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ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

EFFECT OF SHEAR WALL AREA TO FLOOR AREA RATIO ON THE SEISMIC RESPONSE OF REINFORCED CONCRETE BUILDINGS

A Thesis Submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Structural Engineering

BY

Tenagnework Shumate

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The undersigned have examined the thesis entitled '**Effect of Shear Wall Area to Floor Area Ratio on the Seismic Response of Reinforced Concrete Buildings**' presented by **Tenagnework Shumate**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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UNDERTAKING

I certify that this research work titled "**Effect of Shear Wall Area to Floor Area Ratio on the Seismic Response of Reinforced Concrete Buildings**" is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

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ABSTRACT

An analytical study is performed to assess the effect of different shear wall area to floor area ratios on the response of high rise reinforced concrete buildings under earthquake loading. In order to achieve this a total of 116 building models that have 8, 15, 20, 25, 30, 35 and 40 number of stories with different shear wall ratios are generated. The seismic response of this building models are examined by performing response spectrum analysis using ETABS 16.2.0 software program. Variation of the main parameters that affect the seismic performance of buildings, which are inter story drift, roof top displacement and base shear responses, with varying shear wall ratios are studied and compared with the approximate results given by literatures. The analytical result shows that story drift decreases with increasing shear wall area to floor area ratios but, the rate of reduction is lower for higher shear wall ratios. Increasing shear wall area to floor area ratios beyond 2% has not significant effect on reducing story drift.

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Table of Contents

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 General

The demand for high rise buildings increase around the world due to the scarcity of land with increasing number of populations. Because these buildings are highly affected by lateral forces due to wind and earthquake actions, they need especial attention during the design process. A number of researches have been conducted to study the influence of these actions, especially earthquake action, on buildings' performance [1]. In order to avoid a significant damage, loss of life and assets caused by earthquakes, increasing the seismic resistance of structures is essential.

The important parameters that provide seismic resistance and prevent excessive structural damage of reinforced concrete structures are deformation capacity and seismic performance. One of the most efficient methods to enhance the stiffness and deformation capacity of buildings under earthquake loading is providing properly designed and detailed reinforced concrete structural walls (shear walls). Shear walls are load bearing members of structural system which carry lateral loads induced by the earthquakes and provide substantial energy dissipation capacity. They also provide extensive lateral strength, stiffness and deformation capacity which make them necessary for high rise buildings to save damage due to earthquake [2].

One of the major requirements in the seismic design of multi-story reinforced concrete buildings is to have the lateral story drift within the code-specified limits, which minimizes the structural damage under earthquake loading. Generally, under seismic forces of moderate to high magnitude, these requirements are difficult to satisfy unless a sufficient quantity of shear wall is provided in the building. Shear walls improve the lateral stiffness of the building and thus control the story drift of the building substantially. As a result, almost all of the seismic codes recommend the employment of shear walls for the design of RC buildings against seismic forces.

To determine the level of expected drifts, such as roof and inter story drifts, which can be used to estimate the level of damage of structural system in the seismic evaluation, an information about the shear wall area to floor area ratio of a building is required. However, there is only a limited number of research studies are conducted on the correlation between shear wall ratios and drifts. Therefore, this analytical study is performed to evaluate the effect of different shear wall area to floor area ratios, which can be utilized in the preliminary assessment and design stages, on the seismic response of reinforced concrete buildings with shear walls.

1.2 Objective

The seismic performance of buildings can be enhanced by providing shear walls. Proper detailing of shear walls can also lead to ductile behavior of structures during strong earthquake shaking. At the preliminary assessment and design stage of reinforced concrete buildings with shear walls, it is necessary to know the sufficient shear wall area to floor area ratios which should be provided. The main objective of this research is to assess the seismic response of multi-story reinforced concrete buildings having different shear wall ratios and to study the relationship between shear wall area to floor area ratio (%) with inter story drift, roof displacement and base shear responses. This helps to know the change of the response of the structure with shear wall ratios and to compare the outputs with the approximate results given by literatures.

1.3 Scope of the Study

This analytical study is limited to

- Regular reinforced concrete buildings
- Straight shear walls with rectangular cross sections
- Symmetrical arrangements of shear walls

1.4 Thesis Outline

The seismic response of high rise reinforced concrete buildings with varying shear wall area to floor area ratios are assessed in this thesis. In the first part, general information on the contribution of shear walls for seismic performance of buildings, the objectives and scopes of this analytical study are presented. On the second part, literatures written by previous researchers regarding structural walls, their classifications and modeling methods; wall indexes and their relations with responses are reviewed. The third part detailed the structural properties of the analyzed building models including material and cross sectional properties; the variation of shear wall ratios and the method of analysis used to analyze the building models. The analytical results and findings of this analytical study are discussed in fourth part. Finally, in the fifth part conclusions and recommendations for future studies are provided respectively.

2. LITERATURE REVIEW

2.1 Structural Walls

One of the most commonly used lateral load resisting systems in reinforced concrete buildings is shear wall system. It is often used in multistory buildings to resist lateral loads such as wind, seismic and blast loads. In addition, when the frame system alone is insufficient to withstand all the lateral loads or when partition walls are needed to be load bearing walls, replacing columns and beams, this structural walls are recommended. Providing structural walls increase the safety, stability and durability of structures exposed to earthquake loading. In this study the term ‘Structural wall’ is used interchangeably with the term ‘Shear wall’.

Shear walls have very high in-plane stiffness and strength which helps to limit inter story drifts leading to reduced structural damages, to resist large horizontal loads and support gravity loads. This enhance the seismic performance of medium-rise to high-rise reinforced concrete buildings. Additionally, the concrete walls can be easily incorporated into architectural layout of buildings with minimal impact to the functional space.

Reinforced concrete walls are designed to carry flexural, shear and axial loads under earthquake loads. During wind loading and low to moderate seismic loading structural walls are intended to behave elastically to prevent non-structural damage in the building. However, during sever earthquakes it is expected that the walls will be exposed to inelastic deformation. Therefore, structural walls must be designed to withstand forces that cause inelastic deformations while maintaining their ability to carry load and dissipate energy. The analysis and design of buildings with shear walls became simple using commercially available computer programs based on the finite element method (FEM). To investigate the behavior of shear walls under earthquake loading and to evaluate their effect on the seismic performance of reinforced concrete structures, many experimental and analytical studies have been performed.

As the number of stories increased for a building model, the need for shear wall provision is critical. This is because to reduce the vulnerability or to save the damage of high rise building due to earth quake. In addition to obtain desirable performance of shear wall structure, symmetry in position of shear wall in plan is a key factor [2].

[3] presented one of the use of reinforced concrete walls which is seismic strengthening of existing high-rise structures. It is stated that old buildings with RC frame systems which were

not built in accordance with the contemporary regulations have insufficient resistance to lateral load. So as a basic strengthening method addition of reinforced concrete walls are recommended to increase horizontal rigidity, bearing capacity, ductility and dissipation capability of seismic energy.

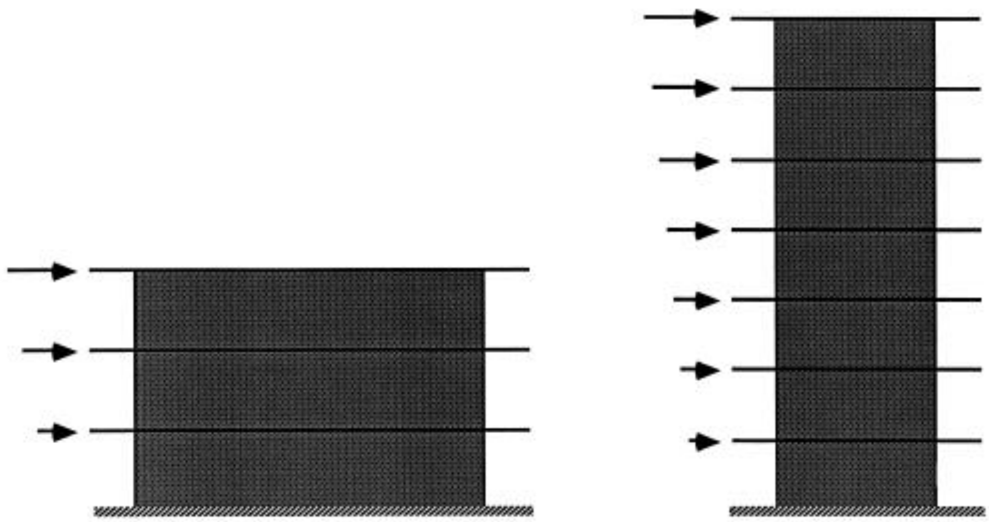
[4] Observed the positive effect of structural walls by comparing the performance of two RC buildings, which were affected by the May 19, 2011 Simav earthquake in Turkey, in which the building with structural wall survived without any structural damage but the building with no structural wall collapsed. Analytical models of the two buildings were developed to investigate the influence of structural walls on the seismic performance of RC buildings by conducting response history and pushover analyses. Results of detailed analyses of the two buildings indicated that the building with structural walls should respond better to strong ground motion, and this was confirmed by the relative behaviors of the two buildings.

[5] observed that even if the shear walls were reinforced in the traditional manner for gravity and overturning, without consideration given to special details for ductility buildings containing shear walls have exhibited very satisfactory performance during the earthquakes of the last thirty years. The report of the investigation on the behavior of modern structures in a dozen earthquakes throughout the world, starting with the Skopje earthquake of 1963 through the Armenian earthquake of 1988, showed not a single concrete building containing shear walls collapsed. Although there were cases of cracking of various degrees of severity, no lives were lost in these buildings. It is indicated that the main reason for the collapse of hundreds of reinforced concrete frame structures were excessive inter story distortions that caused shear failures of columns. Even where collapse of frame structures did not occur and no lives were lost, the large inter story drifts of frames caused significant property losses. The paper concluded that building economical concrete buildings to resist sever earthquakes cannot be afforded without shear walls.

[6] presented a new code format, which increase design flexibility, to design buildings with reinforced concrete shear wall using displacement-based analytical procedure. The procedure used a computed strain distribution to determine the required transverse reinforcement at wall boundaries for concrete confinement and to restrain buckling of longitudinal reinforcement. This can be applied to walls of various cross sectional shapes.

2.1.1 Classification of Structural Walls

Concrete shear walls can be classified based on different criteria. [7] classified concrete wall elements as solid walls, perforated walls, or coupled walls and punched walls. The aspect ratios (the ratio of height h_w to length l_w in the plane of loading) used to classify the solid structural walls. If the aspect ratios of the walls is less than or equal to two ($h_w/l_w \leq 2$) then the walls are considered as short or squat walls. This walls behavior is dominated by shear which leads to brittle failure. So, special attention should be give during designing of this walls. Shear walls with aspect ratios equal to or exceed four ($h_w/l_w \geq 4$) are referred as slender walls which controlled by flexure. Intermediate walls which have intermediate aspect ratios influenced by both flexure and shear.



a. Squat Wall   b. Slender Wall

Figure 2-1 Types of Structural Walls *[8]*

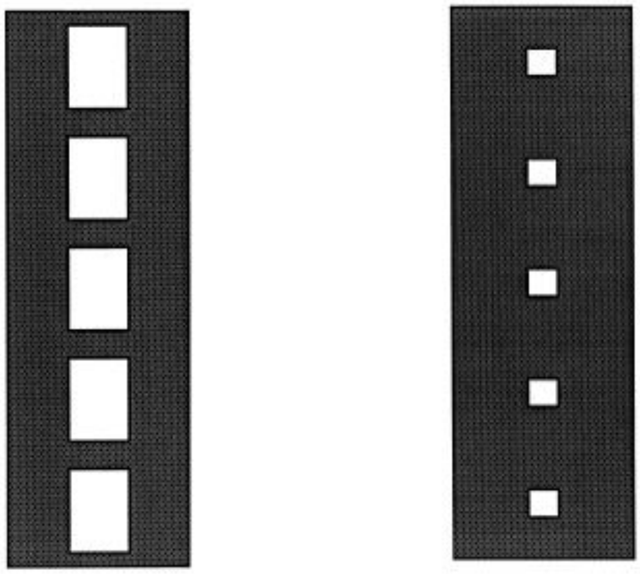
According to [9] reinforced concrete walls in use are classified in to four types which are Slender ductile walls, Squat ductile walls, Coupled walls and large, lightly reinforced walls. On the other hand, reinforced concrete walls may constitute basic structural elements in four building structural systems namely uncoupled wall systems, dual systems (wall-equivalent of frame-equivalent systems), coupled wall systems and systems with large, lightly reinforced walls.

Slender reinforced concrete structural walls are the most commonly used type of walls in mid- to high-rise buildings as a main lateral load resisting element in earthquake regions. Different researches have been carried to investigate the seismic behavior of this walls. An experimental and analytical study of slender reinforced concrete structural walls with an opening at the base were summarized [10]. The evaluation of a displacement-based approach for the selection of transverse boundary reinforcement, and the evaluation of strut and-tie models for the selection of horizontal shear reinforcement were the primary objectives of the research. Experimental results show that properly reinforced slender structural walls with openings at the base exhibit stable hysteretic behavior and significant ductility. The large opening at the base did not significantly influence the behavior of the wall compared with results for walls without openings. It is stated that displacement-based design technique allowed transverse boundary reinforcement to be provided based on the estimated compression strain in the concrete rather than selected based on a nominal stress value. This procedure worked well to ensure that the concrete in the boundary elements had adequate confinement to prevent crushing at high strains. The good agreement between the predicted and experimental moment-curvature relations indicates that displacement-based design is an effective procedure for assessing detailing requirements for transverse reinforcement at wall boundaries. The boundary regions performed well even though the measured compression strains differed somewhat from the strains assumed in the design model. On the other hand, [11] assessed the need for transverse reinforcement at wall boundaries of slender structural walls with unsymmetrical cross sections (e.g., walls with T-shaped cross sections) by experimental study using displacement-based design method. [12] also provide additional experimental evidence on the seismic performance of non-rectangular slender reinforced concrete structural walls with L-shaped and T-shaped sections under simulated gravity and seismic loads.

The seismic behavior of squat reinforced concrete shear walls which exhibit shear mode of failure studied by [13]. An experimental program conducted using wall aspect ratio, amount of distributed reinforcement both vertically and horizontally and compressive strength of concrete as test parameters. After maximum strength shown by the walls and the influence of vertical distributed reinforcement on the seismic behavior of walls, conclusions are drawn concerning the deformation capacity, energy absorption, dissipation characteristics and strength deterioration.

As [14] indicated, the use of coupled shear walls is one of the potential option in comparison with special moment resistant frame and shear wall frame combination systems in high rise reinforced concrete buildings. Coupled shear walls are consisted of two shear walls interconnected by beams along their height. The behavior of the coupled shear walls mainly governed by the coupling. It is also stated that the use of properly designed coupled wall systems leads to a more efficient and economical structural system than single walls. This is due to the significant strength, stiffness, and energy dissipation possessed by the coupled walls. The elastic response parameters of coupled wall structures and parameters that will permit an accurate initial estimate of the global behavior of a coupled system, the local behavior of the coupling beams and the interaction between the global and local behaviors were investigated by [15]. The response parameters of interest were lateral displacement, inter story drift and coupling beam deformations. In order to investigate appropriate parameters for identifying efficient coupled wall geometries, an initial parametric study of over 2000 coupled wall geometries is reported. These analyses permitted the evaluation of the sensitivity of the structural response to various geometric parameters. Using elastic analysis and gross section properties, the role of representative geometric parameters in the response of coupled structures is illustrated.

There is another wall system which seem similar with coupled wall system that is "Pierced wall system". Walls which have openings that constitute a small portion of the wall's cross section necessary for doors and windows are called pierced walls. The difference between coupled and pierced wall systems is the area of the opening and the coupling involved. The small openings on the pierced structural wall do not influence the seismic performance of the walls significantly. [8] indicated that walls, when they serve as partition walls, needed to be pierced for window, door or other openings. It is stated that there is a marked difference between coupled wall systems and pierced wall systems even if they have openings along one vertical axis. In the coupled wall system, the openings are big enough to separate the walls and energy is mainly dissipated through coupling beams. On the other hand, a pierced wall system behaves as a single isolated wall in which the effect of openings are neglected depending on the opening-to-wall area ratio.



a. Coupled Wall System b. Pierced Wall System

Figure 2-2 Types of Wall Systems *[8]*

Structural walls can also be classified as orthogonal, barbell, tubular, T, C, L and Z shaped based on their cross sectional shapes. Due to the ease in design orthogonal shape of structural walls are more preferable [9].

