้านข้างของอาคาร งานวิจัยนี้แบ่งเป็นสองขั้นตอน โดยขั้นตอนแรกคือการหาตำแหน่งที่ดีที่สุดของผนังโครงสร้างในอาคาร จากนั้นจะทำการตัดผนังโครงสร้างชั้นบนบางส่วนออกเพื่อเป็นการประหยัดงบประมาณในการก่อสร้าง ผนังที่ใช้ในงานวิจัยครั้งนี้เป็นผนังโครงสร้างแบบไม่มีช่องเปิด โครงสร้างอาคารถูกจำลองในโปรแกรม ETABS ห้ารูปแบบจำลองต่างกันโดยรูปแบบจำลอง A คือรูปแบบจำลองที่ไม่มีผนังโครงสร้างในอาคารส่วนรูปแบบจำลอง B, C, D และ E ปีนรูปแบบจำลองที่มีผนังโครงสร้างในตำแหน่งที่สมมาตรของแผนผังอาคาร การโยกตัวด้านข้าง การเคลื่อนตัวสัมผัสและโมเมนต์พลิกคว่ำของแต่ละชั้นในทิศทาง x และ y ถูกนำมาพิจารณาและเปรียบเทียบกันเพื่อหารูปแบบจำลองที่ให้สติฟเนสมากที่สุด แรงเฉือนที่ฐานของอาคารคำนวณโดยใช้การวิเคราะเชิงสเปกตรัมตอบสนองของแรงสถิตย์เทียบเท่าซึ่งอ้างอิงตามข้อกำหนดของกรมโยธาธิการและผังเมือง (มยผ 1302-61, ร่างสุดท้าย) หลังจากหาตำแหน่งของผนังโครงสร้างได้แล้วจะเข้าสู่ขั้นตอนการลดปริมาณของผนังโครงสร้างและค่าของการเคลื่อนตัวสัมผัสระหว่างชั้นจะถูกตรวจสอบอีกครั้งเพื่อให้แน่ใจว่ามีค่าไม่เกินค่าที่ยอมให้ นอกจากนี้ได้ทำการตรวจสอบแรงเฉือน แรงตามแนวแกนและเปอร์เซ็นต์การรับแรงในผนังกับเสาด้วย

สาขาวิชา วิศวกรรมโยธา ลายมือชื่อนักศึกษา

ปีการศึกษา 2562 ลายมือชื่ออาจารย์ที่ปรึกษา

THEARITH CHEN : EFFECTIVE POSITIONS AND OPTIMUM LEVEL OF THE CURTAILMENT OF STRUCTURAL WALLS IN HIGH-RISE WALL-FRAME REINFORCED CONCRETE STRUCTURES UNDER SEISMIC LOADING. THESIS ADVISOR: ASST. PROF. MONGKOL JIRAVACHARADET, Ph.D., 127 PP.

BUILDING STIFFNESS/LINEAR STATIC ANALYSIS/RESPONSE SPECTRUM/SEISMIC ANALYSIS/STRUCTURAL WALLS

Structural walls (also known as shear walls) have been known worldwide that they work very effective in in-plane lateral load resistances, typically wind and seismic forces. This thesis presents a study of finding the most effective positions and optimum level of the curtailment of RC structural walls in a simulated RC building subjected to seismic load. In high-rise structures, shear walls could be reduced in thickness or completely removed from some upper stories without providing any significant affect in the performance of lateral load resistances of the buildings; however, the procedure of shear walls reduction must be done carefully and correctly. There are 2 important steps in this research. First, find the most suitable locations of structural walls in the building. Then remove some shells of shear walls from the upper stories to be economical. Structural walls without any opening are used. By using ETABS, 5 models are created. Model A does not have any structural wall. Model B, C, D and E consist of structural walls in different positions, and they are placed symmetrically in the plan view of the building. Story displacements, story-drift ratios and overturning moments in x and y-directions are discussed and compared to each other to find the model which provides the highest stiffness. The seismic base shear is calculated by using response

spectrum equivalent static analysis covered by the DPT 1302-61 Code (final draft). After finding the locations of shear walls, the procedure of shear walls curtailment is started, and story-drift ratios are checked again to make sure they are not greater than the allowable value. Moreover, shear forces, axial forces, and percentage of load resistances of walls and frames are also investigated.

School of Civil Engineering Student's Signature

Academic Year 2019 Advisor's Signature

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CHAPTER I

INTRODUCTION

1.1 Problem Statement

In the past, engineers never thought seismic was going to happen in Thailand, but later on, Thailand has become one of the countries which located in a seismic-prone area, especially, in the northern part of the Kingdom. As a result, in 2014, an earthquake of 6.3 magnitude occurred in Chiang Rai Province, northern part of Thailand and a lot of buildings and infrastructures were destroyed. Hence, seismic affects are now considered in the building design and become a popular topic for Thai structural engineers. There are different types of the protections of buildings against earthquake such as using viscous dampers, tuned mass dampers, base isolation, shear walls (also known as structural walls), etc. However, in this research, shear walls are used to demonstrate the capacity of earthquake load resistance in a 25 stories wall-frame reinforced concrete (RC) building.

For tall buildings, it is necessary to provide adequate stiffness to resist the lateral forces caused by wind and earthquake. When such buildings are not properly designed for these forces, there may be very high stresses, vibrations, and sidesway when the forces occur. The results may include not only severe damages to the buildings but also considerable discomfort for their occupants. When reinforced concrete walls with their very large in-plane stiffnesses are placed at certain convenient and strategic locations, often they can be economically used to provide the needed resistance to horizontal loads. Such walls, called *shear walls*, are in effect deep vertical cantilever beams that provide lateral stability to structures by resisting the in-plane shears and bending moments caused by the lateral forces. As the strength of shear walls is almost always controlled by their flexural resistance, their name is something of a misnomer. It is true, however, that on some occasions they may require some shear reinforcing to prevent diagonal tension failures. Indeed, one of the basic requirements of shear walls designed for high seismic forces is to ensure flexure rather than shear-controlled design. The usual practice is to assume that the lateral forces act at the floor levels. The stiffnesses of the floor slabs horizontally are quite large as compared to the stiffnesses of the walls and columns. Thus, it is assumed that each floor is displaced in its horizontal plane as a rigid body. The lateral forces, usually from wind or earthquake loads, are applied to the floor and roof slabs of the building, and those slabs, acting as large beams lying on their sides or diaphragms, transfer the loads primarily to the shear walls parallel to the direction of lateral loads. Shear walls are commonly used for buildings with flat-plate floor slabs. In fact, this combination of slabs and walls is the most common type of construction used today for tall apartment buildings and other residential buildings. (McCormac and Brown, 2013).

Wall-frame structures are structures in which the lateral load is resisted in part by the walls and in part by the frames. The lateral-force analysis of shear wall–frame buildings must account for the different deformed shapes of the frame and the wall. Due to the incompatibility of the deflected shapes of the wall and the frame, the fractions of the total lateral load resisted by the walls and frames differ from story to story. Near the top of the building, the lateral deflection of the walls in a given story tends to be larger than that of the frames in the same story and the frames push back on the wall. This alters the forces acting on the frames in these stories. At some floors the forces change direction by the range of possible moment diagrams in the wall. This means that the frame resists a larger fraction of the lateral loads in the upper stories than it does in the lower stories (Wight, 2015).

Generally, shear walls resist more lateral loads than frames. In high-rise wall-frame buildings, shear walls can be reduced in thickness or completely removed from some upper stories to be economical. The reduction or remove of shear walls from the upper part of the structures does not provide any significant affect to the performance of lateral load resistances of the buildings; however, these processes must be done carefully and correctly. When lateral load occurs, the upper part of shear walls could have negative shear forces and may lead to an unreasonable design. To adjust this error, the process of the reduction of shear walls from the upper part of the building is satisfied (Nollet and Smith, 1993).

1.2 Research Objectives

The main objectives of this study are as below:

(i) To study the appropriate positions of shear walls in a high-rise wall-frame RC building subjected to seismic load.

(ii) To study the optimum level of the curtailment of shear walls from the upper part of the building.

(iii) To study the effects of the performance of seismic load resistance when shear walls are curtailed.

1.3 Scope of the Study

In this study, the 25 stories RC wall-frame structure subjected to seismic load is investigated. It is a simulated building and is supposed to be in Chiang Rai Province, Mae Lao District, northern part of Thailand. The shape of this building is regular. To withstand the lateral load, shear walls without any opening are used. The method of analysis is equivalent static analysis and covered by the DPT 1302-61 Code (final draft). By using ETABS, 5 models are created. Model A does not have any shear wall. Model B, C, D, and E consist of shear walls in different positions and they are placed symmetrically in the plan view of the building. Story displacements, story-drifts, and overturning moments in x and y-directions are discussed and compared to each other to find the model which provides the highest stiffness. After finding the most effective position of shear walls, the curtailment from the upper part of the building is started. Story displacements, story-drifts, shear forces, bending moments, and the percentage of forces resisted by walls and frames after shear walls are curtailed are discussed. This building is analyzed by using strength design method (SDM) covered by the DPT 1302-61 Code (final draft).

CHAPTER II

LITERATURE REVIEW

2.1 General Statement

Wall-frame structures consist of a combination of shear walls and moment resisting frames, which act jointly in resisting both gravity and horizontal loading. When shear walls are situated in advantageous positions in a building, they can be very efficient in resisting lateral loads originally from wind or earthquakes. It is common in high-rise wall-frame structures to reduce in size and number, or to eliminate entirely, the shear walls in the upper part of the building where fewer elevator shafts are required.

2.2 Previous Studies

2.2.1 Locations of Shear Walls

Magendra, Titiksh, and Qureshi (2016) presented a paper on optimum positioning of shear walls in a 10 stories reinforced concrete building subjected to seismic load. This study was done by changing the locations of shear walls radically in the plan view of the building with the help from ETABS software. The analysis was done by keeping zero eccentricity between the center of rigidity of shear walls and the center of mass of the building. Story-drifts, story displacements, story shear forces, and overturning moments were discussed. Finally, they concluded that shear walls behave more effectively than conventional frames when subjected to earthquake load. Shear walls provide more safety to the designer, and although it is a little costly, they are extremely effective in terms of structural stability. After using shear walls, story-drifts and story displacements are significantly reduced. The most effective positions of shear walls are at the core of the structures and those shear walls should be placed in the form of box shape.

Tuppad and Fernandes (2015) carried out a study on optimum location of shear walls in multi-story buildings subjected to seismic behavior using genetic algorithm. The main aim was to minimize the lateral displacement of every story. The work suggested the idea to optimize in the input variables in MATLAB and ETABS. The procedures were done by creating 6 different models; one model did not have any shear wall and the rests consisted of shear walls in difference positions. The method of analysis was equivalent static analysis. Eventually, they concluded that without shear walls, the building has large displacements. After providing shear walls, the building has low displacements and the best location of shear walls is near the core of the building. Genetic algorithm is the best procedure for finding the best solution among several solutions. By providing shear walls to high-rise buildings, structural seismic behavior will be affected to a great extent and also the stiffness and the strength of the buildings will be increased.

Madan, Malik, and Sehgal (2015) provided a paper on seismic evaluation with shear walls and braces for buildings. The idea was to compare the seismic response of reinforced concrete frames with shear walls, braces, and their combinations. The dynamic analysis was carried out by using three-dimensional modelling in STAAD. Pro V8i software. Floors were assumed to act as rigid diaphragms. Finally, they concluded that shear walls and braces improve the seismic performance of structures. Shear walls reduce more lateral displacements than braces; however, the combination of shear walls and braces is found to be the most effective arrangement for lateral load resistance in the elastic range.

Subhan (2016) researched about the design of shear walls in response spectrum method and to study effect of vertical stiffness irregularity on multi-story. The result were tabulated by executing response spectrum analysis using ETABS software in the type of optimum story displacements, base shear reactions, story-drifts, and mode shapes. Effect of irregularity was studied by producing openings in shear walls and also by varying the thickness of shear walls along the stories. The author inferred that shear walls are very effective component in seismic resistance. The moments in columns get reduced when shear walls are actually created in the framework. The highest story displacement of the structure is actually cut back by fifty percent when shear walls are actually provided. Shear walls with openings and different thickness are stable and strong still adequate to withstand seismic load. For more secure style, the thickness of shear walls must arrange between 150 mm to 400 mm. Shear walls in structures should be symmetrically located in approach to decrease twisting. They need to be put symmetrically along one or even both directions in approach.

Sud, Shekhawat, and Dhiman (2014) studied on best placement of shear walls in a reinforced concrete space frame based on seismic response. A five stories reinforced concrete building was modelled in STAAD. Pro V8i software. Five models were created. Model 1 did not have any shear wall, while other four models consisted of shear walls in different locations in the plan view of the building. Story-drifts, story displacements, and shear forces and bending moments in columns were investigated. The results proved that lateral load resisting capacity of buildings increases significantly in case of shear walls introduction. The structures consist of shear walls at core perform very well in lateral load resistance.

2.2.2 Curtailment of shear walls

Nollet and Smith (1993) researched on behavior of curtailed wall-frame structures using continuum model. They explained that when a wall-frame structure is loaded laterally, the lower part of the structure deflects in a flexural configuration, i.e., concavity downwind, and the upper part in a shear configuration, i.e., concavity upwind, with a point of inflection at the transition. The greater the racking shear rigidity of the frames relative to the flexural rigidity of the walls, the lower the level of the point of inflection. When a wall-frame structure deflects laterally under horizontal loading, horizontal interaction forces occur between the walls and frames. Typical distributions of these interaction forces for the planar model of a uniform wall-frame structure, and the resulting shear forces and bending moment carried by the walls and frames are shown in figures 2.1(a), (b), and (c), respectively.

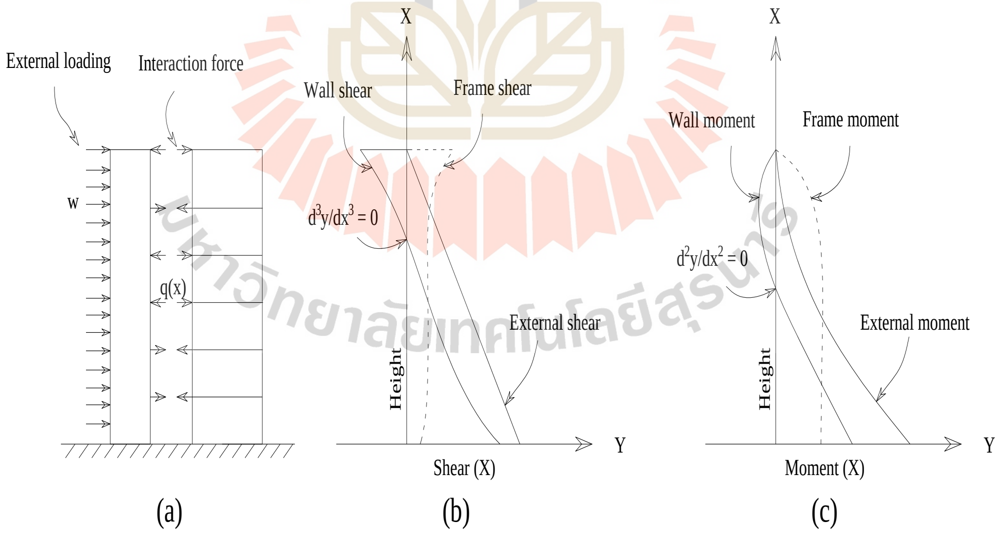


Figure 2.1 Forces in uniform wall-frame structure: (a) Horizontal interaction between wall and frame; (b) Typical distributions of shear in wall and frame; and (c) Typical distributions of moment in wall and frame (Nollet and Smith, 1993)

The behavior of wall-flame structures having curtailed walls is not obvious. An understanding is made easier, however, by first reviewing the known behavior of the corresponding full-height wall-flame structure. Referring to the distribution of bending moment for the full-height-wall structure [Figure 2.1(c)]; the wall moment in the region above the point of inflection, where $d^2y/dx^2 = 0$, is opposite in sense to the external load moment, while the moment in the frame (which is carried mainly by axial forces in the columns) is actually greater than the external load moment. Therefore, if the wall were curtailed anywhere in the region above the point of inflection, the moment carried by the frame would be reduced to become equal to the external moment. Similarly, for the distribution of the shear force in the full-height-wall structure [Figure 2.1(b)], the shear in the wall above the point of zero shear, where $d^3y/dx^3 = 0$, is opposite in sense to the external load shear, while the shear in the frame exceeds the external shear. Therefore, if the wall were curtailed anywhere in that uppermost region, the shear in the frame would be reduced to become equal to the external load shear. An inspection of Figures 2.1(b) and 1(c) shows that if the wall were curtailed between the points of zero shear and inflection, the shear in the frame above the curtailment level would be increased by a small amount while the moment in the frame above that level would be reduced. If the wall were curtailed below the point of contraflexure, both the shear and the moment in the frame would increase. On the basis of the preceding discussion, it is evident that the levels of zero moment and zero shear in the wall of the full-height-wall structure should be taken as levels of reference in assessing the effects of curtailing the wall on the shear and moment distributions. The effect of wall curtailment on the top deflection of the whole structure may be regarded in another way as the effect on the top deflection of the flame due to changes in the distributions of shear and moment in the frame caused by curtailment of the wall. Any significant modification to those force distributions could lead to significant changes in the top deflection. Since curtailment of the wall between the two reference levels should produce changes in the force distributions that are either beneficial, or of little detriment to the frame, the resulting change in top deflection of the frame should also be small. Considering that the effects of curtailment vary according to the level of curtailment, there should be an optimum level of curtailment that produces minimum changes in the force distributions, and consequently in the top deflection. In order to investigate the effects of curtailment in more detail, and to assess the behavior of curtailed wall-frame structures, a mathematical solution for a continuum model of the curtailed structure is developed.

A particular wall-frame example structure was analyzed with a full-height wall, and then with the wall curtailed at the optimum level to produce a minimum deflection, as explained before. The structure was analyzed first by computer using a discrete member model and a frame analysis program, and then by the approximate analysis using the continuum solution. An indication of the accuracy of the continuum method is given by comparing results from the two methods for the deflected shapes, the maximum deflections, and the change in the top drift, for both the curtailed wall-frame and the corresponding full-height wall structure.

Finally, the authors concluded that the elimination, reduction in number, or reduction in size of the shear walls at certain levels up the height of a wall-frame structure is not necessarily detrimental to the lateral load performance of the structure. Indeed, if the structural changes are made at a level or levels above the point of contraflexure in the wall of the equivalent uniform wall-frame structure, the top deflection changes negligibly. At the same time the moment resisted by the frame above the change level is reduced, without creating any significant transfer of horizontal interaction between the wall and the frame.

Atik et al. (2014) proposed a paper on optimum level of shear wall curtailment in wall-frame buildings: the continuum model revisited. They explained that under lateral load, the shear wall deflects essentially in flexural shape and the frame deflects in shear shape. For this reason, these components are forced to interact horizontally through the floor slabs. Consequently, the upper part of the shear wall could play a negative role and may lead to unreasonable design by introducing additional internal forces to the system. A solution for such a uniform wall-frame structure has been developed using an equivalent continuous medium or "continuum model" (Heidebrecht and Smith, 1973). This simple model is very useful in the preliminary stages of the design of tall building structures subject to lateral loading. It has been widely used in the literature for both static and dynamic application of shear wall-frame structures. A generalized theory for tall building structures, allowing for axial deformation of the columns, was first proposed by Smith et al. (1984). Then Nollet and Smith (1993) developed a generalized theory for the deflection of wall-frame buildings on the basis of a continuum model. Their model has been used to analyze the effect of the wall curtailment on the performance of the structure. The deflection at the top of the structure is minimized to provide guidance for the optimum level of wall curtailment. They found that the optimum level is generally situated between the points of inflection and zero shear in the corresponding full-height wall structure. In contrast, some results of their study showed that, in spite of existing negative moments and shear forces in the shear wall, there is no need to curtail the wall. Such a result seems inconsistent and requires a thorough review of the calculation. It is well known that the maximum positive or negative moment (mathematically, the local maxima or minima) corresponds to the zero shear point (mathematically, the zero point of the first derivative). If the level of curtailment leads to the removal of the negative shear in the wall by making it equal to zero at the top of the wall, the minimum moment (local minima) will be also at the top of the wall. According to boundary conditions, the moment at the top of the wall is equal to zero, and consequently, the moment over the entire height of the wall remains positive. In other terms, the level of curtailment that leads to eliminate the negative shear in the wall by making it equal to zero at the top, leads at the same time to remove the negative moment.

Finally, the authors concluded that the continuum model is a simple and efficient tool but should be used carefully. It is highly sensitive to the calculation precision because the use of hyperbolic functions that need high calculation precision for high values of the variables. The optimum level of curtailment always lies between the point of inflection and the zero shear force in the corresponding full-height wall structure. This result is very useful in the search for the optimum level of curtailment. The optimum level of curtailment which results in the minimum top deflection of the structure eliminates, at the same time, the negative moments and negative shear forces in the wall. It corresponds to a zero shear force at the top of the wall which presents a simpler alternative to determine the optimum level of curtailment.

Bhatt, Titiksh, and Rajepandhare (2017) proposed a paper on effect of curtailment of shear walls for medium rise structures. The lateral load resistances of a dual system comprising of moment resisting frame (MRF) and shear walls were studied. Six different cases of shear wall curtailment were considered by terminating the shear walls at intermediate heights of a G+9 story building. The models were subjected to lateral and gravity loadings in accordance with IS provision and response spectrum analysis (RSA) were carried out. ETABS software was used. Story-drifts, story displacements, story shears, and story stiffness were discussed. They concluded that the models displaced acceptable performance in terms of drifts and displacements, even when the shear walls were curtailed up to half the height of the original structure. At the level of curtailment, story drift was increased by almost 40%, floor displacement was increased by 15%, story forces near the bottom floor got decreased by almost 25% and stiffness was reduced by almost 90%.

Fatima, Humraz, and Vuyyuru (2017) researched about seismic performance evaluation of reinforced concrete structure with optimum curtailment in shear walls. The comparative study of dynamic characteristic between the structures with full shear walls and curtailed shear walls at different levels was carried out. The results obtained were compared with the building consisted of full shear walls. The RC moment resisting frame considered was loaded with gravity loads, dead loads, live loads, and Bhuj earth quake loading. Base shear and joint displacements were discussed. The analysis method were linear static, linear dynamic, nonlinear static, and nonlinear dynamic with the help of SAP2000 Version 18. The results show that the decrease and increase in the values of base shear and displacements of buildings with curtailed shear walls are marginal when compared with full height shear wall. As a closing remark it is understood that the curtailment of shear wall up to two third height of building has marginal effect on distribution of base shear and displacements. It is concluded that nonlinear time history analysis provides reasonably accurate results when compared with nonlinear static analysis.

CHAPTER III

METHODOLOGY OF THE PRESENT WORK

3.1 General

Determination of earthquake demands on the structure is one of the challenging jobs in the field of structural engineering. A lot of researchers have carried out in this area to propose simplified methods that will predict results with reasonable accuracy. Structural response to earthquakes is a dynamic phenomenon that depends on dynamic characteristics of structures and the intensity, duration, and frequency content of the exciting ground motion. Although the seismic action is dynamic in nature, building codes often recommend equivalent static load analysis for the design of earthquake-resistant buildings due to its simplicity. The use of static load analysis in establishing seismic design quantities is justified because of the complexities and difficulties associated with dynamic analysis. Dynamic analysis becomes even more complex and questionable when nonlinearity in materials and geometry is considered. Therefore, the analytical tools used in earthquake engineering have been a subject for further development and refinement, with significant advances achieved in recent years. Despite the aforementioned concerns over the use of dynamic analysis, it is used in practice to carry out special studies of tall buildings and irregular structures because of its superiority in reflecting seismic response more accurately, when used properly. These studies often include a large number of analyses under different ground motion records and different structural parameters to provide insights of the structural behaviors. With the advent of personal computers and the subsequent evolution in information technology, coupled with extensive research in nonlinear material modeling, more reliable computational tools have become available for using in design of buildings. The seismic analysis methods so far used in estimating the demand on the structure can be classified in four big groups: (1) linear static analysis, (2) linear dynamic analysis, (3) nonlinear static analysis, and (4) nonlinear dynamic analysis. This thesis demonstrates the design of a 25 stories reinforced concrete structure located in Chiang Rai Province, Thailand. The building is subjected to a high level seismic load. ETABS software is used to analyze the internal forces and mode shapes. The method of analysis is response spectrum equivalent static and covered by the DPT 1302-61 Code (final draft) using strength design method (SDM).

3.2 ETABS Software

ETABS is a sophisticated, yet easy to use, special purpose analysis and design program developed specifically for building systems. ETABS 2017 features an intuitive and powerful graphical interface coupled with unmatched modeling, analytical, design, and detailing procedures, all integrated using a common database. Although quick and easy for simple structures, ETABS can also handle the largest and most complex building models, including a wide range of nonlinear behaviors necessary for performance based design, making it the tool of choice for structural engineers in the building industry. The program can automatically generate lateral wind and seismic load patterns to meet the requirements of various building codes. Three dimensional mode shapes and frequencies, modal participation factors, direction factors and participating mass percentages are evaluated using eigenvector or ritz-vector analysis. P-Delta effects may be included with static or dynamic analysis. Response spectrum analysis, linear time history analysis, nonlinear time history analysis, and static nonlinear (pushover) analysis are all possible. The static nonlinear capabilities also allow users to perform incremental construction analysis so that forces that arise as a result of the construction sequence are included. Results from the various static load cases may be combined with each other or with the results from the dynamic response spectrum or time history analyses.

3.3 Linear Static Analysis

In Thailand, the department of public works and town and country planning has produced a code to design the buildings subjected to seismic load called DPT 1302. This code has been developed from the original codes, ASCE7-05 and IBC 2006, to fulfil the demands in the field of civil engineering in the Kingdom.

DPT 1302 has been changed, rearranged, and updated in some of its parts by the local researchers to make it suitable with the situations of the buildings in Thailand. This code consists of the specifications of equivalent static (linear static) analysis which can be used with regular buildings and some cases of irregular structures. Besides linear static analysis, DPT 1302 code also provides the specifications on the method of linear dynamic analysis for the reinforced concrete structures.

3.3.1 Base Shear

The calculation of earthquake force using equivalent static load is started by finding the shear force at the base of the structure then distribute that force to every story in the building. DPT 1302 code used IBC 2006 as a reference and proposed a formula:

$$V = C_s \cdot W \tag{3.1}$$

where

C_s = coefficient of seismic force

W = effective weight of the structure

The coefficient of seismic force is calculated by:

$$C_s = S_a\left(\frac{I}{R}\right) \geq 0.01 \tag{3.2}$$

where

S_a = spectrum acceleration

R = response modification factor

I = Important factor of the structure

3.3.2 Fundamental Period of Structures

The fundamental period of the building, (T) can be calculated in two different formulas:

1st formula

This is an approximated method.

Reinforced concrete structure: $T = 0.02\ H$ (3.3)

Steel structure: $T = 0.03\ H$ (3.4)

where, H is the full height of the structure above ground surface and has the unit in meter.

2nd formula

This formula was proposed by Rayleigh. The idea of this method is to lump the mass of every story at the floor levels and the lateral loads also supposed to act at every floor level which resisted by the stiffness of structural members such as beams, columns, and slabs. The fundamental period calculated from the 2nd formula should not greater than 1.5 times of the fundamental period calculated from the 1st formula.

$$T = 2\pi\sqrt{\frac{\sum_{i=1}^{n} W_i \delta_i^2}{g\sum_{i=1}^{n} F_i \delta_i}} \tag{3.5}$$

where

W_i = weight of the structure

δ_i = floor displacement at story i

F_i = lateral forces act at story i

g = gravity of the earth

n = number of story in the building

T = fundamental period (second)

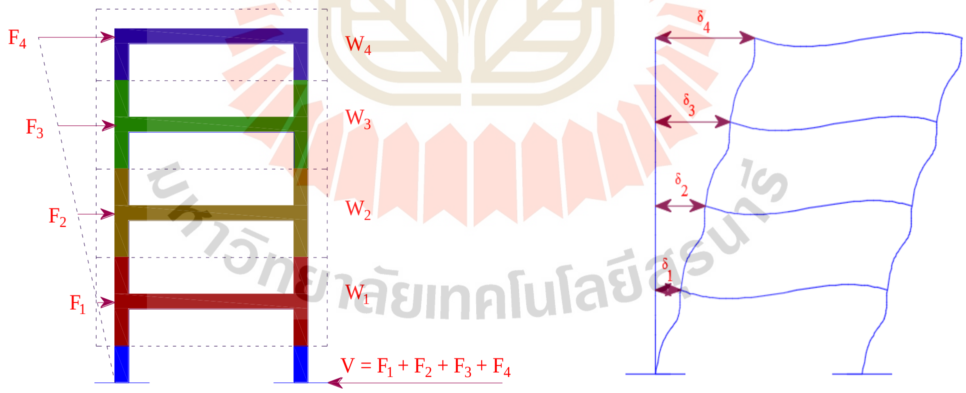


Figure 3.1 Fundamental period of structures calculated using Rayleigh's formula

$$T = 2\pi\sqrt{\frac{1}{g}\left[\frac{W_1\delta_1^2+W_2\delta_2^2+W_3\delta_3^2+W_4\delta_4^2}{F_1\delta_1+F_2\delta_2+F_3\delta_3+F_4\delta_4}\right]} \tag{3.6}$$

3.3.3 Weight of Structures

The weight W used in Rayleigh's formula is the summation of weight W_i of all stories using the tributary area as shown in **Figure 3.1**. The weight W_i is the summation of self-weight of the building and superimposed dead load such as toppings, tiles, walls, air conditioners, etc. If the building is a warehouse, W_i should add more 25% of live load. The story weight W_i of every story should be considered only in half-length between the lower and the upper stories as shown in **Figure 3.2**.