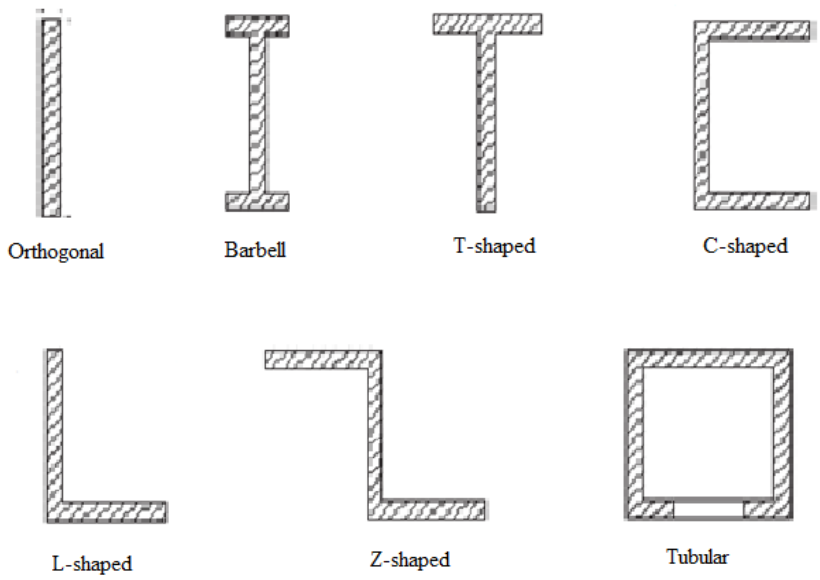


Figure 2-3 Various Cross-Sections of Structural Walls

[16] Discusses the issues encountered in the design of a non-rectangular reinforced concrete shear walls especially shear wall with T-shaped prototype. It was indicated that a particular

care during design should be given for the behavior and performance of this non-rectangular shear walls during a seismic event. Appropriate detailing of boundary elements of the wall without undue congestion, detailing of joint between web and flange to address potential vertical shear transfer problems and estimating relative stiffness for appropriate distribution of design loads were some of the issues of particular concern.

2.2 Wall Indexes

The proportioning of shear walls that are used for resistance of lateral loading due to earthquakes is indicated by wall index. Generally, shear wall index is determined by taking the ratio of the total area covered by shear wall at a typical story in one principal direction to the plan area of that story.

Approximate values of wall indexes that can be used at the preliminary design stages are proposed in different literatures.

A large number of buildings located in Viña del Mar which experienced the 1985 Chile earthquake was investigated by [17] to define the typical characteristics of medium-rise buildings having five to twenty-three stories and to describe the nature and distribution of earthquake damage. Data sheets for 178 different buildings were compiled, which represents 322 individual structures, 319 of which had structural walls. Most of the buildings had large amount of shear wall index ranged from 3 to 8%. The amount of wall area appears to be nearly independent of the height of the building, with an average value of 6%. 90% of the buildings with shear walls didn’t experience damage due to the sever earthquake even if they were lightly reinforced without special confinement details and boundary elements. This showed the possibility of having damage due to sever earth quake decrease as the shear wall ratio used in a building increase.

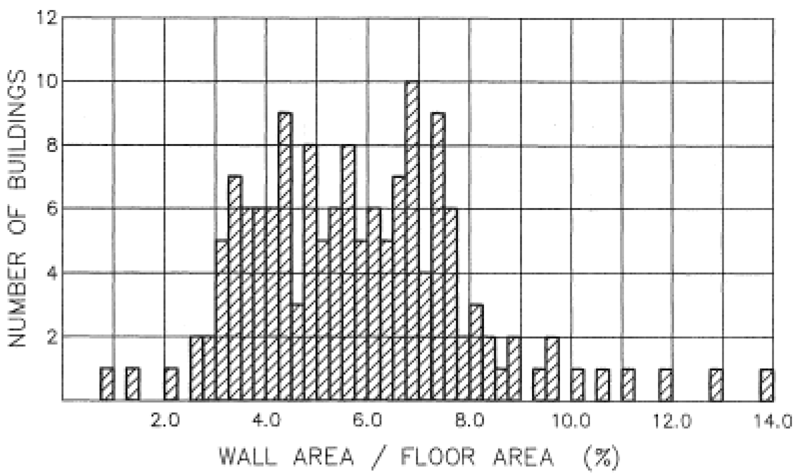


Figure 2-4 Ratio of Wall Area to Floor Area for Buildings in Viña del Mar *[17]*

[18] present a simplified method of ranking reinforced concrete, low-rise (up to five stories), monolithic buildings according to their vulnerability to seismic damage by using wall and column indexes. As an input the method only used the dimension of the structure and the position of a building on a two-dimensional plot using the wall and column indexes. A total of 46 institutional buildings that suffered various levels of damage during the Erzincan Earthquake of 1992 were tested for the ranking process.

The wall index (*WI*) is defined as the ratio of the sum of the 100% of total cross-sectional area of reinforced concrete walls (A_{cw}) at the base of the building and 10% of total cross-sectional area of non-reinforced masonry infill walls at the base in one horizontal direction (*Amw*) to the total floor area (A_{ft}) above base in a building. So the wall index $WI = (A_{cw} + A_{mw} /10) / A_{ft}) *$ 100. Column index (*CI*) is defined as the ratio of 50 percent of the total cross-sectional area of columns (A_{col}) above base to the total floor area which is $CI = (A_{col} / 2A_{ft})$ *100. Wall index changes between 0 to 1 percent for more than half of the buildings. Since the stiffness of the overall building depends on the stiffness of the individual elements, the difference in stiffness and strength of elements were accounted by assigning different weights to column, reinforced concrete wall, and non-reinforced infill wall areas in determining indexes.

An evaluation method is proposed by plotting wall index values against column index values on a graphical scheme. This scheme (figure) helps to evaluate the relative vulnerability of buildings in a given region. A building that falls into the triangular region formed by "Boundary 1" and two axes is more vulnerable than a building outside of this region. The deficiency of the method is that it does not consider the changes in material quality, story height, girder properties, and continuity of framing. However, it offers a practical and quick method of determining the buildings that are most vulnerable to the earthquakes.

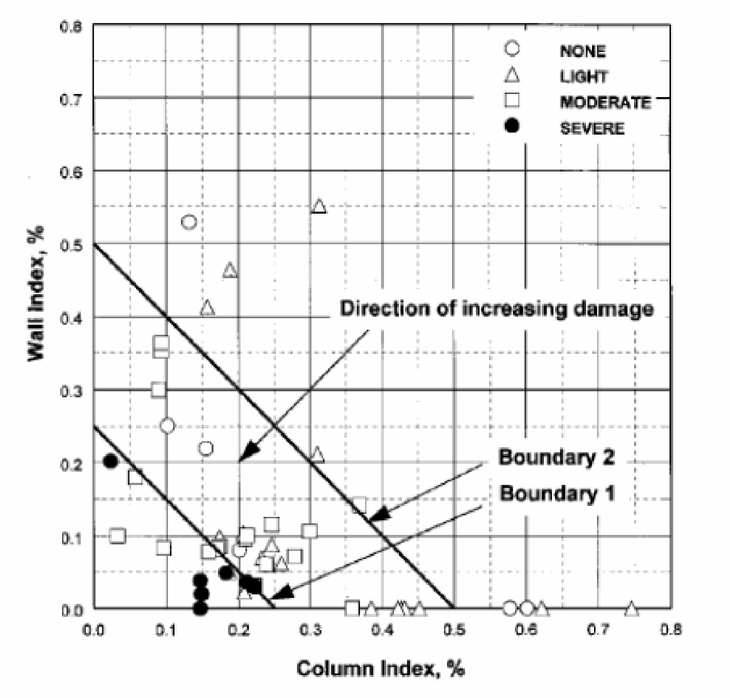


Figure 2-5 Proposed Evaluation Method by Hassan and Sözen (1997)

2.3 Research on Wall Ratios and Responses

The main cause of lateral deformation of buildings is the lateral force induced by strong ground motions. This deformation leads to damage of both structural and nonstructural components of a building. To determine the expected damage of a building under earthquake loading, information about the structure's deformation such as roof drift and inter story drift is mandatory. However, there is limited study conducted on the relationship between lateral drift and shear wall ratios.

[19] showed that ratio of wall cross sectional area to floor plan area, the wall aspect ratio and the wall configuration, the axial load, and the reinforcement ratios are primary variables that affect shear wall detailing in designing RC shear walls. To estimate the variation of roof drift with shear wall ratio an analytical procedure proposed and for different shear wall aspect ratios the effect of shear wall ratio on the behavior is obtained. The procedure started by computing the elastic spectral displacement from elastic spectral acceleration based on making

assumptions. A formula proposed by [20] to estimate the fundamental period of structural wall buildings based on cracked section stiffness was used to estimate the displacement of building from a displacement spectrum. Then the roof displacement approximated by multiplying the spectral displacement by 1.5 to account for the difference between the displacement of a SDOF oscillator and the building system the oscillator represents. By repeating this procedure for several wall aspect ratios a figure plotted which is valid for elastic or inelastic responses.

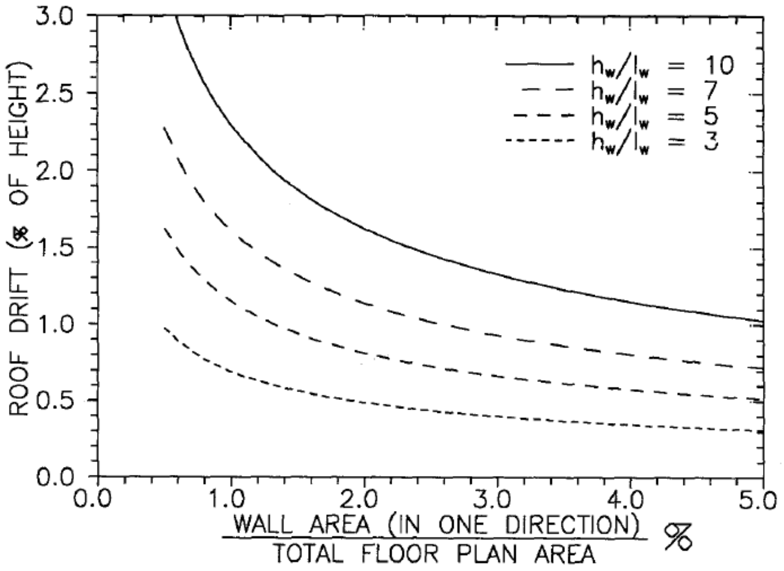


Figure 2-6 Estimate of Roof Drift Ratio by *[19]*

[20] describe the primary variables expressed by Wallace (1994) determine the need for confined boundary elements of structural walls. The procedure used to estimate the response of structural walls is the same as Wallace's. For various shear wall ratios periods (*T*) and roof drifts are estimated. The study concluded that for buildings with a shear wall aspect ratio equal to or less than five and ratios of wall area to floor plan area in one direction of 1.5% or greater, less or 1% roof drifts are expected during a significant ground motions.

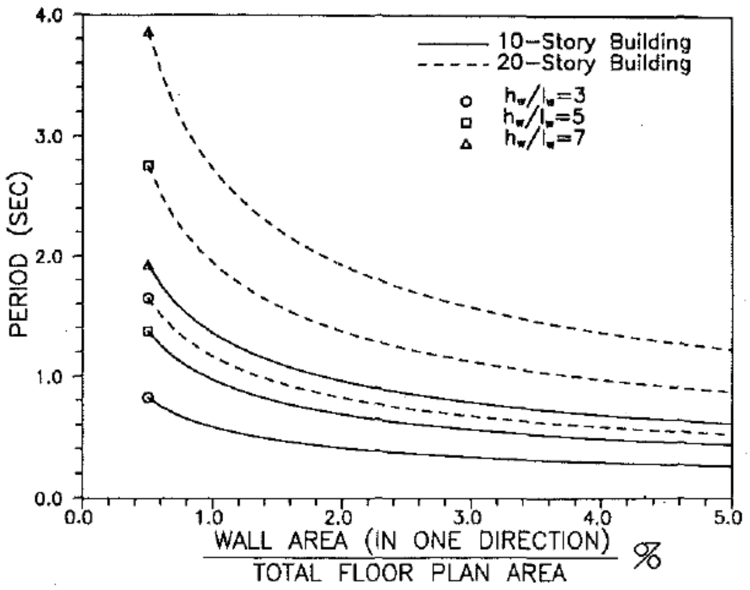


Figure 2-7 Estimate of Fundamental Period for Shear Wall Buildings by *[20]*

[21] performed an analytical study, by generating 24 mid-rise building models having five and eight stories, to assess shear wall area to floor area ratio effects on the seismic behavior of RC buildings. A nonlinear time history analysis was carried out using PERFORM-3D software to examine the behavior of buildings having shear wall ratios ranging between 0.51 and 2.17%. The shear wall area to floor area ratio is determined by dividing the total shear wall area in one principal direction to the plan area of the ground floor ($\sum A_w/A_p$). Only the y-direction of the building models, which is more vulnerable to damage, was examined throughout the study. In the analyses, seven different ground motion records were applied to the building models, and roof and inter story drifts and base shear responses were the main parameters considered in the study. The analytical results indicated that at least 1.0% shear wall ratio should be provided in the design of midrise buildings to control the drift. In addition, when the shear wall ratio increases beyond 1.5%, it was observed that the improvement of the seismic performance is not as significant.

An analytical study was performed by [22] to investigate how the seismic behavior of existing mid-rise reinforced concrete buildings influenced by shear wall area to floor area ratio. For the study five existing school buildings that have different number of stories, floor plans, cross-sectional areas of the members and material properties were selected and modeled. The retrofitted cases of these existing buildings and additional buildings having varying shear wall ratios were designed, based on the structural properties of the existing buildings, and analyzed. In addition, the orientation of the columns of the existing reinforced concrete building was changed and the building redesigned with different shear wall ratios to explore the effect of column stiffness on the seismic behavior. Totally, twenty-four midrise reinforced concrete building models having shear wall ratios ranging between 0 and 2.5% both in longitudinal and transverse direction and number of stories between three to five were used. A nonlinear direct integration time history analysis was performed for all buildings by utilizing the software program, SAP2000 v14.2.0. under seven different ground motion records. The results indicated that roof drifts and plastic deformations reduce with increasing shear wall ratios, but the rate of decrease is lower for higher shear wall ratios. Buildings with 1.00% shear wall ratio have significantly lower roof drifts and plastic deformations when compared to buildings with 0.00% or 0.50% shear wall ratio. Roof drifts and plastic deformations are minimized when the shear wall ratio is increased to 1.50%. After this limit, addition of shear walls has only a slight effect on the seismic performance of the analyzed buildings.

[23] proposed an approximate limit values of wall indexes, by assessing the effect of shear wall ratios on the performance of buildings, which can be used in preliminary assessment and design of reinforced concrete buildings having shear walls. A total of 45 building models having 2, 5, and 8 stories with shear walls ratios varying between 0.53 and 3.60% were used for both elastic and inelastic pushover analyses performed by SAP2000 software. The results obtained from the analysis, which are the roof drift and inter story drift for different shear wall ratios, were compared with the values given in literatures. In addition, the seismic performance of the building models investigated by relating with various wall ratios. Based on the analysis results the paper concluded that drift is not the primary concern for low to mid-rise buildings with shear walls.

[24] The effect of shear wall ratio on the seismic performance of buildings having inadequate seismic resistance was investigated in this study in order to determine the critical shear wall ratio. Two different buildings which have been heavily damaged or collapsed in August 17, 1999 Kocaeli Earthquake, Turkey were selected and modeled with shear wall ratio of 2, 1.5, 1, and 0.5 percent using SAP2000 software. The strong ground motion which had the highest peak ground acceleration was selected and used for the analysis. A nonlinear response history analyses was performed and results showed that the building without shear walls responded worse under the selected strong ground motion but, when the structural wall ratio increases, seismic performance of the buildings improves considerably.

[25] An analytical study is performed to evaluate the effect of shear wall area ratio to floor area ratio on the seismic behavior of multistoried RC structures with soft story at ground floor. For this purpose, 12 building models that have 5, 8 and 12 stories and shear wall area ratios ranging between 0.70 and 1.31% in both directions were generated and three ground motion records were selected. Then, the behavior of these building models under earthquake loading was examined by carrying out Response Spectrum Analysis and Linear Time History Analysis, by using structural analysis software called E-TABS. The Main parameters considered in this study was the relationship between shear wall area and base shear, relationship between shear wall area and roof drift, story drift and inter story drift. The analytical result indicated that at least 0.91% shear wall ratio should be provided in the design of multistoried buildings to control the drift. In addition, when the shear wall ratio increases beyond 1.11%, it was observed that the improvement of the seismic performance was not as significant.

[26] an analytical study was performed to investigate the relationship between shear wall area with base shear, roof displacement and story drift for 5, 8 and 12 story RC building models with increasing Shear wall area ratio by considering the ground floor as soft story. Both Response Spectrum Analysis and Time History Analysis conducted and the results compared.

To know the effect of structural wall indexes on drift ratio for 5 story reinforced concrete building, both linear elastic and in elastic push over analysis performed by [27]. In addition, the results of the analysis compared with the results obtained from Wallace method. For the analysis 5 different models having shear wall ratios varying between 0.53 and 3.6% for each number of stories were created. The study concluded for the entire wall ratio, the roof drift ratio is less in Wallace method from Elastic analysis and very less obtained in case of inelastic analysis. In all the methods, the value of drift ratio changes significantly at lower wall ratio and becomes nearly constant at higher wall ratio.

2.4 Modeling of Structural Walls

To investigate the behavior of reinforced concrete shear walls under lateral loads, which enable the designers to predict their seismic response in a building when subjected to a sever ground motion, several experimental and analytical studies were conducted. [28] indicated that predicting the behavior of RC walls under lateral loads requires enhanced numerical tools, which account most of the important factors that could affect the response of RC walls, that are calibrated using controlled experimental tests. It is also stated that factors to be considered during modeling of RC shear walls include wall cross-sectional dimensions, aspect ratios, axial-flexure interaction, amount of reinforcement, bond between reinforcement and concrete, and effect of connecting members.

In order to know the behavior of a structure under different loading condition an analysis should be made by modeling a structure having reasonable structural properties. The assumptions made for the modeling of structure should be precise in order to get accurate analysis result. Different literatures provide different analytical modeling methods to predict the inelastic response of reinforced concrete structural wall systems.

[29] Assessed the behavior of a five-story archetype RC wall-frame building obtained using two conceptually different RC wall modeling approaches which are SFI-MVLEM, which captures the interaction among axial/flexural and shear responses and nonlinear shear deformations (coupled model); and beam-column model (fiber model). Nonlinear response-history analysis was used to perform the analysis.

Generally modeling of reinforced concrete structural walls can be classified in to two categories which are macroscopic and microscopic models. Macroscopic models (global response models) are based on a simplified modeling of the overall behavior of the system with reasonable accuracy. Some of the commonly used macroscopic models are the equivalent beam model, equivalent truss model and multiple-vertical line element models. Microscopic model is based on detailed and refined modeling to determine the local response. The general technique used for microscopic modeling is Finite element method. Different techniques of modeling, which are macro models, combined models and micro models such as finite element models and fiber models, for nonlinear analysis of reinforced concrete walls under seismic actions were presented by [30]**.**

[31] investigated the effectiveness of macroscopic model in simulating the nonlinear response of slender reinforced concrete shear walls. The model relates the predicted flexural response directly to uniaxial material behavior without incorporating any additional empirical relations. Comparison between experimental and analytical results also made and results showed excellent agreement. In addition, the study verified that the lateral load versus top displacement response of reinforced concrete shear walls can be efficiently predicted by microscopic model.

[28] Discussed modeling techniques of reinforced concrete structural walls used by different researchers. The two main approaches which are the macro-models such as lumped plasticity, multi-axial spring models, truss models and combined models; and micro-models such as finite element models and fiber models explained in the paper. In addition, the efficiency of each

model in representing both the global and local behavior of reinforced concrete shear walls also discussed.

2.4.1 Macroscopic Models

[32] Used one of the macroscopic model method which is the multiple-vertical-line-element model (MVLEM) to model and simulate the inelastic response of reinforced concrete structural walls. The sensitivity of analytically predicted global and local wall responses to changes in variation of model and materials parameters were investigated. The study verified that the important response characteristics associated with cyclic behavior of reinforced structural walls governed by flexure were captured by the MVLEM. A flexible platform provided by the macroscopic wall model presented by the paper to assess the influence of various material and behavioral features in the nonlinear responses of slender RC structural walls.

[33] An overview of reinforced concrete shear-wall models which modeled based on macroscopic approach that can be incorporated in nonlinear analysis of multistory reinforced concrete frame-wall structures given on the paper. An analytical and experimental results with reference to isolated walls and frame-wall structure presented to evaluate the effectiveness and reliability of selected wall models.

To describe the in-plane and out-of-plane behavior of a reinforced concrete wall member a macroscopic model, macro plate model, was proposed by [34]. The numerical derivation of macro plate model, which is a four-node element, presented based on the theory of elasticity and theory of plate bending.

A macro model was developed by [35] to represent the flexural and shear behavior of structural walls. The model consists of nonlinear springs, which are capable of describing the hysteretic characteristics of reinforced concrete structures, connected by linear beam elements. Strength deterioration and softening parameters are included in the model. The model response compared with experimental result and showed close agreement. The tested element predicted both shear and flexural components of deformation under both monotonic and cyclic loading accurately.

2.4.2 Microscopic Models

To examine the behavior of individual materials, concrete and reinforcement, and bond between them, reinforced concrete structural walls are modeled using this microscopic approach. When detail evaluation of local response of shear walls is needed this approach is more feasible. Finite element model (FEM) and fiber model are the most known types of microscopic models.

Finite element models are used to solve many complicated engineering problems by simplifying in to smaller elements. Both the global and local seismic behavior of reinforced concrete shear walls can be obtained by this method using finite number of small elements. To simplify the complex configuration of a system, the system divided in to a number of smaller components (finite elements). These smaller components are selected such that their geometry, most of the time square and rectangular geometry preferred, is easier to simulate a complex configuration. Shell element is used to apply this method on reinforced concrete shear walls. Since the analysis is complex, time consuming and needs large storage capacity, most of the time it is done with the help of software.

2.5 Structural Systems

The main structural systems in use in earthquake-resistant reinforced concrete buildings are frame systems, wall systems and dual systems. According to their behavior under horizontal seismic actions, structural systems covered by EC8-1/2004 belong to one of the following structural types:

- Frame System: A structural system in which both the vertical and lateral loads are mainly resisted by 3D ductile frames with a base shear that exceeds 65% of the total shear resistance of the whole structural system.
- Ductile wall system: Structural systems in which vertical and lateral actions are mainly resisted by vertical structural ductile walls, either coupled or uncoupled, with a shear resistance at the building base that exceeds 65% of the total shear resistance of the whole structural system.
- Dual system: A structural system in which support for the vertical loads is mainly provided by a 3D frame system and resistance to lateral loads is covered in part by the frame system and in part by coupled or uncoupled structural walls. From the structural point of view these systems must be classified in two different categories, that is:
    - Frame – equivalent dual systems, in which the shear resistance of the frame system at the building base is greater than 50% of the total shear resistance of the whole structural system, and

- Wall – equivalent dual systems, in which the shear resistance of the walls at the building base is higher than 50% of the total seismic resistance of the whole structural system.

An overview of these systems together with their corresponding base shear resistance is given in table 2-1 below.

Table 2-1 Main Structural Systems for Earthquake Resisting Reinforced Concrete Buildings

Type of structural system	**Percentage of base shear resisted by the system**	
Frame system	>65%	Resisted by frames
Wall system	>65%	Resisted by walls
Dual system		
Frame equivalent	>50%	Resisted by frames
Wall equivalent	>50%	Resisted by walls

This classification of structural systems helps to evaluate the behavior factor of the building and also it is a better way to identify the type of failure mode that is likely to appear under a strong seismic action.

3. MODELING AND ANALYSIS OF BUILDINGS

3.1 Description of Building Models

In order to achieve the aim of this analytical study, 60 office building models that have 8, 15, 20 and 30 stories with the same floor plans but different shear wall areas and arrangements are generated. The bases for the generation of this structural models are models used by [23] which were taken from an investigation about building inventory in Zeytinburnu/ İstanbul. As Soydas stated the shear walls are located in axes similar to the practice in the inventory.

By taking the floor area and shear wall location from the inventory, new high rise building models are generated by ETABS 16.2.0 software program for the application of response spectrum analysis following the new Ethiopian building code. Shear wall ratios of the modeled buildings are changed to obtain different shear wall ratios. In the building models, a range of shear wall ratios between 0.53 to 3.6 percent (Table 3-1) are studied by using five different models having different shear wall ratios for each number of stories. Each models have different number of shear walls which are model 1 has 18 shear walls, model 2 has 10 shear walls, models 3 has 26 shear walls, model 4 has 24 shear walls and model 5 has 24 shear walls.

Moreover, 56 new building models, which have 0.5, 1.0, 1.5, 2, 2.5, 3, 3.5 and 4% shear wall ratios are analyzed to investigate the effect of shear wall ratios on the seismic response of high rise buildings. Unlike the models generated from the inventory this models have similar floor plans, column and wall arrangements, number of shear walls and columns. But they have different number of stories and shear wall areas. This helps to reduce the different parameters, that exist on building models from the inventory, which affect the responses and examine shear wall ratio's effect with increasing number of stories. This building models have 8, 15, 20, 25, 30, 35 and 40 number of stories.

Shear wall area to floor area ratio (also referred to as shear wall ratio) is determined by dividing total area of shear walls at a typical story in the direction of seismic analysis to the floor plan area of that story ($\sum A_w/A_p$).

Sample calculation of shear wall ratio for model 1 (model based on the inventory) having 20cm wall thickness is given below:

Shear wall ratio (%) = $\frac{\sum A_w}{A_p}$

$$= \left[\frac{(8*3*0.2)+(2*2*0.2)}{15*30}\right] * 100 = 1.24\% \text{ ………for X- direction}$$

$$= \left[\frac{8*3*0.2}{15*30}\right] * 100 = 1.07\% \text{.............for Y- direction}$$

Table 3-1 Shear Wall Ratios of Building Models Generated Based on the Inventory

Number of stories	Model ID	Shear wall thickness	Shear wall ratio (%) X direction	Shear wall ratio (%) Y direction
8	1	20cm	1.24	1.07
		25cm	1.56	1.33
		30cm	1.87	1.6
	2	20cm	0.71	0.53
		25cm	0.89	0.67
		30cm	1.07	0.8
	3	20cm	1.78	1.51
		25cm	2.22	1.89
		30cm	2.67	2.27
	4	20cm	2.31	0.8
		25cm	2.89	1
		30cm	3.47	1.2
	5	20cm	0.53	2.4
		25cm	0.67	3
		30cm	0.8	3.6
15	1	20cm	1.24	1.07
		25cm	1.56	1.33
		30cm	1.87	1.6
	2	20cm	0.71	0.53
		25cm	0.89	0.67
		30cm	1.07	0.8
	3	20cm	1.78	1.51
		25cm	2.22	1.89
		30cm	2.67	2.27
	4	20cm	2.31	0.8
		25cm	2.89	1
		30cm	3.47	1.2

	5	20cm	0.53	2.4
		25cm	0.67	3
		30cm	0.8	3.6
20	1	20cm	1.24	1.07
		25cm	1.56	1.33
		30cm	1.87	1.6
	2	20cm	0.71	0.53
		25cm	0.89	0.67
		30cm	1.07	0.8
	3	20cm	1.78	1.51
		25cm	2.22	1.89
		30cm	2.67	2.27
	4	20cm	2.31	0.8
		25cm	2.89	1
		30cm	3.47	1.2
	5	20cm	0.53	2.4
		25cm	0.67	3
		30cm	0.8	3.6
30	1	20cm	1.24	1.07
		25cm	1.56	1.33
		30cm	1.87	1.6
	2	20cm	0.71	0.53
		25cm	0.89	0.67
		30cm	1.07	0.8
	3	20cm	1.78	1.51
		25cm	2.22	1.89
		30cm	2.67	2.27
	4	20cm	2.31	0.8
		25cm	2.89	1
		30cm	3.47	1.2
	5	20cm	0.53	2.4
		25cm	0.67	3
		30cm	0.8	3.6

All models have the same rectangular floor plan area having 450m^2 and story height of 2.9m. The number of frames, span length and arrangement of shear walls are given in Figures below. Rectangular shear walls having the same thickness and; a length of 3 and 2 meters are used in a given model. However, to obtain different shear wall ratios in a given model thickness of the shear walls are changed as 20, 25 and 30cm.

Structural members which are beams and columns are modeled as frame members; and slabs are modeled as shell element and assumed to be rigid diaphragms on their own planes. At each floor level frames and walls are connected together by means of rigid diaphragms (in horizontal plane). Fixed supports are applied to all ground supports.

Stiffness modifiers are used to assume cracked section stiffness. The elastic flexural and shear stiffness properties taken equals to one-half of the corresponding stiffness of the un cracked elements. In addition, to consider the reduction in torsional stiffness of the elements, torsional stiffness of the cracked sections is taken as 10% of the torsional stiffness of the un cracked section.

The design data, according to [36], used in the study of building models for each stories are given below:

For 8 story building models the concrete compressive strength and yield strength of reinforcement are taken as C20/25 and S400, respectively. For the specified concrete strength 30GPa and for reinforcement 200GPa modulus of elasticity are taken from EBCS - 2. All beams have 250 x 400 mm cross sectional dimension and columns have a dimension of 400 x 400 mm. Thickness of slab equals 120mm.

The 15 story building models have similar material property and beam dimension with the previous models. The cross sectional dimension taken for columns are 700 x 700 mm, 600 x 600 mm and 500 x 500 mm for exterior columns of different stories and 800 x 800 mm, 700 x 700 mm, 600 x 600 mm and 500 x 500 mm for interior columns. Slab thickness is taken as 150mm.

For 20 story building models C25/30 concrete compressive strength with 31GPa modulus of elasticity are taken. The reinforcing property and beam dimensions are similar with previous models. The dimension of columns is 800 x 800 mm, 700 x 700 mm, 600 x 600 mm and 500 x 500 mm for exterior columns and 900 x 900 mm, 800 x 800 mm, 700 x 700 mm, 600 x 600 mm and 500 x 500 mm for interior columns are used for different stories. Slab thickness is taken as 200mm.

For 25 story building models the concrete compressive strength and reinforcement yield strength are taken as C40/50 and S500, respectively. Modulus of elasticity equals 35GPa for concrete and 200GPa for reinforcement. The cross sectional dimension of beam in all models is 300 x 500 mm. Exterior columns have 900 x 900 mm, 800 x 800 mm, 700 x 700 mm and

600 x 600 mm dimensions and interior columns have 1000 x 1000 mm, 900 x 900 mm, 800 x 800 mm, 700 x 700 mm and 600 x 600 mm dimensions for different stories. 250mm of slab thickness is taken.

For 30 story building models all member properties and material properties are the same as the previous 25 story building models except the concrete compressive strength which is C50/60 with 37GPa modulus of elasticity and 300mm slab thickness.