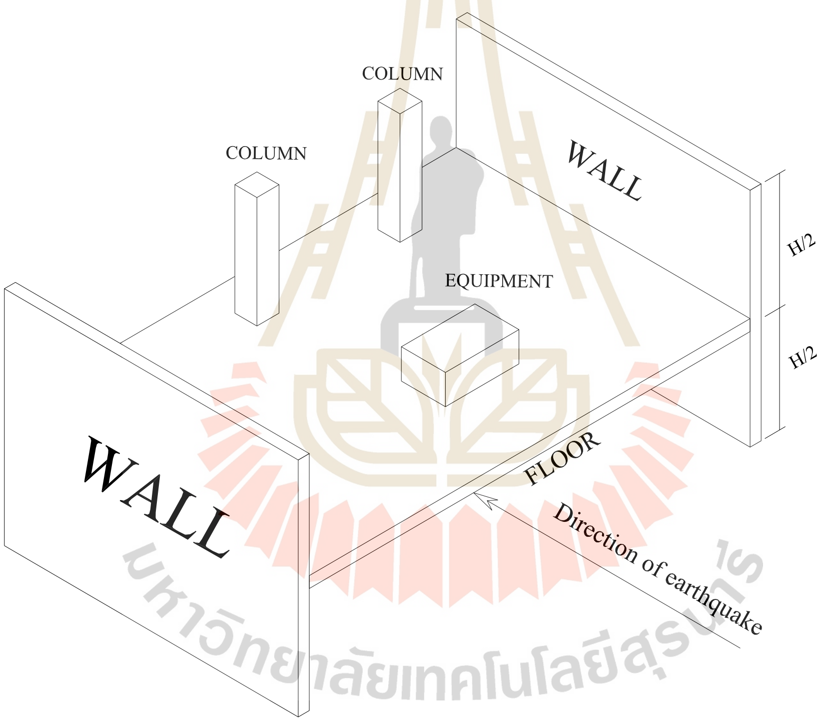


Figure 3.2 Story weight

H = Story height

3.3.4 Response Spectrum Curves

Spectrum acceleration S_a has the unit in g (g = 9.81m/s^2) and varies depend on the locations of the structures.

Case 1: Response spectrum curve for all zones in Thailand, except Bangkok

Spectrum acceleration S_a is divided into two cases, case 1, for $S_{D1} \leq S_{DS}$ and case 2, for $S_{D1} \geq S_{DS}$ as shown in **Figures 3.3** and **3.4**, respectively, where, S_{DS} and S_{D1} are the response spectrum accelerations at 0.2 and 1 second, respectively.

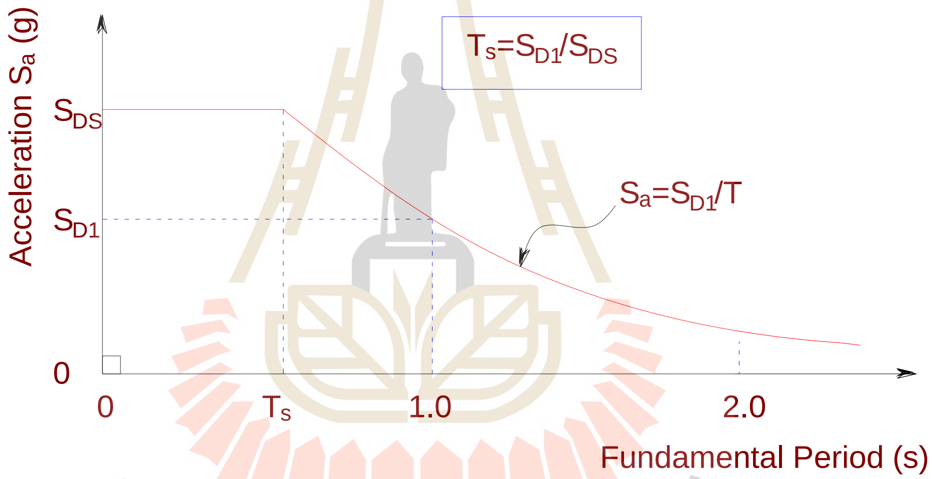


Figure 3.3 Spectrum acceleration for equivalent static analysis for all zones in Thailand, except Bangkok in case $S_{D1} \leq S_{DS}$

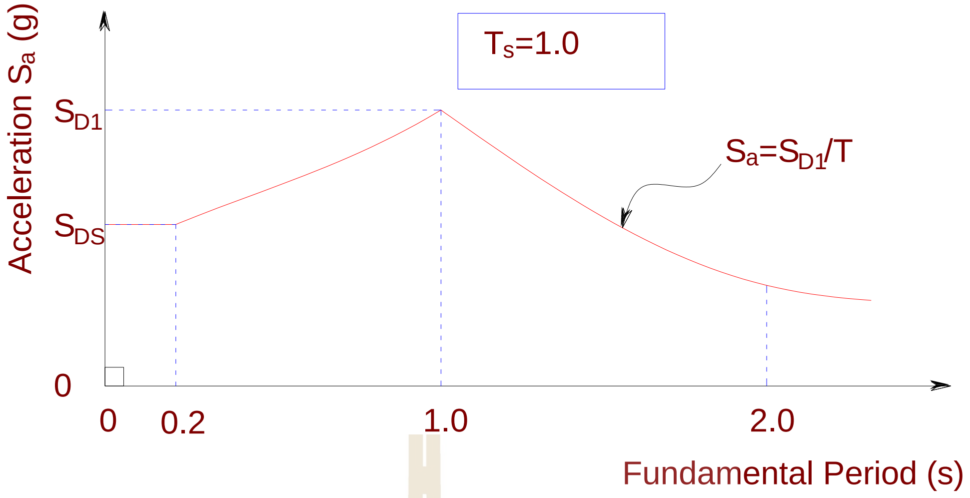


Figure 3.4 Spectrum acceleration for equivalent static analysis for all zones in Thailand, except Bangkok in case $S_{D1} \geq S_{DS}$

The step of calculations are first started by finding the fundamental period (T) leads to get the value of S_a from the **Figure 3.3** or **3.4**. Then the coefficient of seismic load is obtained, $C_s = S_a(\frac{I}{R}) \geq 0.01$.

Case 2: Response spectrum curve for all zones in Bangkok

Spectrum acceleration in Bangkok is divided into 10 different zones; however, the curves and other parameters related to all zones in Bangkok are not discussed here since the present project does not locate in this capital city.

3.3.5 Spectrum Accelerations at Short Period and 1 Second

S_S and S_1 are the response spectrum accelerations at short period (0.2 second) and 1 second, respectively. DPT 1302-61 (final draft) provides the values of S_s and S_1 of Chiang Rai Province as shown in **Table 3.1**.

Table 3.1 Spectrum accelerations at 0.2 and 1 second in Chiang Rai Province

District	S_S (*g*)	S_1 (*g*)
Doi Luang	1.015	0.329
Wiang Chiang Rung	0.931	0.267
Khun Tan	0.769	0.175
Chiang Khong	0.796	0.202
Chiang Saen	0.984	0.296
Thoeng	0.763	0.16
Pa Daet	0.772	0.157
Phaya Mengrai	0.787	0.188
Phan	0.831	0.175
Mueang Chiang Rai	0.917	0.25
Mae Chan	1.022	0.306
Mae Fa Luang	1.015	0.292
Mae Lao	0.884	0.22
Mae Suai	0.894	0.212
Mae Sai	0.891	0.278
Wiang Kaen	0.767	0.182
Wiang Chai	0.879	0.229
Wiang Pa Pao	0.855	0.195

3.3.6 Coefficients of Soil

The level of seismic vibration can be changed subjected to the location of the structure. To adjust the response spectrum accelerations more suitable and accuracy, DPT 1302-61 (final draft) provides the site coefficients at the considered location as follow:

$$S_{MS} = F_a \cdot S_S \tag{3.7}$$

$$S_{M1} = F_V \cdot S_1 \tag{3.8}$$

where

F_a = site coefficient at the considered location at 0.2 second

F_v = site coefficient at the considered location at 1.0 second

S_{MS}= corrected spectrum acceleration at the considered location at 0.2 second and has the unit in *g*

S_{M1}= corrected spectrum acceleration at the considered location at 1.0 second and has the unit in *g*

Table 3.2 Site coefficient at the considered location at 0.2 second (Fa)

Type of soil	**Maximum spectrum acceleration at 0.2 second (*g*)**				
	$S_S \leq 0.1$	$S_S = 0.5$	$S_S = 0.75$	$S_S = 1.0$	$S_S \geq 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1	1	1	1	1
C	1.2	1.2	1.1	1	1
D	1.6	1.4	1.2	1.1	1
E	2.5	1.7	1.2	0.9	0.9
F	Site-specific ground motion procedures				

Table 3.3 Site coefficient at the considered location at 1.0 second (Fv)

Type of soil	Maximum spectrum acceleration at 1.0 second (*g*)				
	$S_1 \leq 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 \geq 0.5$
A	0.8	0.8	0.8	0.8	0.8
B	1	1	1	1	1
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	2.4
F	Site-specific ground motion procedures				

In case the type of soil is unknown, DPT 1302 proposes to use the soil type D.

3.3.7 Important Factor of Structure

DPT 1302-61 (final draft) proposes the important factor (I) depending on the occupancy category to reduce dangers when earthquake occurs. The occupancy category is divided into 4 types as shown in **Table 3.4**.

Table 3.4 Important factor and occupancy category of buildings for earthquake load

Type of Structure	Occupancy Category	Important Factor (I)
Buildings and other structures that represent a low hazard to human life in the event of failure, including, but not limited to: • Agricultural facilities • Certain temporary facilities • Minor storage facilities	I (Less)	1.0
All buildings and other structures except those listed in Occupancy Categories I and IV	II (Common)	1.0
Buildings and other structures that represent a substantial hazard to human life in the event of failure, including, but not limited to: • Buildings and other structures where more than 300 people congregate in one area • Buildings and other structures with daycare facilities with a capacity greater than 150	III (High)	1.5

Table 3.4 Important factor and occupancy category of buildings for earthquake load (Continued)

Type of Structure	Occupancy Category	Important Factor (I)
• Buildings and other structures with elementary school or secondary school facilities with a capacity greater than 250 • Buildings and other structures with a capacity greater than 500 for colleges or adult education facilities • Health care facilities with a capacity of 50 or more resident patients, but not having surgery or emergency treatment facilities • Jails and detention facilities	III (High)	1.25
Buildings and other structures designated as essential facilities, including, but not limited to: • Hospitals and other health care facilities having surgery or emergency treatment facilities • Fire, rescue, ambulance, and police stations and emergency vehicle garages • Designated earthquake, hurricane, or other emergency shelters	IV (Strong)	1.5

Table 3.4 Important factor and occupancy category of buildings for earthquake load (Continued)

Type of Structure	**Occupancy Category**	**Important Factor (I)**
Designated emergency preparedness, communication, and operation centers and other facilities required for emergency response • Power generating stations and other public utility facilities required in an emergency • Ancillary structures (including, but not limited to, communication towers, fuel storage tanks, cooling towers, electrical substation structures, fire water storage tanks or other structures housing or supporting water, or other fire-suppression material or equipment) required for operation of Occupancy Category IV structures during an emergency • Aviation control towers, air traffic control centers, and emergency aircraft hangars • Water storage facilities and pump structures required to maintain water pressure for fire suppression • Buildings and other structures having critical national defense functions	IV (Strong)	1.5

3.3.8 Response spectrum accelerations

Response spectrum accelerations of vibration at 0.2 second (S_{DS}) and 1.0 second (S_{D1}) are:

$$S_{DS} = \frac{2}{3} S_{MS} \quad (3.9)$$

$$S_{D1} = \frac{2}{3} S_{M1} \quad (3.10)$$

3.3.9 Seismic Design Category

In ASCE7-05, the seismic design category is divided into six categories (A, B, C, D, E, and F); however, DPT 1302 divides only four categories, those are: A, B, C, and D. Category A does not need to consider about seismic design, and increasing all the ways to D, the most important seismic design.

Table 3.5 Seismic design category based on short period response acceleration parameter (S_{DS})

S_{DS}	**Seismic Design Category**		
	Occupancy Category I or II	**Occupancy Category III**	**Occupancy Category IV**
$S_{DS} < 0.167$	A	A	A
$0.167 \leq S_{DS} \leq 0.33$	B	B	C
$0.33 \leq S_{DS} \leq 0.50$	C	C	D
$0.50 \leq S_{DS}$	D	D	D

Table 3.6 Seismic design category based on 1 second period response acceleration parameter (S_{D1})

S_{D1}	Seismic Design Category		
	Occupancy Category I or II	**Occupancy Category III**	**Occupancy Category IV**
$S_{D1} < 0.067$	A	A	A
$0.067 \leq S_{D1} \leq 0.133$	B	B	C
$0.133 \leq S_{D1} \leq 0.20$	C	C	D
$0.20 \leq S_{D1}$	D	D	D

In case the occupancy categories in **Table 3.5** and **3.6** are different, choose the critical one. If the fundamental period (T) is less than $0.8T_S$, the calculation of occupancy category must follow **Table 3.5** only.

$$T_S=\frac{S_{D1}}{S_{DS}} \text{ if } S_{D1}\leq S_{DS} \tag{3.11}$$

$$T_S=1.0 \text{ if } S_{D1}> S_{DS} \tag{3.12}$$

3.3.10 Structural System Selection

The basic lateral and vertical seismic force-resisting system shall conform to one of the types indicated in **Table 3.7**. Each type is subdivided by the types of vertical elements used to resist lateral seismic forces. The structural system used shall be in accordance with the seismic design category and other limitations indicated in **Table 3.7**. The appropriate response modification coefficient, R, system overstrength factor, Ω_0, and the deflection amplification factor, C_d, indicated in **Table 3.7** shall be used in determining the base shear, element design forces, and design story drift.

Table 3.7 Design coefficients and factors for seismic force-resisting systems

Structural System	Seismic Force-Resisting System	Coefficients			Seismic Design Category		
		R	Ω_o	C_d	B	C	D
1. Bearing Wall System	Ordinary RC Shear Wall	4	2.5	4	✓	✓	*
	Special RC Shear Wall	5	2.5	5	✓	✓	✓
	Ordinary Precast Shear Wall	3	2.5	3	✓	x	x
	Intermediate Precast Shear Wall	4	2.5	4	✓	✓	x
2. Building Frame System	Steel Eccentrically Braced Frame With Moment-Resisting Connections	8	2	4	✓	✓	✓
	Steel Eccentrically Braced Frame With Non-Moment-Resisting Connections	7	2	4	✓	✓	✓
	Special Steel Concentric Braced Frame	6	2	5	✓	✓	✓
	Ordinary Steel Concentric Braced Frame	3.5	2	3.5	✓	✓	x
	Special RC Shear Wall	6	2.5	5	✓	✓	✓
	Ordinary RC Shear Wall	5	2.5	4.5	✓	✓	*

Table 3.7 Design coefficients and factors for seismic force-resisting systems (Continued)

Structural System	Seismic Force-Resisting System	Coefficients			Seismic Design Category		
2. Building Frame System (Continued)	Ordinary Precast Shear Wall	4	2.5	4	✓	x	x
	Intermediate Precast Shear Wall	5	2.5	4.5	✓	✓	x
3. Moment-Resisting Frame	Ductile/Special Steel Moment-Resisting Frame	8	3	5.5	✓	✓	✓
	Special Truss Moment Frame	7	3	5.5	✓	✓	✓
	Intermediate Steel Moment-Resisting Frame	4.5	3	4	✓	✓	*
	Ordinary Steel Moment-Resisting Frame	3.5	3	3	✓	✓	x
	Ductile/Special RC Moment-Resisting Frame	8	3	5.5	✓	✓	✓
	Ductile RC Moment-Resisting Frame With Limited Ductility/Intermediate RC Moment-Resisting Frame	5	3	4.5	✓	✓	*
	Ordinary RC Moment-Resisting Frame	3	3	2.5	✓	x	x

Table 3.7 Design coefficients and factors for seismic force-resisting systems (Continued)

Structural System	Seismic Force-Resisting System	Coefficients			Seismic Design Category		
4. Dual System with Ductile/Special Moment Resisting Frame	Special Steel Concentrically Braced Frame	7	2.5	5.5	✓	✓	✓
	Steel Eccentrically Braced Frame	8	2.5	4	✓	✓	✓
	Special RC Shear Wall	7	2.5	5.5	✓	✓	✓
	Ordinary RC Shear Wall	6	2.5	5	✓	✓	*
5. Dual System With Moment-Resisting Frame With Limited Ductile/Dual System With Intermediate Moment Resisting Frame	Special Steel Concentrically Braced Frame	6	2.5	5	✓	✓	x
	Special RC Shear Wall	6.5	2.5	5	✓	✓	✓
	Ordinary RC Shear Wall	5.5	2.5	4.5	✓	✓	*
6. Shear Wall Frame Interactive System	Shear Wall Frame Interactive System with Ordinary RC Moment Frame And Ordinary RC Shear Wall	4.5	3	4	✓	x	x

Table 3.7 Design coefficients and factors for seismic force-resisting systems (Continued)

Structural System	Seismic Force-Resisting System	Coefficients			Coefficients		
7. Steel Systems Not Specifically Detailed For Seismic Resistance	Steel Systems Not Specifically Detailed For Seismic Resistance	3	3	3	✓	✓	x

✓ = usable; x = do not use; * follow **Section 3.3.11**

where

R = response modification factor

Ω_0 = system overstrength factor

C_d = deflection amplification factor

3.3.11 Maximum Height of Building for Seismic Design Category D

Ordinary RC shear wall, ductility/intermediate RC moment-resisting frame, or intermediate steel moment-resisting frame for seismic design category D should be used with the maximum height of the building as follow:

(1) 40 m for ordinary and intermediate RC moment-resisting frame

(2) 60 m for ordinary RC shear wall

3.3.12 Load Combination

Strength Design Method (SDM):

$$0.75\,(1.4DL + 1.7LL) + 1.0E \qquad (3.13)$$

$$0.9DL + 1.0E \tag{3.14}$$

where

DL = dead load

LL = live load

E = earthquake load

3.3.13 Story-Drift

The design story drift (Δ) shall be computed as the difference of the deflections at the centers of mass at the top and bottom of the story under consideration, See **Figure 3.5**.

The deflections of level x at the center of the mass (δ_x) shall be determined in accordance with the following equation:

$$\delta_x = \frac{C_d \bullet \delta_{xe}}{I} \tag{3.15}$$

where

C_d = the deflection amplification factor

δ_{xe} = the deflections determined by an elastic analysis

I = the importance factor of the building

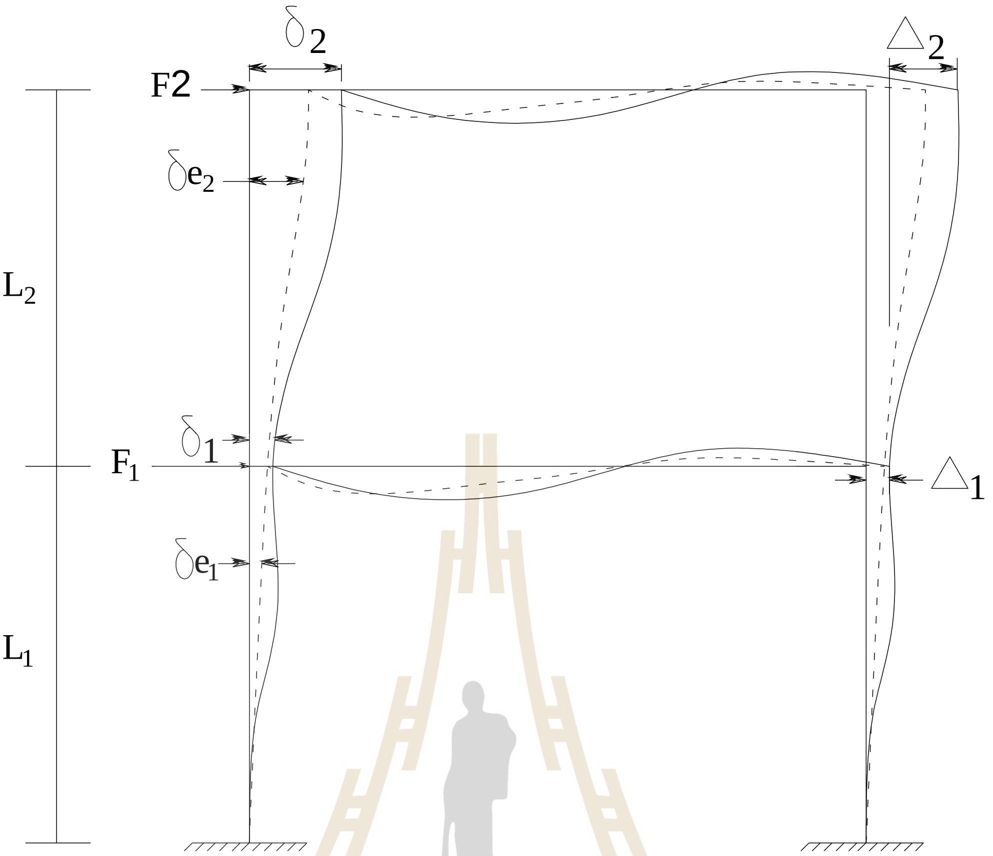


Figure 3.5 Story-drift determination

Story Level 2

F2 = strength-level design earthquake force

δ_{e2} = elastic displacement computed under strength-level design earthquake forces

$\delta_2 = C_d\, \delta_{e2} / I$ = amplified displacement

$\Delta_2 = (\delta_{e2} - \delta_{e1})\, C_d / I \leq \Delta_a$

Story Level 1

F1 = strength-level design earthquake force

δ_{e1} = elastic displacement computed under strength-level design earthquake forces

$\delta_1 = C_d\, \delta_{e1} / I$ = amplified displacement

$\Delta_1 = \delta_1 \leq \Delta_a$

Δ_i = Story Drift

Δ_i / L_i = Story Drift Ratio

δ_2 = Total Displacement

The story-drift should not exceed the allowable story-drift as shown in **Table 3.8**.

Table 3.8 Allowable story drift (Δ_a)

Structure	Occupancy Category		
	I or II	**III**	**IV**
Structures, other than masonry shear wall structures, 4 stories or less with interior walls, partitions, ceilings and exterior wall systems that have been designed to accommodate the story drifts	$0.025h_{sx}$	$0.020h_{sx}$	$0.015h_{sx}$
Masonry cantilever shear wall structures	$0.010h_{sx}$	$0.010h_{sx}$	$0.010h_{sx}$
Other masonry shear wall structures	$0.007h_{sx}$	$0.007h_{sx}$	$0.007h_{sx}$
All other structures	$0.020h_{sx}$	$0.015h_{sx}$	$0.010h_{sx}$

where, h_{sx} is the story height below level x.

There shall be no drift limit for single-story structures with interior walls, partitions, ceilings, and exterior wall systems that have been designed to accommodate the story drifts; however, the structure separation requirement should be considered.

Structures in which the basic structural system consists of masonry shear walls designed as vertical elements cantilevered from their base or foundation support which are so constructed that moment transfer between shear walls (coupling) is negligible.

3.3.14 Inherent Torsion

For diaphragms that are not flexible, the distribution of lateral forces at each level shall consider the effect of the inherent torsional moment, M_t resulting from eccentricity between the locations of the center of mass and the center of rigidity. For flexible diaphragms, the distribution of forces to the vertical elements shall account for the position and distribution of the masses supported.

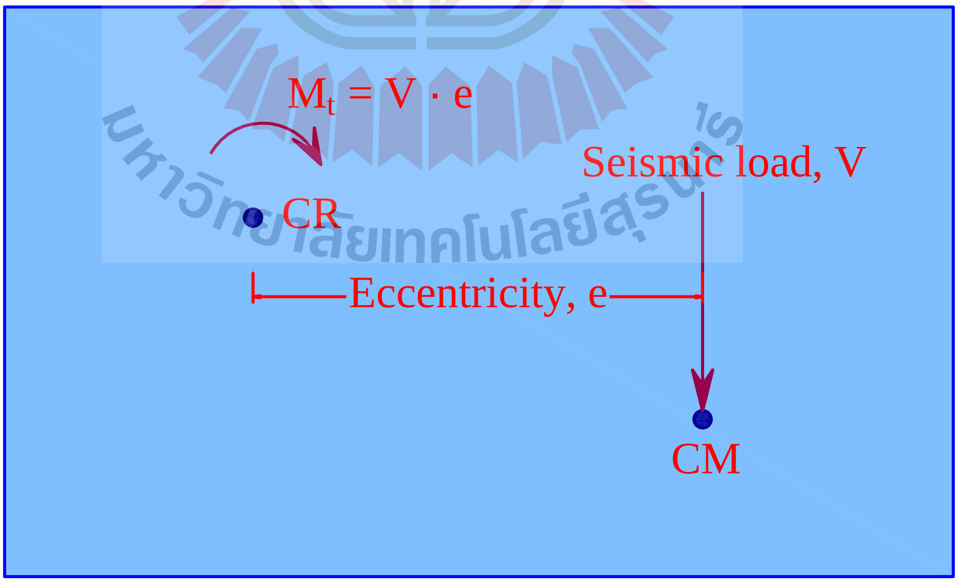


Figure 3.6 Inherent torsion

3.3.15 Accidental Torsion

Where diaphragms are not flexible, the design shall include the inherent torsional moment (M_t) resulting from the location of the structure masses plus the accidental torsional moments (M_{ta}) caused by assumed displacement of the center of mass each way from its actual location by a distance equal to 5 percent of the dimension of the structure perpendicular to the direction of the applied forces.

Where earthquake forces are applied concurrently in two orthogonal directions, the required 5 percent displacement of the center of mass need not be applied in both of the orthogonal directions at the same time, but shall be applied in the direction that produces the greater effect.

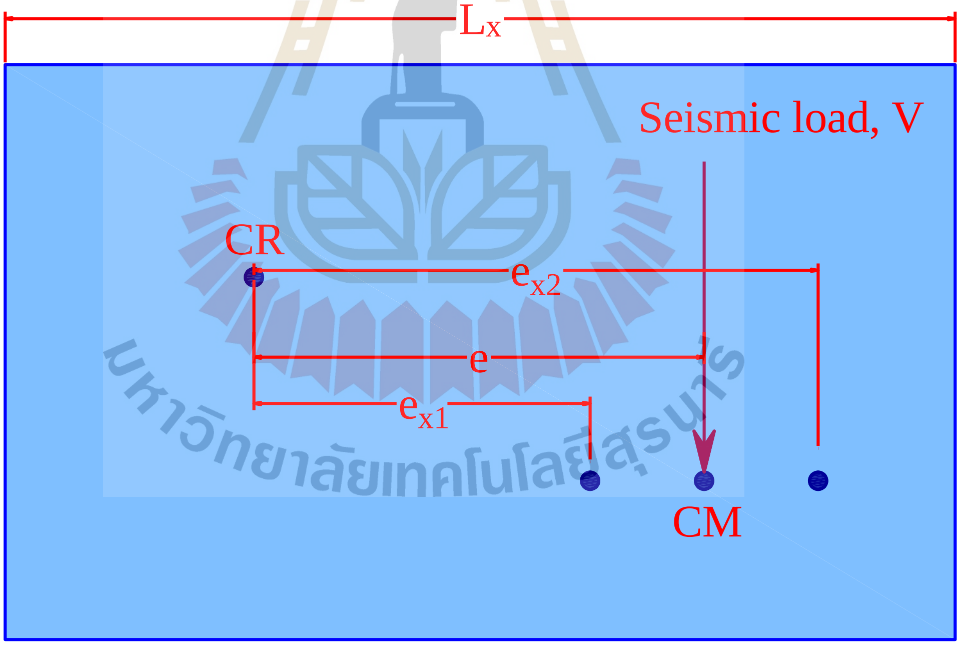


Figure 3.7 Accidental torsion

where

$$e_{x1} = e - 0.05L_x \quad (3.16)$$

$$e_{x1} = e + 0.05L_x \tag{3.17}$$

3.4 Effective Positions of Shear Walls

3.4.1 Summary

This thesis presents a study of finding the most effective position and the level of curtailment of RC shear walls in an RC building to resist seismic load. Shear walls without any opening are used. By using ETABS, 5 models are created. Model A does not have any shear wall. Model B, C, D and E consist of shear walls in different positions and they are placed symmetrically in the plan view of the building. Story displacements, story-drifts and overturning moments in x and y-directions are investigated and compared to each other to find the model which provides the highest stiffness. The process of the reduction of shear walls is made by removing shear walls from the top story downward one by one until shear force at the top of shear walls remains positive and greater than 25% of the total shear forces. After the reduction of shear walls, story-drifts are checked again to make sure they are not greater than the allowable story-drift. The analysis follows the DPT 1302-61 (final draft) code and response spectrum equivalent static analysis method.

3.4.2 Building Properties and Seismic Zone

This building is supposed to be a hospital building which carries the important factor (I), response modification factor (R), system over strength factor (Ω_o) and deflection amplification factor (C_d) are equal to 1.5, 7, 2.5 and 5.5 respectively (**Table 3.4** and **3.7**). The type of soil is D and subjected to a high level seismic load. It is a 25 story building with the area of 30m × 20m. The height of the bottom story is 3.5m and 3.0m for the rests. There are six bays along length and four bays along width.

Every bay is 5.0m length. All columns are 0.4m × 0.4m. The slabs are flat plate with the thickness of 0.16m (no beam and no drop panel) and is subjected to 2 KN/m^2 of supper imposed dead load (S_dead) and 3 KN/m^2 of live load (LL). The concrete in the hold structure is homogeneous with the compressive strength at 28 days (f'_c) is equal to 24 N/mm^2. The grade of rebar is SD40 with the yield stress (f_y), effective yield stress (f_{ye}), ultimate tensile stress (f_u) and effective tensile stress (f_{ue}) are equal to 400 N/mm^2, 440 N/mm^2, 570 N/mm^2, and 627 N/mm^2, respectively. The thickness of the special RC shear walls used in the building is 0.3m. The elasticity of concrete and rebar are 22948 N/mm^2 and 200124 N/mm^2, respectively.

3.4.3 Base Shear

According to the location of the building is in Mae Lao District, so S_s = 0.884 g and S_1= 0.220 g, where S_s and S_1 are Spectrum accelerations at the considered location at 0.2 and 1 second, respectively (**Table 3.1**). For soil type D, F_a = 1.15 g and F_v = 1.9 g, where F_a and F_v are coefficients of soil at the considered location at 0.2 and 1 second, respectively (**Table 3.2** and **3.3**). $S_{DS} = \frac{2}{3} \times F_a \times S_S = 0.678\ g$ and $S_{D1} = \frac{2}{3} \times F_v \times S_1 = 0.279\ g$. Fundamental period of vibration, $T = 0.02H = 1.51\ second > 0.8T_s = 0.33\ second$, where $T_s = \frac{S_{D1}}{S_{DS}}$ and H is the total heights of the building above ground surface (75.5m).

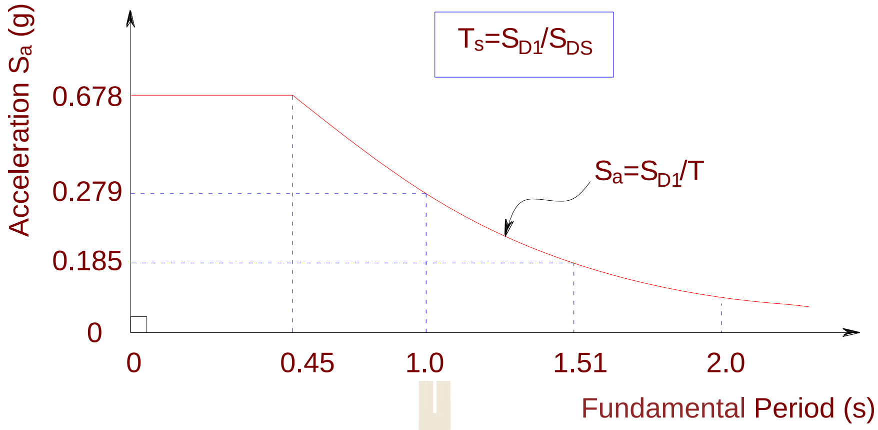


Figure 3.8 The value of S_a = 0.185 g calculated as per DPT 1302-61 code (final draft)

According to **Figure 3.8**, $T = 1.51$ second ➔ $S_a = 0.185\ g$. Base shear coefficient, $C_S = S_a \times \frac{I}{R} = 0.04\ g \geq 0.01 : OK$. To see clearly about the affect caused by seismic load, choose $C_S = 0.10$. Shear force at the base of the building, $V = C_S \times W = 0.10W$, where W is the weight of the building (self-weight plus super imposed dead load). Since $0.5\ second < T = 1.51\ second < 2.5\ second$ ➔ $K = 1 + \frac{T-0.5}{2} = 1.505$, where K is the building height exponent.

3.4.4 Building Form and Locations of Shear Walls Modeled in ETABS

As mentioned earlier, 5 models will be created by changing different location of shear walls to find the model which provide the highest stiffness.

Model A does not consist of any shear wall. Model B, C, D, and E consist of shear walls in different positions in the plan view of the structure as shown in **Figure 3.9** to **Figure 3.15** below.

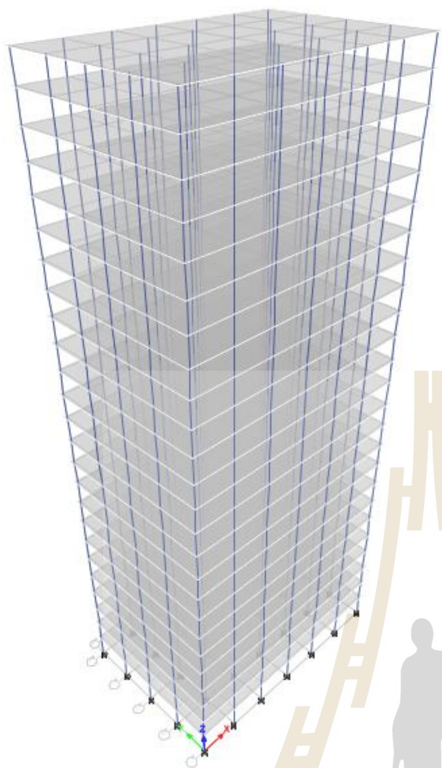


Figure 3.9 3D view

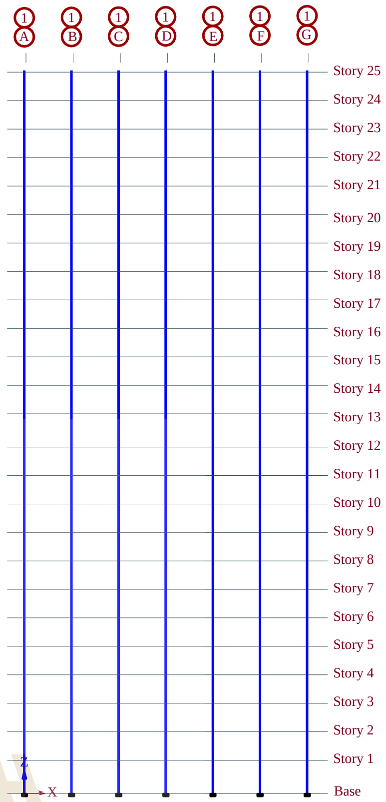


Figure 3.10 Elevation

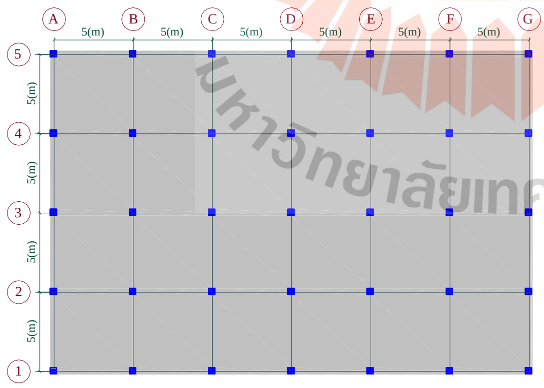


Figure 3.11 Model A

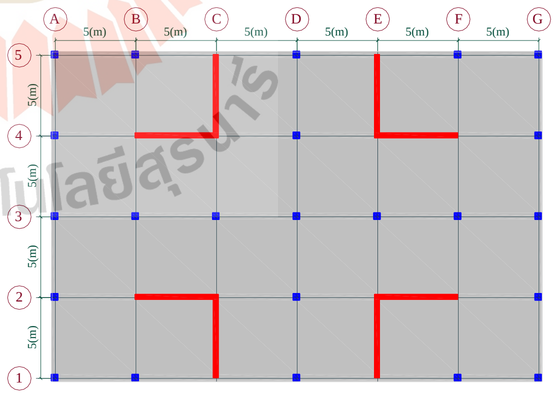
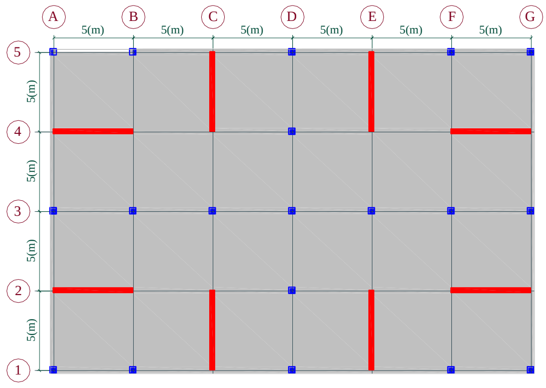


Figure 3.12 Model B



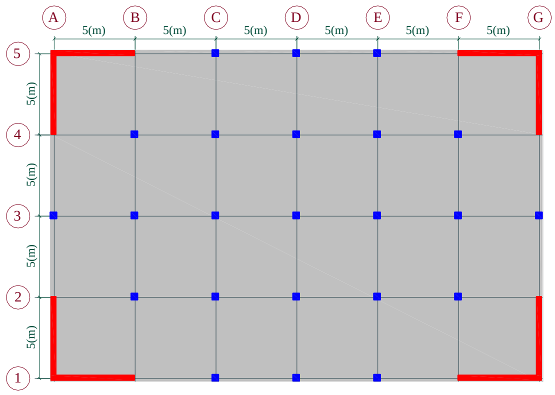


Figure 3.13 Model C

Figure 3.14 Model D

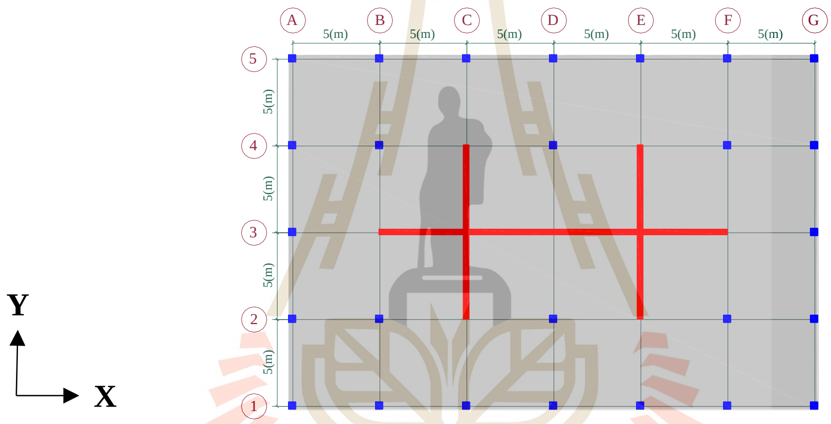


Figure 3.15 Model E

3.4.5 Load Combinations Used in Every Model

Strength design method (SDM) provides 9 load case combinations. These load case combinations will be input in ETABS software.

$$1.4DL + 1.7LL \tag{3.18}$$

$$0.75\ (1.4DL + 1.7LL) + 1.0E_x \tag{3.19}$$

$$0.75\ (1.4DL + 1.7LL) - 1.0E_x \tag{3.20}$$

$$0.75\ (1.4DL + 1.7LL) + 1.0E_y \tag{3.21}$$

$$0.75\ (1.4DL + 1.7LL) - 1.0E_y \tag{3.22}$$

$$0.9DL + 1.0E_x \tag{3.23}$$

$$0.9DL - 1.0E_x \tag{3.24}$$

$$0.9DL + 1.0E_y \tag{3.25}$$

$$0.9DL - 1.0E_y \tag{3.26}$$

DL is the dead load and is equal to self-weight plus superimposed dead load. E_x and E_y are earthquake loads in x and y-directions, respectively.

CHAPTER 4

RESULTS AND DISCUSSIONS

Story displacements, story-drift ratios and over turning moments in x and y-directions are investigated through DPT 1302-61 (final draft). For this project, the allowable story-drift ratio is 0.01 (**Table 3.8**). All floors and walls in every model are meshed into rectangular shapes in the size of 1 m x 1 m.

4.1 Model A

The seismic loads act on every diaphragm in the building is shown in **Figure 4.2**

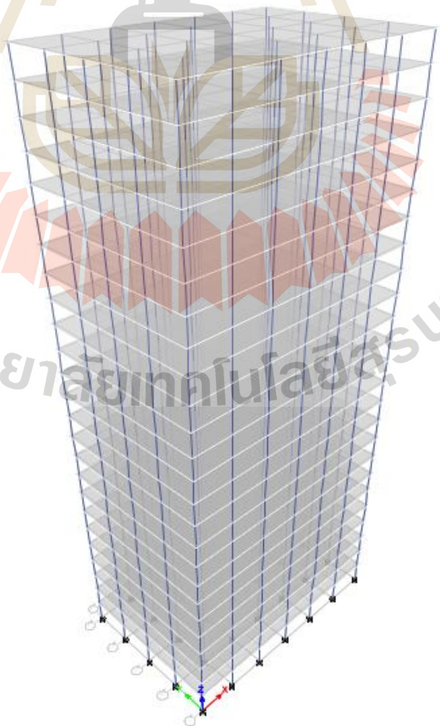


Figure 4.1 3D view of Model A

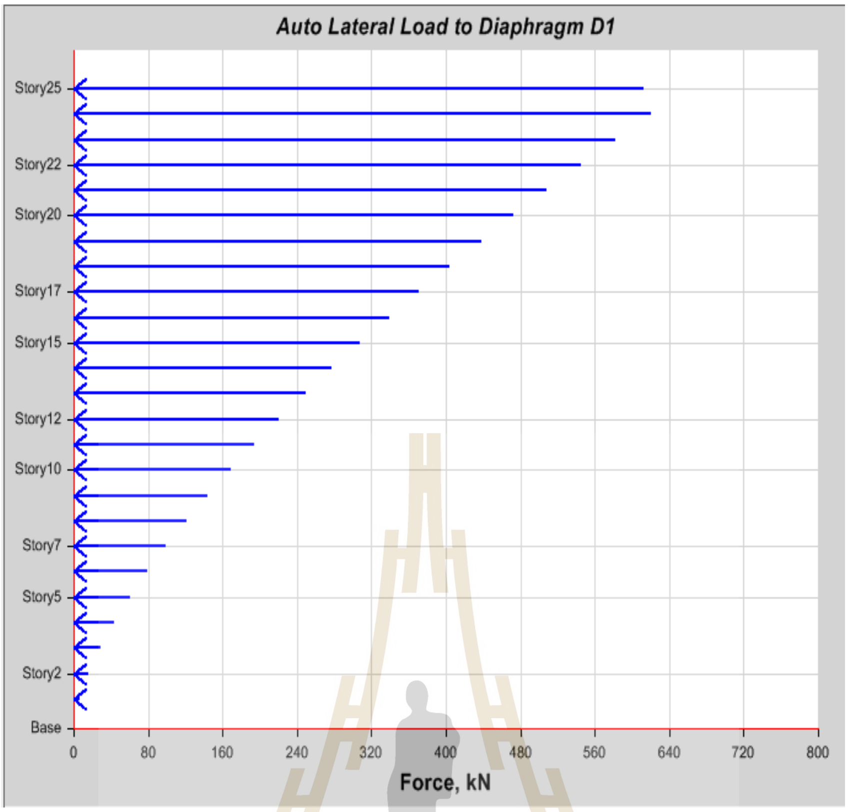


Figure 4.2 Lateral load acting on every diaphragm

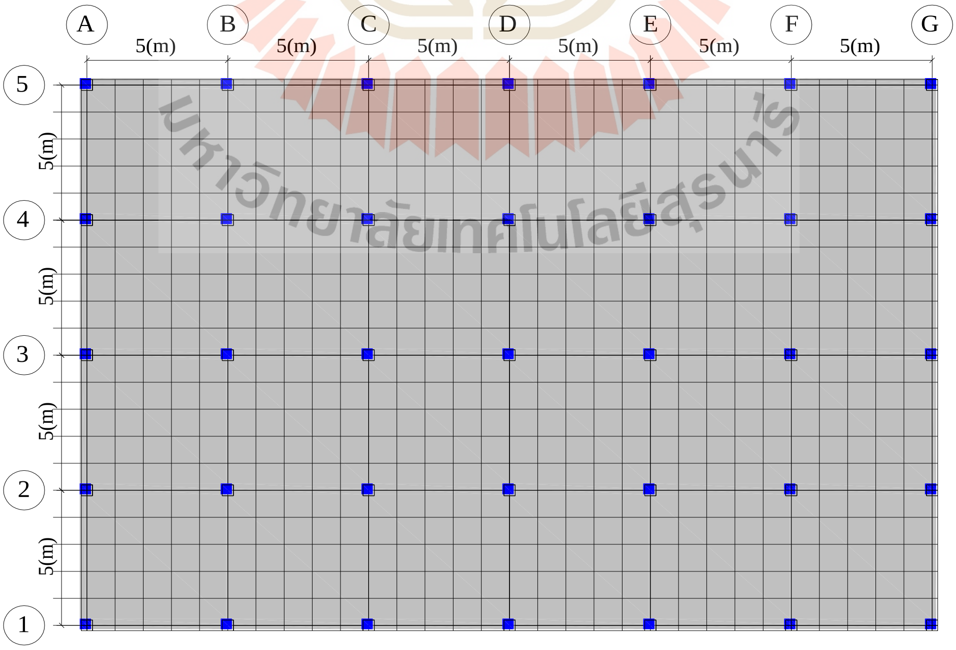


Figure 4.3 All floors are mesh into 1m x 1m

4.1.1 Story Displacements in X-Direction

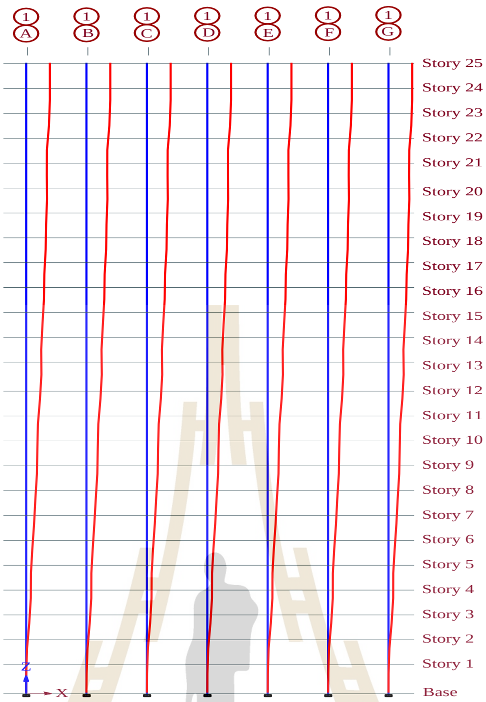


Figure 4.4 Story displacements of Model A in x-direction

Table 4.1 Story displacements of Model A in x-direction

Story	Displacement (cm)	Story	Displacement (cm)
25	187.05	12	112.81
24	185.38	11	103.61
23	183.01	10	94.13
22	179.86	9	84.43
21	175.92	8	74.53
20	171.24	7	64.47
19	165.86	6	54.3
18	159.83	5	44.07
17	153.2	4	33.82
16	146.03	3	23.69
15	138.35	2	13.97
14	130.23	1	5.42
13	121.7	Base	0.00

4.1.2 Story Displacements in Y-Direction

Figure 4.5 Story displacements of Model A in y-direction

Table 4.2 Story displacements of Model A in y-direction

Story	Displacements (cm)	Story	Displacement (cm)
25	190.67	12	113.7
24	188.75	11	104.34
23	186.15	10	94.73
22	182.76	9	84.89
21	178.6	8	74.87
20	173.69	7	64.72
19	168.09	6	54.47
18	161.85	5	44.16
17	155.01	4	33.87
16	147.64	3	23.71
15	139.77	2	13.97
14	131.46	1	5.42
13	122.75	Base	0.00

Table 4.1 and **4.2** show that without structural walls, the structure displaces quite large. At the top story, the displacement in y-direction (190.67 cm) is greater than the displacement in x-direction (187.05 cm), and this is suitable since y-direction is the soft direction. The displacements at zero story (at base) are zero since all supports are fixed.

4.1.3 Story-Drift in X-Direction

Table 4.3 Story-drift ratios in x-direction of Model A

Story	Drift Ratio	Story	Drift Ratio
25	0.006	12	0.031
24	0.008	11	0.032
23	0.011	10	0.032
22	0.013	9	0.033
21	0.016	8	0.034
20	0.018	7	0.034
19	0.02	6	0.034
18	0.022	5	0.034
17	0.024	4	0.034
16	0.026	3	0.032
15	0.027	2	0.028
14	0.028	1	0.015
13	0.03	Base	0.000

4.1.4 Story-Drift in Y-Direction

Table 4.4 Story-drift ratios in y-direction of Model A

Story	Drift Ratio	Story	Drift Ratio
25	0.006	12	0.031
24	0.009	11	0.032
23	0.011	10	0.033
22	0.014	9	0.033
21	0.016	8	0.034
20	0.019	7	0.034
19	0.021	6	0.034
18	0.023	5	0.034
17	0.025	4	0.034
16	0.026	3	0.032
15	0.028	2	0.029
14	0.029	1	0.015
13	0.03	Base	0.000

Table 4.3 and **4.4** show that most stories in Model A provide story-drift ratios greater than the allowable story-drift ratio in both directions. To reduce the values of story-drift ratios, structural walls will be used in the next models.

4.1.5 Overturning Moments

The building does not fail if it satisfies SF = M_r/M_a, where SF is the safety factor against overturning moment and should be equal to or greater than 1.5. M_r is the reaction moment calculated by multiplying the weight of the building (self-weight plus super imposed dead load) with the moment arm to its pivot. M_a is the overturning moment caused by the total lateral forces.

The weight of the building that will use to calculate the safety factor is 0.9DL.

Table 4.5 Story weight of Model A which used only 90% of the real weight

Story	Weight (kN)	Story	Weight (kN)
25	3607.85	12	50509.93
24	7215.70	11	54117.78
23	10823.56	10	57725.63
22	14431.41	9	61333.48
21	18039.26	8	64941.33
20	21647.11	7	68549.19
19	25254.96	6	72157.04
18	28862.82	5	75764.89
17	32470.67	4	79372.74
16	36078.52	3	82980.59
15	39686.37	2	86588.45
14	43294.22	1	90255.68
13	46902.07	Sum	1172611.25

Table 4.6 Moments about y-axis of Model A

Story	M_y (kN-m)	Story	M_y (kN-m)
25	1838.10	12	156027.31
24	5538.43	11	174459.29
23	10986.24	10	193397.21
22	18069.27	9	212768.07
21	26677.75	8	232502.77
20	36704.53	7	252536.39
19	48045.11	6	272808.41
18	60597.68	5	293263.11
17	74263.26	4	313849.97
16	88945.71	3	334524.26
15	104551.87	2	355247.94
14	120991.61	1	379448.53
13	138177.99	Sum	3906220.81

Table 4.7 Moments about x-axis of Model A

Story	M_x (kN-m)	Story	M_x (kN-m)
25	1838.10	12	156027.31
24	5538.43	11	174459.29
23	10986.24	10	193397.21
22	18069.27	9	212768.07
21	26677.75	8	232502.77
20	36704.53	7	252536.39
19	48045.11	6	272808.41
18	60597.68	5	293263.11
17	74263.26	4	313849.97
16	88945.71	3	334524.26
15	104551.87	2	355247.94
14	120991.61	1	379448.54
13	138177.99	Sum	3906220.81

Moments in x and y-directions are equal (3906220.81 kN-m) since the earthquake forces happened in both directions are the same.