Floor plans of five different models which have the same shear wall locations with the practice in the inventory are shown below:

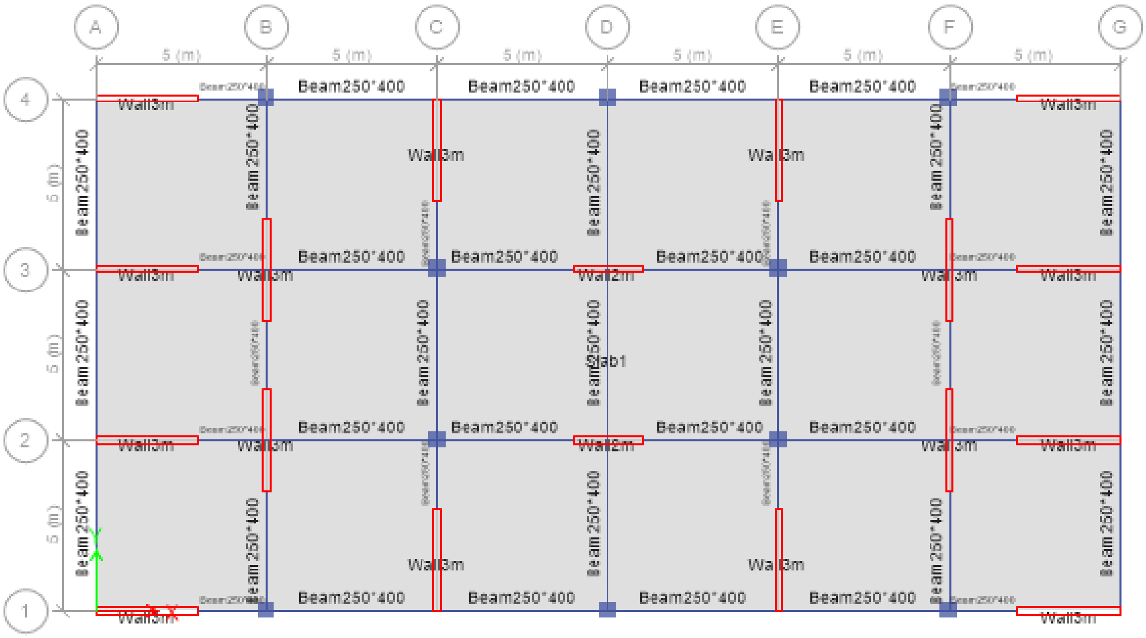


Figure 3-1 Model 1

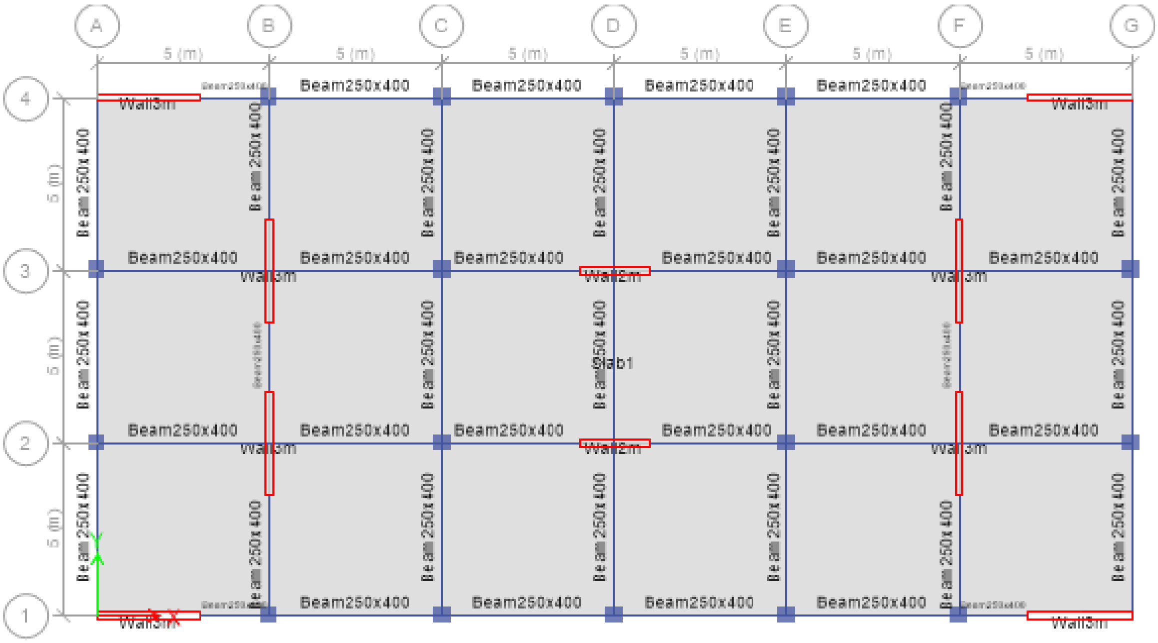


Figure 3-2 Model 2

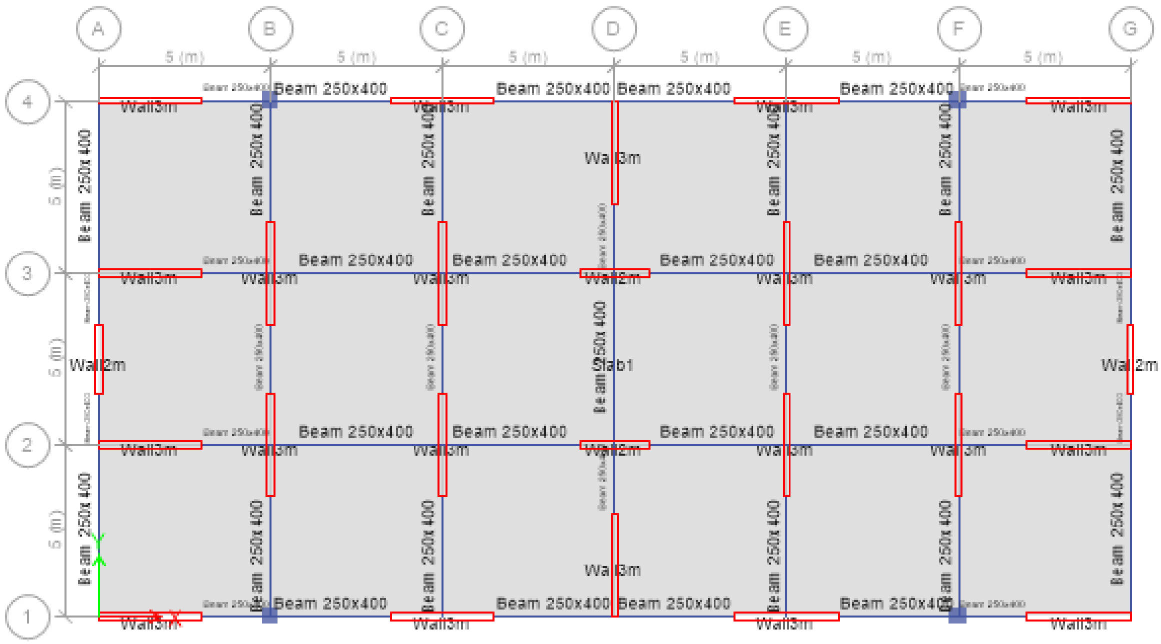


Figure 3-3 Model 3

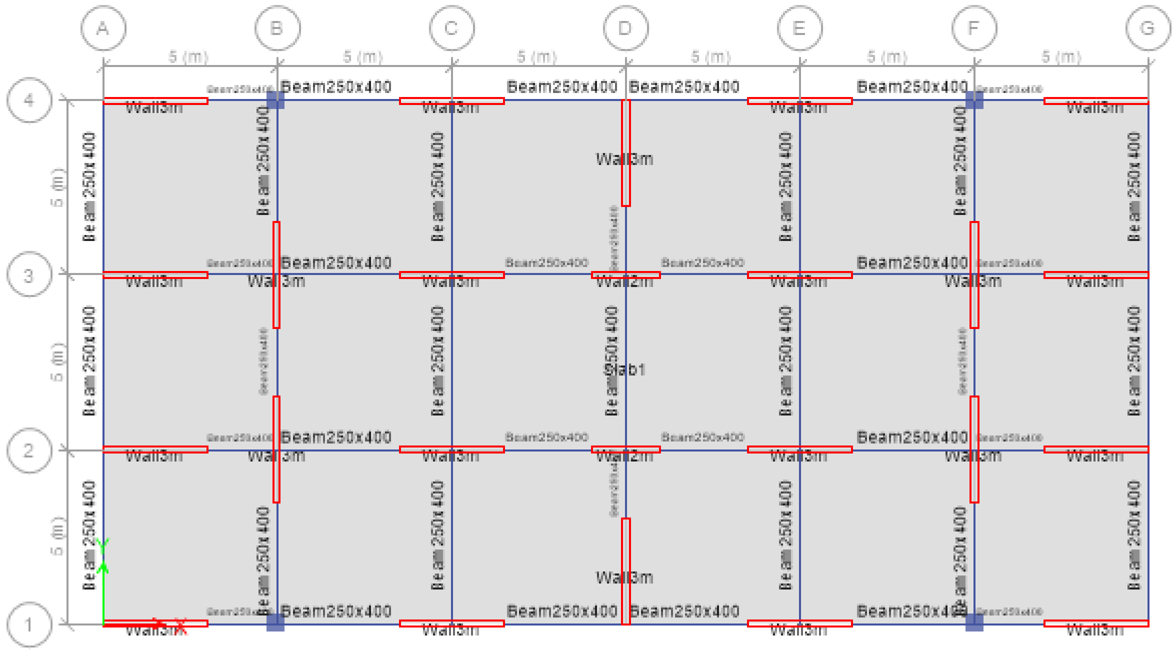


Figure 3-4 Model 4

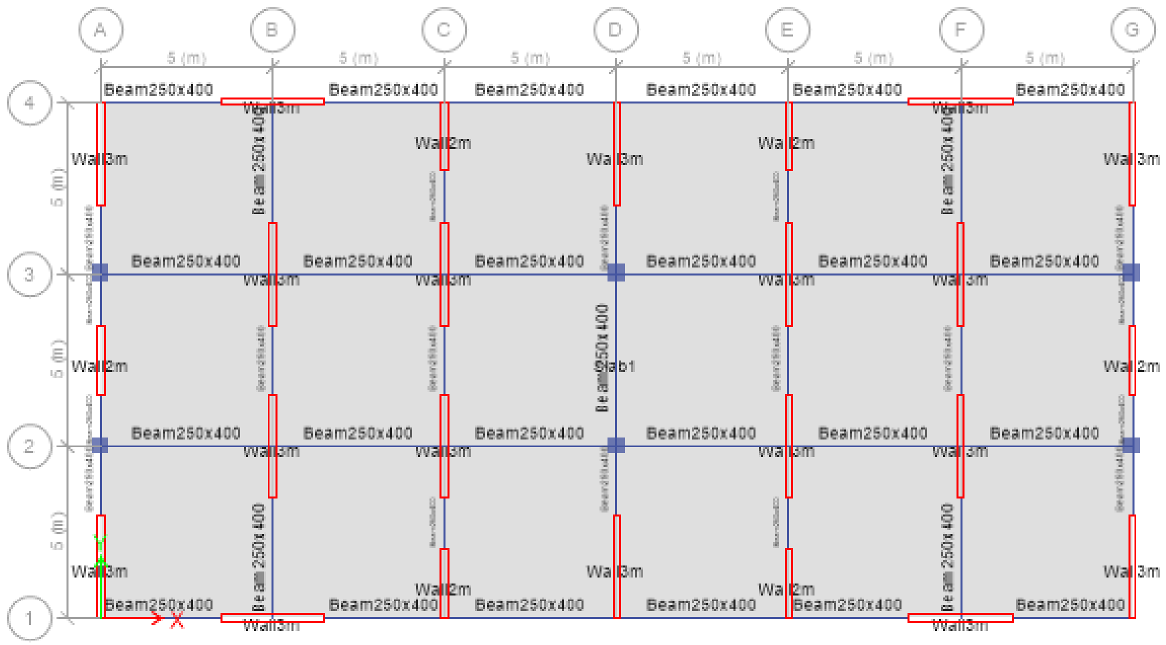


Figure 3-5 Model 5

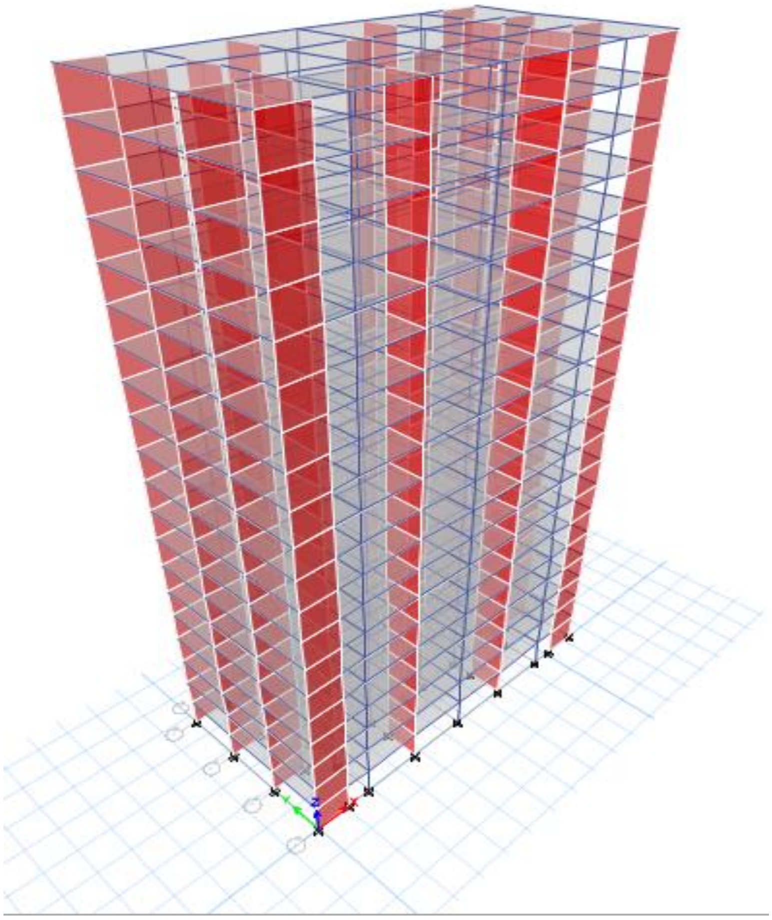


Figure 3-6 3D Structural model of 20 story building Model 1 with 20cm thick shear wall

Furthermore, the floor plan which is used for the 56 building models is given in the figure below. All of the models have this floor plan with the same number and arrangement of shear walls. There are six shear walls in each principal directions. In order to get the required shear wall ratios needed for the analysis, which are 0.5, 1, 1.5, 2, 2.5, 3, 3.5 and 4%, only the length and thickness of shear walls are varied. The number and cross section of shear walls used to obtain the above shear wall ratios for each principal directions are given in the table below.

Table 3-2 Shear Wall Ratios and Their Cross Section

Wall Ratio (%)	Number	Length (m)	Thickness (m)
0.5	6	1.5	0.25
1	4	3.5	0.25
1	2	2	0.25
1.5	6	3.5	0.32
2	6	5	0.3

2.5	6	5	0.38
3	6	5	0.45
3.5	6	5	0.53
4	6	5	0.6

The material and section properties used for this models are provided in Appendix.

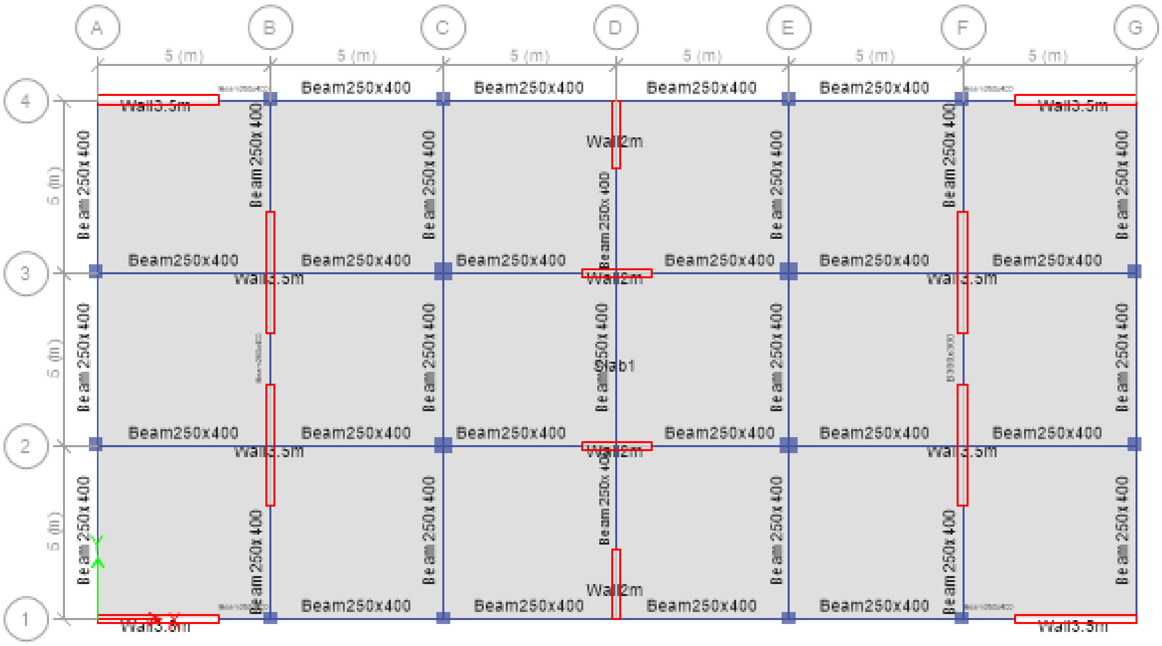


Figure 3-7 Floor Plan of a Building Model with 1% Shear Wall Ratio in Each Direction

3.2 Modal Response Spectrum Analysis

Modal spectral elastic analysis which also called modal response spectrum analysis method is used to analyze the building models under seismic action. It is the reference method of analysis according to [37] and performed in two horizontal directions independently.

In this study the analyzed buildings are assumed to be constructed in Addis Ababa town which is Zone 3 with 0.1g peak ground acceleration (PGA) and they will be designed for ductility class DCM (Ductility Class Medium). The building is classified as importance class II and the corresponding importance factor amounts to $\gamma_I = 1.0$ is used. Therefore, $a_g = \gamma_I * a_{gR} = 0.1g$ which shows that the peak ground acceleration is equal to the reference peak ground acceleration. Soil type B is selected for ground condition assuming that the soils are characterized by gradual increase of mechanical properties with depth.