Safety factor against overturning moment in x-direction,

$$SF_x = \frac{1172611.2 \times 15}{3906220.81} = 4.5 > 1.5 : \text{OK}$$

Safety factor against overturning moment in y-direction,

$$SF_y = \frac{1172611.2 \times 10}{3906220.81} = 3.0 > 1.5 : \text{OK}$$

4.2 Model B

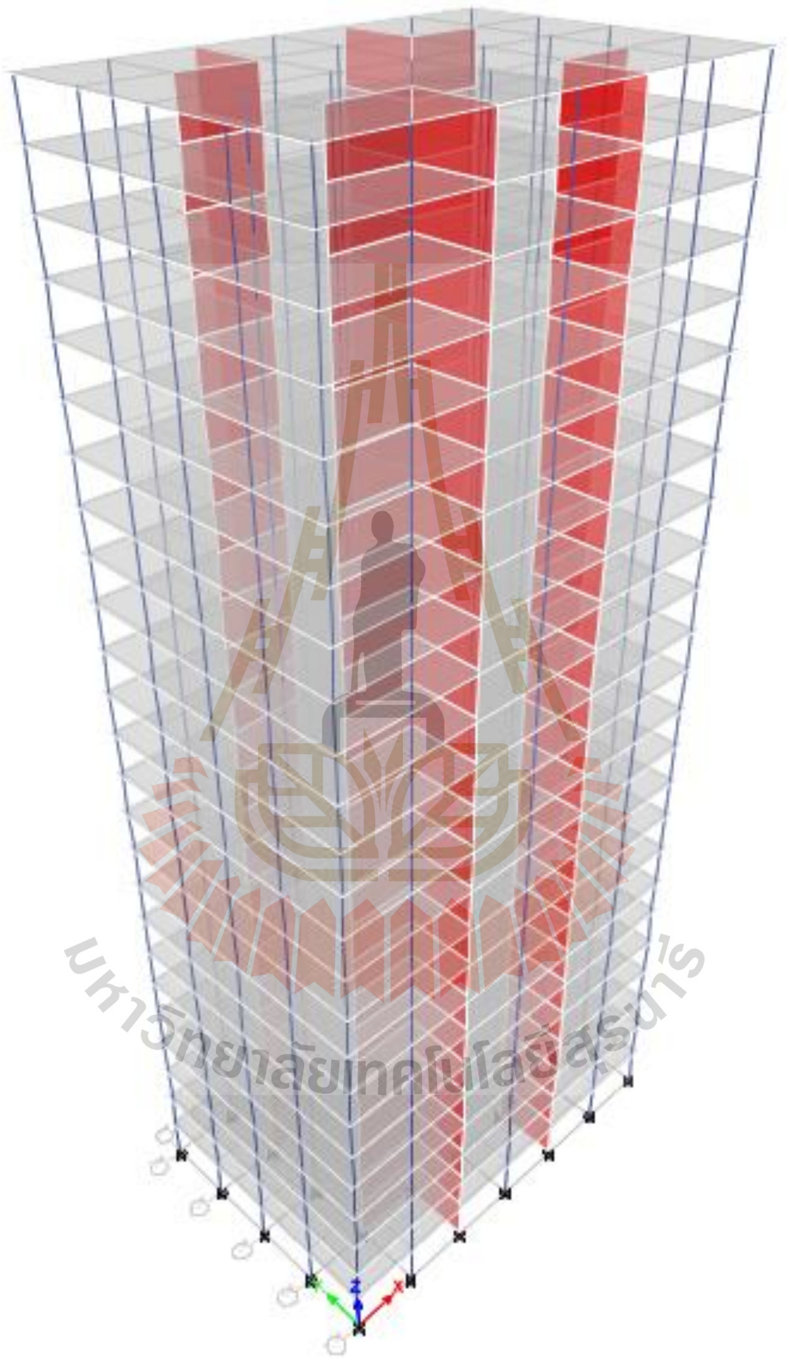


Figure 4.6 3D view of Model B

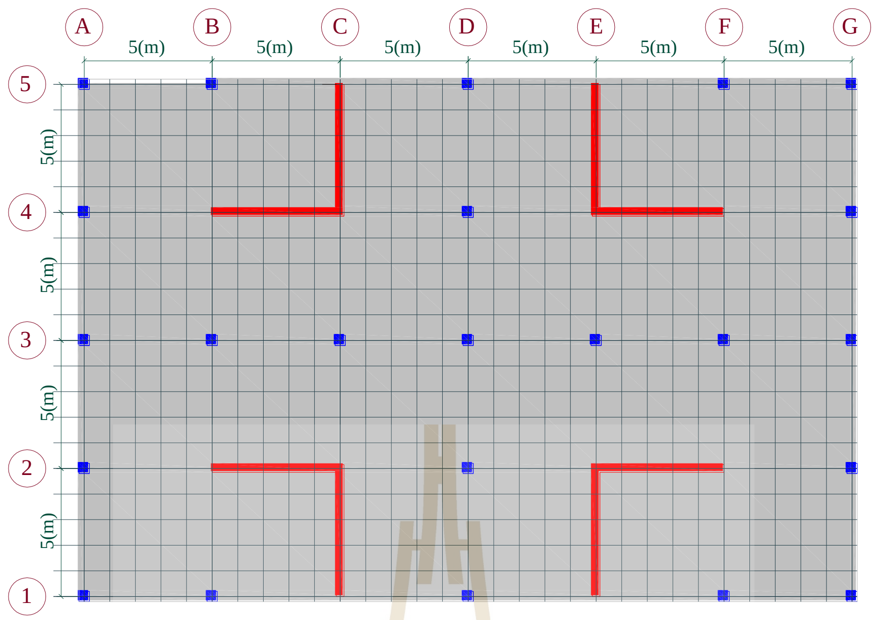


Figure 4.7 Plan view of Model B when all floors and structural walls are meshed into 1m x 1m

4.2.1 Story Displacement in X-Direction

Table 4.8 Story displacement of Model B in x-direction

Story	**Displacement (cm)**	**Story**	**Displacement (cm)**
25	46.44	12	17.24
24	44.3	11	15.06
23	42.14	10	12.95
22	39.95	9	10.93
21	37.73	8	9.01
20	35.49	7	7.22
19	33.23	6	5.56
18	30.94	5	4.08
17	28.64	4	2.78
16	26.33	3	1.7
15	24.03	2	0.86
14	21.74	1	0.28
13	19.47	Base	0.00

4.2.2 Story Displacement in Y-Direction

Table 4.9 Story displacements of Model B in y-direction

Story	Displacement (cm)	Story	Displacement (cm)
25	56.66	12	20.26
24	53.92	11	17.65
23	51.15	10	15.12
22	48.37	9	12.72
21	45.56	8	10.45
20	42.74	7	8.33
19	39.9	6	6.4
18	37.04	5	4.67
17	34.19	4	3.17
16	31.34	3	1.93
15	28.51	2	0.96
14	25.71	1	0.31
13	22.96	Base	0.00

4.2.3 Story-Drift Ratios in X-Direction

Table 4.10 Story-drift ratios of Model B in x-direction

Story	Drift Ratio	Story	Drift Ratio
25	0.007	12	0.007
24	0.007	11	0.007
23	0.007	10	0.007
22	0.007	9	0.006
21	0.007	8	0.006
20	0.008	7	0.006
19	0.008	6	0.005
18	0.008	5	0.004
17	0.008	4	0.004
16	0.008	3	0.003
15	0.008	2	0.002
14	0.008	1	0.001
13	0.007	Base	0.000

After using shear walls, all story-drift ratios are not exceed the allowable story-drift ratio.

4.2.4 Story-Drift Ratios in Y-Direction

Table 4.11 Story-drift ratios of Model B in y-direction

Story	Drift Ratio	Story	Drift Ratio
25	0.009	12	0.009
24	0.009	11	0.008
23	0.009	10	0.008
22	0.009	9	0.008
21	0.009	8	0.007
20	0.009	7	0.006
19	0.01	6	0.006
18	0.01	5	0.005
17	0.009	4	0.004
16	0.009	3	0.003
15	0.009	2	0.002
14	0.009	1	0.001
13	0.009	Base	0.000

All stories do not provide the story-drift ratios greater than 0.01, and that means the building is safe.

4.2.5 Overturning Moments

Table 4.12 Story weight of Model B which used only 90% of the real weight

Story	Weight (kN)	Story	Weight (kN)
25	4249.15	12	59488.04
24	8498.29	11	63737.19
23	12747.44	10	67986.33
22	16996.58	9	72235.48
21	21245.73	8	76484.62
20	25494.88	7	80733.77
19	29744.02	6	84982.92
18	33993.17	5	89232.06
17	38242.31	4	93481.21
16	42491.46	3	97730.35
15	46740.60	2	101979.50
14	50989.75	1	106394.91
13	55238.90	Sum	1381138.65

Table 4.13 Moments about y-axis of Model B

Story	M_y (kN-m)	Story	M_y (kN-m)
25	2095.53	12	194351.43
24	6547.30	11	217478.91
23	13210.63	10	241251.13
22	21943.92	9	265575.81
21	32608.74	8	290365.58
20	45069.95	7	315538.27
19	59195.70	6	341017.26
18	74857.58	5	366731.90
17	91930.68	4	392618.06
16	110293.69	3	418618.86
15	129829.04	2	444685.72
14	150422.95	1	475129.96
13	171965.64	Sum	4873334.24

Table 4.14 Moments about x-axis of Model B

Story	M_x (kN-m)	Story	M_x (kN-m)
25	2095.53	12	194351.43
24	6547.30	11	217478.91
23	13210.63	10	241251.13
22	21943.92	9	265575.81
21	32608.74	8	290365.58
20	45069.95	7	315538.27
19	59195.70	6	341017.26
18	74857.58	5	366731.90
17	91930.68	4	392618.06
16	110293.69	3	418618.86
15	129829.04	2	444685.72
14	150422.95	1	475129.96
13	171965.64	Sum	4873334.24

Safety factor against overturning moment in x-direction of Model B,

$$SF_x = \frac{1381138.65 \times 15}{4873334.24} = 4.25 > 1.5 : \text{OK}$$

Safety factor against overturning moment in y-direction of Model B,

$$SF_y = \frac{1381138.65 \times 10}{4873334.24} = 2.83 > 1.5 : \text{OK}$$

4.3 Model C

Figure 4.8 3D view of Model C

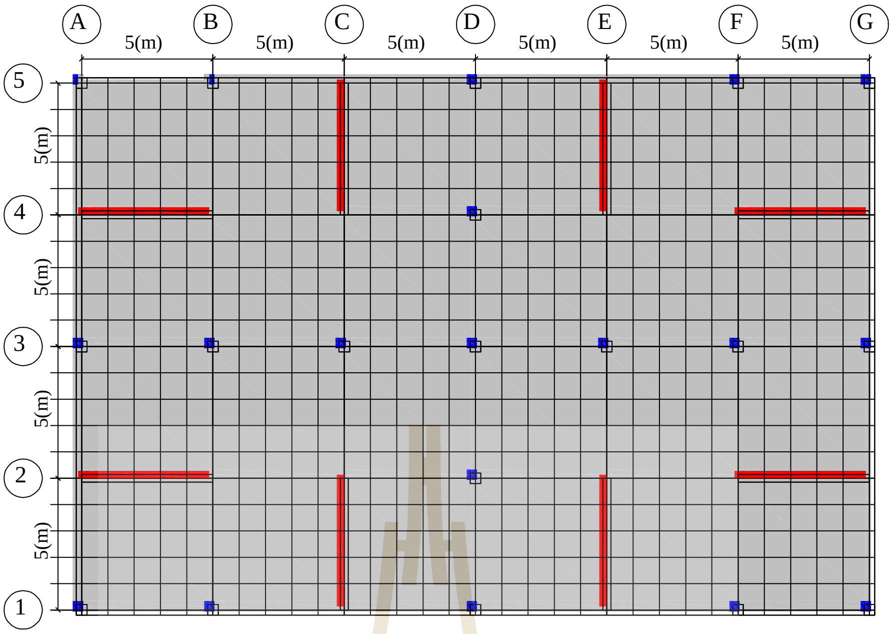


Figure 4.9 Plane view of Model C when all floors and structural walls are meshed into 1m x 1m

4.3.1 Story Displacement in X-Direction

Table 4.15 Story displacement of Model C in x-direction

Story	Displacement (cm)	Story	Displacement (cm)
25	68.31	12	27.75
24	65.57	11	24.41
23	62.77	10	21.13
22	59.91	9	17.94
21	56.99	8	14.88
20	53.99	7	11.98
19	50.9	6	9.28
18	47.74	5	6.83
17	44.51	4	4.66
16	41.22	3	2.84
15	37.88	2	1.42
14	34.51	1	0.45
13	31.12	Base	0.00

4.3.2 Story Displacement in Y-Direction

Table 4.16 Story displacement of Model C in y-direction

Story	Displacement (cm)	Story	Displacement (cm)
25	74.81	12	29.71
24	71.68	11	26.08
23	68.51	10	22.54
22	65.29	9	19.11
21	61.99	8	15.82
20	58.62	7	12.71
19	55.18	6	9.83
18	51.66	5	7.21
17	48.08	4	4.92
16	44.44	3	2.99
15	40.77	2	1.49
14	37.08	1	0.47
13	33.38	Base	0.00

4.3.3 Story-Drift Ratios in X-Direction

Table 4.17 Story-drift ratios of Model C in x-direction

Story	Drift Ratio	Story	Drift Ratio
25	0.009	12	0.011
24	0.009	11	0.011
23	0.01	10	0.011
22	0.01	9	0.01
21	0.01	8	0.01
20	0.01	7	0.009
19	0.011	6	0.008
18	0.011	5	0.007
17	0.011	4	0.006
16	0.011	3	0.005
15	0.011	2	0.003
14	0.011	1	0.001
13	0.011	Base	0.000

4.3.4 Story-Drift Ratios in Y-Direction

Table 4.18 Story-drift ratios of Model C in y-direction

Story	Drift Ratio	Story	Drift Ratio
25	0.01	12	0.012
24	0.011	11	0.012
23	0.011	10	0.011
22	0.011	9	0.011
21	0.011	8	0.01
20	0.011	7	0.01
19	0.012	6	0.009
18	0.012	5	0.008
17	0.012	4	0.006
16	0.012	3	0.005
15	0.012	2	0.003
14	0.012	1	0.001
13	0.012	Base	0.000

4.3.5 Overturning Moments

Table 4.19 Story weight of model C which used only 90% of the real weight

Story	Weight (kN)	Story	Weight (kN)
25	4208.43	12	58918.00
24	8416.86	11	63126.43
23	12625.29	10	67334.86
22	16833.72	9	71543.29
21	21042.14	8	75751.72
20	25250.57	7	79960.15
19	29459.00	6	84168.58
18	33667.43	5	88377.00
17	37875.86	4	92585.43
16	42084.29	3	96793.86
15	46292.72	2	101002.29
14	50501.15	1	105370.19
13	54709.57	Sum	1367898.82

Table 4.20 Moment about y-axis of Model C

Story	M_y (kN-m)	Story	M_y (kN-m)
25	2079.64	12	192022.36
24	6485.42	11	214865.66
23	13074.50	10	238345.51
22	21707.10	9	262370.83
21	32246.57	8	286855.35
20	44559.49	7	311717.96
19	58515.71	6	336883.01
18	73988.47	5	362280.77
17	90854.44	4	387847.91
16	108993.90	3	413528.28
15	128290.75	2	439273.91
14	148632.69	1	469342.98
13	169911.33	Sum	4814674.52

Table 4.21 Moment about x-axis of Model C

Story	M_x (kN-m)	Story	M_x (kN-m)
25	2079.64	12	192022.36
24	6485.42	11	214865.66
23	13074.50	10	238345.51
22	21707.10	9	262370.83
21	32246.57	8	286855.35
20	44559.49	7	311717.96
19	58515.71	6	336883.01
18	73988.47	5	362280.77
17	90854.44	4	387847.91
16	108993.90	3	413528.28
15	128290.75	2	439273.91
14	148632.69	1	469342.98
13	169911.33	Sum	4814674.52

Safety factor against overturning moment in x-direction of Model C,

$$SF_x = \frac{1367898.82 \times 15}{4814674.52} = 4.26 > 1.5 : OK$$

Safety factor against overturning moment in y-direction of Model C,

$$SF_y = \frac{1367898.82 \times 10}{4814674.52} = 2.84 > 1.5 : OK$$

4.4 Model D

Figure 4.10 3D view of Model D

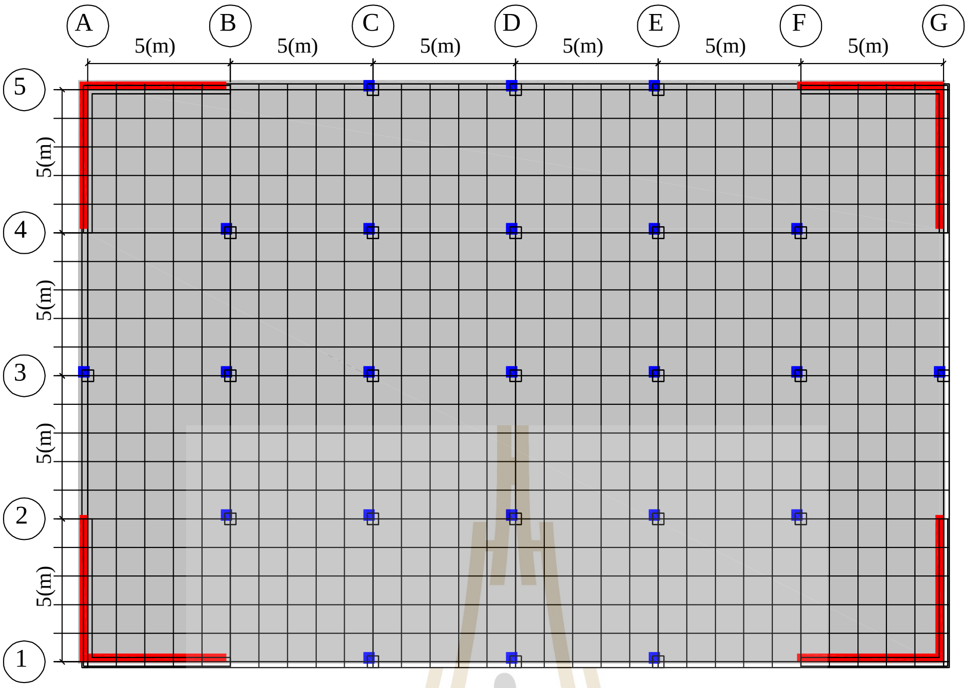


Figure 4.11 Plan view of Model D when all floors and structural walls are meshed into 1m x 1m

4.4.1 Displacements in X-Direction

Table 4.22 Story displacements of Model D in x-direction

Story	Displacement (cm)	Story	Displacement (cm)
25	97.59	12	34.66
24	92.83	11	30.17
23	88.03	10	25.84
22	83.2	9	21.72
21	78.33	8	17.83
20	73.44	7	14.21
19	68.52	6	10.9
18	63.59	5	7.95
17	58.66	4	5.39
16	53.74	3	3.27
15	48.86	2	1.63
14	44.04	1	0.53
13	39.3	Base	0.00

4.4.2 Story Displacements in Y-Direction

Table 4.23 Story displacements of Model D in y-direction

Story	Displacement (cm)	Story	Displacement (cm)
25	93.44	12	33.47
24	88.92	11	29.15
23	84.37	10	24.99
22	79.79	9	21.01
21	75.17	8	17.26
20	70.52	7	13.77
19	65.84	6	10.58
18	61.14	5	7.72
17	56.43	4	5.24
16	51.74	3	3.18
15	47.07	2	1.59
14	42.46	1	0.52
13	37.91	Base	0.00

4.4.3 Story-Drift Ratios in X-Direction

Table 4.24 Story-drift ratios of Model D in x-direction

Story	Drift Ratio	Story	Drift Ratio
25	0.016	12	0.015
24	0.016	11	0.014
23	0.016	10	0.014
22	0.016	9	0.013
21	0.016	8	0.012
20	0.016	7	0.011
19	0.016	6	0.01
18	0.016	5	0.009
17	0.016	4	0.007
16	0.016	3	0.005
15	0.016	2	0.004
14	0.016	1	0.002
13	0.015	Base	0.00

4.4.4 Story-Drift Ratios in Y-Direction

Table 4.25 Story-drift ratios of Model D in y-direction

Story	Drift Ratio	Story	Drift Ratio
25	0.015	12	0.014
24	0.015	11	0.014
23	0.015	10	0.013
22	0.015	9	0.013
21	0.016	8	0.012
20	0.016	7	0.011
19	0.016	6	0.01
18	0.016	5	0.008
17	0.016	4	0.007
16	0.016	3	0.005
15	0.015	2	0.004
14	0.015	1	0.001
13	0.015	Base	0.000

4.4.5 Overturning Moments

Table 4.26 Story weight of Model D which used only 90% of the real weight

Story	**Weight (kN)**	**Story**	**Weight (kN)**
25	4249.15	12	59488.04
24	8498.29	11	63737.19
23	12747.44	10	67986.33
22	16996.58	9	72235.48
21	21245.73	8	76484.62
20	25494.88	7	80733.77
19	29744.02	6	84982.92
18	33993.17	5	89232.06
17	38242.31	4	93481.21
16	42491.46	3	97730.35
15	46740.60	2	101979.50
14	50989.75	1	106394.91
13	55238.90	Sum	1381138.65

Table 4.27 Moments about y-axis of Model D

Story	M_y (kN-m)	Story	M_y (kN-m)
25	2095.53	12	194351.43
24	6547.30	11	217478.91
23	13210.63	10	241251.13
22	21943.92	9	265575.81
21	32608.74	8	290365.58
20	45069.95	7	315538.27
19	59195.70	6	341017.26
18	74857.58	5	366731.90
17	91930.68	4	392618.06
16	110293.69	3	418618.86
15	129829.04	2	444685.72
14	150422.95	1	475129.96
13	171965.64	Sum	4873334.24

Table 4.28 Moments about x-axis of Model D

Story	M_x (kN-m)	Story	M_x (kN-m)
25	2095.53	12	194351.43
24	6547.30	11	217478.91
23	13210.63	10	241251.13
22	21943.92	9	265575.81
21	32608.74	8	290365.58
20	45069.95	7	315538.27
19	59195.70	6	341017.26
18	74857.58	5	366731.90
17	91930.68	4	392618.06
16	110293.69	3	418618.86
15	129829.04	2	444685.72
14	150422.95	1	475129.96
13	171965.64	Sum	4873334.24

Safety factor against overturning moment in x-direction of Model D,

$$SF_x = \frac{1381138.65 \times 15}{4873334.24} = 4.25 > 1.5 : \text{OK}$$

Safety factor against overturning moment in y-direction of Model D,

$$SF_y = \frac{1381138.65 \times 10}{4873334.24} = 2.83 > 1.5 : \text{OK}$$

The moments in x and y-directions of Model B and D are the same since their weights are the same.

4.5 Model E

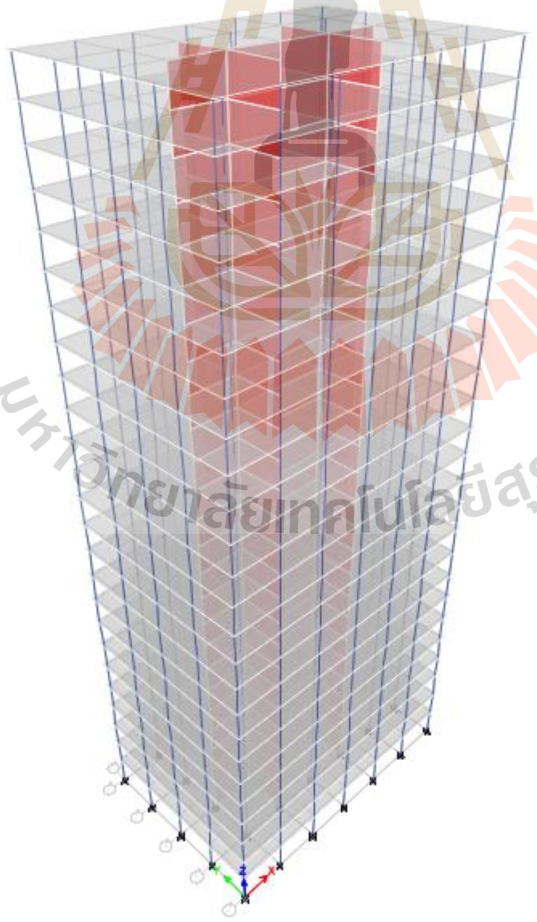


Figure 4.12 3D view of Model E

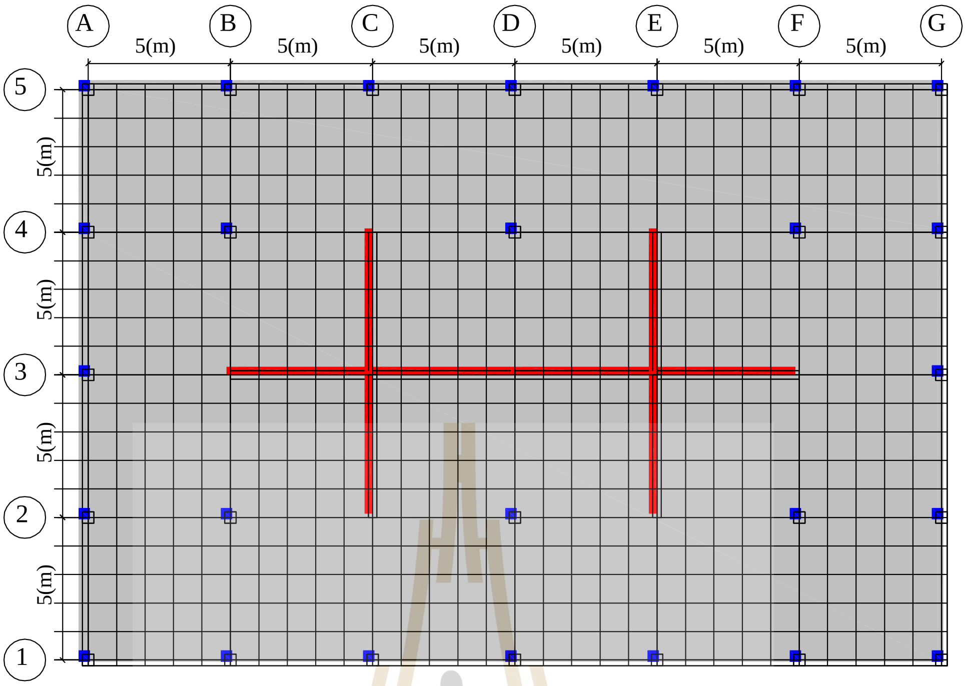


Figure 4.13 Plan view of Model E when all floors and structural walls are meshed into 1m x 1m

4.5.1 Story Displacements in X-Direction

Table 4.29 Story displacements of Model E in x-direction

Story	Displacement (cm)	Story	Displacement (cm)
25	8.96	12	3.29
24	8.54	11	2.88
23	8.11	10	2.49
22	7.67	9	2.12
21	7.23	8	1.77
20	6.79	7	1.43
19	6.35	6	1.13
18	5.9	5	0.85
17	5.45	4	0.61
16	5.01	3	0.4
15	4.57	2	0.22
14	4.13	1	0.09
13	3.7	Base	0.00

4.5.2 Story displacements in Y-Direction

Table 4.30 Story displacements of Model E in y-direction

Story	Displacement (cm)	Story	Displacement (cm)
25	37.08	12	13.2
24	35.28	11	11.5
23	33.46	10	9.85
22	31.62	9	8.29
21	29.78	8	6.81
20	27.92	7	5.44
19	26.05	6	4.18
18	24.18	5	3.06
17	22.31	4	2.08
16	20.44	3	1.27
15	18.59	2	0.65
14	16.76	1	0.22
13	14.96	Base	0.00

4.5.3 Story-drift ratios in X-Direction

Table 4.31 Story-drift ratios in x-direction of Model E

Story	Drift Ratio	Story	Drift ratio
25	0.001	12	0.001
24	0.001	11	0.001
23	0.001	10	0.001
22	0.001	9	0.001
21	0.001	8	0.001
20	0.001	7	0.001
19	0.001	6	0.001
18	0.001	5	0.001
17	0.001	4	0.001
16	0.001	3	0.001
15	0.001	2	0.000
14	0.001	1	0.000
13	0.001	Base	0.000

4.5.4 Story-Drift Ratios in Y-Direction

Table 4.32 Story-drift ratios in y-direction of Model E

Story	Drift	Story	Drift
25	0.006	12	0.006
24	0.006	11	0.005
23	0.006	10	0.005
22	0.006	9	0.005
21	0.006	8	0.005
20	0.006	7	0.004
19	0.006	6	0.004
18	0.006	5	0.003
17	0.006	4	0.003
16	0.006	3	0.002
15	0.006	2	0.001
14	0.006	1	0.001
13	0.006	Base	0.000

4.5.5 Overturning Moments

Table 4.33 Story weight of Model E which used only 90% of the real weight

Story	**Weight (kN)**	**Story**	**Weight (kN)**
25	4279.68	12	59915.57
24	8559.37	11	64195.25
23	12839.05	10	68474.94
22	17118.73	9	72754.62
21	21398.42	8	77034.31
20	25678.10	7	81313.99
19	29957.79	6	85593.67
18	34237.47	5	89873.36
17	38517.15	4	94153.04
16	42796.84	3	98432.72
15	47076.52	2	102712.41
14	51356.20	1	107163.44
13	55635.89	Sum	1391068.53

Table 4.34 Moments about y-axis of Model E

Story	M_y (kN-m)	Story	M_y (kN-m)
25	2109.13	12	196255.65
24	6599.01	11	219615.01
23	13323.42	10	243625.76
22	22139.30	9	268194.66
21	32906.77	8	293233.45
20	45489.29	7	318659.08
19	59753.62	6	344394.16
18	75570.03	5	370367.30
17	92812.30	4	396513.70
16	111357.86	3	422775.89
15	131087.90	2	449104.79
14	151887.48	1	479855.07
13	173645.66	Sum	4921276.29

Table 4.35 Moments about x-axis of Model E

Story	M_x (kN-m)	Story	M_x (kN-m)
25	2109.13	12	196255.65
24	6599.01	11	219615.01
23	13323.42	10	243625.76
22	22139.30	9	268194.66
21	32906.77	8	293233.45
20	45489.29	7	318659.08
19	59753.62	6	344394.16
18	75570.03	5	370367.30
17	92812.30	4	396513.70
16	111357.86	3	422775.89
15	131087.90	2	449104.79
14	151887.48	1	479855.07
13	173645.66	Sum	4921276.30

Safety factor against overturning moment in x-direction of Model E,

$$SF_x = \frac{1391068.53 \times 15}{4921276.29} = 4.24 > 1.5 : \text{OK}$$

Safety factor against overturning moment in y-direction of Model E,

$$SF_y = \frac{1391068.52 \times 10}{4921276.3} = 2.83 > 1.5 : OK$$

4.6 Summary of All Models

Story displacements, story-drift ratios, and overturning moments of every model are shown **Tables 4.36**, **4.37**, **4.38**, **4.39**, **4.40**, **Figures 4.14**, **4.15**, **4.16** and **4.17** below.

Table 4.36 Summary of lateral story displacements of all models in x-direction

Story	Model A	Model B	Model C	Model D	Model E
25	187.05	46.44	68.31	97.59	8.96
24	185.38	44.30	65.57	92.83	8.54
23	183.01	42.14	62.77	88.03	8.11
22	179.86	39.95	59.91	83.20	7.67
21	175.92	37.73	56.99	78.33	7.23
20	171.24	35.49	53.99	73.44	6.79
19	165.86	33.23	50.90	68.52	6.35
18	159.83	30.94	47.74	63.59	5.90
17	153.20	28.64	44.51	58.66	5.45
16	146.03	26.33	41.22	53.74	5.01
15	138.35	24.03	37.88	48.86	4.57
14	130.23	21.74	34.51	44.04	4.13
13	121.70	19.47	31.12	39.30	3.70
12	112.81	17.24	27.75	34.66	3.29
11	103.61	15.06	24.41	30.17	2.88
10	94.13	12.95	21.13	25.84	2.49
9	84.43	10.93	17.94	21.72	2.12
8	74.53	9.01	14.88	17.83	1.77
7	64.47	7.22	11.98	14.21	1.43
6	54.30	5.56	9.28	10.90	1.13
5	44.07	4.08	6.83	7.95	0.85
4	33.82	2.78	4.66	5.39	0.61
3	23.69	1.70	2.84	3.27	0.40
2	13.97	0.86	1.42	1.63	0.22
1	5.42	0.28	0.45	0.53	0.09
Base	0.00	0.00	0.00	0.00	0.00

The displacement at the base of the building of every model is zero since all supports at base are fixed. The values in **Table 4.36** are plotted in **Figure 4.14** below.

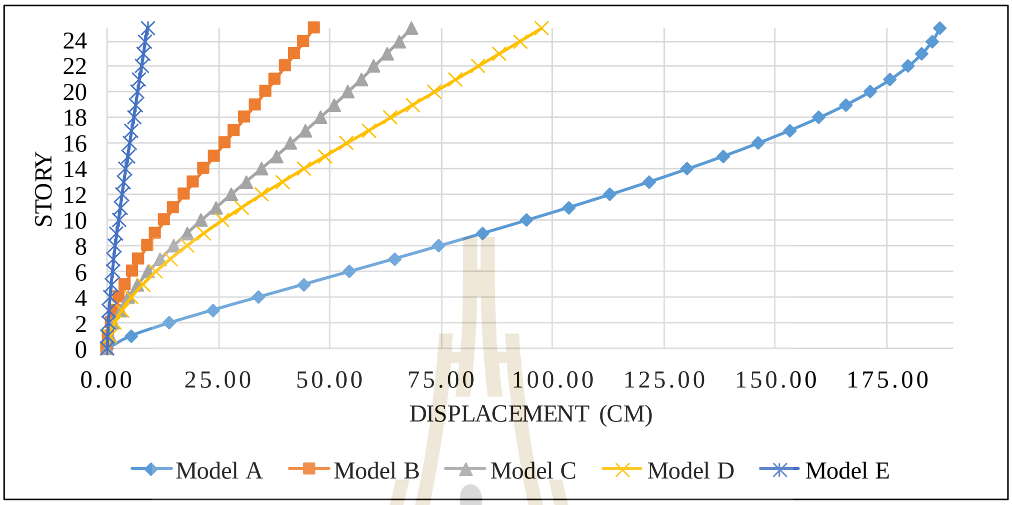


Figure 4.14 Story displacements in x-direction

Table 4.37 Summary of lateral story displacements of all models in y-direction

Story	Model A	Model B	Model C	Model D	Model E
25	190.67	56.66	74.81	93.44	37.08
24	188.75	53.92	71.68	88.92	35.28
23	186.15	51.15	68.51	84.37	33.46
22	182.76	48.37	65.29	79.79	31.62
21	178.60	45.56	61.99	75.17	29.78
20	173.69	42.74	58.62	70.52	27.92
19	168.09	39.90	55.18	65.84	26.05
18	161.85	37.04	51.66	61.14	24.18
17	155.01	34.19	48.08	56.43	22.31
16	147.64	31.34	44.44	51.74	20.44
15	139.77	28.51	40.77	47.07	18.59
14	131.46	25.71	37.08	42.46	16.76
13	122.75	22.96	33.38	37.91	14.96
12	113.70	20.26	29.71	33.47	13.20
11	104.34	17.65	26.08	29.15	11.50
10	94.73	15.12	22.54	24.99	9.85
9	84.89	12.72	19.11	21.01	8.29

Table 4.37 Summary of lateral story displacements of all models in y-direction (Continued)

Story	Model A	Model B	Model C	Model D	Model E
8	74.87	10.45	15.82	17.26	6.81
7	64.72	8.33	12.71	13.77	5.44
6	54.47	6.40	9.83	10.58	4.18
5	44.16	4.67	7.21	7.72	3.06
4	33.87	3.17	4.92	5.24	2.08
3	23.71	1.93	2.99	3.18	1.27
2	13.97	0.96	1.49	1.59	0.65
1	5.42	0.31	0.47	0.52	0.22
Base	0.00	0.00	0.00	0.00	0.00

The values in **Table 4.37** are plotted in **Figure 4.15** below.

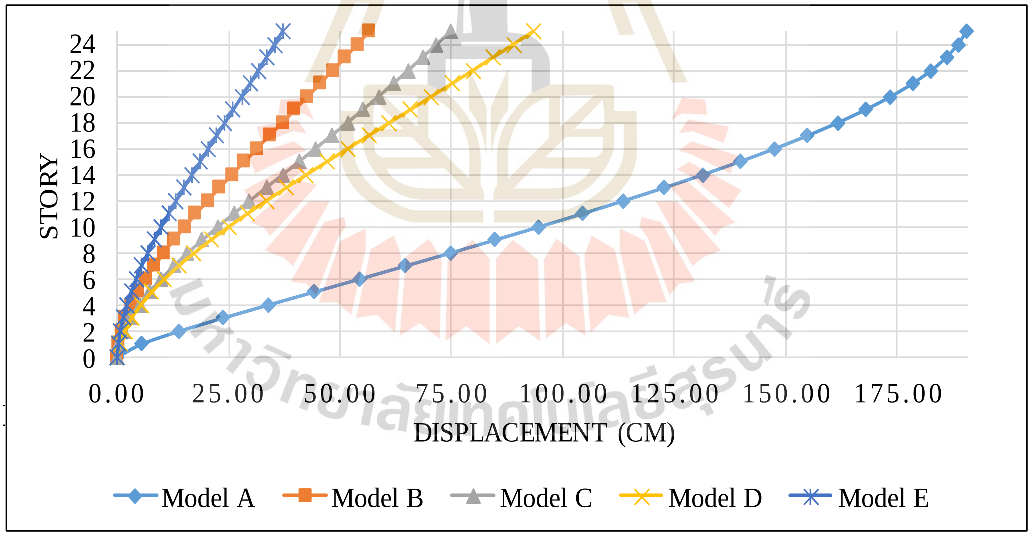


Figure 4.15 Story displacements in y-direction

Figures 4.14 and **4.15** show that Model E gives the lowest displacements in both x and y-directions. Model A gives the largest displacements since it does not have any shear wall to resist the lateral load.

Table 4.38 Summary of story-drift ratios of all models in x-direction

Story	Model A	Model B	Model C	Model D	Model E
25	0.006	0.007	0.009	0.016	0.001
24	0.008	0.007	0.009	0.016	0.001
23	0.011	0.007	0.010	0.016	0.001
22	0.013	0.007	0.010	0.016	0.001
21	0.016	0.007	0.010	0.016	0.001
20	0.018	0.008	0.010	0.016	0.001
19	0.02	0.008	0.011	0.016	0.001
18	0.022	0.008	0.011	0.016	0.001
17	0.024	0.008	0.011	0.016	0.001
16	0.026	0.008	0.011	0.016	0.001
15	0.027	0.008	0.011	0.016	0.001
14	0.028	0.008	0.011	0.016	0.001
13	0.03	0.007	0.011	0.015	0.001
12	0.031	0.007	0.011	0.015	0.001
11	0.032	0.007	0.011	0.014	0.001
10	0.032	0.007	0.011	0.014	0.001
9	0.033	0.006	0.010	0.013	0.001
8	0.034	0.006	0.010	0.012	0.001
7	0.034	0.006	0.009	0.011	0.001
6	0.034	0.005	0.008	0.010	0.001
5	0.034	0.004	0.007	0.009	0.001
4	0.034	0.004	0.006	0.007	0.001
3	0.032	0.003	0.005	0.005	0.001
2	0.028	0.002	0.003	0.004	0.000
1	0.015	0.001	0.001	0.002	0.000
Base	0.00	0.00	0.00	0.00	0.00

The values in **Table 4.38** are plotted in **Figure 4.16** below.

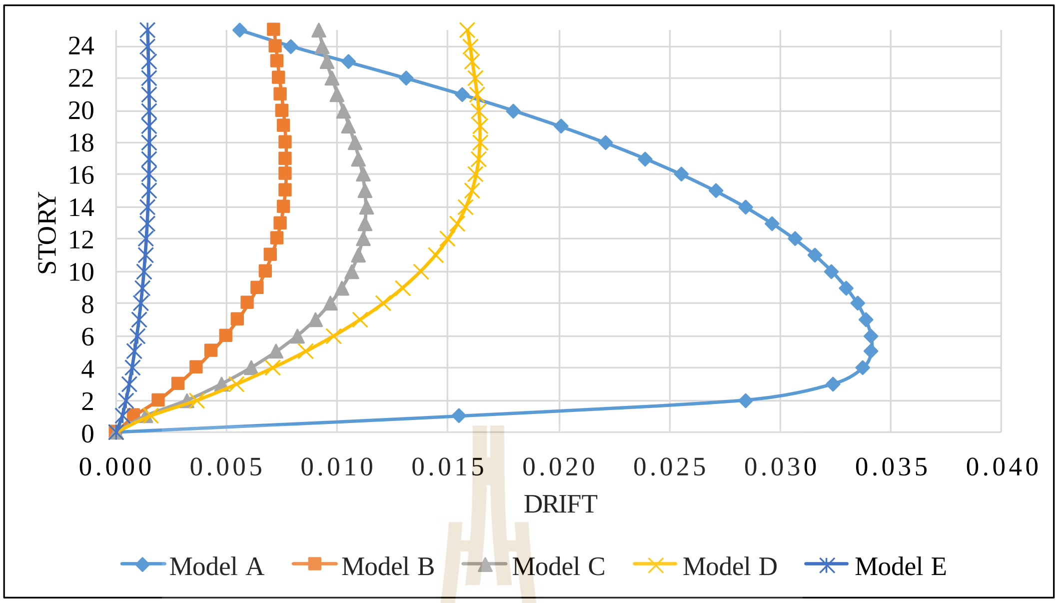


Figure 4.16 Story-drifts in x-direction

Table 4.39 Summary of story-drift ratios of all models in y-direction

Story	Model A	Model B	Model C	Model D	Model E
25	0.006	0.009	0.010	0.015	0.006
24	0.009	0.009	0.011	0.015	0.006
23	0.011	0.009	0.011	0.015	0.006
22	0.014	0.009	0.011	0.015	0.006
21	0.016	0.009	0.011	0.016	0.006
20	0.019	0.009	0.011	0.016	0.006
19	0.021	0.010	0.012	0.016	0.006
18	0.023	0.010	0.012	0.016	0.006
17	0.025	0.009	0.012	0.016	0.006
16	0.026	0.009	0.012	0.016	0.006
15	0.028	0.009	0.012	0.015	0.006
14	0.029	0.009	0.012	0.015	0.006
13	0.030	0.009	0.012	0.015	0.006
12	0.031	0.009	0.012	0.014	0.006
11	0.032	0.008	0.012	0.014	0.005
10	0.033	0.008	0.011	0.013	0.005
9	0.033	0.008	0.011	0.013	0.005
8	0.034	0.007	0.010	0.012	0.005

Table 4.39 Summary of story-drift ratios of all models in y-direction (Continued)

Story	Model A	Model B	Model C	Model D	Model E
7	0.034	0.006	0.010	0.011	0.004
6	0.034	0.006	0.009	0.010	0.004
5	0.034	0.005	0.008	0.008	0.003
4	0.034	0.004	0.006	0.007	0.003
3	0.032	0.003	0.005	0.005	0.002
2	0.029	0.002	0.003	0.004	0.001
1	0.015	0.001	0.001	0.001	0.001
Base	0.00	0.00	0.00	0.00	0.00

The values in **Table 4.39** are plotted in **Figure 4.17** below.

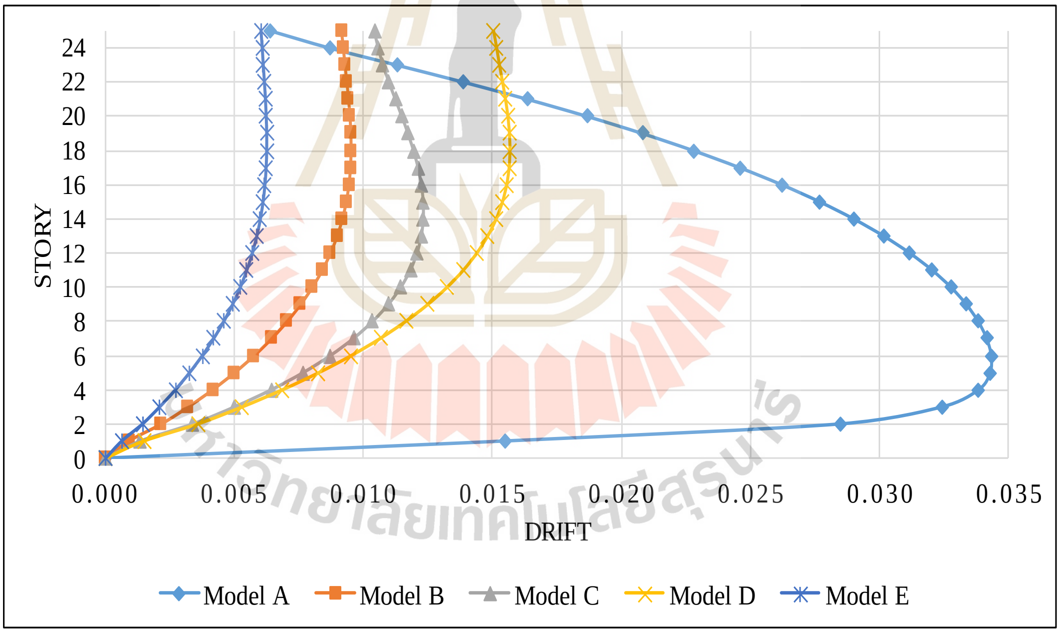


Figure 4.17 Story-drift ratios in y-direction

Figures 4.16 and **4.17** prove that Model E provides the lowest story-drift ratios in both x and y-directions.

Model A and D are not the good choices of the design since their story-drift ratios are greater than the allowable story-drift ratio as mentioned in the DPT 1302-61 (final draft).

Table 4.40 Safety factors against overturning moment

Model	**SF_x**	**SF_y**
A	4.50	3.00
B	4.25	2.83
C	4.26	2.84
D	4.25	2.83
E	4.24	2.83

Table 4.40 shows that every model does not fail by overturning moment since its safety factors are greater than 1.5 in both x and y-directions. Model A provides the highest safety factors in both directions since its overturning moments are smaller than other models.

According to the results above, it is clearly shown that Model E is the most appropriate positions of shear walls because it provides low displacements, low story-drift, and enough safety factors against overturning moments.

4.7 Curtailment of Structural Walls

Model E is used to demonstrate the behaviors of the structure when structural walls are curtailed.

Intuitively, it might be thought that curtailing the shear walls would cause the building to drift more and to have larger internal forces than the corresponding, more substantial, wall-frame structure with full-height walls. In fact, this is not necessarily the case. In some circumstances the curtailed structure drifts less and has comparable or even smaller internal forces than the corresponding full-height-wall structure.

The process of the reduction of structural walls is made by removing structural walls from the top story downward one by one until the shear force at the top of structural walls remains positive and greater than 25% of the total shear forces. After the reduction of structural walls, story-drift ratios are checked again to make sure they are not greater than the allowable story-drift ratio.

Structural walls are assigned into eight different piers, those are P1, P2, P3, P4, P5, P6, P7, and P8 as shown in **Figure 4.18** below.

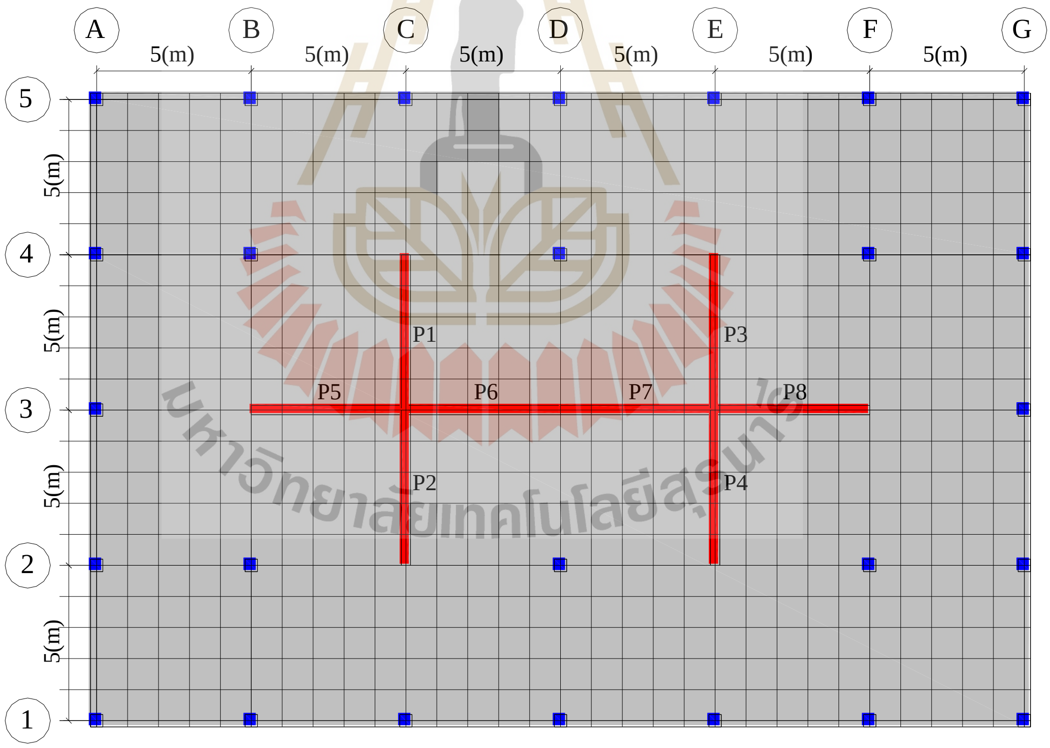


Figure 4.18 Pier labels

ETABS gives the most suitable results of the reduction of structural walls as shown in **Figures 4.19**, **4.20**, **4.21**, **4.22**, **4.23**, and **4.24**.

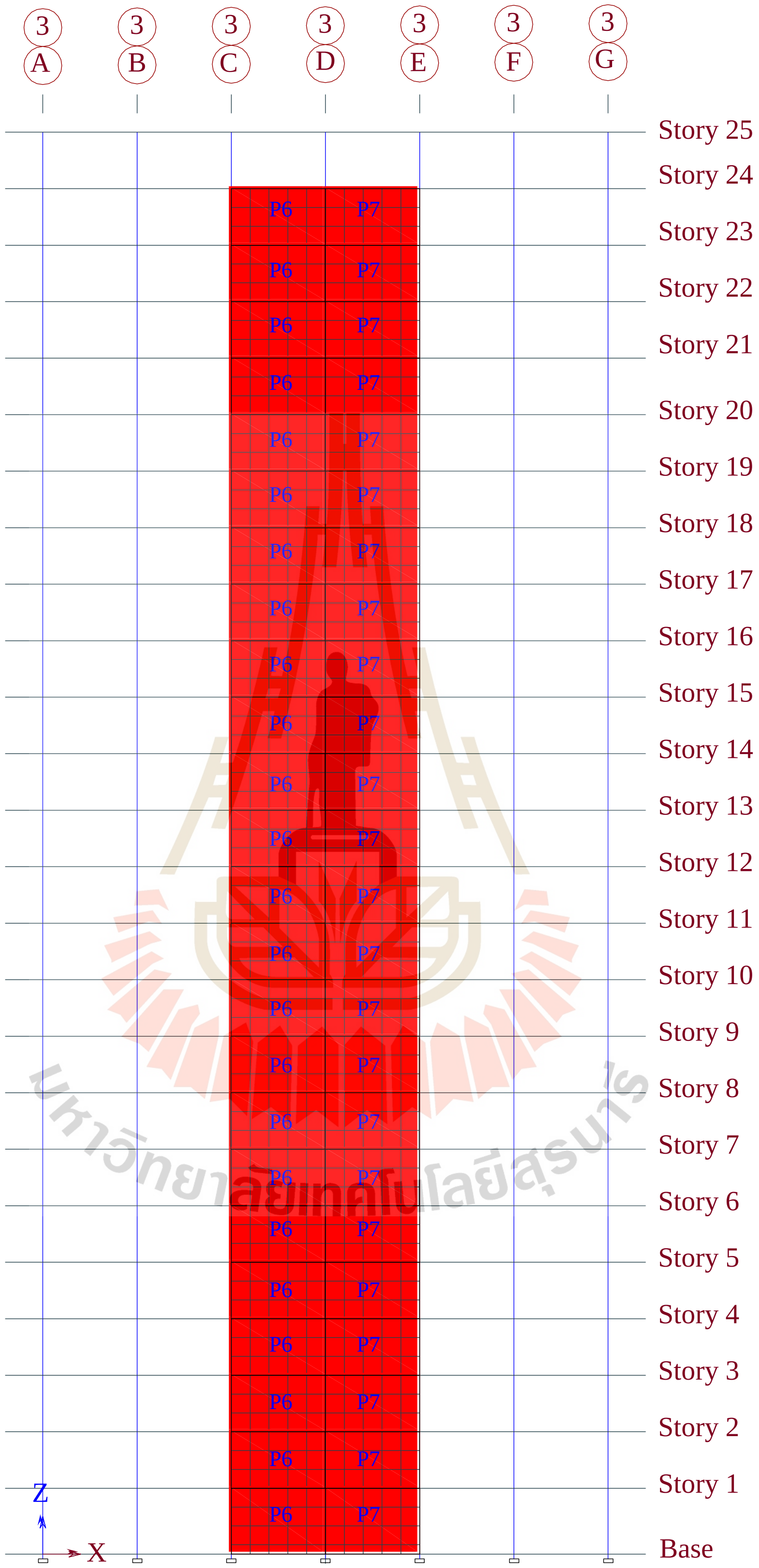


Figure 4.19 Elevation view 3

P5 and P8 are completely removed from the structure. Two shells of P6 and P7 are removed from the top story.

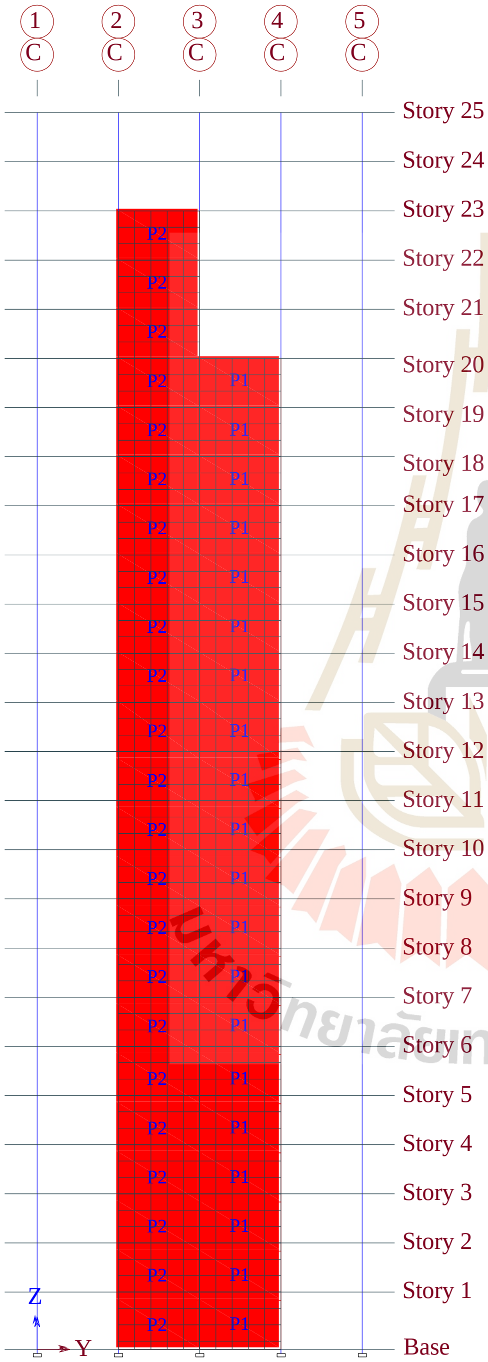


Figure 4.20 Elevation view C

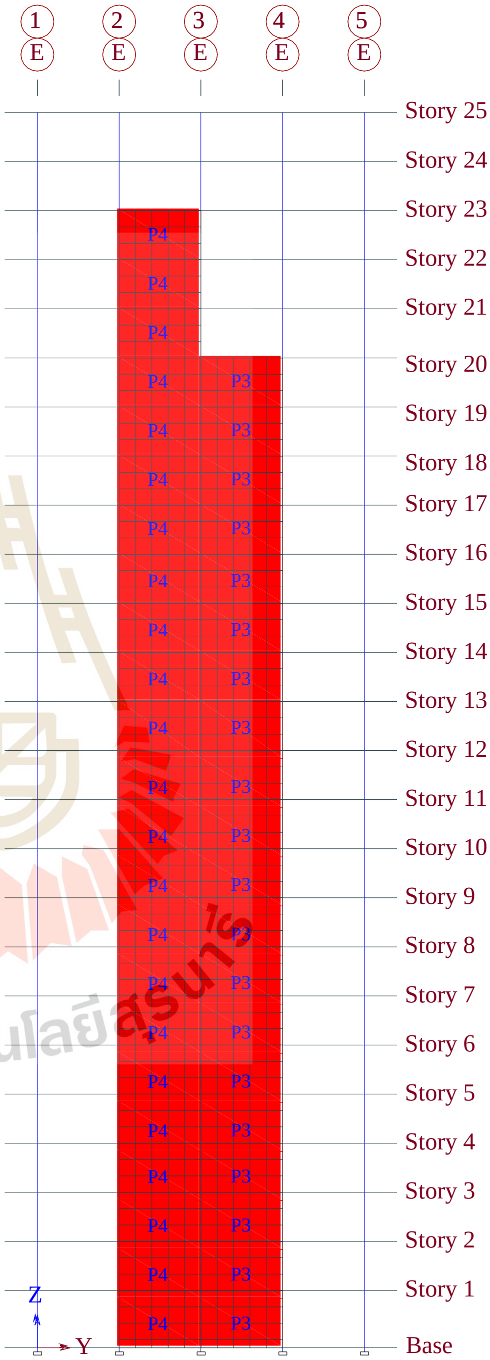


Figure 4.21 Elevation view E

P2 and P4 are removed from the top two stories. P1 and P3 are removed from the top five stories. All shells of structural walls and floors are meshed into 1m x 1m.