The design response spectrum (i.e. the elastic response spectrum reduced by the behavior factor q) is used for the design of the building. The design spectrum for horizontal components of the seismic action, $S_d(T)$ is given in ES EN 1998-1: 2015 as follows:

$$0 \leq T \leq T_B : S_d(T) = a_g \, . \, S \, .[\frac{2}{3} + \frac{T}{T_B}(\frac{2.5}{q} - \frac{2}{3})]$$

$$T_B \leq T \leq T_C : S_d(T) = a_g \, . \, S. \frac{2.5}{q}$$

$$T_C \leq T \leq T_D : S_d(T) \begin{cases} = a_g \, .S. \frac{2.5}{q}.\left(\frac{T_C}{T}\right) \\ \geq \beta. \; ag \end{cases}$$

$$T_D \leq T : S_d(T) \begin{cases} = a_g \, .S. \frac{2.5}{q}.\left(\frac{T_C T_D}{T^2}\right) \\ \geq \beta. \; ag \end{cases}$$

Where

$S_d(T)$: Design spectrum;

T: Vibration period;

T_B: Lower limit of the period of constant spectral acceleration branch;

T_C: Lower limit of the period of constant spectral acceleration branch;

T_D: Value defining the beginning of constant displacement response range of the spectrum

a_g: Design ground acceleration

S: Soil factor

q: Behavior factor;

β: Lower bound factor for the horizontal design spectrum which has 0.2 recommended value;

Assuming the surface-wave magnitude of the earthquake is greater than 5.5 (Type 1 spectrum) values of parameters for ground type B of 5% damping are S = 1.2, T_B(s) = 0.15, T_C(s) = 0.5 and T_D(s) = 2.

3.2.1 Behavior Factor

Determination of the behavior factor ‘q’ depends on the ductility class, regularity in elevation and plan, and structural system. Before calculating the value of the behavior factor the type of the structural system should be identified first. These structural systems may be Frame system, wall system, wall-equivalent system and frame-equivalent system depending on the percentage of base shear force taken by walls at the building base. The percentage of base shear force carried by shear walls for different shear wall ratios, for each building model with different number of stories is given in the table below:

Table 3-3 Percentage of Base Shear Force Carried by Shear Walls

Wall Ratio	**8 Story**	**15 Story**	**20 Story**	**25 Story**	**30 Story**	**35 Story**	**40 Story**
0.5	65.5029	43.3743	37.0856	32.6192	27.1165	21.5450	17.9929
1	68.7181	55.4937	53.2910	49.4736	45.0815	41.6224	37.9856
1.5	71.5362	60.4470	58.0592	55.1938	51.0378	47.2510	42.1860
2	76.4250	62.1049	61.5824	60.5431	59.2439	56.3008	52.1283
2.5	80.1638	67.2409	66.7751	65.4413	64.5712	62.5489	57.4241
3	82.6743	70.8913	70.5133	70.0106	68.4515	66.3668	61.3775
3.5	84.7548	74.0610	73.7758	73.1133	71.8522	70.5924	64.9934
4	86.6014	76.9316	76.7409	75.4214	74.9560	73.2631	68.3602

The behavior factor q for each horizontal direction is calculated by equation (ES EN 1998-1: 2015)

$$q = q_o k_w \geq 1.5$$

where;

q_o is the basic value of the behavior factor, dependent on the type of structural system and on its regularity in elevation.

k_w is the factor reflecting the prevailing failure mode in structural systems with walls.

The basic value of the behavior factor, q_o, for frame, dual and coupled wall systems which are regular in elevation and will be designed as a DCM (Ductility Class Medium) can be estimated by the equation below but for uncoupled wall systems $q_o = 3$.

$$q_o = 3.0 \frac{\alpha_u}{\alpha_1}$$

where;

α_1: is the value by which the horizontal seismic design action is multiplied in order to first reach the flexural resistance in any member in the structure, while all other design actions remain constant;

α_u: is the value by which the horizontal seismic design action is multiplied, in order to form plastic hinges in a number of sections sufficient for the development of overall structural instability, while all other design actions remain constant. The factor α_u may be obtained from a nonlinear static (push over) global analysis.

The approximate values of α_u/α_1 taken for the analyzed buildings are 1.2 for wall-equivalent dual system and 1.3 for frame and frame-equivalent dual systems.

The factor k_w reflecting the prevailing failure mode in structural systems with walls is taken as 1.00 for frame and frame – equivalent dual systems and for wall and wall – equivalent systems it is taken as;

$$k_w = \left(\frac{1+\alpha_0}{3}\right) \leq 1, \text{ but not less than } 0.5$$

where α_o is the prevailing aspect ratio of the walls of the structural system.

If the aspect ratios h_{wi}/l_{wi} of all walls *i* of a structural system do not significantly differ, the prevailing aspect ratio α_o may be determined from the following expression:

$$\alpha o = \frac{\sum h_{wi}}{\sum l_{wi}}$$

Where;

h_{wi} is the height of wall *i*; and

l_{wi} is the length of the section of wall *i*.

For example, the prevailing aspect ratio α_o, for 15 story building model with 1% shear wall ratio having a total of 12 shear walls with 2.9m height, in which 8 of them have 3.5 length and 4 of them have 2m, will be

$$\alpha o = \frac{\sum h_{wi}}{\sum l_{wi}} = \frac{12*2.9}{8*3.5+4*2} = 0.97$$

$$\text{Then } k_w = \left(\frac{1+0.97}{3}\right) = 0.65 \leq 1$$

Therefore, the behavior factor *q* for uncoupled wall system with basic value of the behavior factor $q_o = 3$ will be:

$$q = q_o k_w \geq 1.5$$

$$q = 3*0.65 = 1.97$$

The values of the behavior factors for 63 building models having different shear wall areas are determined using the above procedures. The values are listed in the table below.

Table 3-4 Behavior Factors for Different Structural Systems

Number of Stories	Shear Wall Ratio (%)	Structural System	*q*
8	0.5	Uncoupled Wall system	3
	1	Uncoupled Wall system	1.97
	1.5	Uncoupled Wall system	1.97
	2	Uncoupled Wall system	1.58
	2.5	Uncoupled Wall system	1.58
	3	Uncoupled Wall system	1.58
	3.5	Uncoupled Wall system	1.58

	4	Uncoupled Wall system	1.58
15	0.5	Frame-equivalent dual system	3.9
	1	Wall-equivalent dual system	1.9
	1.5	Wall-equivalent dual system	1.9
	2	Wall-equivalent dual system	1.9
	2.5	Uncoupled Wall system	1.58
	3	Uncoupled Wall system	1.58
	3.5	Uncoupled Wall system	1.58
	4	Uncoupled Wall system	1.58
20	0.5	Frame System	3.9
	1	Wall-equivalent dual system	1.9
	1.5	Wall-equivalent dual system	1.9
	2	Wall-equivalent dual system	1.9
	2.5	Uncoupled Wall system	1.58
	3	Uncoupled Wall system	1.58
	3.5	Uncoupled Wall system	1.58
	4	Uncoupled Wall system	1.58
25	0.5	Frame System	3.9
	1	Frame-equivalent dual system	3.9
	1.5	Wall-equivalent dual system	1.9
	2	Wall-equivalent dual system	1.9
	2.5	Uncoupled Wall system	1.58
	3	Uncoupled Wall system	1.58
	3.5	Uncoupled Wall system	1.58
	4	Uncoupled Wall system	1.58
30	0.5	Frame System	3.9
	1	Frame-equivalent dual system	3.9
	1.5	Wall-equivalent dual system	1.9
	2	Wall-equivalent dual system	1.9
	2.5	Uncoupled Wall system	1.58
	3	Uncoupled Wall system	1.58
	3.5	Uncoupled Wall system	1.58
	4	Uncoupled Wall system	1.58

35	0.5	Frame System	3.9
	1	Frame-equivalent dual system	3.9
	1.5	Frame-equivalent dual system	3.9
	2	Wall-equivalent dual system	1.9
	2.5	Wall-equivalent dual system	1.9
	3	Uncoupled Wall system	1.58
	3.5	Uncoupled Wall system	1.58
	4	Uncoupled Wall system	1.58
40	0.5	Frame System	3.9
	1	Frame-equivalent dual system	3.9
	1.5	Frame-equivalent dual system	3.9
	2	Wall-equivalent dual system	1.9
	2.5	Wall-equivalent dual system	1.9
	3	Wall-equivalent dual system	1.9
	3.5	Uncoupled Wall system	1.58
	4	Uncoupled Wall system	1.58

The design response spectrum can be determined by reducing the elastic response spectrum with this values of behavior factors.

Then the shape of design spectrum for elastic analysis looks

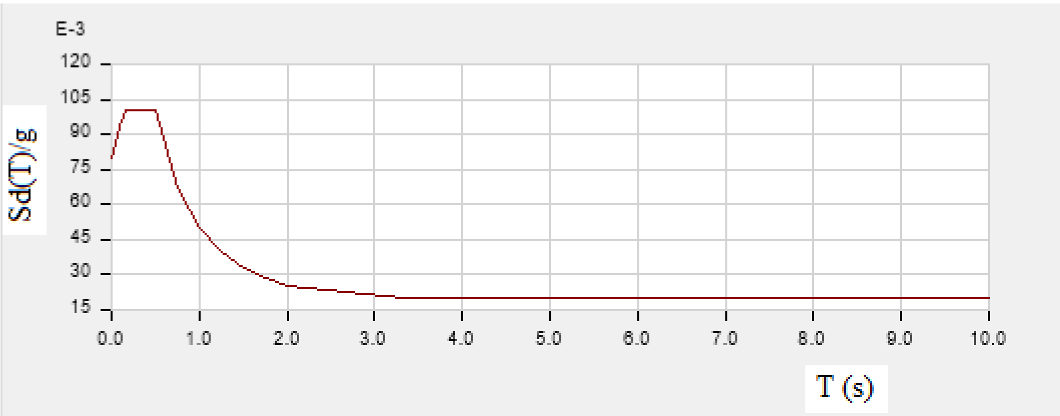


Figure 3-8 Shape of Design Spectrum for q = 3

In addition, the behavior factors are used to obtain the actual displacements of a point of structural system (d_s) by multiplying the displacement of the same point (d_e) obtained by modal response spectrum analysis based on design response spectrum.

$$d_s = qd_e$$

where

d_s is the displacement of a point of the structural system induced by the design seismic action

q is the behavior factor introduced into the analysis of the system

d_e is the displacement of the same point of the structural system as determined by the linear analysis based on the design response spectrum

3.2.2 Number of Modes

The number of modes taken in to account includes all mode responses which have significant contribution to the global response. This are modes which have the sum of effective modal masses at least 90% of the total mass of the structure and with effective modal masses greater than 5% of the total mass. As an initial the equation for the minimum number of modes to be accounted in a spatial analysis given by ES EN 1998-1: 2015 is taken.

That is $k \geq 3.\sqrt{n}$

Where;

k is the number of modes taken in to account and;

n is the number of stories above the foundation or the top of a rigid basement.

Therefore, the number of modes taken for building models with 1% shear wall ratios are k = 12 for 8 story, k = 12 for 15 story, k = 17 for 20 story, k = 20 for 25 story, k = 23 for 30 story, k = 25 for 25 story and k = 25 for 40 story.

3.2.3 Combination of Modal Responses

In order to determine the peak value of the total response, peak modal responses are combined by using the complete quadratic combination (CQC) method. First the independency between the natural periods of any two successive modes of vibration are checked by the equation

$$T_j \leq 0.9 * T_i \quad (i<j)$$

Where T_j, T_i are the natural periods of any two successive modes of vibration taken in to account for the determination of seismic effects. The result shows that the natural periods of major contributing modes are not independent which means they are closely spaced. So CQC (complete quadratic combination) method which is the most viable option for any structure is selected.

3.2.4 Second-Order Effect (P-Δ Effect)

The need for accounting second order effect (P-Δ effect) is checked by the equation given below (ES EN 1998-1: 2015):

$$\theta = \frac{P_{tot} . d_r}{V_{tot} . h} \leq 0.10$$

Where

θ is the inter story drift sensitivity coefficient;

P_{tot} is the total gravity load at and above the story considered in the seismic design situation;

d_r is the design inter story drift, evaluated as the difference of the average lateral displacement 'd_s' at the top and bottom of the story under consideration;

V_{tot} is the total seismic story shear;

h is the inter story height

If the inter story drift sensitivity coefficient 'θ' value is less than 0.1 the second-order effects need not be taken in to account. Sample estimation of the inter story drift sensitivity coefficient for each number of story is given in Appendix A-1.

As an alternative the global second order effect in buildings can be determined by:

According to ES EN 1992-1-1:2015

The global second order effects in buildings may be ignored if;

$$F_{V,Ed} \leq k_1 \cdot \frac{n_s}{n_s + 1.6} \cdot \frac{\sum E_{cd} I_c}{L^2}$$

Where:

$F_{V,Ed}$ is the total vertical load (on braced and bracing members)

n_s is the number of stories

L is the total height of building above level of moment restraint

E_{cd} is the design value of the modules of elasticity of concrete

I_c is the second moment of area (uncracked concrete section) of bracing member(s). The recommended value for k_1 is 0.31.

The above equation is valid only if all of the following conditions are met:

- Torsional instability is not governing, i.e. structure is reasonably symmetrical
- Global shear deformations are negligible (as in a bracing system mainly consisting of shear walls without large openings)
- Bracing memebers are rigidly fixed at the base, i.e. roations are negligible
- The stiffness of bracing members is reasonably constant along the height
- The total vertiacal load increases by approximately the same amount per storey

k_1 in the above equation may be replaced by k_2 if it can be verfied that the bracing memebers are uncracked in ultimate limit state.The recommended value for k_2 is 0.62.

3.2.5 Damage Limitations

To protect the structure from non-structural damage during frequent earthquakes, the deformation capacity (inter story drifts) should be checked with the code-specified deformation limits. According to EN 1998-01 the damage limitation requirement will be:

$$d_r \, . \, \nu \leq \alpha \, . \, h$$

where

d_r is the design inter story drift evaluated as the difference of the average lateral displacements d_s in center of mass at the top and bottom story under consideration;

h is the story height;

α is a factor which takes into account the type of the non-structural elements and their arrangements into the structure. A value of 0.005 is taken assuming the building have non-structural elements of brittle materials attached to the structure;

ν is the reduction factor which takes into account the lower return period of the seismic action associated with the damage limitation requirement. The value of 'ν' is taken as 0.5 for important class II.

4. ANALYTICAL RESULTS OF BUILDING MODELS

The software program, ETABS 16.2.0 is used to perform the analyses of building models using response spectrum analysis. The variation of main parameters that affect the seismic performance of these building models, which are inter story drift, roof displacement and base shear responses, with different shear wall area to floor area ratios are determined for each principal directions. Analytical results are provided for

- Building models generated from an investigation about building inventory in Zeytinburnu/ İstanbul indicated by Ozan Soydas (2009) which have varying shear wall ratios between 0.53 and 3.47%.
- Newly generated building models with varying shear wall ratios between 0.5 and 4%.

4.1 Inter story Drift

The variation of the maximum inter story drift with increasing shear wall area to floor area ratio of building models for each direction are displayed in Figure 4-1 and Figure 4-2 for 60 building models generated from the building inventory. Trend lines approximated by second order polynomials are used to represent the results.