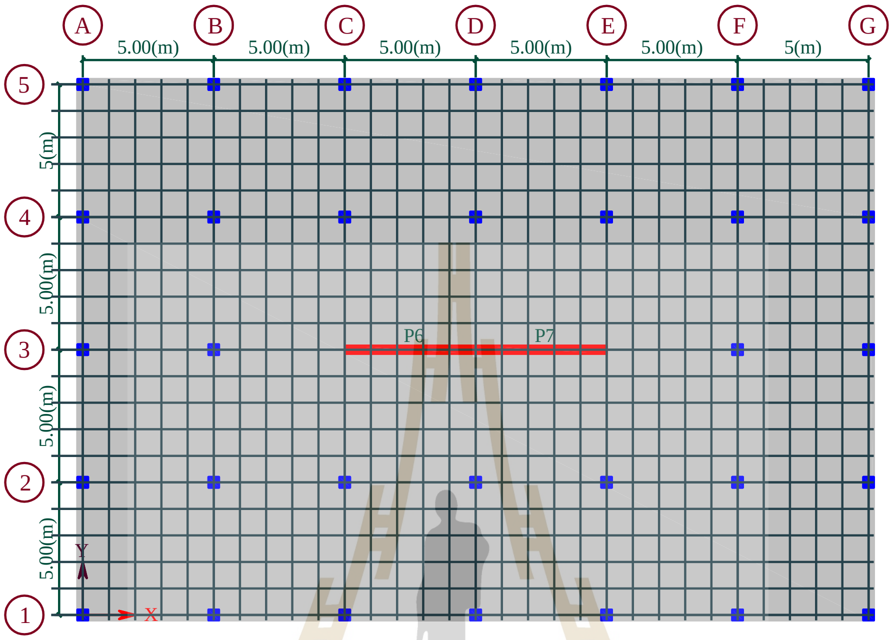


Figure 4.22 Plan view story 24

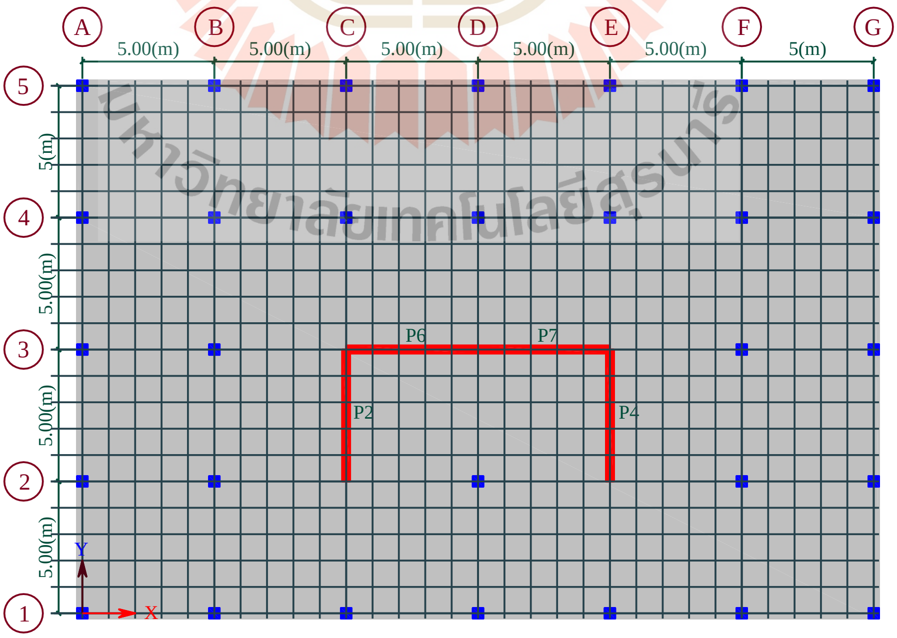


Figure 4.23 Plan view story 23, 22 and 21

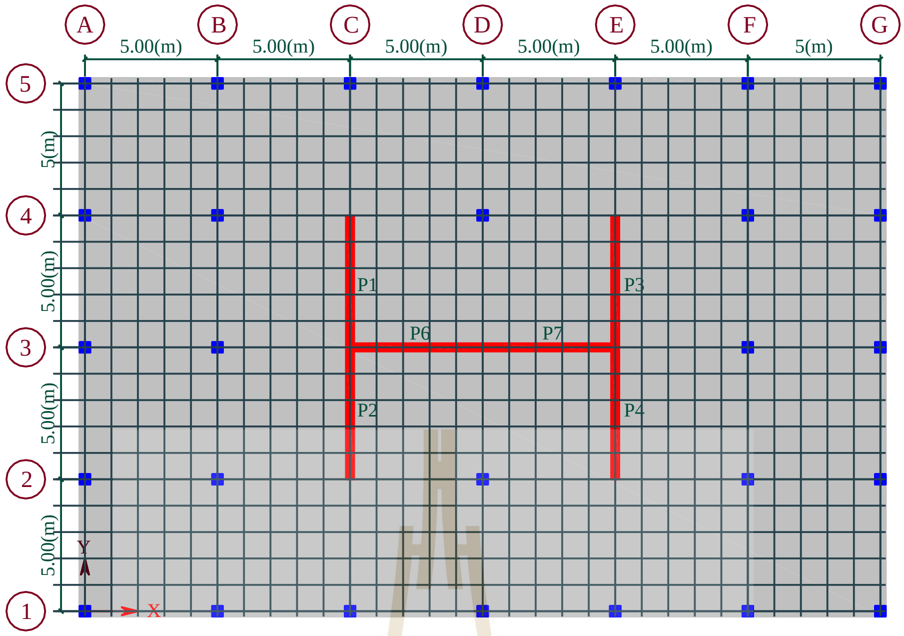


Figure 4.24 Plan view of story 20 downward to the base

4.7.1 Story-Drift Ratios

Table 4.41 Story-drift ratios in x and y-directions after shear walls are curtailed

Story	Drift Ratio in x-direction	Drift Ratio in y-direction
25	0.003	0.005
24	0.003	0.007
23	0.003	0.007
22	0.003	0.008
21	0.003	0.008
20	0.004	0.008
19	0.004	0.008
18	0.004	0.008
17	0.004	0.008
16	0.004	0.008
15	0.004	0.008
14	0.004	0.008
13	0.003	0.008
12	0.003	0.008

Table 4.41 Story-drift ratios in x and y-directions after shear walls are curtailed (Continued)

Story	Drift Ratio in x-direction	Drift Ratio in y-direction
11	0.003	0.007
10	0.003	0.007
9	0.003	0.007
8	0.003	0.006
7	0.003	0.006
6	0.002	0.005
5	0.002	0.005
4	0.002	0.004
3	0.001	0.003
2	0.001	0.002
1	0.001	0.001
Base	0.000	0.000

Table 4.33 shows that the story-drift ratios of the structure in both x and y-directions are still acceptable even if some shells of structural walls have been removed.

4.7.2 Overturning Moments

Table 4.42 Story weight of Model E after structural walls are curtailed

Story	Weight (kN)	Story	Weight (kN)
25	4279.68	12	59915.57
24	8559.37	11	64195.25
23	12839.05	10	68474.94
22	17118.73	9	72754.62
21	21398.42	8	77034.31
20	25678.10	7	81313.99
19	29957.79	6	85593.67
18	34237.47	5	89873.36
17	38517.15	4	94153.04
16	42796.84	3	98432.72
15	47076.52	2	102712.41
14	51356.20	1	107163.44
13	55635.89	Sum	1391068.53

Table 4.43 Overturning moments in x and y-directions of Model E after structural walls are curtailed

Story	M_x (kN-m)	M_y (kN-m)
25	1881.97	-1881.97
24	5731.88	-5731.88
23	11550.09	-11550.09
22	19270.37	-19270.37
21	28765.35	-28765.35
20	39960.23	-39960.23
19	52778.71	-52778.71
18	67095.43	-67095.43
17	82788.43	-82788.43
16	99739.30	-99739.30
15	117833.25	-117833.25
14	136959.22	-136959.22
13	157010.05	-157010.05
12	177882.58	-177882.58
11	199477.83	-199477.83
10	221701.19	-221701.19
9	244462.60	-244462.60
8	267676.80	-267676.80
7	291263.63	-291263.63
6	315148.34	-315148.34
5	339262.03	-339262.03
4	363542.17	-363542.17
3	387933.32	-387933.32
2	412388.18	-412388.18
1	440950.17	-440950.17
Sum	4483053.12	-4483053.12

$$SF_x = \frac{1391068.53 \times 15}{4483053.12} = 4.65 > 1.5 : \text{OK}$$

$$SF_y = \frac{1391068.53 \times 10}{4483053.12} = 3.10 > 1.5 : \text{OK}$$

The safety factors of Model E (with curtailed structural walls) are greater than the safety factors of other models since the shear force occurred in every story get decreased after structural walls are curtailed.

4.7.3 Story Displacements

Table 4.44 Percent of displacement increases in x-direction when structural walls are curtailed

Story	Displacement (full structural walls, cm)	Displacement (curtailed structural walls, cm)	Percent of increase (%)
25	8.96	15.31	70.81
24	8.54	14.58	70.76
23	8.11	13.80	70.26
22	7.67	13.03	69.75
21	7.23	12.25	69.36
20	6.79	11.49	69.16
19	6.35	10.73	69.14
18	5.90	9.97	69.07
17	5.45	9.21	69.01
16	5.01	8.46	68.95
15	4.57	7.71	68.88
14	4.13	6.97	68.80
13	3.70	6.25	68.71
12	3.29	5.54	68.61
11	2.88	4.85	68.48
10	2.49	4.19	68.34
9	2.12	3.56	68.18
8	1.77	2.97	68.00
7	1.43	2.41	67.82
6	1.13	1.89	67.64
5	0.85	1.43	67.52
4	0.61	1.02	67.49
3	0.40	0.66	67.78
2	0.22	0.37	68.60
1	0.09	0.15	70.31
Base	0.00	0.00	0.00

Average = 68.86%

Table 4.45 Percent of displacement decreases in y-direction when structural walls are curtailed

Story	**Displacement (full structural walls, cm)**	**Displacement (curtailed structural walls, cm)**	**Percent of decrease (%)**
25	37.08	33.47	-9.73
24	35.28	32.22	-8.66
23	33.46	30.61	-8.51
22	31.62	28.98	-8.35
21	29.78	27.32	-8.26
20	27.92	25.63	-8.2
19	26.05	23.92	-8.18
18	24.18	22.21	-8.14
17	22.31	20.5	-8.1
16	20.44	18.79	-8.06
15	18.59	17.1	-8.02
14	16.76	15.42	-7.98
13	14.96	13.77	-7.94
12	13.2	12.16	-7.91
11	11.5	10.59	-7.87
10	9.85	9.08	-7.84
9	8.29	7.64	-7.8
8	6.81	6.28	-7.77
7	5.44	5.02	-7.73
6	4.18	3.86	-7.7
5	3.06	2.82	-7.66
4	2.08	1.92	-7.62
3	1.27	1.18	-7.58
2	0.65	0.6	-7.5
1	0.22	0.2	-7.36
Base	0.00	0.00	0.00

Average = -8.02%

After some shells have been removed, the story displacement in x-direction increases 68.86% in average. However, in y-direction, it decreases 8.02% in average.

4.7.3 Pier Forces

The percentages of shear force resisted by piers (structural walls) in both directions for all stories are shown in **Table 4.46** and **4.47** below.

Table 4.46 Shear force resisted by piers in x-direction

Story	Pier shear force (kN)	Story shear force (kN)	Shear force resisted by pier (%)
25	0	627.32	0
24	839.27	1299.51	64.58
23	1376.65	1969.81	69.89
22	2029.98	2601.89	78.02
21	2606.7	3191.54	81.68
20	3069.57	3768.65	81.45
19	3628.03	4307.13	84.23
18	4118.11	4803.88	85.72
17	4571.41	5260.06	86.91
16	4985.95	5676.84	87.83
15	5364.65	6055.43	88.59
14	5709.13	6397.09	89.25
13	6021.05	6703.1	89.82
12	6301.96	6974.82	90.35
11	6553.48	7213.63	90.85
10	6777.24	7420.99	91.33
9	6974.91	7598.44	91.79
8	7148.23	7747.57	92.26
7	7299.03	7870.08	92.74
6	7429.3	7967.79	93.24
5	7540.56	8042.67	93.76
4	7637.6	8096.83	94.33
3	7709.04	8132.67	94.79
2	7827.37	8152.91	96.01
1	7827.37	8152.91	96.01
Base	7462.65	8161.23	91.44

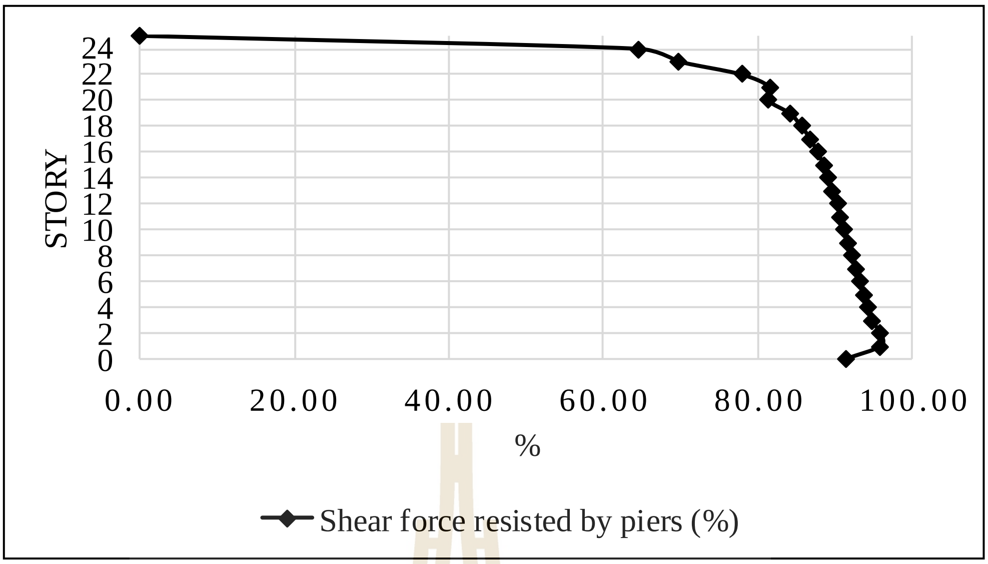


Figure 4.25 Percent of shear force resisted by piers in x-direction

The percentages of shear force resisted by piers in story 25 is zero since it does not have any shell of structural walls in this story.

Table 4.47 Shear force resisted by pier in y-direction

Story	**Pier shear force (kN)**	**Story shear force (kN)**	**Shear force resisted by piers (%)**
25	0	627.32	0
24	0	1299.51	0
23	1241.07	1969.81	63
22	1694.24	2601.89	65.12
21	2283.69	3191.54	71.55
20	2881.43	3768.65	76.46
19	3381.41	4307.13	78.51
18	3863.83	4803.88	80.43
17	4318.16	5260.06	82.09
16	4735.01	5676.84	83.41
15	5118.75	6055.43	84.53
14	5470.64	6397.09	85.52

Table 4.47 Shear force resisted by pier in y-direction (Continued)

Story	Pier shear force (kN)	Story shear force (kN)	Shear force resisted by piers (%)
13	5792.62	6703.10	86.42
12	6086.47	6974.82	87.26
11	6354.07	7213.63	88.08
10	6597.32	7420.99	88.9
9	6818.18	7598.44	89.73
8	7018.7	7747.57	90.59
7	7200.96	7870.08	91.5
6	7367.35	7967.79	92.46
5	7519.79	8042.67	93.5
4	7662.63	8096.83	94.64
3	7791.21	8132.67	95.8
2	7941.59	8152.91	97.41
1	7955.83	8152.91	97.58
Base	7955.83	8161.23	97.48

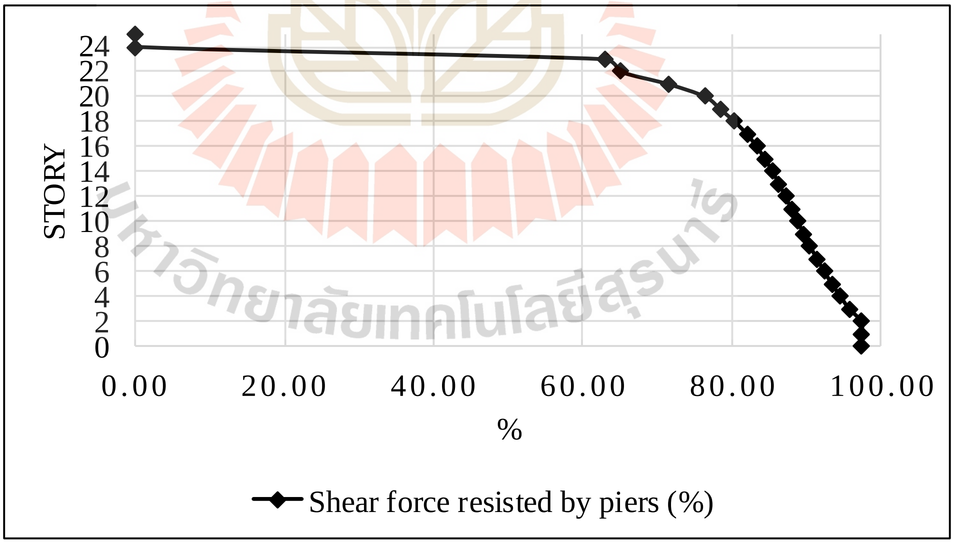


Figure 4.26 Percent of shear force resisted by piers in y-direction

Table 4.46 and **4.47** express that structural walls take nearly 100% of the total shear force in the story. As results, structural walls take 91.44% and 97.48% of the total shear force at the base of the structure in x and y-directions, respectively. The rests, 8.56% and 2.52%, are resisted by frames.

4.7.4 Comparison of Shear Force and Overturning Moment in Case of Using Full Height and Curtailed Structural Walls

- In x-direction

Table 4.48 Percent of shear force decrease in x-direction after structural walls are curtailed

Story	V_x (full shear walls)	V_x (curtailed shear walls)	% of decrease
25	-635.60	-627.32	-1.30
24	-1433.18	-1267.10	-11.59
23	-2181.93	-1908.99	-12.51
22	-2882.91	-2544.97	-11.72
21	-3537.19	-3138.44	-11.27
20	-4145.85	-3694.60	-10.88
19	-4710.02	-4238.53	-10.01
18	-5230.84	-4740.60	-9.37
17	-5709.50	-5201.95	-8.89
16	-6147.21	-5623.74	-8.52
15	-6545.21	-6007.20	-8.22
14	-6904.79	-6353.56	-7.98
13	-7227.29	-6664.12	-7.79
12	-7514.08	-6940.20	-7.64
11	-7766.60	-7183.21	-7.51
10	-7986.35	-7394.58	-7.41
9	-8174.88	-7575.83	-7.33
8	-8333.86	-7728.57	-7.26
7	-8465.03	-7854.47	-7.21
6	-8570.24	-7955.35	-7.17
5	-8651.49	-8033.13	-7.15
4	-8710.96	-8089.93	-7.13
3	-8751.08	-8128.10	-7.12
2	-8774.62	-8150.33	-7.11
1	-8784.92	-8159.90	-7.11
Base	-8786.66	-8161.23	-7.12

Average = -8.24 %.

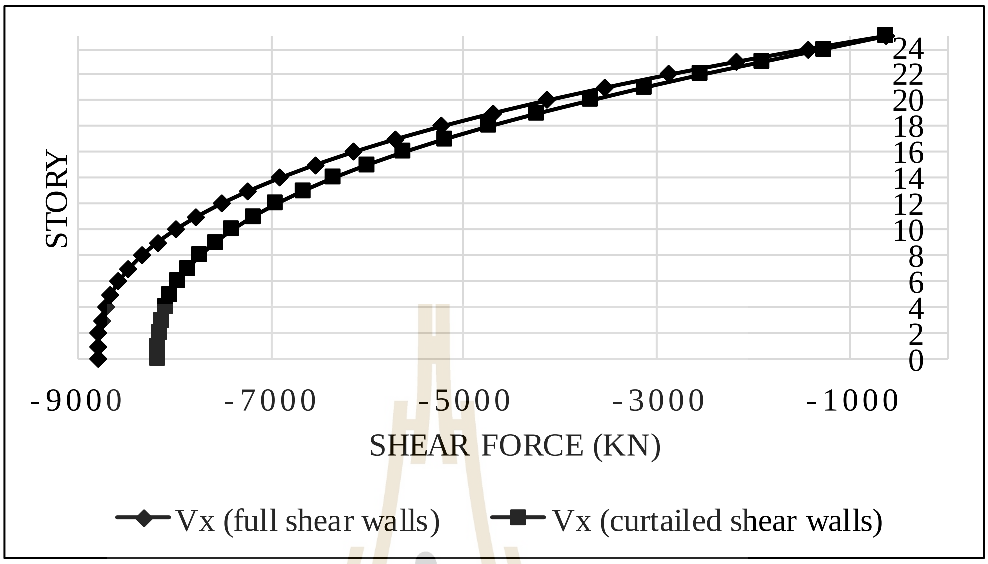


Figure 4.27 Differentiation of shear force in x-direction after structural walls are curtailed

Table 4.49 Percent of moment decrease about x-axis after structural walls are curtailed

Story	M_x (full shear walls)	M_x (curtailed shear walls)	% of decrease
25	0.00	0.00	0.00
24	2109.13	1881.97	-10.77
23	6599.01	5731.88	-13.14
22	13323.42	11550.09	-13.31
21	22139.30	19270.37	-12.96
20	32906.77	28765.35	-12.59
19	45489.29	39960.23	-12.15
18	59753.62	52778.71	-11.67
17	75570.03	67095.43	-11.21
16	92812.30	82788.43	-10.80
15	111357.86	99739.30	-10.43
14	131087.90	117833.25	-10.11
13	151887.48	136959.22	-9.83

Table 4.49 Percent of moment decrease about x-axis after structural walls are curtailed (Continued)

Story	M_x (full shear walls)	M_x (curtailed shear walls)	% of decrease
12	173645.66	157010.05	-9.58
11	196255.65	177882.58	-9.36
10	219615.01	199477.83	-9.17
9	243625.76	221701.19	-9.00
8	268194.66	244462.60	-8.85
7	293233.45	267676.80	-8.72
6	318659.08	291263.63	-8.60
5	344394.16	315148.34	-8.49
4	370367.30	339262.03	-8.40
3	396513.70	363542.17	-8.32
2	422775.89	387933.32	-8.24
1	449104.79	412388.18	-8.18
Base	479855.07	440950.17	-8.11

Average = -9.69 %.

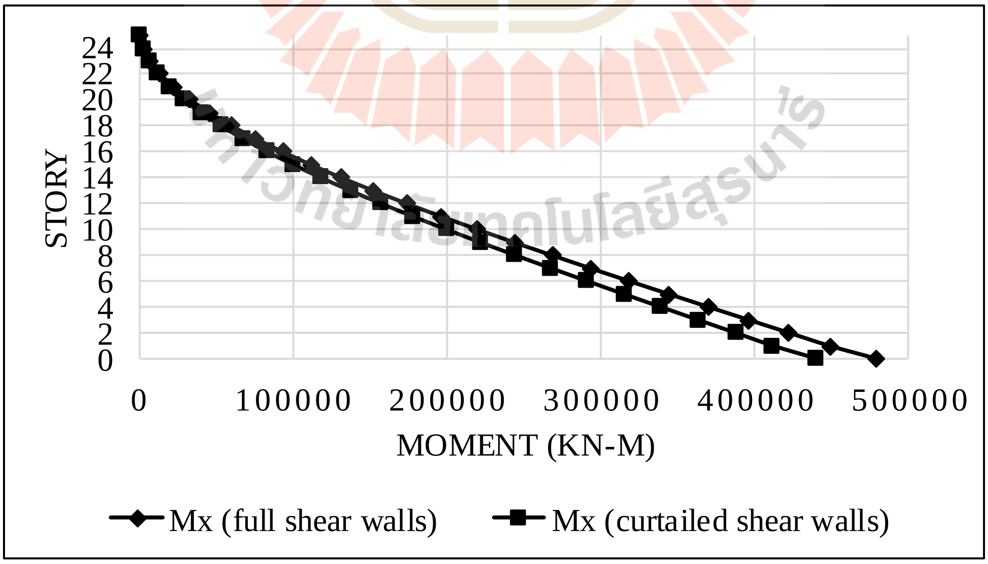


Figure 4.28 Differentiation of moment about x-axis after structural walls are curtailed

- In y-direction

Table 4.50 Percent of shear force decrease in y-direction after structural walls are curtailed

Story	V_y (full shear walls)	V_y (curtailed shear walls)	% of decrease
25	-635.60	-627.32	-1.30
24	-1433.18	-1267.10	-11.59
23	-2181.93	-1908.99	-12.51
22	-2882.91	-2544.97	-11.72
21	-3537.19	-3138.44	-11.27
20	-4145.85	-3694.60	-10.88
19	-4710.02	-4238.53	-10.01
18	-5230.84	-4740.60	-9.37
17	-5709.50	-5201.95	-8.89
16	-6147.21	-5623.74	-8.52
15	-6545.21	-6007.20	-8.22
14	-6904.79	-6353.56	-7.98
13	-7227.29	-6664.12	-7.79
12	-7514.08	-6940.20	-7.64
11	-7766.60	-7183.21	-7.51
10	-7986.35	-7394.58	-7.41
9	-8174.88	-7575.83	-7.33
8	-8333.86	-7728.57	-7.26
7	-8465.03	-7854.47	-7.21
6	-8570.24	-7955.35	-7.17
5	-8651.49	-8033.13	-7.15
4	-8710.96	-8089.93	-7.13
3	-8751.08	-8128.10	-7.12
2	-8774.62	-8150.33	-7.11
1	-8784.92	-8159.90	-7.11
Base	-8786.66	-8161.23	-7.12

Average = -8.24 %.

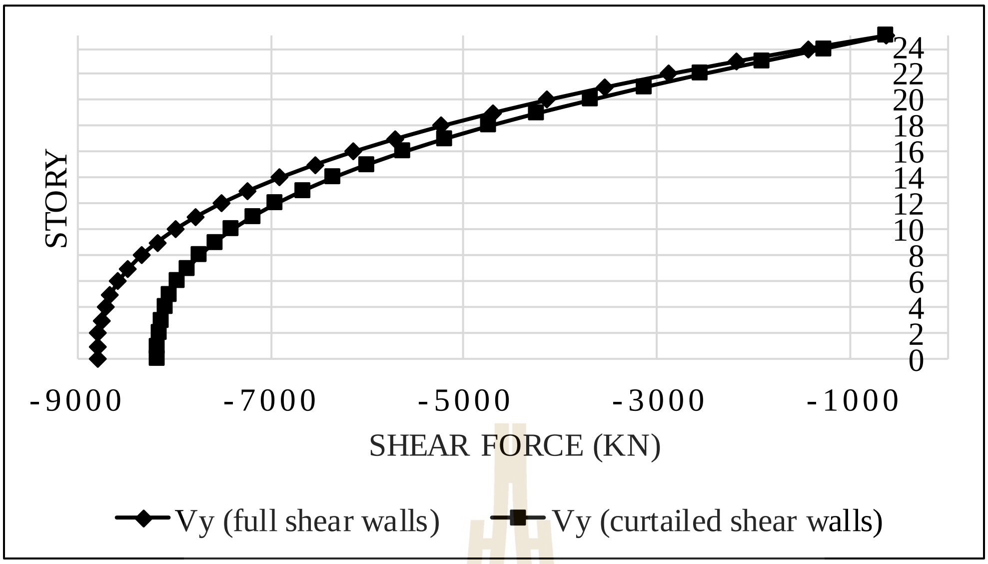


Figure 4.29 Differentiation of shear force in y-direction after structural walls are curtailed

Table 4.51 Percent of moment decrease about y-axis after structural walls are curtailed

Story	M_y (full shear walls)	M_y (curtailed shear walls)	% of decrease
25	0.00	0.00	0.00
24	-2109.13	-1881.97	-10.77
23	-6599.01	-5731.88	-13.14
22	-13323.42	-11550.09	-13.31
21	-22139.30	-19270.37	-12.96
20	-32906.77	-28765.35	-12.59
19	-45489.29	-39960.23	-12.15
18	-59753.62	-52778.71	-11.67
17	-75570.03	-67095.43	-11.21
16	-92812.30	-82788.43	-10.80
15	-111357.86	-99739.30	-10.43
14	-131087.90	-117833.25	-10.11
13	-151887.48	-136959.22	-9.83
12	-173645.66	-157010.05	-9.58
11	-196255.65	-177882.58	-9.36

Table 4.51 Percent of moment decrease about y-axis after structural walls are curtailed (Continued)

Story	M_y (full shear walls)	M_y (curtailed shear walls)	% of decrease
10	-219615.01	-199477.83	-9.17
9	-243625.76	-221701.19	-9.00
8	-268194.66	-244462.60	-8.85
7	-293233.45	-267676.80	-8.72
6	-318659.08	-291263.63	-8.60
5	-344394.16	-315148.34	-8.49
4	-370367.30	-339262.03	-8.40
3	-396513.70	-363542.17	-8.32
2	-422775.89	-387933.32	-8.24
1	-449104.79	-412388.18	-8.18
Base	-479855.07	-440950.17	-8.11

Average = -9.69 %.

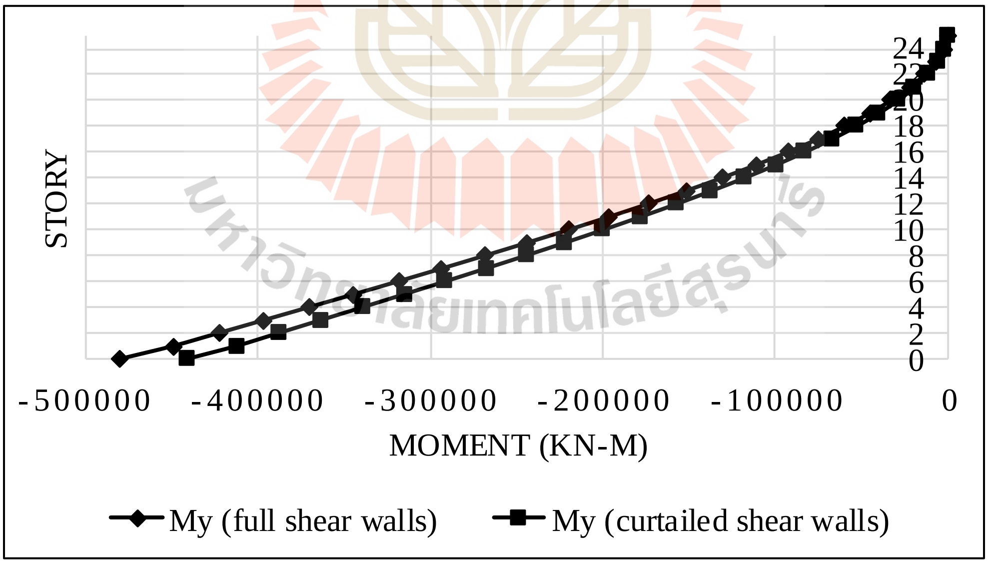


Figure 4.30 Differentiation of moment about y-axis after structural walls are curtailed

The values of shear forces in x and y-directions are the same since the seismic forces occurred in x and y-directions are equal.