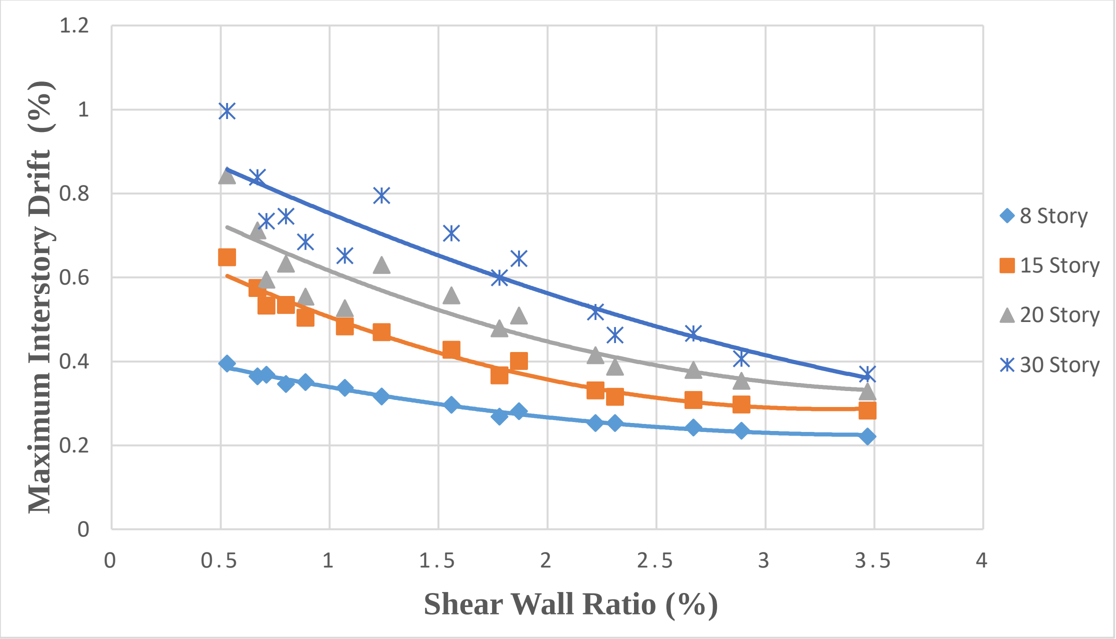


Figure 4-1 Variation of Maximum Inter story Drift with Shear Wall Ratio for X direction

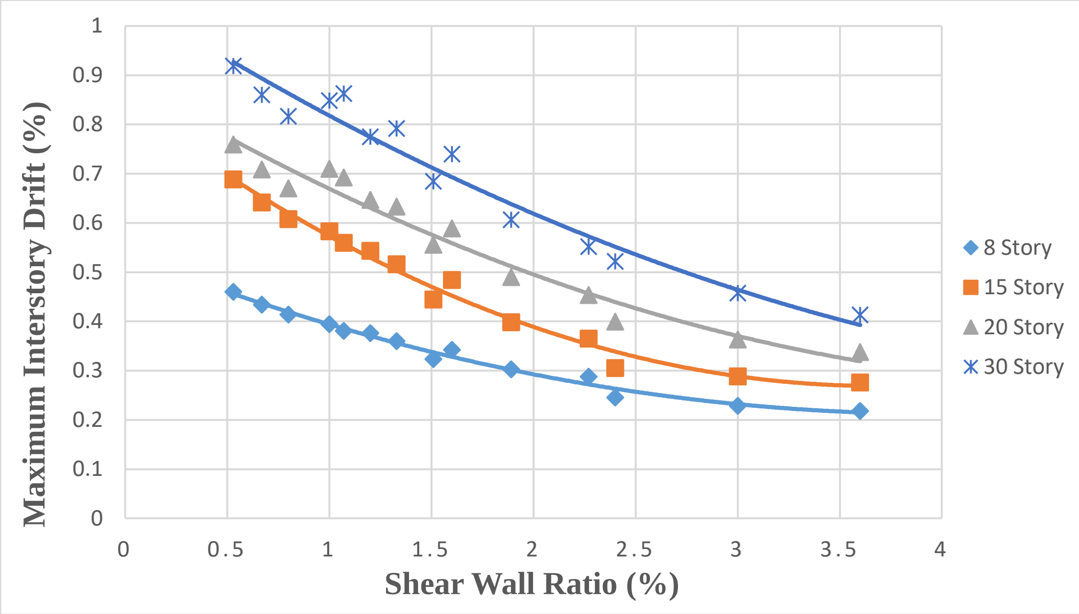


Figure 4-2 Variation of Maximum Inter story Drift with Shear Wall Ratio for Y direction

As the figure shows, the maximum inter story drift decreases with increasing shear wall area to floor area ratio. But it can be seen that there is not a constant reduction between consecutive values, this because that the five models taken from the inventory have different shear wall and column arrangements and numbers.

It can be seen from the result that the reduction in drift levels nearly become constant after 2.22% of shear wall area to floor area ratio. So this shows that increasing the shear wall ratio beyond this point has not significant effect on reducing story drift.

The maximum inter story drift variation for 56 building models which have 0.5, 1, 1.5, 2, 2.5, 3, 3.5 and 4% shear wall ratios is given in the figure below for both X and Y directions.

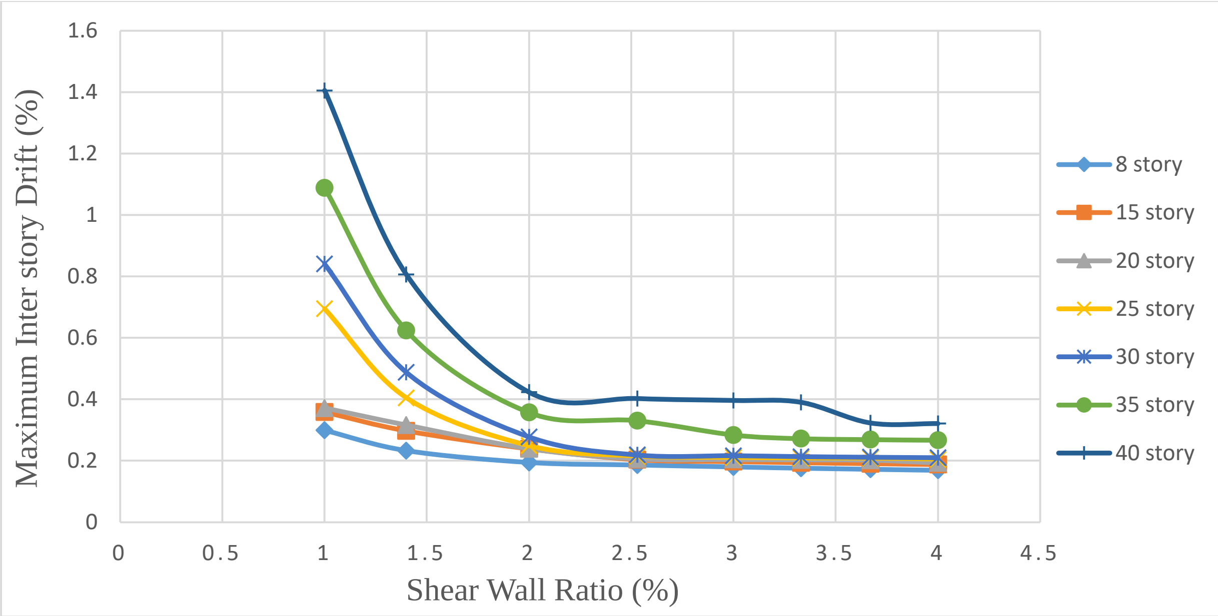


Figure 4-3 Variation of Maximum Inter story Drift with Shear Wall Ratio for X direction

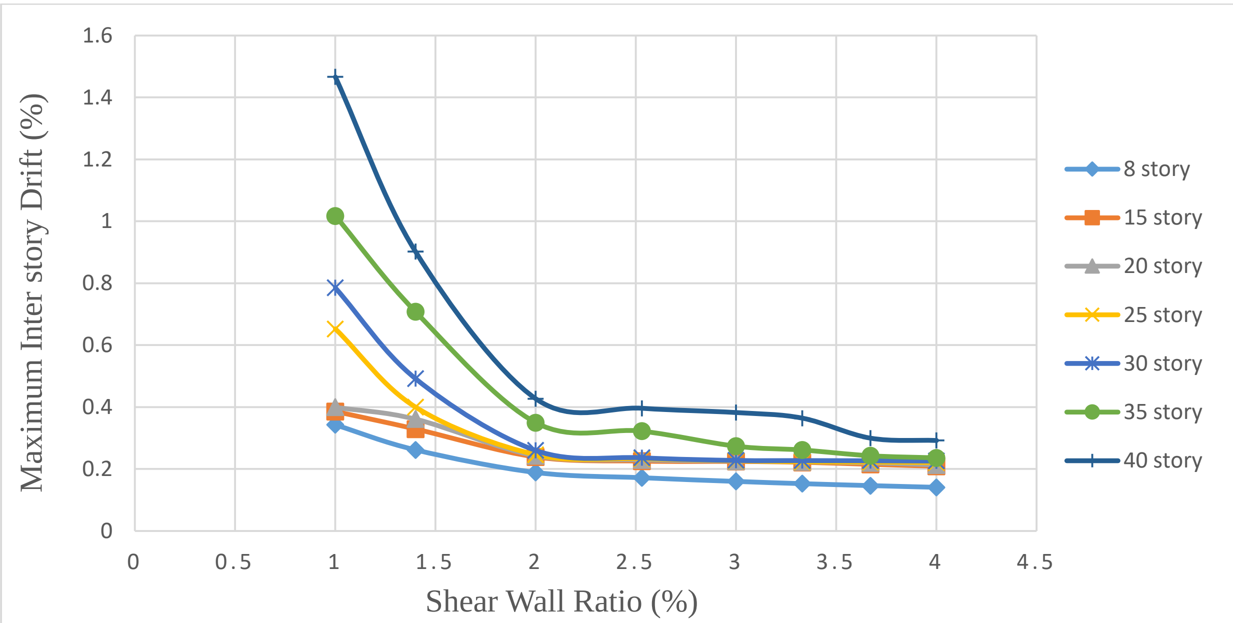


Figure 4-4 Variation of Maximum Inter story Drift with Shear Wall Ratio for Y direction

As can be observed from the figure, increasing shear wall ratio decreases the maximum inter story drift. The percent decrease of story drift at lower shear wall ratio is high compared to higher shear wall ratios. At higher shear wall ratios even increasing the wall ratio at higher rate don’t have a significant change in the inter story drift. But on the contrary, small increasing on shear wall ratio have a significant change on the percent decrease of inter story drift at lower shear wall ratios.

The result shows that for shear wall ratios up to 2%, there is a great difference between inter story drift values with increasing number of stories. This is because of the change in the classification of the system, with increasing number of stories, due to the reduction in percent base shear force carried by the shear walls.

A significant decrease in the inter story drift is shown for increasing shear wall area to floor area ratios between 0.5 and 2%. This contradict the value of shear wall ratio, which is 1%, given by literatures as a rule of thumb to be used in design. This value was concluded from assuming a significant decrease in inter story drift up to 1% shear wall ratio. This may be true for low to mid rise buildings but not for high rises. It is also observed that 0.5 and 1% shear wall ratios are not sufficient to satisfy damage limitation requirement.

4.2 Roof Top Displacement

The variation of roof displacement with shear wall ratio is given in Figure 4-7 and Figure 4-8.

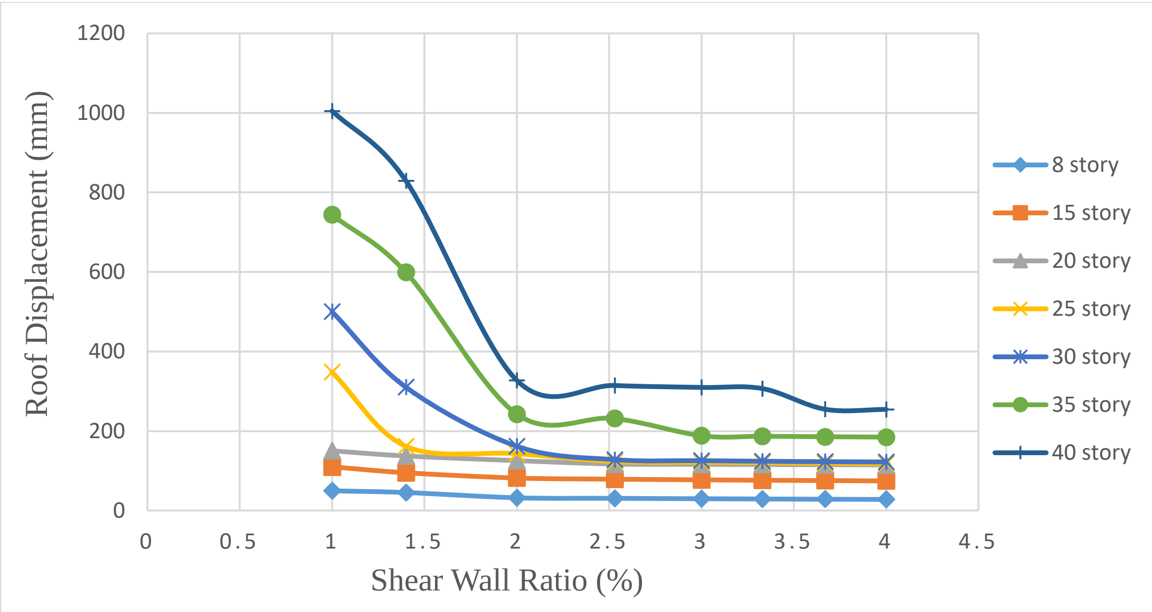


Figure 4-5 Variation of Roof Displacement with Increasing Shear Wall Ratio for X direction

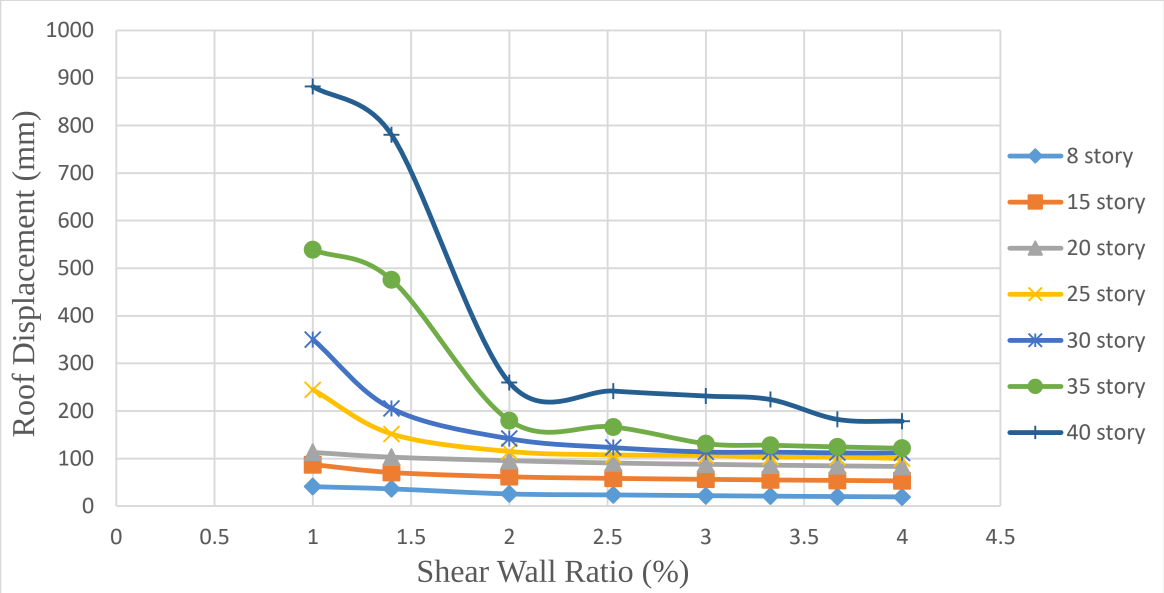


Figure 4-6 Variation of Roof Displacement with Increasing Shear Wall Ratio for Y direction

When the shear wall area to floor area ratio increases the roof displacement decreases. The result shows that the level of reduction between the roof displacements have higher value between 0.5 and 1% shear wall ratios for up to 25 stories; and between 1.5 and 2% shear wall ratios for 30 and higher stories.

4.3 Roof Top Displacement Ratio

Roof top displacement ratio is the ratio between the actual top displacement in the center of mass to the total height of the building. As the result (Figure 4-9) shows building models with up to 35 stories satisfy the ratio limit after 2% shear wall ratio and on the other hand building model with 40 story satisfy the limit after 3% shear wall ratio.

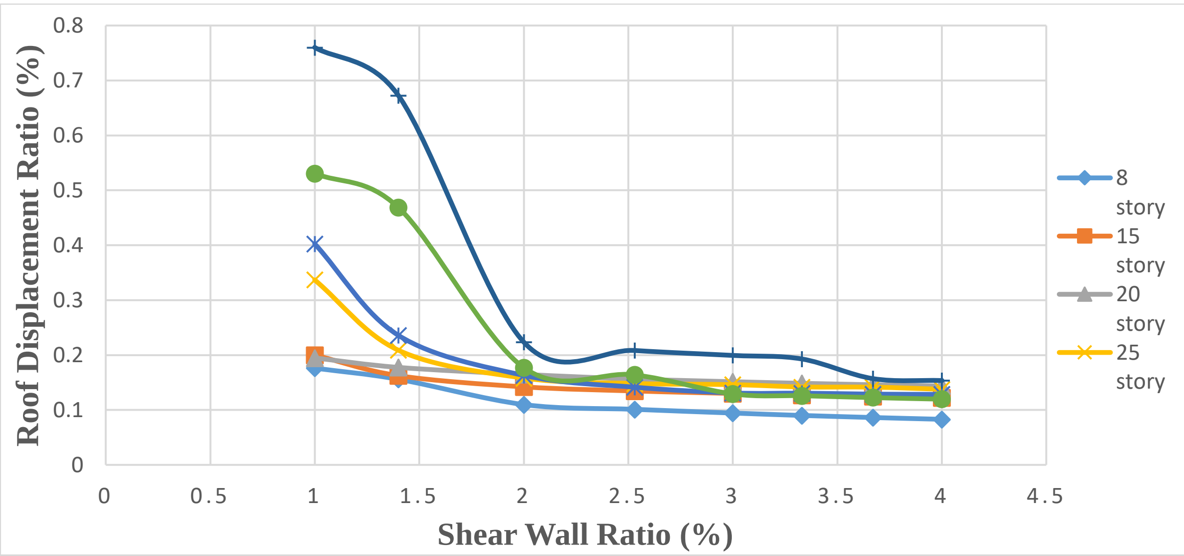


Figure 4-7 Variation of Roof Displacement Ratio with Increasing Shear Wall Ratio

4.4 Base Shear Carried by Shear Walls

In order to determine the contribution of shear walls in carrying the applied lateral loads, the percentage of total base shear force carried by reinforced concrete shear walls with increasing shear wall area to floor area ratios are compared.