4.7.5 Structural Walls Behavior at the certain curtailed level

After some shells of structural walls are removed, level 24, 23 and 20 are the points where structural and non-structural stories are met. These levels will be discussed.

Level 24 consist of 2 shells of structural walls which resist the seismic load in x-direction as shown in **Figure 4.32**.

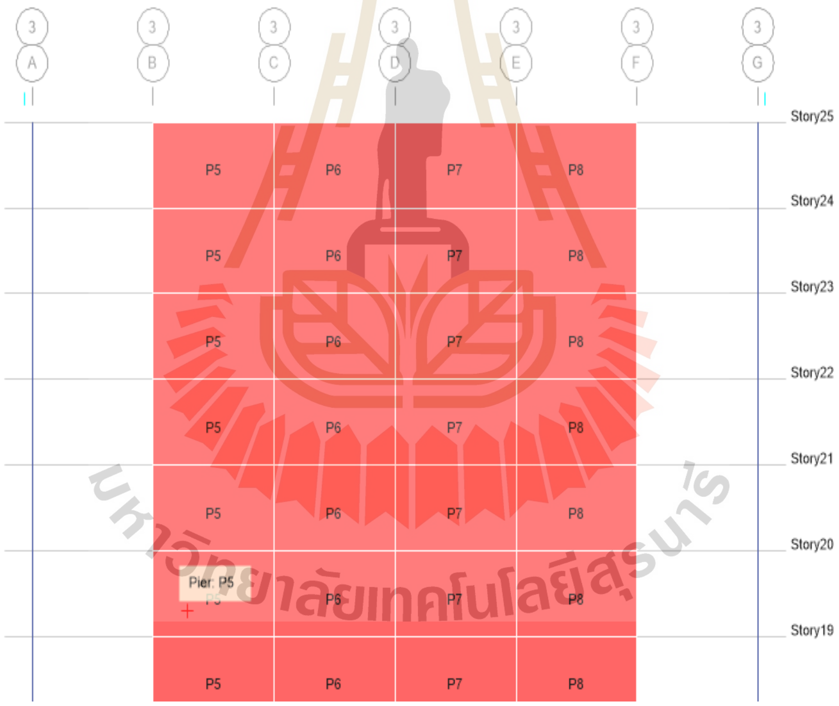


Figure 4.31 Structural walls which are used to resist the earthquake load in x-direction before the curtailment

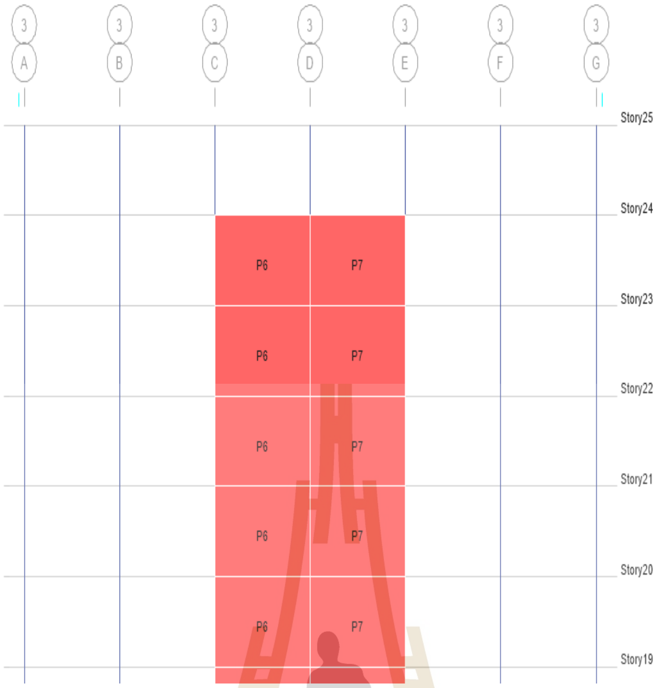


Figure 4.32 only P6 and P7 are used to resist the earthquake load in x-direction after the curtailment

Figure 4.31 and **4.32** show that structural walls are curtailed to story 24 (only in x-direction). Pier 5 and pier 8 (P5 and P8) are completely removed from the building. Therefore, there are only 2 shells of structural walls (P6 and P7) which are used to resist the earthquake load in x-direction.

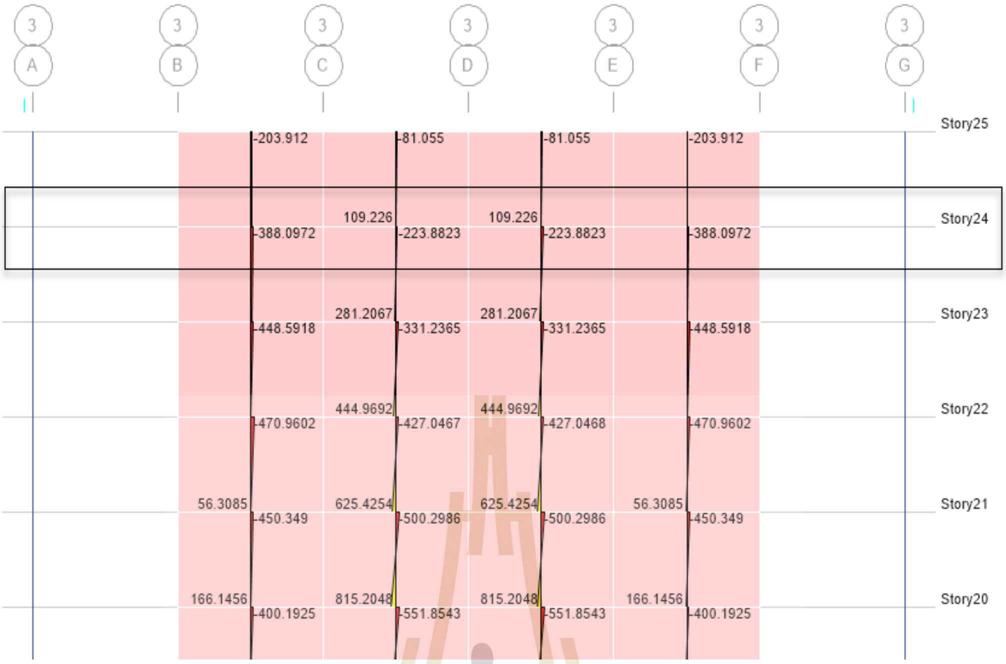


Figure 4.33 Moments in P5, P6, P7 and P8 at story 24 before the curtailment (kN-m)

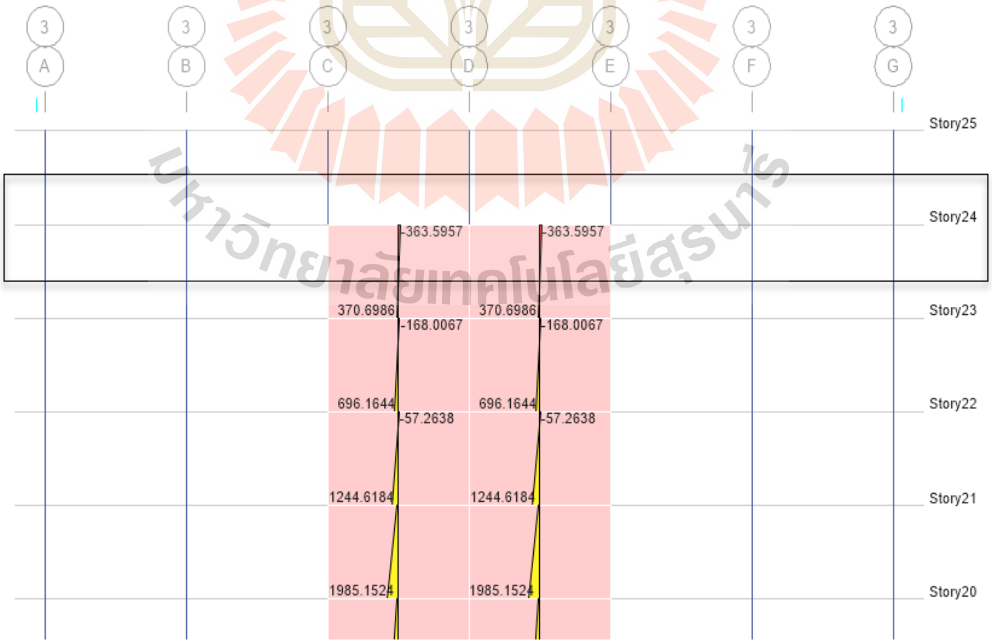


Figure 4.34 Moments in P6 and P7 at story 24 after the curtailment (kN-m)

Table 4.52 Moments in piers before and after the curtailment

Pier	Moment before the curtailment (kN-m)	Moment after the curtailment (kN-m)
P5	-388.10	-
P6	-223.88	-363.60
P7	-223.88	-363.60
P8	-388.10	-

Before the curtailment, the maximum moments are in pier 5 and pier 8 (-388.10 kN-m), and the minimum moments are in pier 6 and pier 7 (-223.88 kN-m). After the reduction, piers 6 and pier 7 change from minimum to the maximum moments (from -223.88 kN-m to -363.60 kN-m).

Table 4.53 Shear force and moment at story 24 after the structural walls are curtailed

Story shear force (kN)	V_x = -1267.10 kN
Story moment (kN-m)	M_y = -1881.97 kN
Shear forces in piers (P6 and P7) (kN)	V_x = = 806.86
Moments in piers (P6 and P7) (kN-m)	M_y = -727.20

Where, V_x and M_y are the shear force in x-direction and moment about y-direction, respectively.

Table 4.53 shows that pier 6 and pier 7 resist 63.68% of the total shear force and 38.64% of the total moment which occurred in story 24.

Level 23 consist of pier 2 and pier 4 (P2 and P4) to resist the seismic load in y-direction.

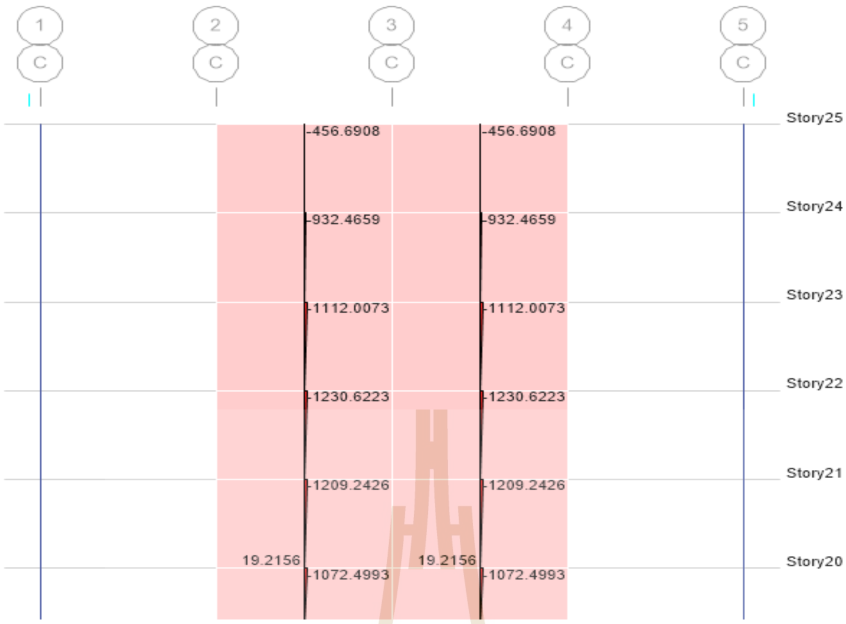


Figure 4.35 Moment in P1 and P2 before the curtailment (kN-m)

Before the curtailment, the moments are P1 = P2 = P3 = P4 = -1112.00 kN-m.

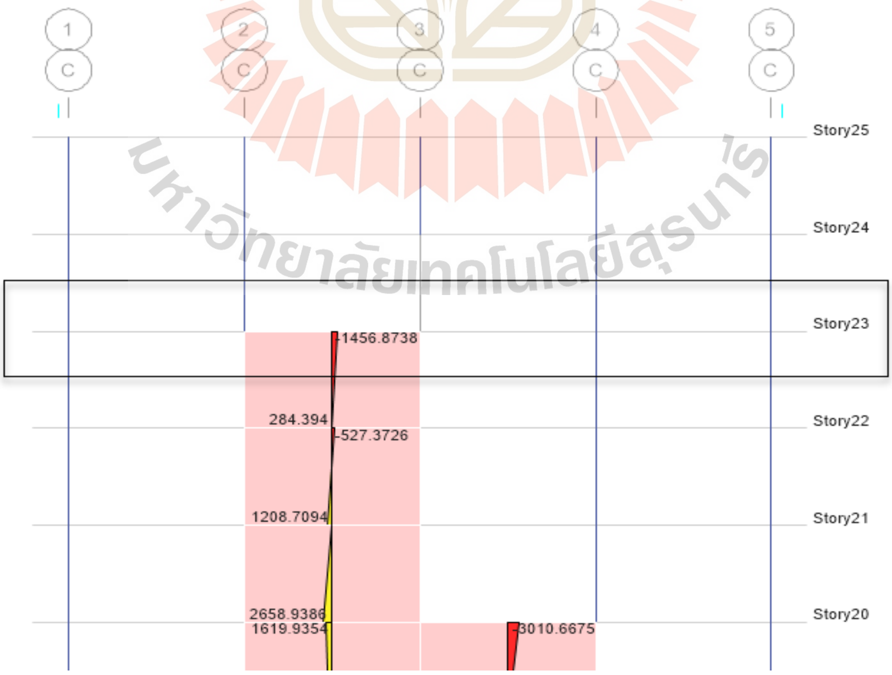


Figure 4.36 Moment in P2 at story 23 after the curtailment (kN-m)

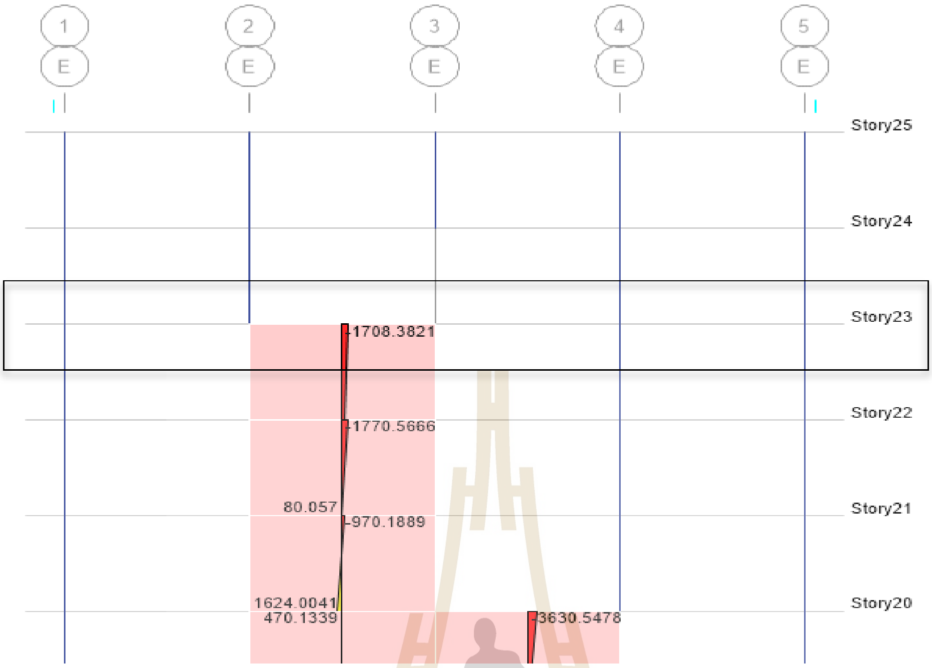


Figure 4.37 Moment in P4 at story 23 after the curtailment (kN-m)

Before the curtailment, every pier has the same moment (-1112.00 kN-m); after the curtailment, the maximum moment is in P4 = -1708.38 kN.

Table 4.54 Shear force and moment at story 23 after the curtailment

Story shear force (kN)	V_y = -1908.99 kN
Story moment (kN-m)	M_x = 5731.88 kN-m
Shear forces in piers (P2 + P4) (kN)	V_y = 958.50
Moments in piers (P2 + P4) (kN-m)	M_x = -3165.25

Table 4.54 shows that at story 23, P2 and P4 resist 50.21% of the total shear force and 55.22% of the total moment.

Level 20 consists of four piers to resist the seismic load in y-direction (P1, P2, P3 and P4).

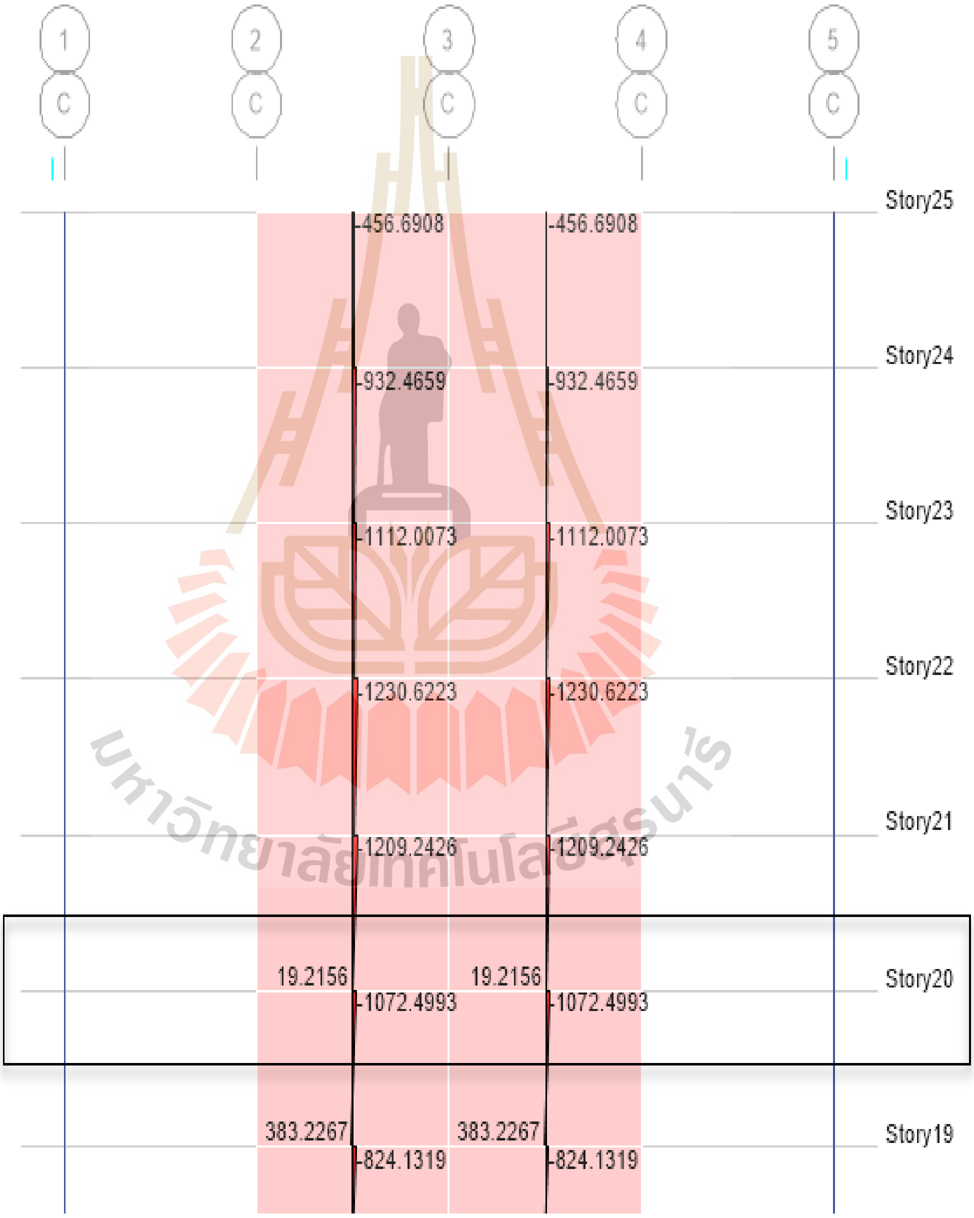


Figure 4.38 Moment in P1 and P2 at story 20 before the curtailment (kN-m)

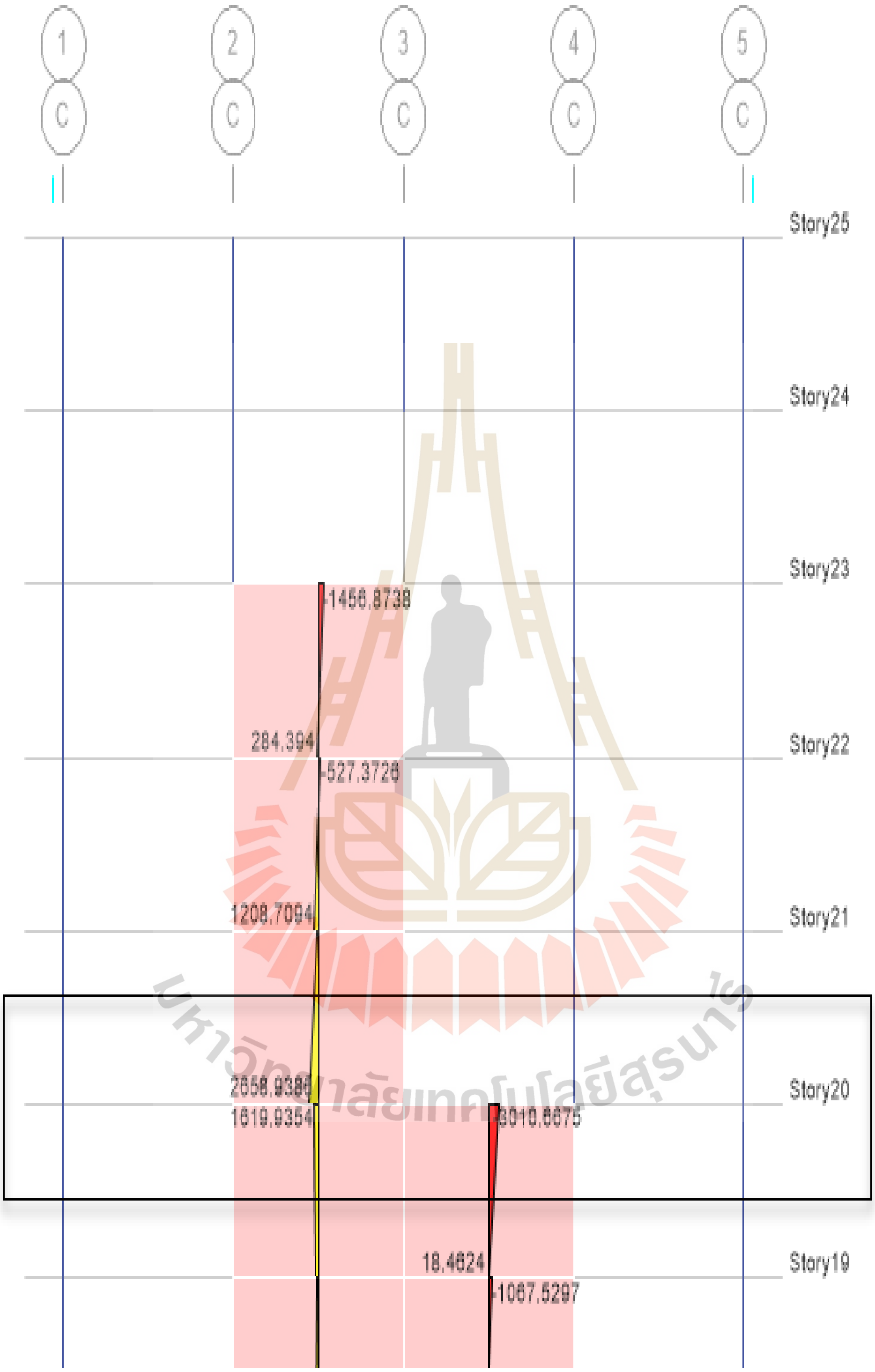


Figure 4.39 Moment in P1 and P2 at story 20 after the curtailment (kN-m)

Before the curtailment, moment occurred in P1, P2, P3 and P4 are equal, which is -1072.50 kN-m.

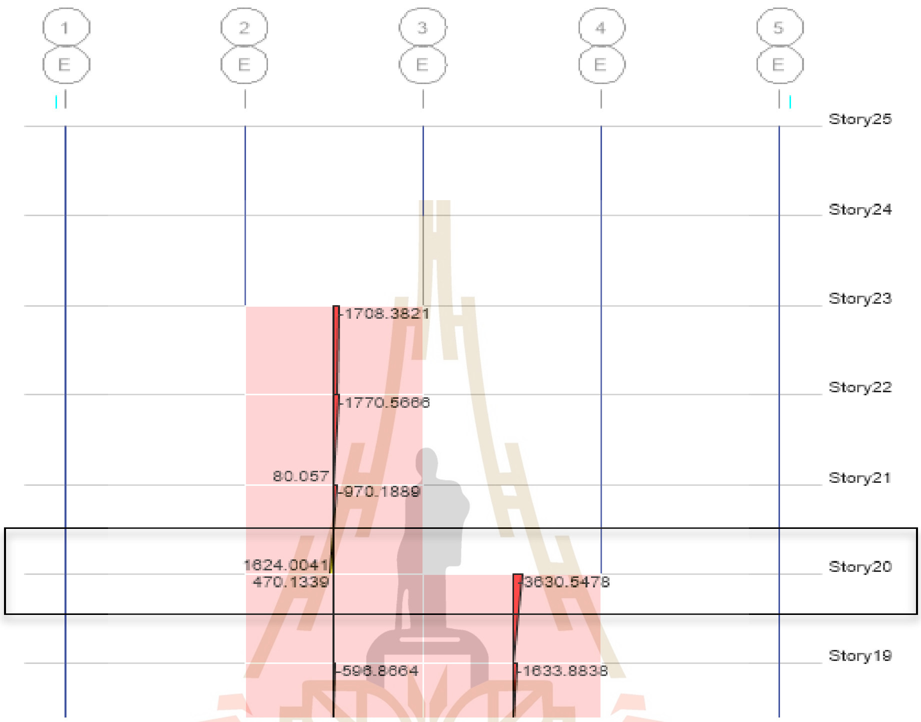


Figure 4.40 Moment in P3 and P4 at story 20 after the curtailment (kN-m)

Before the curtailment, all piers have the same moment (-1072.50 kN-m). After the curtailment, the maximum moment is in P3 (-3630.55 kN-m). It means that it increases 3.36 times when some structural walls are removed.

Table 4.55 Shear force and moment at story 20 after the curtailment

Story shear force (kN)	V_y = -3694.60 kN
Story moment (kN-m)	M_x = 28765.35 kN-m
Shear forces in piers (P1+ P2 + P3 + P4), (kN)	V_y = 3059.71
Moments in piers (P1 + P2 + P3 + P4), (kN-m)	M_x = 731.29

After the curtailment, at story 20, structural walls resist 82.82% of the total shear force and 30.35% of the total moment which occurred in this story.

4.7.4 Moment in Columns

Two columns, G1 and D2 are investigated at stories 24 and 12. The positions of G1 and D2 are shown in **Figure 4.41**.