The points on the graph showed the percentage of the average shear force carried by the ground floor shear walls to the total base shear. The results of the computed percentage of base shear force carried by shear walls, for each number of stories with different shear wall ratios, in each principal directions are represented in the figure below.

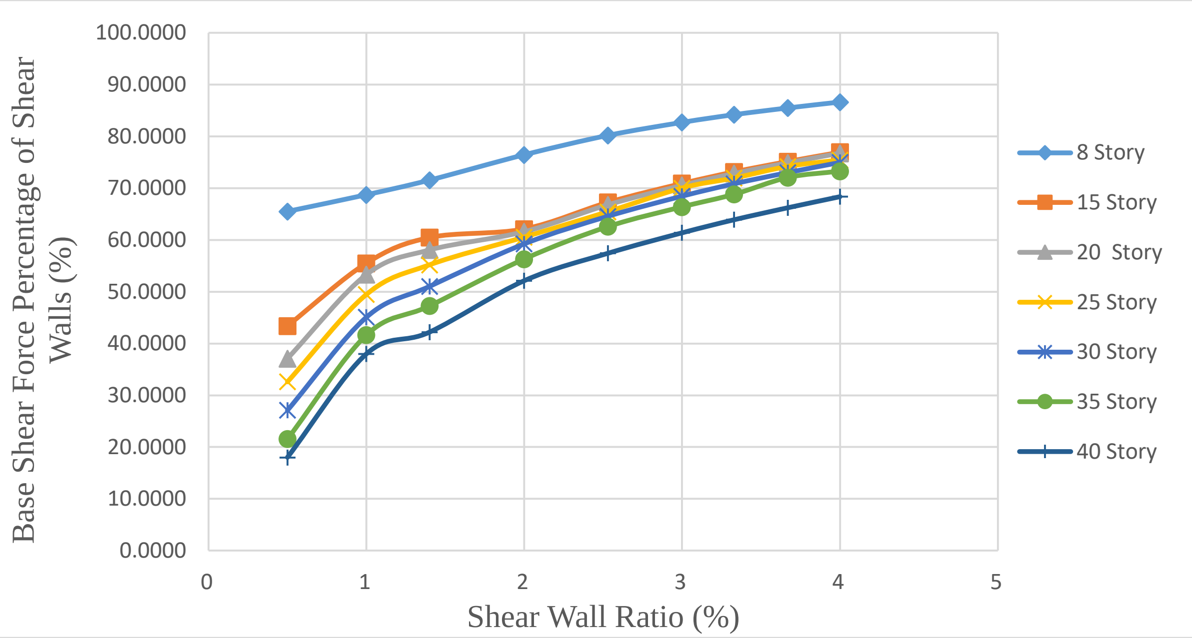


Figure 4-8 Percentage of Base Shear Carried by Shear Walls

From the figure it can be easily observed that the percentage of base shear carried by shear walls increase with increasing shear wall ratios. The percent increases significantly until the shear wall ratio has reached 1%. On the other hand, the percentage of base shear carried by shear walls reduce with increasing number of stories. This is because that when height of a building increase the stiffness of shear wall reduces unless the section of shear wall changed. So this shows that the contribution of shear walls significantly affected by number of stories.

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The aim of this study is to assess the response of high rise reinforced concrete buildings having different shear wall area to floor area ratios under earthquake loading and to investigate the variation of the responses of the structure, which are inter story drift, roof drift and base shear, with increasing shear wall ratios. Based on the results obtained from the response spectrum analysis the following conclusions are obtained:

- The inter story drift decreases with increasing shear wall area to floor area ratio. The change in the reduction of the story drift is high for lower shear wall ratio values compared to higher values. At higher shear wall ratio values, increasing the wall ratio at higher rate have very small change in the reduction of story drift. On the contrary, at lower shear wall ratio increasing the wall ratio even at lower rate have a greater effect.
- The reduction in drift levels nearly become constant after 2% shear wall ratio so this shows that increasing the shear wall ratio beyond this point has not significant effect on reducing story drift.
- Shear wall ratios beyond 1% should be used to satisfy the damage limitation requirement given by ES EN 1998-1: 2015.
- The 1% shear wall ratio given by literatures to be used as a rule of thumb in designing buildings is not sufficient to limit the observed drift.
- As the story number increases the story drift and the reduction level between story drifts also increases.
- In addition, the roof displacement also decreases with increasing shear wall ratio. The result shows that the level of reduction between the roof displacements have higher value for lower shear wall ratios especially between 1.5 and 2% compared to higher ratios.

5.2 Recommendation for Future Study

In this analytical study the influence of variation in shear wall ratio on the seismic response of high rise reinforced concrete buildings having shear walls is assessed. To improve and support the findings of this study, further investigations should be made considering different parameters and methodologies. This may include

- Examine the effect of non-rectangular shear walls, this may include L-shaped or T-shaped structural walls, under earthquake loading.
- Study the effect of un symmetric configuration of wall and irregularity in plan
- Investigate the effect of variation in shear wall ratios on reinforced concrete buildings having longer spans
- Investigate the nonlinear behavior of the analyzed building models using other method of analysis such as time history analysis.

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APPENDIX A. Data and Analysis Results for Building Models

A.1. Sample Calculation to check the need of P-Δ effect for 8 story with 0.5% wall ratio

Story	Load Case/Combo	Dir	Drift	q	Drift*q	P	V	θ	Classification
Story8	Comb3 Max	X	0.000741	3	0.002223	4108.35	211.55	0.043	Non-Sway
Story8	Comb3 Min	X	0.000741	3	0.002223	4108.35	-211.55	0.043	Non-Sway
Story8	Comb4 Max	X	0.000741	3	0.002223	4108.35	211.55	0.043	Non-Sway
Story8	Comb4 Min	X	0.000741	3	0.002223	4108.35	-211.55	0.043	Non-Sway
Story8	Comb5 Max	X	0.000741	3	0.002223	4108.35	211.55	0.043	Non-Sway
Story8	Comb5 Min	X	0.000741	3	0.002223	4108.35	-211.55	0.043	Non-Sway
Story8	Comb6 Max	X	0.000741	3	0.002223	4108.35	211.55	0.043	Non-Sway
Story8	Comb6 Min	X	0.000741	3	0.002223	4108.35	-211.55	0.043	Non-Sway
Story8	Comb7 Max	X	0.000741	3	0.002223	4108.35	211.55	0.043	Non-Sway
Story8	Comb7 Min	X	0.000741	3	0.002223	4108.35	-211.55	0.043	Non-Sway
Story8	Comb8 Max	X	0.000741	3	0.002223	4108.35	211.55	0.043	Non-Sway
Story8	Comb8 Min	X	0.000741	3	0.002223	4108.35	-211.55	0.043	Non-Sway
Story8	Comb9 Max	X	0.000741	3	0.002223	4108.35	211.55	0.043	Non-Sway
Story8	Comb9 Min	X	0.000741	3	0.002223	4108.35	-211.55	0.043	Non-Sway
Story8	Comb10 Max	X	0.000741	3	0.002223	4108.35	211.55	0.043	Non-Sway
Story8	Comb10 Min	X	0.000741	3	0.002223	4108.35	-211.55	0.043	Non-Sway
Story8	Comb11 Max	X	0.000741	3	0.002223	4108.35	211.55	0.043	Non-Sway
Story8	Comb11 Min	X	0.000741	3	0.002223	4108.35	-211.55	0.043	Non-Sway
Story8	Comb12 Max	X	0.000741	3	0.002223	4108.35	211.55	0.043	Non-Sway
Story8	Comb12 Min	X	0.000741	3	0.002223	4108.35	-211.55	0.043	Non-Sway
Story8	Comb13 Max	X	0.000741	3	0.002223	4108.35	211.55	0.043	Non-Sway
Story8	Comb13 Min	X	0.000741	3	0.002223	4108.35	-211.55	0.043	Non-Sway
Story8	Comb14 Max	X	0.000741	3	0.002223	4108.35	211.55	0.043	Non-Sway
Story8	Comb14 Min	X	0.000741	3	0.002223	4108.35	-211.55	0.043	Non-Sway
Story8	Comb15 Max	X	0.000741	3	0.002223	4108.35	211.55	0.043	Non-Sway
Story8	Comb15 Min	X	0.000741	3	0.002223	4108.35	-211.55	0.043	Non-Sway
Story8	Comb16 Max	X	0.000741	3	0.002223	4108.35	211.55	0.043	Non-Sway
Story8	Comb16 Min	X	0.000741	3	0.002223	4108.35	-211.55	0.043	Non-Sway
Story8	Comb17 Max	X	0.000741	3	0.002223	4108.35	211.55	0.043	Non-Sway

Story	Load Case/Combo	Dir	Drift	q	Drift*q	P	V	θ	Classification
Story8	Comb17 Min	X	0.000741	3	0.002223	4108.35	-211.55	0.043	Non-Sway
Story8	Comb18 Max	X	0.000741	3	0.002223	4108.35	211.55	0.043	Non-Sway
Story8	Comb18 Min	X	0.000741	3	0.002223	4108.35	-211.55	0.043	Non-Sway
Story7	Comb3 Max	X	0.000904	3	0.002712	8216.7	329.50	0.068	Non-Sway
Story7	Comb3 Min	X	0.000904	3	0.002712	8216.7	-329.50	0.068	Non-Sway
Story7	Comb4 Max	X	0.000904	3	0.002712	8216.7	329.50	0.068	Non-Sway
Story7	Comb4 Min	X	0.000904	3	0.002712	8216.7	-329.50	0.068	Non-Sway
Story7	Comb5 Max	X	0.000904	3	0.002712	8216.7	329.50	0.068	Non-Sway
Story7	Comb5 Min	X	0.000904	3	0.002712	8216.7	-329.50	0.068	Non-Sway
Story7	Comb6 Max	X	0.000904	3	0.002712	8216.7	329.50	0.068	Non-Sway
Story7	Comb6 Min	X	0.000904	3	0.002712	8216.7	-329.50	0.068	Non-Sway
Story7	Comb7 Max	X	0.000904	3	0.002712	8216.7	329.50	0.068	Non-Sway
Story7	Comb7 Min	X	0.000904	3	0.002712	8216.7	-329.50	0.068	Non-Sway
Story7	Comb8 Max	X	0.000904	3	0.002712	8216.7	329.50	0.068	Non-Sway
Story7	Comb8 Min	X	0.000904	3	0.002712	8216.7	-329.50	0.068	Non-Sway
Story7	Comb9 Max	X	0.000904	3	0.002712	8216.7	329.50	0.068	Non-Sway
Story7	Comb9 Min	X	0.000904	3	0.002712	8216.7	-329.50	0.068	Non-Sway
Story7	Comb10 Max	X	0.000904	3	0.002712	8216.7	329.50	0.068	Non-Sway
Story7	Comb10 Min	X	0.000904	3	0.002712	8216.7	-329.50	0.068	Non-Sway
Story7	Comb11 Max	X	0.000904	3	0.002712	8216.7	329.50	0.068	Non-Sway
Story7	Comb11 Min	X	0.000904	3	0.002712	8216.7	-329.50	0.068	Non-Sway
Story7	Comb12 Max	X	0.000904	3	0.002712	8216.7	329.50	0.068	Non-Sway
Story7	Comb12 Min	X	0.000904	3	0.002712	8216.7	-329.50	0.068	Non-Sway
Story7	Comb13 Max	X	0.000904	3	0.002712	8216.7	329.50	0.068	Non-Sway
Story7	Comb13 Min	X	0.000904	3	0.002712	8216.7	-329.50	0.068	Non-Sway
Story7	Comb14 Max	X	0.000904	3	0.002712	8216.7	329.50	0.068	Non-Sway
Story7	Comb14 Min	X	0.000904	3	0.002712	8216.7	-329.50	0.068	Non-Sway
Story7	Comb15 Max	X	0.000904	3	0.002712	8216.7	329.50	0.068	Non-Sway
Story7	Comb15 Min	X	0.000904	3	0.002712	8216.7	-329.50	0.068	Non-Sway
Story7	Comb16 Max	X	0.000904	3	0.002712	8216.7	329.50	0.068	Non-Sway
Story7	Comb16 Min	X	0.000904	3	0.002712	8216.7	-329.50	0.068	Non-Sway

Story	Load Case/Combo	Dir	Drift	q	Drift*q	P	V	θ	Classification
Story7	Comb17 Min	X	0.000904	3	0.002712	8216.7	-329.50	0.068	Non-Sway
Story7	Comb18 Max	X	0.000904	3	0.002712	8216.7	329.50	0.068	Non-Sway
Story7	Comb18 Min	X	0.000904	3	0.002712	8216.7	-329.50	0.068	Non-Sway
Story6	Comb3 Max	X	0.001043	3	0.003129	12325.05	396.73	0.097	Non-Sway
Story6	Comb3 Min	X	0.001043	3	0.003129	12325.05	-396.73	0.097	Non-Sway
Story6	Comb4 Max	X	0.001043	3	0.003129	12325.05	396.73	0.097	Non-Sway
Story6	Comb4 Min	X	0.001043	3	0.003129	12325.05	-396.73	0.097	Non-Sway
Story6	Comb5 Max	X	0.001043	3	0.003129	12325.05	396.73	0.097	Non-Sway
Story6	Comb5 Min	X	0.001043	3	0.003129	12325.05	-396.73	0.097	Non-Sway
Story6	Comb6 Max	X	0.001043	3	0.003129	12325.05	396.73	0.097	Non-Sway
Story6	Comb6 Min	X	0.001043	3	0.003129	12325.05	-396.73	0.097	Non-Sway
Story6	Comb7 Max	X	0.001043	3	0.003129	12325.05	396.73	0.097	Non-Sway
Story6	Comb7 Min	X	0.001043	3	0.003129	12325.05	-396.73	0.097	Non-Sway
Story6	Comb8 Max	X	0.001043	3	0.003129	12325.05	396.73	0.097	Non-Sway
Story6	Comb8 Min	X	0.001043	3	0.003129	12325.05	-396.73	0.097	Non-Sway
Story6	Comb9 Max	X	0.001043	3	0.003129	12325.05	396.73	0.097	Non-Sway
Story6	Comb9 Min	X	0.001043	3	0.003129	12325.05	-396.73	0.097	Non-Sway
Story6	Comb10 Max	X	0.001043	3	0.003129	12325.05	396.73	0.097	Non-Sway
Story6	Comb10 Min	X	0.001043	3	0.003129	12325.05	-396.73	0.097	Non-Sway
Story6	Comb11 Max	X	0.001043	3	0.003129	12325.05	396.73	0.097	Non-Sway
Story6	Comb11 Min	X	0.001043	3	0.003129	12325.05	-396.73	0.097	Non-Sway
Story6	Comb12 Max	X	0.001043	3	0.003129	12325.05	396.73	0.097	Non-Sway
Story6	Comb12 Min	X	0.001043	3	0.003129	12325.05	-396.73	0.097	Non-Sway
Story6	Comb13 Max	X	0.001043	3	0.003129	12325.05	396.73	0.097	Non-Sway
Story6	Comb13 Min	X	0.001043	3	0.003129	12325.05	-396.73	0.097	Non-Sway
Story6	Comb14 Max	X	0.001043	3	0.003129	12325.05	396.73	0.097	Non-Sway
Story6	Comb14 Min	X	0.001043	3	0.003129	12325.05	-396.73	0.097	Non-Sway
Story6	Comb15 Max	X	0.001043	3	0.003129	12325.05	396.73	0.097	Non-Sway
Story6	Comb15 Min	X	0.001043	3	0.003129	12325.05	-396.73	0.097	Non-Sway
Story6	Comb16 Max	X	0.001043	3	0.003129	12325.05	396.73	0.097	Non-Sway
Story6	Comb16 Min	X	0.001043	3	0.003129	12325.05	-396.73	0.097	Non-Sway
Story6	Comb17 Max	X	0.001043	3	0.003129	12325.05	396.73	0.097	Non-Sway
Story6	Comb17 Min	X	0.001043	3	0.003129	12325.05	-396.73	0.097	Non-Sway
Story6	Comb18 Max	X	0.001043	3	0.003129	12325.05	396.73	0.097	Non-Sway
Story6	Comb18 Min	X	0.001043	3	0.003129	12325.05	-396.73	0.097	Non-Sway

Story	Load Case/Combo	Dir	Drift	q	Drift*q	P	V	θ	Classification
Story5	Comb3 Max	X	0.001151	3	0.003453	16433.4	442.42	0.128	Sway
Story5	Comb3 Min	X	0.001151	3	0.003453	16433.4	-442.42	0.128	Sway
Story5	Comb4 Max	X	0.001151	3	0.003453	16433.4	442.42	0.128	Sway
Story5	Comb4 Min	X	0.001151	3	0.003453	16433.4	-442.42	0.128	Sway
Story5	Comb5 Max	X	0.001151	3	0.003453	16433.4	442.42	0.128	Sway
Story5	Comb5 Min	X	0.001151	3	0.003453	16433.4	-442.42	0.128	Sway
Story5	Comb6 Max	X	0.001151	3	0.003453	16433.4	442.42	0.128	Sway
Story5	Comb6 Min	X	0.001151	3	0.003453	16433.4	-442.42	0.128	Sway
Story5	Comb7 Max	X	0.001151	3	0.003453	16433.4	442.42	0.128	Sway
Story5	Comb7 Min	X	0.001151	3	0.003453	16433.4	-442.42	0.128	Sway
Story5	Comb8 Max	X	0.001151	3	0.003453	16433.4	442.42	0.128	Sway
Story5	Comb8 Min	X	0.001151	3	0.003453	16433.4	-442.42	0.128	Sway
Story5	Comb9 Max	X	0.001151	3	0.003453	16433.4	442.42	0.128	Sway
Story5	Comb9 Min	X	0.001151	3	0.003453	16433.4	-442.42	0.128	Sway
Story5	Comb10 Max	X	0.001151	3	0.003453	16433.4	442.42	0.128	Sway
Story5	Comb10 Min	X	0.001151	3	0.003453	16433.4	-442.42	0.128	Sway
Story5	Comb11 Max	X	0.001151	3	0.003453	16433.4	442.42	0.128	Sway
Story5	Comb11 Min	X	0.001151	3	0.003453	16433.4	-442.42	0.128	Sway
Story5	Comb12 Max	X	0.001151	3	0.003453	16433.4	442.42	0.128	Sway
Story5	Comb12 Min	X	0.001151	3	0.003453	16433.4	-442.42	0.128	Sway
Story5	Comb13 Max	X	0.001151	3	0.003453	16433.4	442.42	0.128	Sway
Story5	Comb13 Min	X	0.001151	3	0.003453	16433.4	-442.42	0.128	Sway
Story5	Comb14 Max	X	0.001151	3	0.003453	16433.4	442.42	0.128	Sway
Story5	Comb14 Min	X	0.001151	3	0.003453	16433.4	-442.42	0.128	Sway
Story5	Comb15 Max	X	0.001151	3	0.003453	16433.4	442.42	0.128	Sway
Story5	Comb15 Min	X	0.001151	3	0.003453	16433.4	-442.42	0.128	Sway
Story5	Comb16 Max	X	0.001151	3	0.003453	16433.4	442.42	0.128	Sway
Story5	Comb16 Min	X	0.001151	3	0.003453	16433.4	-442.42	0.128	Sway
Story5	Comb17 Max	X	0.001151	3	0.003453	16433.4	442.42	0.128	Sway
Story5	Comb17 Min	X	0.001151	3	0.003453	16433.4	-442.42	0.128	Sway
Story5	Comb18 Max	X	0.001151	3	0.003453	16433.4	442.42	0.128	Sway
Story5	Comb18 Min	X	0.001151	3	0.003453	16433.4	-442.42	0.128	Sway
Story4	Comb3 Max	X	0.001211	3	0.003633	20565.85	493.59	0.151	Sway
Story4	Comb3 Min	X	0.001211	3	0.003633	20565.85	-493.59	0.151	Sway
Story4	Comb4 Max	X	0.001211	3	0.003633	20565.85	493.59	0.151	Sway

Story	Load Case/Combo	Dir	Drift	q	Drift*q	P	V	q	Classification
Story2	Comb4 Min	X	0.001047	3	0.003141	28830.75	-623.77	0.145	Sway
Story2	Comb5 Max	X	0.001047	3	0.003141	28830.75	623.77	0.145	Sway
Story2	Comb5 Min	X	0.001047	3	0.003141	28830.75	-623.77	0.145	Sway
Story2	Comb6 Max	X	0.001047	3	0.003141	28830.75	623.77	0.145	Sway
Story2	Comb6 Min	X	0.001047	3	0.003141	28830.75	-623.77	0.145	Sway
Story2	Comb7 Max	X	0.001047	3	0.003141	28830.75	623.77	0.145	Sway
Story2	Comb7 Min	X	0.001047	3	0.003141	28830.75	-623.77	0.145	Sway
Story2	Comb8 Max	X	0.001047	3	0.003141	28830.75	623.77	0.145	Sway
Story2	Comb8 Min	X	0.001047	3	0.003141	28830.75	-623.77	0.145	Sway
Story2	Comb9 Max	X	0.001047	3	0.003141	28830.75	623.77	0.145	Sway
Story2	Comb9 Min	X	0.001047	3	0.003141	28830.75	-623.77	0.145	Sway
Story2	Comb10 Max	X	0.001047	3	0.003141	28830.75	623.77	0.145	Sway
Story2	Comb10 Min	X	0.001047	3	0.003141	28830.75	-623.77	0.145	Sway
Story2	Comb11 Max	X	0.001047	3	0.003141	28830.75	623.77	0.145	Sway
Story2	Comb11 Min	X	0.001047	3	0.003141	28830.75	-623.77	0.145	Sway
Story2	Comb12 Max	X	0.001047	3	0.003141	28830.75	623.77	0.145	Sway
Story2	Comb12 Min	X	0.001047	3	0.003141	28830.75	-623.77	0.145	Sway
Story2	Comb13 Max	X	0.001047	3	0.003141	28830.75	623.77	0.145	Sway
Story2	Comb13 Min	X	0.001047	3	0.003141	28830.75	-623.77	0.145	Sway
Story2	Comb14 Max	X	0.001047	3	0.003141	28830.75	623.77	0.145	Sway
Story2	Comb14 Min	X	0.001047	3	0.003141	28830.75	-623.77	0.145	Sway
Story2	Comb15 Max	X	0.001047	3	0.003141	28830.75	623.77	0.145	Sway
Story2	Comb15 Min	X	0.001047	3	0.003141	28830.75	-623.77	0.145	Sway
Story2	Comb16 Max	X	0.001047	3	0.003141	28830.75	623.77	0.145	Sway
Story2	Comb16 Min	X	0.001047	3	0.003141	28830.75	-623.77	0.145	Sway
Story2	Comb17 Max	X	0.001047	3	0.003141	28830.75	623.77	0.145	Sway
Story2	Comb17 Min	X	0.001047	3	0.003141	28830.75	-623.77	0.145	Sway
Story2	Comb18 Max	X	0.001047	3	0.003141	28830.75	623.77	0.145	Sway
Story2	Comb18 Min	X	0.001047	3	0.003141	28830.75	-623.77	0.145	Sway
Story1	Comb3 Max	X	0.000523	3	0.001569	32993.1	664.45	0.078	Non-Sway
Story1	Comb3 Min	X	0.000523	3	0.001569	32993.1	-664.45	0.078	Non-Sway

Story	Load Case/Combo	Dir	Drift	q	Drift*q	P	V	θ	Classification
Story1	Comb4 Max	X	0.000523	3	0.001569	32993.1	664.45	0.078	Non-Sway
Story1	Comb4 Min	X	0.000523	3	0.001569	32993.1	-664.45	0.078	Non-Sway
Story1	Comb5 Max	X	0.000523	3	0.001569	32993.1	664.45	0.078	Non-Sway
Story1	Comb5 Min	X	0.000523	3	0.001569	32993.1	-664.45	0.078	Non-Sway
Story1	Comb6 Max	X	0.000523	3	0.001569	32993.1	664.45	0.078	Non-Sway
Story1	Comb6 Min	X	0.000523	3	0.001569	32993.1	-664.45	0.078	Non-Sway
Story1	Comb7 Max	X	0.000523	3	0.001569	32993.1	664.45	0.078	Non-Sway
Story1	Comb7 Min	X	0.000523	3	0.001569	32993.1	-664.45	0.078	Non-Sway
Story1	Comb8 Max	X	0.000523	3	0.001569	32993.1	664.45	0.078	Non-Sway
Story1	Comb8 Min	X	0.000523	3	0.001569	32993.1	-664.45	0.078	Non-Sway
Story1	Comb9 Max	X	0.000523	3	0.001569	32993.1	664.45	0.078	Non-Sway
Story1	Comb9 Min	X	0.000523	3	0.001569	32993.1	-664.45	0.078	Non-Sway
Story1	Comb10 Max	X	0.000523	3	0.001569	32993.1	664.45	0.078	Non-Sway
Story1	Comb10 Min	X	0.000523	3	0.001569	32993.1	-664.45	0.078	Non-Sway
Story1	Comb11 Max	X	0.000523	3	0.001569	32993.1	664.45	0.078	Non-Sway
Story1	Comb11 Min	X	0.000523	3	0.001569	32993.1	-664.45	0.078	Non-Sway
Story1	Comb12 Max	X	0.000523	3	0.001569	32993.1	664.45	0.078	Non-Sway
Story1	Comb12 Min	X	0.000523	3	0.001569	32993.1	-664.45	0.078	Non-Sway
Story1	Comb13 Max	X	0.000523	3	0.001569	32993.1	664.45	0.078	Non-Sway
Story1	Comb13 Min	X	0.000523	3	0.001569	32993.1	-664.45	0.078	Non-Sway
Story1	Comb14 Max	X	0.000523	3	0.001569	32993.1	664.45	0.078	Non-Sway
Story1	Comb14 Min	X	0.000523	3	0.001569	32993.1	-664.45	0.078	Non-Sway
Story1	Comb15 Max	X	0.000523	3	0.001569	32993.1	664.45	0.078	Non-Sway
Story1	Comb15 Min	X	0.000523	3	0.001569	32993.1	-664.45	0.078	Non-Sway
Story1	Comb16 Max	X	0.000523	3	0.001569	32993.1	664.45	0.078	Non-Sway
Story1	Comb16 Min	X	0.000523	3	0.001569	32993.1	-664.45	0.078	Non-Sway
Story1	Comb17 Max	X	0.000523	3	0.001569	32993.1	664.45	0.078	Non-Sway
Story1	Comb17 Min	X	0.000523	3	0.001569	32993.1	-664.45	0.078	Non-Sway
Story1	Comb18 Max	X	0.000523	3	0.001569	32993.1	664.45	0.078	Non-Sway
Story1	Comb18 Min	X	0.000523	3	0.001569	32993.1	-664.45	0.078	Non-Sway

A-2 Values of Responses in X- Direction

	Wall ratio (%)	Story Drift (%)	Roof Drift (%)	Roof Disp (mm)
8 Story	0.5	0.4863	0.1919	
	1	0.298849	0.249599	49.94147
	1.4	0.232854	0.201334	45.62717
	2	0.19434	0.175222	32.40896
	2.53	0.186124	0.170008	31.03752
	3	0.179804	0.165584	29.99788
	3.33	0.175696	0.162582	29.34218
	3.67	0.172062	0.159896	28.74494
	4	0.168744	0.157368	28.203
15 Story	0.5	0.89489	0.19835	
	1	0.35834	0.25707	109.7307
	1.4	0.29716	0.21774	95.133
	2	0.23864	0.19418	82.0439
	2.53	0.203188	0.185492	79.25754
	3	0.197026	0.179014	77.578
	3.33	0.19355	0.173958	76.58576
	3.67	0.19039	0.167322	75.72308
	4	0.187546	0.162582	74.96468
20 Story	0.5	0.98278	0.223599	
	1	0.37145	0.26201	150.3869
	1.4	0.31597	0.22933	137.37
	2	0.23921	0.20938	125.5425
	2.53	0.205874	0.194972	116.94212
	3	0.204136	0.18881	116.10946
	3.33	0.20303	0.1817	115.5849
	3.67	0.201924	0.174432	115.1188
	4	0.192918	0.173168	114.70484
25 Story	0.5	1.01049	0.24874	
	1	0.69459	0.37557	348.0126
	1.4	0.40489	0.23788	161.956
	2	0.24909	0.21204	143.412

	2.53	0.215196	0.203188	123.5402
	3	0.211088	0.190864	121.5652
	3.33	0.209034	0.188652	120.7278
	3.67	0.208718	0.186282	119.053
	4	0.205084	0.17933	118.3736
30 Story	0.5	1.20588	0.3978	
	1	0.84045	0.4251	500.2101
	1.4	0.48773	0.2964	310.46
	2	0.27759	0.21546	162.0472
	2.53	0.218672	0.207928	128.36236
	3	0.21646	0.1975	125.84226
	3.33	0.213458	0.19513	124.32862
	3.67	0.211404	0.191812	123.25738
	4	0.209982	0.189916	122.50688
35 Story	0.5	1.45548	0.47541	
	1	1.08849	0.47541	743.6676
	1.4	0.624	0.33306	599.04
	2	0.3572	0.22781	242.5597
	2.53	0.3306	0.21622	231.496
	3	0.284084	0.206348	188.07056
	3.33	0.272076	0.203188	186.75758
	3.67	0.268916	0.202714	185.49358
	4	0.26702	0.20145	184.7178
40 Story	0.5	1.68753	0.5343	
	1	1.40517	0.5226	1004.5191
	1.4	0.80613	0.40794	828.9645
	2	0.42332	0.26904	327.5942
	2.53	0.4028	0.24168	314.4158
	3	0.39653	0.23978	309.6069
	3.33	0.39045	0.22629	306.6999
	3.67	0.323268	0.221042	254.70548
	4	0.321372	0.219462	254.29468

A-3 Values of Responses in Y- Direction

	Wall ratio (%)	Story Drift (%)	Roof Drift (%)	Roof Disp (mm)
8 Story	0.5	0.6138	0.3043	
	1	0.342583	0.241522	40.94448
	1.4	0.261616	0.197	36.2283
	2	0.188494	0.149152	25.47908
	2.53	0.17143	0.136986	23.44562
	3	0.15958	0.128138	21.88142
	3.33	0.152312	0.122924	20.85916
	3.67	0.145992	0.118026	19.98068
	4	0.140462	0.113918	19.21754
15 Story	0.5	0.89441	0.31668	
	1	0.38532	0.26125	86.9649
	1.4	0.3287	0.22344	70.623
	2	0.23845	0.19038	61.7481
	2.53	0.22515	0.176012	58.4916
	3	0.224044	0.173326	56.52292
	3.33	0.221358	0.163214	55.31896
	3.67	0.214722	0.145676	54.23508
	4	0.208718	0.141252	53.2539
20 Story	0.5	1.00008	0.3543	
	1	0.39957	0.28234	112.9626
	1.4	0.36119	0.22857	102.999
	2	0.24244	0.21166	95.6498
	2.53	0.229258	0.209666	90.70938
	3	0.225466	0.194972	87.95702
	3.33	0.222622	0.18723	86.2601
	3.67	0.219462	0.178066	84.74646
	4	0.212826	0.173484	83.3845
25 Story	0.5	1.29441	0.37362	
	1	0.65208	0.34437	244.4598
	1.4	0.39957	0.247	151.4566

	2	0.24586	0.22496	114.589
	2.53	0.233366	0.220568	107.4084
	3	0.226256	0.203662	105.8758
	3.33	0.223254	0.194498	102.8422
	3.67	0.222148	0.185176	102.5262
	4	0.220726	0.179962	99.7612
30 Story	0.5	1.5288	0.39078	
	1	0.78507	0.39078	350.1927
	1.4	0.49191	0.285	205.314
	2	0.26011	0.23408	141.8388
	2.53	0.236526	0.229574	123.15152
	3	0.227836	0.208244	114.02544
	3.33	0.227362	0.201766	113.70154
	3.67	0.22673	0.190074	112.2037
	4	0.225782	0.187704	111.8087
35 Story	0.5	1.77294	0.5187	
	1	1.01712	0.5187	538.6758
	1.4	0.70746	0.40521	475.917
	2	0.34941	0.25175	179.9775
	2.53	0.32186	0.24168	166.5711
	3	0.273182	0.221832	131.35488
	3.33	0.261016	0.216618	128.00844
	3.67	0.242372	0.199554	124.49768
	4	0.235578	0.196236	121.65052
40 Story	0.5	1.83495	0.60996	
	1	1.4664	0.61698	881.6457
	1.4	0.90207	0.48555	780.3705
	2	0.42674	0.29222	259.5324
	2.53	0.39596	0.28234	241.8985
	3	0.38209	0.27588	231.4941
	3.33	0.36404	0.27113	223.9454
	3.67	0.29941	0.233524	182.39994
	4	0.291826	0.23068	178.4215