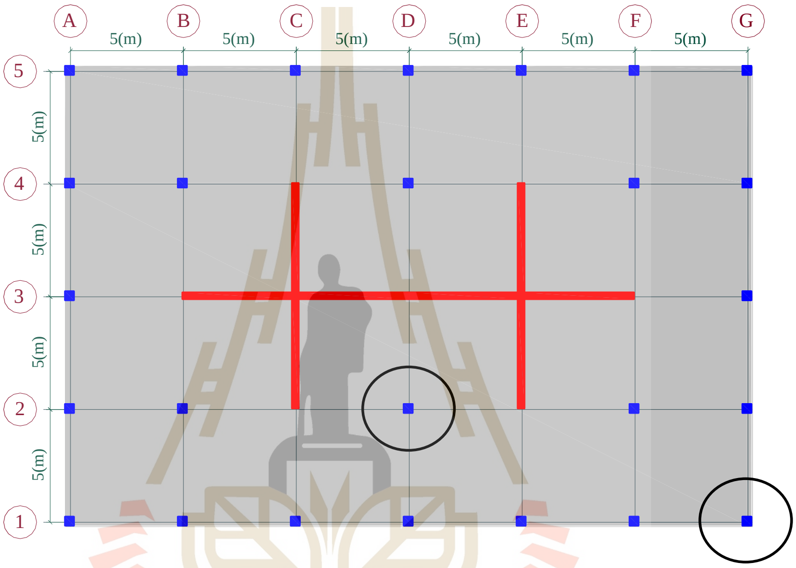


Figure 4.41 Locations of columns G1 and D2

Table 4.56 Moment about x and y-axes of G1 at story 24 and 12

Column G1				
Story 24				
Full shear walls	**Moment**	**Value (kN-m)**	**Percent of increase/decrease (%)**	
	M_x	-8.80	484.34	M_x
	M_y	-60.06		
Curtailed shear walls	M_x	-51.42	22.48	M_y
	M_y	-73.56		
Story 12				
Full shear walls	M_x	13.55	-35.80	M_x
	M_y	28.32		
Curtailed shear walls	M_x	9.98	18.14	M_y
	M_y	33.46		

For the column G1 at story 24, the moments increase 484.34% and 22.48% about x and y-axes, respectively, after shear walls are curtailed. However, at story 12, the moment decreases 35.80% about x-axis and increases 18.14% about y-axis.

Table 4.57 Moment about x and y-axes of D2 at story 24 and 12

Column D2				
Story 24				
	Moment	**Value (kN)**	**Percent of increase/decrease (%)**	
Full shear walls	M_x	-147.71	-28.36	M_x
	M_y	17.24		
Curtailed shear walls	M_x	-105.82	13.12	M_y
	M_y	19.51		
Story 12				
Full shear walls	M_x	86.30	-7.08	M_x
	M_y	10.15		
Curtailed shear walls	M_x	80.60	10.76	M_y
	M_y	11.24		

For the column D2 at story 24, the moments decreases 28.36% and increases 13.12% about x and y-axis, respectively, after shear walls are curtailed. Meanwhile, it decreases 7.08% and increases 10.76% about x and y-axis, respectively.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Without using any structural wall, wall-frame structures have large lateral displacements and story-drift ratios which caused by seismic force. After using structural walls, the lateral story displacements and story-drift ratios are decreased, and the most suitable position of structural walls is at the core of the structure (in case the plan view of the structure is symmetry). In case the structures are consisted of structural walls, their overturning moment is greater than the overturning moment of those which are not consisted of structural walls since shear force increases when structural walls are provided.

The elimination of structural walls from some upper parts of wall-frame structures is not necessarily detrimental to the lateral load performance of the structures.

In this research project, 66 shells of structural walls have been eliminated from some upper stories of the building without providing any effect on the lateral load performance of the wall-frame structure. For the upper stories which do not have any structural wall, the frames resist 100% of the total lateral load. Whereas the stories which consist of structural walls, most of the lateral load is resisted by structural walls. After the reduction of structural walls, the story displacements get increased in x-direction, and decreased in y-direction.

If structural walls are placed continuously in straight line, the first and last shells of structural walls resist moment more than the inside structural walls. For instance, in x-direction, P5 and P8 resist the moment more than P6 and P7.

When structural walls are curtailed, the exterior columns in the stories which do not have any structural wall will have large moment, but at the lower stories, moment in the exterior columns does not change very much. However, moment in the interior columns is not significant change no matter structural walls are curtailed or not.

For this research, the most suitable location of structural walls is Model E (structural walls are at the core of the structure), and 66 shells of structural walls have been removed from the upper stories without providing any effect on the lateral load performance of the building. Lateral story displacements are discussed, story-drift ratios and overturning moments are checked, and all are acceptable. However, in the real construction, P-delta effect should be checked since the lateral story displacements are large. Moreover, the method of analysis should be done by using both linear and nonlinear behaviors and compare their results together to get more accuracy response, and this could be the next research project.

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APPENDIX A

LIST OF PUBLICATIONS

List of Publications

INTERNATIONAL JOURNAL PAPER

Chen T., and Jiravacharadet M., **Effective positions of RC structural walls in RC buildings under seismic loading**., International Journal of Civil Engineering and Technology (IJCIET) 10(2019) pp. 1020-1029.

NATIONAL CONFERENCE

Chen T., and Jiravacharadet M., (2019), **Reduction of Shear Walls in High-Rise Wall-Frame Buildings Subjected to Seismic Load**. The 24th National Convention on Civil Engineering, Udonthani, Thailand, July 10th – 12th.

International Journal of Civil Engineering and Technology (IJCIET)
Volume 10, Issue 01, January 2019, pp. 1020-1029, Article ID: IJCIET_10_01_094
Available online at http://www.iaeme.com/ijciet/issues.asp?JType=IJCIET&VType=10&IType=01
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EFFECTIVE POSITIONS OF RC STRUCTURAL WALLS IN RC BUILDINGS UNDER SEISMIC LOADING

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ABSTRACT

This paper presents a study of finding the most effective position of RC structural walls in an RC building to resist with seismic load. Structural walls without any opening are used. By using Etabs, 5 models are created. Model 1 does not have any structural wall. Model 2, 3, 4 and 5 consist of structural walls in different positions and they are placed symmetrically in the plan view of the building. Story displacements, story-drifts and overturning moments in x and y-directions are checked and compared to each other to find the model which provides the highest stiffness. The calculation follows DPT 1302-61 code and Response spectrum equivalent static analysis method.

KEYWORDS: Building stiffness, linear static analysis, Response spectrum, Seismic analysis, Structural walls

Cite this Article: Thearith Chen and Mongkol Jiravacharadet, Effective Positions of Rc Structural Walls in Rc Buildings Under Seismic Loading. International Journal of Civil Engineering and Technology, 10(01), 2019, pp. 1020–1029

http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=10&IType=01

1. INTRODUCTION

In the past, engineers never thought seismic was going to happen in Thailand, but later on, Thailand has become one of the countries which located in a seismic-prone area, especially, in the northern part of the country. In 2014, an earthquake of 6.3 magnitude occurred in Chiang Rai Province, northern part of Thailand and a lot of buildings and infrastructures were destroyed [1]. Hence, seismic affects are now considered in the building design and become a popular topic for Thai structural engineers. There are different types of the protections of buildings against earthquake such as using viscous dampers, tuned mass dampers, base isolation, structural walls (also known as shear walls), etc. However, in this paper, structural walls are used to demonstrate the capacity of resisting against earthquake load in a reinforced concrete (RC) building. RC structural walls are RC walls which provide large in-plane stiffness. They work very effective in resisting with axial forces, shear forces and bending moments [2]. RC structural walls can be used to separate rooms, enclose elevators, be stairwells to support staircases or resist with lateral loads occurred from wind and seismic. They can be used either without any opening or with openings such as windows and doors and they may be simple planar walls or many walls segments connected together [3].

The position of structural walls should be placed correctly, otherwise they will provide disadvantages instead of advantages. These structural walls generally start from the foundation and continue upward along the building height and their minimum thickness can be 150 millimeters [4].

Reference [4] determined the most suitable position of structural walls in multi-story buildings and concluded that structural walls should be placed at the middle or at the corners of the buildings and should be placed in the form of a box. Reference [5] carried out a study to determine the best position of structural walls in multi-story buildings using genetic algorithm and proved that the best position of structural walls is only at or near the core of the buildings. Reference [6] evaluated about the usage of structural walls and braces in buildings subjected to seismic and stated that the correct place of structural walls is at the point where the center of mass and the center of rigidity are met. Reference [7] researched about the design of structural walls using response spectrum method and showed that structural walls work very well to reduce internal forces of every member both in regular and irregular buildings. Reference [8] presented about the best placement of structural walls in a reinforced concrete space frame based on seismic response and illustrated that the building consists of structural walls has lower displacements and internal forces than the building without any structural wall. Reference [9] studied about the significant of structural walls in multi-story buildings subjected to earthquake and summarized that structural walls increase much stiffness and strength to the structures.

In this study case, the main goal is to find the appropriate positions of structural walls in a reinforced concrete building subjected to seismic load. It is a simulated building and is supposed to be in Chiang Rai Province, Mae Lao District, northern part of Thailand. To withstand with this lateral load, special RC structural walls are used. Special RC structural walls are RC walls which provide high capacity of ductility and can resist at least 25% of the total lateral loads. In the step of analysis, the accidental torsion is also considered by taking the eccentricity (e) is equal to 5% of the total length. The eccentricity (e) is the length measured from the center of mass (CM) to the center of rigidity (CR) perpendicular to the directions of lateral loads [10]. The structures are modeled in Etabs program. Story displacements, story-drifts and overturning moments in x and y-directions are checked and compared to each other to find the model which provides the highest stiffness.

2. BUILDING PROPERTIES AND SEISMIC ZONE

This structure is supposed to be a six stories police station building which carries the important factor (I), response modification factor (R), system over strength factor (Ω_o) and deflection amplification factor (C_d) are equal to 1.5, 7, 2.5 and 5.5 respectively [10]. The type of soil is D and subjected to a high level seismic force.

It is a six stories building with the area of 30 m × 20 m. The bottom story is 3.5 m height and 3.0 m for the rests. There are six bays along length and four bays along width. Every bay is 5 m. All columns are the same size that is 0.3 m × 0.3 m. The slab of every floor is a flat plate with the thickness of 0.16 m (no beam and no drop panel) and is subjected to 2 kn/m^2 of super imposed dead load (S_dead) and 3 kn/m^2 of live load (LL). The concrete in the hold structure is homogenous with the compressive strength at 28 days (f'_c) is equal to 24 N/mm^2. The standard of rebar is SD40 with the yield strength (f_y) is equal to 400 N/mm^2. The thickness of the special RC structural walls is 0.3 m.

3. BUILDING FORM AND LOCATIONS OF STRUCTURAL WALLS MODELED IN ETABS

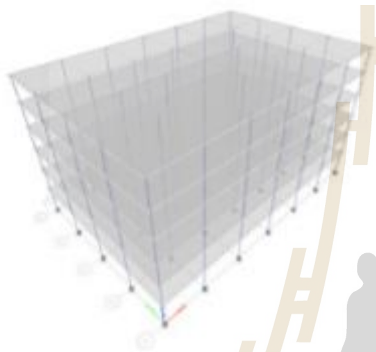

Figure 1: 3D View

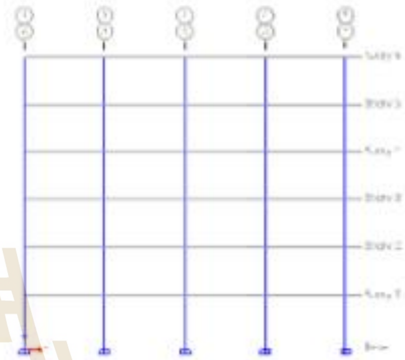

Figure 2: Elevation

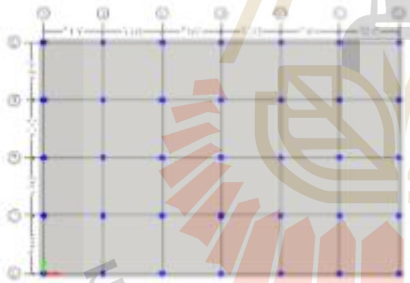

Figure 2: Model 1

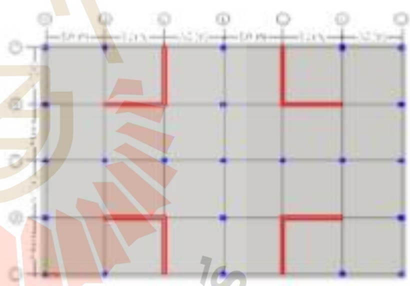

Figure 4: Model 2

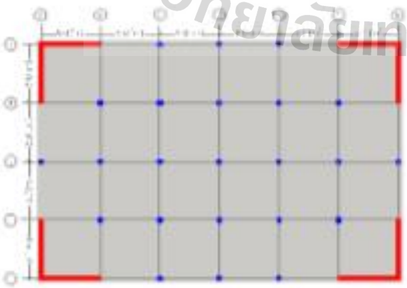

Figure 5: Model 3

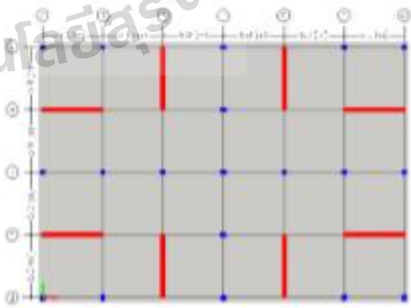

Figure 6: Model 4

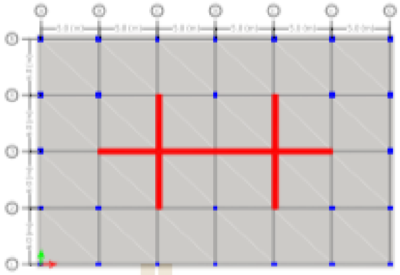

Figure 7: Model 5

4. ANALYSIS METHOD

This project is analyzed by using Response spectrum equivalent static analysis and covered by the DPT 1302-61 code using strength design method (SDM). The seismic loads in x and y-directions are considered, however, these two lateral loads are not supposed to occur in the same time. All supports at the base of the columns are supposed to be fixed.

4.1. Load combinations

Strength design method (SDM) provides 9 load case combinations.

$$1.4DL + 1.7LL \quad (1)$$

$$0.75\,(1.4DL + 1.7LL) + 1.0E_x \quad (2)$$

$$0.75\,(1.4DL + 1.7LL) - 1.0E_x \quad (3)$$

$$0.75\,(1.4DL + 1.7LL) + 1.0E_y \quad (4)$$

$$0.75\,(1.4DL + 1.7LL) - 1.0E_y \quad (5)$$

$$0.9DL + 1.0E_x \quad (6)$$

$$0.9DL - 1.0E_x \quad (7)$$

$$0.9DL + 1.0E_y \quad (8)$$

$$0.9DL - 1.0E_y \quad (9)$$

DL is the dead load and is equal to self-weight plus super imposed dead load. E_x and E_y are earthquake loads in x and y-directions respectively.

4.2. Response spectrum curve

Since the location of the building is not in Bang Kok, fig 8 must be used.

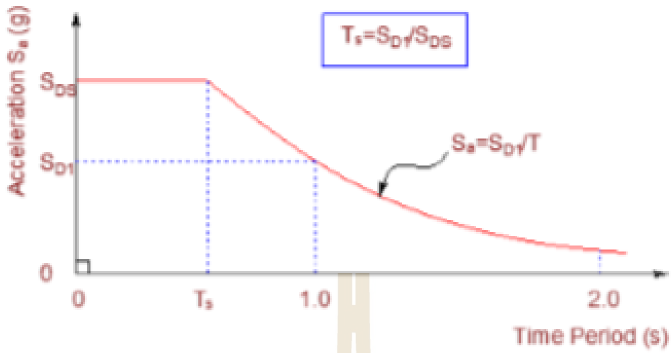

Figure 8: Spectrum acceleration for equivalent static analysis for all zones in Thailand, except Bang Kok in case $S_{D1} \leq S_{DS}$

S_{DS} and S_{D1} are the response spectrums at 0.2 and 1 second respectively. According to the location of the building is in Chieng Rai, so $S_S = 0.884g$ and $S_1 = 0.220g$, where S_S and S_1 are Spectrum accelerations at the considering location at 0.2 and 1 second respectively. For soil type D, $F_a = 1.15g$ and $F_v = 1.9g$, where F_a and F_v are coefficients of soil at the considering location at 0.2 and 1 second respectively. $S_{DS} = \frac{2}{3} \times F_a \times S_s = 0.678g$ and $S_{D1} = \frac{2}{3} \times F_v \times S_1 = 0.279g$. Natural period of vibration, $T = 0.002H = 0.37\ second > 0.8T_s = 0.33\ second$, where $T_s = \frac{S_{D1}}{S_{DS}}$ and H is the total heights of the building above ground surface (18.5m).

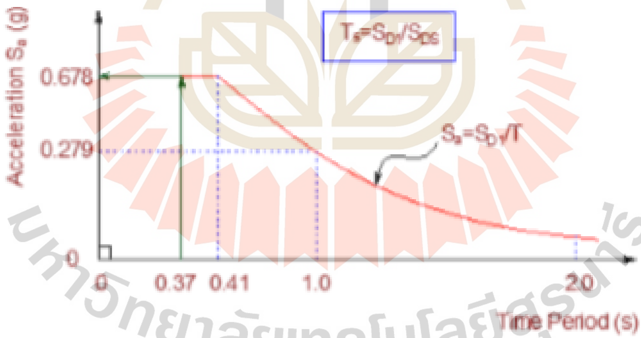

Figure 9: The value of $S_a = S_{DS} = 0.678g$ calculated as per DPT 1302-61 code

According to Fig 9, $T = 0.37$ second ➔ $S_a = S_{DS} = 0.678g$. Base shear coefficient, $C_S = S_a \times \frac{I}{R} = 0.1453g \approx 0.15 \geq 0.01 : OK$. Shear force at the base of the building, $V = C_S \times W = 0.15W$, where W is the weight of the building (self-weight plus super imposed dead load). Since $T = 0.37$ second ≤ 0.5 second ➔ K= 1.0, where K is the Building height exponent.

5. RESULTS AND DISCUSSION

Story displacements, story-drifts and over turning moments in x and y-directions are checked through DPT 1302-61 code. For this project, the allowable story drift is 0.01 [10].

5.1. Story displacements

Table 1: Story displacements in x-direction (cm)

Story	Model 1	Model 2	Model 3	Model 4	Model 5
6	15.7612	0.542	0.5636	1.1092	0.1282
5	14.6064	0.4337	0.4498	0.8748	0.1116
4	12.6142	0.3234	0.3345	0.6407	0.0913
3	9.8855	0.2164	0.2231	0.4181	0.0683
2	6.6095	0.1203	0.1235	0.2231	0.0442
1	3.0769	0.0447	0.0457	0.0764	0.0211
0	0	0	0	0	0

Table 2: Story displacements in y-direction (cm)

Story	Model 1	Model 2	Model 3	Model 4	Model 5
6	15.6985	0.5581	0.564	1.1273	0.362
5	14.5428	0.4457	0.4501	0.8883	0.2916
4	12.5558	0.3316	0.3347	0.65	0.2193
3	9.8387	0.2213	0.2232	0.4237	0.1486
2	6.5796	0.1227	0.1236	0.2258	0.0846
1	3.066	0.0454	0.0457	0.0772	0.0335
0	0	0	0	0	0

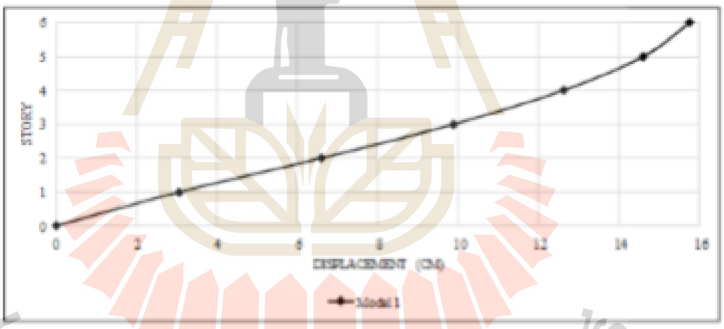

Figure 10: Story displacements in x-direction for Model 1

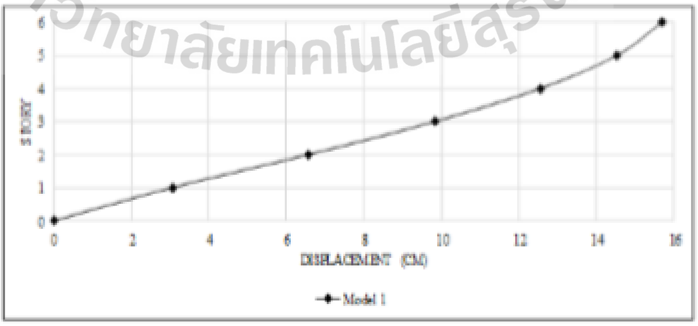

Figure 11: Story displacements in y-direction for Model 1

Model 1 (no structural wall) is plotted separately from other four Models because its values (both story displacements and story drifts) are too high compared to other Models. If Model 1 is plotted in the same graph with the other four models, it is difficult to see the curves consist of small values (Model 2 to Model 5).

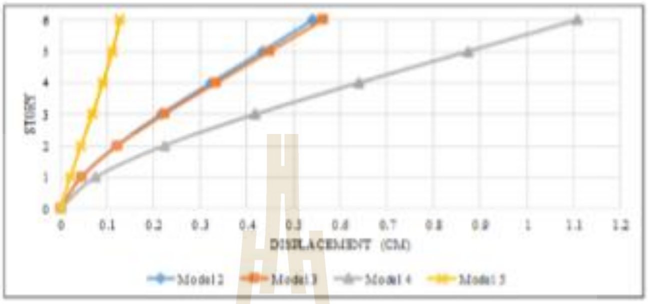

Figure 12: Story displacements in x-direction

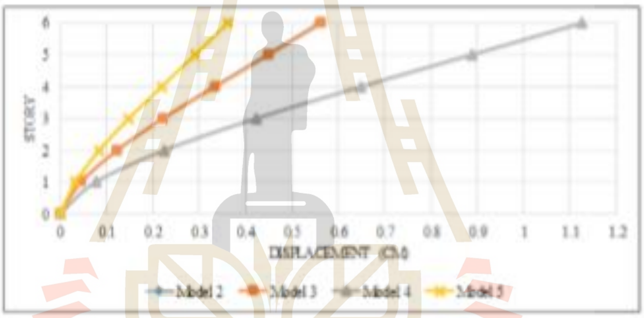

Figure 13: Story displacements in y-direction

The tables and graphs above show that after putting structural walls, the displacements are significantly reduced, meanwhile, Model 5 provides the highest reduction values of story displacements. As a result, for x-direction, the displacement at the top of the building reduces 122.94 times compared to Model 1 (from 15.7612 cm to 0.1282 cm). Similarly, it reduces 43.36 times in y-direction (from 15.6985 cm to 0.3620 cm).

5.2. Story-drifts

Table 3: Story-drifts in x-direction

Story	Model 1	Model 2	Model 3	Model 4	Model 5
6	0.0042	0.0004	0.0003	0.0009	0.0001
5	0.0072	0.0004	0.0003	0.0009	0.0001
4	0.0098	0.0004	0.0003	0.0008	0.0001
3	0.0118	0.0003	0.0003	0.0007	0.0001
2	0.0127	0.0002	0.0002	0.0005	0.0001
1	0.0094	0.0001	0.0001	0.0002	0.0000
0	0.0000	0	0	0	0

Table 4: Story-drifts in y-direction

Story	Model 1	Model 2	Model 3	Model 4	Model 5
6	0.0045	0.0004	0.0003	0.0010	0.0004
5	0.0078	0.0004	0.0004	0.0010	0.0004
4	0.0106	0.0004	0.0003	0.0010	0.0004
3	0.0127	0.0004	0.0003	0.0009	0.0003
2	0.0137	0.0003	0.0002	0.0006	0.0003
1	0.0102	0.0001	0.0001	0.0003	0.0001
0	0.0000	0	0	0	0

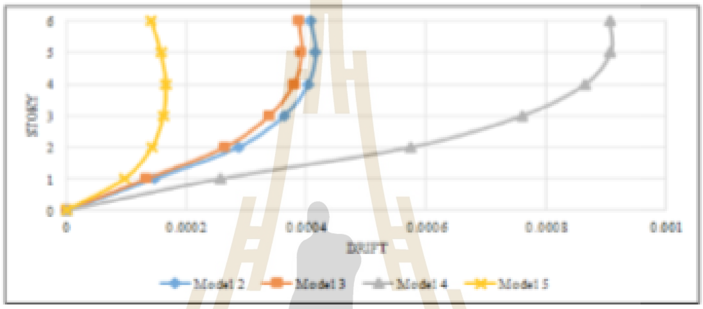

Figure 14: Story-drifts in x-direction

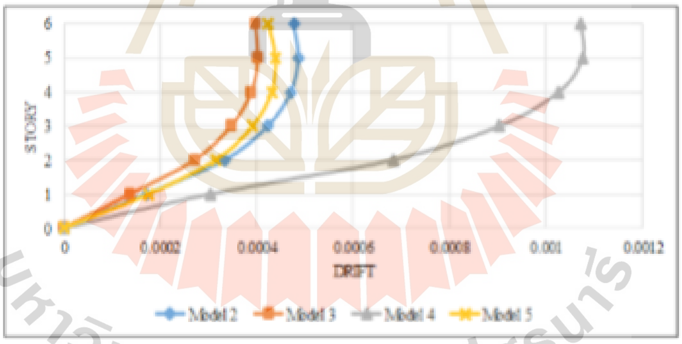

Figure 15: Story-drifts in y-direction

As mentioned earlier, the allowable story-drift is 0.01. Table 4 shows that Model 1 provides the story-drifts greater than 0.01 at the first, second, third and fourth floors. After using the structural walls, all Models and stories provide the story-drifts less than 0.01 and that means the building is safe. Fig 14 shows that Model 5 provides the smallest story-drifts and Fig 15 shows that Model 3 provides the smallest story-drifts. However, Model 5 is considered to be the most appropriate position of structural walls. As a result, in Table 3 and 4, the story-drifts of the second floor reduce 127 times and 45.66 times in x and y-directions respectively compared to the nonstructural wall model.

5.3. Overturning moments

The building does not fail if it satisfies $SF = M_r/M_a$, where SF is the safety factor against overturning moment and should be equal to or greater than 1.5. M_r is the reaction moment calculated by multiplying the weight of the building (self-weight plus super imposed dead load) with the moment arm to its pivot. M_a is the overturning moment caused by the total lateral forces. Etabs provides the safety factors against overturning in x and y-directions as shown in Table 5 below.

Table 5: Safety factors against overturning moment in x and y-directions

Model	SF in x-dir.	SF in y-dir.
Model 2	9.61	6.40
Model 3	9.61	6.40
Model 4	9.62	6.41
Model 5	9.60	6.40

All the models consist of structural walls provide the safety factors greater than 1.5 both in x and y-directions. Hence, this building has sufficient weight to resist against overturning moments.

6. CONCLUSIONS

Depend on the results above, a few points can be concluded.

- The best position of structural walls is Model 5.
- Table 1, Table 2, Table 3, Table 4, Fig 12, Fig 13, Fig 14 and Fig 15 prove that structural walls have very high in-plane stiffness to reduce story displacements and story-drifts caused from seismic load.
- The longer distance between structural walls, the lower stiffness they provide. The closer distance, the higher stiffness (Model 5 provides the highest stiffness and Model 4 provides the lowest stiffness).
- A single shell of structural wall withstand very well with axial forces, shear forces and bending moments, so no need to use columns at its both ends because it has already been a column by itself.
- The most effective position of structural walls is at the core of the building (Model 5 expressed the highest stiffness).

6.1. Recommendations

To make the structural walls reach the maximum stiffness, the following conditions should be satisfied:

- All shells of structural walls should be connected to one another as a rigid object.
- Put structural walls at the middle of the building (at core) so that they can be connected to one another.
- All shells of structural walls should be put symmetrically so that the center of mass (CM) and the center of rigidity (CR) are at the same point (when CM and CR are at the same point, the building does not have any torsion moment caused by lateral loads).

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BIOGRAPHY

Mr. Thearith Chen was born in 1990 in Tbong Khmum Province, Cambodia. He finished high school in 2018 from Tbong Khmum High School. In 2015, he graduated his bachelor's degree in civil engineering from the National University of Laos under the Government Exchange Scholarship between Cambodia and Laos PDR. After finishing bachelor's degree, he started work immediately as an office engineer at Engineering Design and Consultant, Vientiane, Laos PDR, for one year. Then he moved to Phnom Penh, Cambodia, to work as a site engineer for one year at Borey Lay Kung. In 2018, he received the Thailand Scholarship to pursue his master's degree of civil engineering, specialized in structural design for two years at Suranaree University of Technology, Nakhon Ratchasima, Thailand. During his two years period study, he published one international journal and one national conference.